Correlation and Chronology of the Miocene-Pliocene Bidahochi Formation, Navajo and Hopi Nations, Northeastern Arizona

by Todd A. Dallegge

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Approved:

Michael H. Ort, Ph.D. Co-Chair

Ronald C. Blakey, Ph.D. Co-Chair

Jim I. Mead, Ph.D.

Charles E. Barker, Ph.D.

Abstract

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The Mio-Pliocene Bidahochi Formation contains a record of geologic events for the evolution of the southern Colorado Plateau. The deposits of this formation recorded the interaction of phreatomagmatic volcanism with lacustrine and fluvial sedimentation. The formation of the Bidahochi depositional basin is related to drainage blockage by elevation of rift flanks from the Rio Grande Rift in New Mexico. Based on ^{40}Ar-^{39}Ar dating of interbedded, distally-derived felsic ash beds, onset of sedimentation occurred ~16 Ma . Lacustrine sedimentation rates ranged from 0.3 to 10 cm/ka. The felsic ash beds were geochemically correlated to ash beds and tuffs in the northern Basin and Range Province that have sources from the Snake River Plain and southwestern Nevada volcanic fields. The Hopi Buttes volcanic field erupted into the evolving lacustrine/fluvial system and the subsequent mafic phreatomagmatic activity produced abundant maars, tuff rings, scoria cones, and lava flows. Volcanic activity occurred periodically from 8.5-4.2 Ma. Erosion has since removed most sediments not capped by tuff and lava flows, creating abundant scattered mesas and buttes across the landscape. The style of volcanism, in conjunction with erosion, have produced complex stratigraphic relations. Using the interbedded felsic ash beds and lithogenetic packages, the isolated outcrops are correlated and the basin parameters defined. Basin geometry and sedimentalogic relations define a lake with a maximum surface area of 30,000 km^2 near the end of lacustrine deposition. A water budget was established by estimating paleoclimatic conditions and used to determine what drainage area was necessary to maintain this large lake. These calculations determined that the area encompassed by the Little Colorado River watershed could not have provided enough water to maintain the lake. Based on the water budget calculations and other paleogeographic considerations, the ancestral Colorado River must have flowed into this basin. Combining the available literature and the new evidence presented in this study, new paleogeographic reconstructions of the southern Colorado Plateau are porposed for Miocene and Pliocene time.

Acknowledgments

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Chapter 1 - Introduction

The purpose of this study is to analyze the Bidahochi Formation from a stratigraphic and chronologic perspective. Many issues exist about this formation and include: (1) the viability of the informal stratigraphic subdivisions; (2) the chronology of geologic events; (3)the Miocene basin morphology, and (4) regional paleogeographic relations.

Study Area

The Miocene/Pliocene Bidahochi Formation covers ~ 16,000 km^2 of the southern portion of the Colorado Plateau (Love, 1989). The study area for this research occurs ~ 70 km north of Holbrook, Arizona and ~ 185 km east of Flagstaff, Arizona (Figure 1.1). The study area is bounded on the north by Roberts Mesa and extends east/southeast to the Greasewood area. It encompasses the Hopi Buttes volcanic field to the west and south and occurs primarily on Navajo Nation lands, with a portion (northwestern corner) occurring on Hopi Tribe lands. The area is characterized by high-desert plateau vegetation. Low-lying topography is dominated by sagebrush and grasses while the mesas and buttes are sparsely covered by pinyon-juniper woodlands. The area is used by the Navajo and Hopi people for residences and the grazing of livestock.

Geologic Setting and Previous Studies

Regional geologic setting

The Bidahochi Formation occurs on the stable intercontinental region known as the Colorado Plateau (Figure 1.2). The Colorado Plateau was affected by deformation from the Laramide and Basin and Range orogenic events (Late Cretaceous to Miocene age). The plateau was elevated to its present altitude sometime during middle Tertiary time(Nations et al., 1985; Elston and Young, 1991) to late Tertiary time (McKee and McKee, 1972; Lucchitta, 1984). Much of the upper Mesozoic stratigraphy was removed from the Plateau prior to unconformable deposition of the Bidahochi Formation on Triassic (Chinle, Wingate, and Moenave Formations) through Early Cretaceous Formations (Dakota, and Toreva Formations [Akers et al., 1971]). The southern portion of the Colorado Plateau near the study area is drained by the Little Colorado River (LCR), Rio Puerco River, Zuni River, and many minor ephemeral streams and washes

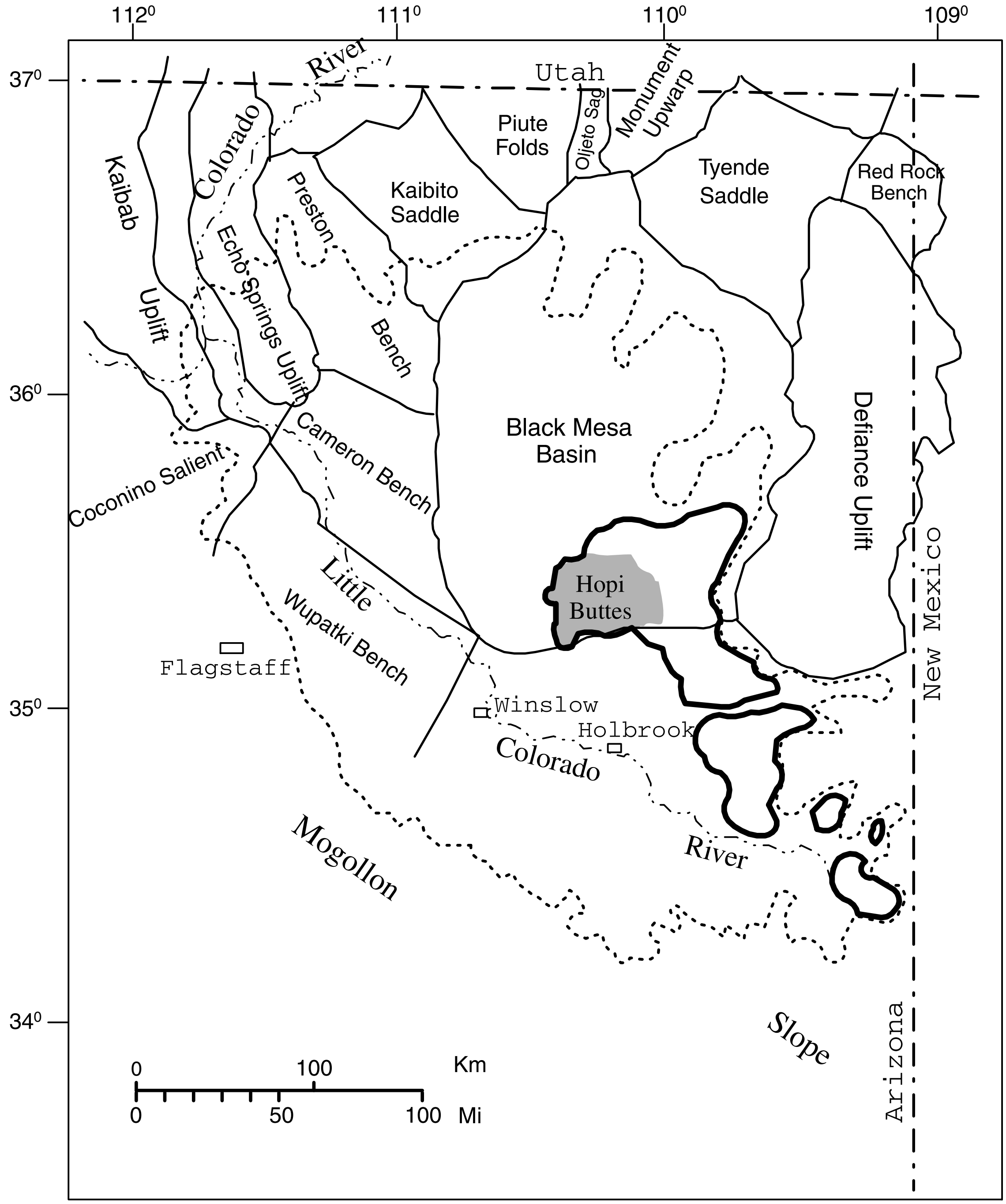


Figure 1.1 Physiographic provinces of northeastern Arizona (from Kelley, 1958). The study area is noted by the gray area around the Hopi Buttes. Dashed outline defines the inferred limit of Hopi Lake (from Scarborough, 1989). Thick solid line is current location of Bidahochi Formation deposits (from Repenning et al., 1958).

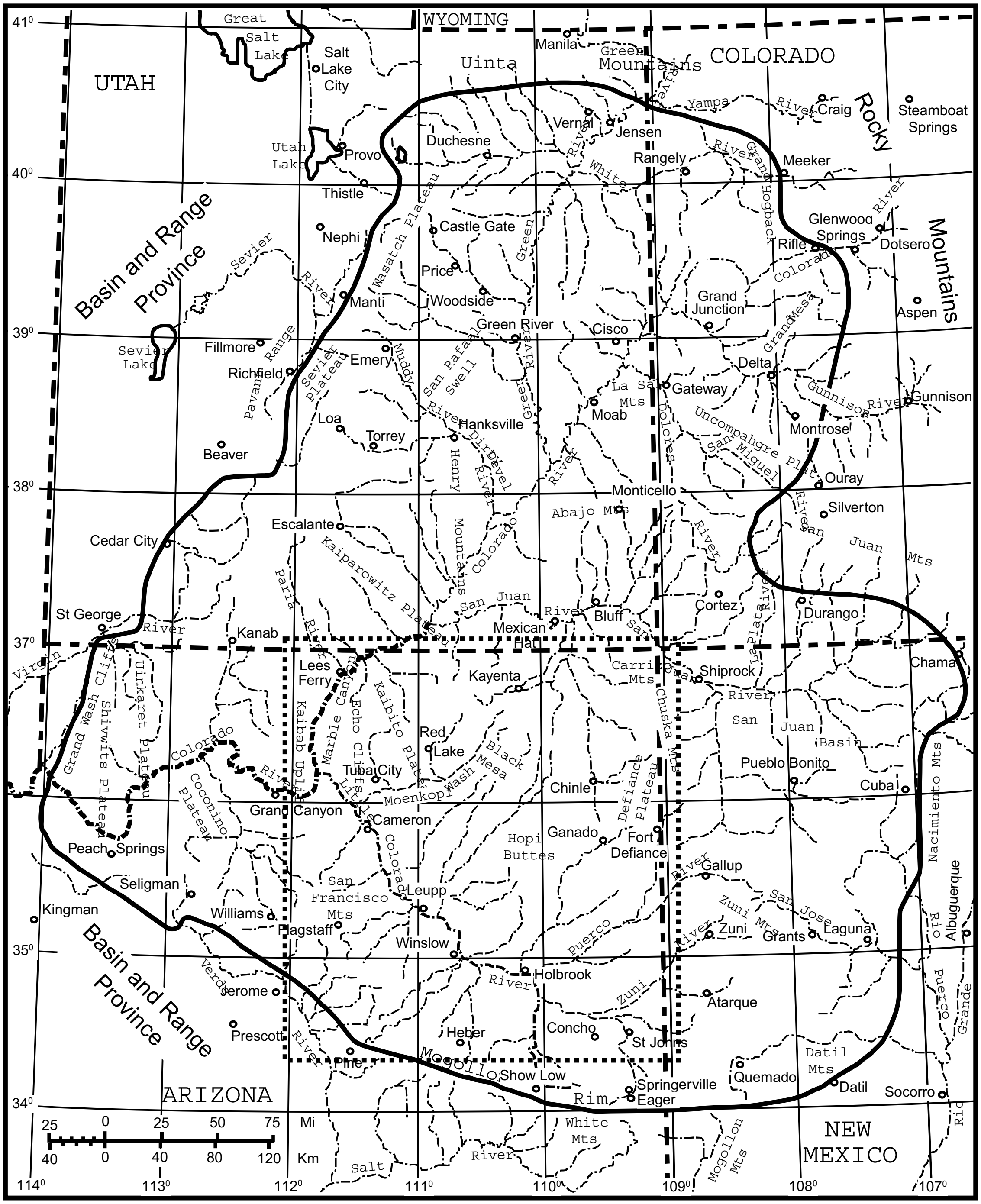


Figure 1.2 Regional map of the Colorado Plateau area (solid thick line). Most physiographic areas and communities are listed. Modified from Hunt (1956). Abbreviations: Mts - mountains, Plat - plateau. Dashed box delineates the area in Figure 1.1.

(Figure 1.3). Runoff from the southern Colorado Plateau reaches base level when the LCR joins the Colorado River which eventually empties into the Gulf of California.

Previous studies

Tertiary deposits in this area were first recognized by Newberry (1861) and then described briefly by Gregory (1917). The name Bidahochi Formation was first applied to these sediments by Reagan (1924, 1932) and a measured section at Bidahochi Butte was described. Williams (1936) recognized a large paleolake which he termed Hopi Lake. The formation was described in detail and informally subdivided into three members (Figure 1.3), lower, middle, and upper by Repenning and Irwin (1954). The lower member consists of fine-grained sedimentary rocks, primarily claystone, mudstone, siltstone, and minor fine-grained sandstone and localized conglomerate. It was interpreted as lacustrine in origin (Williams, 1936; Repenning and Irwin, 1954; Repenning et al., 1958; Shoemaker et al., 1962; and Sutton, 1974b). The middle member consists of mafic lava, tuff, and volcaniclastic material derived from the Hopi Buttes volcanic field. The volcanic deposits are interbedded with claystone, sandstone, and mudstone. Volcanism was characterized by phreatomagmatic eruptions that formed abundant maars, diatremes, and tuff rings (Sutton, 1974b; Shafiqullah and Damon, 1986b; White, 1989, 1991; Ort et al., 1998). Eruptions are interpreted to have occurred in a fluctuating lacustrine to playa environment (White, 1989). The upper member consists of abundant cross-bedded sandstone and siltstone with minor claystone. It has been interpreted as fluvial and eolian in origin (Repenning and Irwin, 1954; Repenning et al., 1958; Howell, 1959, Shoemaker et al., 1962). Twelve felsic ash beds that were derived from outside the Hopi Buttes volcanic field have been reported interbedded within the formation (Shoemaker et al., 1957). Shoemaker et al. (1957, 1962) further subdivided the formation into six members. The lower four members of Shoemaker et al. are roughly equivalent (see Chapter 2) to the lower member of Repenning and Irwin (1954). Howell (1959) conducted a regional study of the Bidahochi and surrounding formations. Volcanic deposits and vents of the Bidahochi Formation, produced by the Hopi Buttes volcanic field, were described in detail by Williams (1936), Hack (1942), Shoemaker et al. (1962), Sutton (1974a, b), Shafiqullah and Damon (1986b), Wenrich and Mascarenas (1982), Wenrich (1989), White and Fisher (1989), and White (1987, 1988, 1989, 1990a, b, 1991, 1992). Fossil material from Bidahochi sediments was described by Reagan,

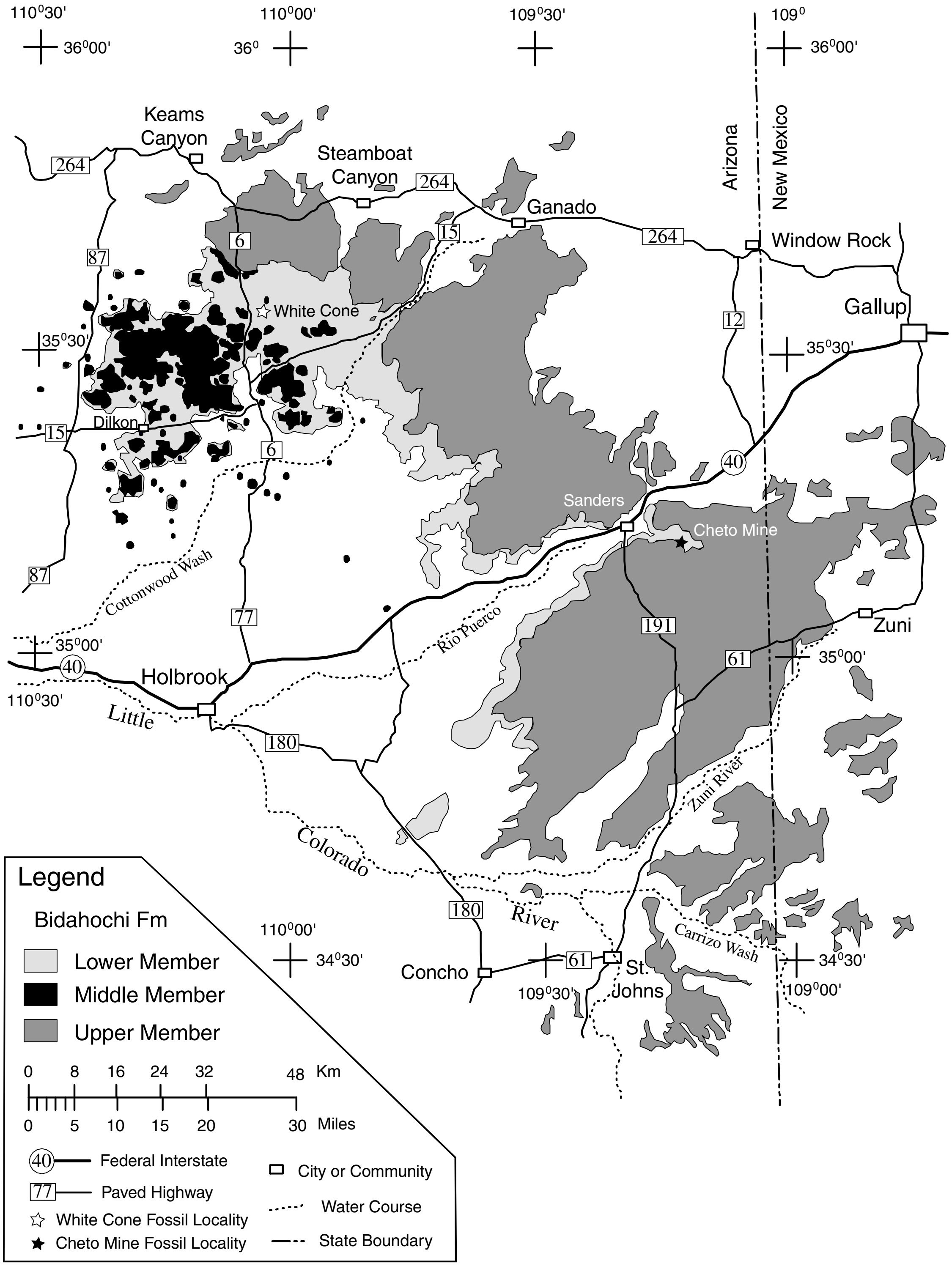


Figure 1.3 Map of the Bidahochi Formation showing the three informal members of Repenning and Irwin (1954) subdivision. Modified from Repenning et al. (1958).

(1929, 1932), Stirton (1936), Lance (1954), Taylor (1957), Uyeno and Miller (1965), Breed (1973), Sutton (1974b), and Baskin (1975, 1979). Love (1989) completed a comprehensive literature review of the Bidahochi Formation.

The lower and upper chronologic boundaries of the Bidahochi Formation are poorly constrained. Most of the isotopic and fossil dates are from the middle and upper portions of the formation. Love (1989) suggests that onset of Bidahochi sedimentation occurred about 9 Ma (or possibly 12 Ma) and then ceased by 4 Ma. Most of the volcanic material within the formation apparently was emplaced between 8.5 and 6 Ma with a few eruptions between 4.4 and 4.2 Ma (Shafiqullah and Damon, 1986a, b). Shafiqullah and Damon (1986b) suggested that the hiatus (6.0-4.4 Ma) may be due to sampling bias. Of the 300+ vents in the Hopi Buttes volcanic field, only a few dates have been published (Table 1.1). Baskin (1975, 1979) placed an age of late Hemphillian (~5 Ma) for mammalian fossil material from White Cone Peak (Figure 1.3). Vertebrate material from the Cheto Mine area east of Sanders, Arizona (Figure 1.3), is considered Clarendonian (~ 9-12 Ma) or possibly Barstovian (~ 12-16 Ma) in age (Lance, 1954; Howell, 1959; Breed, 1973; Lindsay and Tessman, 1974). Howell (1959) believed the beds at the Cheto mine area are older than the Bidahochi Formation, but other workers have placed them within the lower member of the Bidahochi Formation (Love, 1989). The fauna from the Cheto Mine site have identified species that are not known to have been extant at the same time interval (Love, 1989 citing a personnel communication with E. H. Lindsay). These problems and the uncertainty whether this locality is within the Bidahochi Formation are why Love (1989) suggested that the formation may be as old as 12 Ma.

Recent studies of sanidine from a felsic vitric ash bed (interpreted as coming from a distant large-volume eruption) at Triplets Mesa in the lower section of the Bidahochi Formation yielded an ^{40}Ar-^{39}Ar date of 13.71   0.08 Ma (Dallegge et al., 1998) (Table 1.1). This tuff bed is 75 m above the base of the formation implying that the underlying part of the formation is older than 13.71 Ma.

In addition to the study here, there are two other graduate students conducting research on the Bidahochi Formation. Jorge Vazquez (1998) has mapped Wood Chop Mesa (Figure 2.2), focusing on the volcanic stratigraphy and volcaniclastic sedimentation. Jason Hooten (in progress) is mapping an area near

Table 1.1 Previously reported isotopic dates for Bidahochi Formation (ages as reported by references)

Reported Age (Ma)	Analysis Type	Sample Type	Location	Reference
2.1 ± 0.2 (average)	fission-track	sphene from granodiorite	W110° 8.2' N35° 23.0' Coliseum diatreme	Naeser, 1971
4.1 (error not reported)	K-Ar	porphyritic, hyalopilitic and vesicular basalt	SW1/4, NE1/4, sec. 12, T25N, R21E - White Cone Peak area	Evernden et al., 1964
4.32 ± 0.59	Ar^{40}/Ar^{39}	basalt dike	N35° 22.63' W110° 03.55' Hoskietso diatreme	Damon et al., 1996
4.51 ± 0.18	Ar^{40}/Ar^{39}	basalt spatter flow in agglomerate	N35° 35.73' W110° 02.5' White Cone diatreme	Damon et al., 1996
5.5 ± 1.1	Fission-track	apatite from gabbro	W110° 3.5' N35° 22.7' Hoskietso diatreme	Naeser, 1971
6.12 ± 0.13	Ar^{40}/Ar^{39}	dense porphyritic basalt dike	N35° 31.22' W110° 04.06' Deshgish Butte	Damon et al., 1996
6.69 ± 0.14	Ar^{40}/Ar^{39}	monchiquite flow, vuggy, porphyritic	N35° 32.6' W110° 05.97' Teshim Butte	Damon et al., 1996
6.69 ± 0.16	K-Ar	trachybasalt	2.2 miles NW of White Cone Trading Post	Scarborough et al., 1974
6.71 ± 0.17	Ar^{40}/Ar^{39}	monchiquite flow, dense, slightly vuggy	N35° 28.5' W110° 06.8' Gray Mesa	Damon et al., 1996
6.75 ± 0.15	Ar^{40}/Ar^{39}	monchiquite flow, dense	N35° 27.8' W110° 14.68' Flat Mesa	Damon et al., 1996
6.76 ± 0.14	Ar^{40}/Ar^{39}	basalt dike	N35° 28.3' W110° 24.22' Bobcat Butte	Damon et al., 1996
7.15 ± 0.24	Ar^{40}/Ar^{39}	monchiquite, porphyritic olivine	N35° 32.93' W111° 09.37'	Damon et al., 1996
7.17 ± 0.16	Ar^{40}/Ar^{39}	monchiquite, dense	N35° 28.27' W110° 11.28'	Damon et al., 1996
7.51 ± 0.17	Ar^{40}/Ar^{39}	vesicular monchiquite flow w/ phenocrysts of biotite and pyroxene	N35° 28.37' W110° 24.35' Bobcat Butte diatreme	Damon et al., 1996
7.99 ± 0.18	Ar^{40}/Ar^{39}	monchiquite dike	N35° 33.63' W110° 05.57'	Damon et al., 1996
8.01 ± 0.185	Ar^{40}/Ar^{39}	basalt bomb	N35° 33.38' W110° 05.4'	Damon et al., 1996
8.01 ± 0.74	Ar^{40}/Ar^{39}	monchiquite w/ partially altered olivine	N35° 19.38' W110° 19.13'	Damon et al., 1996
8.67 ± 0.27	Ar^{40}/Ar^{39}	monchiquite dike	N35° 19.58' W110° 19.6'	Damon et al., 1996
13.71 ± 0.08 (2)	Ar^{40}/Ar^{39}	sanidine from a felsic ash bed of member 3	N35° 19.151' W110° 17.535'	Dallegge et al., 1998

west of Echo Spring Mountain (Figure 2.2) and focusing on lower diatreme facies and petrology of the associated magmas.

Methods of Investigation

The various techniques and methods used in this investigation are described in Appendix A and in the sections to follow.

Goals of the Research

The goals of this research are to analyze the Bidahochi Formation from a stratigraphic and chronologic perspective. Emphasis is placed on gathering data that will: (1) resolve problems associated with the informal subdivisions; (2) provide a chronology for the Bidahochi Formation; (3) define the basin morphology and (4) reconstruct the paleogeography of northeastern Arizona. This study does not focus on detailed sedimentologic analyses. Observations made during field reconnaissance and measuring sections, in addition to published reports, are used to identify shoreline facies and reconstruct the basin configuration. The study is primarily focused on the pre-Hopi Buttes volcanism units of this formation within the vicinity of the Hopi Buttes volcanic field (Figure 1.3); only minor work was done on the Hopi Buttes volcanic units and upper member of the Bidahochi Formation.

Informal subdivisions

The first goal of this research was to evaluate the usage of two informal stratigraphic subdivisions of the Bidahochi Formation. The problem concerns locating boundaries between members and the use of members in areas outside of the Hopi Buttes volcanic field. There is also a problem in the definition of the middle member of Repenning and Irwin (1954) which they based on the occurrence of the volcanic material from the Hopi Buttes volcanic field. Due to the eruptive style of the Hopi Buttes volcanic field, complex stratigraphic relations occur.

Bidahochi Formation chronology

The second goal for this research is to provide a more thorough chronology for the Bidahochi Formation. Very little age control exists on either the upper and lower boundaries of the formation or the timing of events for the evolution of this basin. A more complete chronology will provide sedimentation rates and a better understanding of the evolution of this system through time.

Basin morphology

The third goal for this research is to define the basin that provided the accommodation space for the Bidahochi Formation deposits. The mechanism for basin formation and the timing for this event has not been resolved. The morphology of this basin has been briefly considered but not well documented. Correlation of existing Bidahochi stratigraphy has been poorly documented. The goal was to establish a correlation of the current deposits and to analyze the deposits in order to determine the morphology of the basin.

Paleogeography of northeastern Arizona

Resolution of depositional and stratigraphic problems should clarify the paleogeographic relations of northeastern Arizona during Miocene-Pliocene time. Various theories have been proposed for the flow direction of the upper Colorado River prior to the dissection of the East Kaibab Monocline and the development of the Grand Canyon. These previous studies have the ancestral Colorado River flowing in four different compass directions; southeast (McKee et al., 1967), southwest (Hunt, 1969), northwest (Lucchitta, 1984), and northeast (Ranney, 1998).

The data and interpretations in the following chapters will provide some clarity to the problems listed above. A secondary goal to those listed above is to renew interest in this area for further scientific research. Many of the complexities of this part of the country may ultimately be deciphered within the deposits of the Bidahochi Formation and other regional features.

Chapter 2 - Stratigraphy

Two informal stratigraphic subdivisions have been reported for the Bidahochi Formation. The validity of both subdivision schemes has been questioned and several problems occur when applying these subdivisions across the entire regional extent of the formation. The purpose of this study was to evaluate the two subdivisions and determine which one was more appropriate or, if necessary, propose a revision that can be adequately used across the entire extent of the Bidahochi Formation. Volcanic material from the Hopi Buttes volcanic field constitutes a significant portion of the Bidahochi Formation. The emplacement of material from this volcanic field has created complex stratigraphic relations that hinders the placement of this material into either of the two previous proposed informal stratigraphic subdivisions. Based on field observations, a system is proposed that explains the complexities of the relations of the Hopi Buttes volcanic deposits with those of the surrounding systems. A revised stratigraphic nomenclature is proposed herein that can be used across the entire extent of the formation.

Previous Subdivisions

The Bidahochi Formation was informally subdivided by Repenning and Irwin (1954) and Shoemaker et al. (1957). The Repenning and Irwin (1954) subdivision splits the formation into three members; a lower lacustrine member, a middle volcanic member, and an upper fluvial and eolian member. Shoemaker et al. (1957) subdivided the Bidahochi Formation into six members for mapping purposes. The lower four members of Shoemaker et al. are roughly equivalent to the lower member (Figure 2.1) of Repenning and Irwin (1954). Members 5 and 6 are roughly equivalent to the middle and upper members, respectively.

Member Descriptions

The Shoemaker et al. (1957) stratigraphic subdivision is used to describe the Bidahochi Formation deposits. Table 2.1 lists the rock types and characteristics for each member described below. The information in Table 2.1 is based primarily on the reference sections at Wood Chop Mesa (Location 16 on Figure 2.2) and east of Greasewood (Location 12 on Figure 2.2) (see Appendix B for measured section

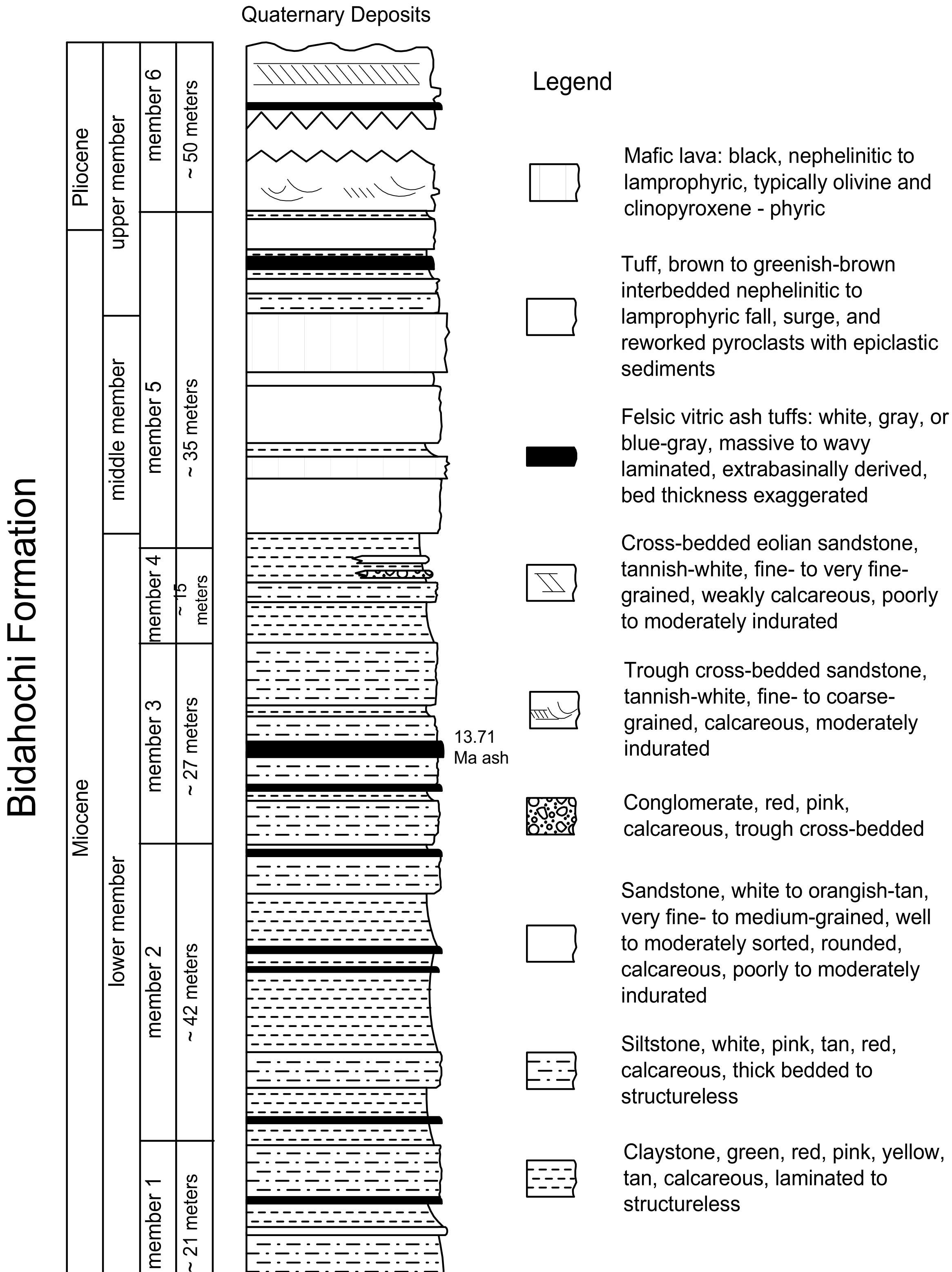


Figure 2.1 Generalized stratigraphic section of the Bidahochi Formation. Ash bed or lithologic unit thicknesses are not to scale. Lithology noted on column is roughly equivalent to amount of that type of sediment present.

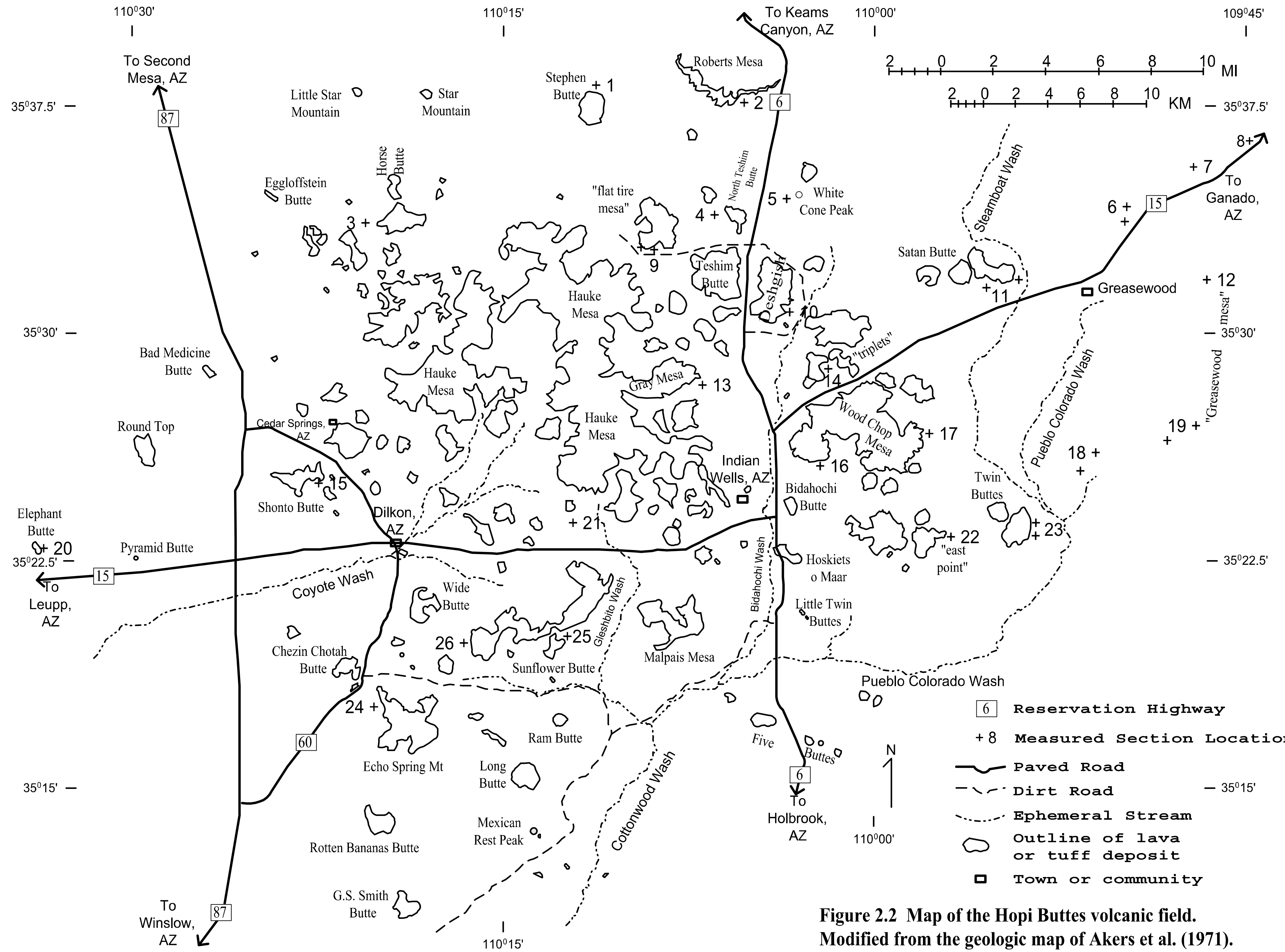


Figure 2.2 Map of the Hopi Buttes volcanic field. Modified from the geologic map of Akers et al. (1971).

descriptions). Variation between claystone and siltstone was field determined by tasting samples for clay and silt content. The term mudstone is used for rocks with equal amounts of clay and silt.

Common characteristics among members

Sedimentary units within the Bidahochi Formation are commonly poorly consolidated. They are partially to thoroughly cemented by calcite and/or clay. The units weather into brightly colored badlands-style topography. Commonly the units display very little depositional structures or post-deposition features. Close visual inspection reveals potential microscopic details within the rocks, but this technique was not employed for this study. Many individual units, including thin beds (e.g., 30 cm thickness) can be traced laterally for several kilometers. The first four members are fine-grained with clay and silt dominating the rock type present. Glass shard-rich felsic ash beds are noted within all members.

member 1

Member 1 (Figure 2.3a) is composed of red mudstone, siltstone, and claystone, interbedded with minor thin lenticular sandstone. A basal pebble conglomerate occurs in several localities on the unconformity between this member and the Mesozoic units. One or two felsic ash beds are present in some localities. Selenite nodules up to 2 cm in length occur locally in the upper units of this member. Mudstone units contain matrix supported, sand-sized material that appears to have no apparent bedding orientation. Thin lenticular sandstone units are rippled laminated and are 1 to 7 cm in thickness.

member 2

Member 2 (Figure 2.3a) is composed of varied colored, interbedded claystone, siltstone, marl, and ash (Table 2.1). This member is very cyclic with the various colors (green, brown, red, pinkish-tan, yellow, white) and rock types commonly repeating themselves in a systematic manner. Individual beds are commonly thin, <30 cm and alternate between claystone and siltstone. Green claystone beds of this unit are very calcareous and are commonly laminated. The laminations are composed of silt-sized material that commonly is iron-oxide stained near the outcrop surface. This member also locally contains abundant selenite nodules in the lower half of the member. The gypsum is not bedded or confined to one horizon and occurs as clusters (roses) of large selenite crystals (up to 3 cm in length). Iron-oxide staining is common at the base of this unit and within many of the green claystone (claystone/marl) units. The marl is white and

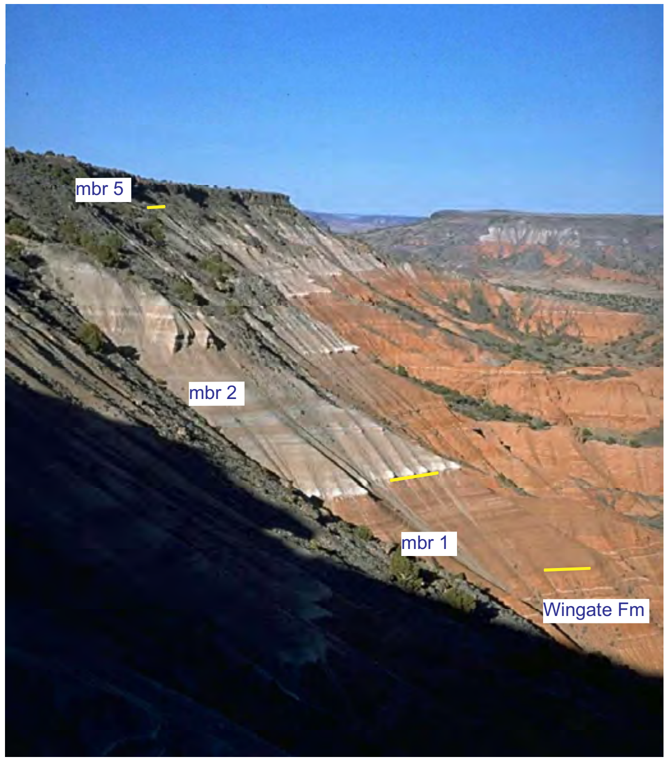
Table 2.1 Detailed characteristics of the Bidahochi Formation members. Rock types are listed in order of prevalence (top most prevalent).

	Rock Type	Color	Grain Size and Texture	Cement	Sedimentary Structures	Weathering Profile	Secondary Components
member 1	mudstone	red	clay and silt	calcareous/ clay	none to thick bedded	popcorn slopes	medium to coarse, matrix supported, sand grains. 0 to 2 felsic ash beds may be present
	claystone	red	clay	clay/ calcareous	structureless to laminated	popcorn slopes	
	siltstone	pinkish-red	silt, fine sand	calcareous/ clay	structureless	break in slope	
	sandstone	pinkish-tan	very fine- to fine-grained, well sorted, subrounded	weakly calcareous	structureless to wavy ripple	ledges	
	basal conglomerate	pinkish-white	pebbles to granules	compaction	structureless to trough x-bedded	ledge	
member 2	claystone	green, red, yellow, brown	clay	clay/ calcareous	structureless to laminated	popcorn slopes	units very cyclic and repetitive, fining upward common, gypsum, Fe oxide staining common
	siltstone	pinkish-tan	silt, fine sand	calcareous/ clay	structureless	break in slope	
	marl	white, lt green	clay present		structureless	ledges	
	ash	white, tan, gray	felsic, vitric	none to calcareous	structureless or wavy laminated	ledges	
member 3	siltstone	pinkish-tan	silt, fine sand	calcareous, no clay	structureless to thick bedded	break in slope/cliffs	dominated by siltstone, calcified slopes
	claystone	green	clay	clay/ calcareous	structureless to laminated	popcorn slopes	
	sandstone	pinkish-tan	very fine- to fine-grained, well sorted, subrounded	very calcareous	structureless to planar x-bedded	cliffs	
	ash	white, blue-gray, gray	felsic, vitric	none to calcareous	wavy laminated or structureless	ledges	
member 4	claystone	green and red	clay	clay/ calcareous	structureless to laminated	popcorn slopes	red lower part, green upper part coarser material only found in red unit thicker in eastern areas
	siltstone	pinkish-tan	silt, fine sand	calcareous/ clay	structureless to one bed	break in slope	
	localized sandstone	red, pinkish tan, orange	fine to coarse grained, well to mod sorted, subrounded	calcareous	planar and trough x-bedded	ledge	
	localized conglomerate	red, pinkish tan	granules to pebbles	calcareous	trough x-bedded to planar tabular	ledge	

Table 2.1 continued	Rock Type	Colors	Grain Characteristics	Cement	Sedimentary Structures	Weathering Profile	2ndary Components
member 5	tuff	brown, green-ish brown	fine to coarse lapilli, blocks	welded, calcareous	planar tabular, trough cross-bedded	cliffs, cap rock	volcanic material is interbedded
	mafic lava	black	nephelinitic to lamprophyric	crystalline	found as bombs within other units	cap rock	and common throughout all
	volcaniclastic sandstone	brown, tan	fine to coarse, poorly sorted, subangular	calcareous	planar tabular, planar/ trough cross-bedded	cliffs	non- volcanic units.
	siltstone	tan, pinkish tan, green	silt with abundant volcanic clasts	calcareous	planar bedded, soft sediment deformed	break in slope	White Cone member of
	volcaniclastic claystone	green, brown, lavender	clay, mafic clasts present	clay/ calcareous	structureless to laminated	popcorn slopes	Shoemaker et al. mammal, fish,
	sandstone	tan, white	fine to medium, poor to well sorted, subrounded	calcareous to friable	trough and planar x-bedded	ledges	and mollusks fossils at White
	accidental clasts	pink, green, red, tan	pieces of Mz rocks and older Bidahochi Fm	varies	bombs brought out by volcanic eruptions	resistant knobs in unit	Cone Peak
member 6	sandstone	tan, white	fine- to med-grained, well to mod sorted, subangular to rounded	calcareous	planar tabular, high angle planar/ trough cross-bedded	cliffs and ledges	sandstones form large cross-bedded units in places
	siltstone	tan, pinkish-tan	silt, fine sand	calcareous	planar tabular to structureless	slopes	concretions are abundant in upper
	claystone	green, brown	clay	clay/ calcareous	structureless to laminated	popcorn slopes	units, fish and mollusk fossils
	ash	white, tan	felsic, vitric	none to calcareous	wavy laminated or structureless	ledges	locally abundant
	volcaniclastic sandstone	grayish-white, tan	fine to coarse grained, mod sorted, subangular to rounded	calcareous	planar tabular, trough cross-bedded	ledges	

Most dominant character is listed first. Information based primarily on reference sections at Wood Chop Mesa and east of Greasewood (locations #16 and #12 on Figure 2.2). Variations exist at other localities.

a)



b)

Figure 2.3 a) Vertical cliff section (location 25 on Figure 2.2) showing members 1, 2, and 5. Member 1 is 19.5 meters thick. b) Southeast corner of Red Clay Mesa (location number 14 on Figure 2.2) showing members 3 through 5. The 13.71 Ma ash bed is 0.28 meters thick. The mesa is capped by a thin layer of mafic lava.

contains abundant silt- and sand-sized material. In some locations, small ostracods (<3 mm in diameter) are noted within the marl. Several thin (commonly <12 cm) felsic to intermediate ash beds are interbedded with these units. These ash beds are generally altered and mixed with surrounding rock types.

member 3

Member 3 (Figure 2.3b) is dominated by pinkish-tan siltstone with minor beds of green claystone, pinkish-tan sandstone, and white or blue-gray ash (Table 2.1). Very little clay-sized material is present within the siltstone units of this member. Several diagnostic ash beds occur interbedded with the siltstone. The ash beds are wavy-laminated and commonly loosely consolidated. The ash beds form small to moderate ledges against the slopes of the siltstone. The structure of these ash beds is undulatory with wavelengths up to 1 meter and amplitudes up to 30 cm. Laminae within the ash beds in some locations are disturbed and form U-shaped depressions and contortions. Thin ash beds (>10 cm) commonly pinch-out and are discontinuous. Sandstone units with this member have poorly-defined, planar cross-stratification. The green siltstone/claystone units of this member are laterally continuous and can be traced from butte to butte for several kilometers in some areas. This unit pinches out to the west/southwest (see Chapter 4) and is not distinguishable in the Sunflower Butte area (Figure 2.2). The units of this member weather to form smooth, steep slopes and small cliffs.

member 4

Member 4 (Figure 2.3b) is composed of green and red claystone with minor interbedded siltstone (Table 2.1). The lower portion of this member is red and the upper portion is green. The red units pinch out to the west/southwest and is discontinuous in western locations. This red unit is not present in the reference section on the southwest corner of Wood Chop Mesa (location 16 on Figure 2.2) but occurs on the northeastern side of the mesa (~ 5 km away). The red unit increases in thickness dramatically to the east from ~3 m near Red Clay Mesa (location 14 on Figure 2.2) to 36 m southeast of Greasewood, Arizona (location 19 on Figure 2.2). In the east it contains localized trough cross-bedded sandstone and conglomerate. Clasts in this conglomerate are dominated by chert, petrified wood, and carbonate fragments. At other nearby eastern localities, this member onlaps the Mesozoic Wingate Formation and defines the eastern portion of the basin (see Chapter 4).

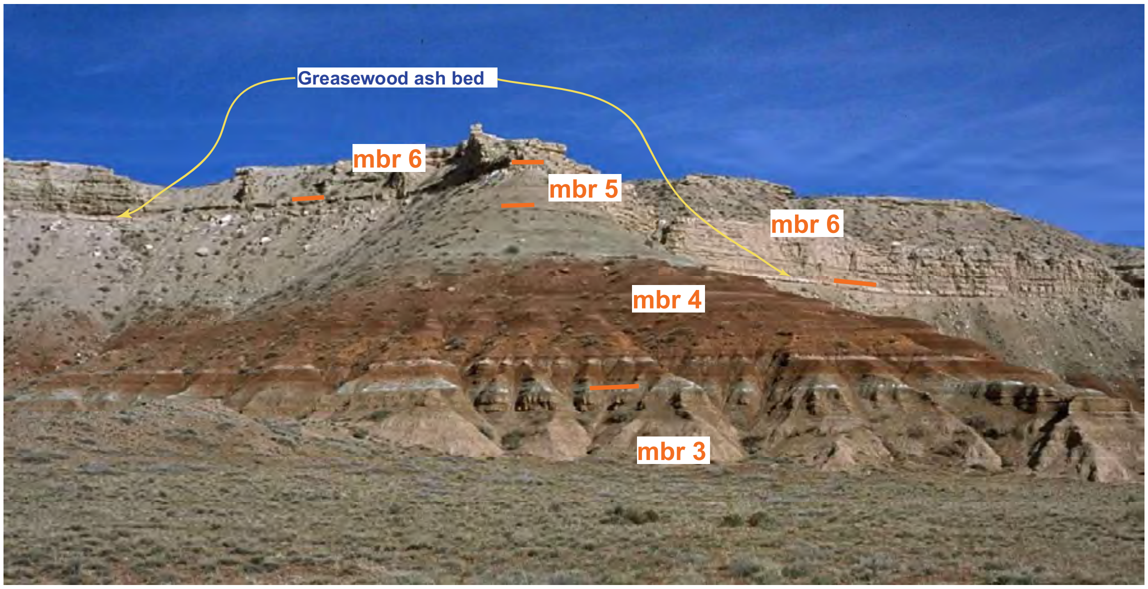
member 5

Member 5 (Figures 2.3 and 2.4a) is composed of brown, green, black, lavender, and tan tuff, lava, volcaniclastic sandstone, claystone, siltstone, and sandstone (Table 2.1). The volcanic deposits are nephelinitic to lamprophyric in composition and originated from the Hopi Buttes volcanic vents. This member is dominated by the input from phreatomagmatic eruptions that formed abundant maars, diatremes, and tuff rings (Shoemaker et al., 1957; Sutton, 1974b; Shafiqullah and Damon, 1986b; White, 1989, 1991; Ort et al., 1998, Vazquez, 1998). The tuff from this unit contains juvenile and accidental material. The tuff is thin- to thick-bedded and ranges from clast supported to matrix supported. The tuff commonly displays antidunes, cross-stratification, bomb sags, and scour structures. Volcanic material dominates this member with the vicinity of the Hopi Buttes volcanic field. Outside the area occupied by the Hopi Buttes volcanic field, the deposits are dominated by claystone, siltstone, and volcaniclastic sandstone. The volcaniclastic sandstone is composed of subangular to subrounded volcanic clasts from the Hopi Buttes volcanic field. The fine-grained units commonly contain beds of matrix-supported volcanic clasts. Shoemaker et al. (1957) informally designated this member as the White Cone member. The units that make up the middle section of White Cone Peak are within member five. The fossil locality from White Cone Peak has produced material that Baskin (1975, 1979) assigned an age of late Hemphillian (~ 5 Ma). Mammal, fish, and molluscan fauna have been collected from this locality. An asymmetrical lenticular bed of trough cross-bedded sandstone occurs at the base of White Cone Peak. The volcanic units of this member are very resistant and form the cap rock for most of the buttes and mesas of the area.

member 6

Member 6 (Figure 2.4) is composed of white, tan, buff, and green sandstone and siltstone with minor amounts of claystone (Table 2.1). This member contains abundant detrital material from the Hopi Buttes volcanic field. Sandstone units are commonly trough cross-bedded and fine upwards. Planar-tabular sandstone beds are common. Beds of this member are poorly to moderately indurated. Calcified concretions occur as thin lenticular sandstone bodies. In some locations, sandstone units are very fine- to fine-grained, rounded, well sorted, frosted, and high-angle, planar cross-bedded. Paleocurrent readings from channel axes and foreset beds indicate south-flowing streams (Love, 1989; Appendices B-2, B-12). Several felsic ash

a)



b)

Figure 2.4 a) Red Clay Mesa section (location 14 on Figure 2.2) showing members 3, 4, and 5. Member 4 is approximately 12 meters thick. b) Roberts Mesa area showing member 6.

beds occur within this member. Fish (Uyeno and Miller, 1965) and molluscan fossils occur locally in the channel sandstone units. The majority of member six is currently exposed to the north and east of the Hopi Buttes volcanic field (Figure 1.3). The deposits of this member occur farther to the north and east of the study area than the lower 4 members have been noted. No evidence has been found to suggest that this member once covered the lava capped plateaus of the Hopi Buttes volcanic field.

Member Contacts

Shoemaker et al. (1957, 1962) noted that all contacts between members were gradational. Thus, determining contacts between members is difficult in many areas. This study has been able to determine several of the contacts with some degree of certainty throughout the study area. The contacts between units are listed in Table 2.2.

In addition, it should be emphasized that the Hopi Buttes volcanic field causes many stratigraphic complications (see below). In this area, deposits from the maars (crater fill) and diatremes (volcanic necks, emplaced magma, brecciated tuff and wall rock) cross-cut all members of the Bidahochi Formation as well as Mesozoic and Quaternary units. These cross-cutting relations make member boundaries difficult to recognize (see stratigraphic subdivision discussion below).

Depositional Setting

Williams (1936) first described the depositional setting of the Bidahochi Formation as lacustrine and named the paleolake Hopi Lake. Later workers also supported a lacustrine interpretation for members 1 through 4 and parts of member 5 (Williams, 1936; Repenning and Irwin, 1954; Repenning et al., 1958; Shoemaker et al., 1962; and Sutton, 1974b). Based on evidence from the eruption features from the Hopi Buttes volcanic field, White (1989, 1990b) interpreted the environment in which the volcanic eruptions took place as fluctuating from lacustrine to playa. Member 6 was interpreted as fluvial and eolian in origin (Repenning and Irwin, 1954; Repenning et al., 1958; Howell, 1959, Shoemaker et al., 1962). Observations made during this study are consistent with those from previous interpretations. Other pertinent observations and comparisons are presented in the following sections.

The lenticular, ripple cross-bedded sandstone beds and the abundance of mudstone and siltstone of member 1 were deposited during the early stages of basin filling. There may be some question as to the

Table 2.2 Characteristics for determining the contacts between members of the Bidahochi Formation.

Contact	Contact Type	Characteristics for Identification
Mesozoic/ Bidahochi Formation member 1	angular unconformity	1) A small pebble lag gravel is commonly present at the base consisting of resistant lithologies including chert, quartz, metavolcanic clasts, dolostone, rhyolite, and petrified wood. 2) The Mesozoic units tend to be very well indurated with the Wingate weathering to form rounded nodular blocks while the Bidahochi Formation members are friable to poorly indurated. 3) The mafic minerals present in the Mesozoic units tend to be badly altered while the ones in the Bidahochi Formation are not as altered. 4) The color of the Bidahochi Formation member 1 is red while the Mesozoic contacts are orange (Wingate Fm), purple (Chinle Fm), or tan (Dakota Fm)
member 1/member 2	gradational to locally sharp	1) The contact is placed above the last major red mudstone unit and below the first thick green claystone/white marl unit. 2) The green claystone/white marl unit is commonly iron-oxide stained.
member 2/member 3	gradational	1) The contact is placed where siltstone becomes predominant over cyclic claystone/siltstone. The contact can usually be placed at the base of the first thick bed (usually > 50cm) of pinkish-tan siltstone. 2) The siltstone of member 3 contains very little interstitial clay and forms a break in slope or cliffs. 3) Member 3 contains from 1-3 green claystone units of moderate thickness (~30cm to 1m).
member 3/member 4	gradational to locally sharp	1) The contact is placed at the base of the green claystone of member 4. 2) The green claystone unit is commonly iron-oxide stained. 3) If the green claystone is not present then the contact is placed below the first red claystone unit of member 4.
member 4/member 5	gradational	1) This contact is placed at the first occurrence of detritus material from the Hopi Buttes volcanic field (Shoemaker et al., 1957, 1962). 2) Close inspection of the outcrop is necessary to determine this pick. 3) Near the Hopi Buttes volcanic field, the mafic detritus occurs as scattered matrix supported grains. Outbound from the Hopi Buttes volcanic field, the mafic detritus occurs as bedded reworked material.
member 5/member 6	gradational to sharp	1) This contact is placed at the base of the first thick sequence of trough and planar cross-bedded sandstone. 2) The cross-bedded sandstone forms cliffs overhanging the less resistant claystone of member 5.
member 6/ Quaternary units	erosional-scour and unconformity	1) This contact is placed at the scour or unconformable contact between the light colored poorly indurated sandstone of member 6 and the unconsolidated sand and gravel of the Quaternary units. 2) The Quaternary units are commonly light orange in color. 3) On top of mesas and buttes, the Quaternary units are generally stabilized dunes. 4) In some areas, the Quaternary units have back filled erosional channels cut into the Bidahochi Formation.

existence of Hopi Lake at this time. The rippled sandstone units and scattered sand-sized grains within the claystone units may be related to a fluvial setting rather than a lacustrine setting as previously proposed . By late member 1 time, the basin had probably began to fill with water. This is noted by the thick claystone beds and occurrence (in some localities) of silty marl at the transition between members 1 and 2. The gypsum in the upper portions of this member is probably related to the early stages of lake formation and resulted from periodic drying of small water-filled depressions.

Repenning and Irwin (1954) and Shoemaker et al. (1962) used the regional uniformity of the stratigraphy, fine-grained character, and rarity of cross-stratified units to infer a lacustrine setting for member 2. These similar features were noted at many localities in this study. In addition, the fine-grained units throughout this formation are commonly structureless or thinly laminated. Other studies have also used thin and parallel laminations as well as structureless clayey muds to infer lacustrine environments (Picard and High, 1972; Sly, 1978). The thin beds, alternating colors, and cyclic nature of the member 2 units may be related to climatic effects on Hopi Lake. The gypsum in this member is probably secondary, similar to member 1, and was deposited either in the subsurface layers immediately after burial or from later diagenetic events. The iron-oxide staining within this member is developing from ferromagnesian minerals occurring within the silt partings of the laminated clays. It also occurs at the base of members two and three, possibly suggesting minor soil development or exposure resulting from changes within the lacustrine environment.

Member 3 was also interpreted as lacustrine in origin (Williams, 1936; Repenning et al., 1958; and Shoemaker et al., 1962). The ash beds within this unit display signs of standing water deposition (see Chapter 3). The interbedded green siltstone and claystone beds are similar to those in member 2 and suggest a similar setting. The dominance of siltstone as the main rock type suggests that changes occurred within this environment that did not exist during member 2 deposition. The siltstone units of this member contain very little interstitial clay-sized material (determined by XRD analyses and field tasting). The dominance of siltstone and lack of clay-sized material may suggest several things: (1) a shortage of clay-sized material transported to the basin, (2) the clay-sized material was post-depositional removed by diagenetic processes, or (3) energy levels were too high to settle out clay-sized material. Member 3 is predominately located in the eastern half of the field area and can be traced to the edges of the lake basin. These onlapping relations and coarser nature would suggest that energy levels were higher due to shallow near-shore processes and/or migration of the shoreline.

Shoemaker et al. (1958) interpreted the red trough cross-bedded conglomerate, sandstone, and mudstone units of member 4 as delta lobes. Shoemaker et al. suggested that this member formed as two deltas prograded out into the lacustrine system. The pinching-out of this member to the west and the large sediment wedge located near the margin of the basin supports Shoemaker et al. s interpretation of a deltaic system. The abundance of petrified wood and carbonate fragments suggests a fluvial system was eroding this material from the Chinle Formation and transporting it to the eastern margin of Hopi Lake. The fining westward nature of the red units represents progressively greater distance from shore and from the source area that was providing clastic material. The green claystone units that occur above the red units (more common in the west) suggest that a similar environment to the lower members was occurring at this time. The characteristics of these green claystone units would still imply the existence of a lacustrine environment that had a prograding deltaic system along the eastern margin of the lake.

Member 5 is composed of eruptive material from the Hopi Buttes volcanic field and sedimentary deposits similar to the members below. The paleoenvironment for this unit is covered below in the discussion of the Hopi Buttes volcanic field.

This study agrees with the fluvial and eolian setting for member 6 presented by previous studies (Repenning and Irwin, 1954; Repenning et al., 1958; Howell, 1959, Shoemaker et al., 1962). The trough cross-bedded sandstones, fish fossils, and thin interbedded siltstone and mudstone units are all indicative of a fluvial environment. In areas where the fine-grained, well sorted, frosted, high-angle planar cross-bedded sandstones occur, they represent eolian dune activity, probably located on the flood plain of the fluvial system during times of aridity or low flow. These environments would be similar to the current conditions occurring in the Little Colorado River valley.

Hopi Buttes Volcanic Field

Material from the Hopi Buttes volcanic field makes up a portion of the rock types that form the Bidahochi Formation. Approximately 300 volcanic vents and their associated erupted material from the

Hopi Buttes volcanic field cover 800 km^2 of the outcrop distribution of the Bidahochi Formation (Williams, 1936; Hack, 1942; Shoemaker et al., 1962; Ort et al., 1998). Clastic sediment from the volcanic field was incorporated into the ongoing depositional system that was forming the fine-grained siliciclastic sediments in the basin. In other areas, tuff and lava flows covered some of these fine-grained siliciclastic deposits. Erosion has since removed the sediments not capped by tuff and lava flows, creating abundant scattered mesas and buttes across the landscape (Figure 2.5). The style of volcanism, in conjunction with erosion, have produced complex stratigraphic relations within the Bidahochi Formation.

Style of Hopi Buttes volcanism

Hopi Buttes volcanism produced abundant landforms including maars, tuff rings, diatremes, agglomerate domes, small shields, lava flows, and scoria cones (Ort et al., 1998). Many of these landforms were produced by the interaction of magma and water, termed phreatomagmatism. This process is very important to this study because this system tends to create complex relations within the surrounding stratigraphy.

Phreatomagmatism in the Hopi Buttes volcanic field produced maars, tuff rings, and diatremes. Maar volcanoes are downward-projecting cone-shaped craters cut below previous ground level that are wide relative to rim height (Fisher and Schmincke, 1984) (Figure 2.6). A tuff ring is composed of phreatic, phreatomagmatic, and magmatic debris (Ort et al., 1998) that forms a ring around the eruptive vent. Diatremes occur below the maars and form cone-shaped areas that can extend for several kilometers below the surface. The diatremes consist of several levels of juvenile material that are mixed with the surrounding country rock (Ort et al., 1998). Maars, tuff rings, and diatremes form when rising magma comes in contact with aquifers, shallow-water lakes, or water saturated sediments. If confining pressure exists (usually due to overlying strata), then the pressure build-up from the water/magma interaction can cause an explosion that blasts the overlying rock away. These holes are further enlarged by continuation of the eruptive processes and build-up of pressures and then are commonly filled in with material from the eruption (in this case mafic tuff and scoria and reworked sedimentary rocks) or by late stage emplacement of lava. Lava fills the crater and/or flows out across the surface when water, the driving mechanism of this type of eruptive

Figure 2.5 Photo showing the buttes and mesas formed by erosional events. Photo taken from the southwest side of Wood Chop Mesa, view to the south.

process, is prevented from interacting with the uprising magma. If the maar is not filled by lava, it can be filled with material from sedimentation processes occurring nearby (e.g., lacustrine, fluvial, eolian).

Paleoenvironment of volcanism

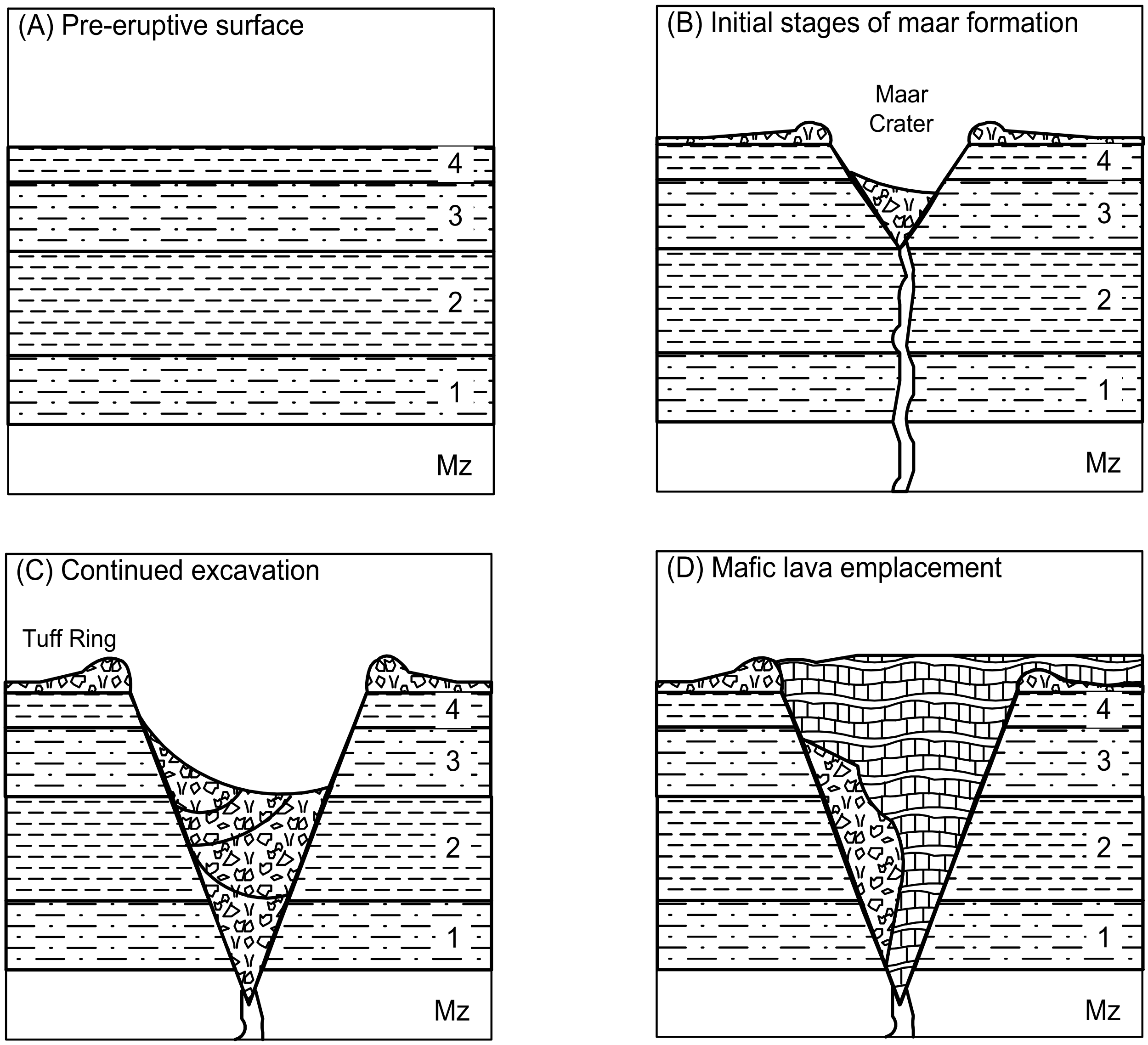
Various hypotheses have been suggested to explain the products produced by the interaction of Hopi Buttes volcanic field with the coeval depositional environments that produced the fine-grained units of the Bidahochi Formation. Previous workers have applied their interpretations to the entire duration of the eruptive phase of the Hopi Buttes volcanic field. Although this may be applicable in many areas, various conflicts occur throughout the lateral and vertical extent of the volcanically produced deposits.

previous interpretations

Hopi Buttes volcanism is characterized by mafic units consisting of interbedded volcanogenic sediments, primary volcanic deposits, mudrocks, maar crater sediments, and lavas (Repenning et al., 1958; Shoemaker et al., 1962; White, 1989, 1990a; Ort et al., 1998). The volcanic units were first interpreted as having interacted with Hopi Lake and the sedimentation processes occurring in the lake (Williams, 1936; Sutton, 1974b). Hack (1942) and Shoemaker et al. (1962) suggested that this environment was dominated by a swampy fluvial plain. White (1990a, 1990b, 1991) describes features such as dessication structures, eolian dune deposits, paleosols, and stream channels. White interpreted these features as the result of deposition in a playa setting with localized ephemeral lakes occurring during the period of volcanism. Vazquez (1998) has noted localized evidence for eruptions into water such as hyaloclastite and possibly wave-reworked tuff, but reports a predominance of subaerial features (e.g. surge flow tuff, subaerial lava flows).

new observations

Several contact and physical relations between sedimentary and volcanic rocks are used to interpret the paleoenvironment of deposition during the eruptions of the Hopi Buttes volcanic field. These relations are: (1) gradational and hyaloclastite contacts between volcanic and nonvolcanic deposits, (2) relations of lacustrine deposits with early stage volcanic units, (3) lateral stratigraphic relations away from the Hopi Buttes volcanic field, and (4) relative elevations of the pre-eruptive surfaces for individual maars.



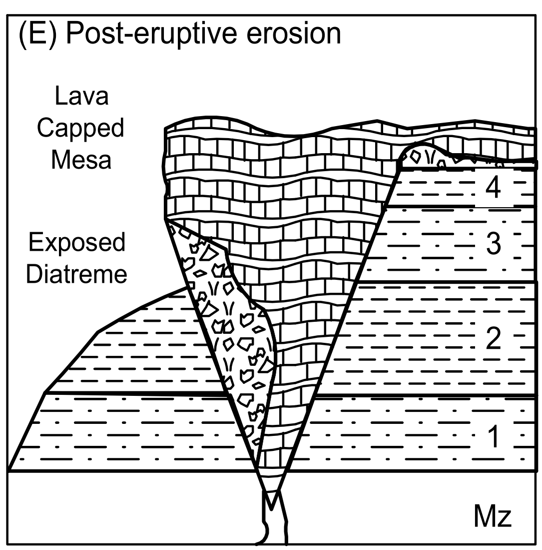


Figure 2.6 Diagrammatic illustration of maar style volcanic processes. Panel (A) is the pre-eruptive surface after lower member Bidahochi Fm deposition. Panel (B) is early maar crater formation with ejecta forming small maar rim around crater and back-filling a portion of the crater. Panel (C) is continued maar eruptions with excavation down into pre-Bidahochi deposits (Mz). Continued buildup of fallout tuff to form tuff ring. Panel (D) mafic lava emplacement after the cessation of the phreatic process. Lava pools up in crater and may flow out over previous tuff material and/or lower member Bidahochi Fm. Panel (E) is post-eruptive erosion that has removed much of the softer Bidahochi sediments. The lava flow serves to cap the soft sediments in some areas and allow preservation of section. Note: volcanic material can be in contact with any of the older units due to this type of eruptive process. Toreva blocks are also common.

(1) At several localities the base of the lava flow, in contact with the claystone units below, displays a hyaloclastic texture (fragmental volcanic rock derived by the quenching of lava). In localized areas, the carapace of lava flows and dikes have a peperitic texture (Vazquez, 1998). The base of some lava flows is rubbley. In several localities, the contact between the pyroclastic volcanic material and the lower fine-grained sedimentary units is gradational. At these gradational contacts, mafic tuff and mafic aphanitic clasts are matrix-supported within the fine-grained lacustrine units. These matrix-supported clast units are interbedded with layers of fallout tuff, surge-emplaced tuff, claystone, and volcanic sandstone (Figure 2.7). These interbedded contacts are cyclic and occur vertically over several 10s of cm. Commonly, the contact between the lava (or tuff) and sedimentary units is very sharp and abrupt. In some locations, the lava fills scour-like channels cut into the easily eroded sedimentary units below.

(2) In several localities, discrete sequences of volcanic activity are separated by a thick interbedded sedimentary sections. These relations are best exhibited at the north end of Hauke Mesa and White Cone Peak areas.

The Hauke Mesa (Figure 2.2) area contains vast expanses of volcanic deposits from the Hopi Buttes volcanic field. The majority of the mesa is composed primarily of fallout tuff, tuff sandstone, bombs, and lava flows with subordinate siltstone, claystone, and sandstone. Two discrete sequences of volcanism, separated by the sedimentary deposits (Figure 2.8), are well exposed at flat tire mesa (Figure 2.2, Appendices B-9e and B-9w). Within the lower sequence of volcanic units, several beds of claystone and siltstone are interbedded with tuff and volcanic sandstone (Figure 2.8). At the top of this volcanic sequence, rounded, planar cross-bedded, reverse-graded volcanic sandstone lies above a tuff layer with large (up to 1 meter in length) mafic bombs. Directly above these volcanic sandstone units, alternating beds of claystone and siltstone onlap these deposits. An ash bed within one of the siltstone layers is 6.5 m above the lower volcanic sequence and 10.6 m below the contact with the upper volcanic sequence maar rim deposits (Figure 2.8, Appendix B-9w). This ash layer can be traced around the mesa to the east where it occurs only 3 m above the same cross-bedded volcanic sandstone that is above the tuff bed with the mafic bombs (Figure 2.9, Appendix B-9e).

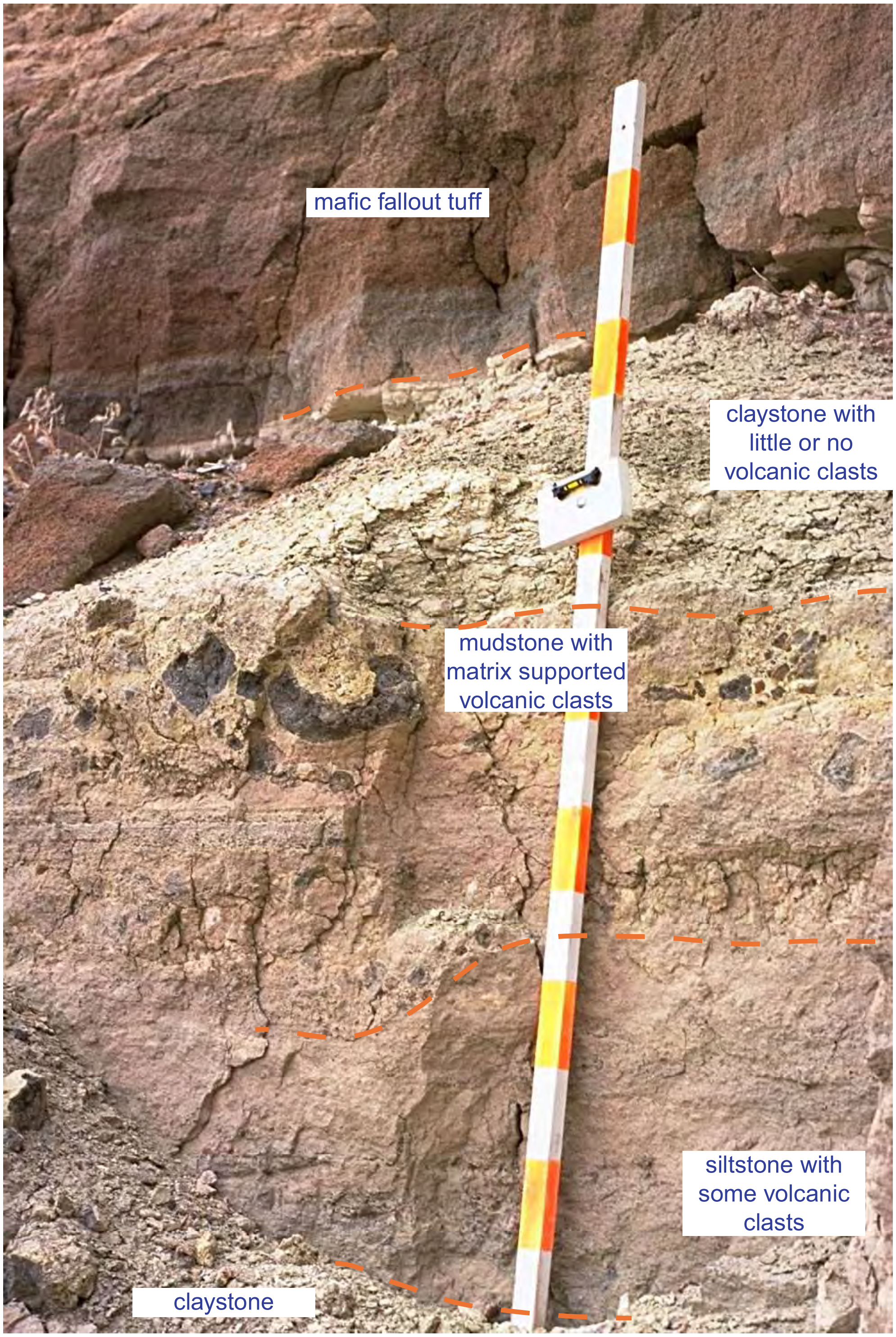


Figure 2.7 Photo at the vertical cliff section (location 25 on Figure 2.2) showing the gradational nature of the contact between members 2 and 5. Matrix supported volcanic material varies throughout units with very little occurring in the upper green claystone unit. Jacob staff is 1.5 meters in height.

At White Cone Peak (location 5 on Figure 2.2), a thin interval of mafic tuff is interbedded with siltstone and claystone. This tuff forms a discrete ledge around the base of the peak. The tuff is overlain by siltstone and claystone (Appendix B-5). The sedimentary units contain matrix-supported clasts from the Hopi Buttes volcanic field. North of White Cone Peak, tuff and lava from the White Cone maar are exposed above correlatable siltstone and claystone units at the cone as well as the thin ledge of tuff.

(3) A thick section of lacustrine deposits located to the north and east of the Hopi Buttes volcanic field is noted at the same stratigraphic interval as the tuffs and lava flows within the Hopi Buttes volcanic field. This relation is observed at Roberts Mesa and east of Greasewood, Arizona. At Roberts Mesa (location 2 on Figure 2.2, Appendix B-2), only a thin layer (1.4 m) of mafic tuff is easily recognizable (Figure 2.10). Above this ledge of tuff is a thick sequence (18.7 m) of lacustrine claystone and siltstone that contains varying amounts of matrix-supported and reworked mafic clasts from the Hopi Buttes volcanic field. Above the claystone and siltstone interval, the contact with the upper member is observed (Figure 2.10).

Similar observations are noted near Greasewood, Arizona (locations 6-8, 12 on Figure 2.2, Appendices B-6,B-7,B-8, and B-12). At these locations, siltstone, claystone, and sandstone of member 5 contains mafic volcanic material from the Hopi Buttes volcanic field. This Hopi Buttes material is rounded, well sorted, and chemically altered (pyroxene and olivine phenocrysts are altered). Commonly the mafic volcanic material occurs as individual beds of clast-supported tuff sandstone. The beds of member 5 are thin to thick bedded with graded (normal and reverse) and massive beds present. Scour marks and rip-up clasts are common. Above these units of member 5, a thick ledge-forming ash bed occurs just below the base of member 6 (Appendices B-6, B-12).

(4) The relative elevations of the pre-eruptive surfaces of individual maars vary considerably. Since maar eruptions occur at the surface and extend into the subsurface, the relative elevations of individual maar lava flows can be used to determine the last known pre-eruptive surface prior to coverage by lava. Erosion may have contributed to some changes in elevation prior to lava flowing across the surface and preserving it, but in the case of gradational, hyaloclastic, and peperitic contacts, the pre-eruptive surface

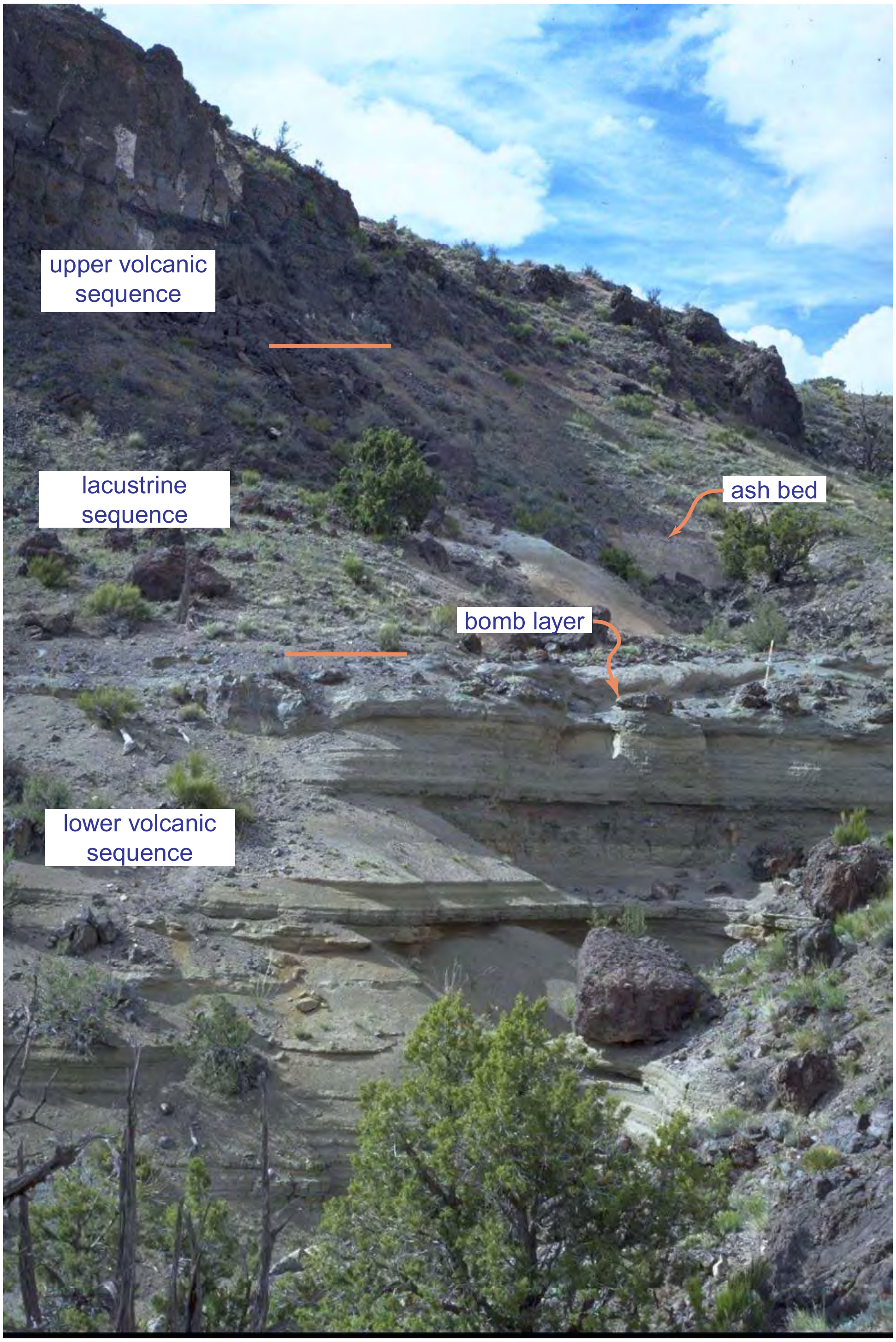


Figure 2.8 Photo of 'Flat Tire Mesa' west outcrop location. Two volcanic sequences are separated by lacustrine units. The lower sequence consists of surge-deposited tuff, reworked tuff, and fallout tuff with minor beds of nonvolcanic claystone and siltstone. A mafic bomb layer occurs near the top of lower sequence just below a unit of cross-bedded reworked tuff. A 1.5 m Jacob staff is to the right of the bomb layer label. See text for further description.

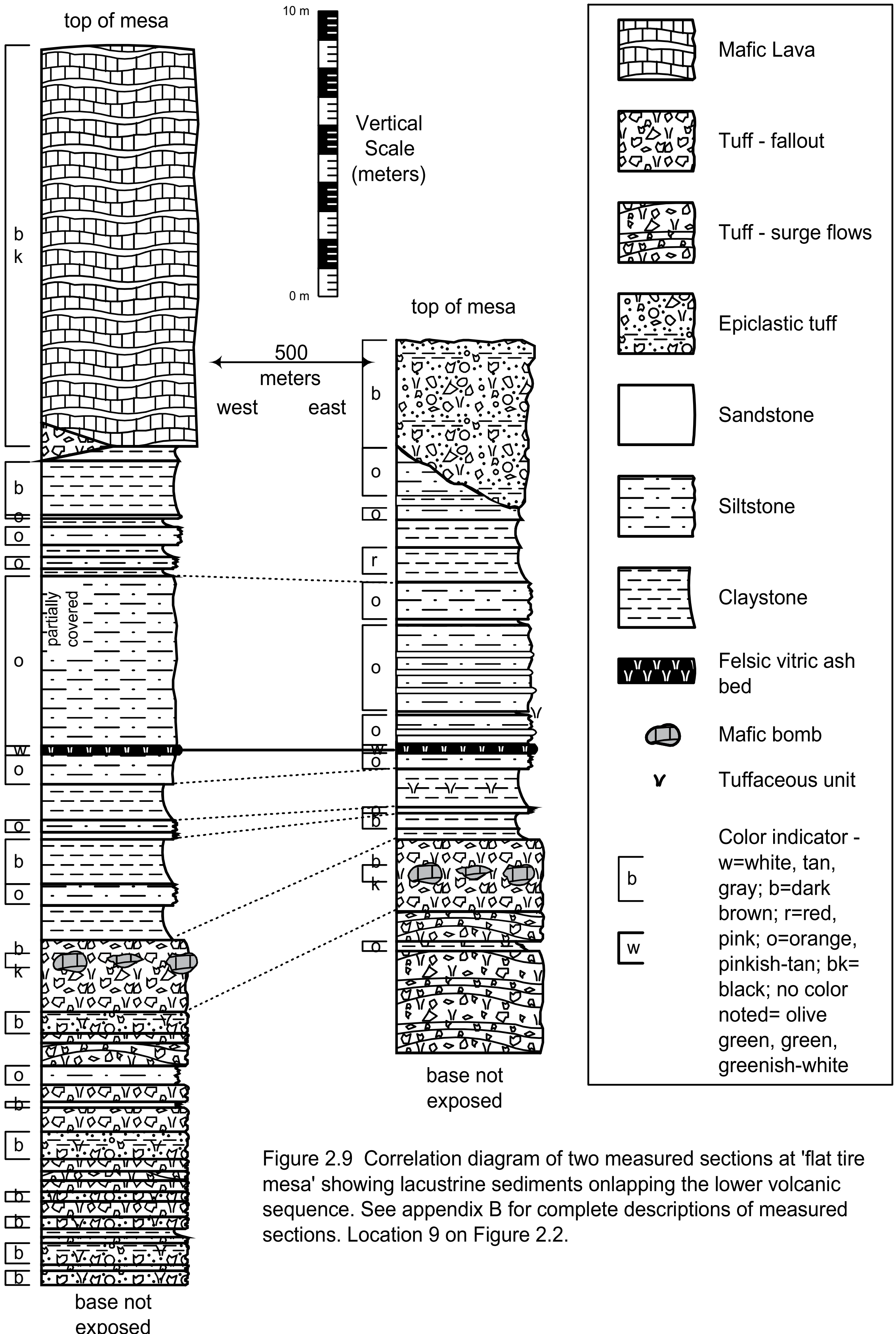


Figure 2.9 Correlation diagram of two measured sections at 'flat tire mesa' showing lacustrine sediments onlapping the lower volcanic sequence. See appendix B for complete descriptions of measured sections. Location 9 on Figure 2.2.

can be easily recognized. Plates 1 and 2 graphically illustrate the variation in relative elevations of individual maar lava flows.

paleoenvironment interpretation

This study contends that White s (1990a, 1990b, 1991) playa interpretation for the setting the Hopi Buttes volcanic field erupted into is agreeable. The features he observed on and around Hauke Mesa support only minor water/magma interaction most likely from interactions of groundwater and/or water-saturated sediment. Vazquez (1998) reports at Wood Chop Mesa are also indicative of lava flowing across dry to slightly wet sediments. Evidence presented above is also suggestive of a volcanic/playa interaction. The hyaloclastic and peperitic textures suggest that the lava or dikes came in contact with standing water or water-saturated sediments. The rubbley bases of some lava flows suggests that the they flowed over relatively dry ground. Previous observations, particularly White s, have been used to characterize the entire environment for the Bidahochi Formation across the basin during the eruptive phases of the Hopi Buttes volcanic field. This application of environment across the basin and throughout time is in error. Several relations presented above imply that coeval fine-grained sedimentation was occurring nearby during the eruptive phase of the Hopi Buttes volcanic field.

The gradational contacts between sedimentary units and volcanic units and the matrix-supported volcanic clasts within claystone and siltstone units implies that eruptive material from the Hopi Buttes volcanic field was incorporated into these lacustrine units as they were being deposited. The cyclic nature of these gradational contacts and the vertical distance over which they occur (Figure 2.7) suggests that lacustrine deposition was occurring during and between eruptions of the volcanic field. The sharp and conformable contacts between volcanic and sedimentary units may indicate that no prolonged soil development (paleosols) or erosional unconformities occurred between eruptions. This implies that volcanism was coeval with fine-grained sedimentation and that no basin-wide hiatus in sedimentation occurred prior to volcanism. Some of these sharp contacts may have developed due to the phreatomagmatic emplacement of lava or tuff.

The upper beds of the lower volcanic sequence at flat tire mesa with the rounded clasts, planar x-bedding, and reversed grading may represent wave reworking of previously deposited tuff. The tracing of

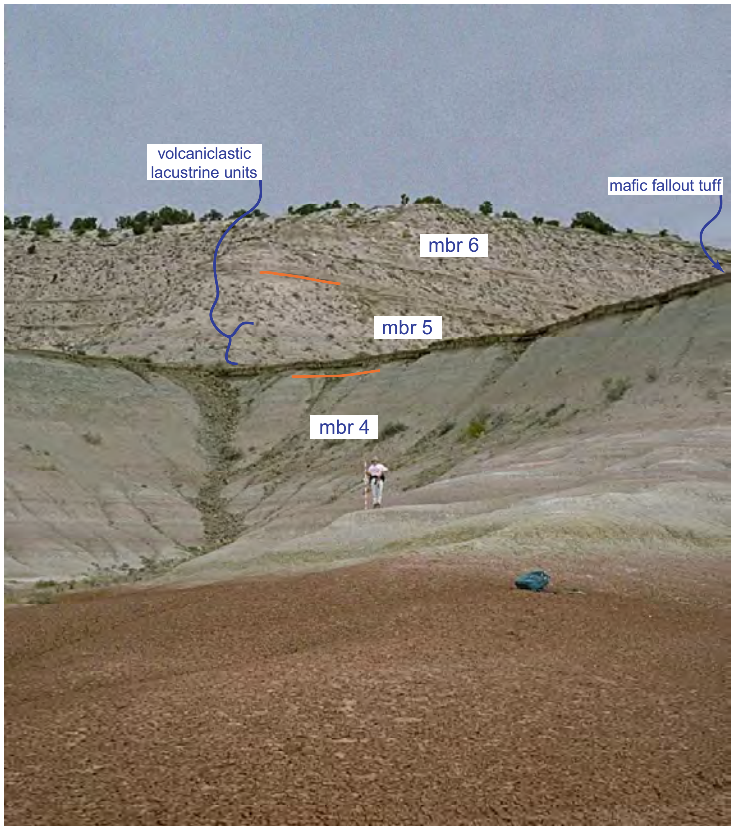


Figure 2.10 Outcrop photo of Roberts Mesa section (location 2 on Figure 2.2). Note the ledge of fallout tuff and the volcaniclastic lacustrine units above ledge. Person is holding a 1.5 m Jacob staff.

Figure 2.11 Photo to the west from the top of Echo Spring Mountain. San Francisco Mountains are in background. Erosion has exposed the necks and lower diatremes of the maars in this area.

the ash bed, claystone, and siltstone units along the mesa shows that the lacustrine units onlap the slightly dipping (measured 2-7 degrees) lower volcanic sequence and the reworked tuff. The eruption of the upper sequence of volcanic deposits implies that a significant amount of lacustrine sedimentation (~17 m) occurred in between these two eruptive periods. A similar observation to this one is noted at White Cone Peak and White Cone maar. The fine-grained units occurring above the thin layer of tuff are below the pre-eruptive surface for White Cone maar and separate two different periods of volcanic activity.

Sedimentary deposits and the tuff layer at White Cone Peak are correlatable to those at Roberts Mesa (Plate 2). Baskin (1975, 1979) reported a late Hemphillian age (~6-5 Ma) for vertebrate fauna from beds directly above these tuff and sedimentary units. This would chronologically place these lacustrine deposits at Roberts Mesa and White Cone Peak within the time-frame (8.5 - 4.2 Ma) of the eruptions of the Hopi Buttes volcanic field. The matrix-supported volcanic clasts within the lacustrine units and the time interval above suggests that lacustrine deposition was occurring coeval with volcanism.

The sedimentary units near Greasewood, Arizona, suggest that lacustrine deposition was occurring throughout the eruptive history of the Hopi Buttes volcanic field. The rounded, well sorted, and chemically altered individual beds of clast-supported mafic volcanic material suggest that this material was transported to the site of deposition. Bedding, scour, and rip-up characteristics at this location may suggest deposition by turbidity currents. Such a process implies transport of the volcanic material from the distant Hopi Buttes volcanic field area to this location. The boundary between member 5 and 6 can be recognized at this location and suggests, stratigraphically, that these beds are within the eruptive interval of the Hopi Buttes volcanic field.

The relative elevations of individual maar lava flows supports ongoing lacustrine deposition between eruptions. The lava flows covering the lacustrine sediment have preserved the pre-eruptive surface and clearly show that variable amounts of sediment were deposited between eruptions.

In conclusion, the paleoenvironment of volcanism was quite varied. This depositional basin was potentially quite large (see Chapter 4) and therefore, multiple depositional settings were most likely occurring simultaneously across the basin. It is apparent that lacustrine deposition occurred between two different phases of volcanism in at least two locations and persisted to at least member 6 time (~5 - 4 Ma).

There is no evidence to show a hiatus in lacustrine deposition in areas away from the Hopi Buttes volcanic field. The large buildup of volcanic material in the Hauke Mesa area and central areas of the Hopi Buttes volcanic field in general, probably created a playa setting due shallow-water conditions or topographic expression of the area. The onlapping relations of lacustrine units in the flat tire mesa would indicate that this was most likely a topographic high and that filling of the lacustrine basin created onlapping conditions. This topic will be covered further in Chapter 4.

Problems with Previous Subdivisions

There are several problems that arise when using either of the two informal subdivisions of the Bidahochi Formation stratigraphy. As stated above, there is some confusion in picking the contacts (Figure 2.1) between the lower and middle member of Repenning and Irwin (1954) or member 4 and 5 of Shoemaker et al. (1957) and the contact with the middle and upper member or member 5 and 6 (of Repenning and Irwin (1954) and Shoemaker et al. (1957), respectively). The volcanism from the Hopi Buttes volcanic field also creates problems due to the emplacement process and resulting landforms produced by the phreatomagmatic eruptions.

Recognition of member boundaries

As stated above, the members of Shoemaker et al. (1957) are roughly equivalent to the three members of Repenning and Irwin (1954). The Shoemaker et al. subdivision differs because they used the first appearance of Hopi Buttes volcanic material in the claystone beds as the contact between their fourth and fifth members (Figure 2.1). Shoemaker et al. stated that the contact is conformable and gradational between these members. Repenning and Irwin (1954) defined their middle member based on the volcanic material from the Hopi Buttes volcanic field. They placed the contact between their lower and middle members at an unconformity they described at the base of the lava flows capping many of the mesas and buttes. Shoemaker et al. (1962) did not recognize the regional unconformity that Repenning and Irwin used to place the contact between their lower and middle members. This study has also been unable to locate this unconformity and has found several areas where the contact is gradational, thus eliminating the existence of a region-wide erosional unconformity.

The contact between the middle and upper members was placed by Repenning and Irwin at the tops of the lava-capped plateaus. In areas between mesas or away from the volcanic field, claystone and siltstone deposits contain abundant volcaniclastic material. These volcaniclastic units occur at the same stratigraphic horizons, or higher, than lava flows and tuff of the middle member in the Hopi Buttes volcanic field. Because of this relation, Shoemaker et al. (1957) placed this contact (Figure 2.1) so that these volcaniclastic lacustrine units would be part of their member 5 (~ Repenning and Irwin s middle member). They picked their contact between members 5 and 6 to occur at the change in deposits from dominantly claystone and siltstone to dominantly cross-bedded sandstone.

Another boundary problem occurs, especially with the Repenning and Irwin subdivision, when trying to determine the lower/middle member boundary away from the focus of the Hopi Buttes volcanic field. In areas to the east and north, very little volcanic material is preserved in its original depositional context. Instead, it has been thoroughly reworked and incorporated into the depositional system that was present away from the volcanic field. Using Repenning and Irwin's subdivision in this area is very problematic because it is hard to determine what constitutes enough volcanic material present for picking the contact. The Shoemaker et al. (1958) scheme works better here because they used the first occurrence of volcanic material to place the contact. This can usually be accomplished with close inspection.

Complexities resulting from style of volcanism and erosion

Hopi Buttes volcanism produced a variety of complex relations within the Bidahochi Formation stratigraphy. In many places, volcanism has excavated down into the Mesozoic stratigraphy (Figure 2.6). The subsurface excavated cone and resulting fill can place the middle volcanic member (or member 5) in contact with beds of the lower member (members 1 through 4). This can even place the middle member (member 5) in contact with Mesozoic units (Figure 2.6).

Erosion makes it very difficult to determine the contact between volcanic and sedimentary units of the lower members. In western exposures, erosion has removed most of the sedimentary cover. Many of the buttes and mesas are eroded so that the diatremes below the maars are exposed (Figure 2.11). This produced erosive relations that suggest that lava or tuff deposits of member 5 are in contact with the lower four members. Toreva blocks often result from the erosive process and can add to the difficulty when trying to determine stratigraphic relations.

Other areas that do not fit well into the proposed subdivision of Repenning and Irwin (1954) are the two distinct volcanic sequences at Hauke Mesa and White Cone maar mentioned above. At these locations, sedimentary units were clearly deposited between two eruptive phases of the Hopi Buttes volcanic field. This relation would place the middle member in two stratigraphic positions. Clearly this would eliminate the use of Repenning and Irwin's (1954) middle member as currently defined.

<u>Stratigraphic Clarification</u>

From the problems discussed above, it is apparent that some clarification of the Bidahochi stratigraphy is warranted. The system of Repenning and Irwin (1954) has conflicts primarily because they define the middle member based mostly on the existence of Hopi Buttes volcanic material. Therefore, it is suggested here that this system should be eliminated entirely. The Shoemaker et al. (1957) system has minor problems but can still be adequately used if several clarifications are noted that deal with the complexities of the Hopi Buttes volcanic material. Shoemaker et al. described their member 5 in 1962 and used an informal field designation of the White Cone member to distinguish it from their previous descriptions. In areas near the diatremes, they placed the contact at the first occurrence of limburgite detritus. This commonly includes 1.5-3 m of claystone with volcanic material at the base. Shoemaker et al. (1962) noted that this member exhibits abrupt local facies changes related to the distribution of the diatremes and primarily consists of mafic tuff and lava flows near the diatremes. Away from the diatremes, the White Cone member consists mainly of claystone, minor sandstone, and vitric tuff, with only thin beds of mafic tuff or tuffaceous claystone. They noted that the variation in thickness of this member is great, with 61-91 m of mafic tuff occurring west of the community of Indian Wells (Figure 2.2).

It is suggested hereafter that the Shoemaker et al. (1962) scheme should be used. This eliminates the member 5 usage and adopts the informal White Cone member field term as previously described by Shoemaker et al. (1962). One minor clarification to this scheme is that the same contact between members 4 and 5 can be used away from the diatremes as described in Table 2.2. Use of this nomenclature will help to eliminate confusion when discussing the complex relations between sedimentary units and the volcanic units of the Hopi Buttes volcanic field.

Chapter 3 - Interbedded Ash Beds

Shoemaker et al. (1957) noted 12 individual ash beds within the claystone and siltstone sequences (members 1-4) of the Bidahochi Formation. These ash beds were one of the primary foci of this study. They were instrumental in determining limiting ages on the stratigraphy, establishing chronohorizons across the basin, and correlating outcrops across the field area.

General Ash Bed Descriptions

The ash beds are felsic to intermediate in composition (petrographic determination) and were not derived from the ultramafic Hopi Buttes volcanic field. They are fallout tephra deposits from distant, large-volume eruptions that were deposited in Hopi Lake (Shoemaker et al., 1962) and preserved within the fine-grained lacustrine units. The term ash bed will be used throughout to differentiate these felsic, distally derived ash beds from the mafic to ultramafic tuff from the Hopi Buttes volcanic field. The color of the intermediate composition ash beds is gray to green-gray, while the felsic beds tend to be white, tanish-white, or light blue-gray. Ash beds that have not been calcified or thoroughly reworked with surrounding rock types are wavy laminated, friable, homogeneous, and vitric. Intermediate composition ash beds are commonly altered to bentonite and/or other clays. In some locations the entire ash bed is wavy (Figure 3.1), with some beds having up to 1 meter wavelengths and 30 cm amplitudes. The ash beds range in thickness from 1 cm to 60 cm. The contact at the bottom of the ash bed is commonly sharp whereas the upper contact is gradational and mixed with the overlying rock type. The degree of calcification varies from none to completely indurated. Ash beds that are completely calcified are structureless and form prominent ledges. The friable ash beds form breaks in slope with white stripes of color across the outcrop. The thicker, more competent ash beds form prominent ledges that can be traced along the edges of the buttes and mesas (Figure 2.3b).

Several thick (>10 cm) ash beds were sampled on the centimeter scale to look for vertical and lateral variations in characteristics, such as grain size, shard type, and phenocryst composition. This sampling revealed that slight variations occur, especially in grain size and shard type (Figure 3.2). Many of the ash beds have cyclic repetitions in characteristics. Phenocrysts show a fining upward relation in each

a)

b)

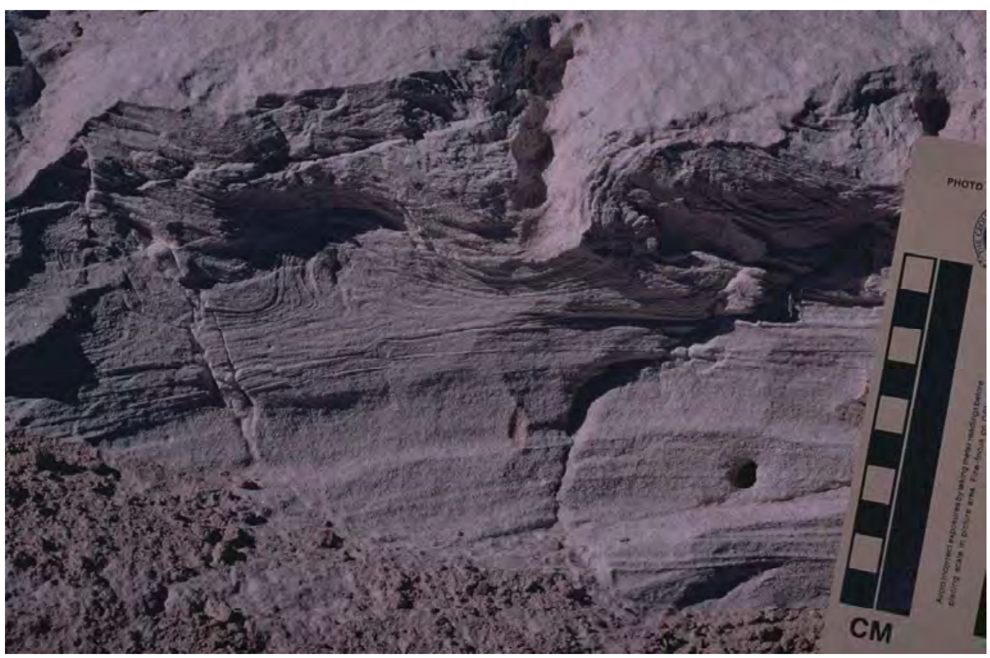


Figure 3.1 a) Photo of 13.71 Ma ash bed at Triplets location (#14 on Figure 2.2). Note the undulatory nature of the entire ash bed. Rock hammer is 28 cm long. b) Close-up photo of same ash bed above. Note the fine wavy laminated nature of the ash bed and the soft sediment deformation features.

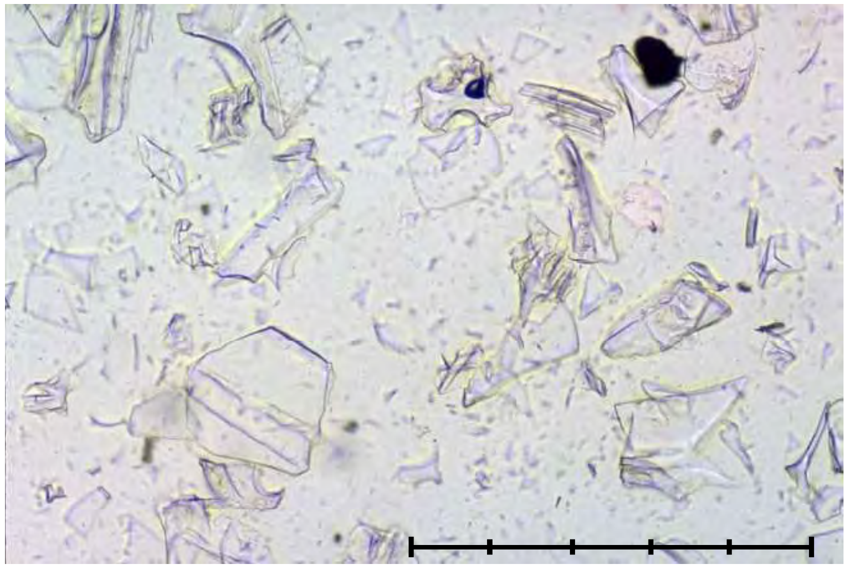
cycle. Glass shards show an inverse relation where the small and needle-like shards tend to be at the base of each cycle while the broad flat shard types tend to be at the top. Little variability exists in individual ash bed characteristics across the basin.

In some locations the ash beds are associated with marl deposition (e.g. Wood Chop Mesa - Appendix B-13, and vertical cliff section - Appendix B-15). The ash beds are associated with the fine-grained sediments and, in most cases, do not occur with coarser sandstone, tuff, or conglomerate deposits. They occur interbedded with claystone and siltstone, predominantly within the lower 4 members. The only exception to this fine-grained association is an ash bed at location 8 (Figure 2.2). Here this ash overlies a pebble conglomerate that is in contact with Mesozoic Wingate Formation (see Plate 1 and Appendix B-8). The upper portion of this ash bed is thoroughly reworked with sand and is overlain by another pebble conglomerate layer.

These ash beds contain wavy laminations, fine upwards, are compositional homogeneous, and show slight vertical shard-size variations. These ash beds were deposited in a standing water environment (Shoemaker et al. (1962) and preserved by subsequent deposition of fine-grained material. Most of these ash beds occur within the fine-grained units that have been interpreted as lacustrine in origin. The reworked upper surfaces suggest that continuing sedimentation and other sedimentation processes (e.g., storm-induced wave action or agitation of the water column, erosion and transportation of ash and other clastic sediment from outlying areas, etc.) mixed the upper surface of the ash bed after deposition. The homogeneous nature of these ash beds is a function of their distal nature. Variation in characteristics decreases as a function of the distance traveled. The cyclic nature of the thicker ash beds probably represents multiple eruptions in the source area over several days to weeks. It may also represent variations in ash distribution into the atmosphere where various wind patterns brought ash to the basin at different times. The ability of the wind to carry these ash beds may also have contributed to the slight vertical variations in characteristics.

The alteration of the intermediate ash beds is probably related to increased amounts of easily altered minerals such as hornblende and magnetite. The decreased glass content of these intermediate beds is a function of the eruption composition.

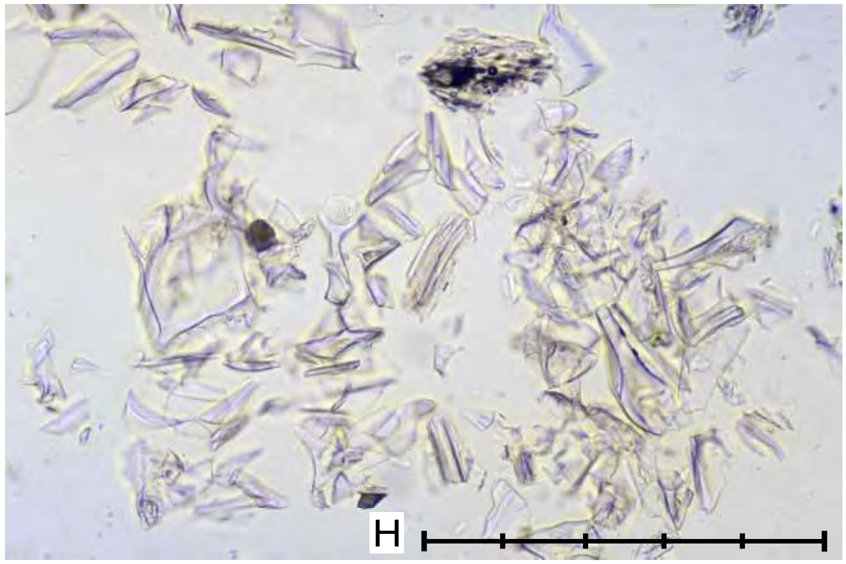
a)



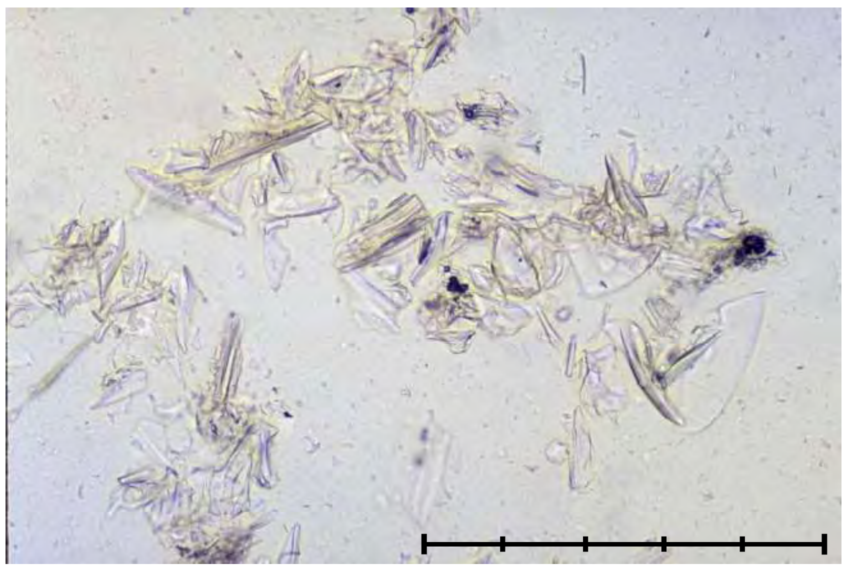
b)

Figure 3.2 Photomicrographs of the 13.71 Ma ash bed at Triplets Mesa showing the vertical variation within the bed. Bar scale is in 0.1 mm increments totaling 0.5 mm. All photomicrographs are in plane-polarized light. Samples of glass shards were mounted in epoxy spread on thin section and covered with cover glass. The ash bed was sampled at various intervals, measured from the base up. a) Interval sampled from 1 to 2 cm. Sample #971107A. b) Interval sampled from 5 to 7 cm. Sample #971107B. Grain labeled S at bottom center is sanidine. c) Interval sampled from 12 to 14 cm. Sample #971107C. Grain labeled H at bottom center is hornblende. d) Interval sampled from 19 to 21 cm. Sample #971107D. e) Interval sampled from 26 to 28 cm. Sample #971107E.

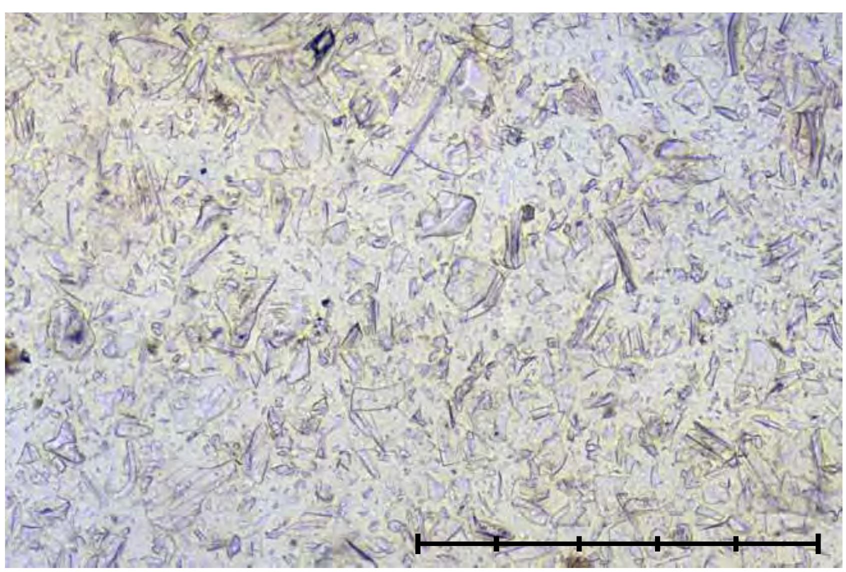
c)



d)



e)



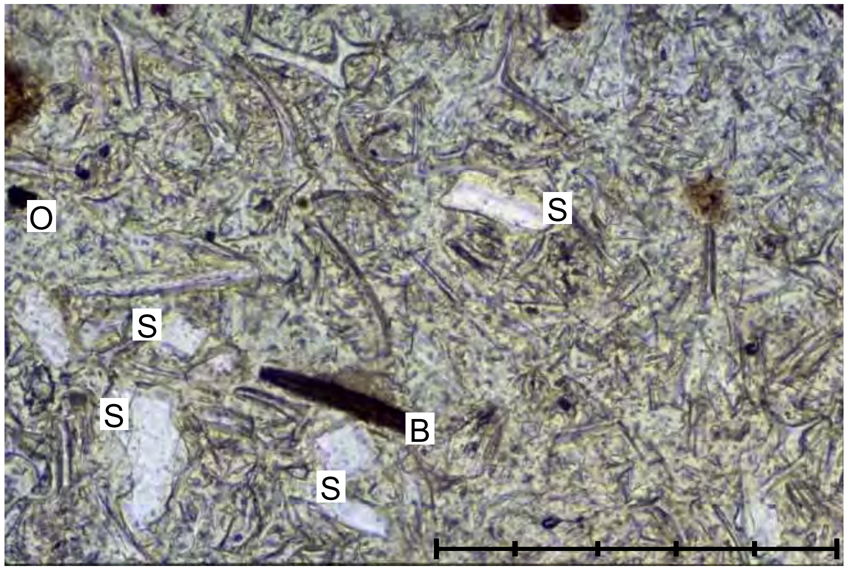
Petrography

Petrographically these ash beds are commonly vitric and have variable mineral compositions. Some beds are almost entirely composed of glass shards. Constituent mineral grains accompanying the glass shards within the ash beds are sanidine, blue-green and green-brown hornblende, biotite, plagioclase, opaque minerals (commonly magnetite), and muscovite (Figure 3.3). Brown glass is more common in intermediate ash beds but does occur within the felsic varieties. Small phenocrysts of plagioclase, orthopyroxene and magnetite are noted in some of the brown glass fragments (Figure 3.4a). The intermediate ash beds, in comparison with the felsic ash beds, have lesser amounts of clear glass shards, abundant altered glass and minerals, and increased amounts of intermediate minerals (hornblende, magnetite, and biotite). Average grain size of the glass shards varies from 0.01 mm to 0.13 mm with the constituent mineral grain sizes ranging a half to a full order of magnitude smaller than the accompanying glass shards. Shard type, mineral composition, and grain size does not vary significantly from location to location within the same ash bed. Alteration of the ash beds varies from none to complete alteration of the glass to bentonite (Figure 3.4b, c) or clays (smectite/illite). Alteration is not restricted to the entire bed or any horizon and can vary laterally along one bed.

A variety of glass shard morphologies are noted within the ash beds. The types present, as well as the amounts of each type, vary among the different ash horizons. Shard morphologies present are lath, needle, bubble wall (tricuspid), attached needle, snowflake, and blocky (Figures 3.5 and 3.6).

The shard types are a function of the eruption style and vary with gas content, viscosity, eruption rate, and cooling rate and can be useful for characterizing individual ash beds. The homogeneity of the ash beds reflect the distal nature of the source area. The long transport distance through the air tends to sort the characteristics due to the capacity of wind to carry the material. This results in homogeneity and consistency in grain characteristics from location to location across the depositional basin. The homogeneous nature of the ash bed was crucial for correlating purposes because textural and compositional characteristics were the basis for the correlations in areas where ^{40}Ar-^{39}Ar or glass shard geochemistry results were not available. Other textural features such as pumice or lattice frameworks were also useful for characterizing the ash beds.

a)



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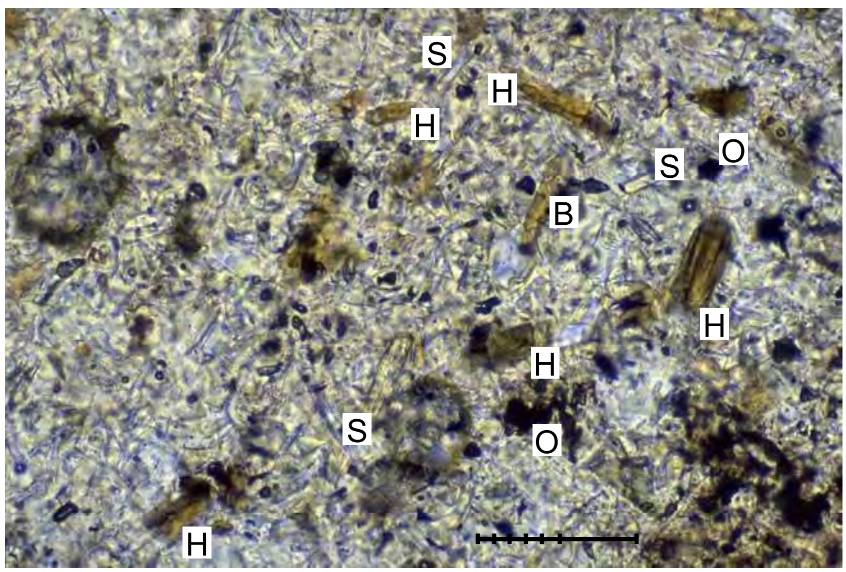
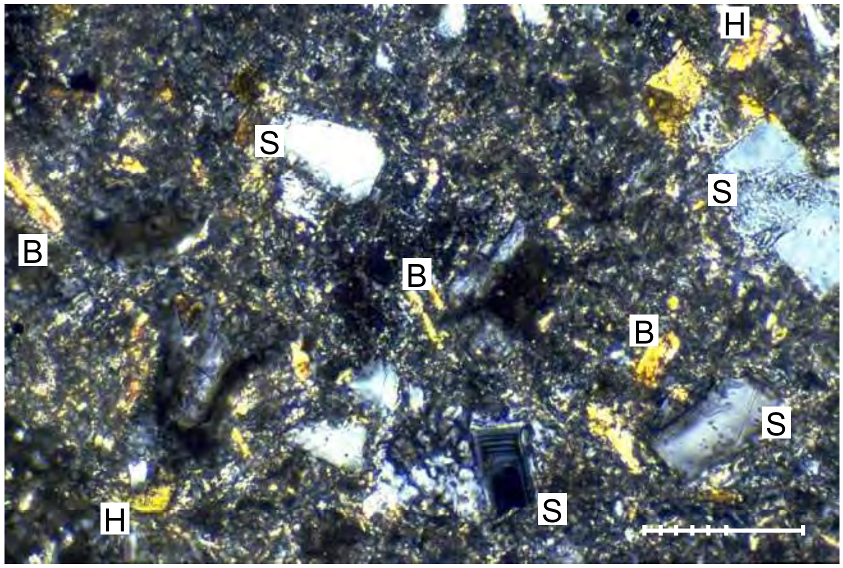
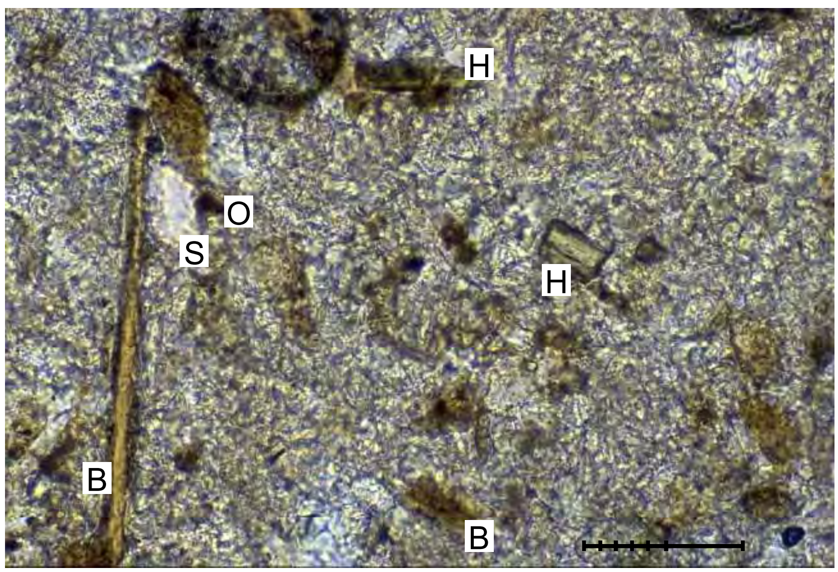


Figure 3.3 Photomicrographs showing the various constituent mineral grains accompanying the glass shards within the ash beds. Bar scale in a) is in 0.1 mm increments and in b), c), and d) is in 0.01 mm increments. Photomicrographs a), b), and d) are plane-polarized light. Photomicrograph c) is in cross-polarized light. Mineral labels are; H - hornblende, S - sanidine, B - biotite, and O - opaque minerals. a) Grain mount thin section of 13.71 Ma ash bed sample #970718H from location 23 on Figure 2.2. b) Thin section of Wood Chop D ash bed sample #970712K from location 22 on Figure 2.2. c) Grain mount thin section of Wood Chop C ash bed sample #971004H from location 16 on Figure 2.2. Note the zoned volcanic sanidine at bottom center. d) Grain mount thin section of Wood Chop B ash bed sample #980118F from location 22 on Figure 2.2.

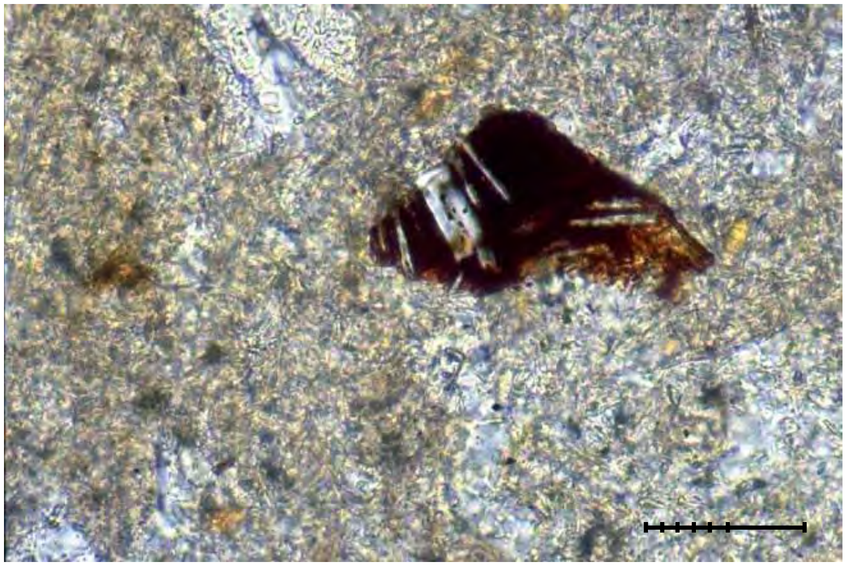
c)



d)



a)



b)

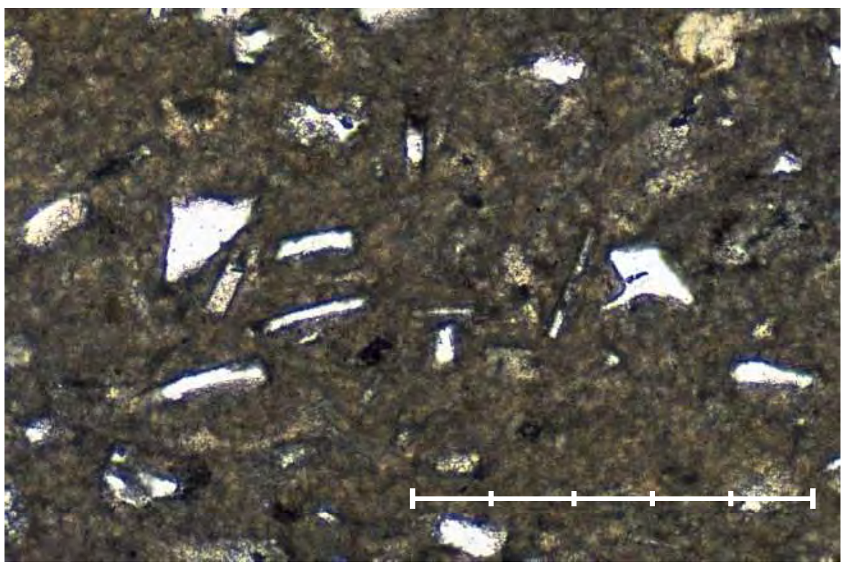
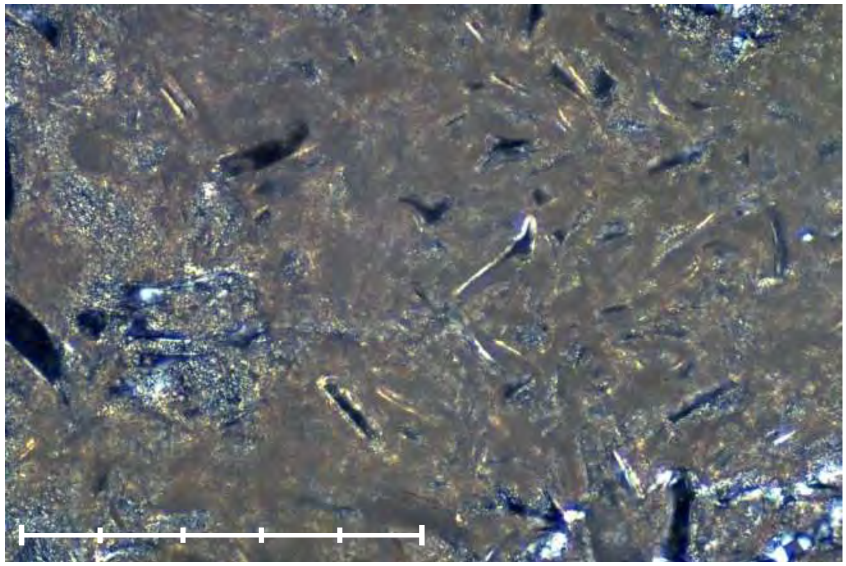


Figure 3.4 a) Photomicrograph showing phenocrysts of plagioclase in a brown glass fragment. Grain mount thin section of sample #970713B of Wood Chop A ash bed at location 13 on Figure 2.2. Bar scale is in 0.01 mm increments. Photomicrographs are in plane-polarized light. b) and c) Photomicrographs showing the alteration of the Echo Spring Mountain ash bed to bentonite. Clear white areas are holes in the thin section left by dissolved minerals. Bar scale is in 0.1 mm increments. Photomicrographs are in plane-polarized light. Photo b) is thin section of sample #970719B from Wood Chop Mesa (location 16 on Figure 2.2). Photo c) is grain mount thin section of sample #970725A from location 21 on Figure 2.2.

c)



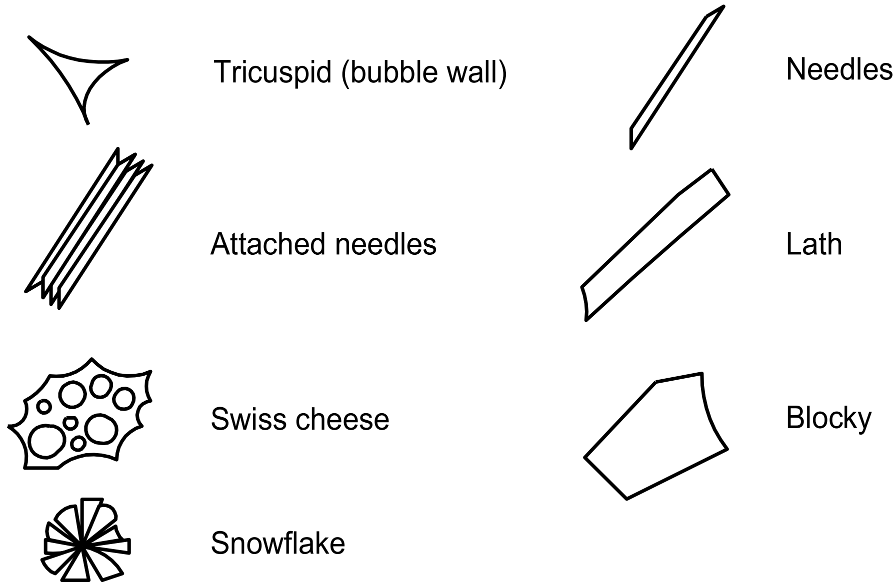
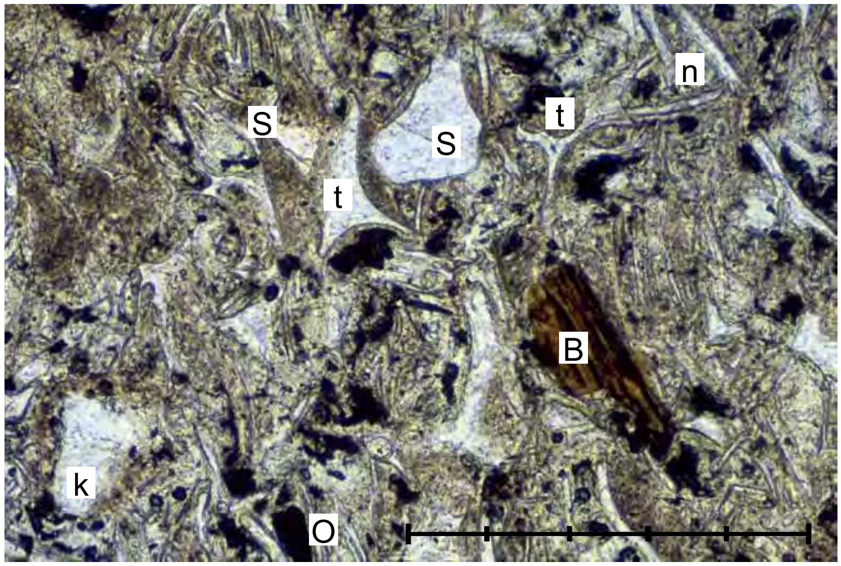


Figure 3.5 Schematic drawing of glass shard morphologies. Drawings not to scale.

a)



b)

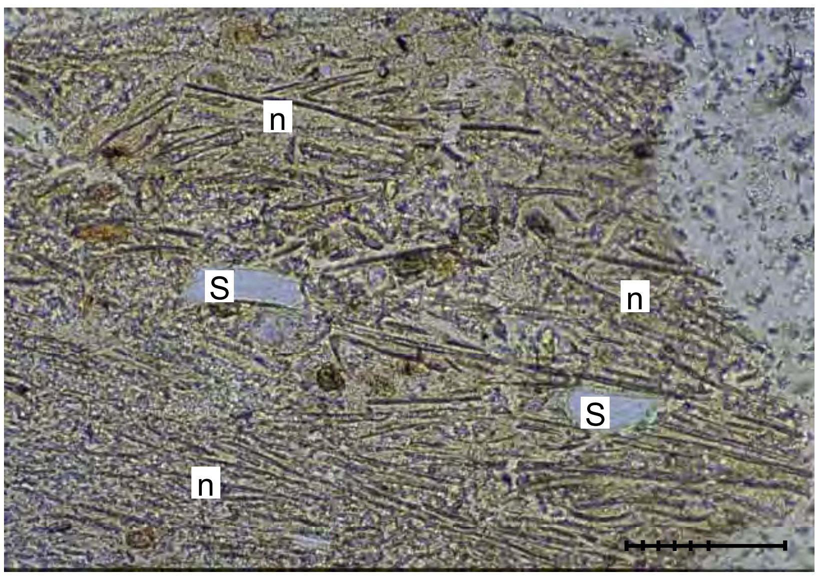
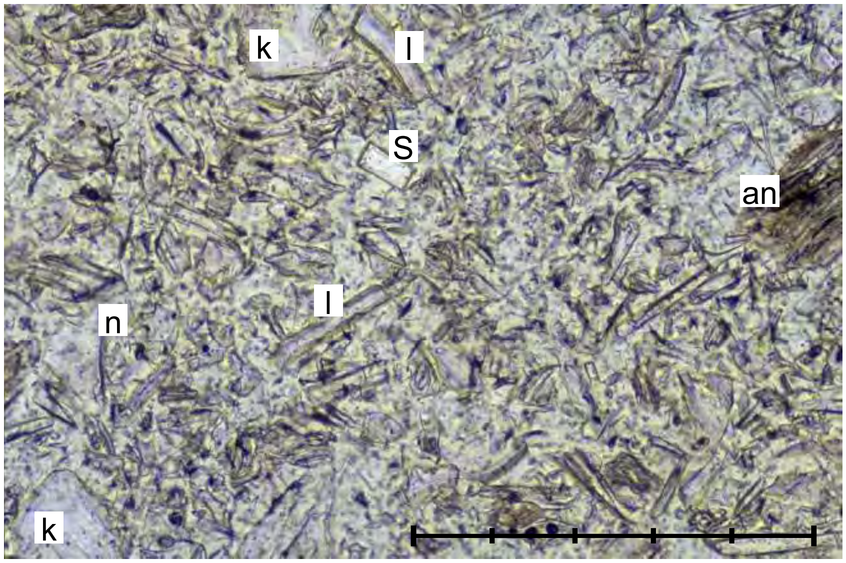
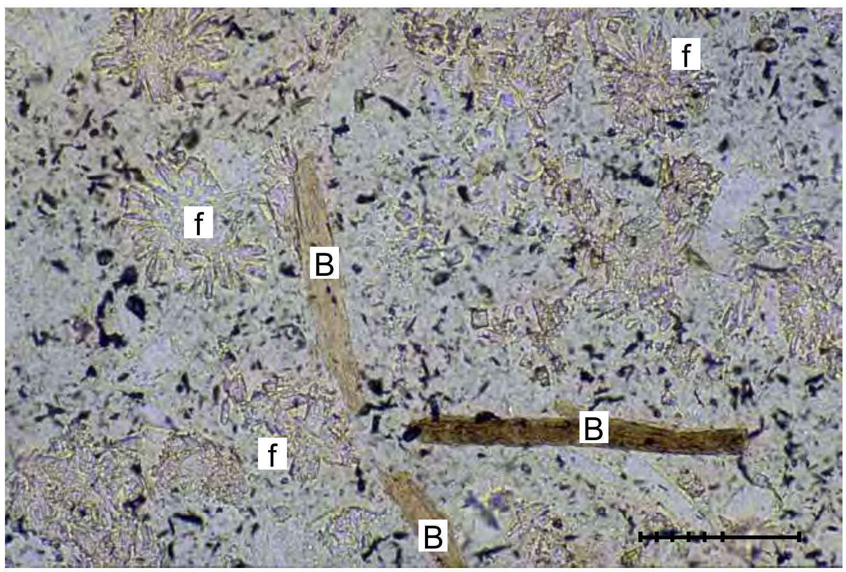


Figure 3.6 Photomicrographs showing the various glass shard types within the ash beds. Bar scale in a) and c) is in 0.1 mm increments and in b), and d) is in 0.01 mm increments. All photomicrographs are plane-polarized light. Mineral labels are; S - sanidine, B - biotite, and O - opaque minerals. Shard type labels are; k - blocky, t - tricuspid (bubble wall), n - needle, an - attached needle. and l - lath. a) Thin section of 13.71 Ma ash bed sample #970315C from location 6 on Figure 2.2. b) Grain mount thin section of pumice ash bed sample #970705B from location 6 on Figure 2.2. c) Grain mount thin section of blue-gray #2 ash bed sample #970704D from location 18 on Figure 2.2. d) Grain mount thin section of Wood Chop D ash bed sample #971004I from location 16 on Figure 2.2.

a)



b)



The alteration of the ash beds is probably due to changes in water depth, variation in rate of burial, or movement of ground water through the ash bed. Variations in pore water chemistry and permeability of the ash bed are potential factors that may have varied at different locations and resulted in variances in cementation and degree of contact with pore fluids.

Ash bed ^{40}Ar-^{39}Ar Analyses

Selected samples were analyzed to determine the absolute age of the sample using ^{40}Ar-^{39}Ar techniques (Appendix A and C). These samples were picked based on their content of potassium-bearing minerals, such as sanidine, biotite, or phlogopite and their importance for determining stratigraphic relations. Samples were analyzed by the New Mexico Geochronology Research Laboratory at the New Mexico Institute of Mining and Technology, Socorro, New Mexico. The resulting dates are listed in Table 3.1. These dates, in conjunction with the geochemical analyses described in the section below, are used to determine the source area for the tephra (see below). These dated units are used to establish chronohorizons across the basin to aid in correlation purposes and to infer sedimentation rates (see Chapter 4).

A sanidine bulk sample from a felsic vitric ash bed (Figure 3.1) within member 3 at Triplets Mesa yielded an ^{40}Ar-^{39}Ar date of 13.71 0.08 Ma (Dallegge et al., 1998, Appendix C). This key marker bed has been informally named the 13.71 Ma ash bed (Ort et al., 1998).

A bulk biotite sample from a felsic ash bed near the base (see Chapter 4 for stratigraphic location) of the formation at location 22 (on Figure 2.2) yielded an ^{40}Ar-^{39}Ar date of 15.46 0.58 Ma. The radiogenic Ar yield is quite low for this sample but a workable plateau exists across 6 heating steps (Appendix C). The low yield is at least partly responsible for the large error on this sample run.

A bulk phlogopite sample from a Hopi Buttes tuff at flat tire mesa yielded an ^{40}Ar-^{39}Ar date of 7.71 0.06 Ma. The radiogenic Ar yield for this sample was adequate and a well defined plateau exists across all steps (Appendix C).

Sanidine from a felsic ash bed north of Greasewood, Arizona, was analyzed using single-crystal laser fusion and yielded an ^{40}Ar-^{39}Ar date of 13.85 0.02 Ma. The radiogenic Ar yield was very high (~100 %). Several peaks from other crystals also appear on the age spectrum and may be related to xenocrystic contamination from erosion of older ash beds below this horizon or from removal of older volcanic rock

Table 3.1 New isotopic dates for Bidahochi Formation

Sample #	Sample Type	Lat/Long	Analysis Type	Location	Reported Age (Ma)
970118B	phlogopite from a mafic tuff	N35° 32.781' W110° 09.114'	Ar^{40}/Ar^{39} - bulk sample	member 5 Flat Tire Mesa (#9)	7.71 ± 0.06 (2)
970315C	sanidine from a felsic ash bed	N35° 33.478' W109° 49.955'	Ar^{40}/Ar^{39} - single crystal	member 3 N of Greasewood (#6)	13.85 ± 0.02 (2)
970719E	biotite from an intermediate ash bed	N35° 25.454' W110° 02.427'	Ar^{40}/Ar^{39} - bulk sample	member 2 SW Wood Chop (#16)	15.19 ± 0.11 (2)*
970712F	biotite from a felsic ash bed	N35° 23.335' W109° 57.032'	Ar^{40}/Ar^{39} - bulk sample	member 1 East Point (#22)	15.46 ± 0.58 (2)

* - considered a maximum age only; Ar-Ar ideograms and age spectra for these dates are in Appendix C

from the vent area. This sample location (#6 on Figure 2.2) is near the eastern shoreline of the basin and may have received contamination from runoff entering the basin.

An ash bed in member 2 at Wood Chop Mesa proved difficult to date. Problems occurred during the early heating steps of this biotite bulk sample. Variability occurred in the Ar measurements, resulting in a broad age spectrum (Appendix C). The run was much better at higher heating steps and the problems during lower steps may have been due to outer-crystal contamination. A plateau cannot be established for this run because 3 steps within error of each other are needed. However, the last two steps are very stable with only small errors associated with these steps and an age of 15.19 ± 0.11 Ma can be calculated using only steps G and H (Appendix C). This age should only be considered a maximum age for this sample.

Ash Bed Geochemistry

Glass shards from selected ash beds were analyzed geochemically. The samples chosen were the same as, or correlatable with, the samples used in the ^{40}Ar-^{39}Ar analysis as well as several others that were used for additional correlation tools. The samples were sent to Michael E. Perkins at the University of Utah in Salt Lake City, Utah, for analysis of the glass shards using an electron microprobe. Table 3.2 is a list of the averages for the glass shard analyses. Individual shard analyses are listed in Appendix D. The geochemical analyses, in conjunction with the isotopic dates in the section above, are used to determine the source area for the ash beds (see section 3.5). This geochemical information is used to characterize and correlate various ash beds (see Chapter 4).

Ash Bed Source Area

The results from the isotopic and geochemical analyses were used to determine the volcanic source area that produced the silicic ash beds in the Bidahochi Formation. The results of the analyses were compared to the database compiled by Mike Perkins and colleagues to look for distinctive geochemical signatures of eruptive volcanic centers that could have provided the source for the tephras in the Bidahochi Formation.

Perkins et al. (1998) split the Basin and Range vitric tuffs in their database into four broad compositional groups (in order of relative abundance): (1) gray metaluminous rhyolite tuffs (Gm tuffs); (2) white metaluminous rhyolite tuffs (Wm tuffs); (3) dacite tuffs; and (4) gray peralkaline rhyolite tuffs (Gp

Table 3.2 Electron microprobe analyses of glass shard samples from the Bidahochi Formation and other regional ash beds:

Sample	Location	n	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	BaO	Na_2O	K_2O	Cl	F	H_2O	-O	Total
970427A	Red Clay Mesa (#14)	22	74.5	0.09	12.2	1.39	0.060	0.040	0.450	0.030	3.3	4.4	0.180	0.40	3.9	0.21	100.7
971107L	Satan Butte	22	74.7	0.15	11.7	1.90	0.030	0.020	0.630	0.000	2.7	4.3	0.09	0.3	5.5	0.15	101.9
970712M	East Point (#22)	21	72.7	0.22	11.0	3.75	0.180	0.010	0.240	0.000	2.8	4.0	0.13	0.3	6.9	0.16	102.1
sv92-94a*	Stewart Valley	22	70.4	0.21	10.7	3.66	0.165	0.01	0.22	0.01	1.2	4.7	0.12	0.2	7.9	0.11	99.4
**	Stewart Valley																

Analyses measured in wt-%, * - Grouse Canyon ash bed (Perkins et al., 1998). ** - Lovelock ash bed (Perkins, 1998, written comunication - data not released) tuffs). These compositional groups are classified based on content of Al, Fe, and Ca in the glass shards (Figure 3.7).

Seventy-nine percent of the 213 individually characterized tuffs that Perkins et al. (1998) reported for Miocene tuffs in the Basin and Range province (Figure 3.8) either came from the Snake River Plain volcanic province or from the southwestern Nevada volcanic field (45% and 34% respectively). The Snake River Plain volcanic field is split into two provinces (Perkins et al., 1998); the older western Orevada province (ca. 16.5-14.5 Ma) and the younger eastern Snake River Plain province (<15 Ma). The Orevada province is predominantly composed of peralkaline rhyolites (Gp) with some metaluminous rhyolites (Gm). The Snake River Plain volcanic province is predominantly metaluminous rhyolites that produced almost entirely Gm tuffs with one exception, the 10.20 Ma Arbon Valley Tuff (Kellogg et al., 1994), a biotite bearing Wm tuff (Perkins et al., 1994). The southwestern Nevada volcanic field (ca. 16-7 Ma; Sawyer et al., 1994) is a major silicic center that produced both peralkaline and metaluminous rhyolites (Perkins et al., 1994). The metaluminous tuffs typically contain biotite (Warren et al., 1989). This field most likely produced many of the 50 Wm tuffs during the interval from ca. 16-10 Ma (Perkins et al., 1994). The Snake River Plain volcanic province is distinguishable from the Southwestern Nevada volcanic field based on Fe content, phenocryst composition, formation temperature, and color (Table 3.3) (M. Perkins, 1998, personal communication).

The geochemical analyses (Table 3.2 and Appendix D) of the 13.71 Ma ash suggest that it is of the same chemical and mineralogical nature (biotite-bearing, white metaluminous rhyolite tuff) as many tuffs from the southwest Nevada volcanic complex (M.E. Perkins, 1998, written communication). The age of the 13.71 Ma ash bed is in accordance with the highest magma output (160-2500 km^3/100 k.y.) interval (ca. 14-11.5 Ma) of the southwestern Nevada volcanic field (Sawyer et al., 1994). Based on these relations, the southwestern Nevada volcanic field is the most probable source area for the 13.71 Ma ash bed (M.E., Perkins, 1998, written communication).

A blue-gray ash bed from Satan Butte (Plate 3) is correlative to the Lovelock ash bed (~13.78 Ma) in the Stewart Valley section, Nevada (Perkins et al., 1998; M.E. Perkins, 1998, written communication). Based on the composition of this blue-gray ash bed and the ash bed from Stewart Valley, they are

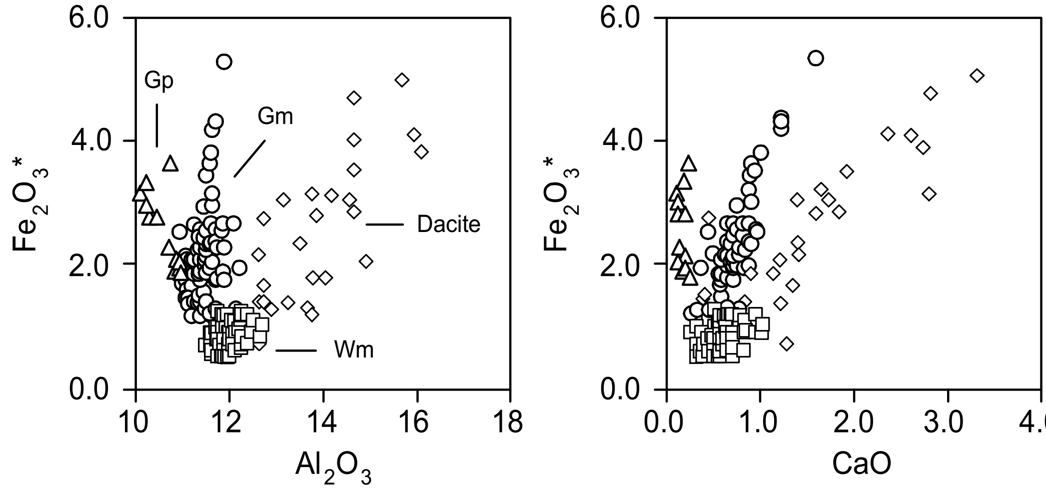


Figure 3.7 Major glass shard compositional groups. Fe_2O_3* (total Fe as Fe_2O_3), Al_2O_3, and CaO content in glass shards. Electron probe analyses with contents in wt%. Each data point is an average of ~20 individual shard analyses from 213 different ash beds. Gm-gray metaluminous rhyolite glass (circles); Gp-gray peralkaline rhyolite glass (triangles); Wm-white metaluminous rhyolite glass (squares); Dacite-dacite glass (diamonds). From Perkins et al. (1998).

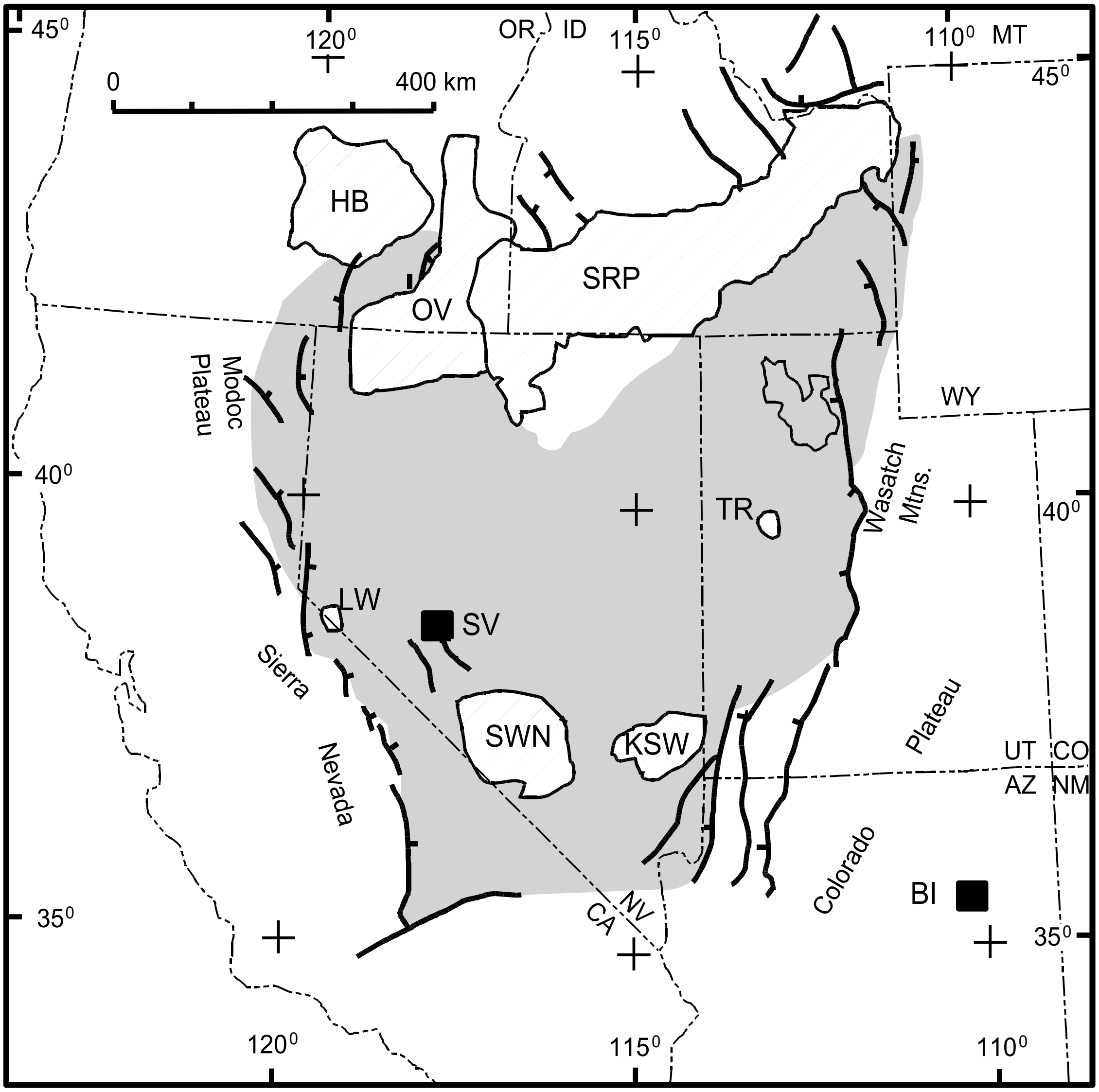


Figure 3.8 Location map of the major centers of middle to late Miocene explosive silicic volcanism (diagonal lined areas) within and around the northern Basin and Range province (shaded gray). The correlative ash localities are: SV--Stewart Valley; BI--Bidahochi Formation. Miocene centers of explosive silicic volcanism are: HB--Harney Basin; (10-5 Ma); KSW--Kane Spring Wash caldera complex (16-14 Ma); LW--Little Walker volcanic center (10-9 Ma); OV--"Orevada" volcanic province (16.5-15 Ma); SRP--Snake River Plain volcanic province (15-5 Ma, progressively younger to the northeast); SWN--southwestern Nevada volcanic field (16-7 Ma); TR--Thomas Range (7-6 Ma). Modified and adapted from Perkins et al. (1998).

correlatable to the Gm tuffs of the Snake River Plain volcanic province (M.E. Perkins, 1998, written communication).

A blue-gray ash bed from east point but stratigraphically below the blue-gray at Satan Butte (Plate 3) is correlative to the Grouse Canyon(?) ash bed (M.E. Perkins, 1998, written communication). The Grouse Canyon(?) ash bed is a Gp tuff and is dated at 13.78 ± 0.04 Ma (Perkins et al., 1994). The source tuff for the Grouse Canyon (?) ash bed has not be analyzed by M. Perkins, but based on reported chemical compositions of lava flows from the Grouse Canyon caldera, M.E. Perkins (1998, personal communication) believes it is correlatable and uses a (?) to denote this relation. The composition of this ash bed in the Bidahochi Formation (Table 3.2) compares well with those listed for the Grouse Canyon (?) ash bed in Perkins et al. (1998).

Ash Bed Characterization

Based on stratigraphic, petrographic, geochemical, and field observations, 16 different ash horizons are established. The reference section at Wood Chop Mesa (location 16 on Figure 2.2) is used to characterize many of the ash horizons. Ash bed horizons that are not present at Wood Chop Mesa are identified by their petrographic identity and relative stratigraphic position to ash beds that are correlatable to those at Wood Chop Mesa. Correlation of various rock types aided in the placement of the ash beds. No stratigraphic section containing all 16 ash beds occurs within the Bidahochi Formation. The stratigraphic hierarchy of these ash horizons is shown in Figure 3.9. The information presented above is instrumental in determining limiting ages on the stratigraphy, establishing chronohorizons across the basin, and correlating outcrops across the field area. These topics are further elaborated on in Chapter 4. All 16 ash bed horizons are informally named based on geographic locations or physical characteristics and denoted by the lower case ash bed.

The Echo Spring Mountain ash bed occurs in western exposures of the Bidahochi Formation and is noted as far east as Wood Chop Mesa (Figure 2.2). This ash bed is stratigraphically the lowest occurring ash bed recognized in member 1. It contains very few crystals and is strongly altered in most locations. It contains rare sanidine, plagioclase, biotite, and green/brown hornblende (Figures 3.4b,c and 3.10a-f). At

Table 3.3 Comparison of tuff characteristic of the Snake River Plain volcanic province and the Southwestern Nevada volcanic field:

	Snake River Plain volcanic Province	Southwestern Nevada volcanic field
Fe content	greater than 1%	less than 1%
Temperature	high temperature rhyolite	moderate temperature rhyolite
Phenocryst	pyroxene common, little or no biotite	biotite -rich, hornblende common
Color*	gray, blue-gray*	white
Tuff produced	Gm with minor Gp (early phase, > 16 Ma)	Wm with some Gp

Data from Perkins et al. (1998) and M. Perkins, 1998, personal communication; * - color of heavily calcified or altered tuffs will vary, can be cleaned to obtain color relations (M. Perkins, 1998, personal communication). Gm - gray metaluminous rhyolite tuff, Gp - gray peralkaline rhyolite tuff, Wm - white metaluminous rhyolite tuff.

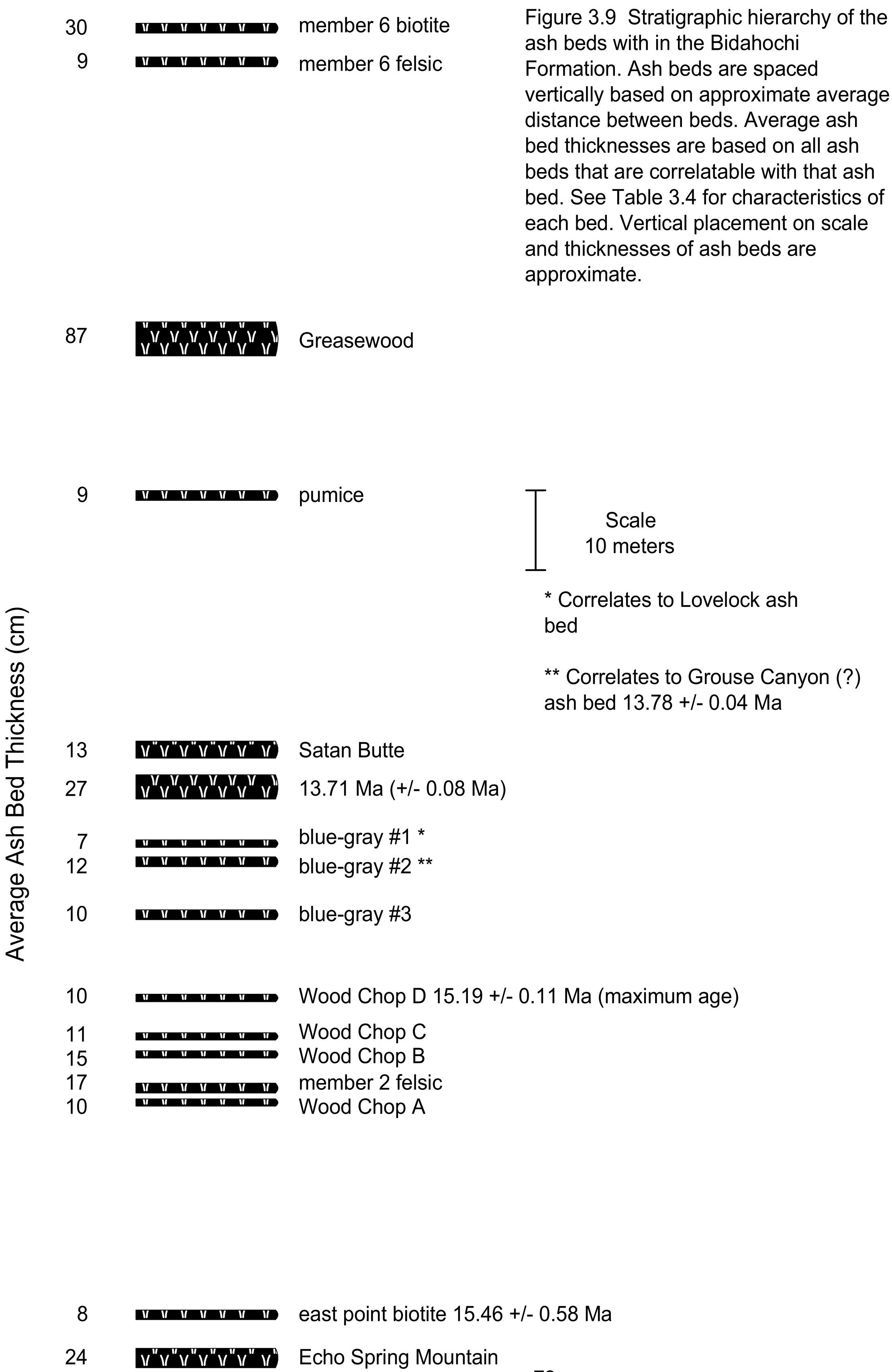


Figure 3.9 Stratigraphic hierarchy of the ash beds with in the Bidahochi Formation. Ash beds are spaced vertically based on approximate average distance between beds. Average ash bed thicknesses are based on all ash beds that are correlatable with that ash bed. See Table 3.4 for characteristics of each bed. Vertical placement on scale and thicknesses of ash beds are approximate.

location 26 (on Figure 2.2), the ash bed is not strongly altered and shard morphologies present are snowflake, lath, needle, and blocky.

The east point biotite ash bed occurs in central and western exposures within member 1 or at the boundary between members 1 and 2. In some locations this ash bed occurs within 1 m of the Echo Spring Mountain ash, while in others it occurs several meters higher in the section. It contains abundant laths of biotite and green/yellow hornblende (Figure 3.10g-f). Plagioclase and opaque minerals are also common. This ash bed is altered in most locations and shard types present are mostly small blocky pieces. The biotite and hornblende grains are commonly aligned parallel to each other in thin section. The east point biotite ash bed is easily distinguished from the Echo Spring Mountain ash by its abundance of phenocrysts, especially biotite, and by its stratigraphic position when applicable.

Several ash beds occur within member 2 that are difficult to distinguish from each other. These beds are informally named Wood Chop A through D ash beds (with A being the oldest) and the member 2 felsic ash bed (Figure 3.9). The Wood Chop ash beds are intermediate in composition and have very similar mineral assemblages and few clear glass shards. Phenocrysts included in the Wood Chop ash beds are biotite, green hornblende, plagioclase, and opaque minerals (Figure 3.3b-d, 3.4a, 3.6d, and 3.10k-m, p-z). Brown glass is common in the Wood Chop ash beds and some brown glass contains microlites of plagioclase and/or opaque minerals. In thin section, these ash beds tend to have a yellow oxidized micro-texture (cross-polarized light). This yellow texture appears to be in the background and outlines the edge of the glass shards. The Wood Chop ash beds are best distinguished by stratigraphic position if all 4 beds are present at one locality. If fewer than 4 beds are recognized at any location, identification of an individual bed is problematic. Slight variations occur within this suite of beds and rarely, in places they can be identified when 2 or 3 beds are present at that location. The Wood Chop D ash bed commonly contains small amounts of long muscovite laths which do not occur in the other beds. The Wood Chop D bed has the most abundant concentration of glass shards of all 4 beds and snowflake shard morphologies are noted with this bed only. Lath and needle types are common with the other 3 Wood Chop ash beds. The member 2 felsic ash bed only occurs at two locations in eastern localities. This ash bed is glass-rich and occurs in the lower sections of member 2. It has lath and needle shard types similar to the Wood Chop ash beds. It

Table 3.4 Characteristics of 16 different ash bed horizons recognized within the Bidahochi Formation. Abbreviations follow table

Ash Name	Composition	Reference locality (on Figure 2.2)	Shard type (Fig. 3.5), (petrographic objective)	Average shard size (mm)	Mineralogy	Other characteristics
member 6 biotite ash	F	Roberts Mesa (location 2)	blocky-A, needles-A, laths-A, attached needles-C, Swiss cheese-R, (10x)	0.04	biotite (long skinny laths)-A, plagioclase?-A, opaques-C, brown glass-C, green/brown-hornblende-O, muscovite (long skinny laths)-O	micas aligned sub-parallel, similar to Wood Chop D ash bed.
member 6 felsic ash	F	Roberts Mesa (location 2)	needles-A, laths-A, blocky-O, (10x)	0.01	brown hornblende-O, opaques-O, green/brown hornblende-R, biotite-R, K-spar-O?, detrital-A	partial shard alteration
Greasewood ash	F	north of Greasewood (location 6)	needles-VA, laths-A, blocky-C, (10x)	0.1	clay/bentonite-A, plagioclase (zoned)-C, opaques-C, brown glass-C	parallel shards, lattice texture with clay in openings, partial shard alteration
pumice ash	I	north of Greasewood (location 6)	pumice fragments-A, needles-A, tricuspid-C, (10x)	0.2 mm	brown glass (some with plagioclase and orthopyroxene microlites)-C, opaques-C, plagioclase?-O, brown hornblende-O	edges of grains have significant yellow alteration (cross-polarized light).
Satan Butte ash	F	Satan Butte (location 11)	needles-A, laths-A, blocky-C, attached needles-C, tricuspid-O, (10x)	0.08	opaques-C, sanidine-O, green/brown-hornblende-O, biotite-R	no visible shard alteration
13.71 Ma ash bed	F	Wood Chop Mesa (location 16)	tricuspid-A, needles-A, blocky-C, laths-C, attached needles-C, (10x)	0.1-0.125	opaques-VA, sanidine-A, green/brown-hornblende-C, biotite-C	no visible shard alteration

Ash Name	Composition	Reference locality (on Figure 2.2)	Shard type (Fig. 3.5), (petrographic objective)	Average shard size (mm)	Mineralogy	Other characteristics
blue-gray #1 ash bed*	F	N of Greasewood (location 6)	laths-A, needles-A, tricuspid-C, blocky-C, attached needles-C, (10x)	0.08	opaques-C to A, sanidine-C, hornblende-R	no visible shard alteration
blue-gray #2 ash bed*	F	N of Greasewood (location 6)	laths-VA, blocky-A, needles-C, tricuspid-C, attached needles-C, (10x)	0.1	opaques-O, sanidine-O, biotite-R, hornblende-R?, crystal-poor.	no visible shard alteration
blue-gray #3 ash	F	Wood Chop Mesa (location 16)	blocky-VA, laths-A, needles-C, tricuspid-C, attached needles-C, Swiss cheese-R, (10x)	0.1	brown glass (some with plagioclase zoned microlites)-C, opaques-O, feldspar (plagioclase? very small)-R, Green/brown hornblende-R, very crystal-poor.	bed fairly calcified, minor shard alteration
Wood Chop D	I	Wood Chop Mesa (location 16)	good glass content (grouped together), laths-A, snowflake-A (bigger 2x), blocky-C, (40x)	0.05	biotite (long skinny laths)-VA, plagioclase (zoned and undulatory)-A, opaques (large)-C, green horn-blende-C, muscovite (long skinny laths)-O, brown glass-R, detrital-A	Some edges of glass having significant yellow alteration (x-polarized light), some calcified areas
Wood Chop C	I	Wood Chop Mesa (location 16)	laths-C, needles-C, blocky-O, (grouped together), (40x)	0.025	biotite (long skinny laths)-VA, plagioclase (zoned)-A, green-hornblende (large)-A, opaques (large)-C, brown glass (some with plagioclase microlites)-C, muscovite (long skinny laths)-O, detrital-C, clay-A, gypsum-C	ash has little or no yellow areas but significant shard alteration, some calcified areas

Ash Name	Composition	Reference locality (on Figure 2.2)	Shard type (Fig. 3.5), (petrographic objective)	Average shard size (mm)	Mineralogy	Other characteristics
Wood Chop B	I	Wood Chop Mesa (location 16)	laths-C, needles-C, (grouped together), (40x)	0.025	plagioclase (zoned)-C, green-hornblende-O, opaques (large)-O, brown glass (some with plagioclase microlites)-O, gypsum-C	partial yellow areas, significant shard alteration, no biotite?
member 2 felsic ash	F	East Twin Buttes (location 23)	laths-VA, needles-A, blocky-C, tricuspid-C, (10x)	0.15	opaques-C, sanidine-O, plagioclase-O, brown glass-O	parallel shards, lattice texture, minor shard alteration
Wood Chop A	I	Wood Chop Mesa (location 16)	laths-A, needles-C, (grouped together) (40x)	0.025	plagioclase (albite and Carlsbad twins)-A, opaques (large)-C to A, green-hornblende-O, brown glass (some with plagioclase and/or opaque microlites)-A, biotite-O, detrital-A, gypsum-C	abundant yellow areas, extensive shard alteration.
east point biotite	I	location 22	blocky-O, mostly tiny pieces, (grouped together), (40x)	0.01	biotite (long skinny laths)-VA, green/yellow hornblende-VA, plagioclase-VA, opaques (large 2x size of other crystals)-C	sub-parallel crystal alignment, significant shard alteration
Echo Spring Mountain ash	F	Wood Chop Mesa (location 16)	snowflake-A, laths-C, needles-O, blocky-O, (40x)	0.025	sanidine-O, plagioclase-O, biotite-O, green/brown hornblende-O, opaques-R?.	extensively shard alteration

Abbreviations: * = correlated by glass geochemistry to Lovelock ash bed; **= correlated to the Grouse Canyon (?) ash bed, F = felsic, I = intermediate; shard types VA = very abundant (> 50% of shards types present), A = abundant (20-30% of shard types present), C = common (10-20% of shard types present), O = occasional (5-10% of shard types present), R = rare (<5% of shard types present); mineralogy VA = very abundant (~5-10% of sample), A = abundant (~3-5% of sample), C = common (~2-3% of sample), O = occasional (~1-2% of sample), R = rare (<1% of sample); w/ = with; 2x = two times larger; K-spar = potassium feldspars; alteration extent = none < minor < partial < significant < extensive contains plagioclase, opaque minerals, brown glass, and occasional sanidine phenocrysts (Figure 3.10n, o). The abundant shards in this ash bed commonly form a lattice-like texture. This ash bed is currently distinguished from the Wood Chop ash beds due to its abundant glass shard content and recognition of sanidine phenocrysts. Based on the correlation diagrams in Plates 1 and 3, this ash bed may be a lateral variation of one of the Wood Chop ash beds. The high glass content, lack of alteration, and variation in textures could be related to variations in deposition or post-depositional changes with this ash bed in eastern locations. Further geochemical analyses are needed to clarify this situation.

The next three ash beds occur near the top of member 2 and within member 3. They commonly display a blue-gray tint in physical appearance and are named blue-gray #1, #2, and #3 ash beds (Figure 3.9). These blue-gray ash beds are vitric and commonly show no alteration. Shard morphology types and grain sizes are similar among these beds. The blue-gray #3 ash bed can also be white in color, especially if it is moderately to well calcified. The blue-gray #3 ash bed is crystal-poor with rare feldspar and hornblende noted. It commonly contains snowflake shards. The blue-gray #1 ash bed is stratigraphically higher than the blue-gray #2 and has a smaller thickness (< 5 cm compared to 10-12 cm). These two ash beds contain opaque minerals and occasional sanidine and hornblende grains. The crystal-poor blue-gray #2 ash bed has rare biotite grains. Blue-gray #1 and #2 ash beds are correlated to the Lovelock and Grouse Canyon (?) ash beds, respectively (see above). These 3 ash beds are best distinguished by their stratigraphic position and thickness but can commonly be differentiated based on the thin section characteristics (Figures 3.6c and 3.10aa-pp) listed above and in Table 3.4.

Above the blue-gray ash beds, two more ash beds occur within the siltstone units of member 3. The 13.71 Ma ash bed occurs above the Blue-gray #1 ash bed and is white, thick (28-34 cm), and forms a prominent ledge throughout the eastern half of the field area. This bed is vitric and commonly friable. Shard size is commonly large (0.1-0.125 mm) but can vary vertically and laterally. It contains sanidine and opaque minerals with some green/brown hornblende and biotite (Figures 3.2, 3.3a, 3.6a, and 3.10qq-vv). It has been dated at 13.71 ± 0.08 Ma (Dallegge et al., 1998). The Satan Butte ash bed occurs less frequently and is thinner (18 cm) than the 13.71 Ma ash bed. The Satan Butte ash bed occurs 1-2 m above and in some locations has a green tint to the bed in outcrop. It has similar mineral and shard compositions but shard grain size tends to be smaller (0.08 mm) (Figure 3.10xx, yy). These two beds are best distinguished by their stratigraphic position and thickness. The thin nature and blue-gray color of the ashes below easily distinguish them from the 13.71 Ma and Satan Butte ash beds.

Two ash beds occur within member 5 along the eastern margin of the field area. The pumice ash bed occurs commonly within the interbedded volcaniclastic sandstone and siltstone units of this member. It has recognizable small pieces of glass pumice and has a yellow oxidized texture similar to that of the Wood Chop ash beds (Figures 3.6b and 3.10zz). It contains brown glass with plagioclase and orthopyroxene microlites. Plagioclase, opaque minerals, and brown hornblende are common. The Greasewood ash bed is white, thick (60 cm), and vitric. The shards are aligned parallel and display a lattice-like texture (Figures 3.10aaa, bbb). Plagioclase, opaque minerals, and brown glass are common. This ash bed has minor alteration. These two ash beds are easily distinguished from each other.

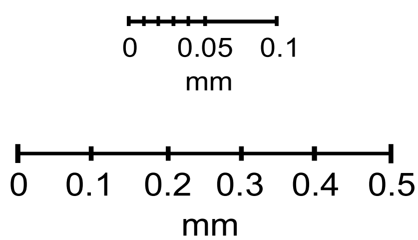
Two ash beds occur within member 6 and are informally named the member 6 felsic and member 6 biotite ash beds. They are both felsic, vitric, and partially altered. The member 6 felsic ash bed has needle, lath, and blocky shard types. It contains brown hornblende, opaque minerals, green/brown hornblende, and biotite (Figure 3.10ccc). The member 6 biotite ash bed has blocky, needle, lath, attached needle, and Swiss cheese shard types (Figure 3.10ddd). It contains abundant biotite laths with plagioclase, opaque minerals, brown glass, green/brown hornblende, and long muscovite laths. The member 6 biotite ash bed occurs near the top of the member and 3 m above the member 6 biotite. The member 6 biotite ash bed is distinguishable from the member 6 felsic ash bed by its abundance of mica and different shard types.

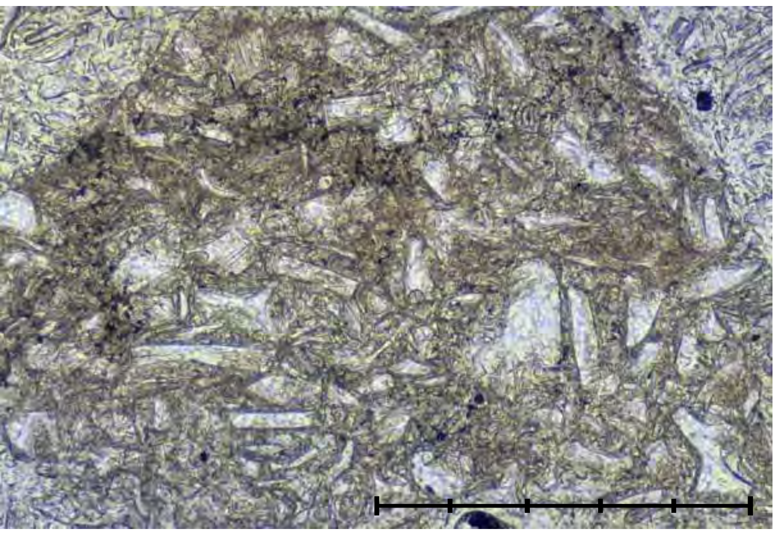
Figure 3.10 Photomicrographs of characterized ash beds showing textural and mineralogical features. All photomicrographs are in plane-polarized light. Mineral labels and scale bar are listed below. Not all minerals present are labeled. Commonly the clear material is glass shards. Mineral labels are located within mineral boundaries or next to mineral with one corner or side touching mineral boundary. Representative photomicrographs are listed for each ash horizon and are referred to in Chapter 4 for correlation purposes. Photos b), f), g), h), bb), tt), vv), zz), aaa), and bbb) are thin sections of ash sample, the remainder are grain mounted thin sections of ash sample. Ash bed sample numbers for the following photos are: a) 970616A, b) 970617A, c) 970704H, d) 970712E, e) 970723B, f) 970724L, g) 970712F, h) 970723C, i) 970725C, j) 980419A, k) 970724E, l) 971004F, m) 980118E, n) 970724G, o) 970802D, p) 970718E, q) 970723K, r) 971004G, s) 970704A, t) 970704B, u) 970713C, v) 970807F, w) 980118G, x) 980418F, y) 970713D, z) 980420A, aa) 970704C, bb) 970807H, cc) 970712L, dd) 970719F, ee) 970724H, ff) 970315D, gg) 970712A, hh) 970712M, ii) 970717C, jj) 970720A, kk) 970628B, ll) 970712B, mm) 970712N, nn) 970717D, oo) 970720B, pp) 970704E, qq) 970808B, rr) 970719G, ss) 970704F, tt) 970718A, uu) 970720C, vv) 970628A, ww) 970720D, xx) 971004L, yy) 980420B, zz) 970718B, aaa) 970315B, bbb) 970705C, ccc) 970802G, ddd) 970802H.

Labeled Minerals

B - biotite
H - hornblende
O - opaque
D - detrital grains
S - sanidine
P - plagioclase
F - feldspar
CO_3 - carbonate fragment

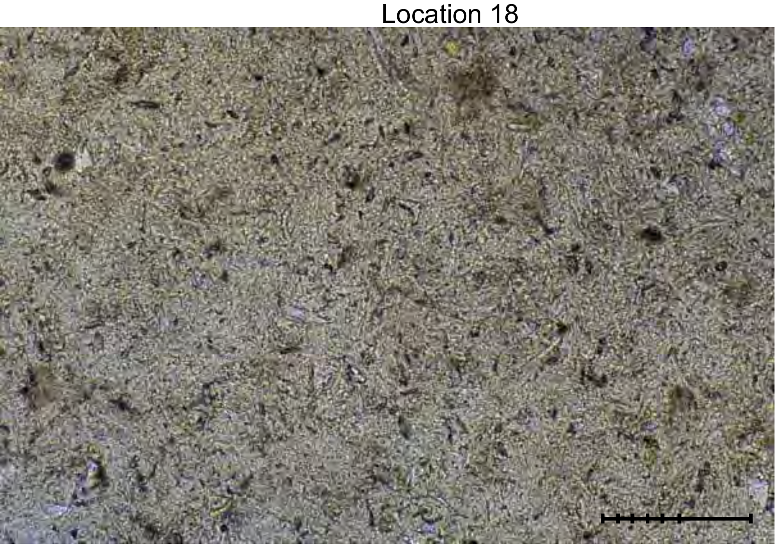
bg - brown or black glass fragment with or without plagioclase and/or other phenocrysts



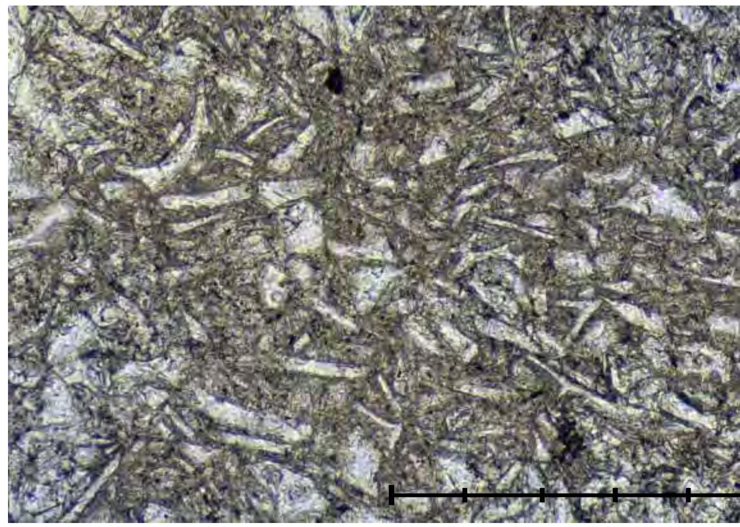


Echo Spring Mountain ash bed
Location 26

Echo Spring Mountain ash bed
Location 18



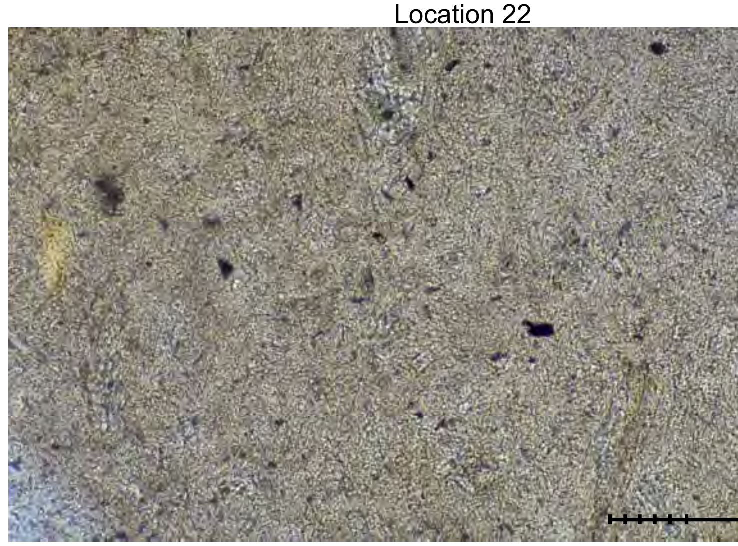
b)

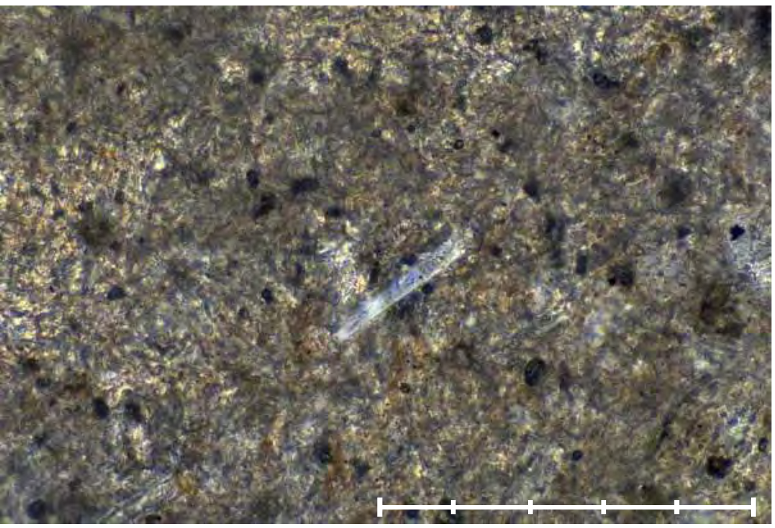


Echo Spring Mountain ash bed
Location 24

Echo Spring Mountain ash be
Location 22

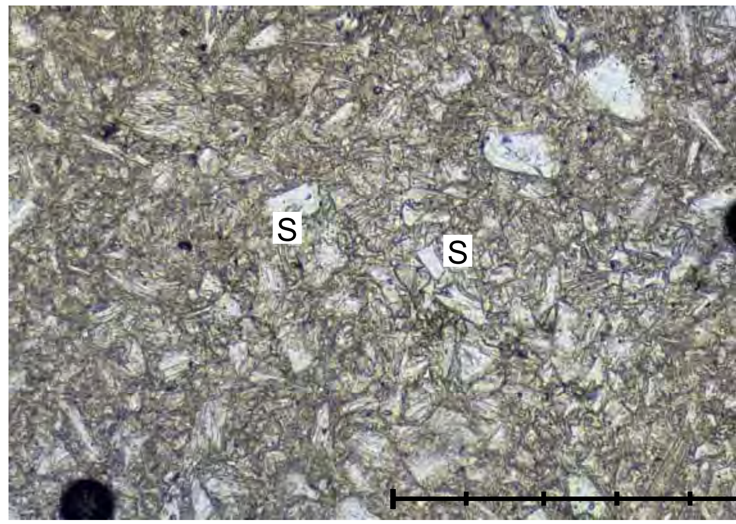
d)





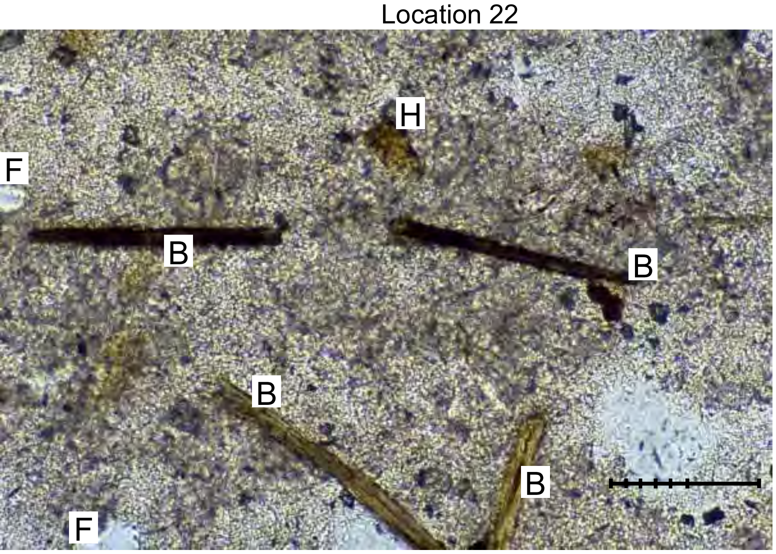
Echo Spring Mountain ash bed
Location 25

f)



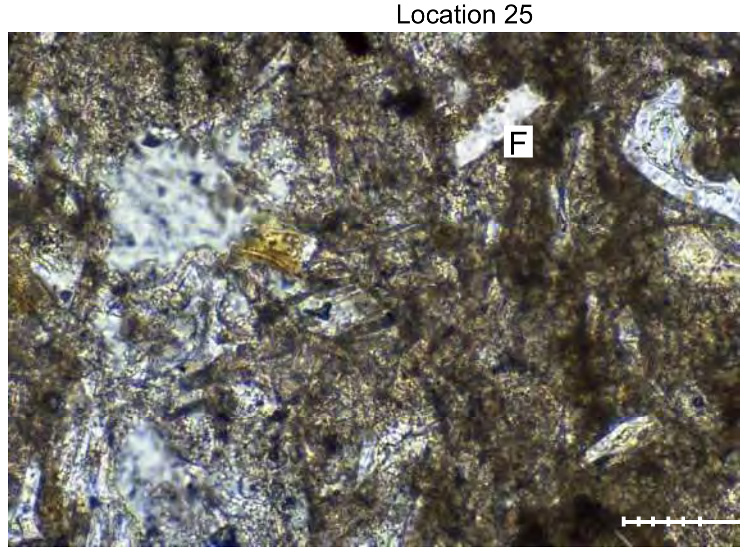
Echo Spring Mountain ash bed
Location 1

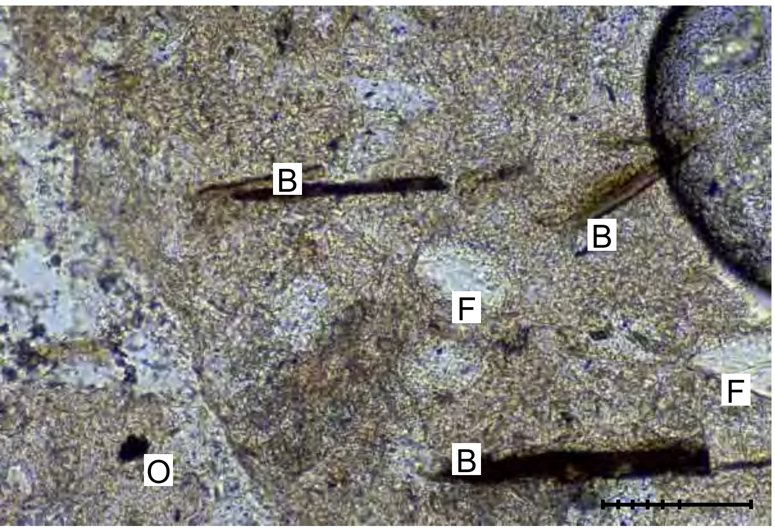
east point biotite ash bed
Location 22



east point biotite ash bed
Location 25

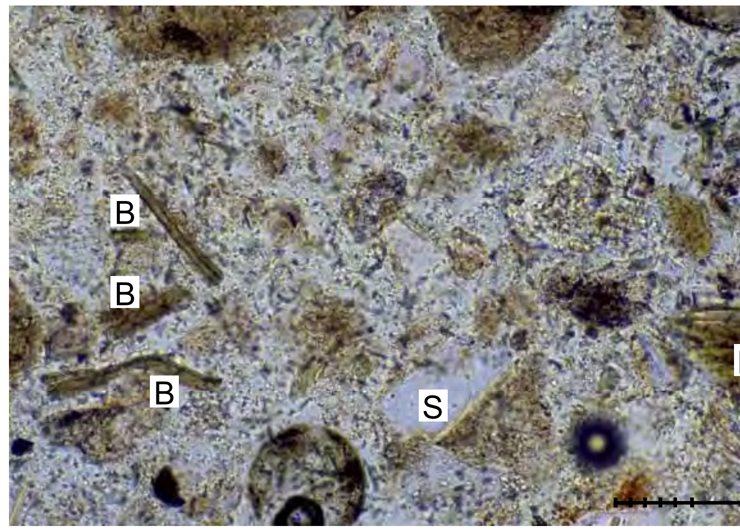
h)





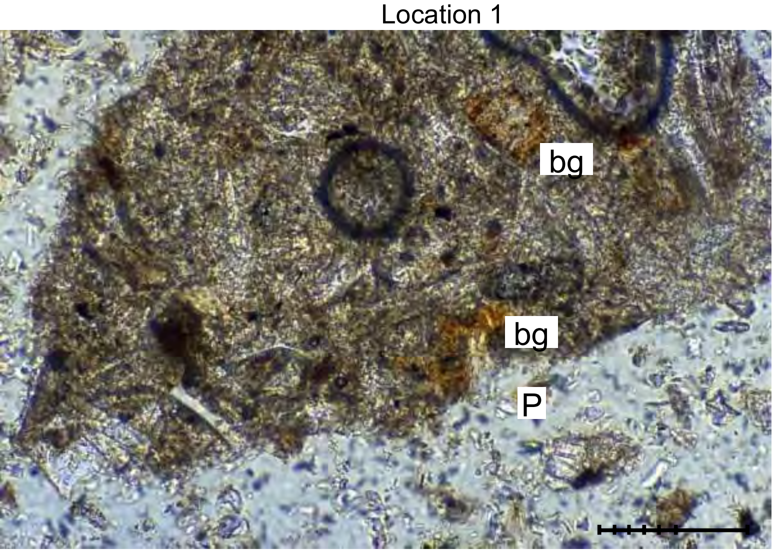
east point biotite ash bed
Location 21

j)



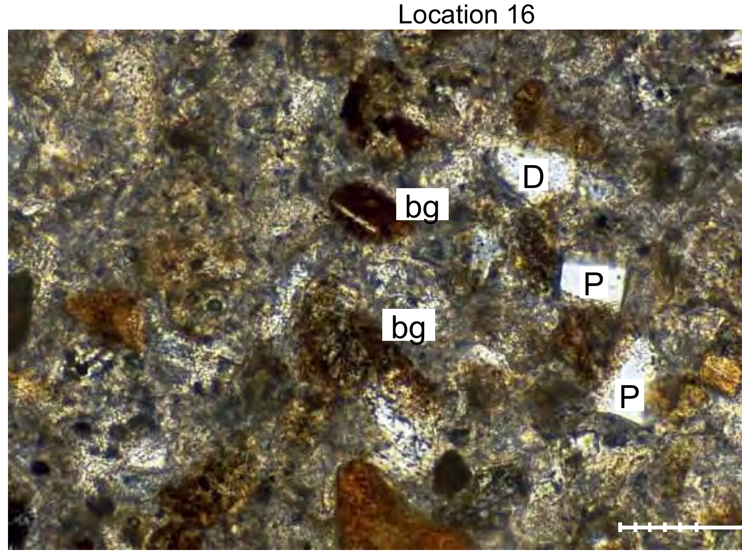
east point biotite ash bed
Location 16

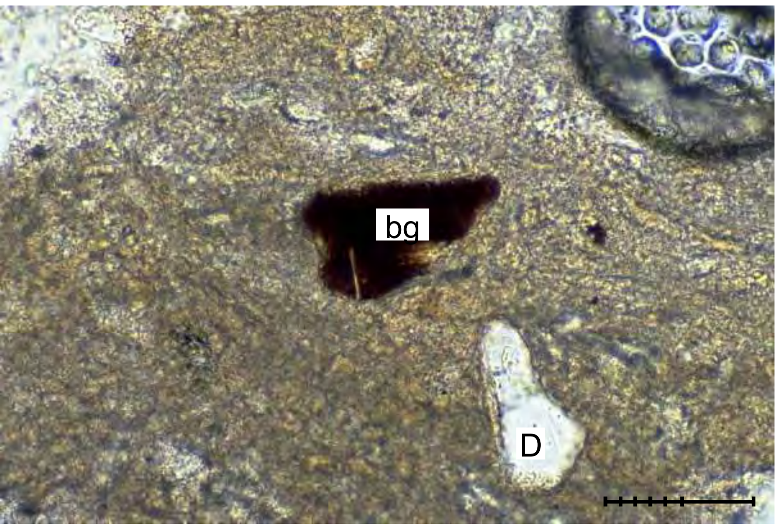
Wood Chop A ash bed
Location 1



Wood Chop A ash bed
Location 16

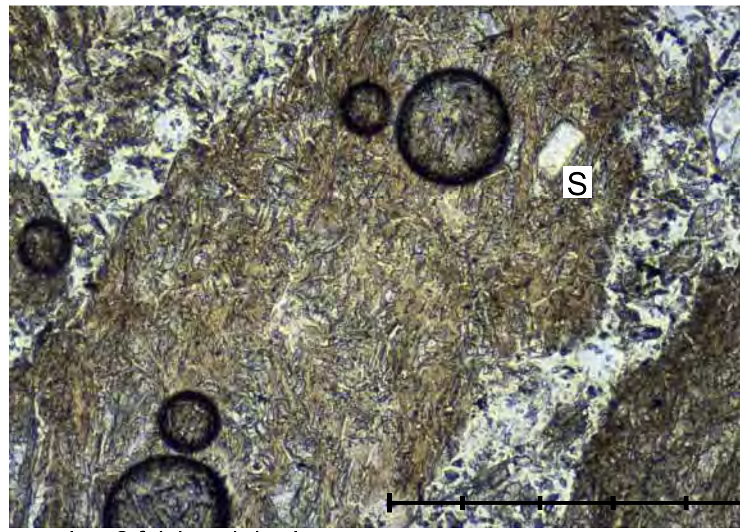
l)





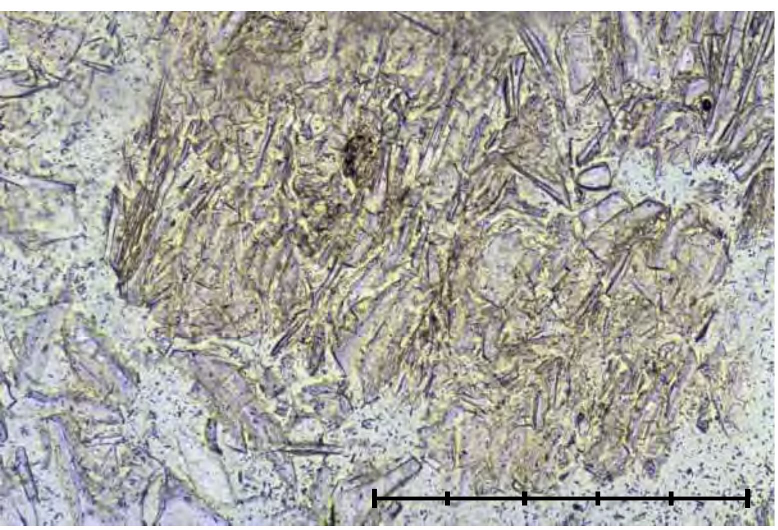
Wood Chop A ash bed
Location 22

n)



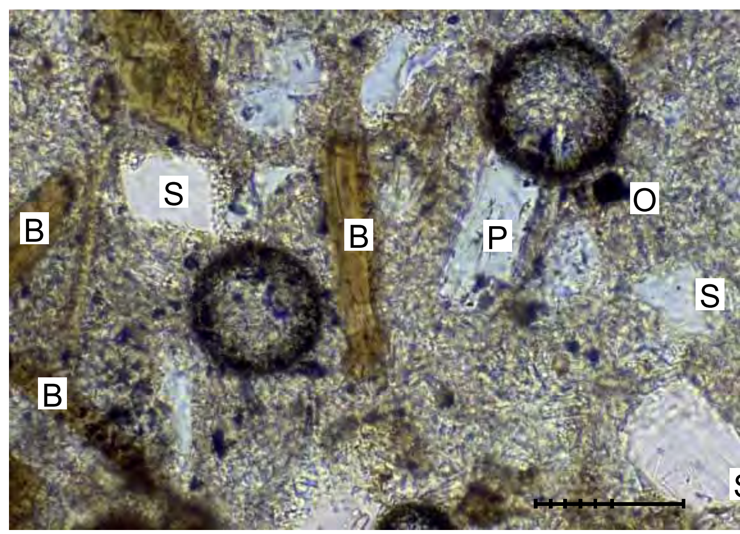
member 2 felsic ash bed
Location 1

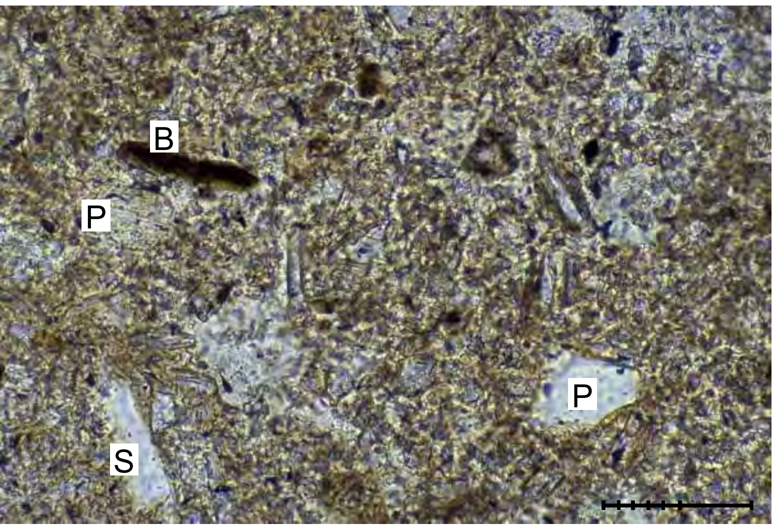
member 2 felsic ash bed
Location 23



Wood Chop B ash bed
Location 23

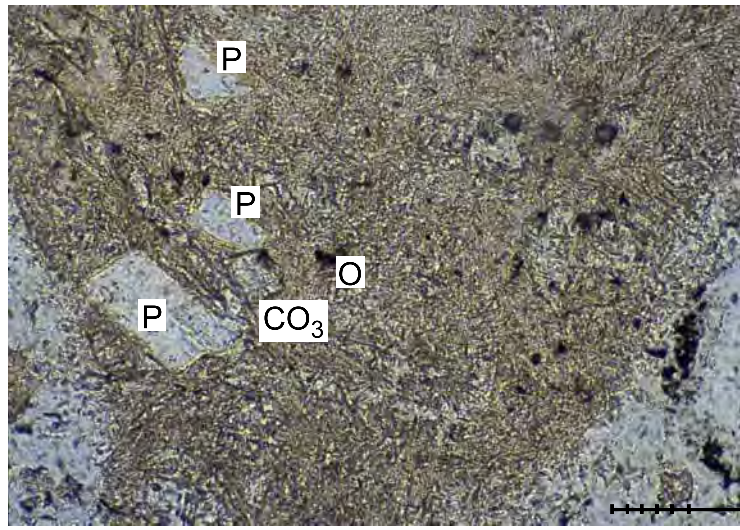
p)





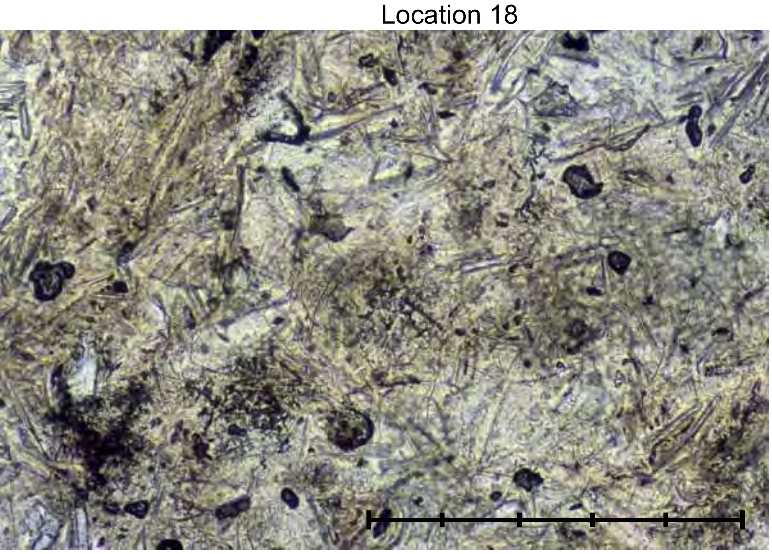
Wood Chop B ash bed
Location 25

r)



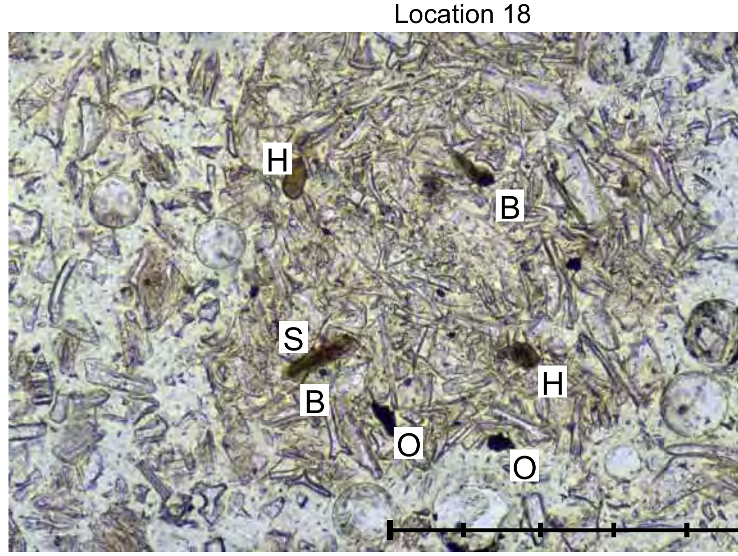
Wood Chop B ash bed
Location 16

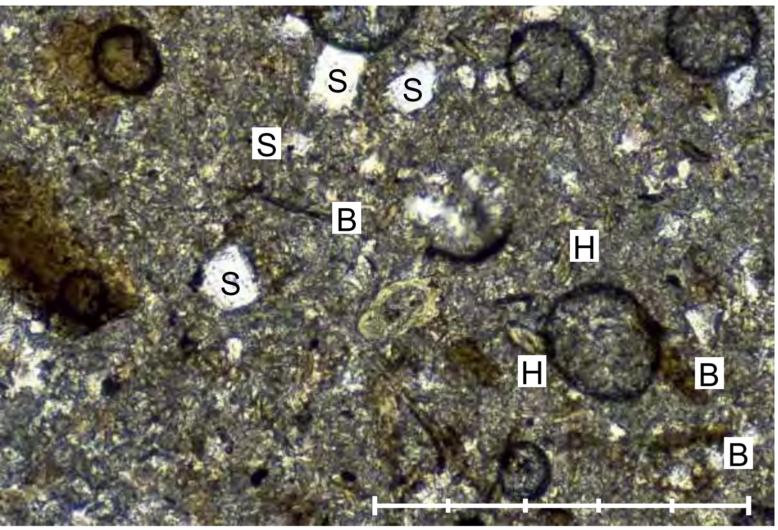
Wood Chop B ash bed
Location 18



Wood Chop C ash bed
Location 18

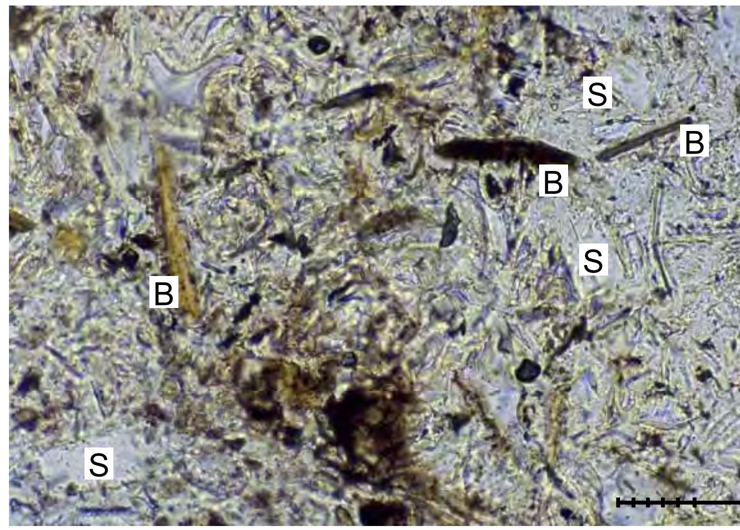
t)





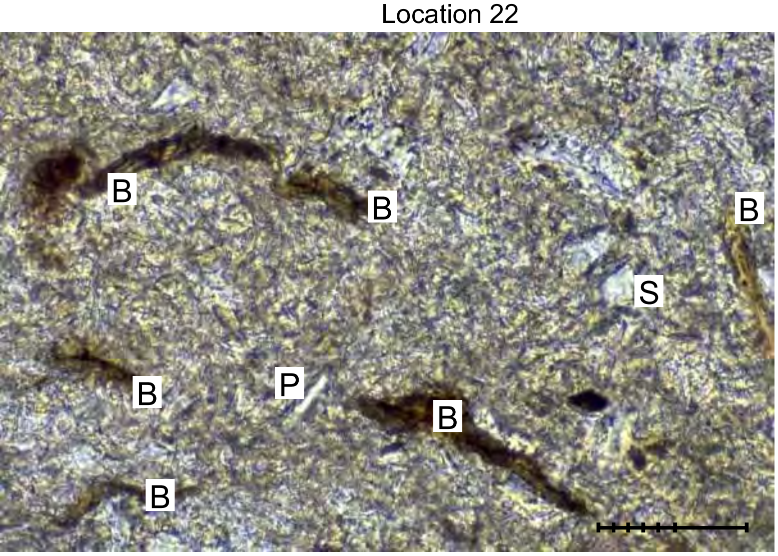
Wood Chop C ash bed
Location 13

v)



Wood Chop C ash bed
Location 23

Wood Chop C ash bed
Location 22



Wood Chop C ash bed
Location 25

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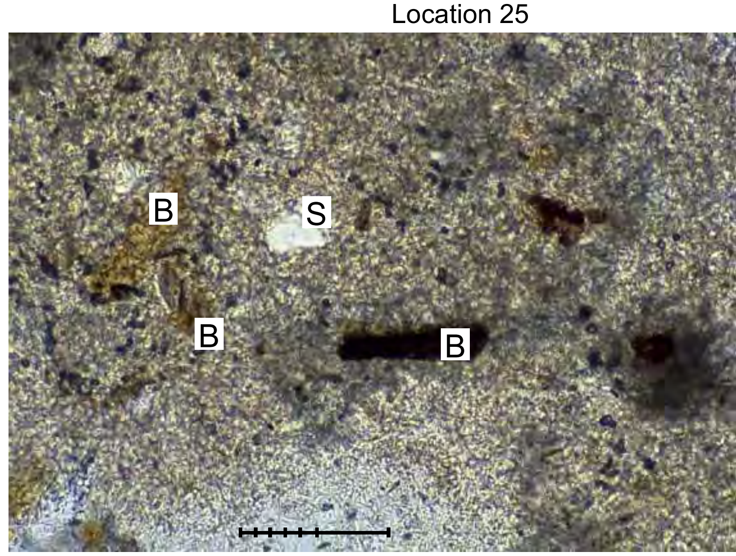
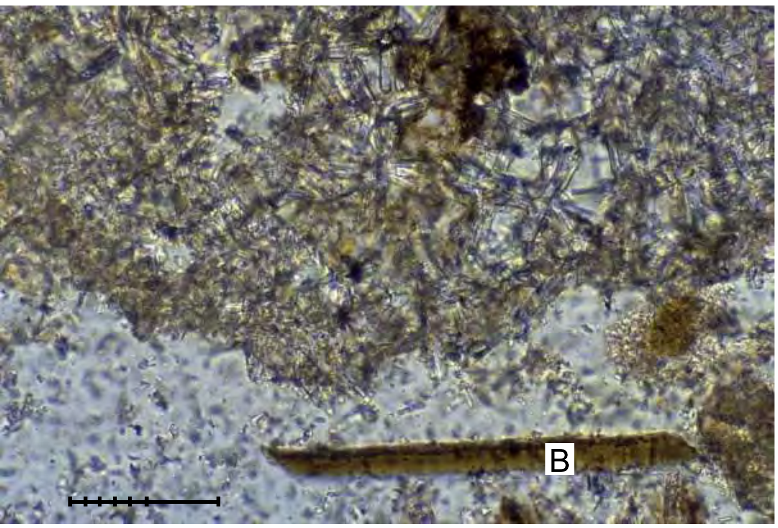
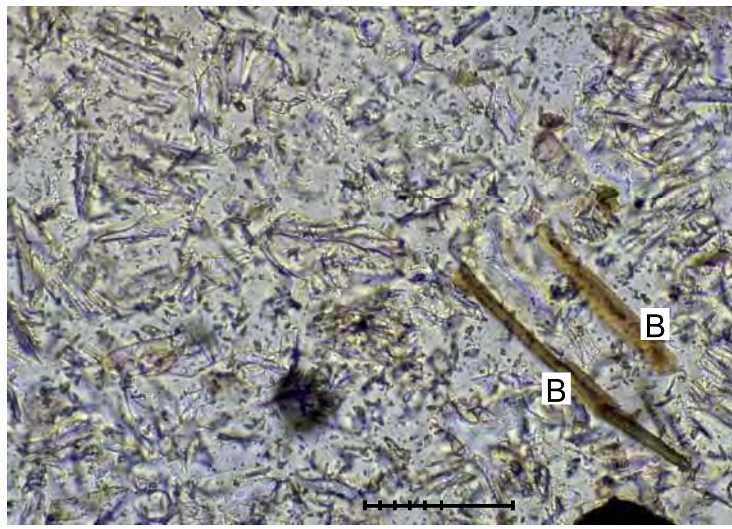




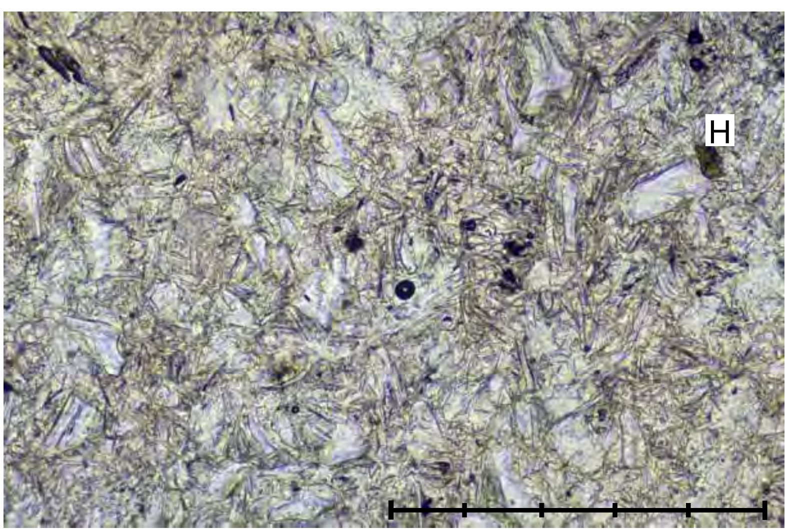
Wood Chop D ash bed
Location 13

z)



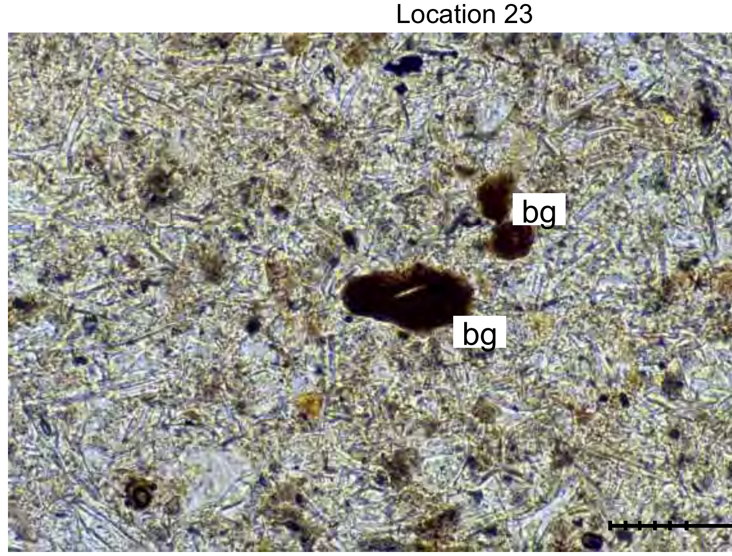
Wood Chop D ash bed
Location 18

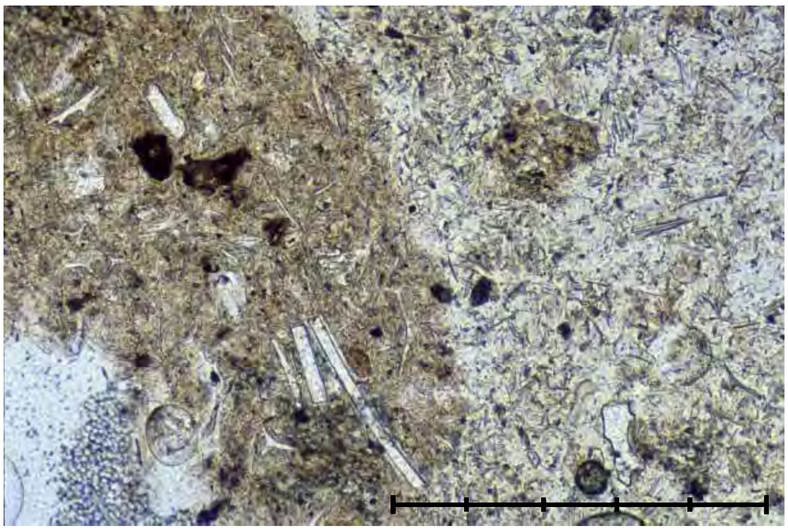
blue-gray #3 ash bed
Location 18



blue-gray #3 ash bed
Location 23

bb)





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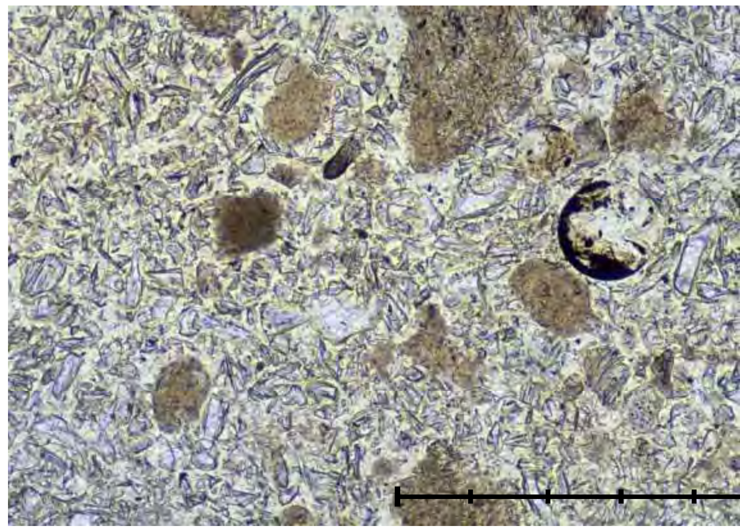
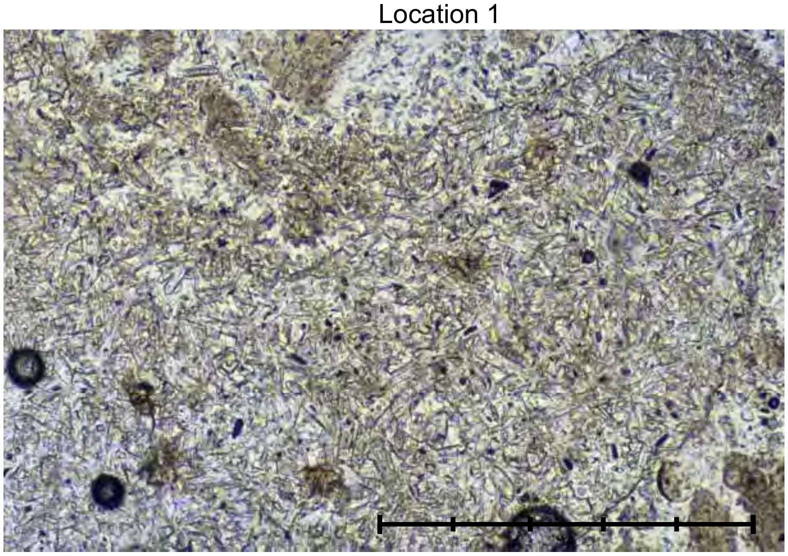


blue-gray #3 ash bed
Location 22

blue-gray #3 ash bed
Location 1

blue-gray #3 ash bed
Location 16

blue-gray #2 ash bed
Location 19



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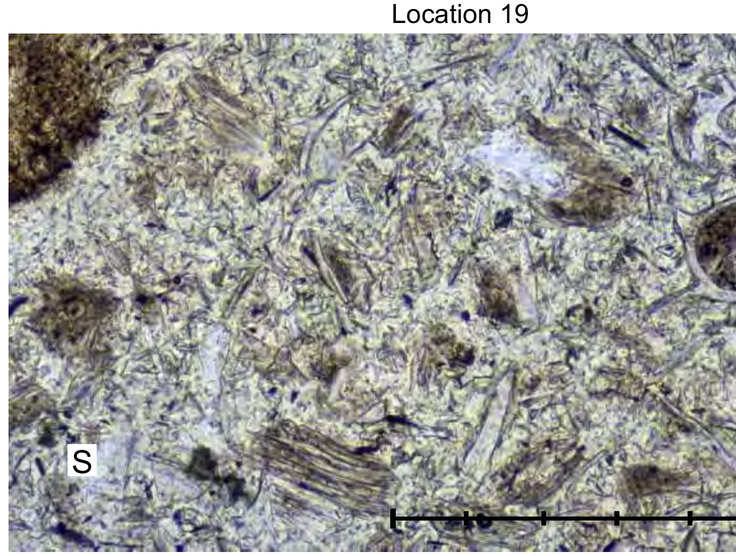
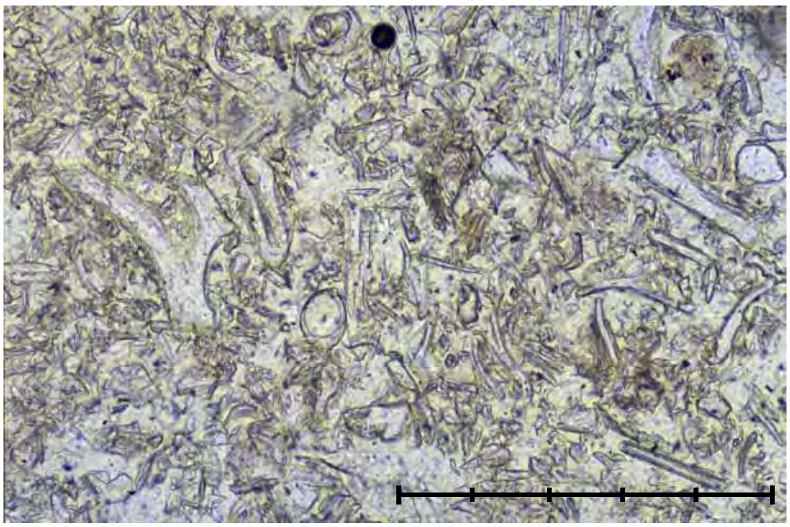
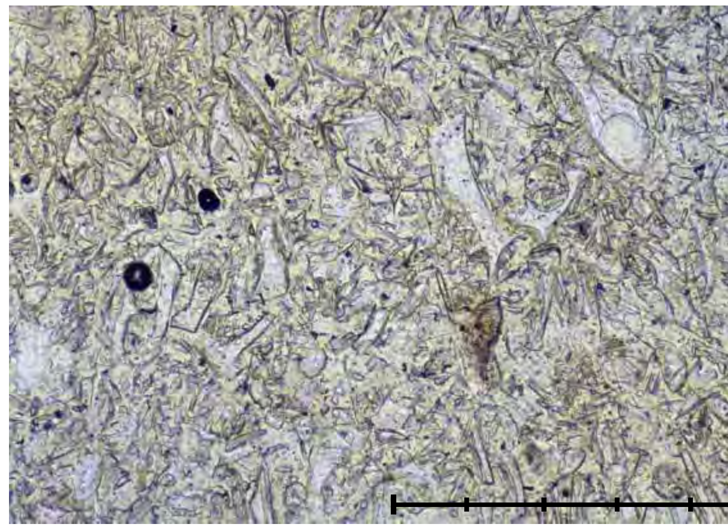




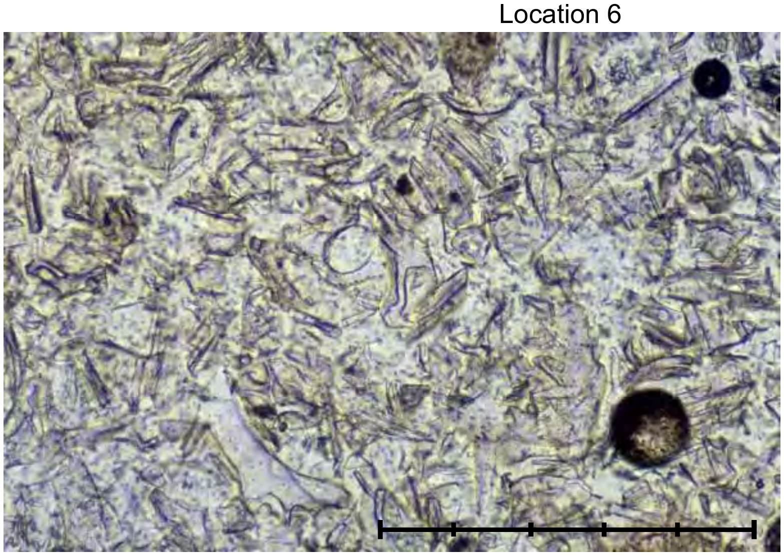
blue-gray #2 ash bed
Location 17

hh)



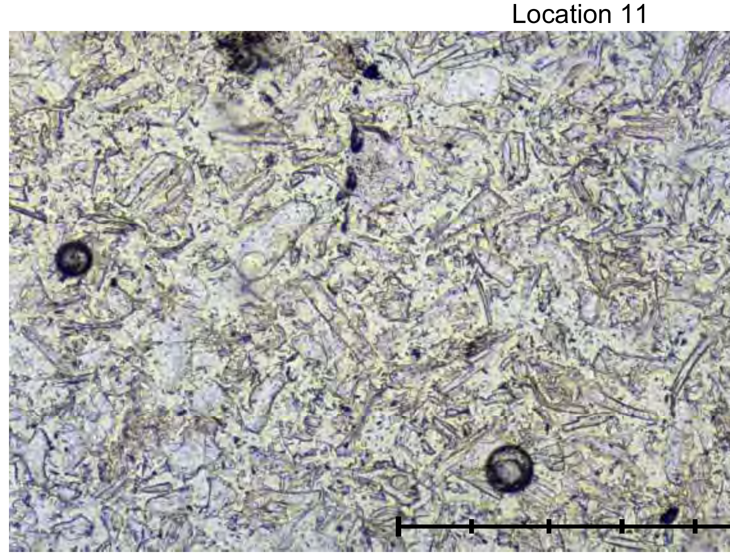
blue-gray #2 ash bed
Location 22

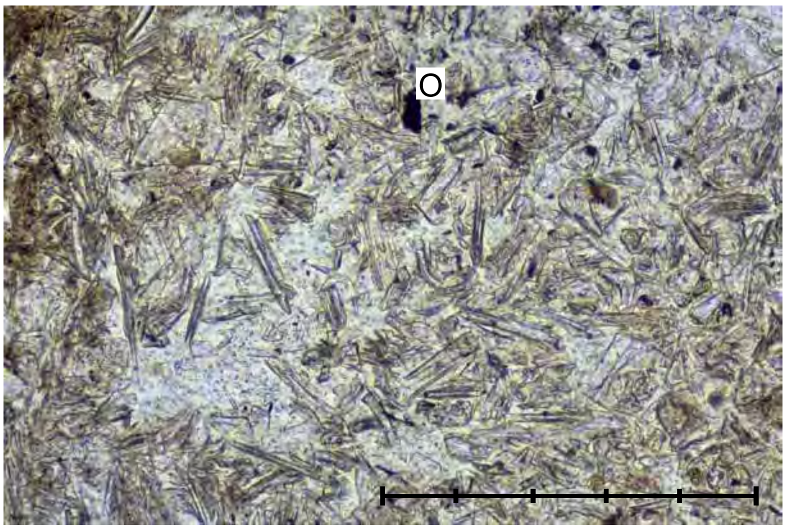
blue-gray #2 ash bed
Location 6



blue-gray #2 ash be
Location 11

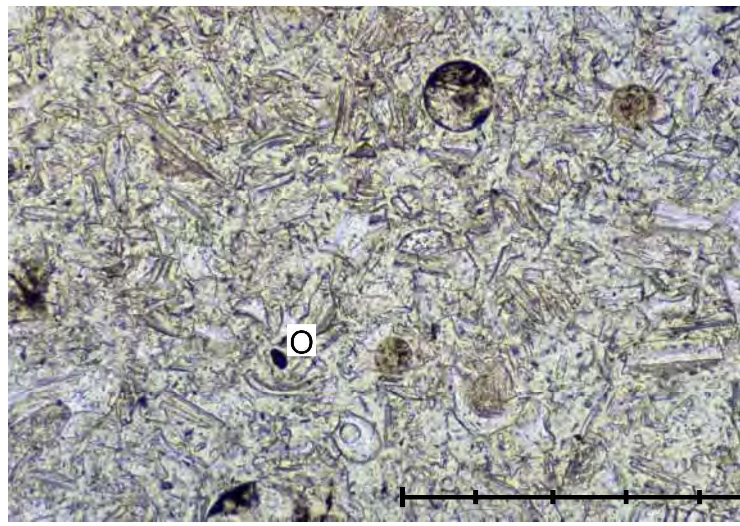
jj)





blue-gray #1 ash bed
Location 19

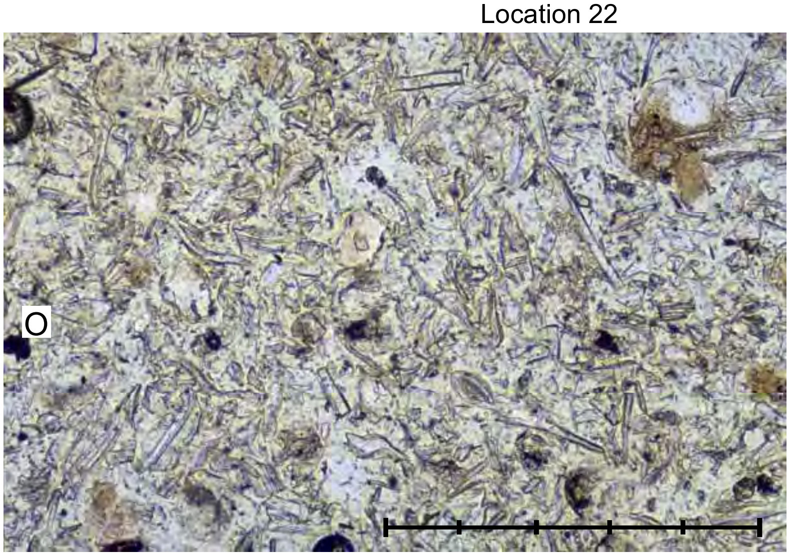
ll)



blue-gray #1 ash bed
Location 17

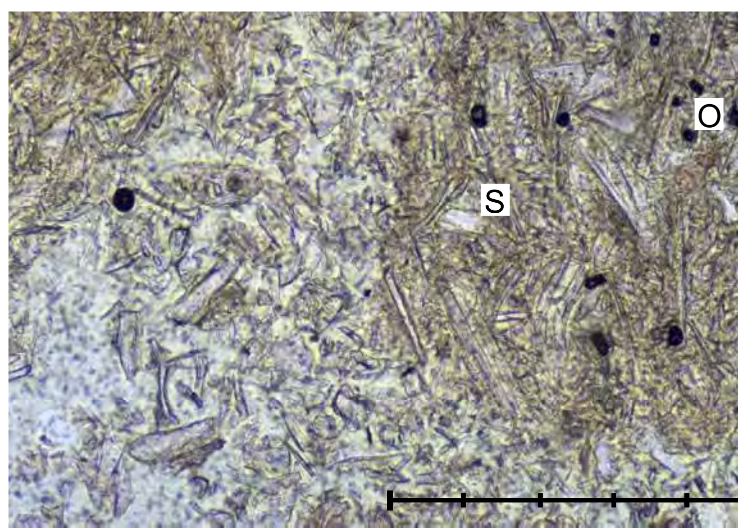
blue-gray #1 ash bed
Location 22

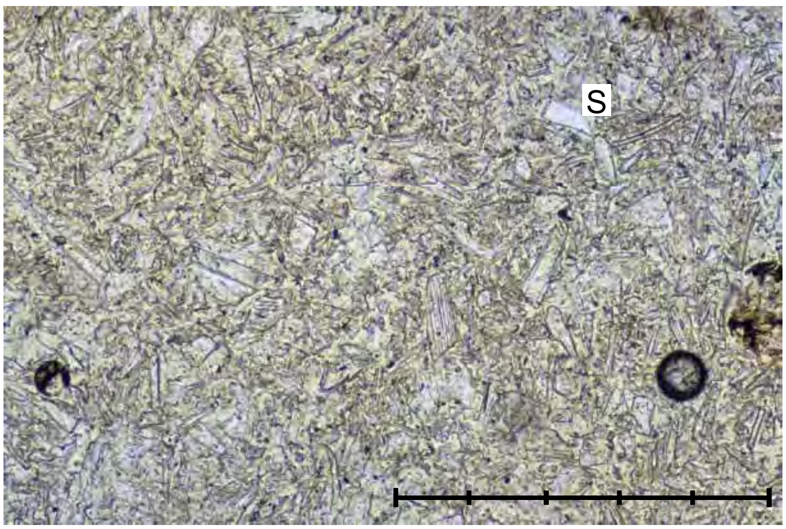
n)



blue-gray #1 ash be
Location 6

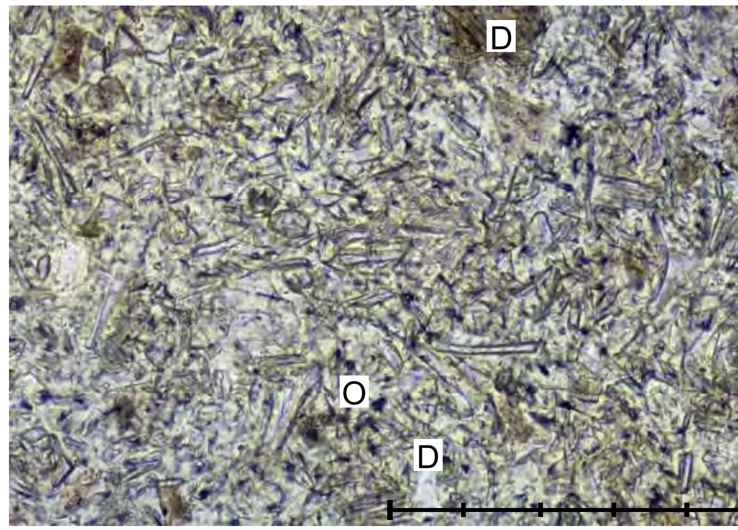
nn)





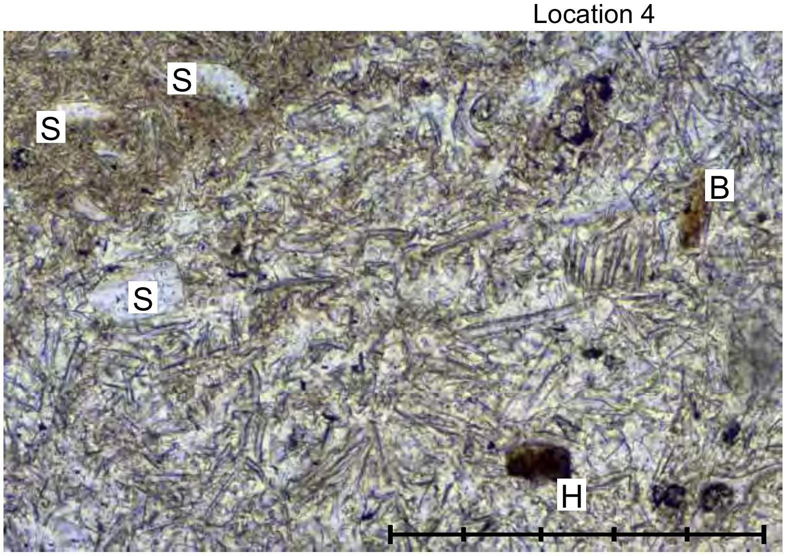
blue-gray #1 ash bed
Location 11

pp)



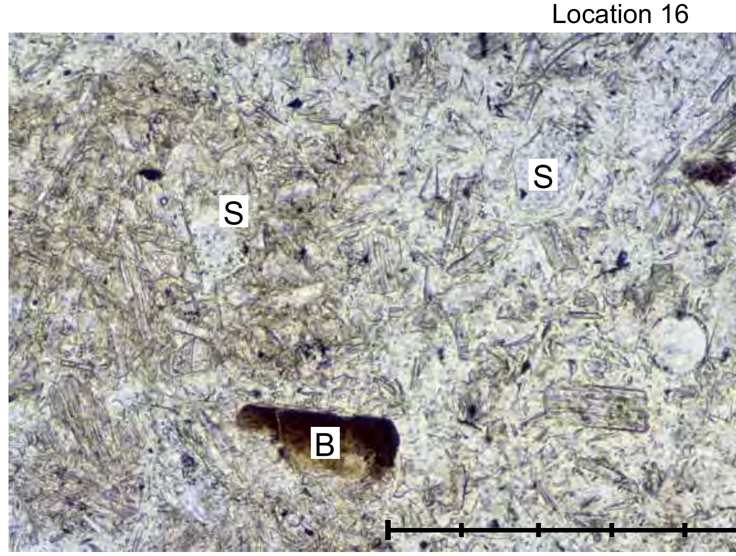
blue-gray #1 ash bed
Location 18

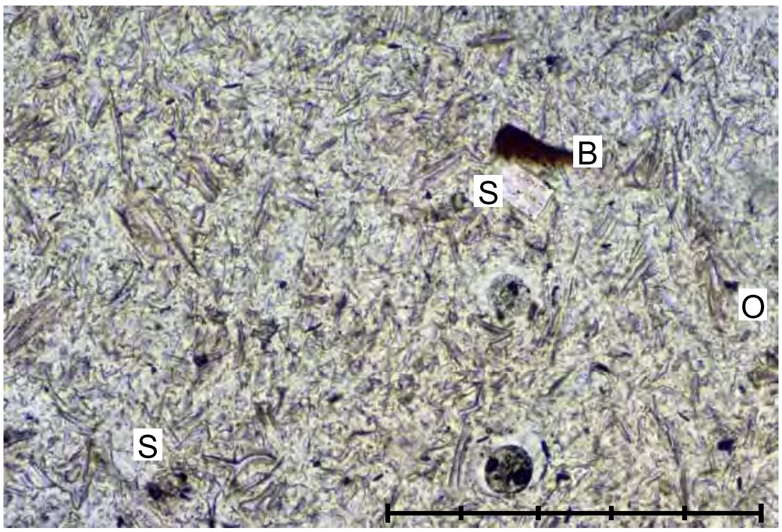
13.71 Ma ash bed
Location 4



13.71 Ma ash b
Location 16

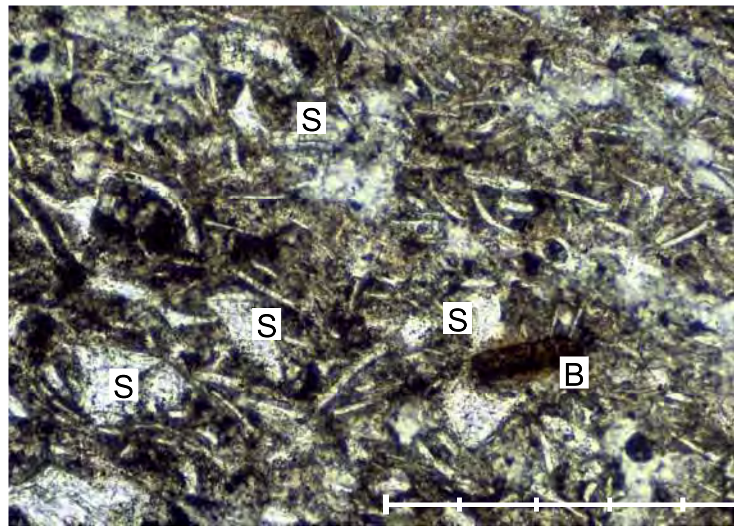
rr)





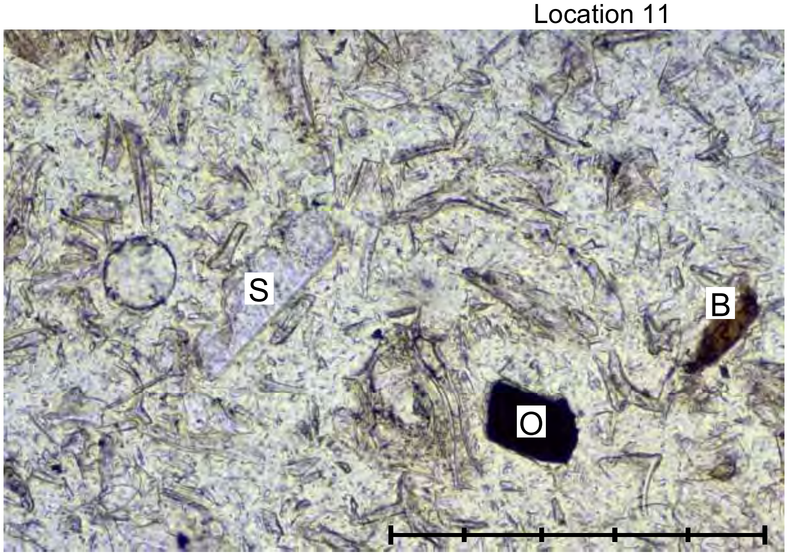
13.71 Ma ash bed
Location 18

tt)



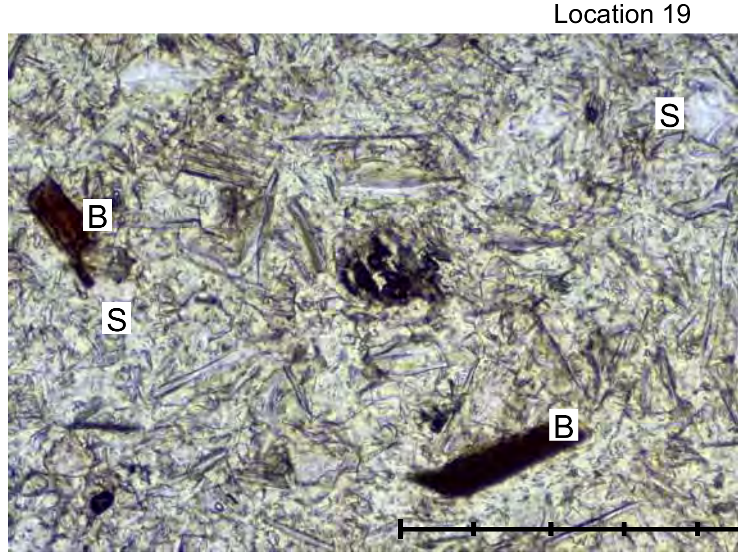
13.71 Ma ash bed
Location 12

13.71 Ma ash bed
Location 11



13.71 Ma ash b
Location 19

vv)



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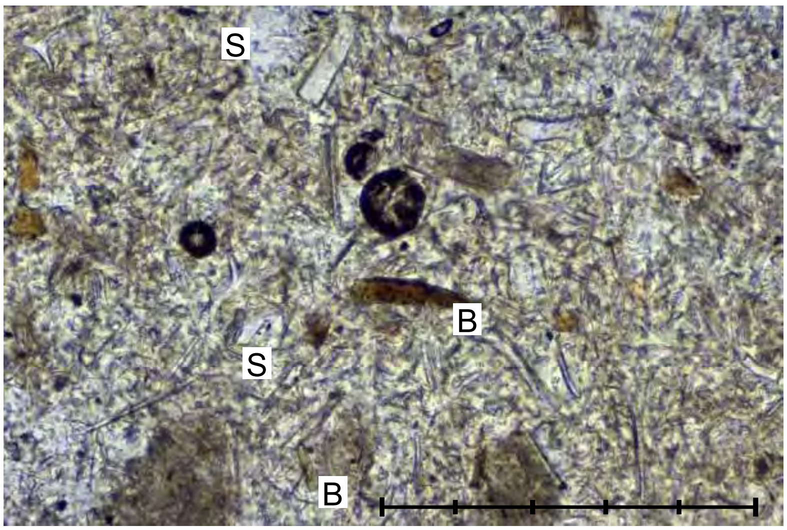
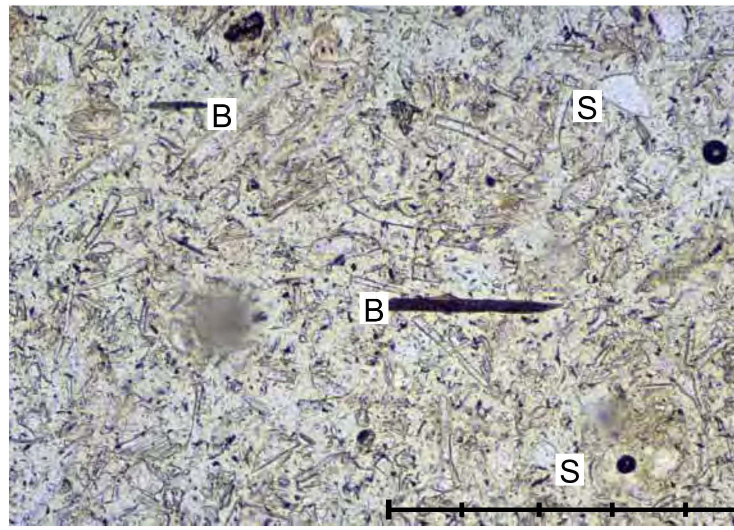


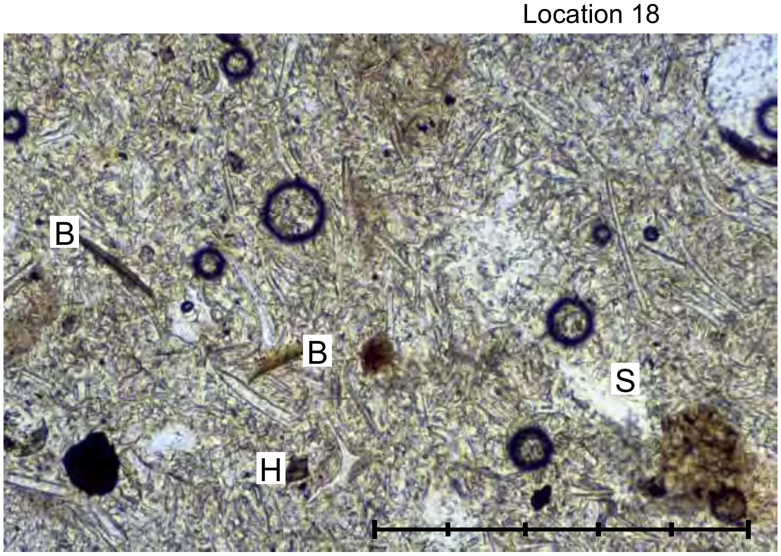
Satan Butte ash bed
Location 11

xx)



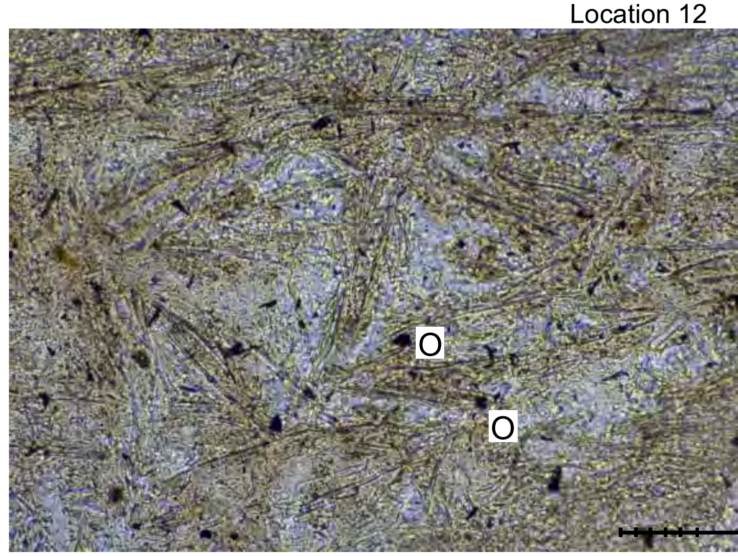
Satan Butte ash bed
Location 16

Satan Butte ash bed
Location 18

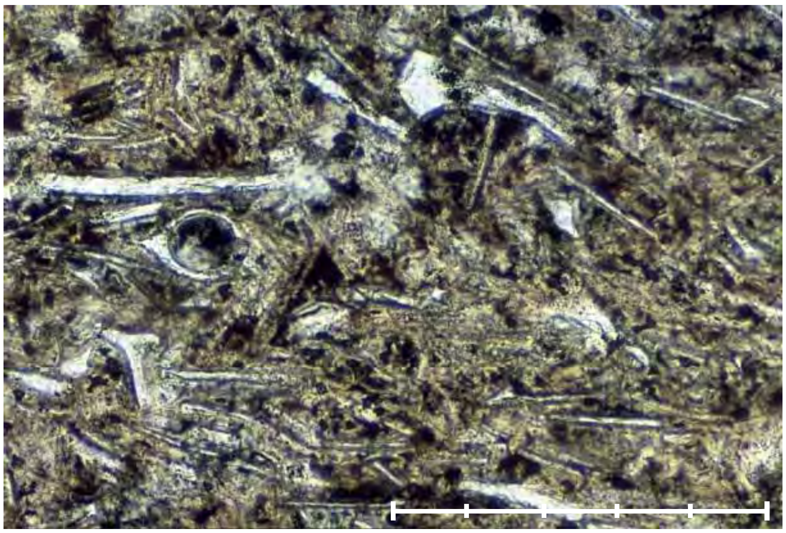


pumice ash be
Location 12

zz)

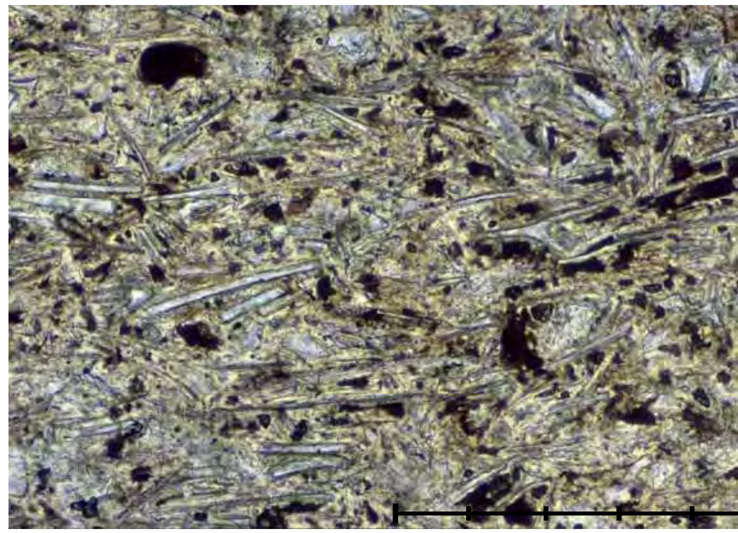


a)



Greasewood ash bed
Location 12

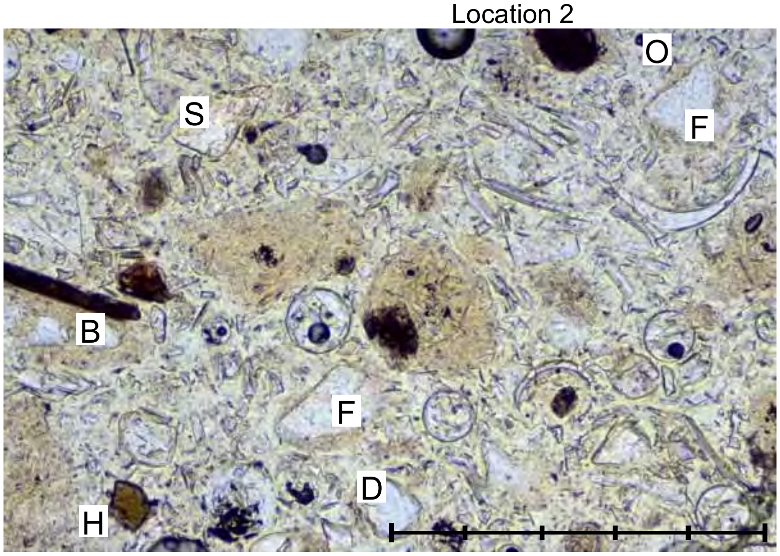
bbb)



Greasewood ash bed
Location 6

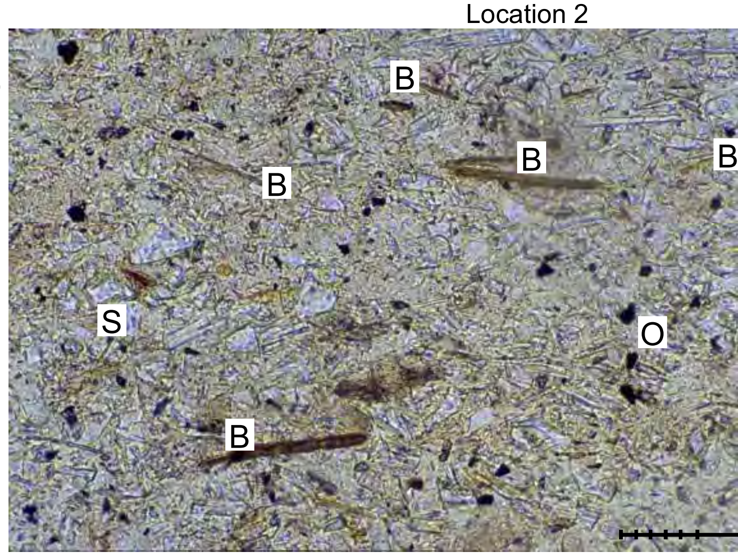
member 6 felsic ash bed
Location 2

c)



member 6 biotite ash b
Location 2

ddd)



Chapter 4 - Basin Morphology

The chronology of tectonic events that formed the basin containing the Bidahochi Formation is poorly known. Evidence from chronostratigraphic and lithostratigraphic analyses are used here to reconstruct a portion of the basin containing the Bidahochi Formation. In this study, the lake depositional area is informally named the Hopi Lake basin and does not include the drainage watershed. These analyses enable the reconstruction of the Hopi Lake shoreline and place age limits on lacustrine deposition within the Hopi Lake basin.

Basin Reconstruction Methods

Hopi Lake basin is reconstructed by correlating tephra beds and lithogenetic packages across the existing outcrop locations of the Bidahochi Formation. Characterizations along with geochemical analyses and isotopic dates of the silicic interbedded ash beds are used to establish chronohorizons across the basin (Figure 3.9). Correlation of the major lithogenetic packages and field observations are used to define basin boundaries when applicable.

The contact between the Bidahochi Formation and the various Mesozoic formations is exposed in several areas to the east and north of the Hopi Buttes volcanic field and is used to define basin deposition in these directions. Where the Bidahochi Formation is no longer present, boundaries for basin deposition are determined by extending the elevation of the maximum lake level (determined by highest modern topographic elevation of known lacustrine units) around the southern Colorado Plateau. This defines the depositional basin at maximum lake inundation. However, this elevation maximum does not allow for any potential differential uplift of the Colorado Plateau caused by regional tectonic events after lacustrine deposition occurred within the Hopi Lake basin. The fluvial and eolian member 6 is not discussed here because it was not the primary focus of this study and it does not constrain the lacustrine depositional basin (see Figure 1.3).

Basin Morphology

The morphology of the Hopi Lake basin was determined by correlation of the tephra and clastic units and defining onlap relations along the margin of the basin. The boundaries of the lacustrine basin, determined by lake level maxima, were extended around the Colorado Plateau to determine the size and extent of the Hopi Lake. Results from this study show that a large Hopi Lake surface area is the preferred option.

A principal question to this study was the location of the southwestern and western boundaries of the Bidahochi Formation. Erosion has removed much of the Bidahochi Formation in western areas (see Chapter 2 and Figures 2.5 and 2.11) r relations in these areas. Two correlation possibilities have been proposed in Dallegge et al. (1998) and Ort et al. (1998):

(1) If the beds (mostly member 4) above the 13.71 Ma ash bed in the eastern side of the basin correlate with the beds can be defined on the southwestern and western sides (Figure 4.1a) and the lake margin was confined roughly to the c 1-4 and the volcanic deposits of the Bidahochi Formation. This would imply that an ancestral Little Colorado River (in a similar position to the present LCR.

(2) If the beds (members 1, 2, and 3) below the 13.71 Ma ash bed in the eastern side of the basin correlate with the be on the west is unconstrained (Figure 4.1b) and the lake in which members 1-4 of the Bidahochi Formation were depos the area containing the present integrated Little Colorado River drainage. This implies that the present integrated drai Plateau did not develop until after draining of the lake, probably ~ 5.5 Ma, and associated development of the Grand

Previous workers are split over which hypothesis is correct. Some prefer a small Hopi Lake surface area (Repenning and Irwin, 1958; McKee et al., 1967; Nations et al., 1985; Scarborough, 1989; and Spencer and Patchett, 1997) while others prefer a large Hopi Lake surface area (Sutton; 1974b; Lucchitta, 1984; Love, 1989).

Ash bed correlation

The results from the ash bed characterizations and the established chronohorizons (Figure 3.9) are used to build two cross-sectional diagrams (southwest/northeast and northwest/southeast) and a generalized fence diagram across the basin (Plates 1 and 2, and Plate 3). The 13.71 Ma ash bed was the primary datum used in the cross-sections (Plates 1 and 2). It is very distinctive and easily recognized by its thickness, stratigraphic position (Figure 3.9), petrographic identity (Table 3.4), and lateral extent. It can be recognized and traced throughout most of the eastern half of the field area. Another ash bed in western exposures is easily recognizable by its thickness, ledge-forming character, stratigraphic position, and high degree of alteration. It is used as a datum for measured sections in western locations where the 13.71 Ma ash bed is

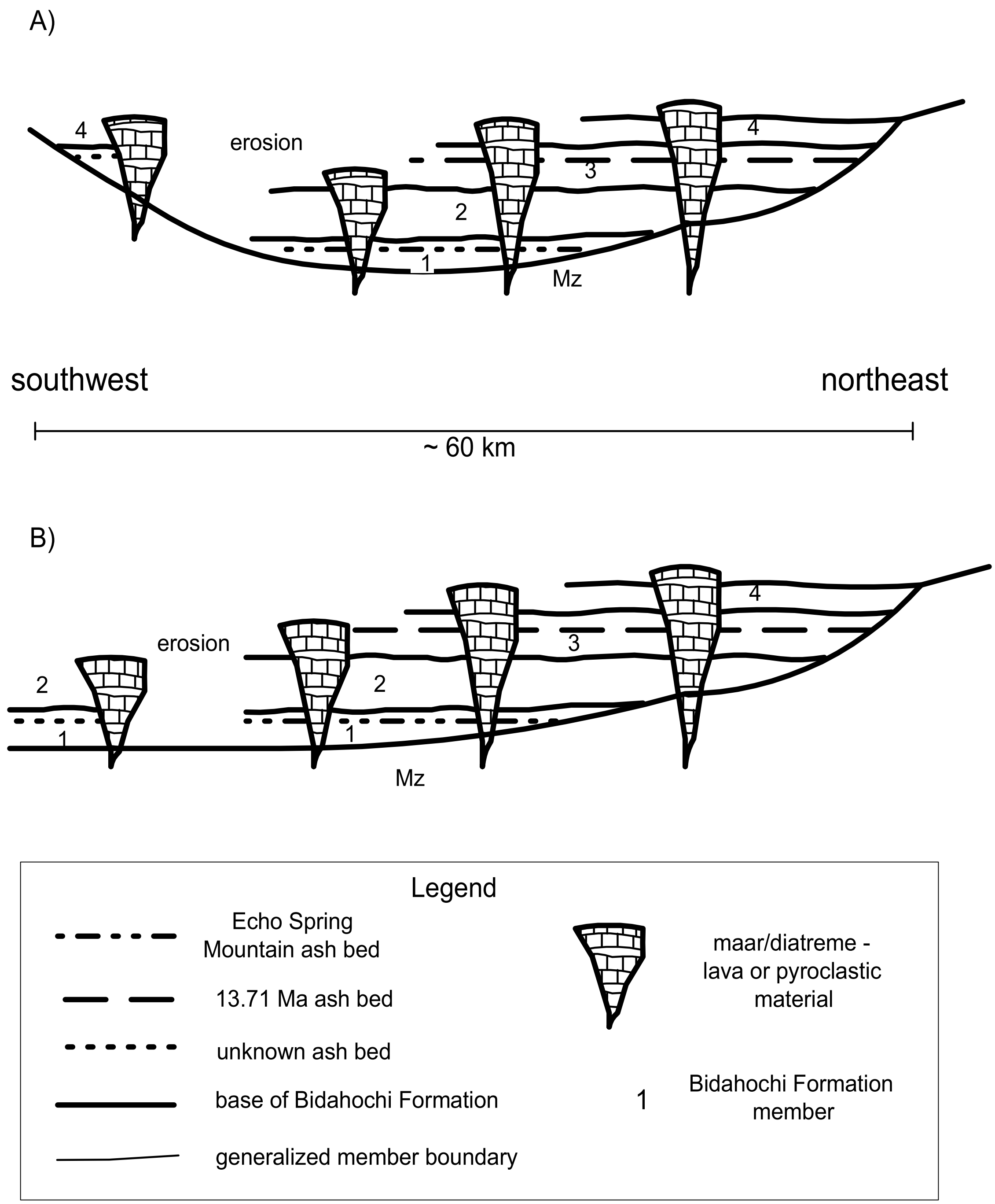


Figure 4.1 Simplified sketch of Bidahochi basin morphology showing two correlation possibilities. See text for description of correlation possibilities. Ash beds were used to establish that option B is preferred. N umbers correspond to Bidahochi Formation members of Shoemaker et al. (1957).

not exposed (Plate 1). This western ash bed is correlated to the Echo Spring Mountain ash at Wood Chop Mesa based on similar petrographic characteristics and stratigraphic position (Figures 3.4b, 3.9, and 3.10b). This correlation is also strengthened by other ash bed correlations and a clastic unit correlation (see below and Plates 1, 2, and 3). The Echo Spring Mountain ash and the 13.71 Ma ash occur in the same section (Plate 1) at Wood Chop Mesa (location 16 on Figure 2.2). This provides a link of the outcrops in the west that lack the 13.71 Ma ash bed with those in the eastern portion of the depositional basin. These correlations show that the basin morphology in Figure 4.1b is preferred and thus, a large Hopi Lake surface area is possible.

Many of the other ash beds are only correlatable locally (e.g. blue-gray #1 ash bed, Satan Butte ash bed, Wood Chop A-D ash beds, etc.). The thickness of these ash beds is considerably less than the two mentioned above. Reworking with the surrounding rock types has caused these ash beds to be discontinuous or absent in some areas. Commonly these ash beds were not identified, probably because of their thin nature or lack of exposure in the colluvium-covered slopes. These ash beds are useful locally and can be traced laterally from butte to butte (Plates 1, 2 and 3).

A problem arises from the dating of an ash bed that correlates well with the 13.71 Ma ash bed. The 13.71 Ma ash bed is correlated across the basin to the east along two cross-sectional lines (Figure 4.2 and Plate 3). The new date of 13.85 ± 0.02 Ma (see Chapter 3, Appendix C) from this ash bed at location 6 (on Figure 2.2) is in conflict with correlations and the previously reported 13.71 ± 0.08 Ma date for this ash bed. The 13.71 Ma date is obtained from a bulk sanidine crystal run that was step-heated in the Mo resistance furnace. The 13.85 Ma date was obtained from single-crystal, CO_2 laser fusion analyses. The two error bars of these dates do not overlap or contain age spectra that clearly suggest they are the same ash bed (Appendix C). However, the single crystal run does contain ages from 7 of the 16 individual crystals that would fall within the upper error range of the 13.71 Ma date if the individual errors on each crystal are used and subtracted from the average 13.85 Ma date. The K/Ca ratios from the two dated ash beds are similar (Appendix C).

Two solutions exist for the discrepancy between the dated ash beds; either this is a new ash bed or there is a problem with analyses due to contamination of one of these ash beds or because of analytical

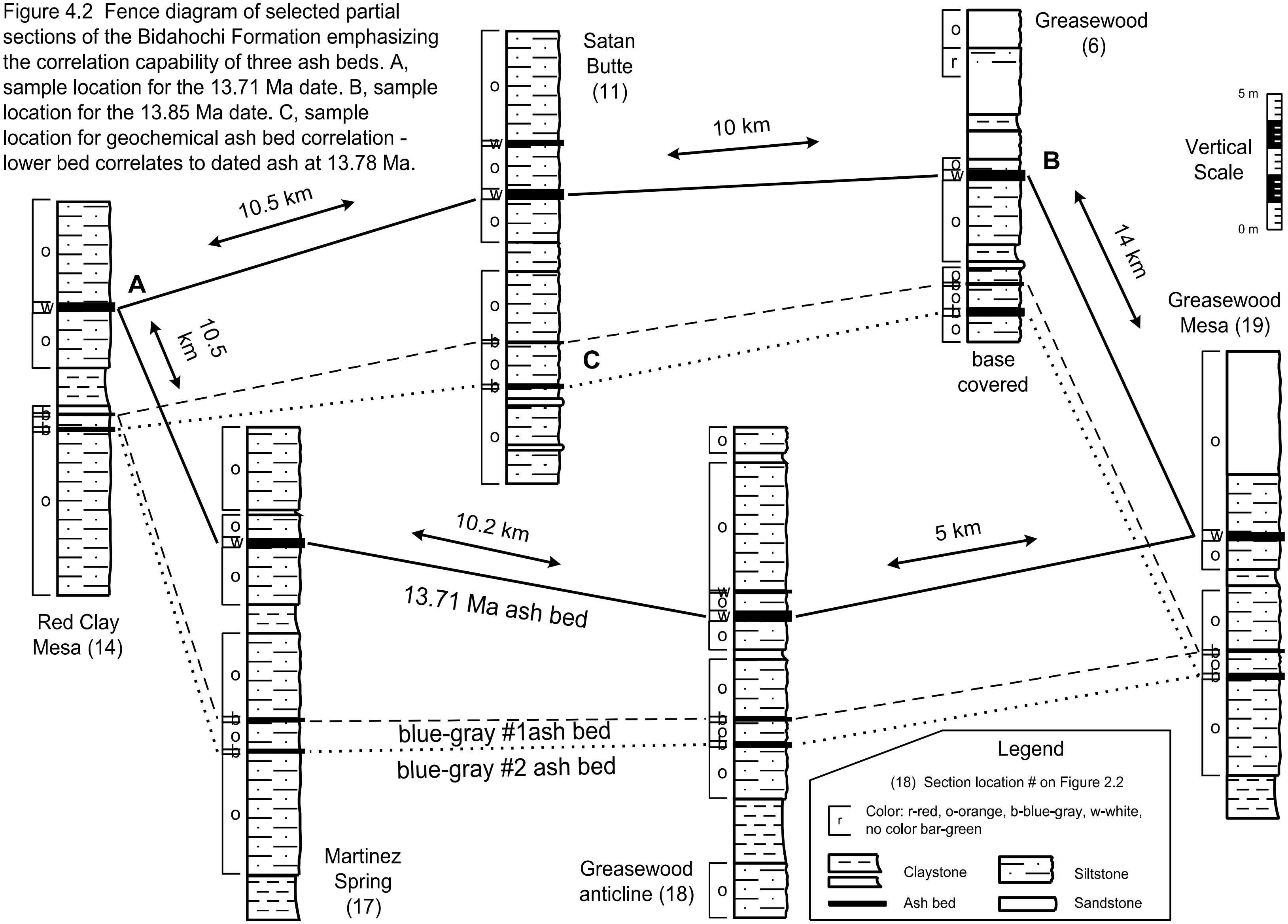


Figure 4.2 Fence diagram of selected partial sections of the Bidahochi Formation emphasizing the correlation capability of three ash beds. A, sample location for the 13.71 Ma date. B, sample location for the 13.85 Ma date. C, sample location for geochemical ash bed correlation - lower bed correlates to dated ash at 13.78 Ma.

error. Petrographically these two ash beds contain similar shard morphologies, phenocryst minerals, and textures (Table 3.4, Figures 3.2, 3.6a). At the location of the sample, dated at 13.85 Ma, the ash bed is well-calcified, white, and 32 cm thick. The 13.71 Ma dated sample is friable, white, and 28 cm thick. Both samples occur within the siltstone units of member 3. The clastic units interbedded with these ash beds are very similar (Figure 4.2).

Several other points are noted that suggest that the two ash beds with the discrepant dates are the same bed. Two ash beds, blue-gray #1 and #2, analyzed geochemically by M. Perkins (Chapter 3) are correlated to the Lovelock and Grouse Canyon (?) ash beds. These two ash beds are very distinctive (blue-gray color, small thickness, vitric) and occur in most of the measured sections in this part of the basin (Figure 4.2, Plate 3). Both of these ash beds occur at the locations of the samples with the age discrepancy. These blue-gray ash beds are stratigraphically below the white ash beds with the discrepancy at these two locations. The correlated date on the Grouse Canyon (?) ash bed is 13.78 ± 0.04 Ma (Perkins et al., 1998). The clastic units occurring around these three ash beds are very similar and can be correlated across the eastern half of the depositional basin. The ash bed dated at 13.85 Ma occurs stratigraphically above the blue-gray #1 and blue-gray #2 ash bed and is in a similar stratigraphic position to the sample dated at 13.71 Ma (Figure 4.2). This implies that the ash bed dated at 13.85 Ma can not be this age and still occur above the blue-gray #1 ash bed and the blue-gray #2 ash bed (correlated to dated Grouse Canyon (?) at 13.78 ± 0.04 Ma) stratigraphically. The K/Ca ratios from the two dated ash beds are very similar (Appendix C) and at least allow the sanidine samples from the two ash beds to be related. There are no petrographic or physical characteristics that suggest they are different beds.

Several ideas are proposed that can explain the discrepancy between the two ash beds. The location of the ash bed dated at 13.85 Ma is very near the basin margin (see below). Older sanidine crystals from previously deposited ash beds to the east could have been eroded and transported to the Hopi Lake basin and mixed with an ash bed during deposition or shortly thereafter. These older sanidine crystals may have been larger than the sanidine from the eruption cloud that produced the 13.71 Ma date. The smaller sanidine crystals may have also been in the sample but the larger ones were selectively picked for analysis by laboratory preparation staff. The larger sanidine crystals are preferred by the New Mexico

Geochronology Research Laboratory because they can be used for single-crystal laser fusion (L. Peters, 1998, personal communication). Crystal and glass shard sizes are noted to vary within the 13.71 Ma ash bed (reported in Chapter 3) and it may also be possible that the sample (ash bed dated at 13.71 Ma) sent to New Mexico Geochronology Research Laboratory was a subset that did not contain any of the larger sanidine crystals. The two sizes of sanidine crystals within the same ash bed suggests that two crystal sizes existed in the magma chamber with the larger crystals having an older closure date, thus making the sample appear older. If these two sizes of crystals occurred in the same magma then the similarity in K/Ca ratio would be explained.

Other explanations are related to the variation in sample analysis for the two ash beds. The single-crystal laser fusion method completely fuses the sanidine crystal in one step and all the Ar gas is released at this point. The bulk-sample furnace method heats the sanidine crystals over multiple heating steps and releases the Ar gas incrementally over each step. With the step-heating method, any radiogenic Ar gas attributed to Cl or Ca contamination of the outer surface of the sanidine crystal will show in the first couple of heating steps and can be factored out of apparent age of the sample. It may be that Cl or Ca contamination went undetected and non-atmospheric Ar gas was included in the apparent age of the laser fusion run, resulting in older apparent ages. The overlap of some of the individual crystal runs suggests that the accuracy reported by the lab may be in error. The last five crystal measurements were high (>13.92 Ma) and were not used in the statistical manipulation of the data. These dates range as high as 15.60 Ma. Using all or part of these older dates would increase the age and also increase the error bar, thus potentially overlapping the error bar on the 13.71 Ma date. This suggests that these two reported dates may be of similar age.

Therefore, based on ash shard morphology, phenocryst composition, stratigraphic position, geochemical ash bed correlations, lithology relations, stratigraphic position, chronologic constraints, and K/Ca ratios, this study contends that the ash bed dated at 13.85 Ma is actually the 13.71 Ma ash bed. The discrepancy between the two dates is probably best explained by the variation in sample runs explained above. For this paper, the 13.71 Ma date will be used, primarily because it seems to be the correct date as noted above, until this discrepancy can be further tested and evaluated.

Lithic unit correlation

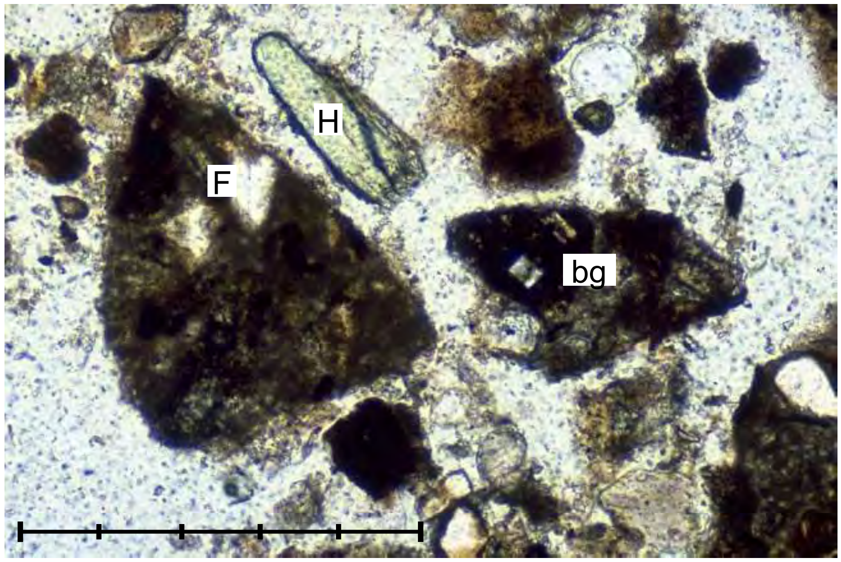
Several diagnostic clastic units can be used to aid in correlation. These beds are correlatable based on petrographic, lithologic, and X-ray diffraction analyses.

A sandstone unit near the base of the formation has a definable petrographic signature that is used to correlate beds in western exposures to beds in the east (Plate 1). This sandstone contains volcanic lithic grains with small thin laths of plagioclase in a glassy matrix (Figure 4.3). Part of the glassy matrix is opacitized (black in color) in some grains while others are stained red-brown. Some glassy lithic fragments also contain phenocrysts of pyroxene and minor hornblende and magnetite (Figure 4.3c, d). This unit is recognized in several locations; 15, 18, 22, 24, and 25 (on Figure 2.2). The stratigraphic position of these sandstone units is similar, near the top of member 1. Based on the similar mineral suites and texture and the stratigraphic position of these sandstone, they are correlative units.

X-ray diffraction analyses were used to determine if the color of the fine-grained units is authigenic or allogenic in origin. Previous workers (e.g., Williams, 1936; Repenning et al., 1958; Shoemaker et al., 1962) have used the uniform and continuous nature of the claystone units to interpret a lacustrine environment. If the clays are diagenetic, then a lacustrine interpretation may need to be re-evaluated because the color banding may not be a product of deposition and thus, the homogeneous nature of the beds is not an indicator of lacustrine deposition. Thirteen samples were analyzed to determine their clay mineralogy (see Appendix A for procedure). Of these samples, only three provided satisfactory results with high enough counts (>500) and interpretable XRD patterns (Appendix E). These three samples show that the dominant clay mineral present is mixed-layer disordered illite/smectite. Minor kaolinite and the gypsum are also distinguishable. These clay minerals and presence of different clay minerals in each sample suggests a detrital origin rather than diagenetic. Therefore, the color banding in the Bidahochi Formation is due to depositional processes and can be used as a correlation tool.

The individual members of the Bidahochi Formation are used for correlation. Even though some of these members locally pinch out, they are still recognizable in most areas and are used to correlate entire packages of sediments (Plates 1, 2, and 3). The multi-colored units of member 2 are very distinctive and can be recognized in areas where other members lose their character. The lateral continuity of claystone beds in

a)



b)

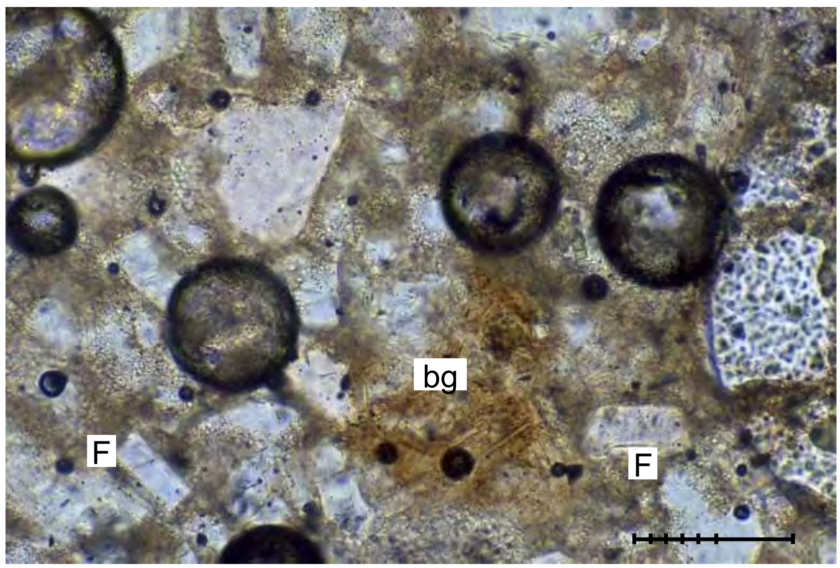
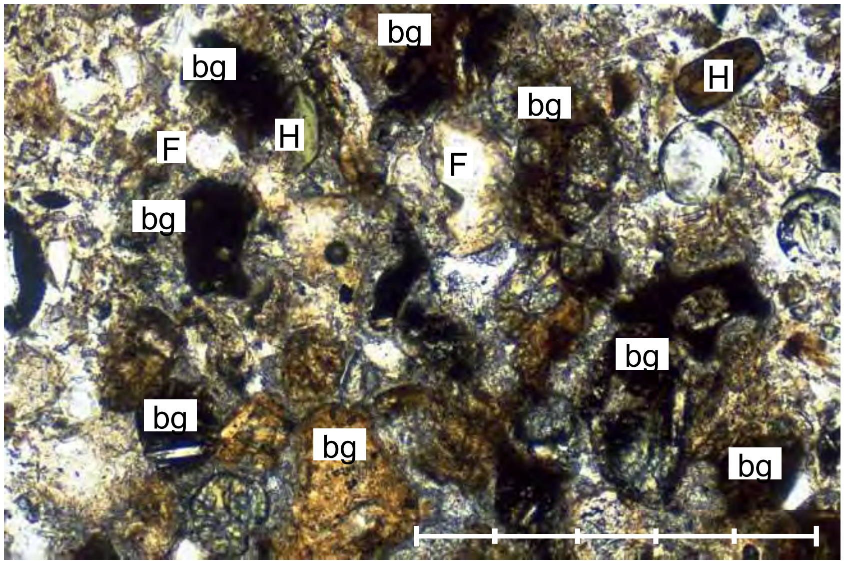
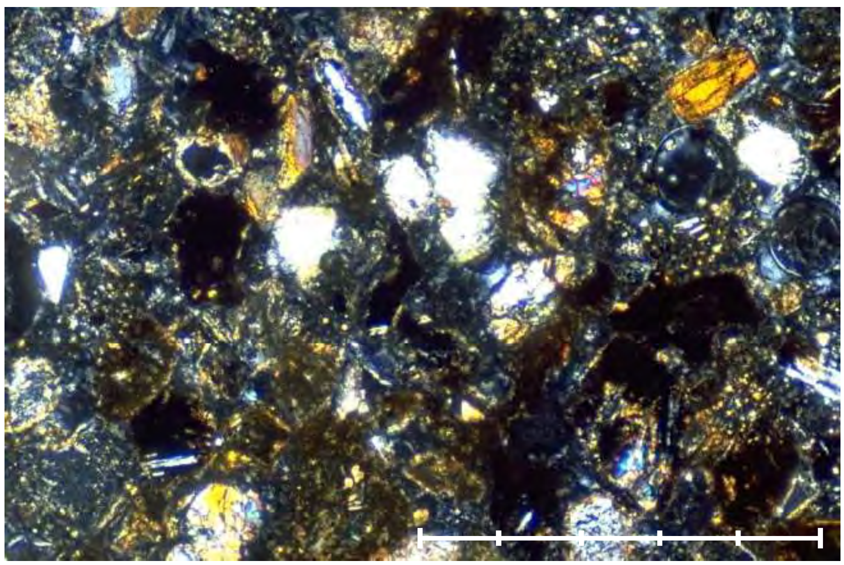


Figure 4.3 Photomicrographs showing the mineralogy within the lower clastic unit. Bar scale in is in 0.1 mm increments and in a), c), and d) is in 0.01 mm increments in b) and e). Photomicrograph d) is in cross-polarized light. Mineral labels are; F - feldspar, bg - brown or black glass with or without plagioclase and/or pyroxene phenocrysts, H - hornblende, M - micrite, Q - quartz. The unlabeled clear grains are commonly quartz or feldspar. All thin sections were made from grain mounts. a) Sample #970704I from location 18 on Figure 2.2. b) Sample #970723D from location 25 on Figure 2.2. c) and d) Sample #970712H from location 22 on Figure 2.2. e) Sample #970807B from location 24 on Figure 2.2. Note in photos c) and d) the pyroxene phenocryst in the brown glass fragment at top right-center.

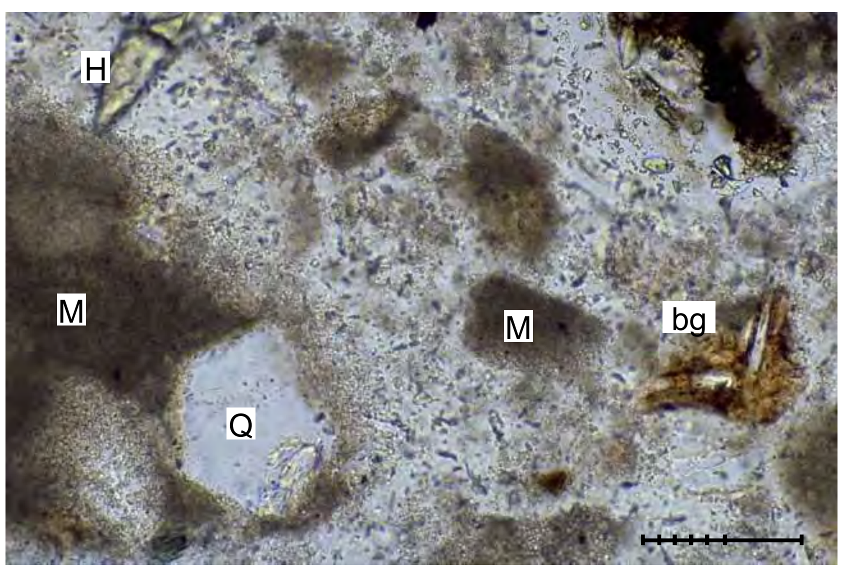
c)



d)



e)



member 3 can be traced for hundreds of meters in the eastern half of the field area (Plate 1). This tracing of individual clay beds is a very successful correlation tool within the area of the Hopi Buttes volcanic field (Plates 1,2) but is not as useful in outlying areas near the basin margins (see below).

Onlap relations

The Bidahochi Formation onlaps the Mesozoic units in at least two localities. One location is along Highway 15 east of Greasewood, Arizona near measured section locations 7 and 8 (on Figure 2.2). Eastward along Highway 15 from location 7, member 3 eventually pinches out (apparent onlap in subsurface) and members 4 and 5 are observed onlapping the Wingate Sandstone at location 8 (Figure 4.4 and Plate 1). The Wingate Sandstone occurs in several places near Highway 15 as isolated erosional remnants surrounding and overlain by units of member 4 (Figure 4.5).

The other location where the Bidahochi Formation onlaps the Mesozoic units is at the west end of Roberts Mesa, ~ 1 km north of Stephen Butte (Figure 2.2). In this location, the Bidahochi Formation onlaps the Cretaceous Toreva Formation and Mancos Shale (units from geologic map of Akers et al., 1971). North of Stephen Butte, the Mancos Shale is exposed in the valley bottom. On the north side of this small valley, isolated outcrops of the Bidahochi Formation are noted (Figure 4.6). These outcrops are in contact with the Mancos Shale and a small paleosol with red hematiferous clays, mottled texture, and root casts is noted at the contact between the formations. To the northwest of this location, the Cretaceous units form the First, Second, and Third Mesas of Black Mesa. No Bidahochi Formation is noted on top of these mesas. Member 6 also appears to onlap the Cretaceous formations (Figure 4.6) and does not cover Black Mesa suggesting that Black Mesa was a topographic high and therefore outside the boundary of the Hopi Lake depositional basin.

Marginal basin features

Several other lithologic and sedimentary features are noted that fix the basin boundaries on the north and east. The Bidahochi Formation at Stephen Butte (Appendix B-17) reflects an abundance of white sand that was derived from the Cretaceous units on the mesas to the northwest. Beds of claystone are intercalated with thick sandstone units at this location. The alternating, multicolored fine-grained units of member 2 can be noted (Figure 4.7) but other members are difficult to distinguish because of the dominance

Figure 4.4 Photograph of the onlapping relations east of Greasewood, AZ. The lower dash blue line occurs at the Mesozoic (Wingate and Moenave Fms)/ Bidahochi Formation contact. The upper dashed blue line is at the top of the red units of member 4. Note the onlapping relation of the red units as they thin to the east. Photo taken from south side of Pueblo Colorado Wash looking to the north.

Figure 4.5 Photo of small outcrop of Wingate and Moenave Formations covered by member 4 of the Bidahochi Formation. The cliff forming units are composed of interbeds of volcaniclastic siltstone and sandstone. The location of this photo is ~1 km west of photo above.

of white sand derived from the Cretaceous units. These white sandstone units at Stephen Butte are fine- to very-fine-grained and contain high-angle, planar cross-bedding. These sandstone units may have been deposited by eolian dunes that encroached on the lake margin.

An ash bed that occurs below Stephen Butte is correlatable with a unit along the road to the north that has ash thoroughly mixed with a medium-grained, poorly sorted, low-angle planar cross-bedded sandstone unit (Figure 4.8). This cross-bedded sandstone was probably deposited by wave action from near-shore beach processes.

Along the eastern side of the basin southeast of Greasewood, Arizona, the units of member 4 form a thick sequence of deposits. Member 4 in this area contains localized trough cross-bedded conglomerate and sandstone lenses and beds. The red beds of this unit are 36 m thick at location 19 (on Figure 2.2) and drastically decrease in thickness to the west (reported in Chapter 2) and the north (Plate 2). Clasts in this conglomerate are dominated by chert and petrified wood fragments, suggesting that the source stream was tapping deposits of the Chinle Formation. Shoemaker et al. (1958, p. 167) interpreted areas of members 3 and 4 as deltas and describe them as: "large lobes extending southwestward from the northeast shore of the ancient Hopi Lake." They placed the source stream for the deltas along the present course of the Pueblo Colorado Wash. At location 8 (on Figure 2.2), the delta deposits are not as thick (16.8 m) as those to the south (36 m) and are interbedded with travertine deposits. The deposits at location 8 were probably along the edge of the delta lobe. Based on these relations, the stream course was probably farther to the south and entered the lake from the east, closer to location 19.

These marginal basin features presented above are why Love (1989, p. 275) stated: "the members of Shoemaker et al. (1957) are clearly interpreted as depositional facies and show complex interfingering relations" and also why Love disapproves of the subdivision of Shoemaker et al. (1957). The chronohorizons commonly cross member boundaries (Plates 1, 2, and 3) which also supports these complex "facies" relations. The lateral change in depositional character is clearly a function of depositional setting. Members 3, 4, and 5 are clearly recognizable and definable, even along basin boundaries where these onlap relations and variations in thickness and characteristics occur. Therefore, this study contends that the Shoemaker et al. (1957) subdivision can still be used effectively despite Love's (1989) statements.

ure 4.6 Composite photograph of the onlapping relations north of Stephen Butte (location 1 on Figure 2.2). Photo is taken from base of
ephen Butte looking north-northeastward. Red dashed line occurs at Mesozoic/Bidahochi Formation contact (Pinyon/Juniper trees tend to be
Bidahochi soil). Orange dashed line occurs at the approximate member 5 member 6 contact. Abbreviations: Tbu - Bidahochi Formation
mber 6; Tbl - Bidahochi Formation members 2-5; Km - Cretaceous Mancos Shale; Km-tl - Cretaceous Mancos and Toreva Formation. lower
ndstone member; Qal - Quaternary alluvial valley fill terrace remnants; A - location of cross-bedded ash and sandstone unit, see text. Geolog
ts from Akers et al. (1971)

Figure 4.7 Outcrop photo of the multi-colored beds of member 2 at Stephen Butte locality (location 1 on Figure 2.2).

Figure 4.8 Outcrop photo of cross-bedded sandstone and ash deposit north of Stephen Butte, see figure 4.6 for location (location 1 on Figure 2.2). The orange lines depict the bedding orientation at this location. The handle of the hoe pick (to right of person) is lying on a bedding plane. The lower horizontal beds contain abundant amounts of felsic ash. See text for further description.

Basin outline

The results from the sections above and the correlation diagrams (Plates 1, 2, and 3) clearly demonstrate that the depositional basin boundary to the north and east is definable and that an unconstrained boundary occurs on the west and southwestern sides of the basin (Figure 4.1b). There is no evidence that the western and southwestern margins of the basin can be determined from stratigraphic correlation (Plate 1). Therefore, Hopi Lake must have extended out beyond the present outcrops and may have extended across the area of the Little Colorado River valley and covered a significant portion of northeastern Arizona. This undefinable basin boundary to the southwest can also be seen on contour maps of the base of the Bidahochi Formation (Figure 4.9). This map attempts to show closure of the depositional basin and restrict it to the current area of the Bidahochi Formation deposits. Based on the information presented above, the depositional basin was most likely larger and no definable boundary is apparent in the Holbrook to St. Johns, Arizona area (Figure 4.9).

A more detailed analysis of the base of the formation in and around the Hopi Buttes volcanic field also demonstrates an undefinable depositional basin boundary to the southwest and shows a varied erosional surface on which the lower members were deposited (Figure 4.10). On these maps, a north to south trending ridge is noted in the area near Dilkon, Arizona. This ridge may have some importance in the distribution of the sediment packages if it was a prominent feature during Bidahochi deposition. Based on the correlations of members 1 and 2 at locations 15, 24, 25, and 26 (Plates 1 and 3), these units do not reflect any evidence of sedimentation differentiation due to a topographic ridge in this area. Therefore, this ridge is probably post-lower members 1-4 in age and may be related to effects created by the Hopi Buttes volcanic field or other regional tectonic events. The Mount Beautiful Anticline on the geologic map of Akers et al. (1971) occurs in a similar position (northwest-southeast trending) as this ridge. Akers et al. show that this ridge folds the Cretaceous units but not the Bidahochi units. This study suggests that the Bidahochi Formation is probably folded at this location. This is based on outcrop attitudes of another undocumented northwest-southeast trending anticline (herein called the Greasewood anticline) south of Greasewood, Arizona. The composite sections measured at this location (Appendix B-18) shows that members 1 and 2 of the

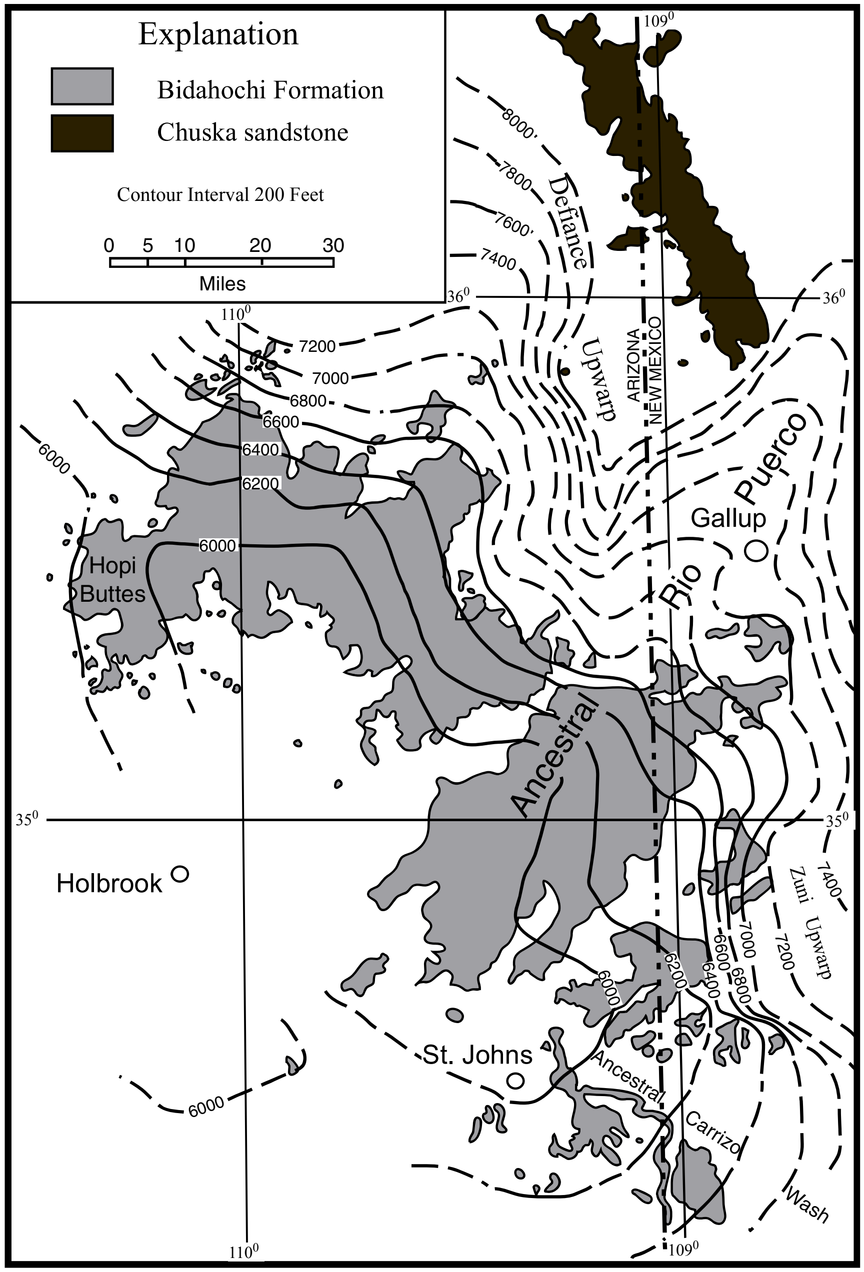


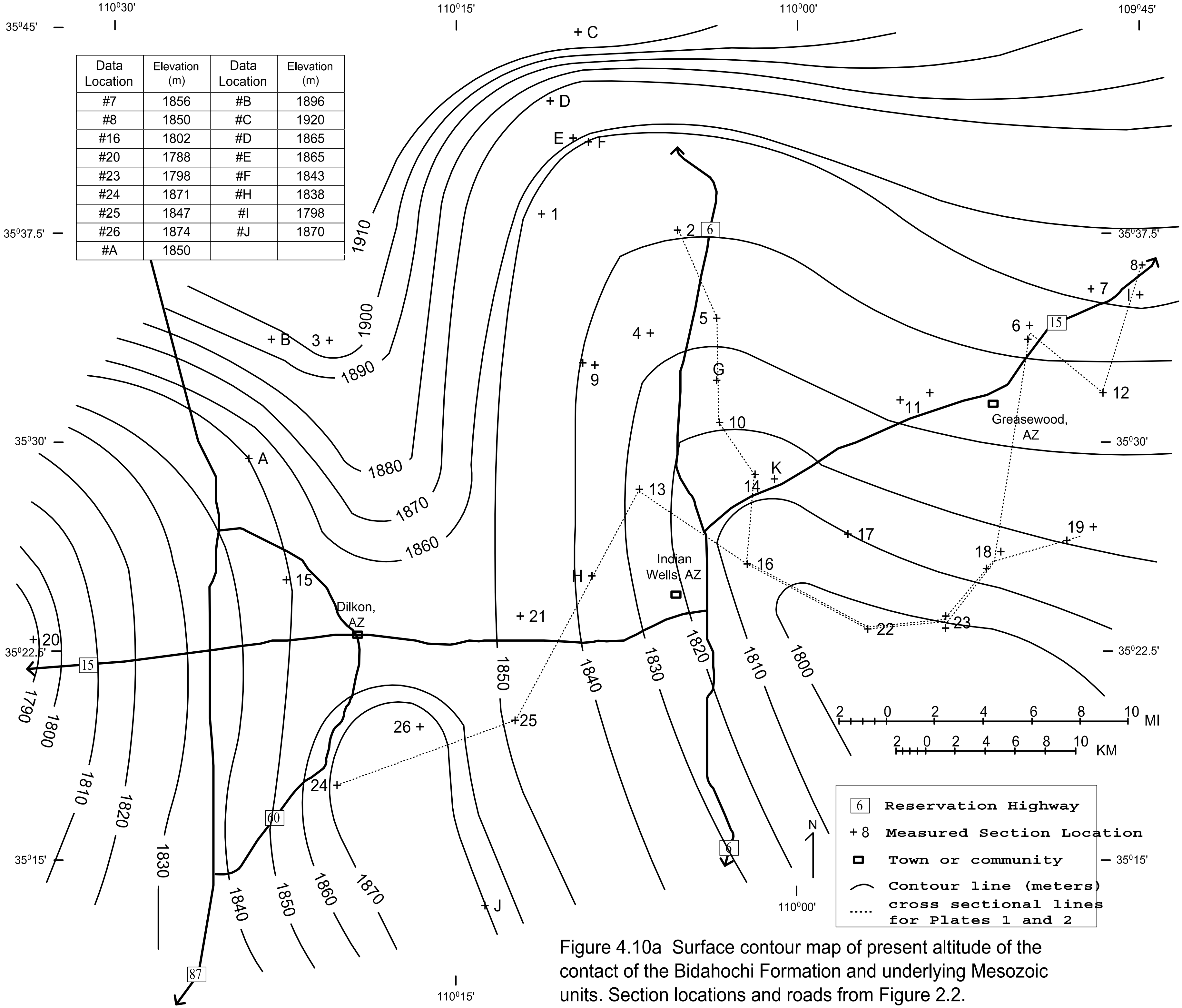
Figure 4.9 Generalized contour map of the erosion surface (Zuni surface of McCann, 1938) that existed prior to Bidahochi Formation deposition. Contours show modern altitude above sea level and not corrected for post-Bidahochi deformation. Adapted and modified from Repenning et al. (1958).

Bidahochi Formation are folded by the anticline with a N80E 07SE measurement on the northeast limb and a N35W 05SW measurement on the southwestern limb.

Lithologic correlation also supports a larger depositional basin area. The sediments fine rapidly to the west (Plate 1) suggesting that some input of sediment was from the east and that the center of the lake may have extended toward the west. Member 2 increases in thickness to the west from ~7 m at location 18 (on Figure 2.2) to ~48 m at location 25 (Plate 1). The opposite occurs with the coarser member 3. It is not recognizable in western locations (location 15, 21, 24, and 25) but is thick in the Wood Chop Mesa area (~27 m). In eastern exposures near the margin of the lake, the base is not exposed, so thickness is undeterminable (E.g., locations 6 and 12). Member 4 shows a similar relationship to member 3. The red unit of member 4 increasing in thickness dramatically to the east from ~3 m near Red Clay Mesa to 36 m southeast of Greasewood, Arizona (Plate 2).

Several outcrops of sedimentary rocks outside the known locations of the Bidahochi Formation have been tentatively correlated with the Bidahochi Formation. Cooley (1962) described 15 m of calcified sandstone and siltstone covered by basalt flows at East and West Sunset Buttes (30 Km southwest of Winslow). These deposits, which occur at elevations between 1,830-1,950 m, where correlated by Cooley (1962) to member 6 deposits at similar elevations east of the Hopi Buttes volcanic field. Nations et al. (1985) correlated Tertiary sediments that Ulrich et al. (1984) mapped along the Mogollon slope and in the Little Colorado River valley with member 6 of the Bidahochi Formation. Light colored (tan, brown, pale red), fine-grained sediments occur along Interstate 40 between Winslow, AZ and Joseph City, AZ in small (less than 2 m thick) lenses and cut and fill structures ~30 m higher than the present Little Colorado River valley. These sediments may correlate to lacustrine units in the Bidahochi Formation or they may be terrace remnants from the Little Colorado River. The fine-grained units of members 1 and 2 can be recognized at Nizhoni Point beneath the maar lava flows of the Painted Desert area of Petrified Forest National Park (Figure 4.11). Bidahochi sediments viewed to the southeast from Tawa Point display a cut and fill sequence similar to the sediments along the Little Colorado River valley.

Based on the evidence presented above, a minimum value for the highest lake level is determined by the highest elevation of lacustrine sediments. This horizon can be traced around the southern Colorado



Data Location	Elevation (m)	Data Location	Elevation (m)
#7	1856	#B	1896
#8	1850	#C	1920
#16	1802	#D	1865
#20	1788	#E	1865
#23	1798	#F	1843
#24	1871	#H	1838
#25	1847	#I	1798
#26	1874	#J	1870
#A	1850		

Figure 4.10a Surface contour map of present altitude of the contact of the Bidahochi Formation and underlying Mesozoic units. Section locations and roads from Figure 2.2.

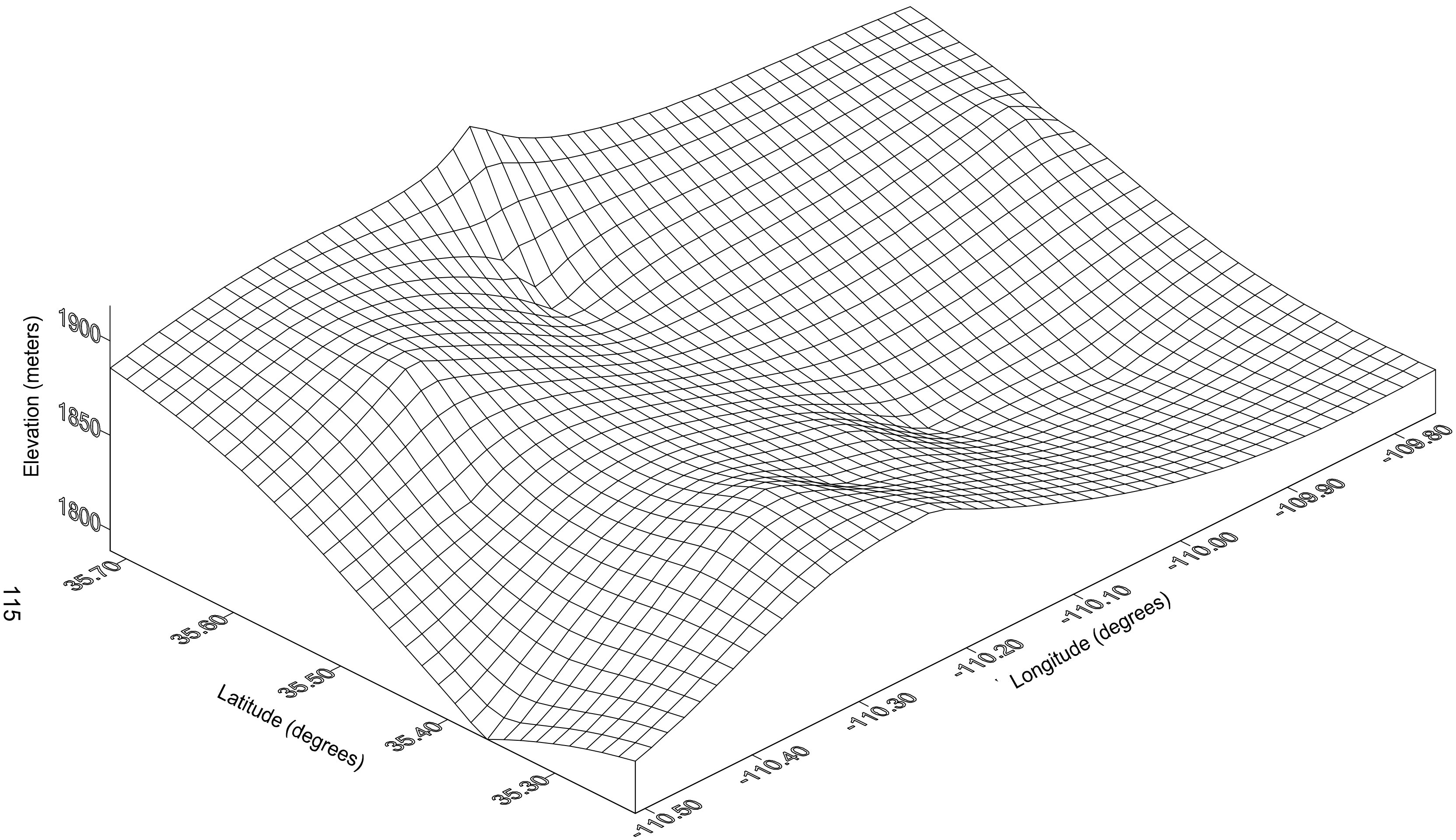


Figure 4.10b Surface contour map on the contact between the Bidahochi Formation and underlying Mesozoic units. Based on contour map from Figure 4.10a.

Plateau to recreate the size of Hopi Lake at maximum lake inundation. The lake maximum is determined along the eastern margin of the basin near Greasewood, AZ. This elevation maximum is established at the present 1859 meter contour interval and hence defines the outline of the Hopi Lake basin during lacustrine deposition. This estimated outline is similar to that of Nations et al. (1985) and Scarborough (1989) (Figures 1.1 and 4.12).

Considerable variation of this lake-level maximum shoreline is possible. Along the eastern margins of the lake where known lacustrine deposits occur, the boundary of the lake may have extended considerably farther to the east (Figure 4.12) and evidence of lacustrine beds in this location would be covered by the fluvial and eolian units of member 6. The lake-level maximum of the southwestern shoreline would have occurred along the gentle dip slope of the Mogollon Slope. Depending on the maximum lake level elevation used, the location of the shoreline on the gentle dip slope could dramatically reduce or increase the surface area of Hopi Lake. Another consideration for this southwestern boundary is the amount of Moenkopi Formation that was stripped off prior to and/or after Bidahochi Formation deposition. If the full section of Moenkopi existed along the southwestern shoreline during Bidahochi deposition, then these deposits would move the shoreline to the northeast and reduce the surface area calculations of Hopi Lake (Figure 4.12). Based on the extensive erosional period during Oligocene time, it is most probable that most of the Moenkopi was stripped off the plateau in these locations. The lake outline based on the present 1859 m contour interval is used to evaluate the size of Hopi Lake and recreate the paleogeography for this portion of the Colorado Plateau (see Chapter 5).

Hopi Lake

With this depositional basin, a question arises concerning how much water is needed to maintain Hopi Lake as a fresh water lake throughout the year. This apparent long-lasting fresh-water lake would require substantial input from a major stream system. This question is addressed by developing a water budget (see Appendix A for method) for Hopi Lake to determine if water from the ancestral upper Colorado River or similar source is needed to maintain this lake. The comparisons, estimates, and calculations used in the following sections are based on static conditions at single points in time. There are not enough data available at this time to account for all the variables of this complex system. This study acknowledges that

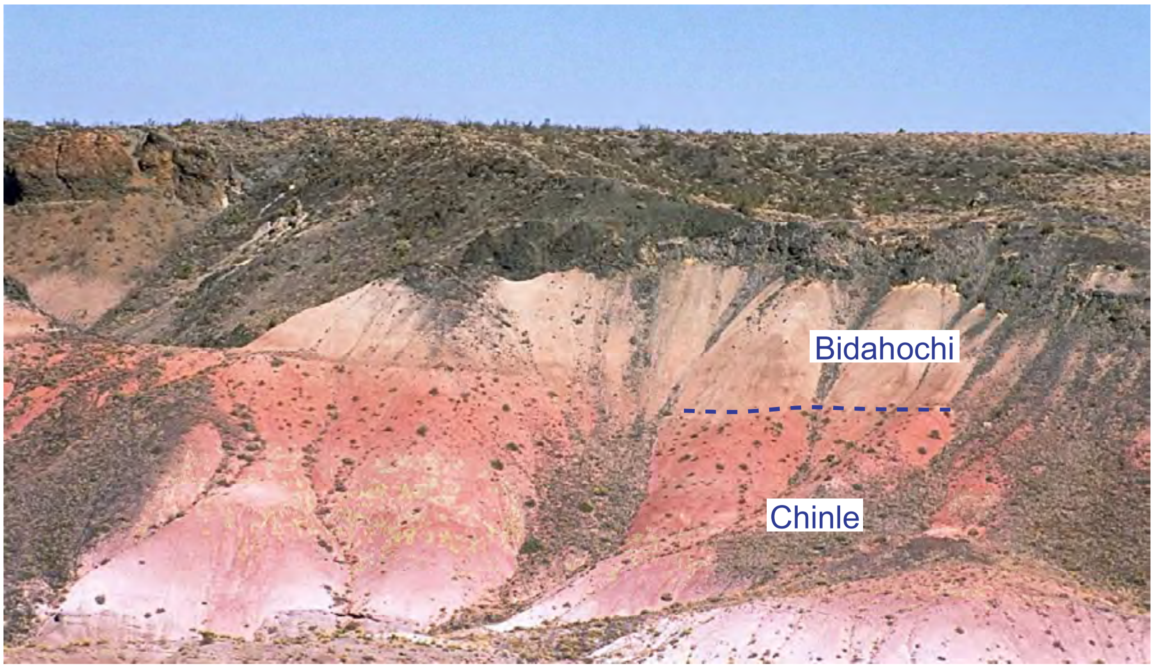


Figure 4.11 Outcrop photo of the Bidahochi Formation at Nizhoni Point, Petrified Forest National Park. Blue dashed line is approximate contact between the Chinle and Bidahochi Formations. The black lava and brown tuff are from the Maar crater that forms this mesa.

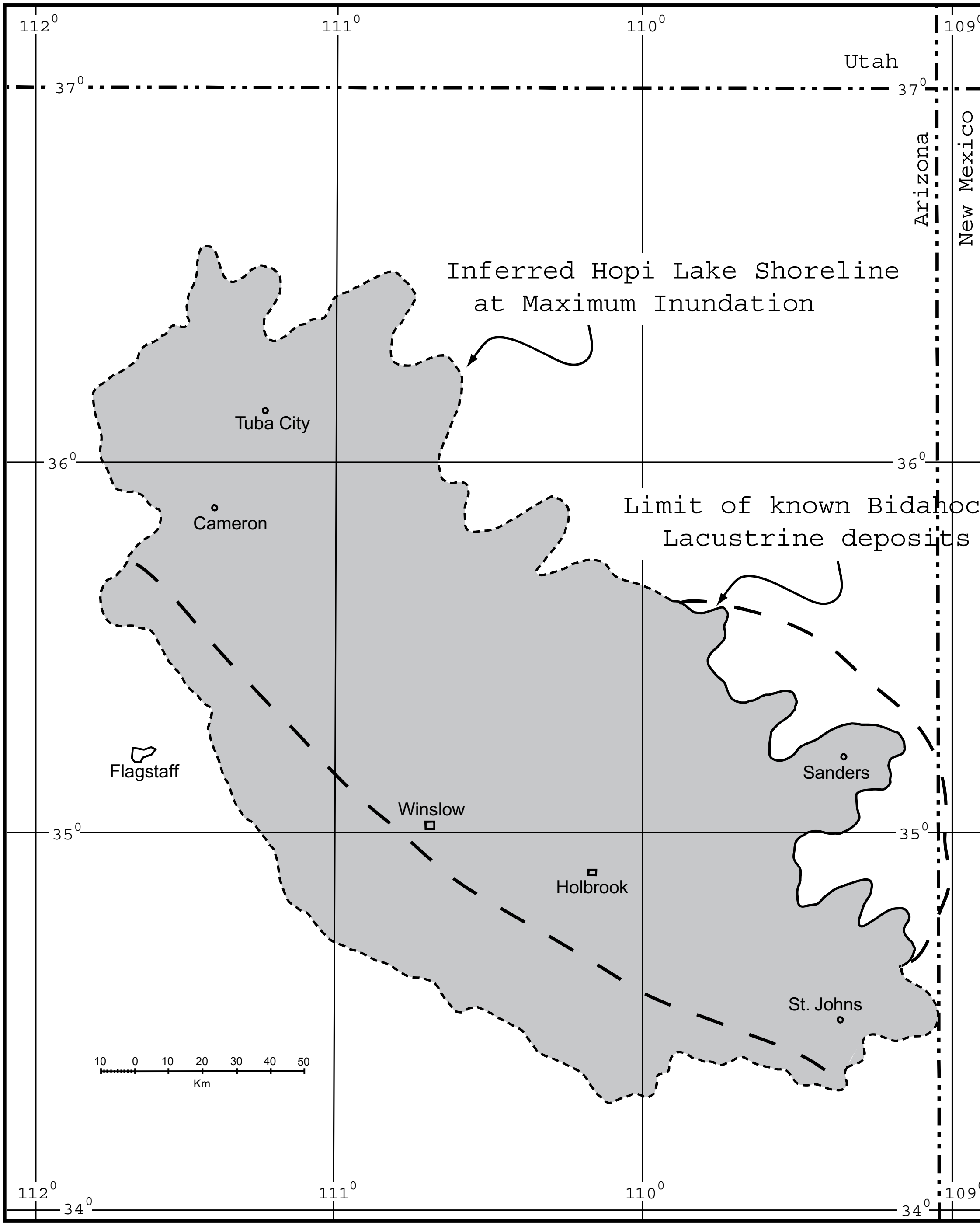


Figure 4.12 Outline of Hopi Lake shoreline during maximum inundation of the basin. recreated based on the present elevation of the upper contact of member 5. This plac present 1859 meter (6100 foot) topography contour line. The heavy dashed line on the the potential extent of lacustrine deposits not exposed below member 6. The heavy da southwestern boundary would have been a potential shoreline approximation if the ent Formation section was present during Bidahochi Formation deposition.

Hopi Lake potentially varied considerably in surface area, water depth, volume, salinity, etc. through time. It is likely that climatic and paleogeographic conditions varied throughout the existence of the lake. Potentially Hopi Lake may have filled and drained multiple times throughout its history. Therefore, this water budget is based on one moment in time when Hopi Lake was at or near maximum inundation. The purpose of looking at this system at maximum lake surface area is to get a feel for how much water was needed to maintain the lake and consequently how large of a drainage basin was necessary to supply the water. The climatic variables estimated for these calculations are purposely wetter and/or cooler than present so as to come up with the most conservative, but possible, estimate. However, it would be reasonable to say that the conditions may have been similar to present day arid conditions of the area.

Several variables are estimated to make the water budget calculations for Hopi Lake depositional basin. The size of the Hopi Lake was previously determined (see above) and the surface area of this lake at maximum lake levels is calculated as ~30,000 km^2. The current drainage basin (Figure 4.13) for the ephemeral Little Colorado River is 69,800 km^2 (Fisk et al., 1994). The Miocene watershed basin feeding Hopi Lake may have been similar in size to the modern LCR watershed, but was probably larger in size due to regional tectonic changes (see below). Based on this it is more likely that Hopi Lake was fed by runoff from all areas of the southeastern portion of the Colorado Plateau. This portion of the plateau, herein referred to as the southeastern Colorado Plateau watershed, would constitute a drainage watershed estimated at 115,000 km^2.

Several climatic variables are estimated in order to create a water budget for Hopi Lake. Schmidt (1991) evaluated weathering profiles on erosion surfaces and sediments on the southern Plateau and determined that the climate was arid to semi-arid from Eocene time to the present. The fresh-water molluscan fauna from White Cone Peak suggests that the late Hemphillian (6-5 Ma) climate was only slightly cooler and/or wetter than today (Taylor, 1957; Amy Morrison, 1998, personal communication). The modern average precipitation rate for northeastern Arizona is 24.66 cm/yr (Montoya and Gustaveson, 1993). Based on modern precipitation rates and the inferred climate during Miocene and Pliocene time, an estimated precipitation rate of 30 cm/yr will be used. The modern average shallow lake evaporation rate for northeastern Arizona ranges from 122 to 137 cm/yr (Linsley et al., 1982). The modern average runoff rates for northeastern Arizona (accounts for evapotranspiration losses) ranges from 0.25 to 2.5 cm/yr (Linsley et al., 1982). Using the slightly higher precipitation rates above and the potentially cooler climate (especially in late Miocene time), an annual runoff rate of 8 cm/yr and an annual lake evaporation rate of 110 cm/year will be estimated for Hopi Lake basin watershed and Hopi Lake. These levels are based on numerical data from Linsley et al. (1982) for present areas of the western United States (northern Utah, northern New Mexico, and western Colorado) with slightly higher precipitation rates and cooler climates.

The calculations estimated below do not account for ground water inflow and discharge because these variables are very difficult to estimate in the geologic record. Since these amounts are negligible in comparison to the volumes calculated, they are not include in the calculations below (following method of Bruce and Rodgers, 1962).

Using the estimates listed above and some best case scenarios, the amount of water available to fill Hopi Lake is calculated. The numerical calculations for the equations used below are found in Appendix A-5.

If all available annual precipitation that fell on the Hopi Lake watershed were allowed to flow into Hopi Lake (including precipitation on lake surface), then the potential annual volume flowing into Hopi Lake is determined using the following equation

$$A_{vp} = P \times B_a \quad \text{(a)}$$

where (A_{vp}) is annual volume potential, (P) is annual precipitation, and (B_a) is basin watershed area. This calculation would result in a potential annual volume added to Hopi Lake of 21 km^3 using the present LCR watershed area and a potential annual volume of 35 km^3 using the southeastern Colorado Plateau watershed area estimate.

The estimates calculated above do not reflect actual runoff amounts. The amount of water that makes it to the lake from the basin is affected by evapotranspiration. Using the estimated runoff rate (8 cm/yr) from above, the volume of water that actually flows into Hopi Lake from the surrounding basin is calculated with the following equation

$$R_{vp} = R_r \times (B_a - L_a) \quad \text{(b)}$$

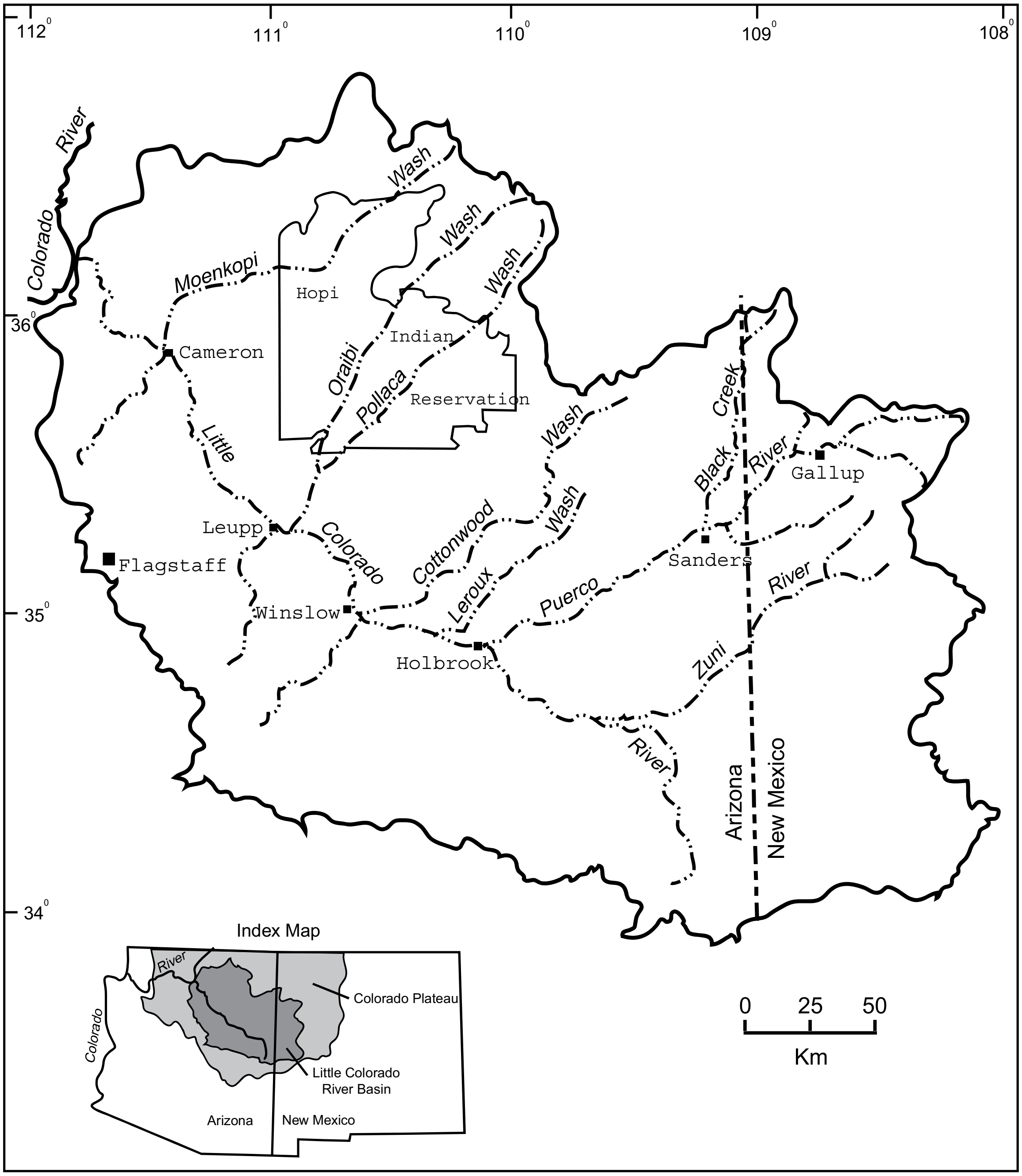


Figure 4.13 Little Colorado River basin on the southern portion of the Colorado Plateau. All rivers and washes within basin are ephemeral. Adapted and Modified from Fisk et al. (1994).

where (R_{vp}) is runoff volume potential, (R_r) is the annual runoff rate, and (B_a - L_a) is basin watershed area minus lake surface area (direct precipitation into the lake is not affected by evapotranspiration). This calculation would result in a potential annual volume added to Hopi Lake of 3 km^3 using the present LCR watershed area and a potential annual volume of 7 km^3 using the southeastern Colorado Plateau watershed area estimate.

The estimates calculated above do not reflect evaporation rates from the surface of Hopi Lake. Using the estimated lake evaporation rate of 110 cm/yr from above, the amount of lake volume lost to evaporation would be calculated with the following equation

$$L_{vl} = E_r \times L_a \qquad (c)$$

where (L_{vl}) is lake volume loss, (E_r) is evaporation rate of lake, and (L_a) is lake surface area. This calculation would result in a potential annual lake volume loss of 33 km^3.

The estimates calculated above in equations (a), (b), and (c) can be combined into one equation

$$F_{vp} = R_r \times (B_a - L_a) + (P \times L_a) - (E_r \times L_a) \qquad (d)$$

where (F_{vp}) is the final lake volume potential change, (R_r) x (B_a - L_a) is the annual runoff rate times the basin watershed area minus the lake surface area, (P x L_a) is the precipitation falling on the lake surface area (assuming the lake has minimal effect on rainfall patterns over the lake), (E_r x L_a) is evaporation rate times the lake area. This calculation describes any annual volume addition or subtraction from the lake. If evaporation is greater than inflow and precipitation then the lake will suffer a volume loss (negative value). The opposite happens if inflow and precipitation are greater than evaporation, lake volume will increase (positive value). In an idealized case and over short periods of geologic time, stable lakes should have equal losses and gains. Using this calculation for Hopi Lake would result in a potential annual volume change of -21 km^3 using the present LCR watershed area and a potential annual volume change of -17 km^3 using the southeastern Colorado Plateau watershed area estimate.

These calculations above show a balanced water budget that maintains a stable lake volume for which inflow and evaporation are equal. This would be appropriate for a closed lake basin. The continuing evaporation of the lake would result in increased lake salinity. This salinity increase would be reflected in the sediment accumulating in the lake deposits in the form of evaporite minerals. Within the Bidahochi

Formation deposits, minimal gypsum and limestone deposits occur. The lack of evaporite minerals combined with the predominance of claystone and siltstone suggest that this lake had low salinity levels. This was probably the result of substantial outflow and turnover of lake water. To maintain a fresh water lake, additional inflow must be added to create discharge (outflow). There is little evidence within the sediments to infer that the lake dried out completely. No paleosols, dessication features, or erosional horizons are noted. Thus, an outflow must be established and evidence for a location of such outflow has not been fully determined.

The lowest topographic area in the Hopi Lake depositional trough would have been near the Mogollon Rim in the Show Low to Springerville areas. Potochnik (1998, personal communication) has noted large paleochannel areas in the upper sequences of the ancestral Salt River Paleocanyon that have southerly flow indicators. The area directly to the north of this location (Show Low to Springerville areas) is covered with late Tertiary to Quaternary volcanic material from the White Mountain and Springerville volcanic fields. During Hopi Lake time this area may have been topographically low enough to allow for an outflow of Hopi Lake prior to coverage by volcanic rocks. Middle Miocene basalt flows in this region were responsible for ponding the northeasterly flow of the ancestral Salt River (Potochnik and Faulds, 1998). These basalt flows would, in effect, have been the dam that held back Hopi Lake and restricted the maximum levels of Hopi Lake.

The lack of saline features within the Bidahochi sediments and the significant lake volume losses calculated above clearly state that the Hopi Lake basin, as currently defined, is not adequate to maintain Hopi Lake. To maintain the lake at equilibrium levels all the precipitation that potentially fell on the southeastern Colorado Plateau watershed (35 km^3) would have to make it to the lake in order to sustain it. This cannot be the case because most of the water falling on the watershed is lost to evapotranspiration processes. The estimated basin watershed needs to be about four times larger (~400,000 km^2) suggesting another major inflow source is required for Hopi Lake.

The present upper Colorado River basin (Figure 1.2) drains an area of 280,000 km^2 which includes tributaries of the upper Colorado, Green, Gunnison, San Juan, and Paria Rivers (Operation of Glen Canyon Dam Final EIS, 1995). Using equation (d) above and including the upper Colorado River basin with the

LCR basin, would result in final volume potential change to Hopi Lake of +2 km^3 (Appendix A). This calculation uses the climatic variables estimated above for the LCR basin and does not reflect changes in precipitation, runoff rates, or other climatic factors that vary with the upper Colorado River basin. Much of the headwaters for the upper Colorado River basin are in the Rocky Mountains. Precipitation and runoff rates would be considerably higher in these areas, suggesting that the values used in the previous calculation would be on the low end. Therefore, this calculation would be modest and the value calculated would be sufficient to maintain Hopi Lake annually and provide a reasonable outflow to maintain fresh water conditions.

The drainages of the upper Colorado River basin during Miocene and Pliocene time may have varied considerably. In addition, climatic variables were most likely varied due to the regional changes that have been noted since the uplift of the Sierra Mountains on the west coast. Of importance to consider with this water budget calculation is the possibility that not all of the upper Colorado River drainages were integrated at this time. A wetter colder climate in this region possible could have compensated for a smaller watershed area (e.g. ancestral San Juan watershed) and supplied enough water to maintain Hopi Lake annually.

Sedimentation Rates

The results from the ^{40}Ar-^{39}Ar analyses allow for some modest calculations of sedimentation rates for the Bidahochi Formation. Sediment thickness is calculated to reflect post-depositional compaction in order to obtain rates of accumulation prior to compaction. The decompaction is calculated by knowing the thickness of the overlying sediments, the interval between chronohorizons, and using estimated values for porosity and porosity-depth curve coefficients for fine-grained sediments (Appendix A, Figure 4.14). The method used for these decompactions and the calculations are listed in Appendix A. The methods used to determine these rates are similar to the water budget in that they are based on static conditions in one location of the study area. This study acknowledges that these rates would vary considerable from location to location and throughout the depositional period of the Bidahochi Formation.

Two dates are known from two ash beds within member 3 (Chapter 3). These are the 13.71 Ma ash bed dated, as the name implies, at 13.71 ± 0.08 Ma (Dallegge et al., 1998) and the blue-gray #2 correlated to the dated (13.78 ± 0.04 Ma) Grouse Canyon (?) ash bed (Perkins et al., 1998). The error bars for these two dates overlap on one end and give a maximum separation age of 190,000 years and a minimum of zero years. The difference between the means is 70,000 years. This interval consists of 85% siltstone and 15% claystone and when decompacted is 7.2 m in thickness. These estimates are used to calculate the sedimentation rate for this interval within member 3 (Table 4.1). Using the difference between the means translates into a sedimentation rate of 10 cm/ka (centimeters per 1000 years). Using the maximum age difference between chronohorizons yields a sedimentation rate of 4 cm/ka.

The age on the east point biotite ash bed (15.46 ± 0.58 Ma) enables an estimate of sedimentation rates from this chronohorizon to the blue-gray #2 ash bed (geochemically correlated to the dated 13.78 ± 0.04 Ma Grouse Canyon (?) ash bed). Based on the error bars for these two dates, differences in age are calculated at a maximum separation age of 2,300,000 years and a minimum separation age of 1,060,000 years. The difference between the means is 1,680,000 years. This interval consists of 43.3% siltstone, 56% claystone, and 0.7% ash and when decompacted is 48 m in thickness. These estimates are used to calculate the sedimentation rate for this interval between the blue-gray #2 ash bed and the east point biotite ash bed (Table 4.1). Using the difference between the means translates into sedimentation rate of 3 cm/ka. Using the maximum age difference between chronohorizons yields a sedimentation rate of 2 cm/ka. Using the minimum age difference between chronohorizons yields a sedimentation rate of 4.5 cm/ka.

Sedimentation rates are calculated for the interval between the 13.71 Ma ash bed and the lava-capped Wood Chop Mesa. Vazquez (1998) reported ages and the volcanic stratigraphy for several flows on Wood Chop Mesa. The Sunshine maar lava flow covers the mesa at the location of the measured section (location 16 on Figure 2.2). The Sunshine maar lava flow is stratigraphically above the 7.21 ± 0.45 Ma Martinez maar lava flow and beneath the 6.99 ± 0.5 Ma Haskie maar lava flow (Vazquez, 1998). The 6.81 ± 0.06 Ma Churro maar lava flow crosscuts the Haskie maar lava flow. The small error bar on Churro flow suggests that the Haskie flow cannot be younger than 6.81 Ma. These relations allow for an estimation of the age of the Sunshine maar lava flow at ~7 Ma. The sediment interval between chronohorizons consists of 81.5% siltstone, 5% claystone, 11.2% mafic tuff, and 2.3% ash and when decompacted is 21 m in thickness.

Chrono-horizon	Initial midpoint interval (m)		Step 1	Step 2	Step 3	Step 4	Step 5		Dominant Lithology
~7 Ma		Level 5	t_{s1} = 20.0						Sunshine Lava
	30.4	Level 4	t_{s1} = 20.8 n_{s1} = 0.543	t_{s2} = 21.0 n_{s2} = 0.547				c = 4.5x10 $^{-4}$ m^{-1} n_{lith} = 0.55	Siltstone
13.71 Ma →									
	44.3	Level 3	t_{s1} = 7.0 n_{s1} = 0.539	t_{s2} = 7.1 n_{s2} = 0.544	t_{s3} = 7.2 n_{s3} = 0.549			c = 4.5x10 $^{-4}$ m^{-1} n_{lith} = 0.55	Siltstone
13.78 Ma →									
	71.0	Level 2	t_{s1} = 46.4 n_{s1} = 0.579	t_{s2} = 47.0 n_{s2} = 0.585	t_{s3} = 47.7 n_{s3} = 0.591	t_{s4} = 48.0 n_{s4} = 0.593		c = 5.0x10 $^{-4}$ m^{-1} n_{lith} = 0.6	Claystone
15.46 Ma →									
	104.85	Level 1	t_{s1} = 21.3 n_{s1} = 0.569	t_{s2} = 21.6 n_{s2} = 0.575	t_{s3} = 21.9 n_{s3} = 0.581	t_{s4} = 22.0 n_{s4} = 0.583	t_{s5} = 22.7 n_{s5} = 0.597	c = 5.0x10 $^{-4}$ m^{-1} n_{lith} = 0.6	Mudstone

Figure 4.14 Block diagram showing the decompaction steps for the intervals between chronohorizons at Wood Chop Mesa (location 16 on Figure 2.2). See Appendix A for calculations. $t_{s(x)}$ - thickness in meters of clastic interval at step x, c - porosity-depth coefficient, nlith - original porosity of lithology.

Table 4.1 Calculated sedimentation rates between chronohorizons at Wood Chop Mesa (location #16 on Figure 2.2). Table shows mean, maximum, and minimum separation ages between chronohorizons.

Chronohorizon	Age	Decompacted Thickness Interval*	Sedimentation Rate
Sunshine lava flow	~7 Ma		
Interval age difference Mean:	 6,710,000 yr	21.0 m	 0.3 cm/ka
13.71 Ma ash bed	13.71 ± 0.08 Ma		
Interval age difference Mean: Maximum: Minimum:	 70,000 yr 190,000 yr error bars overlap	 7.2 m	 10 cm/ka 4 cm/ka
blue-gray #2 ash bed correlated to the dated Grouse Canyon(?) ash bed	13.78 ± 0.04 Ma		
Interval age difference Mean: Maximum: Minimum:	 1,680,000 yr 2,300,000 yr 1,060,000 yr	 48.0	 3 cm/ka 2 cm/ka 4.5 cm/ka
east point biotite ash bed	15.46 ± 0.58 Ma		
	454,000 years	22.7	5 cm/ka**
Base of Bidahochi Formation	Extrapolated age Mean: 15.9 Ma Maximum: 16.6 Ma Minimum: 15.4 Ma		

* - thickness interval between chronohorizons - decompaction data from Figure 4.12 and Appendix A; ** - estimated sedimentation rate - see text; abbreviations: m - meters; yr - years; cm/ka - centimeters per 1,000 years.

Using the estimated age of the Sunshine flow and the mean age on the 13.71 Ma ash bed chronohorizon, a sedimentation rate of 0.3 cm/ka is established (Table 4.1).

Age of Hopi Lake Basin

Previous studies (see Chapter 1) summarized the age of Bidahochi Formation as about 9 Ma (or possibly 12 Ma) to 4 Ma (Love, 1989) with most of the coeval volcanism of the Hopi Buttes volcanic field occurring between 8.5 and 4.2 Ma (Shafiqullah and Damon, 1986a, b). The results of the ^{40}Ar-^{39}Ar analyses of selected ash beds units from this study have enabled new proposed limiting ages on deposition within the Hopi Lake basin.

Using the date from the east point biotite ash bed of 15.46 ± 0.58 Ma and estimates of sedimentation rates from above, an estimation of the onset of sedimentation within the Hopi Lake basin can be made. The sediments of member 1 are mostly mudstone and sandstone. Based on the type of deposits used above to calculate sedimentation rates, the deposits of member 1 (Table 2.1) would have a sedimentation rate in between those calculated for members 2 and 3. Therefore, an estimated rate of 5 cm/ka is used to extrapolate to the base of the Bidahochi Formation. Using a sedimentation rate of 5 cm/ka for the interval between the east point biotite ash bed and the base would yield a maximum age for onset of sedimentation (Table 4.2) at ~15.9 Ma (using the mean age), ~16.6 Ma (using the maximum error range), or ~15.4 (using minimum error range).

Hopi Lake Basin Tectonic Setting

Prior to any regional interpretation of the southern Colorado Plateau, the poorly documented and described tectonic mechanism that formed the Hopi Lake basin must be better defined. Several ideas have been proposed for the formation of the Hopi Lake basin, but none have been related to the present tectonic framework. This study will document the role of the Rio Grande Rift, drainage reversal, and closure of a Laramide structural trough in the formation of Hopi Lake basin.

Previous interpretations

Several hypotheses have been presented to explain the why the Bidahochi Formation was deposited in this area. McKee et al. (1967) suggested that a lake formed when the southeasterly flowing Little Colorado River was reversed along its course. Sutton (1974b) suggested that Hopi Lake could have been dammed behind a northwest-striking cuesta of Triassic rock, probably the resistant Owl Rock Member of the Chinle Formation. This cuesta would have been located near the western exposures of Hopi Buttes and extended towards Sanders, Arizona. In this case, Hopi Lake would have been independent of the Little Colorado River and was probably formed by catastrophic damming of a pre-existing drainage by volcanism or flooding (Sutton, 1974b). Sutton also suggested that the lake could have formed by tectonism causing the area to subside. Shafiqullah and Damon (1986b) suggested that two lakes were involved, one behind a Triassic cuesta at modern day 1800 meter elevation level and the other 100 to 200 m lower within the Little Colorado-Puerco River valleys. They did not propose a damming mechanism.

Love (1989) suggested that local episodic volcanic eruptions may have caused local ponding of drainages. Love (1989) also suggested alluvial plains aggrading from the Zuni uplift area may have caused decreasing gradients of southwest-flowing streams from the Hopi Buttes and Defiance Plateau areas and caused ponding and deposition of the fine-grained units. Love (1989) compares the sedimentation style and climatic regimes of the Ogallala Formation along the eastern flank of the Rocky Mountains to that of the Bidahochi Formation. Love feels that they may be related because: (1) have similar time range (12-4 Ma), (2) have similar alluvial and eolian facies, (3) occur as epicontinental clastic wedge situated downslope from uplifted areas, (4) developed in a similar climatic regime, and (5) have been dissected by streams in late Pliocene and Quaternary time. Similar to Love s idea, Chapin and Cather (1994) have proposed that the Bidahochi Formation formed as a flank deposit (Figure 4.15) along the rift-flank of the Rio Grande Rift during a period of accelerated rifting, middle to late Miocene time. Chapin and Cather (1994, p. 20) state: Both the Ogallala and Bidahochi Formations were broad, sheet-like units that were not confined to discrete structural basins.

The previously proposed mechanisms for the accumulation of sediment in the Hopi Lake depositional basin are not consistent with the type of features observed within the Bidahochi Formation. The cuesta idea of Sutton (1974b) and Shafiqullah and Damon (1986b) does not work because the conclusions presented in Chapter 4 negate the idea of a small lake confined to the present extent of the formation. If a northwest-striking Owl Rock cuesta created a lake basin it would have extended from near Springerville, Arizona, to Kykotsmovi Village on Second Mesa. This cuesta would have been over 220 km long and would have been at an elevation of 1860 m. It is extremely unlikely to have this large of a feature with no breaches in the structure across this region. In addition, the 1-3 degree dip on the Chinle Formation could not account for the elevation needed to confine a lake at the 1860 meter interval in the Holbrook, Arizona, area. The idea of two lakes is also invalid because the lower members can be traced to the southeast from Greasewood, Arizona, down to the Sanders, Arizona, area (Figure 1.3) with no break in sedimentation or geomorphic structure that would suggest two lakes existed at separate topographic elevations. Finally, there is no evidence for catastrophic events forming dams across pre-existing drainages. It may be conceivable that lava flows from the Mormon Mesa or Sunset Mountain (south of Winslow along Mogollon Rim) could have blocked the Little Colorado River to form a lake but the dam would have to be 110 m high in the Winslow, Arizona area and existed for millions of years (Love, 1989). The idea presented by Love (1989) for local upstream ponding of pre-existing drainages by Hopi Buttes volcanism could be applicable, and probably is for deposits of member 5 and member 6. The chronology of events for this basin excludes this type of mechanism for formation of the early basin (~16 Ma).

The idea that the Bidahochi Formation has a similar depositional origin as the Ogallala Formation is unjustified. The similarity of sedimentary features described by Love (1989) are not representative of the entire Bidahochi Formation. The Ogallala Formation, especially along the flanks of the Rocky Mountains in Colorado, contains abundant fluvial features (e.g., lenticular gravel beds, cut and fill sequences, abundant sandy units, and backwater and flood plain type deposits). The Ogallala Formation also contains abundant calcrete horizons and is definitely an aggrading fluvial system. The lower members of the Bidahochi Formation drastically differ from the system that formed the Ogallala Formation. The fine-grained units, interbedded ash beds, and lateral continuation of beds are clearly in contrast to the Ogallala Formation and were not formed in a similar fashion. There may be some merit to this idea in comparing the fluvial member 6 of the Bidahochi Formation with the Ogallala Formation, but this comparison cannot be used for the lacustrine-dominated lower members. Chapin and Cather s (1994) support of an Ogallala-type deposition for the Bidahochi Formation fails for the same reasons stated above. However, their idea of a rift-flank deposit may be closely related to a system that was ultimately responsible for the deposition of the lacustrine members of the Bidahochi Formation.

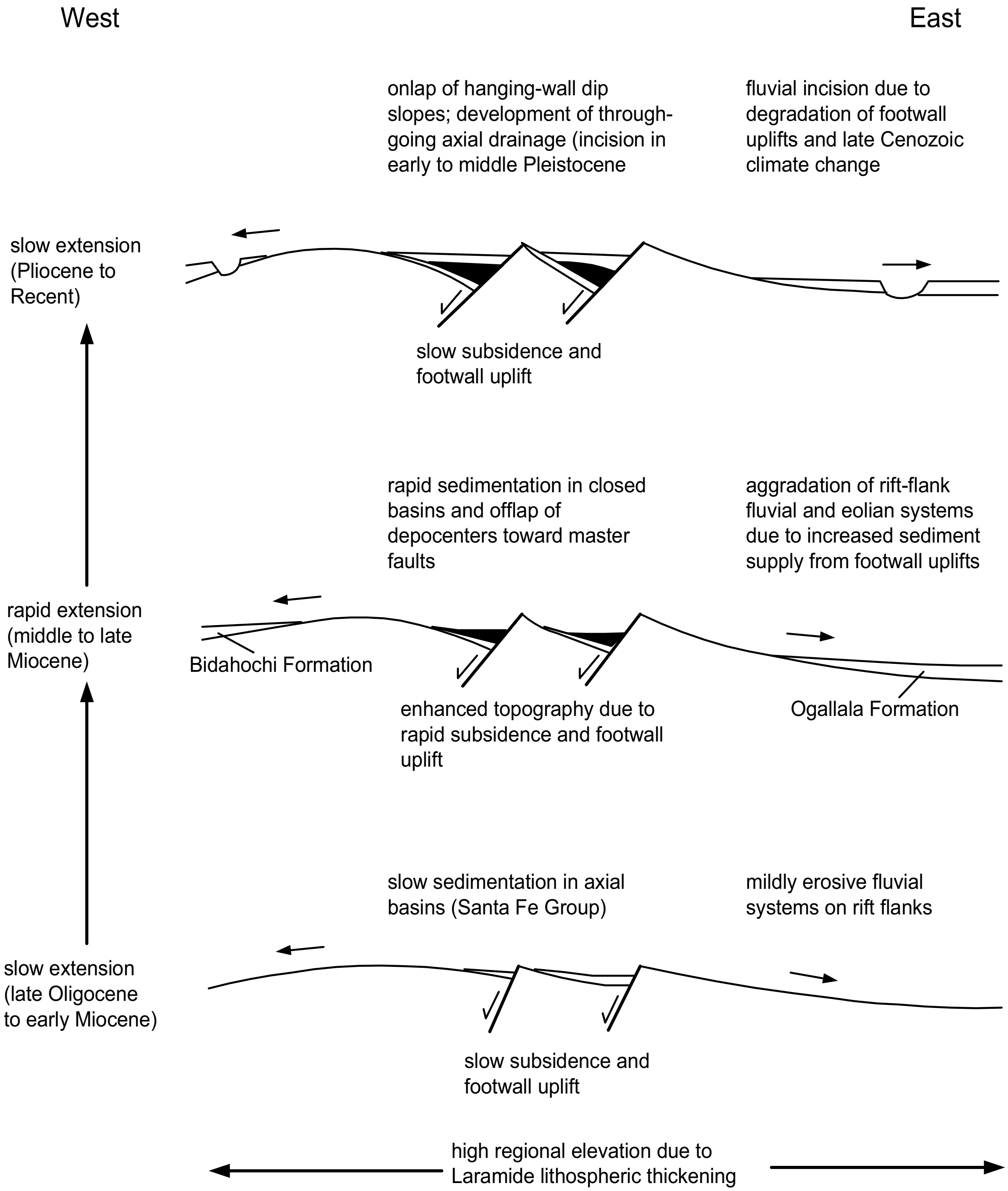


Figure 4.15 Schematic east-west cross sections across the Rio Grande Rift through central New Mexico showing generalized structural and stratigraphic development of rift and rift-flank areas. From Chapin and Cather (1994).

Basin formation

The formation of the Hopi Lake depositional basin is related to closure of a Laramide-aged topographic trough. The southeast end of this trough was probably closed due to elevated rift flanks created by the accelerated phase of Rio Grande rifting in New Mexico. This trough was surrounded by topographic highs constructed by the Laramide Orogeny and subsequent erosional events. Laramide events lifted, folded, and tilted the southern Colorado Plateau to the northeast by Eocene time (see Chapter 5). Erosional escarpments formed on the dip slope and migrated to the northeast. Basin and Range extension in Arizona had defined the Mogollon Rim and effectively cutoff southern Arizona from the southern Colorado Plateau by at least middle Miocene time (Potochnik and Faulds, 1998) and earlier along some portions (Peirce et al., 1979; Nations et al., 1985; Elston and Young, 1991). This formed a physiographic barrier between the Colorado Plateau and the Transition Zone and created localized drainage divides between these two physiographic provinces.

These tectonic and erosional events formed a northwest-southeast trending trough that was bounded on three sides by topographic highs (Figure 4.16). The Kaibab Monocline was the topographic barrier to the west and northwest. The Chuska Mountains and the erosional escarpments of the Kaibito Plateau, Moenkopi Plateau, and Black Mesa formed barriers to the north. The trough was constrained to the northeast by the Defiance Plateau and Zuni uplift and to the south-southeast by the Mogollon-Datil volcanic field. The Mogollon Rim and the gentle northeasterly dip slope (Mogollon Slope) of the Mesozoic and Paleozoic rocks defined the topographic barrier to the south and southwest. This northwest-southeast trending trough was a prominent feature by middle Miocene time.

The only route for drainages out of this topographic trough would have been to the northwest toward the Grand Canyon region, southeast between the Zuni Uplift and Mogollon-Datil volcanic field, or south across a low in the Mogollon Rim. The Kaibab Monocline area and the Mogollon Rim were probably topographically high enough to restrict flow in these directions. It is unlikely that this was a closed basin prior to Bidahochi deposition due to the lack of any sediments in this area of pre-mid Miocene age. Thus, drainages on this portion of the southern Colorado Plateau probably exited the plateau out the southeast end of this topographic trough (Figure 4.16).

Hopi Lake basin began accumulating sediments by ~16 Ma. This onset of sedimentation is in very good agreement with the initiation (16 Ma) of accelerated rifting of the Rio Grande Rift (Cather et al., 1994; Chapin and Cather, 1994). This accelerated event formed extensive rift shoulders along the western edge of the rift in west-central New Mexico (Chapin and Cather, 1994). This rift shoulder would have effectively blocked any possible east-southeast drainage system existing at this time. This rifting event blocked the opening in the northwest-southeast trending trough and created the accommodation space for accumulation of Bidahochi sediments in the Hopi Lake depositional basin. Erosion of the elevated rift-flank and the Defiance and Zuni uplifts, as well as the continuing removal of material from surrounding Laramide features, shed sediments into the Hopi Lake depositional basin.

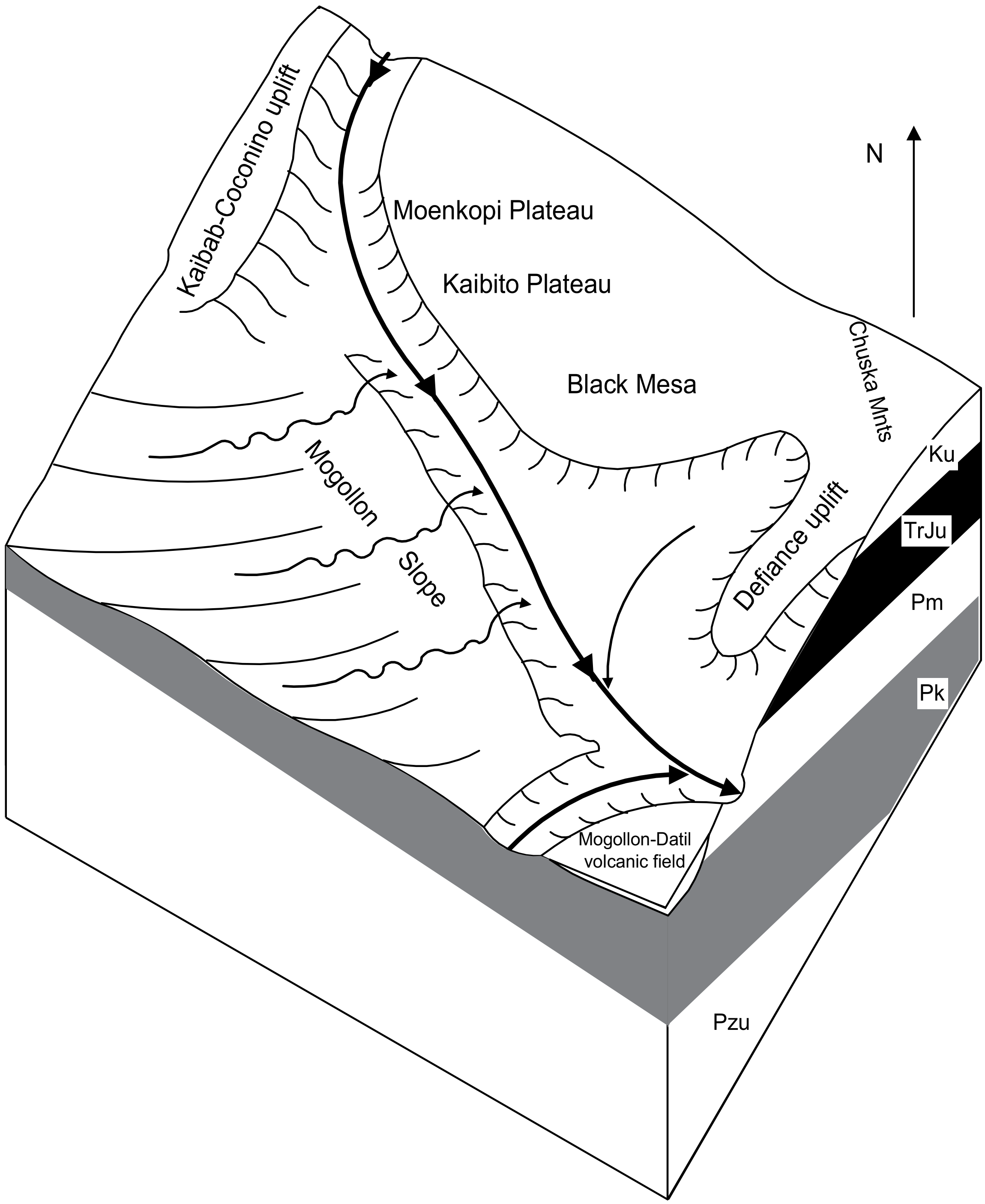


Figure 4.16 Generalized block diagram emphasizing the northwest-southeast trending Laramide aged topographic trough. Abbreviations: Ku - Cretaceous undivided; TrJu - Triassic and Jurassic undivided; Pm - Permian Moenkopi; Pk - Permian Kaibab; Pzu - Paleozoic undivided.

Chapter 5 - Southern Colorado Plateau Paleogeographic Events

The chronology and basin analysis of the Bidahochi Formation presented in this study (Chapters 3 and 4) enables a reconstruction of the paleogeographic events of the southern Colorado Plateau during Miocene and Pliocene time. To place the information presented by this study into perspective, it is necessary to review some of the previous interpretations about the evolution of the southern Colorado Plateau. This summary will synthesize the Cenozoic geologic evolution of the southern Colorado Plateau.

Pre-Bidahochi Formation Events (Late Cretaceous to middle Miocene)

The events that have shaped the southern Colorado Plateau will be covered in three categories; (1) sedimentary and volcanic rock record, (2) regional geologic history, and (3) evolution of integrated drainage patterns. Tables 5.1, 5.2, 5.3 and accompanying figures summarize the main events of this region.

Sedimentary and volcanic rocks

The majority of the Tertiary sedimentary deposits remaining on the southern Colorado Plateau occur as isolated erosional remnants, predominantly capped by volcanic rocks. The deposits listed in Table 5.1 are pertinent to this study.

The deposits used predominantly for interpreting early Tertiary events on the plateau are the Rim gravels (Table 5.1, Figure 5.1) of Cooley and Davidson (1963). Potochnik (1987, 1988, 1989) described deposits of the Rim gravels in the White Mountain Apache Reservation area along the edge of the Mogollon Rim at Trout Creek, Arizona. Potochnik (1989) named these gravel and associated deposits the Mogollon Rim Formation. The Mogollon Rim Formation is now accepted as a formal stratigraphic unit (Potochnik, 1998, personal communication). The Baca, Eagar, and Mogollon Rim Formations (Table 5.1, Figure 5.2) are correlative units (Cather et al. (1994). Based on the age establishment of the Baca and Eagar Formations (Table 5.1), correlative nature with Mogollon Rim Formation, and isotopic dating used by Potochnik (1989), the Mogollon Rim Formation is probably Eocene in age.

The middle to late Miocene Fence Lake Formation (Table 5.1) in west-central New Mexico is composed of fluvial sandstone and conglomerate (McLellan et al., 1982; Lucas and Anderson, 1994). Repenning and Irwin (1954) originally mapped this formation as the upper member of the Bidahochi but others have separated it from the Bidahochi Formation, primarily because of its apparent older, ~14.5 Ma, age (McLellan, et al., 1982; Love, 1989). Based on dated ash (~15.5 Ma) from this study, the Bidahochi and Fence Lake Formations are time-correlative. Future studies should investigate any relation between them.

Several areas on the Colorado Plateau are covered with lava flows and pyroclastic rocks of varying composition (Table 5.1, Figure 5.4). Various lava flows are dated and have been used to constrain the age of many Tertiary sedimentary rocks.

Regional geologic history

The uplift of the southern portion of the Colorado Plateau is clearly post-Late Cretaceous as documented by the youngest marine deposits in the region. The history of Colorado Plateau uplift (Table 5.2) is the topic of much debate. Little argument seems to exist that structural monoclines and folds (Figure 1.1, 5.5) on the southern plateau were formed during the Laramide Orogeny (Kelley, 1958; McKee et al., 1967; Nations et al., 1985; Baars et al., 1988; Potochnik and Faulds, 1998). The Colorado Plateau has remained a relatively cohesive block throughout Tertiary time and has been less severely affected by structural events than surrounding regions.

Recent studies question late Cenozoic uplift of the southwestern Colorado Plateau. A marine origin for the Bouse Formation of southwest Arizona has been used to infer 400-700 m of uplift for the southwestern Colorado Plateau (Lucchitta, 1979). Spencer and Patchett s (1997) Sr isotope work of the Bouse Formation inferred a lacustrine origin. They concluded the Bouse Formation was probably deposited at its present elevation and not elevated by plateau uplift in late Miocene time. Spencer and Patchett (1997) suggested the southwestern Colorado Plateau uplift could be early to middle Cenozoic in age. The southern Rocky Mountains have been structurally connected to the Colorado Plateau since early Cenozoic time and reveal little evidence of post-Eocene uplift (Gregory and Chase, 1992, 1994). An early Cenozoic southwestern Colorado Plateau uplift would be consistent with the southern Rocky Mountains uplift (Spencer and Patchett, 1997). Study of halite in the Hualapai basin and limestone in the adjacent Grand Wash trough have shown they are nonmarine in origin and developed in closed playa basins (Faulds et al., 1997). This nonmarine interpretation contradicts the previous marine interpretations that have been used as evidence for significant uplift of the southwestern Colorado Plateau since late Miocene time (Faulds et al., 1997). Faulds et al. (1997) concluded that most of the differential relief between the southwestern Colorado Plateau was produced by Basin and Range extension between ~16 and 9 Ma.

There is considerable debate about when and how the Mogollon Rim (escarpment) originated. The Mogollon Rim was originally interpreted as a faulted margin but further studies have not revealed evidence of a faulted boundary (Peirce et al, 1979; Nations et al., 1985; Elston and Young, 1991). Instead it is an erosional escarpment that has been assigned multiple initiation ages (Table 5.2). Many of these age assessments have resulted from age determinations of the Mogollon Rim Formation (Rim gravels) and the apparent differentiation of the area and subsequent drainage reversals of once northerly flowing streams from central Arizona (Table 5.3). Nations et al. (1985) suggested that as much as 600 m of relief had formed by scarp retreat by late Oligocene time. This minimum age was defined by the presence of gravels of probable Oligocene age (> 22 Ma) deposited in strike-valley streams flowing at the base of the Mogollon Rim (Peirce et al., 1979; Nations et al., 1985). Peirce et al. (1979) split the Mogollon Rim into seven segments and suggested the rim formed by erosion of the incompetent Supai Formation when it was exposed by multiple northward tilting events since Late Cretaceous time. They believed the erosional activity was confined to a zone only a few kilometers wide south of the present location of the Mogollon Rim. Based on an age assessment of the Mogollon Rim Formation (28-54 Ma bracket on Rim gravels) and evidence in the Fort Apache area, Peirce et al. (1979) suggested erosion had completed the differentiation of the southern Colorado Plateau from the Transition Zone by Oligocene time. Elston and Young (1991) favor formation of the Mogollon Rim, with 600-900 m of relief, as a Laramide event during the Paleocene. They suggested that further Laramide regional uplift buried the Mogollon Rim by north flowing streams that deposited the Mogollon Rim Formation. Late Oligocene drainage reversal and erosion of the Mogollon Rim Formation led to exhumation of the Mogollon Rim with 600-900 m of relief (Elston and Young, 1991).

Evolution of integrated drainage patterns

Previous studies have used the Mogollon Rim, Bidahochi, and Muddy Creek formations and interpretation of geomorphic features to decipher the evolution of drainage systems across the southern Colorado Plateau. The primary focus of many of these studies is the evolution of the Colorado River prior to it flowing through and carving the Grand Canyon.

The regional uplift of the southwestern United States by the Laramide Orogeny determined the drainage patterns of the early Tertiary (Table 5.3). North-flowing streams from the Mogollon Highlands in central Arizona deposited the Mogollon Rim Formation and the deposits in the Coconino and Baca-Eagar basins and fed Lake Uinta in east-central Utah and west-central Colorado (Table 5.4).

Previous studies of the age of initiation of the Mogollon Rim and subsequent drainage reversal are varied. This drainage reversal is based on the age of the Mogollon Rim Formation and formation of the Mogollon escarpment. Depending on previous workers assessments, this age ranges from Paleocene to Miocene (Tables 5.1, 5.2, and 5.3). Potochnik and Faulds (1998) reported that streams were still flowing onto the plateau from central Arizona during early Miocene time. This northeasterly flowing pre-Salt River drainage was blocked by a 14.6 Ma lava flow, ponded, and then reversed direction to flow into the Basin and Range province by ~14 Ma (Potochnik and Faulds, 1998). The variation in these studies suggests that the timing of drainage reversal along the extent of the Mogollon Rim may have differed from location to location.

Drainage patterns on the southern Colorado Plateau from middle Miocene to Recent time have been interpreted in multiple ways (Table 5.3). The ancestral upper Colorado River arrived onto the southern Colorado Plateau by late Oligocene time (Hunt, 1969). The route the ancestral Colorado River used prior to flowing into the Grand Canyon and incising the Muddy Creek Formation prior to 5.5 Ma is a controversial topic (Table 5.3). The flow of the ancestral upper Colorado River into the Grand Canyon is interpreted as a relatively young event. The absence of Colorado River-transported sediment in the Muddy Creek Formation prior to the incision of this formation has been used to infer the absence of the Colorado River in Grand Canyon prior to 5.5 Ma (Lucchitta, 1979, 1984).

<u>Bidahochi Formation Events (Miocene-Pliocene Paleogeographic Interpretation)</u>

This section will examine the Mio-Pliocene evolution of the southern Colorado Plateau from an assessment of the current literature and the incorporation of new evidence from this study (Chapters 2, 3, and 4). The modified hypothesis presented here will document the role of the ancestral upper Colorado River, the Mogollon Rim area, Rio Grande Rift, and Arizona Basin and Range extension on the paleogeographic events of the southern Colorado Plateau during Miocene to Pliocene time.

The following sections briefly describe the events depicted in Table 5.4 and on Figures 5.13 through 5.16. The data used to create this table and associated figures is from Tables 5.1, 5.2, and 5.3 and from ideas extrapolated by this study.

early Miocene (Table 5.4, Figure 5.13)

The ancestral upper Colorado River developed and flowed onto the southern Colorado Plateau by early Miocene time. The river was deflected by the Kaibab-Coconino uplift and flowed southeast along a strike valley below erosional Mesozoic and Paleozoic escarpments (similar to hypothesis of McKee et al., 1967). It may have exited the southern Colorado Plateau through southeastern New Mexico (McKee et al., 1967). The ancestral Salt River (Potochnik and Faulds, 1998) and other drainages from the Mogollon Rim divide were tributaries to the southeasterly flowing ancestral upper Colorado River.

middle Miocene (Table 5.4, Figure 5.14a, b)

The accelerated phase of rifting in the Rio Grande Rift began about 16 Ma and formed extensive rift shoulders (Chapin and Cather, 1994). The elevated rift-flanks of west-central New Mexico deflected the southeastward-flowing river systems and closed off the southeastern end of the northwest-trending trough, resulting in the formation of Hopi Lake depositional basin. Sediment was distributed to Hopi Lake basin from the eroded rift flanks and from the upper Colorado River, ancestral Salt River, and other drainages. Support for the flow of the ancestral Colorado River into Hopi Lake was determined by water budget calculations (Chapter 4). These calculations show that the present watershed area of the southern Colorado Plateau was unable to maintain Hopi Lake at times of maximum inundation.

A basalt flow blocked the ancestral Salt River, created ponding, and reversed its course (Potochnik and Faulds, 1998). The size of Hopi Lake began to expand as the diverted drainages brought sediment into the newly formed basin. Initially the basin had no outflow, but subsequent filling of Hopi Lake eventually formed an outflow area in the ancestral Salt River paleocanyon, thereby maintaining a fresh-water Hopi Lake (by ~14.5 Ma).

late Miocene-Pliocene (Table 5.4, Figures 5.15 and 5.16)

By ~8.5 Ma, ultramafic phreatomagmatic volcanism of the Hopi Buttes volcanic field had begun. Rising magma interacted with groundwater and/or water-saturated sediments to cause phreatomagmatic volcanism that formed abundant maars, tuff cones, tuff rings, and scoria cones. Pyroclastic and lava flows covered portions of the landscape, building up the Hauke Mesa area above lake levels. Only minor volcanic/lacustrine interactions occurred locally along the edge of the volcanic field where lake sedimentation was continuing. A hiatus in volcanism (6-4.4 Ma) allowed the Hopi Lake shoreline to transgress onto marginal volcanic material but did not cover the entire volcanic field due to the large volume of eruptive material in the Hauke Mesa area. Minor volcanism occurred again between 4.4-4.2 Ma and created a second sequence of phreatic deposits which covered portions of the transgressive lacustrine units (flat tire mesa area). Near the end of lacustrine deposition, Hopi Lake had attained a maximum surface area of ~30,000 km^2.

By ~5.5 Ma, the Gulf of California opened and headward erosion began to incorporate interior basins and stream valleys of southern Arizona (Lucchitta, 1984). This process proceeded northward to the Grand Wash Cliffs area and the ancestral lower Colorado River incised into the Miocene Muddy Creek Formation (Lucchitta, 1984). The western Grand Canyon was incised by 3.8 Ma (Elston and Young, 1991). Additional headward erosion dissected the Kaibab uplift, captured the ancestral upper Colorado River, and drained Hopi Lake. When Hopi Lake was at maximum lake levels (~1859 m contour interval), only 275 m (using present elevation of Colorado River cut in the Kaibab-Coconino Uplift) of incision of the Kaibab-Coconino Uplift would have been required to capture the lake and the ancestral upper Colorado River. This small incision amount suggests that previous interpretations (Elston and Young, 1991) of deeply incised ancestral eastern Grand Canyon are not required. A small drainage developing on the western side of the Kaibab-Coconino Uplift could have been responsible for incising the uplift and then capturing the ancestral upper Colorado River and Hopi Lake. Accelerated down-cutting would have resulted from the increased flow of the ancestral upper Colorado River and removal of accumulated sediments in the Hopi Lake basin.

Capture of the ancestral upper Colorado River ultimately drained Hopi Lake. The Little Colorado River system formed on the former Bidahochi Formation deposits and began to exhume the pre-Bidahochi northwest-southeast trending trough. The LCR became integrated with the Colorado River system and initiated a vast erosional event on the southern Plateau that inevitably removed most of the sediments of the Bidahochi Formation in areas not preserved by volcanic rocks. This erosional event would have removed all the speculated coarse-grained material deposited by the ancestral upper Colorado River in the Marble Canyon area. The resulting Grand Canyon formation and down-cutting of the LCR and Colorado Rivers substantially lowered the Marble Canyon area relative to the Hopi Lake basin and Little Colorado River valley.

Table 5.1 Tertiary sedimentary and volcanic rocks on the southern Colorado Plateau.

Name	Age	Location / Figures	Description
Mogollon Rim Formation (Rim gravels)	Miocene (Price, 1950; McKee, et al., 1967; McKee and McKee, 1972) Eocene-Oligocene (Peirce et al., 1979 [54 -28 Ma bracketed age] Paleocene and/or Eocene (Young and Hartman, 1984; Young, 1987, 1989; Elston and Young, 1989; Elston et al., 1989; Potochnik, 1987, 1988, 1989; Elston and Young, 1991, Potochnik and Faulds, 1998) Late Cretaceous to Eocene (Hunt, 1956)	Along the edge of the Mogollon Rim and Transition Zone, Scattered outcrops across southern Colorado Plateau - Shivwits Plateau (Lucchitta, 1975, 1984; Nations et al., 1985), Coconino Plateau (Lucchitta, 1984; Nations et al., 1985; Elston and Young, 1991), Hualapai Plateau (Lucchitta, 1984; Elston and Young, 1991), Paria Plateau (Phoenix, 1963), Bacca basin (Lucas and Ingersol, 1981; Nations et al., 1985, Scarborough, 1989), and north of Grand Canyon, west of the Kaibab uplift (Elston and Young, 1991), Figure 5.1	Eroded gravel deposits (very-resistant Precambrian sedimentary, metamorphic, and plutonic rocks and lower Paleozoic limestones and chert [Nations et al., 1985]) and gravel outcrops capped by lava flows. Reflect source areas from central Arizona (Price, 1950; Peirce et al., 1979; Lucchitta, 1984; Nations et al., 1985; Elston and Young, 1991).
Eagar Formation	middle to late Eocene (Cather et al., 1994)	Baca-Eagar basin of Chapin and Cather (1981), Figure 5.2	Resistant volcanic, metasedimentary, and crystalline rocks (Scarborough, 1989), and sandstone and mudstone (Cather et al., 1994). Fine-grained equivalent of Mogollon Rim Formation (Rim gravels) (Lucas and Ingersoll, 1981).
Baca Formation	middle to late Eocene (Cather et al., 1994)	Eastern side of Baca-Eagar basin, Figure 5.2	Volcanic-free fluvial lithologies (Cather et al., 1994); derived from central Arizona by north and northeasterly flowing streams (Cather and Johnson, 1984; Potochnik; 1989)
fluvial and lacustrine deposits	early Eocene (Young, 1982; Young and Hartman, 1984)	Coconino basin of Nations et al. (1985), Figure 5.2	Lacustrine limestones and interbedded gravel and sandstone
Chuska Formation	Oligocene (Nations et al., 1985; Scarborough, 1989)	Along flanks of Chuska Mountains, Figure 5.3	Sandstone; formed by eolian action reworking Mogollon Rim Formation (Scarborough, 1989).

Name	Age	Location / Figures	Description
Deza Formation of Wright (1954)	Oligocene	Along flanks of Chuska Mountains, below Chuska Formation	Sandstone, shale, and conglomerate; deposited by easterly flowing streams that occasionally ponded (Scarborough, 1989)
Bidahochi Formation	middle Miocene to Pliocene ~16 to 4 Ma	Northeastern Arizona, Figure 1.3	see previous Chapters
Muddy Creek Formation	middle to late Miocene ~12 to 5.5 Ma, Lucchitta, 1979)	Along western edge of Colorado Plateau near present mouth of Grand Canyon, Figure 5.1	Fluvial and lacustrine deposits; deposited in closed basin (Lucchitta, 1979; Nations et al., 1985)
Fence Lake Formation	middle to late Miocene (McLellan et al., 1982; Lucas and Anderson, 1994)	West-central New Mexico	Fluvial sandstone and conglomerate with clasts from Mogollon-Datil volcanic field (McLellan, et al., 1982)
Mogollon-Datil volcanic field	36.2-24.3 Ma (McIntosh et al., 1990)	West-central New Mexico	Andesitic to rhyolitic lavas and pyroclastic rocks (McIntosh et al., 1990)
Rio Grande Rift volcanic rocks	(~28-24 Ma) Baars et al, 1988; McIntosh et al., 1992; Chapin and Cather, 1994)	Central and west-central New Mexico, Figure 5.4	Felsic to mafic lavas and pyroclastic rocks
White Mountain volcanic field	middle to late Tertiary (Berry, 1976; Merrill and Pewé, 1977)	East-central Arizona, Figure 5.4	lavas and pyroclastic rocks
San Francisco volcanic field	late Miocene-Quaternary (Leighty, 1998)	North-central Arizona, Figure 5.4	Continuous suite of rock types - basalt to alkali rhyolite (Holm, 1987)
Hopi Buttes volcanic field	late Miocene to Pliocene 8.5 to 4.2 Ma (Shafiqullah and Damon, 1986a, b)	Northeastern Arizona, Figures 1.3, 5.4	see previous Chapters
lava flows	Mio-Pliocene	Grand Canyon region, Figure 5.4	basaltic lava flows

Table 5.1 continued

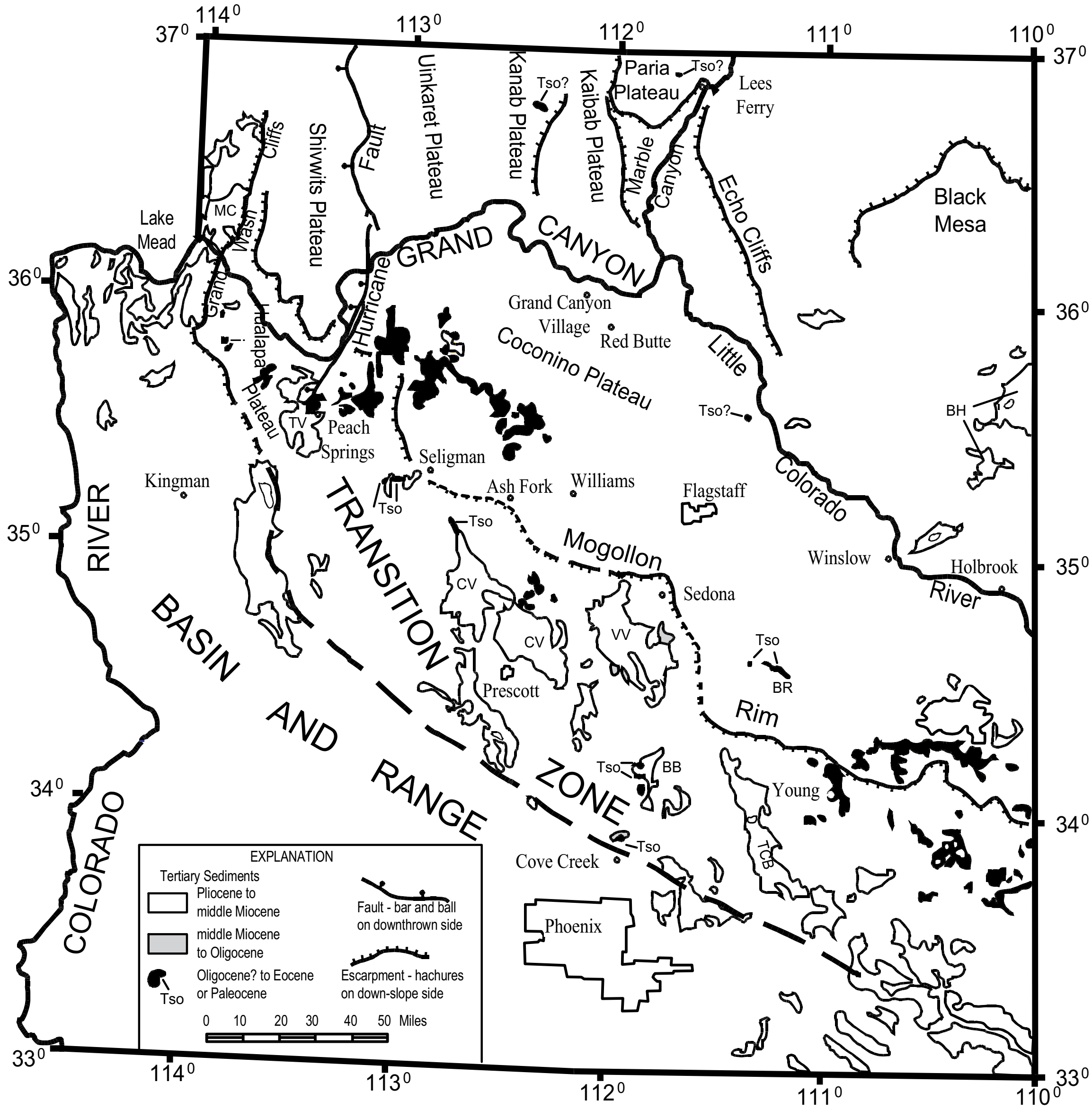


Figure 5.1 Tertiary deposits and physiographic features of central Arizona emphasizing the distribution of the Mogollon Rim Formation (Rim gravels). Abbreviations: MC, Muddy Creek Formation; BH, Bidahochi Formation; BR, Blue Ridge; VV, Verde Valley; CV, Chino Valley; BB, Bloody Basin; TCB, Tonto Creek Basin; TV, Truxton Valley; Tso, older Tertiary sediments (Mogollon Rim Formation [Rim gravels]). Correlative deposits in the Basin and Range Province are not shown. Adapted from Elston and Young (1991).

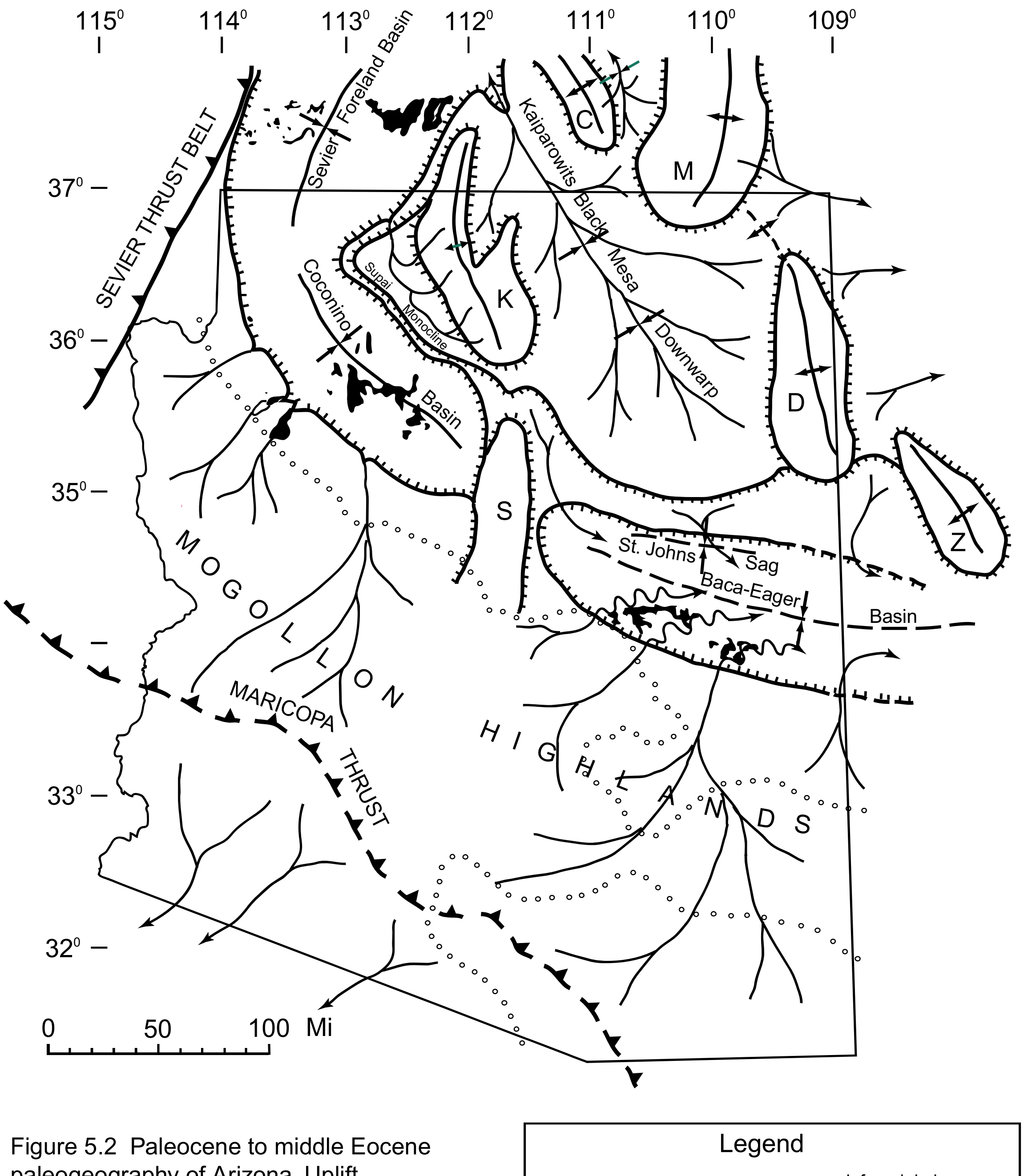


Figure 5.2 Paleocene to middle Eocene paleogeography of Arizona. Uplift abbreviations: D-Definace; M-Monument; K-Kaibab; C-Circle Cliffs; Z-Zuni; S-Sedona Arch. The resulting northward dip to the Colorado Plateau probably formed at this time. Adapted from Nations et al. (1985).

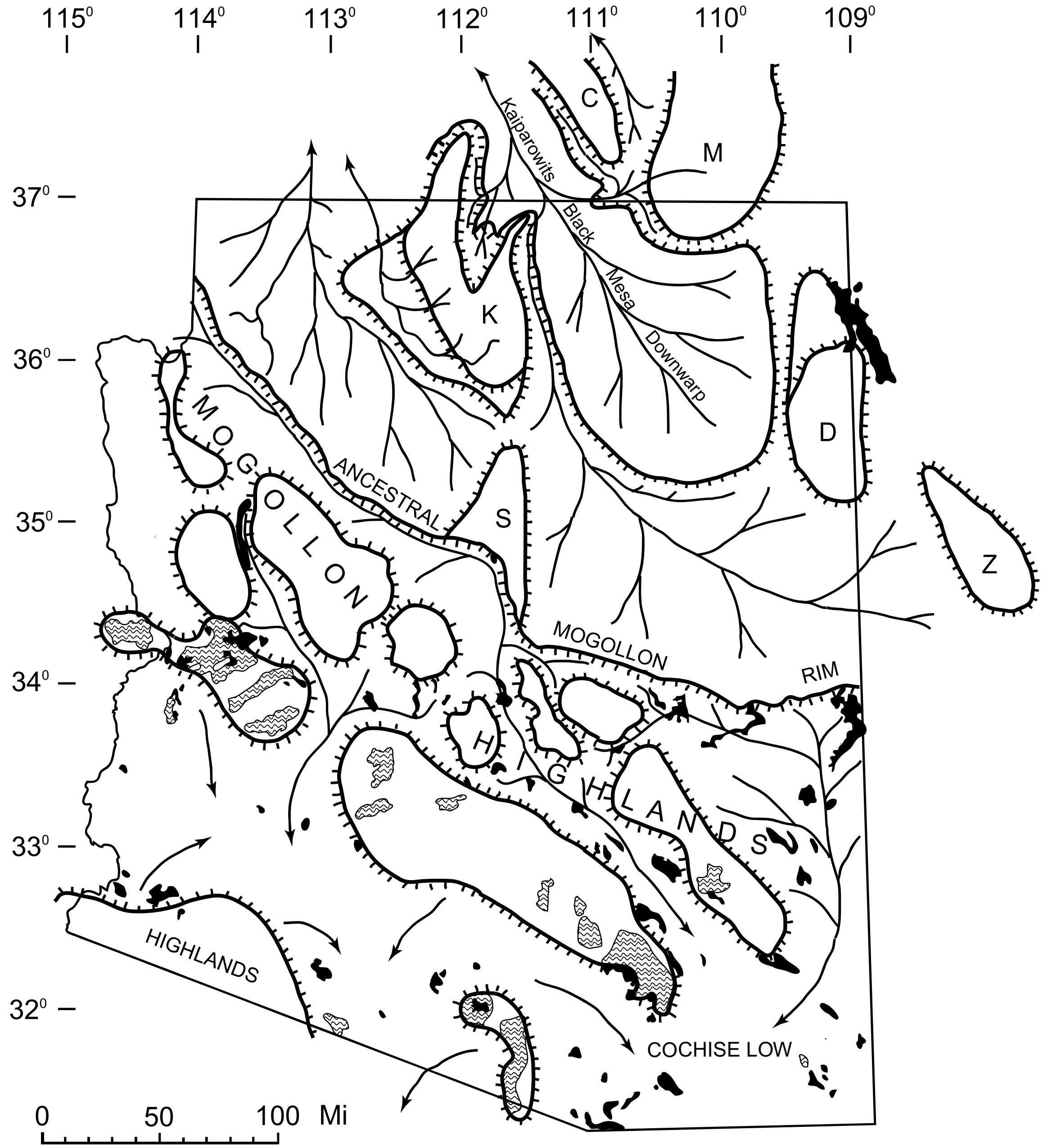
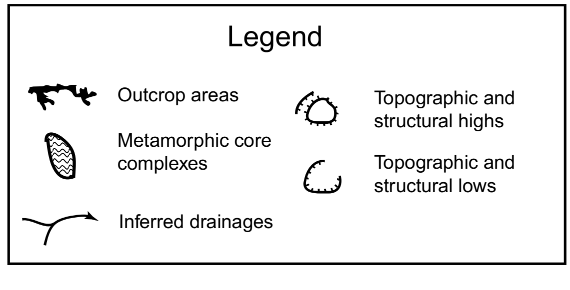


Figure 5.3 Late Oligocene to middle Miocene paleogeography of Arizona. Uplift abbreviations: D-Definace; M-Monument; K-Kaibab; C-Circle Cliffs; Z-Zuni; S-Sedona Arch. Adapted from Nations et al. (1985).



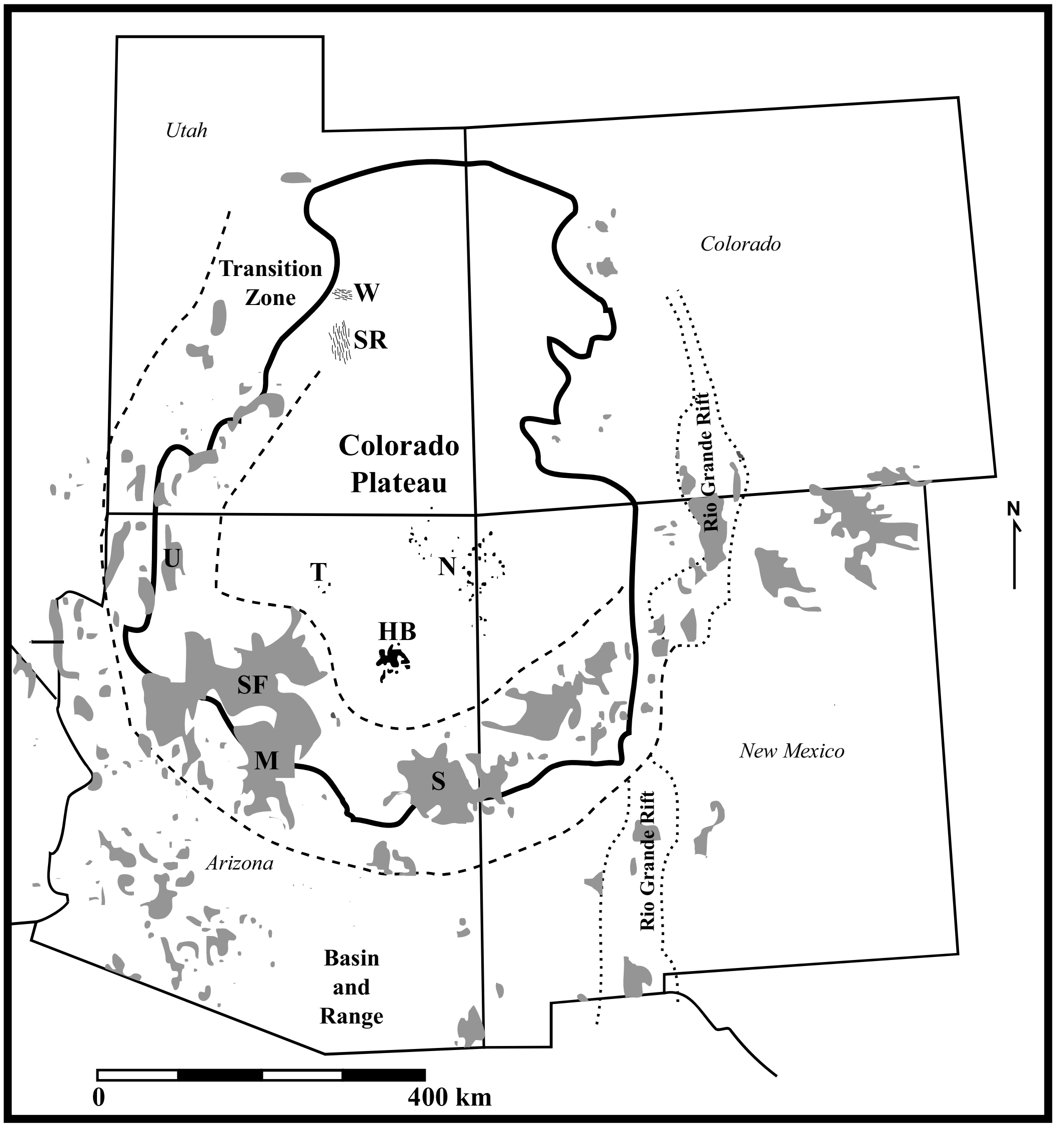


Figure 5.4 Late Cenozoic (<17 Ma) volcanic fields and tectonomagmatic provinces with the Mid-Cenozoic Navajo volcanic field included.
Black areas are Colorado Plateau volcanic fields. Gray areas are volcanic fields in Transition Zone and Rio Grande Rift. Solid black line is physiographic boundary of Colorado Plateau. Boundaries of Transition Zone and Rio Grande Rift are shown as dashed and dotted lines, respectively. Volcanic fields are denoted by letters. HB, Hopi Buttes; M, Mormon; N, Navajo; RC, Raton-Clayton; S, Springerville; SF, San Francisco; SR, San Rafael Swell; T, Tuba City; U, Uinkaret; W, Wasatch Plateau. From Vazquez (1998).

Table 5.2 Regional geologic events for the southern Colorado Plateau

Event	Age	Description
Withdrawal of Cretaceous Sea	Late Cretaceous	Youngest epeiric sea deposits on southern Colorado Plateau
Laramide Orogeny	Late Cretaceous to Eocene	Formation of Rocky Mountains and monoclines and folds on the Colorado Plateau; northeast tilt of Colorado Plateau; formation of pediment surface extending northward toward Utah, New Mexico, and Colorado (Epis and Chapin, 1975; Shafiqullah et al., 1980; Nations et al., 1985), thrusting of Claron Formation strata - late Laramide time (Lundin, 1989; Elston and Young, 1991) Figure 1.1, 5.5
Uplift of Colorado Plateau	Late Cretaceous to early Tertiary	Early uplift (Miller, 1962; Pierce et al, 1979; Nations et al., 1985; Baars et al., 1988; Scarborough, 1989; Elston and Young, 1991, Gregory and Chase, 1992, 1994)
	Late Cretaceous to Miocene	Multiple events (Nations et al., 1985, Elston and Young, 1991)
	late Cenozoic	Significant uplift (McKee and McKee, 1972; Gable and Hatton, 1983; Eaton, 1986, 1987; Lucchitta, 1989; Parsons and McCarthy, 1995)
Deposition of Mogollon Rim Formation	Eocene (see table 5.1)	(Potochnik, 1989) Broad, braided alluvial systems deposited gravel on Laramide erosional pediment surface that extended northward from central Arizona (Epis and Chapin, 1975; Shafiqullah et al., 1980; Nations et al., 1985); Figure 5.1
Initial development of Mogollon Rim (Escarpment)	Paleocene	Differentiates southern Colorado Plateau from Transition Zone of central Arizona; disrupts north flowing drainages flowing from central Arizona; Figures 5.1 and 5.3 (Elston and Young, 1991)
	late Oligocene	(Peirce et al., 1979; Nations et al., 1985)
	Miocene	(Twenter, 1961; McKee and McKee, 1972; Lucchitta, 1979)
Formation of Coconino basin	early Eocene	Accumulating sediments controlled by Kaibab uplift and adjacent down-warping of Coconino Plateau (Nations et al., 1985); Figures 5.2 and 5.5
Formation of Baca-Eagar basin	Eocene	Sediment accumulated (Baca and Eagar Formations) due to blockage of easterly flowing streams by Sierra uplift (Chapin and Cather, 1981); Figures 5.2 and 5.5
Erosion	39-26 Ma	(Elston and Young, 1991) Much of Mogollon Rim Formation and deposits in Baca-Eagar and Coconino basins removed (Hunt, 1956, 1969; Peirce et al., 1979; Nations et al., 1985; Elston and Young, 1991)
Eruption of the Mogollon-Datil volcanic field	36.2-24.3 Ma	Intermediate then felsic volcanism (McIntosh et al., 1990)

Event	Age	Description
Incipient extension of Rio Grande Rift	36-35 Ma (Cather et al., 1994; Chapin and Cather, 1994)	North-trending rift formed by 1-1.5^0 clockwise rotation of the Colorado Plateau with Euler pole located in northeastern Utah (Chapin and Cather, 1994); early rift volcanism (~28-24 Ma) (Baars et al, 1988; McIntosh et al., 1992; Chapin and Cather, 1994). Figure 5.6
Sedimentation onset in Rio Grande Rift	27-25 Ma	Early basin development and deposition along entire rift (Lipman and Mehnert, 1975; Baars et al, 1988, Cather, 1994)
Andesite lava flow	26 Ma	Unconformably overlies the Oligocene Deza and Chuska Formations at Washington Pass, New Mexico (Damon and Shafiqullah, 1981; Scarborough, 1989)
Basin and Range extension in Arizona	early to middle Miocene	(Nations et. al, 1985; Elston and Young, 1991) Formation of Transition Zone and Basin and Range Provinces in southern Arizona; coeval middle to late Tertiary volcanism until about 11 Ma (Elston and Young, 1991)
Accelerated extension of Rio Grande Rift	~16 Ma	Elevated rift-flanks shed sediment inbound to rift and onto flanks (Chapin and Cather, 1994)
Formation of Hopi Lake depositional basin	~16 Ma	Initiation of Bidahochi Formation deposition, member 1 (this paper)
Eruption of White Mountain volcanic field	middle to late Tertiary	(Berry, 1976; Merrill and Pewé, 1977) Volcanism peaked in Salt River paleocanyon region ~15 to 14 Ma (Potochnik and Faulds, 1998)
Deposition of Fence Lake Formation	middle to late Miocene	(McLellan et al., 1982; Lucas and Anderson, 1994) Deposition fluvial sandstone and conglomerate
Formation of closed basin on western margin of Colorado Plateau	~12-5.5 Ma (Lucchitta, 1979)	Deposition of Muddy Creek Formation - alluvial and lacustrine rocks
Hopi Buttes volcanism	8.5 to 4.2 Ma	(Shafiqullah and Damon, 1986a, b) Ultramafic phreatomagmatic volcanism
Eruption of San Francisco volcanic field	late Miocene-Quaternary	(Leighty, 1998) felsic to mafic volcanism (Holm, 1987); Figure 5.4
extension slowed in Rio Grande Rift	Pliocene	Development of axial drainages (Chapin and Cather, 1994)
Erosion	Quaternary	Removal of parts of Bidahochi Formation; continued removal of Mesozoic and Paleozoic rocks

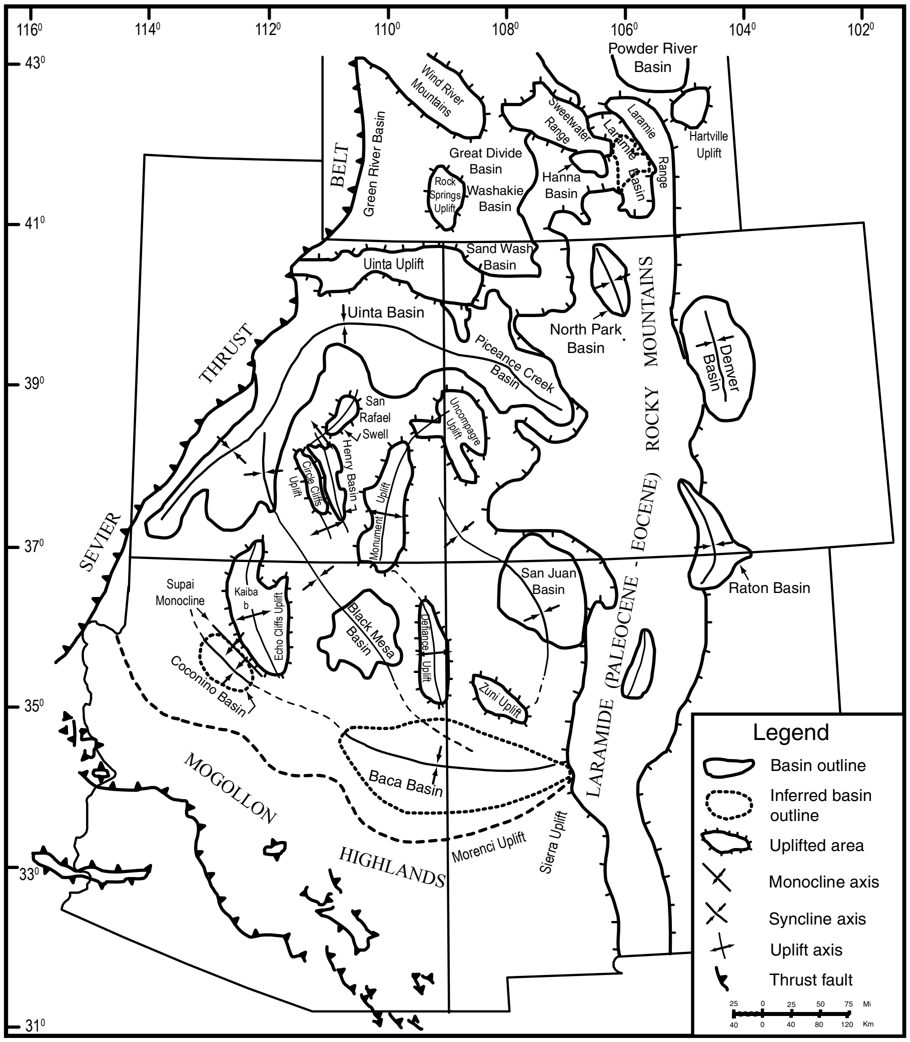


Figure 5.5 Late Cretaceous to Eocene tectonic features of the Colorado Plateau. Modified from Nations et al. (1985).

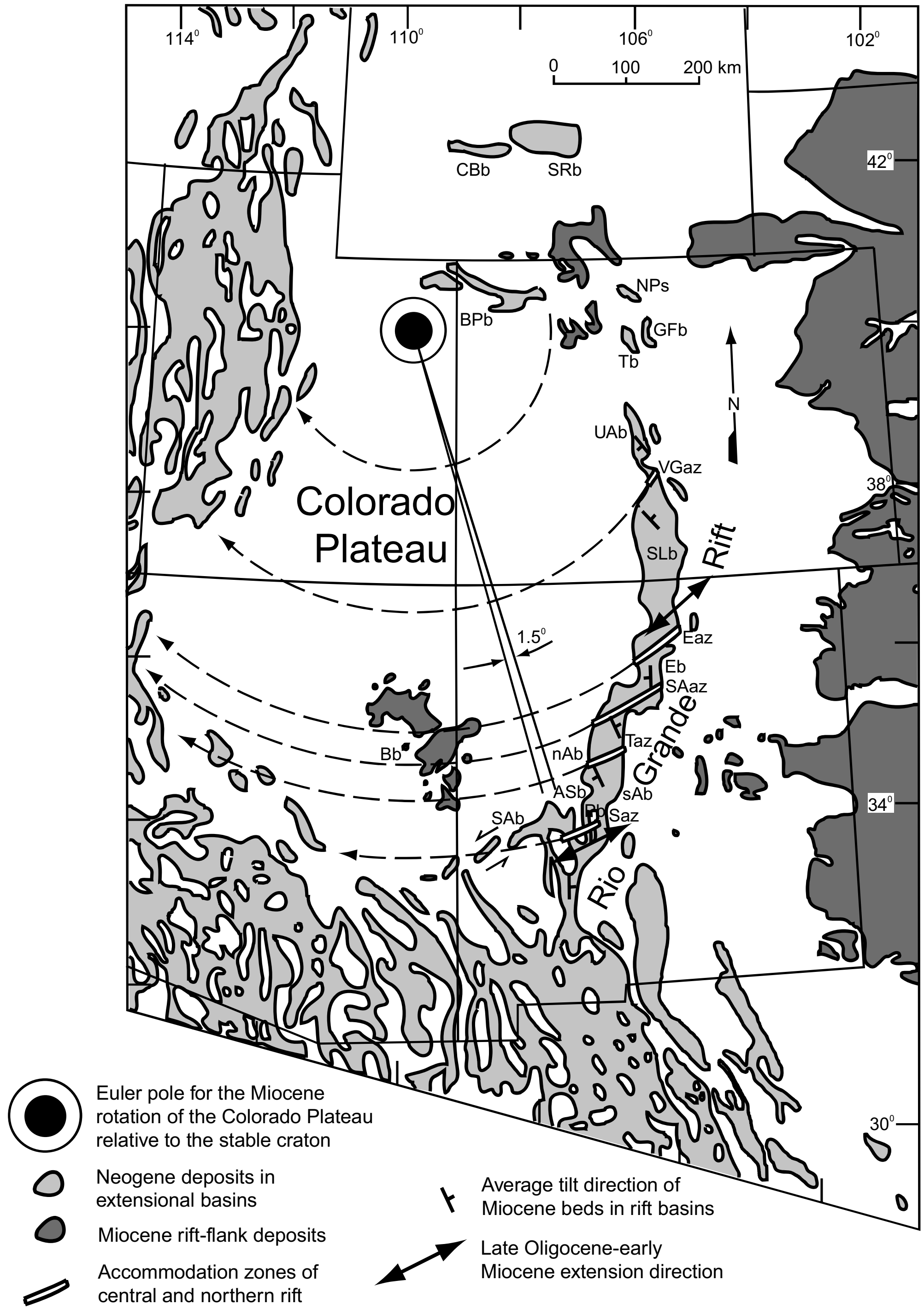


Figure 5.6 Distribution of Neogene basin-fill and rift-flank deposits and selected structural features. Abbreviations for basins (from north to south) are CBb, Circle Bar Basin; SRb, Split Rock Basin; BPb, Browns Park Basin; NPs, North Park syncline; Tb, Troublesome Basin; GFb, Granby-Fraser basin; UAb, Upper Arkansas Basin; SLb, San Luis Basin; Eb, Espanola Basin; nAb, Bb, Bidahochi basin; northern Albuquerque Basin; sAb, southern Albuquerque Basin; Pb, Popotosa basin; ASb, Abbe Springs Basin. Abbreviations for accommodation zones are VGaz, Villa Grove; Eaz, Embudo, SAaz, Santa Ana; Taz, Tijeras; Saz, Socorro. From Chapin and Cather (1994)

Table 5.3 Evolution of integrated Tertiary drainage patterns.

Event and Description (see also Table 5.1 and 5.2)	Age
Braided streams flowed northward from central Arizona to basins in Utah, New Mexico, and Colorado (Epis and Chapin, 1975; Shafiqullah et al., 1980; Grande, 1984; Nations et al., 1985; Potochnik, 1989); flowed into Lake Uinta (Dickinson et al., 1988); Figure 5.2	Paleocene to middle Eocene (Nations et al., 1985)
External drainage for Lake Uinta out through Sevier Thrust Belt ranges and into northwestern Nevada, southern Idaho, and across Oregon, eventually emptying in Pacific Ocean (Dickinson et al., 1988); Figure 5.7	Eocene (Dickinson et al., 1988)
Exterior drainages through Uinta-Green River and Washakie Basins (Figure 5.5), crossed Rocky Mountains, deposited sediment (late Eocene to Oligocene White River Group) in Denver basin and on Great Plains (Nations et al., 1985)	Eocene (Nations et al., 1985)
Streams flow north into Coconino basin from Mogollon Highlands of central Arizona (Nations et al., 1985); Figure 5.2	early Eocene (Nations et al., 1985)
Streams flow north and northeasterly into Baca-Eagar basin from Central Arizona (Cather and Johnson, 1984; Potochnik; 1989); Figure 5.2	middle to late Eocene (Cather et al., 1994)
Sediment bypass; removal and transportation of Mogollon Rim, Baca, and Eagar Formations from southern Colorado Plateau probably by north flowing drainage systems (Peirce et al., 1979; Nations et al., 1985; Potochnik, 1989; Elston and Young, 1991); Figure 5.3	Oligocene to mid-Miocene (references at left)
Streams flow northeasterly from central Arizona through Salt River paleocanyon and onto Colorado Plateau (Faulds 1986; Potochnik and Faulds, 1998)	Oligocene to middle Miocene
Drainage reversal along Mogollon Rim	
Drainage reversal due to erosion of Supai Formation which formed Mogollon Rim (Peirce et al., 1979)	Oligocene
Drainage reversal due to erosion of Mogollon Rim Formation and exhumation (Table 5.2) of Mogollon Rim (Elston and Young, 1991)	late Oligocene
Drainage reversal due to scarp retreat (Nations et al., 1985)	late Oligocene
Drainage reversal due to pre-Salt River drainage blocked by 14.6 Ma lava flow; ponded; reversed direction to flow into Basin and Range province by ~14 (Potochnik and Faulds, 1998)	middle Miocene
Arrival of ancestral Colorado River on southern Colorado Plateau Hunt (1969)	late Oligocene
Evolution of ancestral Colorado River drainage (Figure 5.8)	late Oligocene to Recent
Hunt s (1969) hypothesis - southwest flow; see Figure 5.9	
McKee et al.s (1967) hypothesis - southeast flow; see Figure 5.10	
Lucchitta s (1984) hypothesis - northwest flow; see Figure 5.11	
Ranney s hypothesis - northeast flow; see Figure 5.12	

Event and Description (see also Table 5.1 and 5.2)	Age
Incision of Muddy Creek Formation related to opening of Gulf of California and headward erosion of ancestral lower Colorado River into Muddy Creek basin (Lucchitta, 1984; Nations et al., 1985; Elston and Young, 1991).	~5.5 Ma
Incision of Grand Wash Cliffs and formation of western Grand Canyon related to headward erosion of ancestral lower Colorado River (Elston and Young, 1991)	by 3.8 Ma

Table 5.3 continued

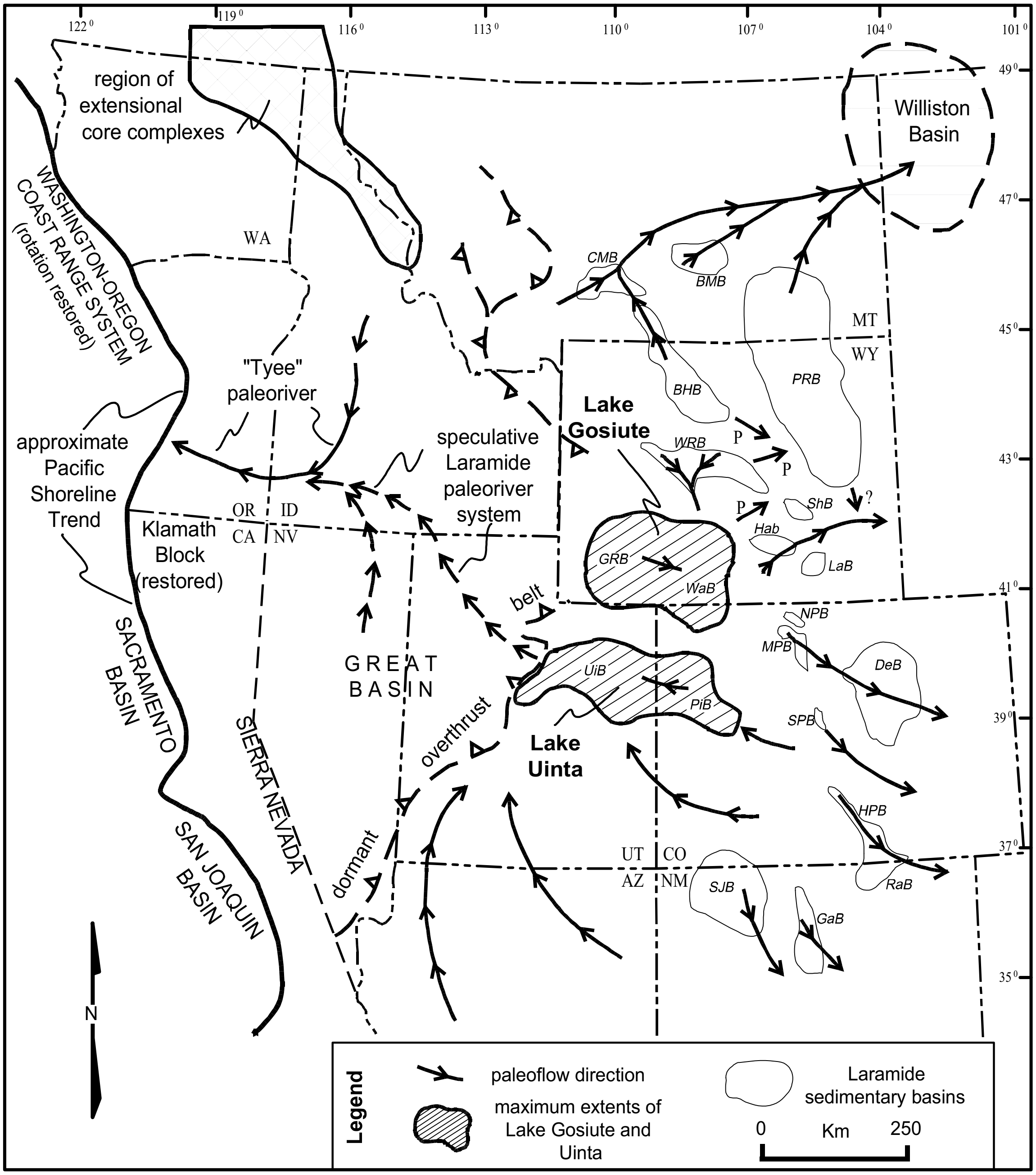


Figure 5.7 Sketch map of the Eocene Pacific watershed showing speculative paleoriver systems (dashed arrows) draining the Laramide province during the highstands of Lake Uinta and Gosiute. The width of Nevada is reduced by half to simulate restoration of Neogene crustal extension across the Great Basin. The schematic paths of other Eocene paleorivers are shown with barbed lines (short arrows with letter P denote earlier Paleocene dispersal routes in central Wyoming). Abbreviations of Laramide basins: BHB - Bighorn; BMB - Bull Mountain; CMB - Crazy Mountains; DeB - Denver; GaB - Galisteo; GRB - Green River; HaB - Hanna; HPB - Huerfano Park; LaB - Laramie; MPB - Middle Park; NPB - North Park; PiB - Piceance Creek; PRB - Powder River; RaB - Raton; ShB - Shirley; SJB - San Juan; SPB - South Park; UiB Uinta; WaB - Washakie; WRB - Wind River. Adapted and modified from Dickinson et al. (1988).

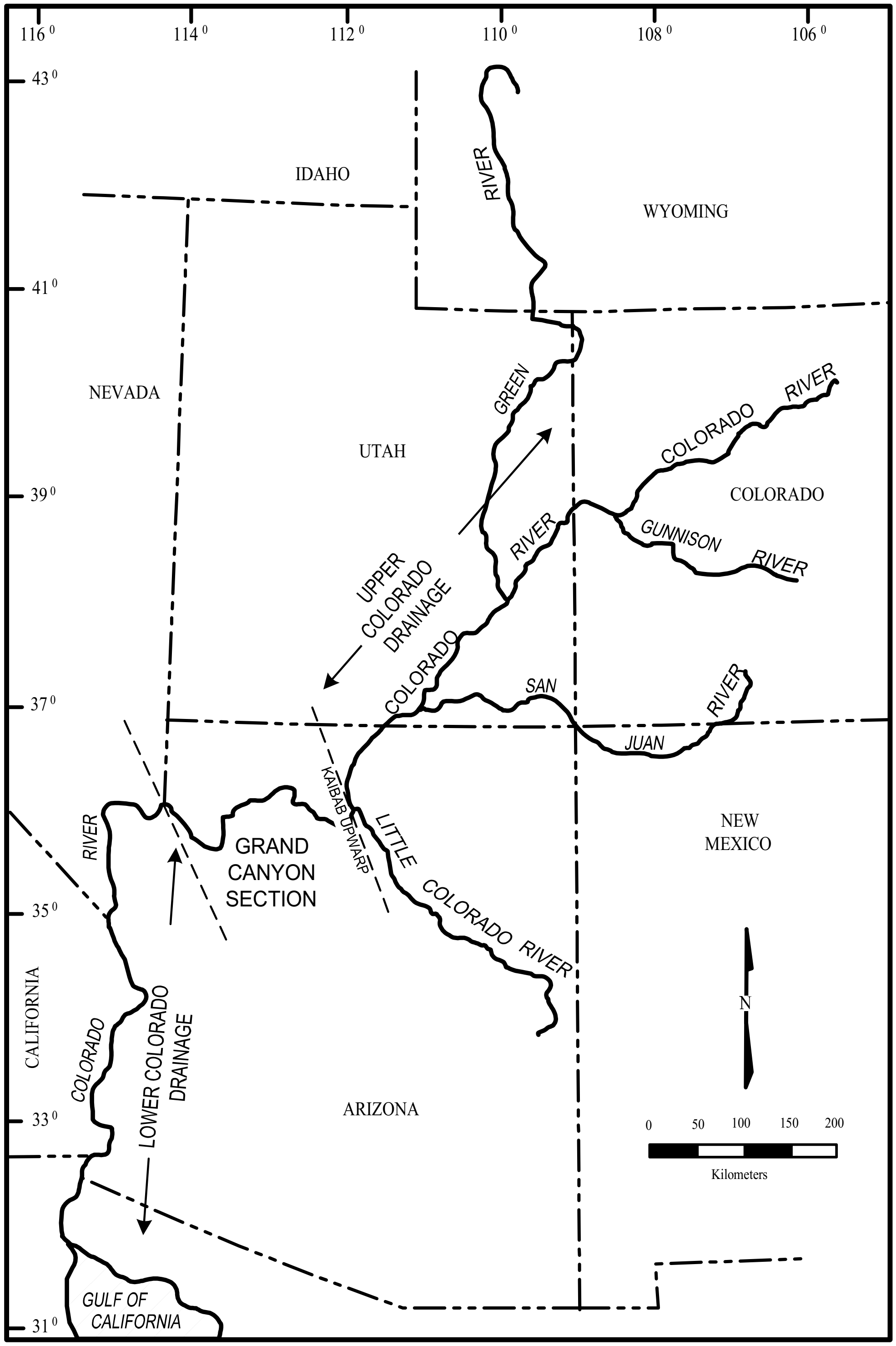
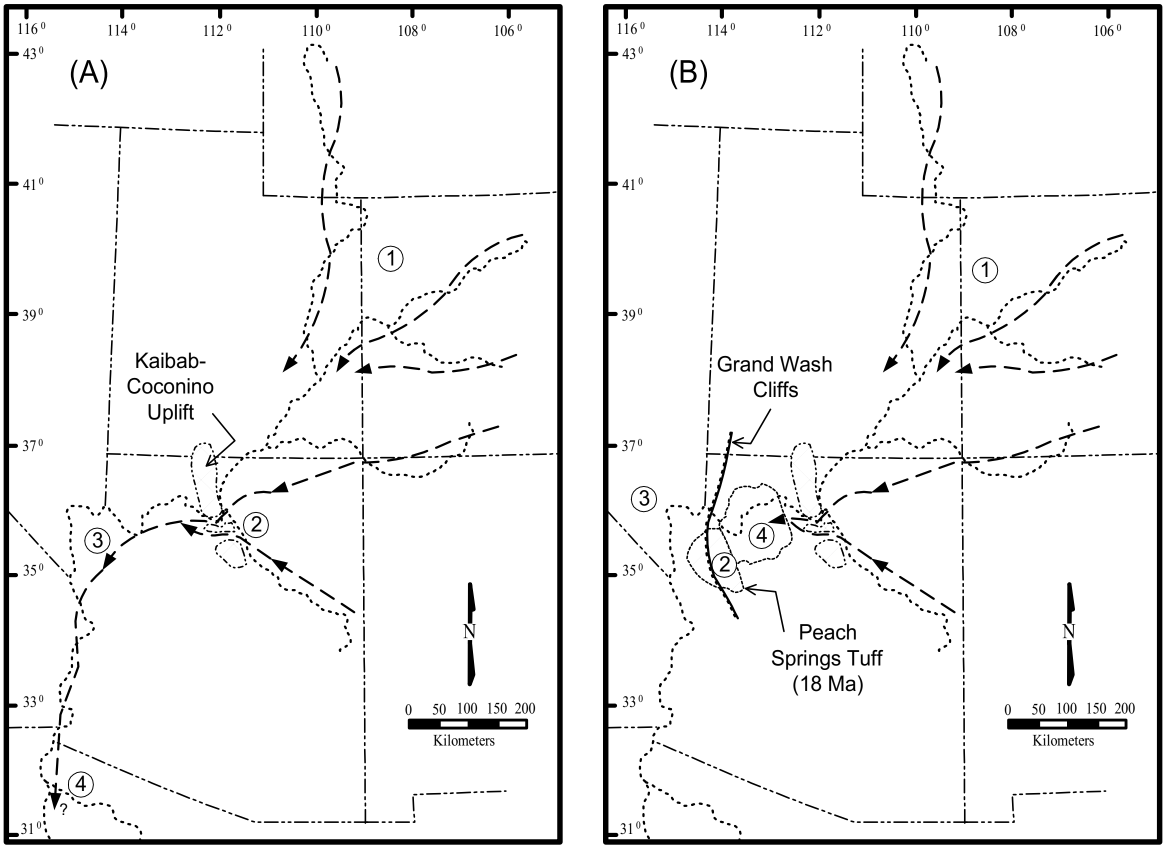
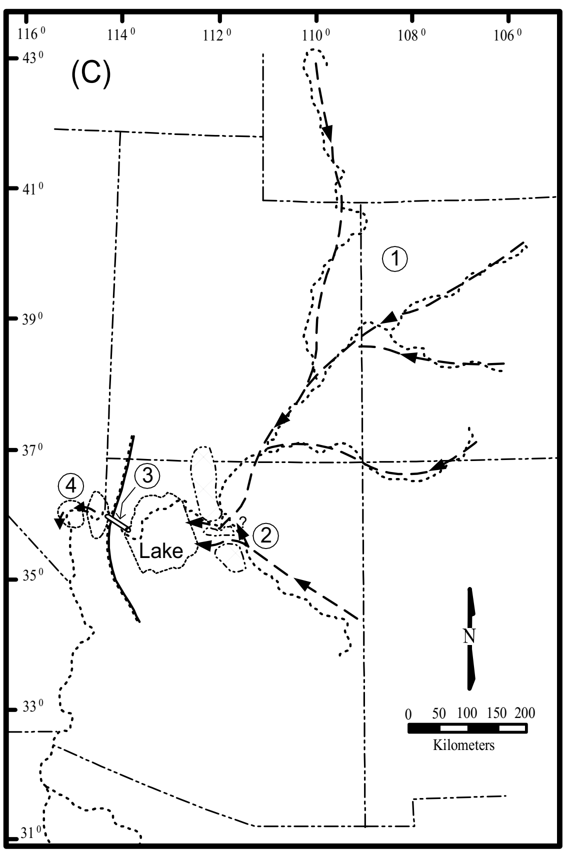


Figure 5.8 Map of the Colorado River system emphasizing the three principal drainage sections. From Lucchitta (1984).





(A) before basin-range faulting:

1. ancestral streams existed probably as early as Oligocene time and became integrated into ancestral upper Colorado drainage
2. ancestral little Colorado drainage crossed southern end of the Kaibab-Coconino uplift
3. ancestral Colorado drainage flowed south of present location and flowed through the Kingman, AZ area
4. continuation unknown - Gulf of California had not yet opened

(B) after emplacement of the Peach Springs Tuff and basin-range faulting

1. streams of upper Colorado drainage evolve toward present system
2. ~18 Ma, Peach Springs Tuff emplaced and blocks ancestral Colorado drainage south of present position
3. north trending basin-range faulting between 18-10 Ma disrupts drainage patterns and causes deposition in interior basins, no external Colorado drainage
4. ponding of ancestral Colorado drainage forms a lake in the Hualapai-Coconino-Kaibab plateau area

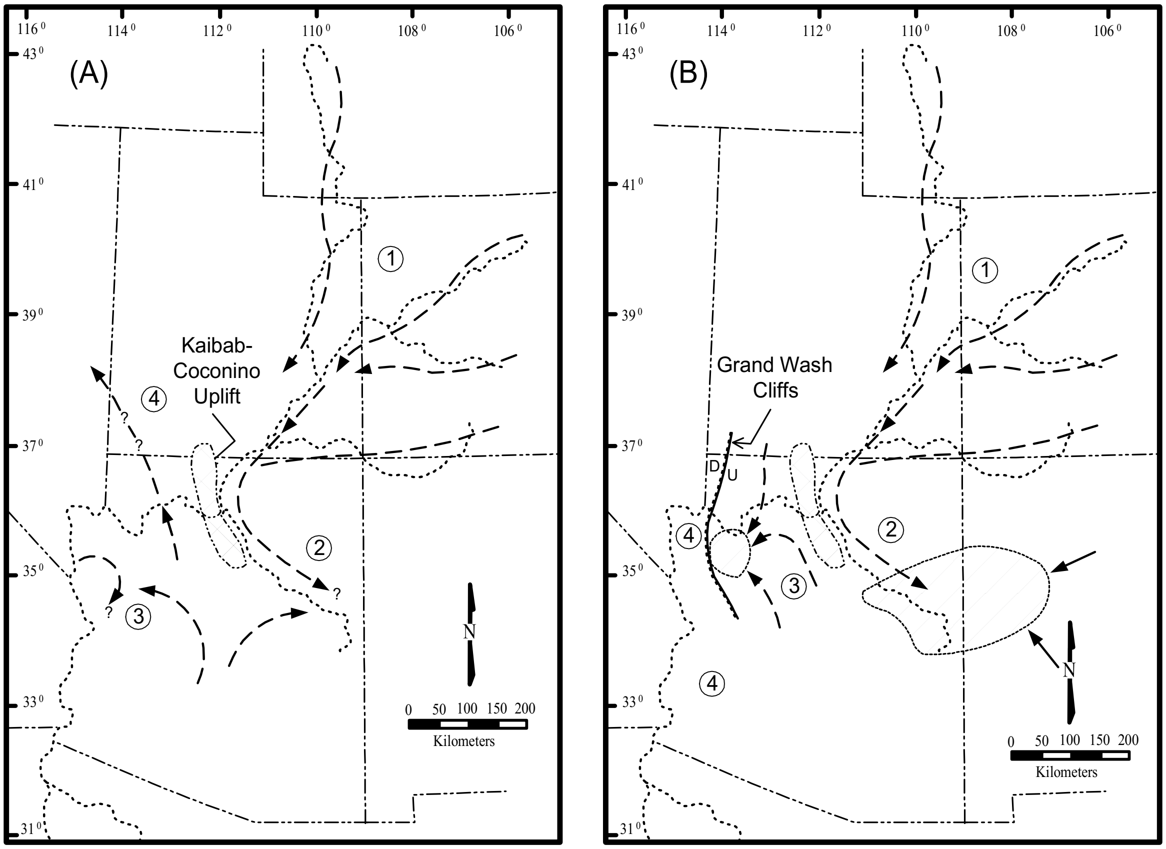
Colorado Plateau becomes structurally and physiographically distinct from the newly formed Basin and Range Province, Grand Wash Cliffs forms western boundary

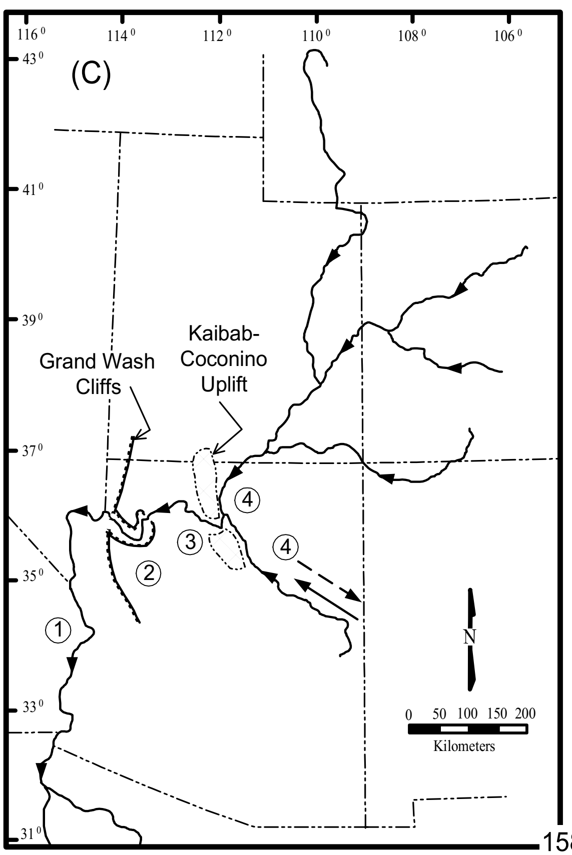
(C) after establishment of subterranean piping

1. streams almost follow present courses in upper Colorado drainage
2. Little Colorado River possibly crosses Kaibab-Coconino uplift through previous gap or it may join Colorado River east of uplift
3. lake discharge through Grand Wash Cliffs by way of subterranean piping in cavernous limestone
4. lakes receive discharge from subterranean piping and deposit the Hualapai limestone in the present day Lake Mead area

The various lakes soon become integrated and drained by drainages of the ancestral lower Colorado drainages. The modern Colorado River quickly cuts the western Grand Canyon and entrenches its course.

Figure 5.9 Hunt's hypothesis. Adapted and modified from Lucchitta (1984).





(A) before basin-range faulting:

1. ancestral streams existed in this area as in Hunt's hypothesis
2. ancestral upper Colorado drainage deflected southeastward by Kaibab-Coconino uplift and flows up the Little Colorado River valley. Possibly exited plateau into the Rio Grande drainage
3. drainage from high terrain on the western and southern plateau areas flows into Peach Springs-Truxton valley area, further continuation unknown
4. Cataract Creek and other drainages may have flowed northwestward

(B) after basin-range faulting

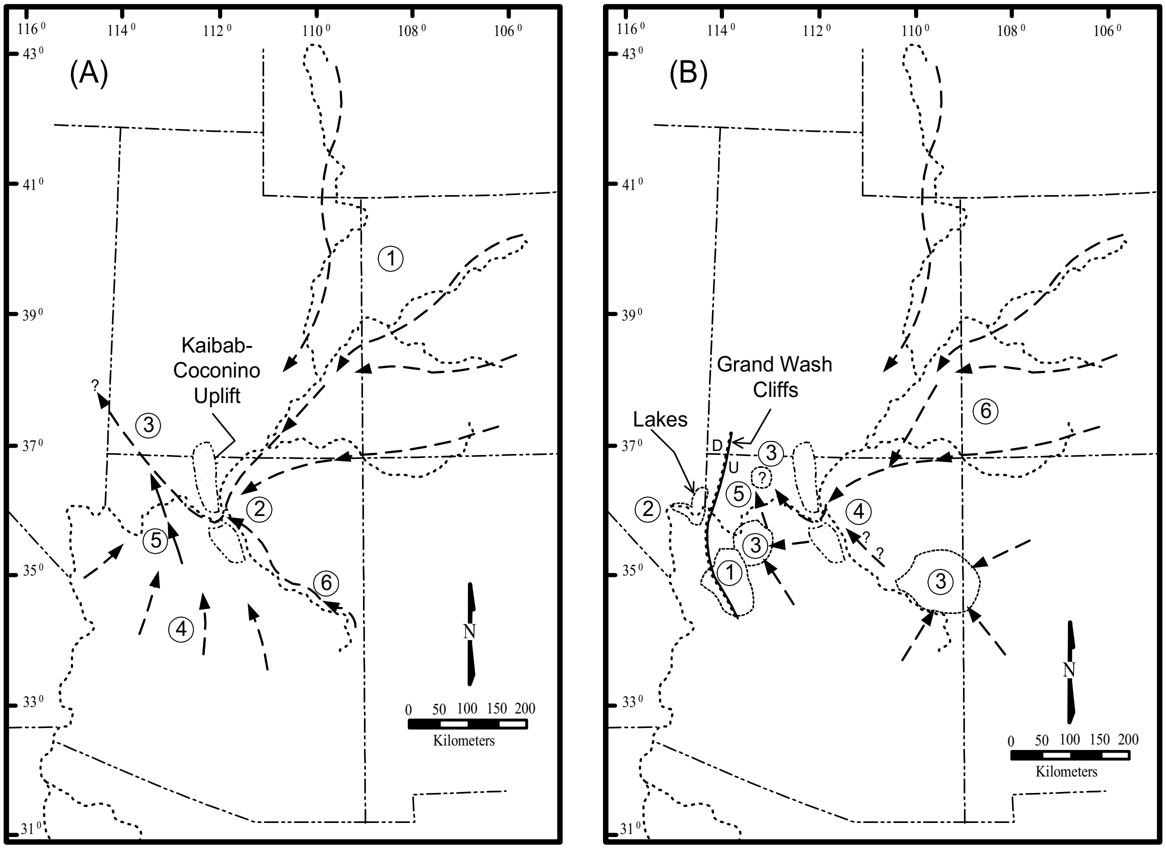
1. ancestral drainage
2. ancestral upper Colorado drainage still deflected by Kaibab-Coconino uplift, ponded in northeastern AZ, and deposited Bidahochi Formation
3. drainage disrupted and ponded by faulting and emplacement of Peach Springs Tuff
4. basin-range faulting disrupts old drainages, separates Colorado Plateau from Basin and Range Province, and creates widespread interior-basin deposition. No exterior flowing drainages

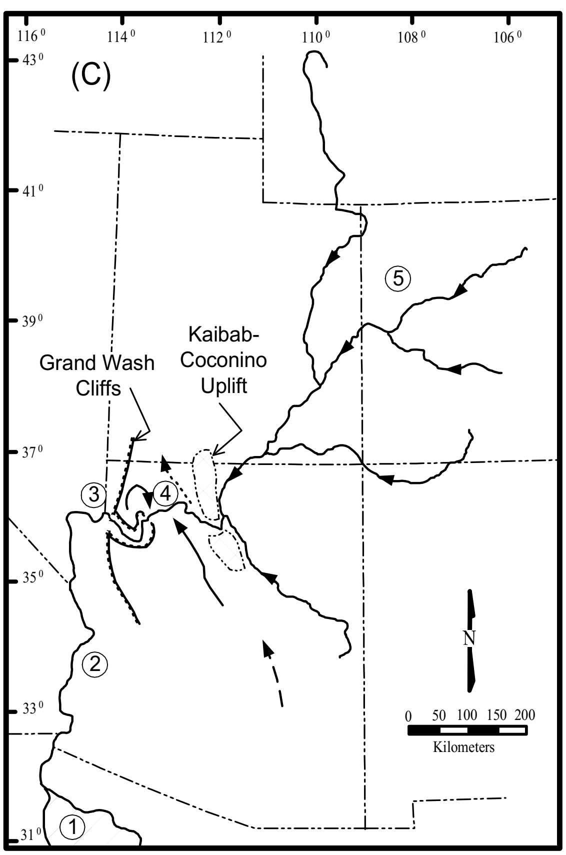
(C) after capture and during headward deepening of the Grand Canyon

1. major river develops by headward erosion and integration of interior basins, forms lower Colorado River drainage
2. river erodes headward through Grand Wash Cliffs and plateau, captures old drainages, and incises Grand Canyon
3. river cuts the Kaibab-Coconino uplift by headward erosion
4. river captures ancestral upper Colorado drainage and reverses the previous southeast flow

The modern Colorado River now in existence

Figure 5.10 McKee et al. hypothesis. Adapted and modified from Lucchittta (1984).





(A) before basin-range faulting:

1. ancestral streams existed in this area as in Hunt's hypothesis
2. ancestral upper Colorado drainage crosses Kaibab-Coconino uplift in relatively shallow strike valley
3. drainage continues NW along strike valley, destination unknown due to younger tectonism and emplacement of volcanic rocks
4. numerous drainages flow onto plateau from surrounding high areas. These drainages are tributary to upper ancestral upper Colorado drainage and deposited the arkosic "Rim gravels"
5. ancestral Cataract creek
6. ancestral Little Colorado River

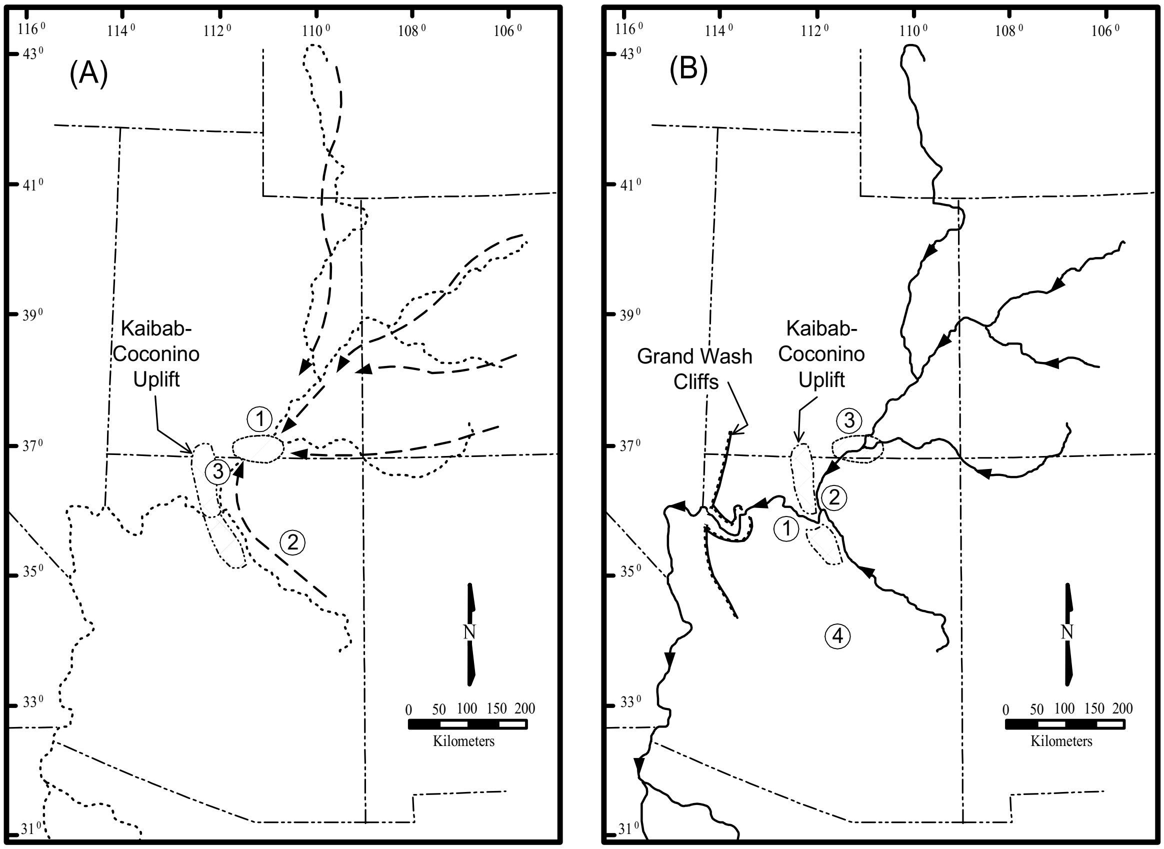
(B) after basin-range faulting

1. peach springs tuff and basin-range faulting disrupt old drainages flowing onto plateau
2. basin-range faulting causes widespread interior-basin conditions, no exterior drainages (18-10 Ma). Lakes present near Grand Wash Cliffs
3. widespread intermittent ponding
4. ancestral upper Colorado drainage still flows through Kaibab-Coconino uplift
5. NW drainage across present course of Colorado River, exists intermittently until ~6 Ma
6. drainage in this area as per Hunt, with local intermittent ponding

(C) during integration of river system

1. Gulf of California opens about 5 Ma
2. major river develops by headward erosion and integration of interior basins and lakes along course of lower Colorado River
3. river erodes headward into Grand Wash Cliffs and plateau, captures drainages, and carves western Grand Canyon
4. river captures ancestral upper Colorado drainage west of Kaibab-Coconino uplift and forms modern Colorado River
5. drainages in this area essentially in modern locations. After formation of Colorado River system, rejuvenated streams extensively erode and downcut drainages and remove great volumes of Mz rocks from plateau. Erosion is interrupted occasionally by aggradation

Figure 5.11 Lucchitta hypothesis. Adapted and modified from Lucchitta (1984).



(A) prior to incision of Kaibab-Coconino Uplift

① ancestral streams drain into a basin in the present Glen Canyon area - based on presence of sediments near Kaiparowits Plateau of Cretaceous and Tertiary age

② Little Colorado River flows along strike valley of Permian and Jurassic rocks and empties into basin

③ barbed drainages in Marble Canyon area drain down the regional dip-slope to the northeast - reflect the direction of streams prior to capture

(B) incision of Kaibab-Coconino Uplift

① headward erosion of ancestral lower Colorado River through western Grand Canyon and Kaibab-Coconino Uplift

② capture of Little Colorado River near present confluence of LCR and Colorado River.

③ capture breaches and destroys basin in Glen Canyon area and integrates drainages to present conditions

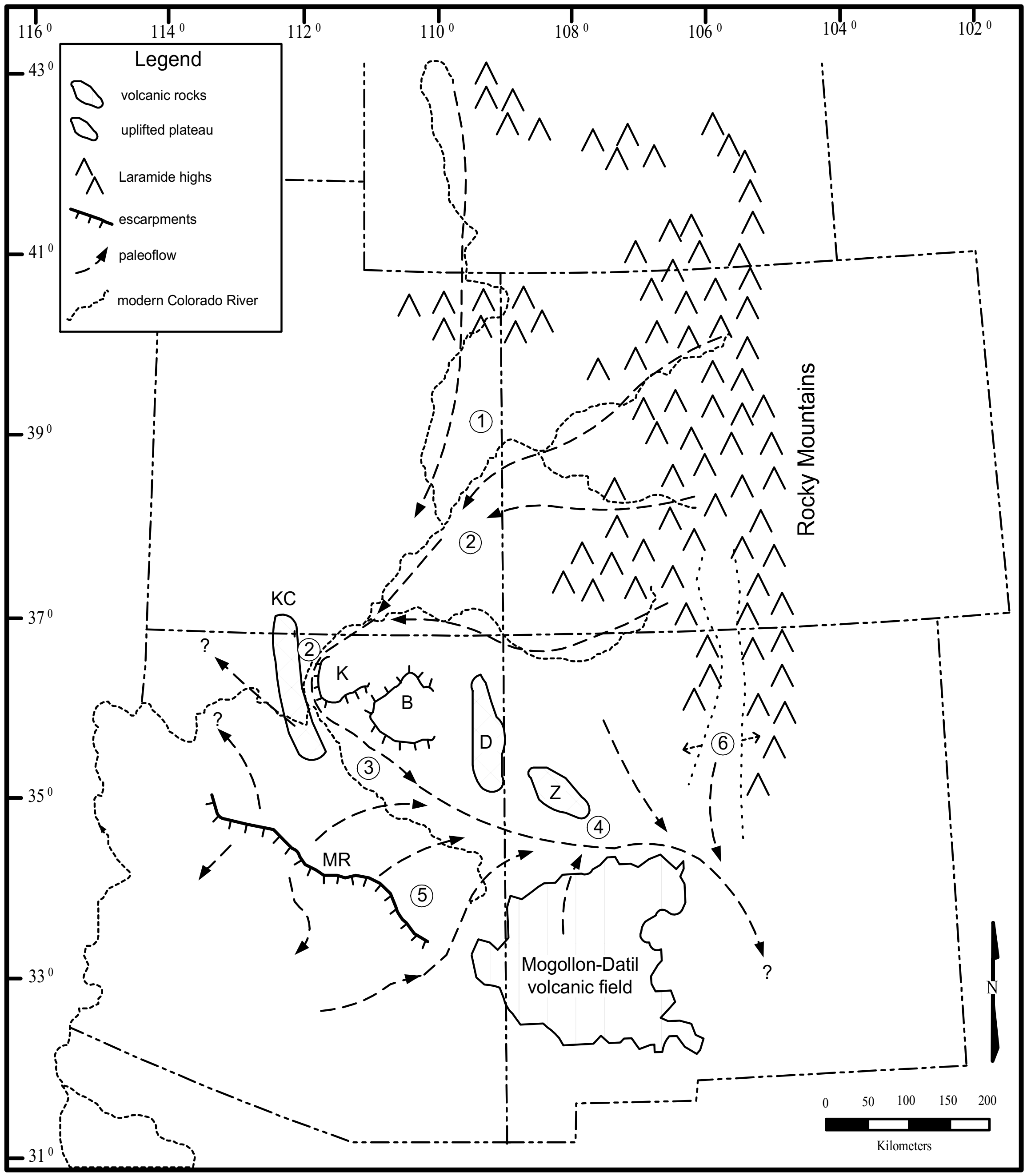
Figure 5.12 Ranney's hypothesis. Extrapolated from abstract of Ranney (1998).

Table 5.4 Miocene-Pliocene paleogeographic events on the southern Colorado Plateau. Numbers refer to numbers on figures.

Figure #	Age	Description
5.13	early Miocene	(1) drainages in ancestral upper Colorado River as per Hunt (1969) (2) by early Miocene, ancestral upper Colorado River drainages flow towards southern Colorado Plateau, deflected to southeast by Kaibab-Coconino uplift (3) ancestral upper Colorado River flows southeast along strike valley created by erosional Mesozoic and Paleozoic escarpments (similar to McKee et al., 1967, Figure 5.10) (4) ancestral upper Colorado River exits southern Colorado Plateau north of Mogollon-Datil volcanic field, joins streams draining southern Rockies (pre-San Juan drainages), flows out through southeastern New Mexico (similar to McKee et al., 1967, Figure 5.10) (5) ancestral Salt River and other drainages from Mogollon Rim divide contribute to southeasterly flowing ancestral upper Colorado River (6) rifting is continuing in northern areas of Rio Grande Rift (Chapin and Cather, 1994)
5.14a	middle Miocene	(1) accelerated phase of Rio Grande Rift (16 to 5 Ma), rift basins form, begin accumulating sediment (Chapin and Cather, 1994) (2) rifting forms extensive rift shoulders (Chapin and Cather, 1994), reactivates Defiance and Zuni uplifts, elevated rift-flanks in west-central New Mexico (Chapin and Cather, 1994) deflect southeastward flowing river systems (3) deflection effectively closes southeastern end of northwest-trending trough - Hopi Lake depositional basin forms, sediment shed to west from erosion of rift-flanks and elevated Defiance and Zuni uplifts - form member 1; by ~15.4 Ma, Hopi Lake fills, begins depositing lacustrine units - repeated cycles of climate, lake levels, and/or sediment influx probably formed repetitive sediment packages of member 2 (4) ancestral Salt River and other drainages flow onto Colorado Plateau (Potochnik and Faulds, 1998), into Hopi Lake basin (5) Emplacement of Peach Springs tuff (18-10 Ma) and Basin and Range faulting causes drainage disruption on western Colorado Plateau, forms interior basins (Lucchitta, 1984, Figure 5.11) (6) delta forms at western end of Hopi Lake where ancestral upper Colorado River enters lake
5.14b	middle Miocene	(1) 14.6 Ma basalt flow blocks ancestral Salt River, creates ponding Potochnik and Faulds, 1998) (2) coarse sediment shed from Mogollon-Datil volcanic field and rift shoulders accumulates as Fence Lake Formation, fine-grained material continues into Hopi Lake basin (3) Hopi Lake basin continues to accumulate lacustrine sediment, periodic drying of sediments creates secondary gypsum deposition until mid-member 2 time (~14.5 Ma), distally derived felsic ash becomes interbedded with lacustrine units (4) Hopi Lake fills with sediment and outflows to south in low created by ancestral Salt River canyon, flow continues into southern Arizona (using Potochnik and Faulds, 1998 recognition of a reversed ancestral Salt River drainage); outflow creates fresh-water lake (5) sedimentation increases (Table 4.1) in Hopi Lake, member 3 is deposited (~13.9 - ~13.5 Ma) (6) drainage from valley areas west of Defiance Uplift flows into Hopi Lake, forms large delta lobes of member 4 along eastern margin of lake

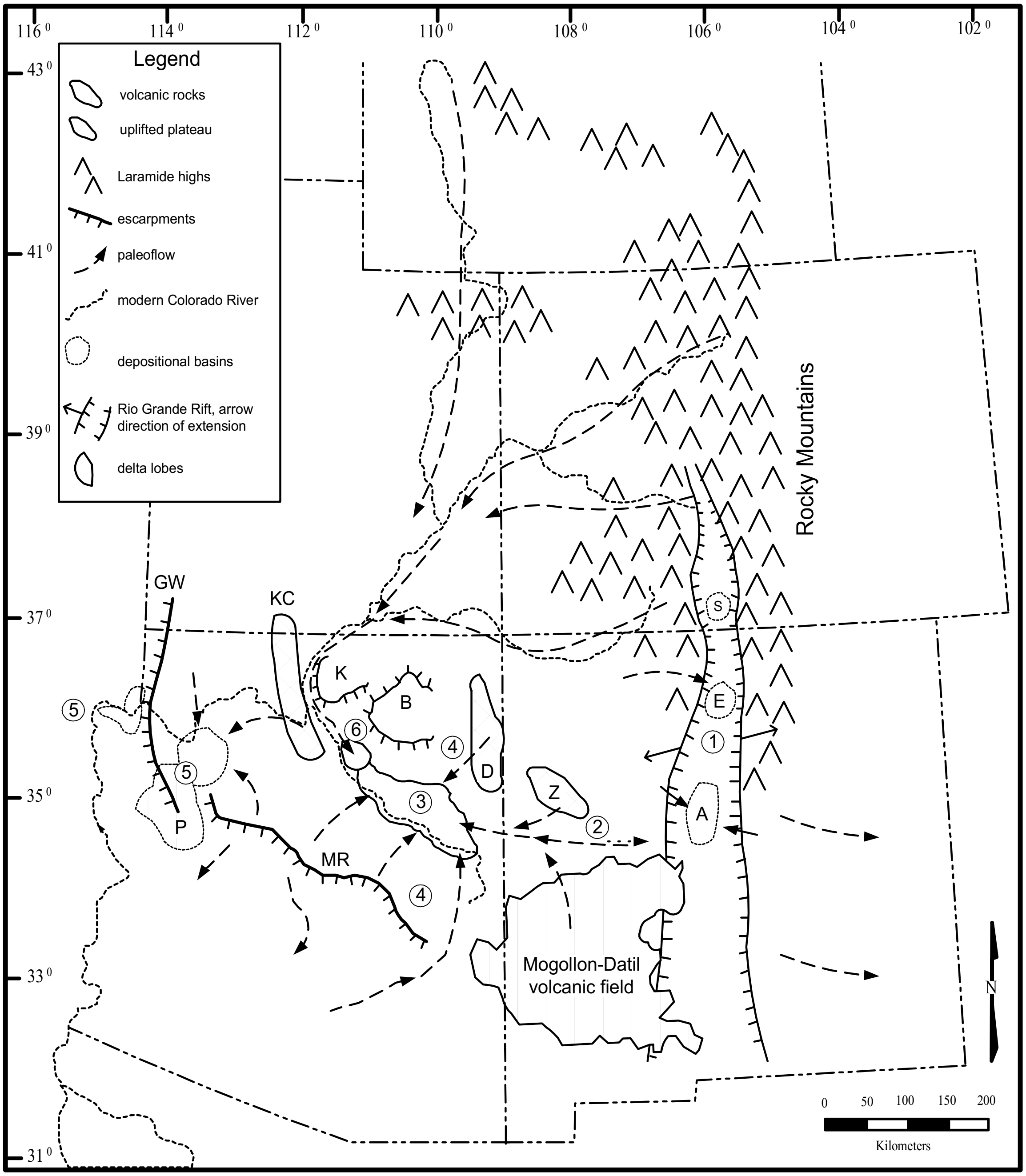
Figure #	Age	Description
5.15	late Miocene - Pliocene	(1) ancestral upper Colorado River continues to drain into Hopi Lake; by ~8.5 Ma, emplacement of Hopi Buttes volcanic field begins, creates buildup of volcanic rocks in Hauke Mesa area, Hopi Lake shoreline regresses away from volcanic buildup; lacustrine sedimentation continuing - White Cone member (2) during hiatus in volcanism (6.4-4 Ma), Hopi Lake transgresses onto marginal volcanic material of Hauke Mesa - deposits lacustrine strata; second phase of eruptions (4-4.2 Ma) emplaces more volcanic rocks onto previous volcanic and lacustrine rocks; Hopi Lake attains maximum surface area ~30,000 km^2 (similar to Nations et al., 1985, Scarborough, 1989) (3) Hopi Lake continues to maintain outlet in ancestral Salt River canyon area (4) rifting slows in Rio Grande Rift (Pliocene -Chapin and Cather, 1994), rift shoulders subside, aggradation of streams forms member 6 (5) opening of Gulf of California ~5 Ma (Lucchitta, 1984), headward erosion of ancestral lower Colorado River and/or the newly developing western Grand Canyon incises Muddy Creek Formation (Lucchitta, 1984; Nations et al., 1985; Elston and Young, 1991)
5.16	Pliocene	(1) headward erosion breaches Kaibab-Coconino uplift (McKee et al., 1967; Elston and Young, 1991; Ranney, 1998) and captures Hopi Lake at present 1859 m (6100 ft) contour interval, lake drains out through Grand Canyon, lower Colorado River, empties into Gulf of California (2) draining of Hopi Lake exposes sediments to erosion; Little Colorado River system establishes and flows to join incising Grand Canyon system (3) axial drainages develop in Rio Grande Rift (Chapin and Cather, 1994), continental divide established on western rift shoulder (4) erosion removes a large portion of Bidahochi Formation and more Mesozoic and Paleozoic rocks from the southern Colorado Plateau, movement of abundant sediment form plateau assists in carving of Grand Canyon

Table 5.4 continued



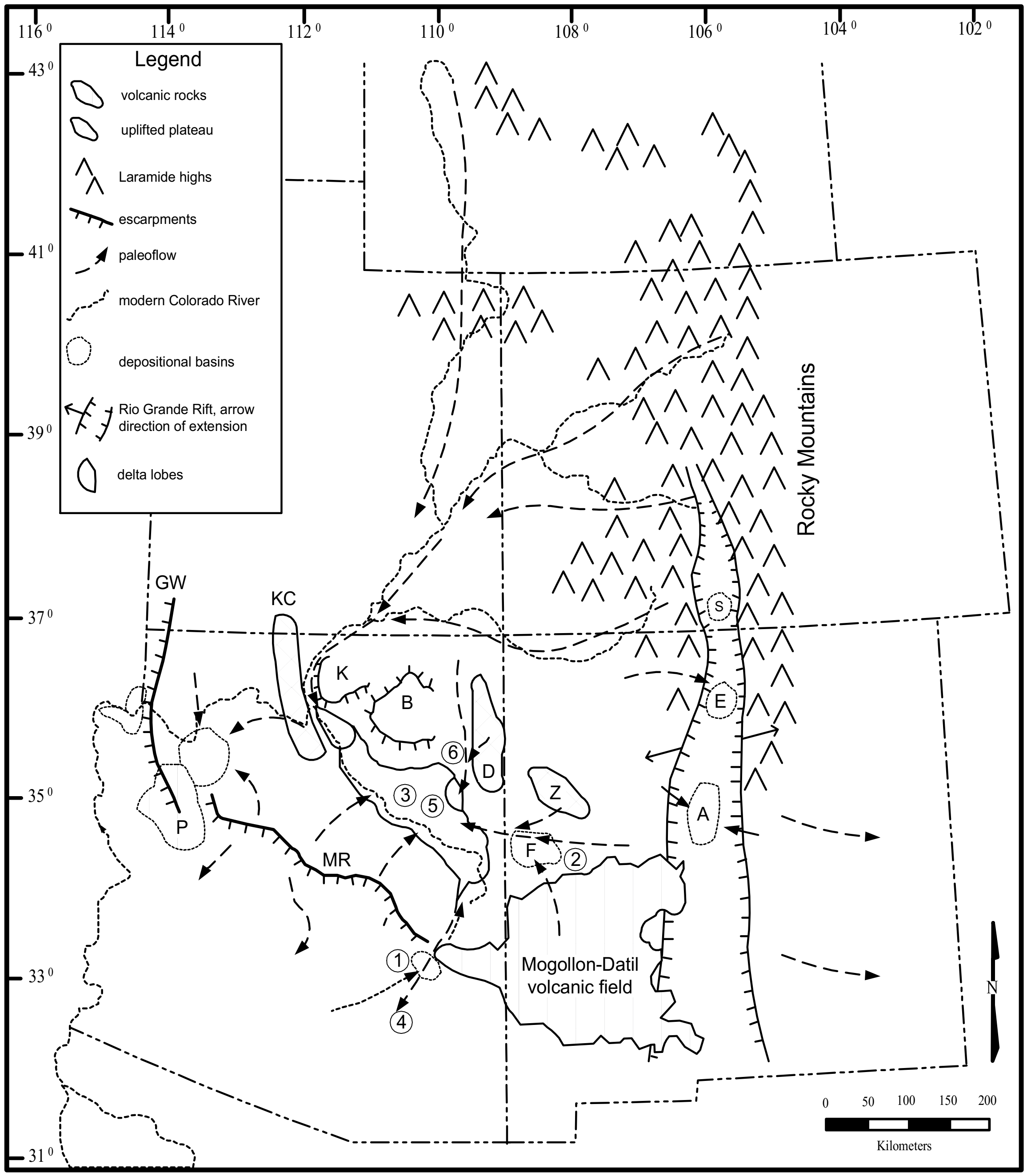
⑤ See Table 5.4 for description of events

Figure 5.13 Early Miocene paleogeographic reconstruction of the southern Colorado Plateau area. Abbreviations: KC - Kaibab-Coconino uplift; K - Kaibito Plateau; B - Black Mesa; D - Defiance uplift; Z - Zuni uplift; MR - Mogollon Rim.



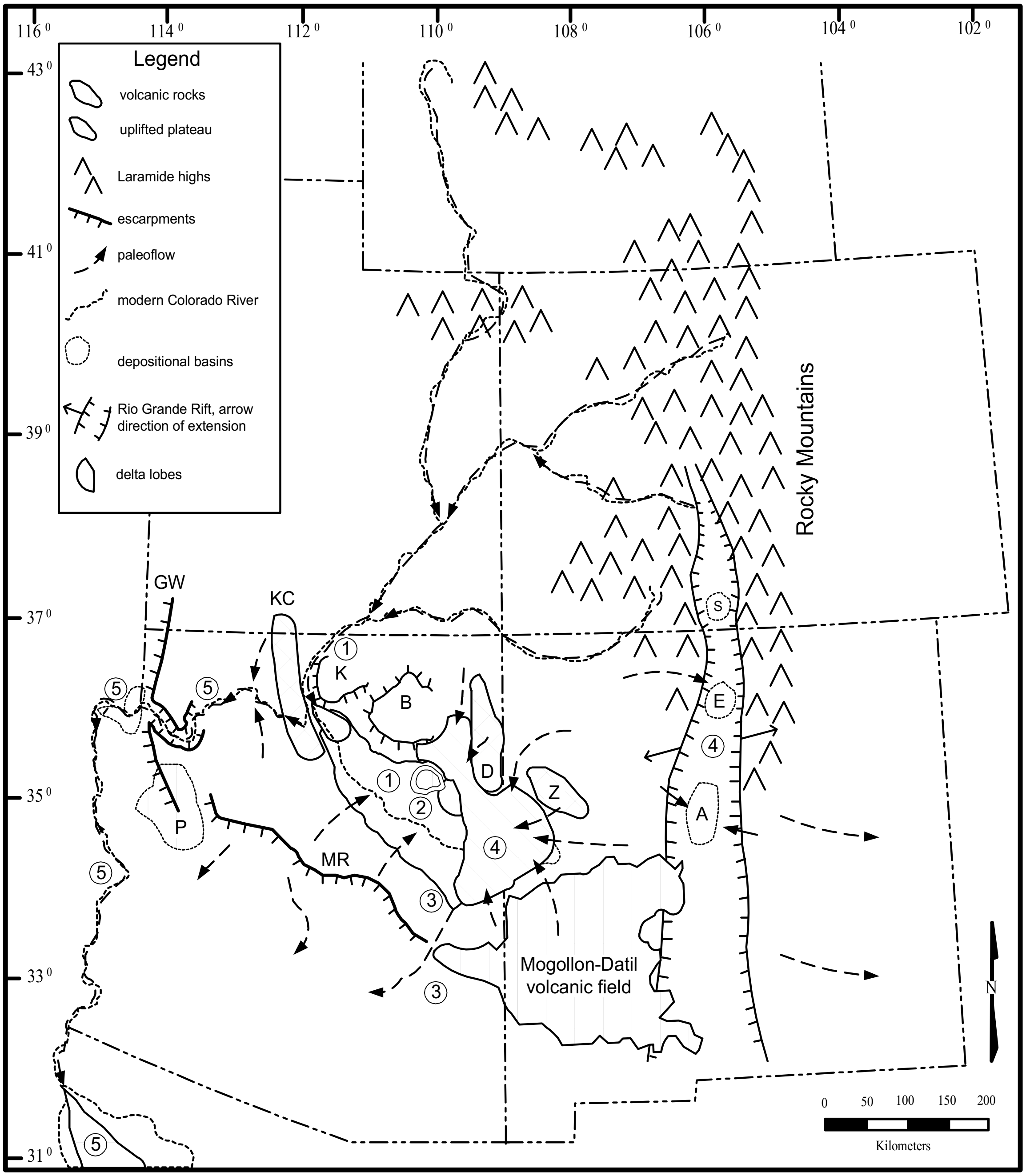
⑤ See Table 5.4 for description of events

Figure 5.14a Middle Miocene paleogeographic reconstruction of the southern Colorado Plateau area. Abbreviations: GW - Grand Wash Cliffs; KC - Kaibab-Coconino uplift; S - San Luis Basin; K - Kaibito Plateau; B - Black Mesa; E - Espanola Basin; D - Defiance uplift; Z - Zuni uplift; A - Alburquerque Basin; P - Peach Springs tuff; MR - Mogollon Rim.



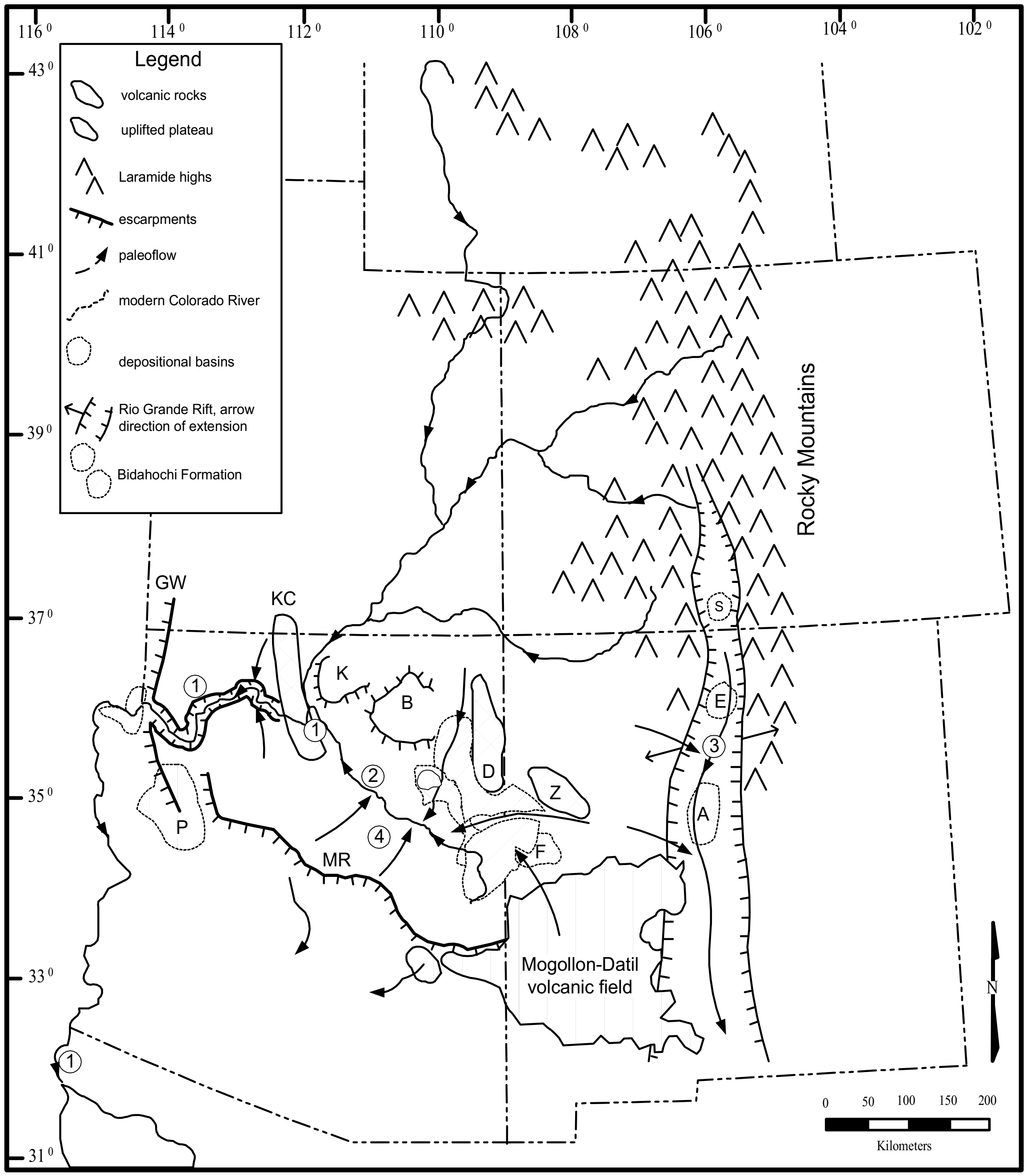
⑤ See Table 5.4 for description of events

Figure 5.14b Middle Miocene paleogeographic reconstruction of the southern Colorado Plateau area. Abbreviations: GW - Grand Wash Cliffs; KC - Kaibab-Coconino uplift; S - San Luis Basin; K - Kaibito Plateau; B - Black Mesa; E - Espanola Basin; D - Defiance uplift; Z - Zuni uplift; A - Alburquerque Basin; P - Peach Springs tuff; MR - Mogollon Rim, F - Fence Lake Fm.



⑤ See Table 5.4 for description of events

Figure 5.15 Late Miocene-Pliocene paleogeographic reconstruction of the southern Colorado Plateau area. Abbreviations: GW - Grand Wash Cliffs; KC - Kaibab-Coconino uplift; S - San Luis Basin; K - Kaibito Plateau; B - Black Mesa; E - Espanola Basin; D - Defiance uplift; Z - Zuni uplift; A - Alburquerque Basin; P - Peach Springs tuff; MR - Mogollon Rim, F - Fence Lake Fm. Member 6 probably covered larger area - not shown in order to emphasize lake size.



⑤ See Table 5.4 for description of events

Figure 5.16 Pliocene paleogeographic reconstruction of the southern Colorado Plateau area. Abbreviations: GW - Grand Wash Cliffs; KC - Kaibab-Coconino uplift; S - San Luis Basin; K - Kaibito Plateau; B - Black Mesa; E - Espanola Basin; D - Defiance uplift; Z - Zuni uplift; A - Alburquerque Basin; P - Peach Springs tuff; MR - Mogollon Rim, F - Fence Lake Fm.

Chapter 6 - Discussion

The purpose of this study was to analyze the lithostratigraphy and chronostratigraphy of the Bidahochi Formation. The goals of this research were to (1) resolve problems associated with the informal subdivisions; (2) provide a chronology for the Bidahochi Formation; (3) define the basin morphology and (4) reconstruct the Miocene-Pliocene paleogeography of northeastern Arizona. The previous chapters have provided valuable information that has helped resolve the goals of the study. This new information has also created additional questions and raised the need for further study of the Bidahochi Formation and surrounding area. The remainder of this chapter will review the success of achieving the goals of the study.

Informal Stratigraphic Subdivisions

This study has documented the problems of previous nomenclature of the Bidahochi Formation and recommended the following: (1) eliminate nomenclature of Repenning and Irwin (1954), (2) adopt modified Shoemaker et al. (1962) subdivision which uses the informal White Cone member, and (3) use member boundaries herein defined.

Additional stratigraphic study is needed. One remaining problematic area occurs in the northwestern portion of the study area near Stephen Butte. Abundant sediment input from the nearby Cretaceous strata of Black Mesa has modified the regional stratigraphy and made recognition of members 1, 3, and 4 difficult. Ash beds in this area provide little help as they are poorly exposed and difficult to correlate with those elsewhere. Geochemical analyses of the ash beds present might provide some insight.

Other problematic areas occur on the margins of the basin, especially in the Greasewood, Arizona area. Onlapping relations have been established but the members in this location show complex interfingering relations and facies changes. The ash bed at location #8 has not been satisfactorily identified or correlated. Geochemical analyses of this ash bed would probably provide some insight into the relation of member 4 with other members at this location. This ash bed may be correlative to the 13.71 Ma ash bed of member 3 and if so, would be useful in correlating the interfingering relations and facies changes in this area.

Chronologic Considerations

Onset of deposition within the basin is clearly pre-15.5 Ma, probably almost 16 Ma and extended to ~4 Ma. This documents that Hopi Lake may have existed for most of the early 9 million years of sedimentation. Lake sedimentation rates for the basin ranged from about 0.3 to 10 cm/ka.

The interbedded ash beds provide critical chronologic relations with the basin, although, further ^{40}Ar-^{39}Ar analyses and geochemical studies are needed to completely understand the age relations. Several of the interbedded ash beds are geochemically correlated to ash beds in the northern Basin and Range. The source areas for these northern Basin and Range ash beds are the southwestern Nevada or the Snake River Plain volcanic fields. A critical factor is the age of transition of the basin from lacustrine to fluvial deposition. The chronology of the fluvial and eolian member 6 has not been clearly documented and needs further study.

Another problem that needs addressing is the chronology of the Hopi Buttes volcanic field. The dozen or so reported dates from this field are inadequate to evaluate such a large (> 300 vents) volcanic field. Shafiqullah and Damon (1986b) noted that a gap in eruption activity from 6 to 4.4 Ma and suggested that this hiatus may be due to sampling bias. The two separate volcanic sequences at the northern end of Hauke Mesa and on flat tire mesa need further consideration. The 7.71 Ma date within the lower sequence places it within the time-frame of early volcanism. A date from the upper part of the sequence is necessary to determine whether or not the time gap presented above is present.

Basin Morphology

Correlation of interbedded ash beds and stratigraphic analyses enabled a reconstruction of Hopi Lake basin. Basin margins were established on the northern and eastern sides but no boundary was definable along the western and southwestern sides. This unconstrained boundary was supported by: (1) fining westward nature of the sediment packages (Plate 1), (2) correlation of Echo Spring Mountain ash bed in western locations with an ash bed near the base of the formation at Wood Chop Mesa (Figure 4.1b), (3) local butte to butte correlations of several ash beds (4) correlation of a lithic sandstone unit across the basin from southwest to northeast (Plates 1, 3), and (5) construction of a surface contour map of the base of formation (Figure 4.10). This unconstrained boundary implies that Hopi Lake extended across the modern

LCR drainage and formed a large lake with a surface area of 30,000 km^2. Substantial inflow from the surrounding basin would have been required to maintain such a lake. Based on a static water budget at maximum inundation, the southern Colorado Plateau watershed including the LCR basin could not have produced enough runoff to compensate for the annual lake evaporation rate. Therefore, the drainage basin must have been considerably larger and required major inflow from a sizeable stream system. This study supports a model that all or part of the upper Colorado River basin would fulfill this need.

The mechanism related to the formation of the Hopi Lake basin appears to be related to the accelerated phase of rifting in the Rio Grande Rift that blocked southeasterly flowing ancestral upper Colorado River. Hopi Lake depositional basin formed when the eastern end of the Laramide-aged, northwest-southeast trending structural trough was closed by the rising flanks of the Rio Grande Rift. Onset of sedimentation and accelerated rifting are in good agreement (~16 Ma). The tectonic mechanism for basin formation needs considerably more detailed analysis. This study was unable to adequately assess this topic and much of the determination was made from timing of events and regional constraints.

Regional Paleogeography

The new information presented in this study, in addition to information from previous studies, enabled a paleogeographic reconstruction for southern Colorado Plateau. This study agrees with and further documents McKee et al. s (1967) suggestion that the ancestral upper Colorado River flowed to the southeast across the plateau and into Hopi Lake. The water budget shows that a large input was necessary to maintain Hopi Lake at times of maximum inundation. The scarcity of carbonate and evaporite sediments and the dominance of clastic sediment in the Bidahochi Formation supports a large sediment-laden river or rivers contributing to the local drainages. Evidence for a southerly outflow may be present in the headwaters of the Salt River paleocanyon in east-central Arizona, but needs further assessment. Hopi Lake was captured when headward erosion incised the Kaibab-Coconino Uplift to the ~1859 m contour interval. Subsequent draining of the lake and resulting diversion of the ancestral upper Colorado River through the Kaibab-Coconino Uplift probably helped form the Grand Canyon. The Little Colorado River formed on surface of the former Hopi Lake basin deposits in response to this newly integrated drainage system and flowed to join Colorado River. Resulting erosion by the developing Little Colorado River drainage system removed most of the Bidahochi Formation.

A problem arising with paleogeographic reconstructions is the uncertainty of estimating paleoclimatic variables for Miocene-Pliocene time. The Miocene-Pliocene climatic variables are estimated based on present regional climatic conditions and from interpretation of available paleoclimatic data. These estimates could vary significantly and a thorough regional reevaluation of available paleoclimatic data for the Colorado Plateau area should be assessed.

Several key caveats are worth noting with this paleogeographic interpretation: (1) most of the evidence for these events has been removed by erosion from the surface of the Colorado Plateau making interpretations subjective, (2) any study of this nature is subject to the author s interpretation and biases about the area and previous workers interpretations, and (3) the main purpose of this type of study is to elicit further debate and research on this topic. Further study is crucial to understand the paleogeographic events of this region.

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Appendix A - Methods for Sample Preparation and Calculations

Measured Sections

Twenty-nine measured sections were completed across the extent of the study area. These sections were measured using a Jacob staff and metric tape measure. The attitude of the beds was determined primarily from bedding planes exposed within ash bed units. Clastic units were measured to the nearest 5 cm with a Jacob staff and tephra units were measured to the nearest 1 cm using the tape measure. Lithologic descriptions and weathering profiles were recorded for each unit. A handheld Global Positioning System (G.P.S.) was used to determine latitude and longitude at each measured section location. A pocket altimeter was used to take elevation measurements at various ash horizons and the basal contact of the formation where exposed. Color was either physical determined by personal perception or by using the abbreviated version of the Munsell Color Chart distributed by the Geological Society of America. The lithologic columns were created using a computer program called Visio Technical 5.0. Samples of interbedded tephra and distinctive clastic units, including claystone, were collected for isotopic, petrographic, and X-ray diffraction analyses.

Tephra Analyses

Thin sections of tephra units were prepared from grain mounts (Table A.1). The thin sections of the tephra samples were analyzed petrographically for mineral content, glass shard morphology, degree of alteration, and other textural characters. These petrographic criteria, in addition to other geochemical analyses were used to characterize individual tephra units for use as correlation tools and to establish chronohorizons across the basin.

Several samples were sent to Bill McIntosh at New Mexico Geochronology Research Laboratory in Socorro, New Mexico for ^{40}Ar-^{39}Ar analyses. The target mineral was sanidine, but biotite was also used.

Samples were sent to Michael Perkins at the University of Utah for geochemical analyses of the glass shards. The samples were analyzed by an electron microprobe and the major oxides were reported (Appendix D). A minimum of 20 individual shards were analyzed per sample and averages were calculated. The average oxide wt-% were compared to the database compiled by Perkins and collogues to look for distinctive geochemical signatures of eruptive volcanic centers that could have provided the source for the tephras in the Bidahochi Formation.

Table A.1 Grain mount preparation steps:

1) The sample is dried, if necessary, on a hot plot set at lowest setting.

2) The sample is then disaggregated, if necessary, by using a mortar and pestle.

3) The sample is placed in labeled ice cube trays treated with a bond releasing agent and filled with enough epoxy to make a thick slurry (~60% sample, 40% epoxy). Care should be taken not to use to much epoxy so that preferential settling of heavier constituents occurred.

4) After epoxy set, the sample is popped out of trays and labeled. The bottom 2 mm of the sample is cut off using the trim blade on a Hillquist machine. The sample is then polished on a lap wheel, mounted to a glass slide, and prepared according to standard thin section preparation.

Clastic Units

Thin sections of clastic units were prepared from grain mounts (Table A.1). The thin sections of the clastic samples were analyzed petrographically for mineral content and textural characters. These petrographic criteria, in addition to stratigraphic relations were used as correlation tools and for determining potential provenance areas.

Various claystone samples were analyzed by X-ray diffraction to determine the type(s) of clay present (Table A.2). These analyses were conducted to see if color could be used as a correlation tool. Clays were identified using Moore and Reynolds (1997) by comparing the Angstroms and shape of the peaks on 001, 002, 003, and 004 planes of the oriented samples and the 2 location of the peak.

Table A.2 Sample Preparation steps for X-ray diffraction analyses:

1) The sample is dried, if necessary, on a hot plate set at lowest setting.

2) The sample is then pulverized in a shatter box to a fine powder.

3) Distilled water and trisodium phosphate (dispersing agent so clays would not flocculate) is added to the sample.

4) The sample is placed in a sonic agitator for 5 minutes to break up remaining bonds between clays and to separate floccculates.

5) The sample is then placed in a centrifuge and spun for 5 minutes at 500 RPM to separate the 2 micron and smaller fraction.

6) The 2 micron supernatant is decanted off. A portion of this sample was then placed on a microscope slide and allowed to dry overnight.

7) The sample is then placed in the X-ray diffraction machine. The 2 angle was set to run between 2 and 35 with a step of 0.02 and one second duration between readings.

8) The resulting diffraction pattern is plotted and the d spacing of the peaks was used to identify the clay minerals present.

Decompaction Calculations

Several clastic intervals were decompacted to infer sedimentation rates within the Bidahochi Formation. The steps used to decompact the selected interval (interval between two established chronohorizons) are listed in Table A.3. The decompaction method follows that of van Hinte (1978). Steps and procedures following below.

Table A.3 Decompaction steps:

1) The thicknesses of the overlying sediments and the clastic interval are calculated from the measured sections in Appendix B.

2) The following values were estimated*: 1) the porosity of lithology at surface conditions ($_{lith}$) and 2) porosity-depth coefficient (c).

3) The midpoint interval (z) is determined by the adding the overlying thickness to half of the thickness of the clastic interval in question.

4) These values are placed into the following equation to determine the porosity at this interval after backstripping one layer. $_{s\#}$ is porosity calculated at present conditions (# refers to step number in sequence).

$$_{s\#} = \ _{lith}\, e^{-cz}$$

5) The following equation is used to calculate the porosity at this level with one level backstripped off. Z is now the midpoint of the clastic interval thickness plus any remaining overlying layers. $_{lith}$ and c always remain the same throughout (lithology dependent). $_{s\#}$ is porosity calculated at this interval with one level backstripped off.

$$_{s\#} = \ _{lith}\, e^{-cz}$$

6) The decompacted thickness is now calculated using the values obtained above and the following equation. $T_{s\#}$ is thickness of this unit at step (#) with one level removed. $T_{s\#-1}$ is thickness of previous step.

$$T_{s\#} = (1 - \ _{s\#}) * T_{s\#-1}/(1 - \ _{s\#})$$

7) If more layers occur below, steps 5 and 6 are repeated for each layer that has to be backstripped off to get back to original depositional conditions.

* - Estimates are based on data from Sclater and Christie (1980). The plot in Figure A.1 shows the porosity vs. depth relations. Values used in this study: $_{lith}$=0.6

claystone/mudstone, $_{lith}$=0.55 siltstone, c=5.0x10^{-4} m^{-1} claystone/mudstone, c=4.0x10^{-4} m^{-1} siltstone.

The following steps were used to decompact 5 clastic intervals at Wood Chop Mesa. Figure 4.13 lists the accompanying values for each of the steps used in the decompaction analysis.

Level 4 Step 1: (backstrip level 5)
$_{s1}$ = $_{lith}$ e^{-cz} $_{lith}$ = 0.55, c = 4.5x10^{-4} m^{-1}, z_1 = 30.4 m
$_{s1}$ = 0.543 (54.3%)
Step 2:
$_{s2}$ = $_{lith}$ e^{-cz} $_{lith}$ = 0.55, c = 4.5x10^{-4} m^{-1}, z_2 = (20.8/2) = 10.4 m
$_{s2}$ = 0.547 (54.7%)

T_{s2} = (1- $_{s1}$) x T_{s1} / (1 - $_{s2}$) T_{s1} = 20.8 m
T_{s2} = 21.0 m

Level 3 Step 1: (backstrip level 4)
$_{s1}$ = $_{lith}$ e^{-cz} $_{lith}$ = 0.55, c = 4.5x10^{-4} m^{-1}, z_1 = 44.3 m
$_{s1}$ = 0.539 (53.9%)
Step 2:
$_{s2}$ = $_{lith}$ e^{-cz} $_{lith}$ = 0.55, c = 4.5x10^{-4} m^{-1}, z_2 = (7.0/2) + 21.0 = 24.5 m
$_{s2}$ = 0.544 (54.4%)

T_{s2} = (1- $_{s1}$) x T_{s1} / (1 - $_{s2}$) T_{s1} = 7.0 m
T_{s2} = 7.1 m
Step 3:
$_{s3}$ = $_{lith}$ e^{-cz} $_{lith}$ = 0.55, c = 4.5x10^{-4} m^{-1}, z_3 = (7.1/2) = 3.55 m
$_{s3}$ = 0.549 (54.9%)

T_{s3} = (1- $_{s2}$) x T_{s2} / (1 - $_{s3}$) T_{s2} = 7.1 m
T_{s3} = 7.2 m

Level 2 Step 1: (backstrip level 3)
$_{s1}$ = $_{lith}$ e^{-cz} $_{lith}$ = 0.6, c = 5.0x10^{-4} m^{-1}, z_1 = 71.0 m
$_{s1}$ = 0.579 (57.9%)
Step 2:
$_{s2}$ = $_{lith}$ e^{-cz} $_{lith}$ = 0.6, c = 5.0x10^{-4} m^{-1}, z_2 = (46.4/2)+7.1+21.0 = 51.3 m
$_{s2}$ = 0.585 (58.5%)

T_{s2} = (1- $_{s1}$) x T_{s1} / (1 - $_{s2}$) T_{s1} = 46.4 m
T_{s2} = 47.0 m
Step 3:
$_{s3}$ = $_{lith}$ e^{-cz} $_{lith}$ = 0.6, c = 5.0x10^{-4} m^{-1}, z_3 = (47.0/2)+7.2 = 30.7 m
$_{s3}$ = 0.591 (59.1%)

T_{s3} = (1- $_{s2}$) x T_{s2} / (1 - $_{s3}$) T_{s2} = 47.0 m
T_{s3} = 47.7 m
Step 4:
$_{s4}$ = $_{lith}$ e^{-cz} $_{lith}$ = 0.6, c = 5.0x10^{-4} m^{-1}, z_4 = (47.7/2) = 23.85 m
$_{s4}$ = 0.593 (59.3%)

$T_{s4} = (1- \quad {}_{s3}) \times T_{s3} / (1 - \quad {}_{s4})$ $\qquad T_{s3} = 47.7$ m
$T_{s4} = 48.0$ m

Level 1 Step 1: (backstrip level 2)
${}_{s1} = \quad {}_{lith}\, e^{-cz}$ $\qquad {}_{lith} = 0.6$, $c = 5.0 \times 10^{-4}$ m^{-1}, $z_1 = 104.85$ m
${}_{s1} = 0.569$ (56.9%)
Step 2:
${}_{s2} = \quad {}_{lith}\, e^{-cz}$ $\qquad {}_{lith} = 0.6$, $c = 5.0 \times 10^{-4}$ m^{-1}, $z_2 = (21.3/2)+47.0+7.1+21.0 =$ 85.75 m
${}_{s2} = 0.575$ (57.5%)

$T_{s2} = (1- \quad {}_{s1}) \times T_{s1} / (1 - \quad {}_{s2})$ $\qquad T_{s1} = 21.3$ m
$T_{s2} = 21.6$ m
Step 3:
${}_{s3} = \quad {}_{lith}\, e^{-cz}$ $\qquad {}_{lith} = 0.6$, $c = 5.0 \times 10^{-4}$ m^{-1}, $z_3 = (21.6/2)+47.7+7.2 = 65.7$ m
${}_{s3} = 0.581$ (58.1%)

$T_{s3} = (1- \quad {}_{s2}) \times T_{s2} / (1 - \quad {}_{s3})$ $\qquad T_{s2} = 21.6$ m
$T_{s3} = 21.9$ m
Step 4:
${}_{s4} = \quad {}_{lith}\, e^{-cz}$ $\qquad {}_{lith} = 0.6$, $c = 5.0 \times 10^{-4}$ m^{-1}, $z_4 = (21.9/2)+48.0 = 58.95$ m
${}_{s4} = 0.583$ (58.3%)

$T_{s4} = (1- \quad {}_{s3}) \times T_{s3} / (1 - \quad {}_{s4})$ $\qquad T_{s3} = 21.9$ m
$T_{s4} = 22.0$ m
Step 5:
${}_{s5} = \quad {}_{lith}\, e^{-cz}$ $\qquad {}_{lith} = 0.6$, $c = 5.0 \times 10^{-4}$ m^{-1}, $z_5 = (22.0/2) = 11.0$ m
${}_{s5} = 0.597$ (59.7%)

$T_{s5} = (1- \quad {}_{s4}) \times T_{s4} / (1 - \quad {}_{s5})$ $\qquad T_{s4} = 22.0$ m
$T_{s5} = 22.7$ m

Water Budget

A water budget was calculated for Lake Hopi by using the reconstructed basin morphology and estimating rainfall, runoff, evaporation, and outflow needed to sustain a fresh-water lake. The size of Hopi Lake is determined by tracing the modern elevation of 6100 ft (1859 m) contour line around northeastern Arizona on the U.S. Geological Survey 1:500,000 scale topographic map. The area is estimated for this lake level using the bar scale from the topographic map and developing a grid system overlay to determine km^2 coverage. The potential Miocene-Pliocene drainage basin was estimated based on the current area of the southeastern portion of the Colorado Plateau and the km^2 coverage was estimated from Figure 4.13. Average rainfall is based on previous paleoclimatic studies of this region (Schmidt, 1991) and modern values. Values for runoff and evaporation are estimated for the drainage basin based on modern analogs.

The water budget was calculated based on the amount of runoff available from the basin reconstruction minus evaporation. This water budget value was compared to lake volume calculations to see if there is enough runoff available to keep this lake volume constant through time and to keep the lake from becoming saline.

Calculations

Total annual volume potential available to Hopi Lake using the LCR basin watershed:

$A_{vp} = P \times B_a$ (a)
(A_{vp}) annual volume potential
(P) is annual precipitation
(B_a) basin watershed area
$A_{vp} = 30\ cm/yr \times 1\ km/\ 100{,}000\ cm \times 69{,}800\ km^2$
$A_{vp} = 21\ km^3$

Total annual volume potential available to Hopi Lake using the southern Colorado Plateau watershed:

$A_{vp} = P \times B_a$ (a)
$A_{vp} = 30\ cm/yr \times 1\ km/\ 100{,}000\ cm \times 115{,}000\ km^2$
$A_{vp} = 35\ km^3$

Runoff volume potential entering Hopi Lake using the LCR basin watershed:

$R_{vp} = R_r \times (B_a - L_a)$ (b)
(R_{vp}) runoff volume potential
(R_r) annual runoff rate
($B_a - L_a$) basin watershed area minus lake surface area
$R_{vp} = 8\ cm/yr \times 1\ km/\ 100{,}000\ cm \times (69{,}800\ km^2 - 30{,}000\ km^2)$
$R_{vp} = 3\ km^3$

Runoff volume potential entering Hopi Lake using the southern Colorado Plateau watershed:

$R_{vp} = R_r \times (B_a - L_a)$ (b)
$R_{vp} = 8\ cm/yr \times 1\ km/\ 100{,}000\ cm \times (115{,}000\ km^2 - 30{,}000\ km^2)$
$R_{vp} = 7\ km^3$

Potential annual lake volume loss:

$L_{wl} = E_r \times L_a$ (c)
(L_w) lake volume loss
(E_r) evaporation rate of lake
(L_a) lake surface area
$L_{wl} = 110\ cm/yr \times 1\ km/\ 100{,}000\ cm \times 30{,}000\ km^2$
$L_{wl} = 33\ km^3$

Final volume potential change to Hopi Lake using the LCR basin watershed:

$F_{vp} = R_r \times (B_a - L_a) + (P \times L_a) - (E_r \times L_a)$ (d)
(F_{vp}) the final volume potential change to lake

(R_r) annual runoff rate
(B_a - L_a) basin watershed area minus the lake surface area
(P x L_a) the precipitation falling on the lake surface area
(E_r x L_a) evaporation rate times the lake area

F_{vp} = 8 cm/yr x 1 km/ 100,000 cm x (69,800 km^2 - 30,000 km^2) + (30 cm/yr x 1 km/ 100,000 cm x 30,000 km^2) - (110 cm/yr x 1 km/ 100,000 cm x 30,000 km^2)

F_{vp} = -21 km^3

Final volume potential change to Hopi Lake using the southern Colorado Plateau watershed:

F_{vp} = R_r x (B_a - L_a) + (P x L_a) - (E_r x L_a) (d)

F_{vp} = 8 cm/yr x 1 km/ 100,000 cm x (115,000 km^2 - 30,000 km^2) + (30 cm/yr x 1 km/ 100,000 cm x 30,000 km^2) - (110 cm/yr x 1 km/ 100,000 cm x 30,000 km^2)

F_{vp} = -17 km^3

Final volume potential change to Hopi Lake using the upper Colorado River basin and the LCR basin watershed:

F_{vp} = R_r x (B_a - L_a) + (P x L_a) - (E_r x L_a) (d)

F_{vp} = 8 cm/yr x 1 km/ 100,000 cm x (69,800 km^2 + 280,000 km^2 - 30,000 km^2) + (30 cm/yr x 1 km/ 100,000 cm x 30,000 km^2) - (110 cm/yr x 1 km/ 100,000 cm x 30,000 km^2)

F_{vp} = +2 km^3

Appendix B - Measured Sections

This appendix contains all the descriptive data for the measured sections used in this study. Lithologic representations of each measured section can be found on either Plates 1 and 2, Figure 2.9, or at the end of this appendix. See Appendix A and text for methods of data collecting and descriptors used. The measured sections were named based on geographic features, local land holder names, or other determinations. The number (B-17) of each measured section corresponds to the location number on Figure 2.2.

Appendix B-1

Location 1 on Figure 2.2 (Stephen Butte section)

Measured by Jacob staff and tape measure on July 24, 1997

Field Assistant: Carey Lang

Location: Hopi Reservation, Jeddito Spring 7.5' Quadrangle, N 35° 38.004' by W 110° 10.973' Located on north end of mesa where sediments are exposed on northeast corner. Included ash bed at road cut on the way to section. The rest of the section starts in the multi-colored clays and moves up along the east facing slope.

Outcrop Attitude: No significant dip to beds measured flat

Measured bottom up

#1 Stephen Butte	Meters
Cliff to top of mesa, no further exposure	
Unit 55 - Mafic lava: N 1 black both surfaces, aphanitic, rubbley base. Unit weathers to cliff.	6+
Unit 54 - Mafic tuff: 5Y 5/2 light olive gray both surfaces, clast supported, little or no matrix, contains large (up to boulder size) mafic bombs, calcite amygdules, lower 3 m medium bedded and rest of unit is thick bedded to structureless. Unit weathers to ledges. Contact sharp with 55.	11.8
Unit 53 - Breccia: N 5 medium gray both surfaces, granules to pebbles, clast supported, mafic with some wall rock lithologies present, calcareous, fines upward, sharply thin-bedded. Unit weathers to cliff. Contact gradational with 54 noted by a depositional change.	3.3
Unit 52 - Tuff sandstone: 10YR 5/4 moderate yellowish-brown both surface, contains large clasts of mafic lava and lower units including Wingate Fm, calcareous, moderately indurated, no primary structure apparent - beds jumbled and rotated out of place. Unit weathers to cliff. Contact undulatory with 53.	6 to 9
Unit 51 - Silty claystone: 10YR 7.5/4 grayish-orange fresh surface, 10YR 5/4 moderate yellowish-brown, more green colored at top, calcareous, structureless, blocky fracture. Very silt rich at upper 0.5 m with abundant Hopi Buttes volcanic material present. Unit partially covered by colluvium. Contact scour with 52.	5.5
contact members 4/5 at 5 m from base of 51	
Unit 50 - Sandstone: 5Y 8/1 yellowish-gray both surfaces, very fine-grained, quartzose, very calcareous, structureless. Unit covered in slope. Contact sharp with 51. Sample #970724K.	0.25
Unit 49 - Claystone: 10YR 7.5/4 grayish-orange fresh surface, 10YR 5/4 moderate yellowish-brown, more green colored at top, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 50.	5.8
Unit 48 - Sandstone: 10YR 7.5/4 grayish-orange both surfaces, very fine-grained, quartzose, weakly calcareous, friable, structureless. Unit weathers to calcified slope. Contact sharp with 49.	0.6

Unit 47 - Claystone: 5YR 5/6 light brown fresh surface, 5YR 5.5/4 light brown, more red colored at top, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 48. 4.1

Unit 46 - Interbedded claystone and sandstone. Claystone: 10Y 4/4 light grayish olive fresh surface, very calcareous, structureless, slightly shaley. Sandstone: 10YR 7.5/4 grayish-orange both surfaces, very fine-grained, quartzose, weakly calcareous, friable, structureless. Bed thicknesses vary but sandstone dominants. Unit weathers to slope. Contact sharp with 47. 1.7

contact members 3/4

Unit 45 - Sandstone: 10YR 7.5/4 grayish-orange both surfaces, very fine-grained, quartzose, weakly calcareous, friable, structureless. Unit weathers to calcified slope. Contact sharp with 46. 2.5

Unit 44 - Sandy micritic limestone (marl): N9 white both surfaces, structureless. Unit weathers to ledge. Contact sharp with 45. Sample #970724J. 0.07

Unit 43 - Sandstone: 10YR 7.5/4 grayish-orange both surfaces, very fine-grained, quartzose, mafic minerals minor, weakly calcareous, friable, structureless. Unit weathers to calcified slope. Contact sharp with 44. 1.6

Unit 42 - Claystone: N9 white and green fresh surfaces, calcareous, structureless. White claystone occurs between two green claystone units. Middle unit may be tuffaceous. Unit weathers to slope. Contact sharp with 43. 0.06

Unit 41 - Sandstone: 10YR 7.5/4 grayish-orange both surfaces, very fine-grained, quartzose, weakly calcareous, friable, structureless. Unit weathers to slope. Contact sharp with 42. 0.16

Unit 40 - Sandstone fining upwards to siltstone then to claystone. Sandstone: 5Y 8/3 grayish-yellow both surfaces, very fine-grained, mafic minerals abundant, weakly calcareous, friable, planar cross-bedded. Siltstone: 5Y 8/3 grayish-yellow both surfaces, calcareous, structureless. Claystone: 5Y 8/3 grayish-yellow both surfaces, calcareous, structureless, blocky fracture. Unit fines to siltstone at 0.65 m and claystone at 1.1 m. Unit weathers to ledge. Contact sharp with 41. Sample #970724I of sandstone. 3.25

contact members 2/3

Unit 39 - Siltstone fining upwards into silty claystone. Siltstone: 5Y 8/1 yellowish-gray both surfaces, slightly sandy, mafic minerals abundant, calcareous, structureless. Silty claystone: 5Y 3.5/2 olive gray fresh surface, 5Y 8/1 yellowish-gray weathered surface, calcareous, structureless. Unit weathers to slope. Contact sharp with 40. 2.05

Unit 38 - Claystone: 5Y 3.5/2 olive gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, iron-oxide staining minor, slightly silty, very calcareous, sparkles, weakly laminated. Unit weathers to popcorn slope. Contact sharp with 39. 2.8

Unit 37 - Silty sandstone and sandstone. Silty sandstone: 10YR 8/3 pale grayish-orange both surfaces, very fine-grained, quartzose, slightly calcareous, friable, structureless. Sandstone: 10Y 8/2 pale greenish yellow both surfaces, fine-grained, moderately sorted, well rounded, weakly calcareous, structureless. Iron-oxide staining common above 0.9 m. Unit coarsens to sandstone at 0.9 m from base then fines back to silty sandstone 1.1 m from base. Unit weathers to calcified slope. Contact sharp with 38. 1.3

Unit 36 - Claystone: 5Y 3.5/2 olive gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, iron-oxide staining minor, very calcareous, weakly laminated. Unit weathers to popcorn slope. Contact sharp with 37. 0.03

Unit 35 - Claystone: 5Y 8/1 yellowish-gray fresh surface, tuffaceous, calcareous, weakly laminated. Unit covered in slope. Contact sharp with 36. 0.02

Unit 34 - Claystone: 5Y 3.5/2 olive gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, iron-oxide staining minor, very calcareous, weakly laminated. Unit weathers to popcorn slope. Contact sharp with 35. 1.1

Unit 33 - Ash bed and claystone. Blue-gray #3 ash bed: N9 white at base, felsic, calcareous, structureless. Claystone: 5Y 3.5/2 olive gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, very calcareous, weakly laminated. Claystone is mixed with ash in middle of unit. Unit weathers to popcorn slope. Contact gradational with 34 due to reworked nature of ash bed. Sample #970724H of ash near base. 0.5

Unit 32 - Silty claystone: 5Y 5/2 light olive gray fresh surface, 5Y 7.5/2 light olive gray weathered surface, calcareous, sparkles, structureless, blocky fracture. At 1.6 m iron-oxide staining common. Unit weathers to popcorn slope. Contact gradational with 33 noted by a mixed zone of sand and clay. 2.05

Unit 31 - Silty sandstone: 10YR 8/3 pale grayish-orange both surfaces, very fine-grained, quartzose, friable, structureless. Unit weathers to slope. Contact sharp with 32. 0.11

Unit 30 - Silty claystone: 5Y 5/2 light olive gray fresh surface, 5Y 7.5/2 light olive gray weathered surface, calcareous, sparkles, structureless, blocky fracture. Unit weathers to popcorn slope. Contact gradational with 31 noted by a mixed zone of sand and clay. 1.0

Unit 29 - Silty sandstone: 10YR 8/3 pale grayish-orange both surfaces, very fine-grained, friable, structureless. Unit weathers to slope. Contact sharp with 30. 1.4

Unit 28 - Silty claystone: 5Y 5/2 light olive gray fresh surface, 5Y 7.5/2 light olive gray weathered surface, calcareous, sparkles, structureless, blocky fracture. Unit weathers to popcorn slope. Contact gradational with 29 noted by a mixed zone of sand and clay. 2.45

Unit 27 - Sandstone: 5Y 8/1 yellowish-gray fresh surface, 10YR 7.5/4 grayish orange weathered surface, fine-grained, well sorted, rounded, very calcareous, well indurated, thin-bedded planar-tabular. Unit weathers to ledge. Contact sharp with 28. 0.19

Unit 26 - Sandstone and claystone. Sandstone: 10YR 8/4 pale grayish-orange fresh surface, very fine-grained, quartzose, friable, weakly planar cross-bedded. Claystone: 10Y 6/2 pale olive fresh surface, 10Y 8/2 pale yellowish-green weathered surface, slightly silty, very calcareous, structureless, blocky fracture. Claystone bed (40 cm thick) occurs at 0.4 m from base. Unit weathers to slope. Contact gradational with 27 noted by a change in degree of induration. 6.4

transferred s along ash to face of mesa

Unit 25 - Member 2 felsic ash bed: N9 white both surfaces, felsic, vitric, bentonized, calcareous, laminated. Unit weathers to ledge. Contact sharp with 26. Sample #970724G. 0.13

Unit 24 - Sandstone: 10YR 8/4 pale grayish-orange fresh surface, very fine-grained, quartzose, friable, structureless. Unit weathers to slope. Contact sharp with 25. 0.6

Unit 23 - Sandstone: 5Y 8/1 yellowish-gray fresh surface, 10YR 7.5/4 grayish orange weathered surface, fine-grained, well sorted, rounded, very calcareous, very well indurated, structureless. Unit weathers to ledge. Contact gradation with 24 noted by a color change and degree of induration.	0.04
Unit 22 - Sandstone: 10YR 8/4 pale grayish-orange fresh surface, very fine-grained, quartzose, friable, structureless. Unit weathers to slope. Contact gradation with 23 noted by a color change and degree of induration.	1.7
Unit 21 - Sandstone: 5Y 8/1 yellowish-gray fresh surface, 10YR 7.5/4 grayish orange weathered surface, fine-grained, poorly sorted, rounded, very calcareous, very well indurated, structureless. Unit weathers to ledge. Contact gradation with 22 noted by a color change and degree of induration. Sample #970724F.	0.19
Unit 20 - Sandstone: 10YR 8/4 pale grayish-orange fresh surface, fine-grained, well sorted, rounded, quartzose, friable, structureless. Unit weathers to slope. Contact gradation with 21 noted by a color change and degree of induration.	1.15
Unit 19 - Claystone: 10Y 6/2 pale olive fresh surface, 10Y 8/2 pale yellowish-green weathered surface, slightly silty, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 20.	1.2
Unit 18 - Sandstone: 10YR 8/4 pale grayish-orange fresh surface, fine-grained, well sorted, rounded, quartzose, friable, weakly cross-bedded. Unit weathers to slope. Contact sharp with 19.	0.2
Unit 17 - Sandstone: 10YR 8/1 yellowish-gray both surfaces, very fine-grained, very calcareous, well indurated, single bed. Unit covered in slope. Contact gradational with 18 noted by a color change and degree of induration.	0.05
Unit 16 - Sandy siltstone: 10Y 6/2pale olive fresh surface, 10Y 8/2 pale greenish-yellow weathered surface, contains very fine-grained sand, weakly calcareous, structureless. Unit weathers to slope. Contact sharp with 17.	0.45
Unit 15 - Wood Chop A ash bed: 10YR 8/2 very pale orange both surfaces, silty, calcareous, structureless. Unit weathers to ledge. Contact sharp with 16. Sample # 970724E.	0.2
Unit 14 - Sandy siltstone: 10Y 6/2pale olive fresh surface, 10Y 8/2 pale greenish-yellow weathered surface, contains very fine-grained sand, weakly calcareous, structureless. Unit weathers to slope. Contact sharp with 15.	0.85
Unit 13 - Sandstone: 10YR 8/4 pale grayish-orange fresh surface, fine-grained, well sorted, rounded, quartzose, friable, weakly cross-bedded. Unit weathers to slope. Contact gradational with 14 noted by a color change.	0.55
Unit 12 - Siltstone fining upwards to claystone. Siltstone: 5Y 8/1 yellowish-gray both surfaces, weakly calcareous, structureless. Claystone: 5Y 7/2 yellowish-gray fresh surface, 10YR 7.5/5 pale grayish-orange weathered surface, very calcareous, structureless, blocky fracture. Unit has abundant iron-oxide staining throughout. Unit fines to claystone 15 cm from base. Above 1 meter unit becomes dark claystone: 10YR 4/4 dark yellowish brown fresh surface, 10YR 6.5/5 gray yellowish-orange weathered surface, calcareous, structureless, blocky fracture. At 3.2 m unit contains a 26 cm zone of sandy siltstone mixed with surrounding claystone. Unit weathers to popcorn slope. Contact sharp with 13. Sample # 970724D of upper claystone.	4.2

Unit 11 - Interbedded sandstone and claystone. Sandstone: 10YR 8/4 pale grayish-orange fresh surface, fine-grained, well sorted, rounded, quartzose, friable, structureless. Claystone: 10Y 6/2 pale olive fresh surface, 10Y 8/2 pale yellowish-green weathered surface, slightly silty, very calcareous, structureless, blocky fracture. Unit has less sandstone layers near top. Iron-oxide staining common throughout unit. Unit weathers to slope. Contact sharp with 12.	2.1
Unit 10 - Sandstone: 10YR 8/1 yellowish-gray both surfaces, very fine-grained, very calcareous, well indurated, single bed. Unit covered in slope. Contact sharp with 11.	0.04
Unit 9 - Sandstone and claystone. Sandstone: 10YR 8/4 pale grayish-orange fresh surface, fine-grained, well sorted, rounded, quartzose, friable, structureless. Claystone: 10Y 6/2 pale olive fresh surface, 10Y 8/2 pale yellowish-green weathered surface, slightly silty, very calcareous, structureless, blocky fracture. Two claystone layers occur at 0.21 m (2 cm thick) and 1.6 m (45 cm). At 2.5 m unit is weakly trough cross-bedded. Unit has random areas of nodular, well cemented sandstone. Unit weathers to slope with some ledges. Contact sharp with 10. Sample #970724C of sandstone.	4.25
Unit 8 - Siltstone: 5Y 8/1 yellowish-gray both surfaces, mafic minerals common, very calcareous, well indurated, sparkles - tuffaceous?, single bed. Unit weathers to ledge. Contact sharp with 9. Sample #970724B.	0.05
Unit 7 - Claystone: 10Y 6/2 pale olive fresh surface, 10Y 8/2 pale yellowish-green weathered surface, slightly silty, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 8.	2.1
Unit 6 - Sandstone: 10YR 8/4 pale grayish-orange both surfaces, fine-grained, well sorted, rounded, quartzose, contains iron-oxide staining, friable, structureless. Unit contains a small layer (15 cm thick) of sandstone that contains abundant mafic minerals, is very calcareous, well indurated, and weakly laminated. Iron-oxide stained zones occur 28 cm from base (35 cm thick) and above the well indurated sandstone (16 cm thick). Unit weathers to slopes and ledge. Contact sharp with 7. Sample #971003J.	1.14
Unit 5 - Interbedded claystone and sandy siltstone. Claystone: 10Y 6/2 pale olive fresh surface, slightly silty, very calcareous, structureless, blocky fracture. Sandy siltstone: 10YR 7/4 grayish orange fresh surface, contains very fine-grained sand, calcareous, structureless. Unit has small sandstone layers of unit 4 that intertongue with claystone at base. Five sandy siltstone layers occur at 2.1 m (8 cm thick), 2.5 m (30 cm), 3.2 m (19 cm), 3.7 m (8 cm), 4 m (16 cm). Unit weathers to popcorn slope with weathered surface of 10YR 7.5/2 very pale yellowish-orange. Contact sharp with 6. Sample #970724A of claystone.	4.3
Unit 4 - Silty sandstone coarsening upwards to sandstone. Silty sandstone: 10YR 7/4 grayish orange fresh surface, 10YR 8/4 gray yellowish-orange weathered surface, very fine-grained, calcareous, structureless. Sandstone: 10YR 7/4 grayish orange fresh surface, 10YR 8/4 gray yellowish-orange weathered surface, fine-grained, moderately sorted, subrounded, calcareous, structureless. Unit weathers to break in slope. Contact gradational with 5 noted by interfingering relations.	0.2
Unit 3 - Claystone: 10Y 6/2 pale olive fresh surface, 10Y 8/2 pale yellowish-green weathered surface, slightly silty, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 4.	0.2
Unit 2 - Sandy siltstone: 10YR 7/4 grayish-orange fresh surface, weathered surface covered, contains very fine-grained sand, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 3.	0.13

Unit 1 - Ash bed and claystone. Echo Spring Mountain ash bed: N9 white both surfaces, felsic, friable, wavy laminated. Claystone: 10Y 6/2 pale olive fresh surface, 10Y 8/2 pale yellowish-green weathered surface, slightly silty, very calcareous, structureless, blocky fracture. Ash bed occurs at base (NM - ~30 cm) then 9.5 m of covered slope to claystone. Unit weathers to ledge popcorn slope. Contact sharp with 2. Sample #970724L of ash bed.	10.45
Base of the formation not exposed	
Total thickness measured	**110.56**

Appendix B-2

Location 2 on Figure 2.2 (Roberts Mesa Section)

Measured by Jacob staff and tape measure on August 2, 1997

Field Assistant: Tara Krapf

Location: Hopi Reservation, Tsin Naan Tee 7.5' Quadrangle, N 35° 37.853' by W 110° 05.374' Near the middle of mesa on south side just north of small community of houses. Section starts in red units of member 4 and proceeds up a steep projection from off the mesa.

Outcrop Attitude: Less than 1 degree dip (taken from unit 10) - measured as flat

Measured bottom up

#2 Roberts Mesa	**Meters**
Removed by erosion, no further exposure	
Unit 44 - Quaternary alluvium and dunes: unconsolidated sand and silt, reworked material from lower Bidahochi units, weakly high-angled planar cross-bedded. Unit weathers to loose slopes and hummocky hills.	NM
Unit 43 - Micritic limestone (marl): N9 white both surfaces, structureless. Unit weathers to ledge. Contact disconformity with 44.	0.03
Unit 42 - Sandstone: 5Y 8/2 gray yellow both surfaces, very fine-grained, calcareous, contains discontinuous areas of heavy calcification, trough cross-bedded. Unit is more calcified above 7.7 m from base. Unit weathers to loose slope with thin well indurated ledges. Contact sharp with 43.	12.2
Unit 41 - Member 6 biotite ash bed: N9 white both surfaces, contains abundant biotite, slightly sandy, calcareous, laminated. Unit weathers to break in slope. Contact gradational with 42 due to reworked upper surface of ash bed. Sample #970802H.	0.3
Unit 40 - Sandstone: 5Y 8/2 gray yellow both surfaces, very fine-grained, calcareous, contains discontinuous areas of heavy calcification, wavy laminated, weakly planar-tabular bedded. Unit weathers to cliff at base and slopes above. Contact sharp with 41.	2.4
Unit 39 - Siltstone: 5YR 7/2 grayish-orange pink both surfaces, calcareous, structureless. Unit weathers to slope. Contact sharp with 30.	0.7

Unit 38 - Member 6 felsic ash bed: N9 white both surfaces, felsic, calcareous, structureless. Unit weathers to ledge. Contact gradational with 39 due to reworked upper surface of ash bed. Sample #970802G. 0.09

Unit 37 - Sandstone: 5Y 8/2 gray yellow both surfaces, very fine-grained, calcareous, wavy laminated, weakly trough cross-bedded, soft sediment deformation common. Upper 25 cm is well indurated. Unit weathers to loose slope then cliff. Contact sharp with 38. 3.65

Unit 36 - Siltstone: 5YR 7/2 grayish-orange pink both surfaces, calcareous, structureless. Unit weathers to ledge. Contact sharp with 37. 0.3

Unit 35 - Claystone: 5Y 8/1 yellowish-gray fresh surface, 10Y 7/2 pale greenish olive weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 36. 0.45

Unit 34 - Sandstone and silty micritic limestone. Sandstone: 5YR 7/2 grayish-orange pink both surfaces, very fine-grained, calcareous, thin to medium planar-tabular bedded at base, above 0.7 m is wavy laminated bedded. Silty micritic limestone (marl): N9 white both surfaces, structureless. Micritic limestone occurs at 0.3 m from the base. Unit weathers to form cliff. Contact sharp with 35. Sample #970802G of limestone. 4.1

Unit 33 - Claystone with interbeds of siltstone. Claystone: 10Y 6/2 pale olive fresh surface, 10Y 7/2 pale greenish olive weathered surface, very calcareous, weakly laminated. Siltstone: 5YR 8/2 very pale orange both surfaces, calcareous, structureless. Siltstone interbeds occur in upper 35 cm of unit. Unit weathers to popcorn slopes. Contact sharp with 34. 1.15

Unit 32 - Sandstone: 5Y 8/2 gray yellow both surfaces, very fine-grained, calcareous, wavy laminated, weakly trough cross-bedded, soft sediment deformation common. Unit weathers to loose slope. Contact sharp with 33. 0.65

Unit 31 - Silty claystone with interbeds of siltstone. Silty claystone: 5Y 6/2 yellowish-olive gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, very calcareous, structureless. Siltstone: calcareous, structureless. Three interbeds (15-20 cm thick) of siltstone occur ~evenly spaced throughout unit. Unit weathers to slopes and breaks in slope. Contact sharp with 32. 2.6

Unit 30 - Sandstone with claystone and siltstone interbeds. Sandstone: 5Y 8/2 gray yellow both surfaces, very fine-grained, quartzose, some mafic minerals noted, calcareous, moderately indurated, trough cross-bedded. Claystone: 10Y 6/2 pale olive fresh surface, very calcareous, structureless. Siltstone: 10YR 6/2 pale yellowish-brown both surfaces, calcareous, structureless. Above 2.3 m unit contains fish fragments - vertebrae and jaw elements. Two claystone interbeds (4 cm thick each) occur at 3 m. Siltstone interbed (12 cm thick) occurs at 3.5 m. Upper 30 cm of unit is well indurated. Unit weathers to slopes and ledges then cliff. Contact sharp with 31. 5.7

Unit 29 - Sandstone: 5Y 8/2 gray yellow both surfaces, very fine-grained, quartzose, some mafic minerals noted, very calcareous, well indurated, laminated planar-tabular bedded. Unit weathers to cliff. Contact gradational with 30 noted by a structural change. Sample #970802D of a small tuffaceous layer at 1.3 m from base. 1.7

Unit 28 - Silty claystone and silty micritic limestone. Silty claystone: N 8.5 white fresh surface, very calcareous, structureless. Silty micritic limestone: 5Y 8/1 yellowish-gray both surfaces, structureless. Micritic limestone bed (12 cm thick) occurs 0.55 m from the base. Degree of calcification varies throughout unit. Unit weathers to irregular slopes and a ledge. Contact sharp with 29. Sample #970802C of micritic limestone.	1.15
Unit 27 - Sandstone: 5Y 8/2 gray yellow both surfaces, very fine-grained, calcareous, wavy laminated, weakly trough cross-bedded, soft sediment deformation common. Upper 1.3 m of unit has well-defined low-angled trough cross-bedding and planar-tabular bedding. Degree of calcification varies throughout unit. Unit weathers to irregular cliffs and slopes. Contact sharp with 28.	9.2
contact members 5/6	
Unit 26 - Silty claystone with interbeds of sandstone. Silty claystone: green and brown 5GY 8/1 light greenish-gray and 10YR 6/2 pale yellowish brown fresh surfaces, calcareous, structureless. Sandstone: 5Y 8/2gray yellow both surfaces, very fine-grained, calcareous, thin wavy planar-tabular bedded. Interbeds of sandstone (2-3 cm thick) occur 1.1 m from base and above. Unit weathers to popcorn slopes. Contact sharp with 27.	2.1
Unit 25 - Sandy siltstone: 10Y8/2 pale greenish-yellow fresh surface, 5Y 8/2 gray yellow weathered surface, slightly argillaceous, calcareous, sparkles, structureless. Top of unit is very sandy (last 30 cm). Unit weathers to popcorn slopes. Contact sharp with 26.	1.4
Unit 24 - Sandstone fining upwards into siltstone. Sandstone: 5Y 8/2 gray yellow both surfaces, very fine-grained, calcareous, thin wavy planar-tabular bedded. Siltstone: 5Y 8/2 gray yellow both surfaces, biotite and mafic minerals abundant, calcareous, structureless. Unit fines to siltstone at 0.6 m. Unit weathers to calcified slopes. Contact sharp with 25.	0.7
Unit 23 - Silty claystone: 10Y 6/2 pale olive fresh surface, 5Y 7/2 yellowish-gray weathered surface, very calcareous, finely laminated. Unit contains gastropods and gypsum at base. Unit is silty near top. Unit weathers to popcorn slopes. Contact sharp with 24. Collected gastropods and clays from units 21, 22, 23 sample# 970802B.	0.5
Unit 22 - Claystone: 10YR 8/2 very pale orange both surfaces, iron-oxide staining abundant, contains black shaley organic-like material (peat?), calcareous, finely laminated. Unit contains large (up to 5 cm), high-spired gastropods. Unit weathers to popcorn slopes. Contact gradational with 23 noted color change.	0.03
Unit 21 - Silt claystone: 10Y 6/2 pale olive fresh surface, 5Y 7/2 yellowish-gray weathered surface, very calcareous, structureless. Unit contains large (up to 5 cm), high-spired gastropods near the top. Unit is silty near top and upper 10 cm contain iron-oxide staining. Unit weathers to popcorn slopes. Contact gradational with 22 noted by color change.	1.6
Unit 20 - Sandstone: 5Y 7/2 yellowish-gray both surfaces, very fine-grained, calcareous, structureless. Unit weathers to small ledge. Contact sharp with 21.	1.3
Unit 19 - Claystone with interbeds of siltstone. Claystone: 5GY 8/1 light greenish-gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, slightly silty, very calcareous, structureless, blocky fracture. Siltstone: calcareous, structureless, occur as two thin beds (20-30 cm thick). Top of unit changes color to 10YR 6/2 pale yellowish-brown. Unit weathers to popcorn slopes. Contact sharp with 20.	5.5

Unit 18 - Silty micritic limestone and siltstone. Silty micritic limestone (marl): N9 white fresh surface, structureless. Siltstone: 10Y 8/2 pale greenish-yellow fresh surface, very calcareous, structureless. Marl has patches and layers of siltstone mixed in. Unit weathers to slopes. Contact sharp with 19. Sample #970802A of white areas.	0.17
Unit 17 - Siltstone: 5Y 8/2 gray yellow fresh surface, 5Y 7/2 yellowish-gray weathered surface, contains mafic volcaniclastic material, calcareous, thin planar-tabular bedded. Unit weathers to slopes. Contact sharp with 18.	0.6
Unit 16 - Silty claystone: 10Y 6/2 pale olive fresh surface, 5Y 7/2 yellowish-gray weathered surface, contains mafic volcaniclastic material, very calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 17.	0.9
Unit 15 - Siltstone: 5Y 8/2 gray yellow fresh surface, 5Y 7/2 yellowish-gray weathered surface, contains mafic volcaniclastic material, calcareous, thin planar-tabular bedded. Bedding in unit is defined by mafic material and clay rich lenses. Unit weathers to slopes. Contact sharp with 16.	1.3
Unit 14 - Claystone: 5GY 4/2 yellow olive green fresh surface, 5Y 7/2 yellowish-gray weathered surface, very calcareous, laminated. Unit becomes silty at 0.45 m consisting of mafic volcaniclastic material. Unit weathers to popcorn slope. Contact gradational with 15 noted by color change.	1.1
Unit 13 - Siltstone: 5Y 8/2 gray yellow both surfaces, contains mafic volcaniclastic material, calcareous, thin planar-tabular bedded. Unit weathers to slopes. Contact sharp with 14.	0.3
Unit 12 - Claystone: 10YR 4/2 dark yellowish-brown fresh surface, 5Y 7/2 yellowish-gray weathered surface, contains mafic volcaniclastic material, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 13.	0.35
Unit 11 - Volcaniclastic siltstone and mafic tuff. Volcaniclastic siltstone: 5Y 7/2 yellowish-gray both surfaces, contains Hopi Buttes volcanic material, calcareous, thin planar-tabular bedded. Mafic tuff: 10Y 5/2 olive fresh surface, weathered surface covered, badly oxidized, reworked, structureless. Unit changes to mafic tuff at 0.4 m from base. Unit weathers to ledges and slopes. Contact sharp with 12.	0.8
Unit 10 - Mafic tuff: 5Y 6/2 yellowish-olive gray fresh surface, 10YR 6/6 dark yellowish-orange oxidized weathered surface, medium to coarse lapilli, fines upwards, clast supported with some silt and sand matrix, contains angular pyroxene and biotite grains, calcareous, two beds separated by a silt-rich zone. Unit weathers to cliff. Contact sharp with 11.	1.35
Unit 9 - Volcaniclastic siltstone: 5Y 7/2 yellowish-gray both surfaces, contains Hopi Buttes volcanic material, calcareous, thin planar-tabular bedded. Unit weathers to ledge. Contact sharp with 10.	0.5
contact members 4/5	
Unit 8 - Siltstone fining upwards into silty claystone. Siltstone: 5Y 8/1 yellowish-gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, calcareous, structureless. Silty claystone: 10R 7/2 orangish-pink fresh surface, very calcareous, structureless. Unit fines upwards twice - to silty claystone at 0.7 m - to siltstone at 1.9 m - to silty claystone at 2.7 m. Unit weathers to popcorn slope with small ledges. Contact sharp with 9.	4.2

Unit 7 - Sandstone: 10YR 6/4 yellowish-orange brown both surfaces, very fine- to medium-gained, poorly sorted, subrounded, quartzose, mafic minerals noted, silty, calcareous. Lower 1.95 m of unit is high-angled planar cross-bedded with paleocurrent reading of 79 from a 75cm thick forset bed. Upper 0.45 m is planar-tabular bedded. Thin lenticular mudstone beds occur at the base and in upper planar-tabular beds. Unit weathers to ledge. Contact sharp with 8.	2.4
Unit 6 - Interbedded silty claystone and siltstone. Silty claystone: 5YR 8/2 orange grayish-pink both surfaces, calcareous, structureless, blocky fracture. Siltstone: 10YR 8/2 very pale orange both surfaces, calcareous, structureless. Unit is predominantly claystone with small beds of siltstone. At top have 30 cm siltstone layer. Unit weathers to slopes and breaks in slope. Contact sharp with 7.	1.3
Unit 5 - Siltstone: 10YR 8/2 very pale orange both surfaces, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 6.	0.28
Unit 4 - Siltstone fining upwards into claystone. Siltstone: 10YR 8/2 very pale orange fresh surface, weathered surface covered, calcareous, structureless. Claystone: 5GY 7/1 pale grayish-yellow green both surfaces, slightly silty in places, very calcareous, structureless. Unit fines to claystone at 0.08 m. Unit weathers to popcorn slope. Contact sharp with 5.	0.75
Unit 3 - Silty claystone: 5YR 8/2 orange grayish-pink both surfaces, calcareous, structureless, blocky fracture. Unit weathers to break in slope. Contact sharp with 4.	0.6
Unit 2 - Siltstone fining upwards into silty claystone. Siltstone: 5Y 8/4 grayish-yellow fresh surface, 5Y 8/2 gray yellow weathered surface, slightly argillaceous, iron-oxide staining common, calcareous, structureless. Silty claystone: 5Y 8/1 yellowish-gray fresh surface, iron-oxide staining common, very calcareous, structureless, blocky fracture. Unit fines upwards twice - to claystone at 0.6 m - to siltstone at 1.2 m - to claystone at 1.35 m. Unit weathers to break in slopes and popcorn slopes. Contact gradational with 3 noted by a color change and increase in silt content.	1.65
Unit 1 - Claystone: 5YR 5/4 light brown fresh surface, 10R 4/4 reddish-brown weathered surface, contains patches of green colored claystone, slightly silty, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 2.	5.5+
Base of the formation not exposed	
Total thickness measured	**83.55**

Appendix B-3

Location 3 on Figure 2.2 (Bell Butte Springs section)

Measured by Jacob staff and tape measure on August 1, 1997

Field Assistant: Tara Krapf

Location: Hopi Reservation, Hauke Mesa 7.5' Quadrangle, N 35° 33.775' by W 110° 20.322' Located in saddle southwest of Horse Butte and southeast of Bell Butte on the eastern most point of butte that Bell Butte Springs originates. Section occurs along western edge of maar rim deposits on west side of saddle.

Outcrop Attitude: N40W 6SW measured from claystone parting of unit number 2

Measured bottom up

#3 Bell Butte Springs	Meters
Removed by erosion, no further exposure	
Unit 28 - Mafic lava: N1 black both surfaces, porphyritic - abundant small crystals of pyroxene, amphibole, and olivine, vertical and horizontal fractures, columnar jointed in some areas. Unit weathers to granulated thin platy segments and forms cliffs and ledges. Measured to top of small cliff only.	13+
Unit 27 - Mafic siltstone and claystone. Mafic siltstone: 10YR 8/2 very pale orange fresh surface, 10YR 8/4 pale yellowish-gray orange weathered surface, contains fine- to coarse-grained sand-sized matrix supported angular mafic aphanitic rock, calcareous, wavy beds, thin- to medium-bedded. Areas with abundant volcanic material have less matrix and are heavily calcified. Claystone, pink fresh surface, calcareous, appears oxidized, structureless, discontinuous. Pink claystone bed is 15 cm thick at maximum and is mixed with mafic rock fragments. Unit weathers to sharp ledges and slopes. Contact sharp with 28.	2.3
Unit 26 - Mafic sandstone and siltstone: 10YR 8/2 very pale orange fresh surface, 10YR 8/4 pale yellowish-gray orange weathered surface, contains fine- to coarse-grained sand-sized clasts of angular mafic aphanitic rock, contains accidental clasts (Wingate Fm and lower Bidahochi units), calcareous, wavy laminated, some lenticular beds, trough and planar cross-bedded, contains antidunes and bomb sags. Unit is structureless to medium-bedded. Unit weathers to ledges and slopes. Contact sharp with 27.	2.0
Unit 25 - Mafic siltstone: 10YR 8/2 very pale orange fresh surface, 10YR 8/4 pale yellowish-gray orange weathered surface, contains fine- to coarse-grained sand-sized angular mafic aphanitic rock, calcareous, wavy beds, thin- to medium-bedded. Areas with abundant volcanic material have less matrix and are heavily calcified. Unit weathers to sharp ledges and slopes. Contact sharp with 26.	0.4
Unit 24 - Mafic sandstone and siltstone: 10YR 8/2 very pale orange fresh surface, 10YR 8/4 pale yellowish-gray orange weathered surface, contains fine- to coarse-grained sand-sized clasts of angular mafic aphanitic rock, contains accidental clasts (Wingate Fm and lower Bidahochi units), calcareous, wavy laminated, some lenticular beds, trough and planar cross-bedded, contains antidunes and bomb sags. Unit contains scours into lower beds of unit - mafic material is generally concentrated in this structures. Unit is structureless to medium-bedded. Unit weathers to ledges and slopes. Contact sharp with 25.	3.9
Unit 23 - Mafic sandstone: 10YR 8/2 very pale orange fresh surface, 10YR 8/4 pale yellowish-gray orange weathered surface, fine- to coarse-grained, volcaniclastic - some beds contain abundant clasts of angular mafic aphanitic rock, calcareous, wavy beds, thin- to medium-bedded. Areas with abundant volcanic material have less matrix and are heavily calcified. Unit weathers to sharp ledges and slopes. Contact sharp with 24.	1.25

Unit 22 - Mafic sandstone and siltstone: 10YR 8/2 very pale orange fresh surface, 10YR 8/4 pale yellowish-gray orange weathered surface, contains fine- to coarse-grained sand-sized clasts of angular mafic aphanitic rock, contains accidental clasts (Wingate Fm and lower Bidahochi units), calcareous, wavy laminated, some lenticular beds, trough and planar cross-bedded, contains antidunes and bomb sags. Unit contains scours into lower beds of unit - mafic material is generally concentrated in this structures. Unit is structureless to medium-bedded. Unit weathers to ledges and slopes. Contact sharp with 23.	2.2
Unit 21 - Mafic sandstone: 10YR 8/2 very pale orange fresh surface, 10YR 8/4 pale yellowish-gray orange weathered surface, fine- to coarse-grained, volcaniclastic - some beds contain abundant clasts of angular mafic aphanitic rock, calcareous, wavy beds, thin- to medium-bedded. Areas with abundant volcanic material have less matrix and are heavily calcified. Unit weathers to sharp ledges and slopes. Contact sharp with 22.	0.3
Unit 20 - Volcaniclastic sandstone: 10YR 8/2 very pale orange fresh surface, 10YR 8/4 pale yellowish-gray orange weathered surface, fine- to coarse-grained, contains abundant clasts of angular mafic aphanitic rock, calcareous, lenticular and weakly trough cross-bedded. Unit weathers to sharp ledges and slopes. Contact sharp with 21.	0.21
Unit 19 - Mafic sandstone and siltstone: 10YR 8/2 very pale orange fresh surface, 10YR 8/4 pale yellowish-gray orange weathered surface, contains fine- to coarse-grained sand-sized clasts of angular mafic aphanitic rock, contains accidental clasts (Wingate Fm and lower Bidahochi units), calcareous, wavy laminated, some lenticular beds, trough and planar cross-bedded, contains antidunes and bomb sags. Unit contains scours into lower beds of unit - mafic material is generally concentrated in this structures. Unit is structureless to medium-bedded. Unit weathers to ledges and slopes. Contact sharp with 20.	3.6
Unit 18 - Mafic sandstone: 10YR 8/2 very pale orange fresh surface, 10YR 8/4 pale yellowish-gray orange weathered surface, fine- to coarse-grained, volcaniclastic - some beds contain abundant clasts of angular mafic aphanitic rock, calcareous, wavy beds, thin- to medium-bedded. Areas with abundant volcanic material have less matrix and are heavily calcified. Unit weathers to sharp ledges and slopes. Contact sharp with 19.	2.1
Unit 17 - Mafic sandstone and siltstone: 10YR 8/2 very pale orange fresh surface, 10YR 8/4 pale yellowish-gray orange weathered surface, contains fine- to coarse-grained sand-sized clasts of angular mafic aphanitic rock, contains accidental clasts (Wingate Fm and lower Bidahochi units), calcareous, wavy laminated, some lenticular beds, trough and planar cross-bedded, contains antidunes and bomb sags. Unit contains scours into lower beds of unit - mafic material is generally concentrated in this structures. Unit is structureless to medium-bedded. Unit weathers to ledges and slopes. Contact sharp with 18.	5.1
Unit 16 - Interbedded sandstone and siltstone. Sandstone: 10YR 8/2 very pale orange fresh surface, 10YR 8/4 pale yellowish-gray orange weathered surface, very fine-grained, volcaniclastic, very calcareous, well indurated, trough cross-bedded. Siltstone: 10YR 8/2 very pale orange fresh surface, 10YR 8/4 pale yellowish-gray orange weathered surface, volcaniclastic, calcareous, structureless. Unit is thin- to medium-bedded. Unit weathers to ledges and slopes. Contact sharp with 17 and noted by increase in recognizable Hopi Buttes material.	1.0 to 1.8

Unit 15 - Mafic sandstone: 5B 6/1 bluish-gray both surfaces, fine- to coarse-grained, poorly sorted, subangular to subrounded, contains accidental clasts (Wingate Fm, Cretaceous, and lower Bidahochi units), mafic aphanitic blocks abundant - up to 60 cm in diameter, pyroxene and amphibole common, calcareous, wavy laminated, some lenticular beds, trough and planar cross-bedded. Unit is thin- to medium-bedded with coarse material primarily in thicker beds. Unit scours deeply at an angle into lower units. Maar rim is defined by change in dip of these beds at this location. Unit weathers to ledges. Contact scour with 16.	0.9 to 2.6
contact members 4?/5	
Unit 14 - Silty claystone: 10Y 6/2 pale olive fresh surface, calcareous, structureless, very blocky fracture. Unit weathers beneath cliff of 15. Contact large scour with 15.	0.3
Unit 13 - Silty claystone fining upwards to claystone. Silty claystone: 10Y 6/2 pale olive fresh surface, calcareous, structureless. Claystone: 5Y 8/1 yellowish-gray both surfaces, very calcareous, structureless, very blocky fracture. At 0.9 m unit changes color to 5YR 7/1 pale grayish-orange pink fresh surface. At 1.35 m unit changes color to 10YR 7/2 pale grayish orange fresh surface. Unit weathers to slope. Contact gradational with 14 noted by a color change and increase in silt.	1.65
Unit 12 - Silty claystone fining upwards into claystone. Silty claystone: 10YR 7/4 grayish-orange fresh surface, 5YR 6/2 grayish-orange brown weathered surface, calcareous, structureless. Claystone: 5YR 5/4 light brown fresh surface, slightly silty, calcareous, structureless, very blocky fracture. Unit weathers to popcorn slope. Contact gradational with 13 noted by a color change.	1.1
Unit 11 - Silty claystone: green and brown colored, very calcareous, structureless. Silt concentrated at base. More green at top. Unit weathers to slope. Contact gradational with 12 noted by a color change.	0.2
Unit 10 - Sandstone fining upwards into sandy siltstone. Sandstone: 5Y 8/2 gray yellow both surfaces, very fine-grained, quartzose, mafic minerals common, weakly calcareous, weakly laminated bedded. Sandy siltstone: 5Y 8/2 gray yellow both surfaces, calcareous, structureless. Unit weathers to loose slope. Contact obscure with 11.	0.6
Unit 9 - Silty claystone: 5GY 6/1 greenish-gray fresh surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 10.	0.14
Unit 8 - Siltstone: 10Y 7/2 pale greenish-olive fresh surface, weathered surface covered, slightly argillaceous, mafic minerals abundant, calcareous, structureless. Unit weathers to slope. Contact sharp with 9.	0.1
Unit 7 - Silty claystone: 5GY 6/1 greenish-gray fresh surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 8.	0.17
Unit 6 - Siltstone: 10Y 7/2 pale greenish-olive fresh surface, weathered surface covered, slightly argillaceous, mafic minerals abundant, calcareous, structureless. Unit weathers to slope. Contact sharp with 7.	0.07
Unit 5 - Sandstone: 5Y 8/2 gray yellow both surfaces, very fine-grained, quartzose, mafic minerals common, weakly calcareous, weakly laminated bedded. Unit weathers to loose slope. Contact sharp with 6.	1.2

Unit 4 - Claystone: 5Y 5/2 light olive gray fresh surface, 5YR 7/2 grayish-orange pink weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 5.	0.05
Unit 3 - Sandy siltstone: 5Y 8/2 gray yellow fresh surface, weakly calcareous, poorly indurate, structureless. Unit weathers to loose slope. Contact sharp with 4.	0.07
Unit 2 - Claystone: 5Y 5/2 light olive gray fresh surface, 5YR 7/2 grayish-orange pink weathered surface, very calcareous, laminated to structureless, blocky fracture. Small brown claystone bed (3cm thick) at base - 10YR 4/2 pale grayish-brown fresh surface. Unit weathers to popcorn slope. Contact sharp with 3.	2.0
Unit 1 - Silty micritic limestone (marl): N9 white both surfaces, contains areas of green clay, sparkles, wavy laminated. Unit weathers to slope. Contact sharp with 2. Sample #970801A.	0.23
Total thickness measured	**46.14**

Appendix B-4

Location 4 on Figure 2.2 (North Teshim Butte section)

Measured by Jacob staff and tape measure on August 8, 1997

Field Assistant: Tracey Fitzner

Location: Navajo Reservation, White Cone 7.5' Quadrangle, N 35° 34.090' by W 110° 06.077' Northwest corner of mesa near small knob of pink siltstone. Section starts on pink knob then transfer to main butte directly to the east.

Outcrop Attitude: measured flat - essentially zero dip measured on unit 7

Measured bottom up

#4 North Teshim Butte	Meters
Cliff to top of mesa, no further exposure	
Unit 23 - Mafic tuff: 10YR 6/6 dark yellowish-orange both surfaces, fine to coarse lapilli, clast supported, calcareous, slightly normal graded, thin to thick planar-tabular bedded. Unit has one large mafic bomb that creates a large sag in this unit and one below - occurs near clastic dike. Unit weathers to large cliff.	6+
Unit 22 - Interbedded mafic sandstone and mafic siltstone. Mafic sandstone: 10Y 7/4 moderate greenish-yellow fresh surface, 5Y 7/2 yellowish-gray weathered surface, fine- to coarse-grained, moderately sorted, angular to subrounded, contains accidental clasts (Wingate Fm and lower Bidahochi units) up to 14 cm in diameter, calcareous, finely wavy laminated, planar-tabular thin-bedded. Mafic siltstone: 10Y 7/4 moderate greenish-yellow fresh surface, 5Y 7/2 yellowish-gray weathered surface, calcareous, thin beds. Large clastic dike occurs within this unit. Unit weathers to cliff. Contact sharp with 23.	1.6

Unit 21 - Argillaceous siltstone fining upward to claystone. Argillaceous siltstone: 10Y 6.5/2 pale olive fresh surface, 10Y 7/2 pale greenish-olive weathered surface, contains matrix supported coarse sand-sized clasts of Hopi Buttes volcanic material, calcareous, structureless, blocky fracture. Claystone: 10Y /2 grayish olive fresh surface, 10Y 7/2 pale greenish-olive weathered surface, contains some matrix supported coarse sand-sized clasts of Hopi Buttes volcanic material, very calcareous, structureless, blocky fracture. At 1.4 m unit fines to claystone. Unit weathers to popcorn slope. Contact sharp with 22. 3.35

Contact members 4/5

Unit 20 - Siltstone: 10YR 7/2 pale grayish-orange both surfaces, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 21. 0.4

Unit 19 - Claystone, 10Y 7/2 pale greenish-olive fresh surface, 5Y 7/1 yellowish-olive gray weathered surface, slightly silty, very calcareous, structureless, very blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 20. 1.85

Unit 18 - Sandy siltstone fines upwards to argillaceous siltstone. Sandy siltstone: 5Y 7.5/1 yellowish-gray fresh surface, calcareous, structureless. Argillaceous siltstone: 10YR 5.5/4 moderate yellowish-brown fresh surface, calcareous, structureless. Entire unit weathered surface 10YR 7/2 pale grayish-orange. Unit weathers to popcorn slopes. Contact sharp with 19. 0.55

Unit 17 - Claystone, 10Y 6/2 pale olive fresh surface, 5Y 7/1 yellowish-olive gray weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 18. 0.55

Unit 16 - Silty claystone, 10Y 7/2 pale greenish-olive fresh surface, 5Y 7/1 yellowish-olive gray weathered surface, very calcareous, structureless, slightly blocky fracture. At 2.0 m unit contains less silt, more blocky, and changes color to 10YR 7/2 pale grayish-orange both surfaces. Unit weathers to popcorn slopes. Contact sharp with 17. 4.7

Unit 15 - Claystone, 5YR 4.5/4 moderate brown fresh surface, 10YR 6/2 pale yellowish-brown weathered surface, slightly silty, calcareous, structureless. Unit weathers to popcorn slopes. Contact gradational with 16 noted by a color change. 1.15

contact members 3/4

Unit 14 - Sandstone: 10YR 7/2 pale grayish-orange both surfaces, very fine-grained, quartzose, calcareous, structureless. Unit weathers to calcified slopes. Contact sharp with 15. 2.9

Unit 13 - Claystone, 10Y 7/2 pale greenish-olive fresh surface, 5Y 7/2 yellowish-gray weathered surface, slightly silty especially near top, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 14. 0.75

Unit 12 - Sandy siltstone: 10YR 7/2 pale grayish-orange both surfaces, calcareous, structureless. Unit weathers to calcified slopes. Contact sharp with 13. 2.35

Transferred across to mesa proper

Unit 11 - Silty claystone, 10Y 7/2 pale greenish-olive both surfaces, very calcareous, structureless, very blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 12. 0.15

Unit 10 - Sandstone: 10YR 7/2 pale grayish-orange both surfaces, very fine-grained, quartzose, calcareous, wavy bedded, weakly trough cross-bedded. Unit weathers to calcified slopes. Contact sharp with 11.	1.7
Unit 9 - Argillaceous siltstone fining upwards in silty claystone: 5Y 7/2 yellowish-gray both surfaces, very calcareous, structureless. Unit fines to silty claystone 40 cm from base. Unit weathers to popcorn slope. Contact sharp with 10.	0.45
Unit 8 - Siltstone with interbeds of sandstone. Siltstone: 10YR 7/2 pale grayish-orange both surfaces, no clay present, calcareous, structureless. Sandstone: 10YR 7/2 pale grayish-orange both surfaces, very fine-grained, calcareous, well indurated, wavy bedded. Sandstone beds are small. At 4.3 m a 30 cm thick sandstone bed is weakly trough cross-bedded. Unit weathers to calcified slope. Contact gradational with 9 noted by increase in clay material.	7.5
Unit 7 - 13.71 Ma ash bed: N9 white both surfaces, fine-grained, felsic, vitric, calcareous, wavy laminated. Unit weathers to prominent ledge. Contact gradational with 8 due to reworked upper surface of ash. Sample #970808B.	0.26
Unit 6 - Sandstone: 10YR 7/2 pale grayish-orange both surfaces, fine-grained, moderately sorted, rounded, quartzose, calcareous, well indurated, wavy at base - structureless otherwise. Unit weathers to ledge. Contact sharp with 7. Sample #971003K.	0.4
Unit 5 - Siltstone: 10YR 7/2 pale grayish-orange both surfaces, no clay present, calcareous, structureless. Unit weathers to calcified slope. Contact sharp with 6.	1.05
Unit 4 - Claystone and siltstone. Claystone: 10Y 5/2 pale grayish-olive fresh surface, 5Y 7/2 yellowish-gray weathered surface, very calcareous, structureless, blocky fracture. Siltstone: 5Y 7/2 yellowish-gray both surfaces, calcareous, sparkles, structureless. Unit coarsen upwards to siltstone 20 cm from base and then fines back to claystone 80 cm from base. Upper claystone beds are weakly laminated. Unit weathers to popcorn slope. Contact sharp with 5.	2.1
Unit 3 - Siltstone: 10YR 7/2 pale grayish-orange both surfaces, no clay present, calcareous, structureless. Unit weathers to calcified slope. Contact sharp with 4.	0.1
Unit 2 - Silty claystone: 10Y 6.5/2 pale olive fresh surface, 5Y 7/2 yellowish-gray weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 3.	0.2
Unit 1 - Siltstone: 10YR 7/2 pale grayish-orange both surfaces, no clay present, calcareous, structureless. Unit weathers to calcified slope. Contact sharp with 2.	0.3+
Base of the formation not exposed	
Total thickness measured	**40.36**

Appendix B-5

Location 5 on Figure 2.2 (White Cone Peak Section)

Measured by Jacob staff and tape measure on July 11, 1997

Field Assistant: Amy Morrison

Location: Hopi Reservation, White Cone 7.5' Quadrangle, N 35° 34.571' by W 110° 02.965' West-southwest corner of cone. Started below prominent tuff ledge and proceed up cone.

Outcrop Attitude: N75E 3SE measured from unit number 8

Measured bottom up

#5 White Cone Peak	**Meters**
Removed by erosion, no further exposure	
Unit 34 - Sandstone: light pinkish white, very fine-grained, contains mudstone rip-up clasts, very calcareous, very well indurated. Unit weathers to form ledge.	1.5
Unit 33 - Interbedded sandstone and mudstone. Sandstone: light greenish-white both surfaces, fine-grained, contains Hopi Buttes volcanic material and rip-up clasts from unit 32, moderately indurated, low-angle planar cross-bedded. Mudstone: light greenish-white both surfaces, slightly tuffaceous, very calcareous, structureless. Unit is dominated by sandstone with only minor thin beds of mudstone. Unit weathers to ledges and slopes. Contact sharp with 34.	2.5
Unit 32 - Interbedded siltstone, sandstone, and mudstone. Siltstone: light green both surfaces, contain abundant Hopi Buttes volcanic material, calcareous, structureless. Sandstone: pinkish-tan both surfaces, very fine-grained, slightly calcareous, structureless. Mudstone: light greenish-white both surfaces, slightly tuffaceous, very calcareous, structureless. Unit is thin to medium bedded defined by changes in lithology. Unit weathers to slopes. Contact sharp with 33.	0.8
Unit 31 - Sandstone: light greenish-white both surfaces, very fine-grained, quartzose, contains claystone rip-up clasts from unit 30, moderately indurated, low-angle planar cross-bedded, some sand bodies have asymmetrical rippled tops with a SE orientation. At 1 m sandstone changes color to light pinkish-tan both surfaces, fine grained, contains Hopi Buttes volcanic material. Unit weathers to cliffs and slopes. Contact sharp with 32.	7.2
contact member 5/6	
Unit 30 - Claystone: light olive green fresh surface, light greenish white weathered surface, very calcareous, slightly shaley. Unit weathers to popcorn slopes. Contact sharp with 31.	1.5
Unit 29 - Siltstone: light tan both surfaces, argillaceous, calcareous, sparkles, structureless. Unit weathers to slope. Contact sharp with 30.	0.3
Unit 28 - Claystone: light olive green fresh surface, light greenish white weathered surface, very calcareous, slightly shaley. Unit weathers to popcorn slopes. Contact sharp with 29.	0.4
Unit 27 - Sandstone: light tan fresh surface, light brownish-tan weathered surface, very fine-grained, poorly indurated, quartzose with some mafic minerals noted, structureless. At 1.5 m sandstone becomes moderately indurated, volcaniclastic, has small layers of interbedded siltstone, wavy planar-tabular bedded. Mollusks fragments occur in upper 1 m of unit. Unit weathers to slopes and ledges. Contact sharp with 28.	2.55
Unit 26 - Claystone: light olive green fresh surface, light greenish white weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 27.	1.45

Unit 25 - Interbedded argillaceous siltstone and siltstone. Argillaceous siltstone: light gray-green both surfaces, very calcareous, structureless. Siltstone: light grayish-green both surfaces, calcareous, structureless. The four siltstone layers (3-4cm thick) occur at 1.5, 2.1, 2.8, and 3.2 m. The fourth siltstone layer contains iron-oxide staining. Contains abundant snails and bivalve clams in lower 0.9 m of unit. Unit weathers to popcorn slopes and breaks in slope. Contact gradational with 26. 3.5

Unit 24 - Siltstone: light grayish-green both surfaces, calcareous, structureless. Contains abundant snails and bivalve clams. Unit weathers to calcified slopes. Contact gradational with 25 noted by increase in clay content. 0.2

Unit 23 - Claystone coarsens upwards into mudstone. Claystone: olive green fresh surface, light green weathered surface, very calcareous, structureless, blocky fracture. Mudstone: brownish-green both surfaces, very calcareous, structureless. Unit coarsens to mudstone 0.3 m from base. Two (3-4 cm thick) bands of white tuffaceous material noted at the base of this unit. Gypsum noted in scree. Unit weathers to popcorn slopes. Contact sharp with 24. Sample #970711E collected near base. 1.4

Unit 22 - Silty claystone: brown fresh surface, light brown weathered surface, very calcareous, shaley. Collected (sample #970711D1) fish vertebrae from surface material of this unit. Unit weathers to popcorn slopes. Contact gradational with 23 noted color change and decrease in grain size. Sample #970711D collected of claystone. 0.1

Unit 21 - Claystone: light olive green fresh surface, light greenish white weathered surface, very calcareous, shaley. Unit weathers to popcorn slopes. Contact gradational with 22 noted by color change and grain size increase. 0.4

Unit 20 - Sandstone: light greenish-brown both surfaces, very fine-grained, tuffaceous, calcareous, contains mafic minerals, laterally continuous low-angle planar cross-bedding, occasional large (up to 1 cm wide) pelecypods and planispiral gastropods at base. Iron-oxidized staining at top of unit. Unit weathers to small cliff. Contact sharp with 21. 0.8

Unit 19 - Claystone coarsens upwards into mudstone. Claystone: olive green fresh surface, light greenish white weathered surface, very calcareous, structureless. Mudstone: brownish-green both surfaces, very calcareous, structureless. Contains abundant snails and bivalve clams near top of unit. Unit is well indurated at top 40 cm and forms ledge. Unit weathers to popcorn slopes and ledge. Contact sharp with 20. 0.95

Unit 18 - Fossiliferous sandstone: light greenish-tan fresh surface, light greenish-white weathered surface, very fine-grained, calcareous, contains mafic minerals, structureless. Contains abundant snails and bivalve clams. Unit weathers to break in slope. Contact sharp with 19. 0.3

Unit 17 - Silty claystone and siltstone. Silty claystone: light olive green fresh surface, light greenish white weathered surface, very calcareous, structureless, silt content decreases upward. Siltstone: brownish-green both surfaces, volcaniclastic, calcareous, structureless. Two small siltstone layers occur at 3.4 m. Partial squirrel jaw collected (sample #970711C1) in surface material of this unit. Unit weathers to popcorn slopes. Contact sharp with 18. 4.95

Unit 16 - Sandstone: light tan fresh surface, light tanish-white weathered surface, very fine-grained, poorly indurated, contains mafic minerals and mica, structureless. Unit weathers to slopes. Contact sharp with 17. 1.55

Unit 15 - Silty claystone and sandstone. Silty claystone: light olive green fresh surface, light greenish white weathered surface, very calcareous, structureless, sparkles - ash(?). Sandstone: tan both surfaces, very fine-grained, poorly indurated, lenticular, contains bivalve clams. Sandstone lense (10 cm) occurs at 2.1 m. Unit weathers to popcorn slopes. Contact sharp with 16. Sample #970711C collected near base.	2.4
Unit 14 - Claystone: brown fresh surface, light tanish-brown weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact gradational with 15 noted by color change. Sample #970711B collected near base.	1.45
Unit 13 - Sandy claystone: light olive green fresh surface, light greenish white weathered surface, very calcareous, structureless, sand content decreases upward. Unit weathers to popcorn slopes. Contact gradational with 14 noted by a color change.	2.4
Unit 12 - Sandstone, light tan both surfaces, very fine- to fine-grained, slightly calcareous, poorly indurated, trough cross-bedded, bedding planes have red iron oxide staining, lenticular and pinches out laterally. Contains pieces of mammal long bones, cricitine rodent dentition, fish vertebrae. PC S50W from 1.5 m forset bed. Unit weathers to ledge. Contact sharp with 13. Sample #970711A1 collected of fossil material.	3.0
Unit 11 - Claystone, light olive green both surfaces, contains Hopi Buttes material, very calcareous, weakly laminated defined by silt partings otherwise structureless, blocky fracture. Unit weathers to popcorn slopes. Contact scour with 12.	1.4
Unit 10 - Mafic tuff: peppered black and greenish-tan both surfaces, medium to coarse lapilli, clast supported, contains euhedral pyroxene and biotite grains, calcareous, one bed. Unit weathers to cliff. Contact sharp with 11.	0.01
Unit 9 - Claystone, light olive green both surfaces, contains Hopi Buttes material, contains medium sand-sized biotite grains, very calcareous, weakly laminated defined by silt partings otherwise structureless, blocky fracture. Top of unit has shaley habit. Unit weathers to popcorn slopes. Contact sharp with 10. Sample #970711A collected near the base.	3.95
Unit 8 - Interbedded mafic tuff and siltstone. Mafic tuff: peppered black and tan both surfaces, coarse-grained at base and fines upwards, clast supported at base of bed and matrix supported at top, calcareous, medium bedded. Siltstone: tan both surfaces, calcareous, contains mafic material, thinly to laminated bedded, some beds are lenticular. Tuff dominates with 5 siltstone beds of 2-10 cm each. Unit weathers to cliff. Contact sharp with 9.	2.0
contact member 4/5	
Unit 7 - Claystone: light olive green fresh surface, light greenish-white weathered surface, silty, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 8.	2.8
Unit 6 - Siltstone: light greenish-white both surfaces, slightly sandy, calcareous, structureless. Unit weathers to popcorn slope. Contact gradational with 7 noted by dominance of claystone.	0.7
Unit 5 - Claystone: light olive green fresh surface, light greenish-white weathered surface, color changes to more light tanish green in places, slightly silty, very calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 6.	2.6

Unit 4 - Sandstone and siltstone. Sandstone: light tanish-white fresh surface, light tan weathered surface, fine-grained, poorly sorted, rounded, silty, very calcareous, structureless. Siltstone: light tan fresh surface, light tanish-white weathered surface, calcareous, structureless. Unit fines upward from sandstone to siltstone at 20 cm. Unit weathers to calcified slopes. Contact sharp with 5.	0.9
Unit 3 - Claystone: light olive green fresh surface, light greenish-white weathered surface, slightly silty, very calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 4.	0.08
Unit 2 - Silty claystone: light pinkish-red fresh surface, tanish-pink weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact gradational with 3 noted by a reduction in silt content.	2.3
Unit 1 - Argillaceous siltstone: light tan fresh surface, light tanish-white weathered surface, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 2.	NM
member 4	
remainder of the formation not exposed	
Total thickness measured	**58.43 m**

Appendix B-6

Location 6 on Figure 2.2 (N of the Greasewood Highway section):

Measured by Jacob staff and tape measure on July 05, 1997.

Field Assistant: Elizabeth Tyack

Location: Navajo Reservation, Greasewood 7.5' Quadrangle, N 35^0 26.998', W 109^0 51.389' composite section - moved north from small section at highway road-cut where blue-gray ash beds are present along 13.71 Ma ash bed (unit 9) to base of cliff and went up to cliff

Outcrop attitude: N65E 04SE measured from the unit 9

Measured bottom up

#6 N of Greasewood Highway	**Meters**
Unit 58 - Recent dune sand	NM
contact Bidahochi Formation member 6/ Recent units	
Unit 57 - Sandstone: white both surfaces, very fine-grained, calcareous, very well indurated, structureless. Unit weathers to thin platy ledges. Contact disconformity with 58.	0.8
Unit 56 - Sandstone: light brown both surfaces, very fine-grained, calcareous, moderately indurated at base and friable above, trough cross-bedded. Unit weathers to cliff then slope. Contact sharp with 57.	4.0

Unit 55 - Sandstone: light brown both surfaces, fine-grained, subangular to rounded, moderately sorted, contains mafic volcanic material, calcareous, trough cross-bedded and rippled, wavy bedding. Unit weathers to cliff. Contact scour with 56.	1.15
Unit 54 - Argillaceous siltstone and claystone. Argillaceous siltstone: brown fresh surface, light brown weathered surface, calcareous, structureless. Claystone: brick red fresh surface, calcareous, structureless. Claystone unit is upper 3 cm of unit. Unit weathers to popcorn slope. Contact sharp with 55.	3.0
Unit 53 - Sandstone: light brown both surfaces, fine-grained, subangular to rounded, moderately sorted, contains mafic volcanic material, very calcareous, trough cross-bedded at base and planar cross-bedded otherwise. Unit weathers to cliff. Contact gradational with 54 noted by grain size change.	2.3
contact members 5/6	
Unit 52 - Siltstone: light greenish-white both surfaces, contains ash material from unit below and mafic volcanic material, calcareous, thin-bedded. Unit weathers to slope. Contact scour with 53.	0.8
Unit 51 - Greasewood ash bed: white fresh surface, light pink weathered surface, vitric, calcareous, weakly laminated, wavy beds, well indurated, top reworked with pinkish-tan siltstone. Unit weathers to cliff. Contact gradational with 52. Samples #970705C, 971003P.	1.1
Unit 50 - Claystone: light olive green fresh surface, greenish-white weathered surface, calcareous, structureless, blocky fracture. Top of unit has mottled texture. Unit weathers to slope below cliff of unit above. Contact sharp with 51.	1.1
Unit 49 - Siltstone: light tanish-brown fresh surface, light tan weathered surface, contains some mafic volcanic material, argillaceous, structureless, blocky fracture. Contact gradational with 50 noted by grain size change.	0.15
Unit 48 - Ash bed: white both surfaces, calcareous, structureless. Unit weathers to small ledge. Contact gradational with 49. Sample #980419F.	0.05
Unit 47 - Claystone with interbedded volcaniclastic siltstone. Claystone: light tanish-green both surfaces, contains some sand-sized mafic volcanic material, calcareous, Structureless. Volcaniclastic siltstone: light tanish-green both surfaces, calcareous, structureless. Unit is thin to medium bedded defined by 10-20 cm thick volcaniclastic siltstone beds. Unit weathers to very small ledges and popcorn slopes. Contact sharp with 48.	2.75
Unit 46 - Tuff sandstone: dark brown with orangish-brown reduction spots both surfaces, coarse-grained, poorly to moderately sorted, subangular, mafic, contains Wingate Fm and lower Bidahochi clasts, calcareous, well indurated, weakly planar cross-bedded, contains antidunes and bomb sags. Unit weathers to small ledge. Contact sharp with 47.	0.19
Unit 45 - Volcaniclastic sandstone: light brown both surfaces, fine-grained, poorly sorted, subangular, contains mafic volcanic material, calcareous, trough cross-bedded. Unit weathers to small ledge. Contact gradational with 46.	0.135
Unit 44 - Claystone and volcaniclastic claystone. Claystone: light tanish-green both surfaces, contains some sand sized mafic volcanic material, calcareous, structureless. Volcaniclastic siltstone: light tanish-green both surfaces, contains abundant sand-sized pyroxene and other mafic volcanic material, calcareous, structureless. Unit coarsens to volcaniclastic siltstone then back to claystone. Unit weathers to a ledge and popcorn slopes. Contact sharp with 45.	0.75

Unit 43 - Volcaniclastic sandstone: greenish-gray both surfaces, fine- to medium-grained, subangular, poorly sorted, contains abundant pyroxene and mafic volcanic material, calcareous, well indurated, wavy beds. Unit weathers to ledge. Contact sharp with 44.	0.17
Unit 42 - Claystone: light tanish-green both surfaces, contains some sand-sized mafic volcanic material, calcareous, volcanic material forms crude thin planar-tabular bedding. Unit weathers to popcorn slopes. Contact sharp with 43.	5.2
Unit 41 - Volcaniclastic siltstone: grayish-white both surfaces, calcareous, moderately indurated, structureless. Unit weathers to small ledge. Contact sharp with 42.	0.035
Unit 40 - Claystone: light tanish-green both surfaces, contains some sand sized mafic volcanic material, calcareous, one bed. Unit weathers to popcorn slopes. Contact gradational with 41.	0.28
Unit 39 - Volcaniclastic sandstone: greenish-gray both surfaces, fine- to medium-grained, subangular, poorly sorted, contains abundant pyroxene and mafic volcanic material, calcareous, well indurated, wavy beds. Unit weathers to ledge. Contact sharp with 40.	0.4
Unit 38 - Claystone: light tanish-green both surfaces, contains some sand sized mafic volcanic material, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 39.	0.35
Unit 37 - Volcaniclastic sandstone: greenish-gray both surfaces, very fine- to coarse-grained, subangular, poorly sorted, contains abundant pyroxene and mafic volcanic material, calcareous, well indurated, normally graded, wavy beds. Unit weathers to ledge. Contact sharp with 38.	0.55
Unit 36 - Pumice ash bed: creamy white both surfaces, calcareous, structureless. Unit weathers to small ledge. Contact sharp with 37. Sample number 970705B.	0.095
Unit 35 - Volcaniclastic sandstone and claystone. Volcaniclastic sandstone: light olive green both surfaces, fine-grained, contains abundant coarse-grained pyroxene and mafic volcanic material, calcareous, structureless. Claystone: light olive green both surfaces, calcareous, structureless. Claystone bed (14 cm) occurs between two sandstone beds. Unit weathers to calcified slopes. Contact sharp with 36.	0.28
contact members 4/5	
Unit 34 - Claystone: dark green fresh surface, greenish-white weathered surface, calcareous, structureless, blocky fracture. Unit has small iron-oxide stain 1.2 m from base. Unit weathers to popcorn slopes. Contact sharp with 35.	1.5
Unit 33 - Sandstone: light tanish-green both surfaces, very fine-grained, calcareous, weakly planar bedded. Unit weathers to calcified slopes. Contact sharp with 34.	0.35
Unit 32 - Silty claystone: light olive gray fresh surface, greenish-white weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 33.	0.45
Unit 31 - Siltstone, tanish-orange fresh surface, light pinkish-tan weathered, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 32.	1.4

Unit 30 - Siltstone and sandstone. Siltstone: light brick red fresh surface, light red weathered surface, calcareous, thin bedded. Sandstone: tanish-orange fresh surface, pinkish-tan weathered surface, very fine-grained, calcareous, structureless. Sandstone occurs as very thin interbeds. Unit weathers to popcorn slopes. Contact gradational with 31 noted by color change. 1.6

Unit 29 - Siltstone, tanish-orange fresh surface, light pinkish-tan weathered, calcareous, structureless. Unit weathers to popcorn slopes. Contact gradational with 30 noted by color change. 0.75

Unit 28 - Granule conglomerate: grayish-red fresh surface, light reddish-brown weathered surface, consist primarily of chert, quartz, petrified wood, and rip up mudstone clasts, sandy matrix, calcareous, structureless. Unit fines upward. Unit weathers to granule covered slopes and ledges. Contact sharp with 29. Sample number 971003L. 0.45

Unit 27 - Interbedded siltstone and sandstone with claystone at top. Arenaceous siltstone: brick red fresh surface, light pink weathered surface, calcareous, contains up to medium sand sized clasts, structureless. Sandstone: tanish-orange fresh surface, pinkish-tan weathered surface, fine-grained, subrounded, moderately sorted, quartzose, calcareous, low-angle planar cross-bedded, well indurated. Claystone: brick red fresh surface, calcareous, structureless. Siltstone dominants sandstone 2:1. Unit fines to red claystone at top. Unit forms popcorn slopes and ledges. Contact sharp with 28. Sample #971003M 5.4

Unit 26 - Silty claystone: light olive green fresh surface, light greenish-white weathered surface, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 27. 0.35

Unit 25 - Argillaceous siltstone, light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 26. 0.32

Unit 24 - Interbedded silty claystone and sandstone. Silty claystone: tanish-brown fresh surface, light tan weathered surface, calcareous, less silt toward top, structureless. Sandstone: tanish-orange fresh surface, pinkish-tan weathered surface, very fine-grained, quartzose, calcareous, Structureless. Two equal units of each rock type. Unit weathers to loose and popcorn slopes. Contact gradational with 25 noted by a grain size change. 0.4

contact member 3/4

Unit 23 - Sandstone: tanish-orange fresh surface, pinkish-tan weathered surface, very fine-grained, quartzose, calcareous, structureless. Coarsens upwards to fine-grained, subrounded, poorly sorted, laminated, low angle planar cross-bedded. Unit has well indurated bed 25 cm from base. Unit forms loose slopes and a ledge. Contact sharp with 24. Sample number 971003N. 1.1

Unit 22 - Claystone: light olive green fresh surface, light greenish-white weathered surface, calcareous, structureless. Unit changes to red color at upper 2-3 cm. Unit weathers to popcorn slopes. Contact sharp with 23. 1.2

Unit 21 - Arenaceous siltstone: brick red fresh surface, light pink weathered surface, calcareous, contains up to medium sand sized clasts, structureless. Unit weathers to loose slopes. Contact sharp with 22. 0.2

Unit 20 - Sandstone: pinkish-tan fresh surface, light tan weathered surface, very fine-grained, weakly calcareous, thin bedded. Unit weathers to loose slopes. Contact sharp with 21. 0.75

Unit 19 - Silty claystone interbedded with siltstone. Silty claystone: tanish-brown fresh surface, light tan weathered surface, calcareous, structureless. Siltstone: light olive gray fresh surface, calcareous, slightly arenaceous, structureless. Unit weathers to popcorn slopes. Contact sharp with 20.	0.2
Unit 18 - Sandstone: pinkish-tan fresh surface, light tan weathered surface, very fine-grained, weakly calcareous, thin bedded. Unit weathers to loose slopes. Contact sharp with 19.	0.15
Unit 17 - Siltstone: light olive gray fresh surface, calcareous, slightly arenaceous, structureless. Unit weathers to calcified slopes. Contact sharp with 18.	0.2
Unit 16 - Silty claystone: tanish-brown fresh surface, light tan weathered surface, calcareous, structureless. Unit fines upwards to very little silt content. Unit weathers to popcorn slopes. Contact sharp with 17.	1.5
Unit 15 - Sandstone: light pinkish-tan both surfaces, very fine-grained, tuffaceous, very calcareous, well indurated, structureless. Unit weathers to ledge. Contact sharp with 16.	0.03
Unit 14 - Sandstone: light pinkish-tan both surfaces, fine-grained, contains chert and some mafic minerals, weakly calcareous, thin bedded. Unit fines upwards to very fine-grained. Unit weathers to loose slope. Contact gradational with 15 noted by tuffaceous component.	1.3
Unit 13 - Sandstone: greenish-white fresh surface, light greenish-white weathered surface, medium-grained, subrounded, poorly sorted, weakly calcareous, structureless. Unit fines upward to reddish siltstone at upper contact. Unit weathers to loose slopes. Contact sharp with 14.	2.5
Unit 12 - Claystone: dark olive green fresh surface, light greenish-white weathered surface, calcareous, laminated at base. Unit weathers to popcorn slopes. Contact sharp with 13.	0.7
Unit 11 - Sandstone: greenish-white fresh surface, light greenish-white weathered surface, very fine-grained, weakly calcareous, structureless. Unit weathers to loose slopes. Contact sharp with 12.	1.1
Unit 10 - Siltstone: 10YR 7/3 grayish-orange both surfaces, weakly calcareous, structureless. Unit weathers to loose slopes. Contact sharp with 11.	0.4
Unit 9 - 13.71 Ma ash bed: N9 white, fine-grained, felsic, vitric, calcareous, finely laminated at base reworked with siltstone of 10 at top, wavy bed. Unit weathers to prominent ledge. Contact gradational with 10 due to reworked upper surface of ash bed. Sample number 970315C.	0.32
Unit 8 - Siltstone: light pinkish-tan both surfaces, arenaceous, mafic minerals present, calcareous, slightly shaley, structureless. Unit weathers to calcified slope. Contact sharp with 9.	2.4
Unit 7 - Claystone: 5YR 5/2 pale brown fresh surface, 10YR 8/1 very pale orange weathered surfaces, slightly silty, calcareous, shaley. Unit weathers to loose slopes. Contact sharp with 8.	0.6
Unit 6 - Sandstone: 10YR 8/2 very pale orange both surfaces, very fine-grained, contains chert and some mafic minerals, weakly calcareous, structureless. Unit weathers to loose slopes. Contact sharp with 7.	0.2

Unit 5 - Siltstone: 10YR 7/3 grayish-orange both surfaces, weakly calcareous, structureless. Unit weathers to loose slopes. Contact sharp with 6.	0.6
Unit 4 - Blue-gray #1 ash bed: N8.5 very light gray fresh surface, 5YR 8/1 grayish-orange pink weathered surface, calcareous, wavy bed. Unit weathers to small ledge. Contact gradational with 5 due to reworked upper surface of ash bed. Sample #970717D.	0.11
Unit 3 - Siltstone: 10YR 7/3 grayish-orange both surfaces, weakly calcareous, structureless. Unit weathers to loose slopes. Contact sharp with 4.	0.8
Unit 2 - Blue-gray #2 ash bed: 5PB 7.5/2 pale blue fresh surface, 5YR 7/1 grayish-orange pink weathered surface, vitric, calcareous, wavy bed. Unit weathers to small ledge. Contact gradational with 3 due to reworked upper surface of ash bed. Sample #970717C.	0.24
Unit 1 - Siltstone: 10YR 7/3 grayish-orange both surfaces, weakly calcareous, structureless. Unit weathers to loose slopes. Contact sharp with 2.	NM
Base of formation not exposed	
Total thickness measured	**40.345**

Appendix B-7

Location 7 on Figure 2.2 (Arnold section)

Measured by Jacob staff and tape measure on July 17, 1997

Field Assistant: Bo Burgess

Location: Navajo Reservation, Greasewood 7.5' Quadrangle, N 35° 35.054' by W 109° 47.404' North of the highway at the first recognizable projection of Wingate Fm from below Bidahochi units. Arnold lives in the house just on the west side of this point and a small Hogan is across the valley on the east side. Section starts at large s/s outcrop of Moenave Formation.

Outcrop Attitude: unable to measure, assumed flat

Measured bottom up

#7 Arnold section	**Meters**
Cliff to top of mesa, not able to measure further	
Unit 32 - Similar material as unit 30 but trough cross-bedded units are more abundant and thicker. See large rip-up clasts of laminated ash within some units. Unit weathers to large cliff, unable to measure further.	NM
Unit 31 - Mafic tuff: 5Y 5/5 olive brown both surfaces, medium lapilli, clast supported, calcareous, structureless. Unit weathers to cliff. Contact sharp with 32.	0.3

Unit 30 - Interbedded siltstone, sandstone, tuff, and tuffaceous claystone. Siltstone: 10YR 7/2 pale grayish orange fresh surface, 10YR 7.5/2 pale orange weathered surface with some mottling present, calcareous, structureless. Sandstone:10YR 7/2 pale grayish orange fresh surface, 10YR 7.5/2 pale orange weathered surface, very fine-grained, volcaniclastic, calcareous, trough cross-bedded. Mafic tuff: 5Y 5/5 olive brown both surfaces, medium lapilli, clast supported, calcareous, single bed. The two mafic tuff beds (5-10 cm thick) occur in the middle of unit. Tuffaceous claystone: N9 white, weakly calcareous, structureless. Tuffaceous claystone beds (1-3 cm) occur throughout unit but are more abundant in upper third of unit. Unit weathers to cliff. Contact sharp with 31. 6.1

contact members 5/6

Unit 29 - Volcaniclastic sandstone fining upwards to volcaniclastic siltstone. Volcaniclastic sandstone: 5Y 7/2 yellowish-gray fresh surface, 5Y 6.5/2 yellowish-gray weathered surface, fine- to medium-grained, moderately to poorly sorted, angular to rounded, contains coarse mafic clasts in lower 1.55 m, very calcareous, thin bedded. Volcaniclastic siltstone: 5GY 4/2 yellow olive green both surfaces, calcareous, structureless. Unit fines upwards to siltstone at 1.55 m. Unit weathers to ledge at base and slopes above. Contact scour with 30. 1.95

Unit 28 - Volcaniclastic sandstone with mafic tuff and claystone fining upwards to volcaniclastic siltstone. Volcaniclastic sandstone: 5GY 4/2 yellow olive green both surfaces, medium- to coarse-grained, moderately to poorly sorted, angular to rounded, contains mafic clasts, calcite lined vugs and pores, very calcareous, thin bedded. Mafic tuff: 5GY 4/2 yellow olive green both surfaces, fine lapilli, clast supported, single bed. Claystone: N9 white, calcareous, well indurated, lenticular. Volcaniclastic siltstone: 5GY 4/2 yellow olive green both surfaces, calcareous, structureless. Mafic tuff occurs as thin bed (5 cm thick) near base. White lenticular claystone beds occur in lower 50 cm of unit. Unit fines upwards to siltstone at 0.5 m. Unit weathers to ledge at base and slopes above. Contact sharp with 29. 2.25

Unit 27 - Claystone coarsening upwards into siltstone: Claystone: 10YR 6/2 pale yellowish-brown fresh surface with areas of white mottling, slightly volcaniclastic, very calcareous, structureless. Siltstone: 5GY 4/2 yellow olive green both surfaces, volcaniclastic, calcareous, structureless. Unit begins to grade into siltstone 1 m from base. Unit weathers to slopes. Contact sharp with 28. Sample #970717B of mottled claystone. 1.95

Unit 26 - Volcaniclastic sandstone: 5GY 4/2 yellow olive green both surfaces, medium- to coarse-grained, moderately to poorly sorted, angular to rounded, contains mafic clasts, calcite lined vugs and pores, very calcareous, structureless. Unit weathers to small cliff. Contact sharp with 27. 0.8

Unit 25 - Claystone: 5GY 4/2 yellow olive green fresh surface, 5GY 8/2 pale grayish-yellow green weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 26. 0.3

Unit 24 - Volcaniclastic sandstone: 5GY 4/2 yellow olive green both surfaces, medium- to coarse-grained, moderately to poorly sorted, angular to rounded, contains mafic clasts, calcite lined vugs and pores, very calcareous, single bed. Unit weathers to small cliff. Contact sharp with 25. 0.35

Unit 23 - Interbedded volcaniclastic siltstone and volcaniclastic sandstone, Volcaniclastic siltstone: 5GY 4/2 yellow olive green both surfaces, calcareous, thin-bedded and lenticular. Volcaniclastic sandstone: 5GY 4/2 yellow olive green both surfaces, fine- to medium-grained, moderately to poorly sorted, angular to rounded, contains mafic clasts and pyroxene amphibole grains from the Hopi Buttes volcanic field, calcareous, thin-bedded. The finer grained beds in this unit punch-out laterally and bed surfaces tend to be undulatory and deformed in places. Unit weathers to cliffs and slopes. Contact sharp with 24. 3.1

contact members 4/5

Unit 22 - Claystone: 5GY 4/2 yellow olive green fresh surface, 5GY 8/2 pale grayish-yellow green weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 23. 1.5

Unit 21 - Claystone: 5YR 5/4 pale light brown fresh surface, 5YR 3.5/4 moderate brown weathered surface, has a pink cast to upper beds, slightly silty, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact gradational with 22 noted by color change. 0.7

Unit 20 - Sandstone: 10R 7.5/3 orange pink both surfaces, very fine-grained, contains coarse sand and granule clasts, calcareous, weakly thin bedded, blocky fracture. Top of unit has a tuffaceous component similar to unit 16. Unit weathers to slope. Contact sharp with 21. 0.45

Unit 19 - Ash bed: N9 white fresh surface, 5YR 8/4 moderate orange pink weathered surface, calcareous, weakly laminated. Unit weathers to break in slope. Contact gradational with 20 due to reworked upper surface of ash bed. Sample #970717A. 0.19

Unit 18 - Siltstone: 10R 7.5/3 orange pink both surfaces, calcareous, structureless. Unit weathers to slope. Contact sharp with 19. 0.25

Unit 17 - Silty claystone: 5R 4/4 moderate grayish-red fresh surface, 10R 6/3 orange red weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 18. 0.25

Unit 16 - Tuffaceous siltstone: 5YR 8/1 pinkish-gray fresh surface, 5YR 6.5/4 light brown weathered surface, contains biotite and glass shards, weakly calcareous, structureless. Unit weathers to slope. Contact sharp with 17. 0.11

Unit 15 - Silty claystone: 5R 4/4 moderate grayish-red fresh surface, 10R 6/3 orange red weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 16. 0.15

Unit 14 - Siltstone: 10R 7.5/3 orange pink both surfaces, calcareous, structureless. Unit weathers to slope. Contact sharp with 15. 0.11

Unit 13 - Silty claystone: 5R 4/4 moderate grayish-red fresh surface, 10R 6/3 orange red weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 14. 0.2

Unit 12 - Siltstone: 10R 7.5/3 orange pink both surfaces, calcareous, structureless. Unit weathers to slope. Contact sharp with 13. 0.23

Unit 11 - Silty claystone: 5R 4/4 moderate grayish-red fresh surface, 10R 6/3 orange red weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 12. 0.4

Unit 10 - Siltstone: 10R 7.5/3 orange pink both surfaces, calcareous, structureless. Unit weathers to slope. Contact sharp with 11.	0.1
Unit 9 - Silty claystone: 5R 4/4 moderate grayish-red fresh surface, 10R 6/3 orange red weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 10.	0.2
Unit 8 - Siltstone: 10R 7.5/3 orange pink both surfaces, calcareous, structureless. Unit weathers to slope. Contact sharp with 9.	0.14
Unit 7 - Silty claystone: 5R 4/4 moderate grayish-red fresh surface, 10R 6/3 orange red weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 8.	0.3
Unit 6 - Sandstone: 10YR 7/4 grayish-orange both surfaces, very fine-grained, contains occasional coarse-grained clasts, calcareous, sparkles, structureless. Unit weathers to slope. Contact sharp with 7.	0.3
Unit 5 - Silty claystone: 5R 4/4 moderate grayish-red fresh surface, 10R 6/3 orange red weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 6.	1.3
Unit 4 - Sandstone: 10YR 7/4 grayish-orange both surfaces, very fine-grained, contains occasional coarse-grained clasts, calcareous, sparkles, structureless. Unit weathers to slope. Contact sharp with 5. Sample #971003S.	0.6
contact Moenave Formation/Bidahochi Formation member 4	
Unit 3 - Granule conglomerate: 10R 7/3 orange pink fresh surface, 5YR 5/4 light brown weathered surface, clast supported, coarse sand matrix, contains predominately quartz and chert clasts, very calcareous, horizontal bedded, weakly normal graded. Unit is localized and has been eroded away laterally. Unit weathers to ledge. Contact disconformity with 4. Sample #971003R.	0 to 0.25
Unit 2 - Moenave Formation - sandstone: 5YR 7.5/2 grayish-orange pink fresh surface, 5YR 6.5/2 grayish-orange pink weathered surface, coarse-grained, poorly sorted, well rounded, very calcareous, well indurated, high-angle planar cross-bedded with sets 2-3 m thick. Unit is localized and has been eroded away laterally. Unit weathers to ledge. Contact sharp with 3. Sample #971003Q.	0 to 1.4 with max of 3.7 nearby
Unit 1 - Wingate Formation - sandstone: 10YR 7/6 grayish-yellowish-orange both surfaces, medium-grained, moderately sorted, rounded, quartzose, structureless. Unit is localized and has been eroded away laterally. Unit has soft sediment deformation on upper surface. Unit not exposed. Contact scour with 2.	NM
Total thickness measured (Bidahochi Fm only)	**24.58**

Appendix B-8

Location 8 on Figure 2.2 (East Lake Margin Section)

Measured by Jacob staff and tape measure on November 7, 1997

Field Assistant: Phil Gensler

Location: Navajo Reservation, Greasewood 7.5' Quadrangle, N 35° 35.171' by W 109° 45.742' North of the highway where a small road cut has exposed a conglomerate and an ash bed. Just before the old Sunrise Trading Post.

Outcrop Attitude: N68W 3SW from unit 3

Measured bottom up

#8 East Lake Margin	Meters
Erosion and/or Quaternary units	
Unit 31 - Sandstone, fine-grained, well indurated. Rest of exposure removed by erosion or covered by Recent dunes. Could be as much as 10 m left of section by impossible to tell due to hummocky topography.	NM
Unit 30 - Volcaniclastic sandstone: 10Y 5/2 olive both surfaces, medium-grained, poorly to moderately sorted, angular to subrounded, contains mafic Hopi Buttes volcanic material, calcareous, low-angled planar cross-bedded. Unit weathers to cliff. Contact sharp with 31.	1.5
Unit 29 - Sandstone: 5Y 7/2 yellowish-gray both surfaces, very fine- to fine-grained, poorly to moderately sorted, angular to subrounded, contains abundant layers of mafic Hopi Buttes material, calcareous, large-scale trough cross-bedded. Paleocurrent reading of S15W. Unit weathers to cliff. Contact sharp with 30.	1.3
Unit 28 - Argillaceous sandstone: 10YR 6/4 yellowish-orange brown both surfaces, fine- to medium-grained, poorly sorted, rounded, calcareous, structureless. Unit weathers to slope but is partially covered by scree. Contact sharp with 29.	0.6
Unit 27 - Sandy travertine: 5YR 8/1 pinkish-gray fresh surface, 5YR 8/5 moderate orange pink weathered surface, contains mafic clasts - especially at top, lattice-like structure. Unit weathers to cliff. Contact sharp with 28.	0.35
Unit 26 - Volcaniclastic sandstone: 5GY 5/1 moderate olive gray both surfaces, fine-grained, moderately sorted, angular to subrounded, contains mafic Hopi Buttes volcanic material, calcareous, low-angle planar cross-bedded. Top of unit contains abundant volcanic material. Unit weathers to ledges. Contact sharp with 27.	1.4
Contact members 5/6	
Unit 25 - Argillaceous sandstone: 10YR 6/4 yellowish-orange brown both surfaces, fine- to medium-grained, poorly sorted, rounded, calcareous, structureless, contains calcified rootlets and has a mottled texture. Unit weathers to slope. Contact sharp with 26.	1.5
Unit 24 - Mafic tuff: N7 light gray both surfaces, medium lapilli, clast supported, calcareous, weakly thin bedded to laminated. Unit weathers to small cliff. Contact sharp with 25.	1.8
Unit 23 - Volcaniclastic sandstone: 5GY 5/1 moderate olive gray both surfaces, fine-grained, moderately sorted, angular to subangular, contains mafic Hopi Buttes volcanic material, calcareous, planar-tabular thin- to laminated-bedded. Unit weathers to ledges. Contact sharp with 24.	1.9

Unit 22 - Volcaniclastic sandstone: 5Y 7/3 dusky yellow gray both surfaces, very fine- to coarse-grained, poorly sorted, contains mafic Hopi Buttes volcanic material, slightly silty, calcareous, thick-bedded. Coarse-grained material occurs as small beds. Unit weathers to cliff. Contact gradational with 23 noted by a structural and grain size change.	0.7
Unit 21 - Volcaniclastic sandstone: 5GY 5/1 moderate olive gray both surfaces, fine-grained, moderate sorted, angular to subangular, contains mafic Hopi Buttes volcanic material, calcareous, laminated planar and trough cross-bedded. Unit weathers to cliff. Contact gradational with 22 noted by a structural and grain size change.	1.1
Unit 20 - Sandy travertine: 5YR 8/1 pinkish-gray fresh surface, 5YR 8/5 moderate orange pink weathered surface, apparent bedding and pillar like structure. Unit weathers to cliff. Contact sharp with 21.	0.3 to 0.65
Unit 19 - Volcaniclastic sandstone: 5GY 5/1 moderate olive gray both surfaces, medium-grained, moderate to poorly sorted, angular to subangular, contains mafic Hopi Buttes volcanic material, calcareous, wavy laminated planar cross-bedded in some areas. Unit weathers to cliff. Contact sharp with 20.	1.15
contact member 4/5	
Unit 18 - Sandstone: 10YR 7/4 grayish-orange both surfaces, fine-grained, poorly sorted - contains some coarse sand, well rounded, argillaceous at bottom, calcareous, wavy laminated planar-tabular bedded. Unit weathers to slope. Contact sharp with 19.	1.9
Unit 17 - Claystone: 10YR 5/2 yellowish-brown fresh surface, arenaceous at top, calcareous, structureless. Unit weathers to popcorn slopes. Contact gradational with 18 noted by disappearance of clay.	1.0
Unit 16 - Travertine: 5YR 8/1 pinkish-gray fresh surface, 5YR 8/5 moderate orange pink weathered surface, slightly arenaceous, apparent bedding and pillar-like structure. Unit weathers to cliff. Contact sharp with 17.	0.11
Unit 15 - Sandstone: 10YR 7/4 grayish-orange both surfaces, fine-grained, poorly sorted - contains some coarse sand, well rounded, calcareous, structureless. Unit weathers to slope. Contact sharp with 16.	0.1
Unit 14 - Travertine: 5YR 8/1 pinkish-gray fresh surface, 5YR 8/5 moderate orange pink weathered surface, slightly arenaceous, apparent bedding and pillar-like structure. Unit weathers to cliff. Contact sharp with 15.	0.25
Unit 13 - Sandstone: 10YR 7/6 yellowish-orange both surfaces, fine-grained, well sorted, rounded, weakly calcareous, structureless. Unit weathers to loose slope. Contact sharp with 14.	0.7
Unit 12 - Travertine: 5YR 8/1 pinkish-gray fresh surface, 5YR 8/5 moderate orange pink weathered surface, slightly arenaceous, apparent bedding and pillar-like structure, contains plant and root casts. Unit weathers to cliff. Contact sharp with 13.	1.0
Unit 11 - Sandstone fining upwards into mudstone. Sandstone: 5YR 6/4 light brown both surfaces, fine- to medium-grained, poorly sorted, well rounded, argillaceous, calcareous, structureless. Mudstone: 5YR 5/6 light brown both surfaces, arenaceous, calcareous, structureless. Unit weathers to slope partially covered by scree. Contact sharp with 12.	1.1

Unit 10 - Conglomerate: 10YR 8/2 very pale orange both surfaces, consists of disc-shaped granules and pebbles, clast supported, contains chert, quartz, quartzite, sandstone, and mudstone clasts, calcareous, moderately indurated, low-angled planar cross-bedded. Unit fines slightly upwards. Unit weathers to ledge and cliff. Contact sharp with 11. 1.4

Unit 9 - Sandstone: 5YR 6/4 light brown both surfaces, fine-grained with some coarse-grained sand, poorly sorted, well rounded, calcareous, laminated trough cross-bedded. Coarse material occurs in troughs. Unit weathers to slope. Contact sharp with 10. 1.1

Unit 8 - Sandstone: 10YR 7.5/2 very pale orange fresh surface, 5Y 6.5/3 dusky yellowish-gray weathered surface, fine-grained, well sorted, well rounded, very calcareous, well indurated, thin- to medium-bedded. Unit weathers to ledge. Contact gradational with 9 noted by a change in structure and induration. 0.13

Unit 7 - Sandstone and claystone. Sandstone: 5YR 6/4 light brown both surfaces, fine-grained with some coarse-grained sand, poorly sorted, well rounded, calcareous, laminated trough cross-bedded. Coarse material occurs in troughs. Claystone: 5YR 6/4 light brown both surfaces, arenaceous, calcareous, structureless. Claystone bed (11 cm thick) occurs at 45 cm above base. Unit weathers to slope. Contact gradational with 8 noted by a change in structure and induration. 0.95

Unit 6 - Sandstone fining upwards into mudstone. Sandstone: 5YR 4/3 moderate brown both surfaces, fine- to very fine-grained, moderately sorted, rounded, argillaceous, calcareous, structureless. Mudstone: red both surfaces, arenaceous, calcareous, structureless. Unit weathers to slope. Contact gradational with 7 noted by a change in grain size and structure. 1.7

Unit 5 - Sandstone: 5YR 6/4 light brown both surfaces, fine- to medium-grained with some coarse granule lenses, poorly sorted, well rounded, calcareous, weakly trough cross-bedded. Unit fines upward into fine-grained sandstone with no coarse material near top. Unit weathers to slope. Contact gradational with 6 noted by change in grain size and structure. 1.4

Unit 4 - Conglomerate and sandstone. Conglomerate: 5YR 7/4 orange brown pink both surfaces, consists of granules and pebbles, clast supported, contains chert, quartz, quartzite, abundant petrified wood, sandstone, and mudstone clasts, calcareous, moderately indurated, weakly trough cross-bedded. Sandstone: 5YR 7/4 orange brown pink both surfaces, medium -grained, moderately sorted, rounded, calcareous, weakly trough cross-bedded. Sandstone occurs as lenses up to 10 cm thick. Unit weathers to ledge. Contact sharp with 5. 1.5

Unit 3 - Ash bed and tuffaceous sandstone. Ash bed: N9 white fresh surface, 5YR 7/3 moderate grayish-orange pink weathered surface, felsic, vitric, calcareous, wavy laminated. Tuffaceous sandstone: 5YR 6/4 light brown both surfaces, fine-grained, subrounded, moderately sorted, calcareous, structureless. Ash bed is basal 0.9 m and upper 1 meter is sandstone mixed with ash. Unit weathers to ledge. Contact sharp with 4. Sample #971003V. 1.9

Unit 2 - Bidahochi Fm - Conglomerate and sandstone. Conglomerate: 5YR 7/4 orange brown pink both surfaces, consists of granules and pebbles, clast supported, contains chert, quartz, quartzite, abundant petrified wood, sandstone, and mudstone clasts, calcareous, moderately indurated, weakly trough cross-bedded, contains plant or wood-like material. Sandstone: 5YR 7/4 orange brown pink both surfaces, medium -grained, moderately sorted, rounded, calcareous, weakly trough cross-bedded. Sandstone occurs as a lense (10 cm thick). Unit weathers to ledge. Contact sharp with 3. Sample #971107V of woody material. 0.55

contact Wingate Formation/member 4 Bidahochi Formation

Unit 1 - Wingate Fm - Sandstone: 5YR 5.5/6 light brown fresh surface, 5YR 6/4 light brown weathered surface, fine-grained, well sorted, rounded, quartzose, calcareous. well indurated, structureless. Unit weathers to calcified slope. Contact disconformity with 2.	NM
Total thickness measured	**30.74 m**

Appendix B-9e

Location 9 on Figure 2.2 (east flat tire mesa section)

Measured by Jacob staff and tape measure on July 23, 1997

Field Assistant: Carey Lang

Location: Navajo Reservation, First Flat Mesa 7.5' Quadrangle, N 35° 32.696' by W 110° 09.067' North of the road in the second gully from the east. Section starts along west side of this gully near the mouth of small canyon.

Outcrop Attitude: dip of unit 10 varies from location to location, measured as flat. The lower volcanic units are at an angular discordance with overlying units.

Measured bottom up

#9 east flat tire mesa	**Meters**
Cliff to top of mesa, not able to measure further	
Unit 19 - Mafic volcanic breccia: Reddish-brown both surfaces, contains accidental material, calcareous, structureless. Unit scours at an angle through lower unit. Unit weathers to cliff.	NM ~5.6
Unit 18 - Interbedded siltstone and claystone. Siltstone: 10YR 7/2 gray yellowish-orange both surfaces, slightly argillaceous, calcareous, structureless. Claystone: 5Y 5/2 light olive gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, very calcareous, structureless, blocky fracture. Unit is volcaniclastic in areas. Unit is fractured and soft-sediment deformed due to emplacement of unit 19. Unit weathers to slope under a cliff. Contact scour with 19.	0.3 to 2.5
Unit 17 - Claystone: 5Y 5/2 light olive gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 18.	1.0
Unit 16 - Claystone: 5Y 4/4 moderate olive brown fresh surface, 5YR 5/4 light brown weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact gradational with 17 noted by a color change.	1.2
Unit 15 - Siltstone: 10YR 7/2 gray yellowish-orange both surfaces, slightly argillaceous, calcareous, structureless. Unit weathers to slope. Contact sharp with 16.	1.3
Unit 14 - Claystone: 5Y 5/2 light olive gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 15.	0.15

Unit 13 - Siltstone interbedded with sandstone. Siltstone: 10YR 7/2 gray yellowish-orange both surfaces, slightly argillaceous, calcareous, structureless. Sandstone: 10YR 7/2 gray yellowish-orange both surfaces, very fine-grained, calcareous, structureless. Unit weathers to slope. Contact sharp with 14. 3.15

Unit 12 - Tuffaceous claystone: white with brown both surfaces, calcareous, structureless. Unit weathers to slope. Contact sharp with 13. Sample #970723L. 0.11

Unit 11 - Siltstone and sandstone. Siltstone: 10YR 7/2 gray yellowish-orange both surfaces, slightly argillaceous, calcareous, structureless. Sandstone: 10YR 7/2 gray yellowish-orange both surfaces, very fine-grained, calcareous, structureless. Sandstone bed occurs 30 cm from base. Unit weathers to slope. Contact sharp with 12. 1.1

Unit 10 - Ash bed: banded with brown claystone fresh surface, N9 white weathered surface, fine-grained, felsic, vitric, calcareous, laminated. Unit weathers to prominent ledge. Contact gradational with 11 due to reworked upper surface of ash bed. Sample #970723KK. 0.22

Unit 9 - Siltstone: 10YR 7/2 gray yellowish-orange both surfaces, slightly argillaceous, calcareous, structureless. Unit weathers to slope. Contact sharp with 10. 0.6

Unit 8 - Claystone and tuffaceous bed. Claystone: 5Y 5/2 light olive gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, very calcareous, structureless, blocky fracture. Tuffaceous bed: N9 white fresh surface, calcareous, structureless. Tuffaceous bed (13 cm thick) occurs at 0.6 m from base. Unit weathers to popcorn slopes. Contact sharp with 9. 1.3

Unit 7 - Siltstone: 10Y 8/2 pale greenish-yellow both surfaces, slightly argillaceous, calcareous, structureless. Unit weathers to slope. Contact sharp with 8. 0.2

Unit 6 - Claystone: 10YR 5/4 moderate yellowish-brown fresh surface, weathered surface covered, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact partially covered by soil with 7. 0.55

Unit 5 - Claystone: 5Y 5/2 light olive gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact gradational with 6 noted by a color change. 0.35

Unit 4 - Mafic tuff: 5Y 7/2.5 yellowish-gray fresh surface, 10Y 6/2 pale olive weathered surface, coarse lapilli, clast supported, little or no matrix present, contains some accidental material, calcareous, thin to thick planar-tabular bedded. A mafic agglutinate bomb layer occurs at 1.1 m with clasts as big as 1 meter long. Upper 1 meter of unit is reworked into low-angled planar cross-beds. Unit weathers to cliff. Contact in angular discordance with 5 due to onlap of units above. 2.5

Unit 3 - Mafic sandstone: 5Y 7/2.5 yellowish-gray fresh surface, 10Y 6/2 pale olive weathered surface, fine- to coarse-grained, moderately sorted, subangular to subrounded, contains accidental clasts (Wingate Fm and lower Bidahochi units), calcareous, finely wavy laminated, some lenticular beds, trough and planar cross-bedded, contains antidunes and bomb sags. Unit is thin- to medium-bedded with coarse material primarily in thicker beds. Unit weathers to ledges and slopes. Contact sharp with 4. 1.1

Unit 2 - Silty claystone: 10YR 8/4 gray yellowish-orange fresh surface, 10YR 7/2 orange yellowish-brown weathered surface, volcaniclastic especially at base, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 3. 0.4

Unit 1 - Mafic sandstone: 5Y 6/2 yellowish-olive gray fresh surface, 5Y 7/4 grayish-yellow weathered surface, fine- to coarse-grained, moderately sorted, subangular to subrounded, contains accidental clasts (Wingate Fm and lower Bidahochi units), calcareous, finely wavy laminated, some lenticular beds, trough and planar cross-bedded, contains antidunes and bomb sags, calcite amygdules in coarser units. Unit is thin- to medium-bedded with coarse material primarily in thicker beds. Unit weathers to ledges and slopes. Contact sharp with 2.	3.5 + rest of unit is covered
Base of the formation not exposed	
Total thickness measured	**25.03**

Appendix B-9w

Location 9 on Figure 2.2 (west flat tire mesa section)

Measured by Jacob staff and tape measure on May 19, 1998

Field Assistant: None

Location: Navajo Reservation, First Flat Mesa 7.5' Quadrangle, N 35° 32.781' by W 110° 09.114' North of the road and west of previous section. In gully up from where stream crosses the road. Follow stream up and stay to the right until large waterfall is present. Section starts just downstream of waterfall and proceeds up over fall and up to mesa on west side of stream.

Outcrop Attitude: dip of unit 28 varies from location to location, measured as flat. The lower volcanic sequence units are at angular discordance with overlying units.

Measured bottom up

#9 west flat tire mesa	**Meters**
Top of mesa, no further exposure	
Unit 38 - Mafic lava: N1 black both surfaces, aphanitic. In nearby locations tuff breccia occurs below lava at claystone contact.	14
Unit 37 - Claystone: 5GY 5/2 dusky yellow green fresh surface, 10Y 6/2 pale olive weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact scour with 38.	0.5
Unit 36 - Claystone: 5YR 4/4moderate brown fresh surface, 5YR 6/4 light brown weathered surface, has patches of green color and white mottled-like spots, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact gradational with 37 noted by a color change.	1.9
Unit 35 - Sandstone: 10YR 7/2 pale grayish-orange both surfaces, very fine-grained, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 36.	0.1
Unit 34 - Claystone: 5GY 5/2 dusky yellow green fresh surface, 10Y 6/2 pale olive weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 35.	0.3

Unit 33 - Siltstone: 10YR 8/2 very pale orange both surfaces, calcareous, structureless, blocky fracture. Unit weathers to break in slope. Contact sharp with 34. 0.7

Unit 32 - Claystone: 5GY 5/2 dusky yellow green fresh surface, 10Y 6/2 pale olive weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 33. 0.4

Unit 31 - Siltstone: 10YR 8/2 very pale orange both surfaces, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 32. 0.4

Unit 30 - Claystone: 5GY 5/2 dusky yellow green fresh surface, 10Y 6/2 pale olive weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 31. 0.3

Unit 29 - Siltstone: 10YR 8/2 very pale orange both surfaces, calcareous, structureless, blocky fracture. Unit weathers to break in slope with last 1.5 m partially covered by colluvium. Contact sharp with 30. 6.0

Unit 28 - Ash bed: N9 white fresh surface, 10YR 8/2 very pale orange weathered surface, fine-grained, felsic, vitric, calcareous, well indurated, wavy laminated. Unit weathers to prominent ledge. Contact gradational with 11 due to reworked upper surface of ash bed. Sample #980106D. 0.22

Unit 27 - Siltstone: 10YR 8/2 very pale orange both surfaces, calcareous, structureless, blocky fracture. Unit weathers to break in slope. Contact sharp with 28. 1.1

Unit 26 - Siltstone fining upwards to claystone. Siltstone: 10Y 7/2 pale greenish-olive fresh surface, 10Y 8/2 pale greenish-yellow weathered surface, argillaceous, calcareous, structureless, blocky fracture. Claystone: 10Y 7/2 pale greenish-olive fresh surface, 10Y 8/2 pale greenish-yellow weathered surface, very calcareous, structureless, blocky fracture. Unit fines to claystone 10 cm from base. Unit weathers to popcorn slope. Contact gradational with 27 noted by a color change and reduction in clay. 1.2

Unit 25 - Siltstone: 10YR 8/2 very pale orange both surfaces, calcareous, structureless, blocky fracture. Unit weathers to break in slope. Contact gradational with 26 noted by a color change and increase in clay. 0.5

Unit 24 - Siltstone: 10Y 7/2 pale greenish-olive fresh surface, 10Y 8/2 pale greenish-yellow weathered surface, argillaceous, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact gradational with 25 noted by a color change and reduction in clay. 0.2

Unit 23 - Claystone: 5YR 4/4 moderate brown fresh surface, 10YR 5/4 brown weathered surface, has patches of green color and white mottled-like spots, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 24. 1.5

Unit 22 - Siltstone: 10YR 8/2 very pale orange both surfaces, arenaceous, calcareous, structureless, blocky fracture. Unit weathers to break in slope. Contact sharp with 23. 0.8

Unit 21 - Claystone: 5GY 5/2 dusky yellow green fresh surface, 10Y 6/2 pale olive weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 22. 1.2

Unit 20 - Mafic tuff: 5Y 5/2 light olive gray both surfaces, very coarse lapilli, clast supported, little or no matrix present, contains some accidental material, very calcareous, medium- to thick-bedded. Unit fines to medium lapilli 1.6 m from base. At 1.1 m, unit contains a bomb layer consisting of huge mafic bombs up to 1.6 m in length. Above bomb layer, tuff is reworked into small low-angled planar cross beds with possible reverse grading. Unit weathers to cliff then slope. Contact in angular discordance with 21 due to onlap of above units. Sample #980118A of glassy mafic bomb. 2.5

Unit 19 - Interbedded mafic sandstone and mafic siltstone. Mafic sandstone: 10Y 6/2 pale olive both surfaces, fine- to coarse-grained, moderately sorted, subangular to subrounded, silty, contains accidental clasts (Wingate Fm and lower Bidahochi units), calcareous, thin to medium planar-tabular bedded. Mafic siltstone, 10Y 6/2 pale olive both surfaces, calcareous, thin beds. Coarse material primarily in thicker beds. Unit weathers to cliff. Contact sharp with 20. 0.8

Unit 18 - Mafic tuff: 5Y 5/2 light olive gray both surfaces, very coarse lapilli, clast supported, little or no matrix present, contains some accidental material, very calcareous, single bed, calcite amygdules. Unit weathers to ledge. Contact sharp with 19. 0.3

Unit 17 - Interbedded mafic sandstone and mafic siltstone. Mafic sandstone: 10Y 6/2 pale olive both surfaces, fine- to coarse-grained, moderately sorted, subangular to subrounded, silty, contains abundant accidental clasts (Wingate Fm and lower Bidahochi units), calcareous, laminated to thin-bedded and trough cross-bedded. Mafic siltstone, 10Y 6/2 pale olive both surfaces, calcareous, thin beds. Some beds are lenticular or truncated by upper units. Unit contains antidunes and large bomb sags (bombs up to 60 cm in diameter). Coarse material primarily in thicker beds. Unit weathers to cliff. Contact sharp with 18. 0.8

Unit 16 - Siltstone: 10YR 8/2 very pale orange both surfaces, calcareous, planar-tabular thin-bedded. Upper 30 cm of unit is mixed with material from unit 17. Unit weathers to slope. Contact gradational with 17 due to mixed zone. 0.7

Unit 15 - Mafic tuff: 5Y 5/2 light olive gray both surfaces, medium to coarse lapilli, clast supported, little or no matrix present, contains some accidental material, biotite common, very calcareous, planar-tabular medium to thick-bedded. Unit weathers to ledges and slopes. Contact sharp with 16. Sample 980118B of biotite rich tuff. 0.6

Unit 14 - Siltstone and mafic tuff. Siltstone: 5Y 3/2 olive gray both surfaces, calcareous, structureless, blocky fracture. Mafic tuff: 5Y 3/2 olive gray both surfaces, coarse lapilli, clast supported, little or no matrix present, contains some accidental material, very calcareous, single bed. Tuff bed (3 cm thick) occurs 10 cm from base. Unit contains mafic bombs up to 6 cm in diameter. Unit is planar-tabular thin-bedded. Unit weathers to ledge. Contact sharp with 15. 0.2

Unit 13 - Mafic tuff: 5Y 5/2 light olive gray both surfaces, medium to coarse lapilli, clast supported, little or no matrix present, contains some accidental material, very calcareous, planar-tabular medium to thick-bedded. Unit weathers to ledges and slopes. Contact sharp with 14. 0.8

Unit 12 - Interbedded mafic sandstone and mafic siltstone. Mafic sandstone: 10Y 6/2 pale olive both surfaces, fine- to coarse-grained, moderately sorted, subangular to subrounded, silty, contains accidental clasts (Wingate Fm and lower Bidahochi units), calcareous, laminated to thin planar-tabular bedded. Mafic siltstone, 10Y 6/2 pale olive both surfaces, calcareous, thin beds. Coarse material primarily in thicker beds. Unit weathers to ledges and slopes. Contact sharp with 13. 1.0

Unit 11 - Mafic tuff: 5Y 5/2 light olive gray both surfaces, medium to coarse lapilli, clast supported, little or no matrix present, contains some accidental material, very calcareous, single bed. Unit weathers to ledge. Contact sharp with 12.	0.4
Unit 10 - Interbedded mafic sandstone and mafic siltstone. Mafic sandstone: 10Y 6/2 pale olive both surfaces, fine- to coarse-grained, moderately sorted, subangular to subrounded, silty, contains accidental clasts (Wingate Fm and lower Bidahochi units), calcareous, laminated to thin planar-tabular bedded. Mafic siltstone, 10Y 6/2 pale olive both surfaces, calcareous, thin beds. Some beds are lenticular or truncated by upper units. Unit contains antidunes and bomb sags. Coarse material primarily in thicker beds. Unit weathers to ledges and slopes. Contact sharp with 12.	0.3
Unit 9 - Mafic tuff: 5Y 5/2 light olive gray both surfaces, medium to coarse lapilli, clast supported, little or no matrix present, contains some accidental material, very calcareous, single bed. Unit weathers to ledge. Contact sharp with 10.	0.4
Unit 8 - Interbedded mafic sandstone and mafic siltstone. Mafic sandstone: 10Y 6/2 pale olive both surfaces, fine- to coarse-grained, moderately sorted, subangular to subrounded, silty, contains accidental clasts (Wingate Fm and lower Bidahochi units), calcareous, laminated to thin planar-tabular bedded. Mafic siltstone, 10Y 6/2 pale olive both surfaces, calcareous, thin beds. Coarse material primarily in thicker beds. Unit weathers to ledges and slopes. Contact sharp with 9.	0.4
Unit 7 - Mafic tuff with mafic siltstone interbeds. Mafic tuff: 5Y 5/2 light olive gray both surfaces, medium lapilli, clast supported, little or no matrix present, contains some accidental material, very calcareous, thin-bedded. Mafic siltstone, 10Y 6/2 pale olive both surfaces, calcareous, thin beds. Siltstone interbeds occur as two 1 cm thick beds. Unit weathers to ledge. Contact sharp with 8.	0.5
Unit 6 - Mafic sandstone fining upwards to mafic siltstone. Mafic sandstone: 10Y 6/2 pale olive both surfaces, fine- to coarse-grained, moderately sorted, subangular to subrounded, silty, contains accidental clasts (Wingate Fm and lower Bidahochi units), calcareous, weakly thin-bedded. Mafic siltstone, 10Y 6/2 pale olive both surfaces, calcareous, thin beds. Unit fines to siltstone 6 cm above base. Unit weathers to break in slope and slopes. Contact sharp with 7.	0.5
Unit 5 - Claystone: 5GY 5/2 dusky yellow green fresh surface, 10Y 8/2 pale greenish-yellow weathered surface, very calcareous, laminated, shaley. Unit weathers to popcorn slopes. Contact sharp with 6.	0.3
Unit 4 - Mafic tuff: 5Y 5/2 light olive gray both surfaces, fine lapilli, clast supported, little or no matrix present, contains some accidental material, very calcareous, single bed. Unit weathers to ledge. Contact sharp with 5.	0.15
Unit 3 - Interbedded mafic sandstone and mafic siltstone. Mafic sandstone: 10Y 6/2 pale olive both surfaces, fine- to coarse-grained, moderately sorted, subangular to subrounded, silty, contains accidental clasts (Wingate Fm and lower Bidahochi units), calcareous, thin to very thin planar-tabular bedded. Mafic siltstone, 10Y 6/2 pale olive both surfaces, calcareous, thin beds. Coarse material primarily in thicker beds. Unit weathers to ledges and slopes. Contact sharp with 4.	0.8
Unit 2 - Mafic tuff: 5Y 5/2 light olive gray both surfaces, fine lapilli, clast supported, little or no matrix present, contains some accidental material, very calcareous, single bed. Unit weathers to ledge. Contact sharp with 3.	0.15

Unit 1 - Mafic sandstone: 10Y 6/2 pale olive both surfaces, very fine- to coarse-grained, moderately sorted, subangular to subrounded, silty, contains accidental clasts (Wingate Fm and lower Bidahochi units), calcareous, thin to very thin planar-tabular bedded. Coarse material primarily in thicker beds. Unit weathers to ledges and slopes. Contact sharp with 2.	0.5 + rest of unit is covered
Base of the formation not exposed	
Total thickness measured	**43.42**

Appendix B-10

Location 10 on Figure 2.2 (Deshgish Butte SE):

Measured by Jacob staff and tape measure on July 06, 1997.

Field Assistant: Elizabeth Tyack

Location: Navajo Reservation, White Cone 7.5' Quadrangle, Lat 35^0 30.491", Long 110^0 03.425' Located on the southeastern point of the Butte.

Outcrop attitude: N30E 06NW measured from unit 15

Measured bottom up

#10 Deshgish Butte SE	**Meters**
Top of mesa, no further exposure	
Unit 29 - Mafic lava: black both surfaces, rubbley at base. Unit weathers to steep cliff.	~ 6.0
Unit 28 - Mafic tuff: Olive brown to tan both surfaces, coarse to fine lapilli, fines upward, calcareous, weakly thick bedded. Unit pinches out to the west under lava flow. Unit weathers to cliff. Contact sharp with 29.	4.0
Unit 27 - Tuff sandstone interbedded with tuff siltstone. Tuff sandstone: light tan to light pinkish-tan both surfaces, medium- to coarse-grained, poorly to moderately sorted, subangular, mafic, contains Wingate Fm and lower Bidahochi clasts, calcareous, well indurated, trough cross-bedded, contains antidunes and bomb sags. Tuff siltstone: light tan to light pinkish-tan both surfaces, calcareous, laminated to thin bedded. Unit contains antidunes and bomb sags. Unit weathers to cliff, Contact sharp with 28.	4.5
Unit 26 - Mafic tuff: Olive brown to tan both surfaces, coarse to fine lapilli, fines upward, calcareous, weakly thick bedded. Unit weathers to cliff. Contact gradational with 27.	2.3
Unit 25 - Volcaniclastic sandstone and volcaniclastic claystone. Volcaniclastic sandstone: light brown both surfaces, fine to coarse-grained, coarsens upwards, poorly sorted, subangular to subrounded, contains abundant mafic Hopi Buttes volcanic material, calcareous, laminated to thin bedded planar. Volcaniclastic claystone: light olive green fresh surface, contains mafic volcanic material, very calcareous, lenticular. Volcaniclastic claystone occurs as 3, 6-10 cm thick beds interbedded with the sandstone. The claystone units are soft-sediment deformed - clastic dikes and disrupted bedding. Unit weathers to cliff. Contact sharp with 26.	0.8

contact members 4/5

Unit 24 - Claystone: light olive green fresh surface, light greenish-white weathered surface, calcareous, structureless, very blocky fracture. Unit forms popcorn slopes. Contact sharp with 25. 1.7

Unit 23 - Interbedded silty claystone and siltstone. Silty claystone: light olive green fresh surface, light greenish-white weathered surface, calcareous, structureless. Siltstone: light tanish orange both surfaces, argillaceous, calcareous, structureless. Unit is thin to medium bedded with siltstone dominant lower half then claystone dominant upper half. Unit forms popcorn and calcified crusted slopes. Contact gradational with 24. 3.3

Unit 22 - Siltstone: light tanish orange both surfaces, argillaceous, calcareous, structureless. Unit weathers to popcorn slopes. Contact gradational with 19. 0.85

Unit 21 - Interbedded claystone and silty claystone. Claystone: brownish-brick red fresh surface, light reddish-tan weathered surface, calcareous, structureless. Silty claystone: light tanish-brown fresh surface, light pinkish-tan weathered surface, calcareous, very thin beds. Unit is medium bedded defined by very thin beds of silty claystone. Unit weathers to popcorn slopes. Contact sharp with 22. 2.5

Unit 20 - Silty claystone: light tanish-brown fresh surface, light pinkish-tan weathered surface, calcareous, structureless. Unit weathers to popcorn slopes. Contact gradational with 21 noted by a color change. 0.6

Unit 19 - Silty claystone: light olive green fresh surface, light greenish-white weathered surface, contains very fine-grained, platy, clear euhedral grains, calcareous, medium bedded defined by 3-5 cm thick sparkly silt rich beds, blocky fracture. Unit forms popcorn slopes. Contact gradational with 20 noted by color change and loss of sparkly material. 1.8

contact members 3/4

Unit 18 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Contains one 30 cm thick, moderately indurated bed, 30 cm above base. Unit weathers to calcified crusted slopes and a small ledge. Contact sharp with 19. 3.4

Unit 17 - Claystone: light olive green fresh surface, light greenish-white weathered surface, silty at base, calcareous, structureless. Unit forms popcorn slopes. Contact sharp with 18. 0.08

Unit 16 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 17. 10.2

Unit 15 - 13.71 Ma ash bed: white, fine grained, felsic, vitric, calcareous, wavy laminated. Unit weathers to prominent ledge. Contact gradational with 16 due to reworked upper surface of ash bed. 0.26

Unit 14 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 15. 1.35

Unit 13 - Argillaceous siltstone: light olive green fresh surface, light greenish-white weathered surface, contains very fine-grained, platy, clear euhedral grains, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 14. 1.0

Unit 12 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact gradational with 13 noted by color change. 3.75

Unit 11 - Argillaceous siltstone: light olive green fresh surface, light greenish-white weathered surface, contains very fine-grained, platy, clear euhedral grains, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 12.	0.4
Unit 10 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Contains one 35 cm thick, moderately indurated, bed 65 cm above base. Unit weathers to calcified crusted slopes and a ledge. Contact sharp with 11.	3.2
contact members 2/3	
Unit 9 - Silty claystone: light olive green fresh surface, light greenish-white weathered surface, contains very fine-grained, platy, clear euhedral grains, calcareous, medium bedded defined by 3-5 cm thick silt rich beds, blocky fracture. Unit forms popcorn slopes. Contact sharp with 10.	1.95
Unit 8 - Siltstone: light grayish-white fresh surface, white weathered surface, very calcareous, well indurated, one bed, contains occasional mollusk shell. Unit weathers to small ledge. Contact gradational with 9.	0.03
Unit 7 - Silty claystone: light olive green fresh surface, light greenish-white weathered surface, contains very fine-grained, platy, clear euhedral grains, calcareous, medium bedded defined by 3-5 cm thick silt rich beds, blocky fracture. Unit forms popcorn slopes. Contact sharp with 8. Sample #970706A.	2.3
Unit 6 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 7.	0.35
Unit 5 - Silty claystone: dark tanish-green fresh surface, light greenish-tan weathered surface, calcareous, structureless. Unit forms popcorn slopes. Contact sharp with 6 .	0.8
Unit 4 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 5.	2.7
Unit 3 - Claystone: dark tanish-green fresh surface, light greenish-tan weathered surface, selenite noted by not abundant, calcareous, structureless. Unit forms popcorn slopes. Contact sharp with 4.	5.1
Unit 2 - Silty claystone: dark tanish-green fresh surface, light greenish-tan weathered surface, contains abundant large clusters of selenite, calcareous, structureless. Unit forms popcorn slopes. Contact gradational with 3 noted by decrease in silt content.	5.0
Unit 1 - Interbedded argillaceous siltstone and siltstone. Argillaceous siltstone: light greenish-brown fresh surface, light greenish-tan weathered surface, contains abundant large clusters of selenite, very calcareous, structureless. Siltstone: light pinkish-tan both surfaces, small individual crystals of selenite noted, calcareous, structureless. Siltstone occurs as thin beds 5-15 cm thick, more abundant near top. Unit weathers to popcorn slopes. Contact gradational with 2 noted by increased clay content.	6.0
Base of formation not exposed	
Total thickness measured	**76.22**

Appendix B-11

Location 11 on Figure 2.2 (Satan Butte composite section)

Measured by Jacob staff and tape measure on July 20, 1997

Field Assistant: Bo Burgess

Location: Navajo Reservation, Satan Butte 7.5' Quadrangle, western location N 35° 31.384' by W 109° 54.905', eastern location N 35° 31.844' by W 109° 54.464' Composite section with one outcrop located along southern side of mesa. From the east it is located past the quarry on the hill on the first low hill south of the mesa that has the 13.71 Ma ash bed clearly noted on side of hill. Second outcrop located on the eastern most projection of the mesa. Started eastern section from the 13.71 ash bed and proceeded up the slope.

Outcrop Attitude: N64E 3NW measured from unit number 10

Measured bottom up

#11 Satan Butte Composite	**Meters**
Top of mesa, no further exposure	
Unit 28 - Mafic lava: N 1 black, porphyritic, contains small olive phenocrysts, very smooth surface. Unit weathers to cliff.	3.0
Unit 27 - Silty claystone: 10Y 8/2 pale greenish-yellow fresh surface, 10Y 8/4 greenish-yellow weathered surface, calcareous, structureless, blocky fracture. Unit fines upwards and gets darker in color 10Y 6/2 pale olive. At 2.4 m sand-sized mafic clasts are common to very abundant. Upper portion of unit is deformed and scoured by lava of 28. Unit weathers to popcorn slope. Contact scour with 28.	3.0
contact member 4/5 - 2.4 m from the base of 27	
Unit 26 - Siltstone: 5YR 7/2 grayish-orange pink fresh surface, 10R 7.5/4 moderate orange pink weathered surface, slightly argillaceous, calcareous, structureless. Unit weathers to small ledge. Contact sharp with 27.	1.1
Unit 25 - Silty claystone: 5YR 6/6 light brown fresh surface, 5YR 5.5/4 light brown weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact scour with 26.	0.8
Unit 24 - Silty claystone: 5Y 7/2 yellowish-gray fresh surface, 5YR 6.5/4 light brown weathered surface, calcareous, structureless. Unit weathers to popcorn slope. Contact gradational with 25 noted by a color change.	1.0
Unit 23 - Claystone: 10Y 8/2 pale greenish-yellow fresh surface, contains red staining (10R 4/6 moderate reddish-brown) in partings and as random patches, very calcareous, structureless to weakly laminated, blocky fracture. Unit not exposed in slope. Contact gradational with 24 noted by appearance of silt.	0.25
Unit 22 - Siltstone: 10YR 7.5/4 grayish-orange fresh surface, 10YR 8/4 grayish-yellow orange weathered surface, argillaceous at top of unit, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 23.	2.05
Unit 21 - Claystone: 5YR 7/2 grayish-orange pink fresh surface, 5YR 6.5/2 grayish-orange pink weathered surface, calcareous, structureless, very blocky fracture. Unit weathers to popcorn slope. Contact sharp with 22.	0.15

Unit 20 - Claystone: 10Y 6/2 pale olive fresh surface, 10Y 8.5/2 pale greenish-yellow weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact gradational with 21 noted by a color change.	0.2
Unit 19 - Tuffaceous siltstone: 5GY 8.5/1 light greenish-gray fresh surface, calcareous, structureless. Unit not exposed in slope. Contact sharp with 20.	0.1
Unit 18 - Claystone: 10Y 6/2 pale olive fresh surface, 10Y 8.5/2 pale greenish-yellow weathered surface, contains iron-oxide staining (5Y 6/6 dusky yellow olive) at base, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 19.	1.95
contact member 3/4	
Unit 17 - Siltstone: 10YR 8/6 pale yellowish-orange fresh surface, calcareous, structureless. Unit not exposed on slope. Contact sharp with 18.	0.3
Unit 16 - Sandstone: 10YR 6/4 yellowish-brown orange both surfaces, very fine-grained, mafic minerals noted, calcareous, structureless. Unit weathers to calcified slope. Contact sharp with 17.	0.3
Unit 15 - Siltstone: 10Y 8/2 pale greenish-yellow fresh surface, calcareous, structureless. Unit not exposed on slope. Contact sharp with 16.	0.05
Unit 14 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, calcareous, structureless. Unit weathers to calcified slope. Contact sharp with 15.	3.55
Unit 13 - Silty claystone: 10Y 7/2 greenish-yellow olive fresh surface, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 14.	0.12
Unit 12 - Siltstone and sandstone. Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, calcareous, structureless. Sandstone: 10YR 8/4 grayish-yellow orange both surfaces, very fine-grained, silty, calcareous, structureless. Sandstone beds occur after 5.55 m (1-2 cm thick) and occur throughout the unit giving it thick bedded appearance. Unit weathers to calcified slope and ledges. Contact sharp with 13.	11.95
Unit 11 - Satan Butte ash bed: 5Y 9/1 pale yellowish-gray both surfaces, fine-grained, felsic, vitric, calcareous, moderately indurated, laminated. Unit weathers to ledge. Contact gradational with 12 due to reworked upper surface of ash bed. Sample #970720D.	0.17
Unit 10 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, calcareous, structureless. Unit weathers to calcified slope. Contact sharp with 11.	1.65
Unit 9 - 13.71 Ma ash bed: N9 white both surfaces, fine-grained, felsic, vitric, weakly calcareous, wavy laminated. Unit weathers to prominent ledge. Contact gradational with 10 due to reworked upper surface of ash bed. Sample #970720C.	0.38
Unit 8 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, calcareous, weakly laminated to thin bedded. Unit weathers to calcified slope. Contact sharp with 9.	1.6
Unit 7 - Argillaceous siltstone: 5Y 7/2 yellowish-gray fresh surface, 5Y 7.5/2 yellowish-gray weathered surface, calcareous, structureless and blocky basal 9 cm but laminated otherwise. Unit weathers to popcorn slope. Contact sharp with 8.	1.05

Unit 6 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, calcareous, weakly laminated to thin bedded. Unit weathers to calcified slope. Contact sharp with 7.	2.6
Unit 5 - Blue-gray #1 ash bed: 5B 8/1 light bluish-gray white both surfaces, felsic, vitric, friable, weakly laminated. Unit weathers to stain on slope. Contact gradational with 6 due to reworking of upper surface of ash bed. Sample #970720B.	0.07
Unit 4 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, calcareous, structureless. Unit weathers to calcified slope. Contact sharp with 5.	1.5
Unit 3 - Blue-gray #2 ash bed: 5B 7/2 pale blue fresh surface, 5B 7.5/2 very pale blue weathered surface, felsic, vitric, friable, laminated. Unit weathers to ledge. Contact gradational with 4 due to reworking of upper surface of ash bed. Sample #970720A.	0.08
Unit 2 - Siltstone and sandstone. Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, calcareous, structureless. Sandstone: 10YR 8/4 grayish-yellow orange both surfaces, very fine-grained, mafic minerals noted, silty, calcareous, structureless. Sandstone beds occur at 1.7 m (25 cm thick) and 2.1 m (15 cm thick). At 3.65 m have a 8 cm bed of well indurated siltstone that forms ledge. Unit weathers to slope and ledges. Contact sharp with 3.	4.1
Unit 1 - Claystone: 5Y 7/2 yellowish-gray fresh surface, 5Y 7.5/2 yellowish-gray weathered surface, has several white bands, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 2.	2.7
Base of the formation not exposed	
Total thickness measured	**45.77**

Appendix B-12

Location 12 on Figure 2.2 (Greasewood Mesa Section North)

Measured by Jacob staff and tape measure on July 18, 1997

Field Assistant: Bo Burgess

Location: Navajo Reservation, Greasewood 7.5' Quadrangle, N 35° 31.145' by W 109° 49.135' East of Greasewood trading post and east of dirt road that runs along the northern portion of the mesa. Directly east of houses along the road.

Outcrop Attitude: N70E 1SE measured from unit number 40

Measure bottom up

#12 Greasewood Mesa North	**Meters**
Rest of unit removed by erosion at this location	
Unit 52 - Volcaniclastic sandstone: 5B 8/1 bluish-gray white fresh surface, 5B 8.5/1 bluish white weathered surface, medium- to coarse-grained, poorly sorted, euhedral to rounded clasts, calcareous, moderately indurated, trough cross-bedded. Unit weathers to form cliff.	1+

Unit 51 - Siltstone: N8.5 very light gray white fresh surface, 10YR 8/2 very pale orange weathered surface, slightly tuffaceous, calcareous, structureless. Unit weathers to slope. Contact sharp with 52.	0.6
Unit 50 - Sandstone: 10YR 8/2 very pale orange fresh surface, 10YR 8/4 pale yellowish-gray orange weathered surface, very fine-grained, mafic minerals common, calcareous, contains lenses and layers that are very calcified and well indurated like unit 48, large sets of high-angled planar cross-bedded. Concretionary calcite is not restricted to bedding or structure but cross bedding planes and cross bed sets. Unit weathers to slopes with concretions that form thin platy projections from slope. Contact sharp with 51.	2.0
Unit 49 - Sandstone: 10YR 8/4 pale yellowish-gray orange both surfaces, very fine-grained, quartzose, calcareous, large sets of high-angled planar cross-bedded. Unit weathers to slope. Contact gradational with 50 noted by variation in induration.	1.1
Unit 48 - Sandstone: 5YR 7/1 pale grayish-orange pink both surfaces, very fine-grained, very calcareous, well indurated, structureless. Unit weathers to ledge. Contact gradational with 49 noted by variation in induration.	0.1
Unit 47 - Sandstone: 10YR 8/4 pale yellowish-gray orange both surfaces, very fine-grained, quartzose, calcareous, large sets of high-angled planar cross-bedded. Unit weathers to slope. Contact gradational with 48 noted by variation in induration.	4.6
Unit 46 - Siltstone: 10YR 8/4 pale yellowish-gray orange fresh surface, 10YR 8/2 very pale orange weathered surface, calcareous, low-angle planar cross-bedded. Unit weathers to calcified slope. Contact sharp with 47.	2.15
Unit 45 - Sandstone: 5YR 7/1 pale grayish-orange pink both surfaces, very fine-grained, very calcareous, well indurated, structureless. Unit weathers to ledge. Contact sharp with 46.	0.09
Unit 44 - Sandy volcaniclastic siltstone: 5YR 7/2 pale grayish orange fresh surface, 5YR 7/1 pale grayish-orange pink weathered surface, volcanic material is matrix supported, calcareous, structureless. Quantity of volcanic material reduces upwards to almost none at the top. Unit weathers to calcified slope. Contact sharp with 45.	1.7
Unit 43 - Sandstone: N8.5 very light gray white fresh surface, N8 very light gray weathered surface, fine-grained, poorly sorted, rounded to subangular, contains thin wavy layers of coarse-grained mafic Hopi Buttes material, very calcareous, trough cross-bedded at base and planar tabular bedded otherwise. Unit weathers to cliff with heavily calcified concretions that form thin platy projections from cliff. Contact sharp with 44.	9.25
Unit 42 - Sandstone: 10YR 8/4 pale yellowish-gray orange fresh surface, 10YR 7/4 grayish-orange weathered surface, fine-grained, moderately to well sorted, round to subangular, high-angled planar and trough cross-bedded. Where unit scours units 41 and 40, material from these underlying units is mixed with material of this unit. Paleocurrent reading of 270 from channel axis, 240 from forset beds. Unit weathers to ledges and slopes. Contact gradational with 43 noted by change in weathering character and structure.	1.4 to 2.05
contact members 5/6	
Unit 41 - Volcaniclastic sandstone: 5B 7/1 light bluish-gray fresh surface, 5B 8/1 light bluish-gray white weathered surface, medium grained, moderately sorted, subrounded to subangular, calcareous, moderately indurated, planar tabular bedded. Contact with 42 is scour which also cuts into ash bed of unit 40.	0.04

Unit 40 - Greasewood ash bed: N9 white fresh surface, felsic, vitric, calcareous, very well indurated, wavy laminated to structureless. Unit weathers to ledge and forms base of cliff. Contact gradational with 41 due to reworked upper surface of ash bed. Sample #970315B.	0.6
Unit 39 - Sandstone fining upwards into interbedded silty claystone and siltstone: Sandstone: tan both surfaces, fine- to medium-grained, moderately sorted, subangular to rounded, calcareous, trough cross-bedded. Silty claystone: 10Y 6/2 pale olive fresh surface, calcareous, structureless, blocky fracture. Siltstone: 5GY 7.5/1 greenish-gray fresh surface, calcareous, structureless. Siltstone: 5Y 7/2 yellowish-gray fresh surface, volcaniclastic, calcareous, structureless. Unit is medium- to thick-bedded (~ 30-50 cm) and soft sediment deformed in places. Unit weathers to slopes and ledges in slope. Contact sharp with 40.	4.7
Unit 38 - Interbedded silty claystone and siltstone: Silty claystone: 10Y 6/2 pale olive fresh surface, calcareous, structureless, blocky fracture. Siltstone: 5GY 7.5/1 greenish-gray fresh surface, calcareous, structureless. Siltstone: 5Y 7/2 yellowish-gray fresh surface, volcaniclastic, calcareous, structureless. Unit is medium- to thick-bedded (~ 30-50 cm). Abundantly volcaniclastic at base and a 25 cm thick zone, 3.4 m from base. Unit weathers to slopes and ledges. Contact sharp with 39.	3.9
Unit 37 - Tuff sandstone: 5Y 7/6 moderate yellow both surfaces, fine- to medium-grained, poorly to moderately sorted, rounded to subangular, mafic, calcareous, high-angle trough and planar cross-bedded. Unit weathers to cliff. Contact sharp with 38.	0.35
Unit 36 - Interbedded silty claystone and siltstone: Silty claystone: 10Y 6/2 pale olive fresh surface, calcareous, structureless, blocky fracture. Siltstone: 5GY 7.5/1 greenish-gray fresh surface, calcareous, structureless. Siltstone: 5Y 7/2 yellowish-gray fresh surface, volcaniclastic, calcareous, structureless. Unit is medium- to thick-bedded (~ 30-50 cm). Unit weathers to slopes and breaks in slope. Contact sharp with 37.	5.65
Unit 35 - Siltstone: 10YR 8/2 very pale orange fresh surface, 10YR 8/3 pale grayish-orange weathered surface, slightly volcaniclastic, one 2 mm thick mafic clast layer in middle of unit, calcareous, structureless. Unit weathers to slope. Contact sharp with 36.	0.09
Unit 34 - Siltstone: 5G 7/1 pale greenish-yellow green both surfaces, slightly argillaceous, calcareous, structureless, blocky fracture. Unit weathers to small ledge. Contact sharp with 35.	0.15
Unit 33 - Volcaniclastic siltstone: 5YR 7/1 pinkish-brown gray both surfaces, contains sand-sized matrix-supported mafic Hopi Buttes clasts, calcareous, structureless, blocky fracture. Unit weathers to break in slope. Contact gradational with 34 noted by color change and lose of volcanic clasts.	0.15
Unit 32 - Claystone: 5YR 7/2 grayish-orange pink both surfaces, slightly volcaniclastic, matrix supported volcanic material, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 33.	0.2
Unit 31 - Volcaniclastic siltstone: 5YR 7/1 pinkish-brown gray both surfaces, contains sand-sized matrix-supported mafic Hopi Buttes clasts, calcareous, structureless, blocky fracture. Unit does not contain volcanic material above 35 cm and is 5Y 7/2 yellowish-gray in color. Unit weathers to ledge. Contact sharp with 32.	0.5

Unit 30 - Volcaniclastic siltstone: 5YR 7/1 pinkish-brown gray both surfaces, contains sand-sized matrix-supported mafic Hopi Buttes clasts, calcareous, structureless, blocky fracture. Unit does not contain volcanic material above 25 cm and is 10Y 8/3 greenish-yellow in color. Unit weathers to popcorn slope. Contact gradational with 31 noted by appearance of volcanic material. 0.45

Unit 29 - Pumice ash bed: N8 very light gray both surfaces, calcareous, structureless. Unit weathers to break in slope. Contact gradational with 30 due to reworked upper surface of ash bed. Sample #970718B. 0.09

Unit 28 - Volcaniclastic claystone: 10Y 8/2 pale greenish-yellow both surfaces, contains sand-sized matrix-supported mafic Hopi Buttes clasts, calcareous, structureless, blocky fracture. Unit weathers to slope. Contact sharp with 29. 0.23

contact members 4/5

Unit 27 - Silty claystone: 10Y 6/2 olive gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 28. 1.45

Unit 26 - Pebble conglomerate: 10R 5/6 reddish-brown both surfaces, clast supported, contains abundant chert, quartz, petrified wood, and mudstone rip-up clasts, matrix composed of silt and fine-grained sand, iron-oxide stained (10Y 7/4 moderate greenish-yellow) upper 10 cm, weakly calcareous, poorly indurated, low-angle trough cross-bedded. Unit weathers to ledge. Contact sharp with 27. 0.6

Unit 25 - Silty claystone: 10R 3/4 dark reddish-brown fresh surface, 10R 5/4 pale reddish-brown weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact scour with 26. 1.25

Unit 24 - Sandstone: 10YR 6/5 yellowish-orange fresh surface, very fine-grained, calcareous, structureless. Unit weathers to ledge. Contact sharp with 25. 1.1

Unit 23 - Silty claystone: 10R 3/4 dark reddish-brown fresh surface, 10R 5/4 pale reddish-brown weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 24. 4.1

Unit 22 - Interbedded silty claystone, siltstone, and sandstone: Silty claystone: 10R 4/4 reddish-brown fresh surface, 10R 6/4 reddish-orange weathered surface, calcareous, very blocky fracture. Siltstone: 5YR 6/5 light brown both surfaces, calcareous, structureless. Sandstone: 5YR 6/5 light brown both surfaces, very fine-grained, calcareous, moderately indurated, structureless. Unit is thin to medium bedded. Sandstone occurs as two 30 cm thick units in lower half of unit and one 60 cm bed at top of unit. Unit weathers to slopes and ledges. Contact sharp with 23. 3.25

Unit 21 - Sandstone: 10YR 6/5 yellowish-orange fresh surface, very fine-grained, calcareous, weakly trough cross-bedded (small sets). Unit weathers to ledge. Contact gradational with 22 noted by color change. 1.45

Unit 20 - Silty claystone coarsening upwards to sandstone: Silty claystone: 10R 4/4 reddish-brown fresh surface, 10R 6/4 reddish-orange weathered surface, calcareous, slightly shaley at base but otherwise structureless, very blocky fracture. Sandstone: 5YR 6/5 light brown both surfaces, very fine-grained, calcareous, moderately indurated, structureless. Unit grades into siltstone then to sandstone at top of unit. Unit weathers to slopes and ledges. Contact gradational with 21 noted by a color change.	1.25
Unit 19 - Siltstone: N8 very light gray fresh surface, 5GY 8/2 pale grayish-yellow green weathered surface, argillaceous, calcareous, structureless, blocky fracture. Unit weathers to small ledge. Contact sharp with 20.	0.2
Unit 18 - Silty claystone coarsening upwards to sandstone: Silty claystone: 10R 4/4 reddish-brown fresh surface, 10R 6/4 reddish-orange weathered surface, calcareous, slightly shaley at base but otherwise structureless, very blocky fracture. Sandstone: 5YR 6/5 light brown both surfaces, very fine-grained, calcareous, moderately indurated, structureless. Unit grades into siltstone then to sandstone at very top of unit. Unit weathers to popcorn slopes. Contact sharp with 19.	1.05
Unit 17 - Sandstone: 5YR 6/5 light brown both surfaces, very fine-grained, contains some fine sand, calcareous, moderately indurated, structureless. Unit weathers to break in slope. Contact sharp with 18.	0.45
Unit 16 - Sandstone: 10YR 7/4 grayish-orange both surfaces, very fine-grained, abundant dark minerals, slightly calcareous, poorly indurated, structureless. Unit weathers to slope. Contact gradational with 17 noted by a color change.	0.1
Unit 15 - Claystone: 5YR 4/4 moderate brown fresh surface, calcareous, shaley. Unit hidden in slope. Contact sharp with 16.	0.03
Unit 14 - Sandstone: 10R 6/4 reddish-orange both surfaces, very fine-grained, silty, contains occasionally coarse sand clast, calcareous, structureless. Unit weathers to slope. Contact sharp with 15.	0.3
contact members 3/4	
Unit 13 - Silty claystone: 5Y 7.5/2 yellowish-gray fresh surface, 5GY 8/2 pale grayish-yellow green weathered surface, calcareous, structureless, very blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 14.	0.55
Unit 12 - Siltstone: 10Y 8/3 greenish-yellow fresh surface, 5GY 8/2 pale grayish-yellow green weathered surface, calcareous, structureless. Unit weathers to popcorn slope. Contact gradational with 13 noted by increase in clay content.	0.35
Unit 11 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, calcareous, structureless. Unit weathers to calcified slope. Contact gradational with 12 noted by a color change.	0.6
Unit 10 - Sandstone: 5Y 7.5/2 yellowish gray both surfaces, fine-grained, well sorted, subrounded, quartzose, calcareous, structureless. Unit weathers to small ledge. Contact sharp with 11.	0.23
Unit 9 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, calcareous, structureless. Unit weathers to calcified slope. Contact sharp with 10.	0.3
Unit 8 - Silty sandstone: 10YR 7/4 grayish-orange both surfaces, very fine-grained, calcareous, structureless. Unit weathers to small ledge. Contact sharp with 9.	0.28

Unit 7 - Claystone: 10YR 6/2 pale yellowish-brown fresh surface, 10YR 7/2 pale grayish-orange weathered surface, calcareous, weakly very thin-bedded (1-1.5 cm) with silt occurring in partitions (1-2 mm thick). Unit weathers to popcorn slopes. Contact sharp with 8.	0.31
Unit 6 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, calcareous, structureless. Unit weathers to calcified slope. Contact sharp with 7.	0.8
Unit 5 - Silty claystone: 10YR 6/2 pale yellowish-brown fresh surface, 5GY 8/2 pale grayish-yellow green weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 6.	0.09
Unit 4 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, calcareous, structureless. Unit weathers to cliff. Contact sharp with 5.	4.6
Unit 3 - Covered section. Crossed valley floor from ash exposure to base of slope.	6
Unit 2 - 13.71 Ma ash bed: N7.5 light gray fresh surface, 5YR 6/4 light brown weathered surface, felsic, vitric, weakly laminated, calcareous, moderately indurated. Unit is poorly exposed, only occurs along the side of small ravines on flat area before mesa. Sample #970718A.	0.17
Unit 1 - Siltstone: 5YR 5.5/3 light brown both surfaces, calcareous, structureless. Unit not exposed. Contact sharp with 2.	NM
member 3	
Base of the formation not exposed	
Total thickness measured	**72.05**

Appendix B-13

Location 13 on Figure 2.2 (Gray Mesa Section)

Measured by Jacob staff and tape measure on July 13, 1997

Field Assistant: Amy Morrison

Location: Navajo Reservation, Indian Wells 7.5' Quadrangle, N 35° 28.358' by W 110° 06.838' On the southeastern most point of mesa

Outcrop Attitude: N5W 2SW measured from unit number 57

Measured bottom up

#13 Gray Mesa	**Meters**
Top of mesa, no further exposure	
Unit 70 - Mafic lava: black both surfaces, phenocrysts of olive and pyroxene, vesicular to scoriaceous, rubbley base. Unit weathers to cliff.	NM

Unit 69 - Conglomeratic mudstone: tan both surfaces, matrix supported, contains vesicular mafic lava, calcareous, structureless. Unit is scoured mixture of claystone and rubbley base of lava flow of 70. Unit weathers to cliff. Contact scour with 70.	0.15 to 1.3
Unit 68 - Interbedded conglomeratic sandstone and volcaniclastic mudstone. Conglomeratic sandstone: brownish-tan pink both surfaces, medium to fine grained, poorly sorted, angular to subangular, contains pebble-sized matrix supported mafic clasts, calcareous, thin- to medium-bedded. Volcaniclastic mudstone: brownish-tan pink both surfaces, calcareous, thin wavy beds. Unit weathers to cliff. Contact sharp with 69.	1.4
Unit 67 - Volcaniclastic siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified slope. Contact scour with 68.	1.7
Unit 66 - Mafic tuff: peppered black and greenish-tan both surfaces, medium to coarse lapilli, clast supported with little or no matrix, contains euhedral pyroxene and biotite grains, calcareous, one bed. Unit weathers to ledge. Contact sharp with 67.	1.5
Unit 65 - Tuff sandstone with lenses of tuff claystone: greenish-brown both surfaces, medium to fine grained, moderate to poorly sorted, angular to subangular, mafic, calcareous, low-angle trough cross-bedded. Unit weathers to cliff. Contact sharp with 66.	4.7
Unit 64 - Claystone: white fresh surface, light olive green weathered surface, calcareous, well indurated, vuggy, structureless. Unit weathers to cliff. Contact sharp with 65.	0.31
Unit 63 - Tuff sandstone: light tanish-green both surfaces, coarse to fine grained, moderate to poorly sorted, angular to subangular, mafic, calcareous, thin bedded. Unit weathers to cliff. Contact sharp with 64.	0.18
Unit 62 - Claystone: white fresh surface, light olive green weathered surface, calcareous, well indurated, vuggy, structureless. Unit weathers to cliff. Contact sharp with 63.	0.23
Unit 61 - Tuff sandstone: light tanish-green both surfaces, coarse to fine grained, moderate to poorly sorted, angular to subangular, contains two fining upward sequences, mafic, calcareous, thin bedded. Unit weathers to cliff. Contact sharp with 62.	0.25
Unit 60 - Volcaniclastic siltstone: light pinkish-tan both surfaces, contains abundant Hopi Buttes volcanic material, calcareous, structureless. Unit weathers to calcified slope. Contact scour with 61.	0.31
Unit 59 - Claystone: white fresh surface, light olive green weathered surface, calcareous, well indurated, vuggy, structureless. Unit weathers to cliff. Contact sharp with 60.	0.08
Unit 58 - Volcaniclastic siltstone: olive green both surfaces, contains matrix supported Hopi Buttes volcanic material, calcareous, structureless. Unit weathers to calcified slope. Contact sharp with 59.	0.1
contact members 4/5	
Unit 57 - Claystone: white fresh surface, light olive green weathered surface, calcareous, well indurated, vuggy, structureless. Unit weathers to cliff. Contact sharp with 58.	0.56
Unit 56 - Claystone: olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 57.	2.1

contact members 3/4

Unit 55 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified slope. Contact sharp with 56.	1.0
Unit 54 - Claystone: brown fresh surface, light brownish-tan weathered surface, small (3 cm) green layer at top, calcareous, laminated. Unit weathers to break in slope and popcorn slopes. Contact sharp with 55.	0.5
Unit 53 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified slope. Contact sharp with 54.	2.0
Unit 52 - Claystone: brown fresh surface, light brownish-tan weathered surface, small (3 cm) green layer at top, calcareous, laminated. Unit weathers to break in slope and popcorn slopes. Contact sharp with 53.	0.35
Unit 51 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to cliff. Contact sharp with 52.	2.9
Unit 50 - Claystone: brown fresh surface, light brownish-tan weathered surface, small (3 cm) green layer at base and at top, calcareous, laminated. Unit weathers to break in slope and popcorn slopes. Contact sharp with 51. Sample #970713E of brown claystone.	0.8
Unit 49 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to cliff. Contact sharp with 50.	1.3
Unit 48 - Sandstone: light pinkish-tan both surfaces, very fine-grained, quartzose, calcareous, trough cross-bedded. Unit weathers to small cliff. Contact sharp with 49.	0.2
Unit 47 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to cliff. Contact sharp with 48.	5.3
Unit 46 - 13.71 Ma ash bed: white both surfaces, fine-grained, felsic, vitric, calcareous, wavy laminated. Unit weathers to prominent ledge. Contact gradational with 47 due to reworked upper surface of ash bed. Sample #970618A.	0.19
Unit 45 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to cliff. Contact sharp with 46.	1.1
Unit 44 - Claystone: light olive green fresh surface, light greenish-white weathered surface, slightly silty, very calcareous, sparkles, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 45.	0.7
Unit 43 - Tuffaceous siltstone: light whitish-green both surfaces, calcareous, moderately indurated, structureless. Unit weathers to cliff. Contact sharp with 44.	1.1
Unit 42 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to cliff. Contact sharp with 43.	0.5
Unit 41 - Sandstone: light pinkish-tan both surfaces, very fine-grained, quartzose, calcareous, trough cross-bedded. Unit weathers to small cliff. Contact sharp with 42.	1.0
Unit 40 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to cliff. Contact sharp with 41.	1.2

Unit 39 - Sandstone: light pinkish-tan both surfaces, fine-grained, moderately sorted, rounded, quartzose, calcareous, trough cross-bedded. Unit weathers to small cliff. Contact sharp with 40.	0.7
Unit 38 - Siltstone: light pinkish-tan both surfaces, contains lenticular areas of light grayish-white material - tuffaceous?, calcareous, sparkles, structureless. Unit weathers to cliff. Contact sharp with 39.	0.14
Unit 37 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to popcorn slope. Contact gradational with 38 noted by appearance of ash.	2.2
Unit 36 - Covered slope.	2.5
Unit 35 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified slope.	2.0
contact members 2/3	
Unit 34 - Claystone: dark olive green fresh surface, light greenish-white weathered surface, has a 6 cm thick iron-oxide stain at base and throughout lower 1.5 m, calcareous, structureless until near top when becomes laminated, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 35.	3.4
Unit 33 - Siltstone: light brown fresh surface, light brownish tan weathered surface, becomes more pink colored near top of unit, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 34.	2.0
Unit 32 - Silty claystone: brown fresh surface, light brownish tan weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 33.	0.7
Unit 31 - Siltstone: light brown fresh surface, light brownish tan weathered surface, calcareous, structureless. Unit weathers to popcorn slopes. Contact gradational with 32 noted by appearance in clay.	0.5
Unit 30 - Claystone: light olive green fresh surface, light greenish-white weathered surface, slightly silty, very calcareous, sparkles, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 31.	0.4
Unit 29 - Wood Chop D ash bed: white both surfaces, very calcareous, moderately indurated, weakly laminated. Unit weathers to break in slope. Contact gradational with 30 due to reworking of upper surface of ash bed. Sample # 970713D.	0.06
Unit 28 - Claystone: light olive green fresh surface, light greenish-white weathered surface, slightly silty, very calcareous, sparkles, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 29.	0.8
Unit 27 - Wood Chop C ash bed: light greenish-white both surfaces, biotite present, very calcareous, moderately indurated, single bed. Unit hidden in slope. Contact gradational with 28 due to reworking of upper surface of ash bed. Sample # 970713C.	0.07
Unit 26 - Claystone: olive green fresh surfaces, light greenish-white weathered surface, has a 5 cm iron-oxide stain at base, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 27.	1.2

Unit 25 - Siltstone: light pinkish-tan both surfaces, slightly argillaceous, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 26. 0.35

Unit 24 - Silty claystone: olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 25. 0.2

Unit 23 - Siltstone: light brown fresh surface, light brownish tan weathered surface, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 24. 0.15

Unit 22 - Silty claystone: olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 23. 0.2

Unit 21 - Siltstone: light brown fresh surface, light brownish tan weathered surface, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 22. 0.9

Unit 20 - Siltstone fining upwards to silty claystone. Siltstone: light olive green white fresh surfaces, light greenish-white weathered surface, has a iron-oxide stain 0.4 m from base, calcareous, structureless, blocky fracture. Silty claystone: olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless, blocky fracture. Unit fines to silty claystone 0.4 m from the base. Unit weathers to popcorn slope. Contact sharp with 21. 1.7

Unit 19 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to popcorn slope. Contact gradational with 20 noted by color change and appearance of iron-oxide staining. 0.09

Unit 18 - Claystone: brown fresh surface, light brown weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 19. 1.3

Unit 17 - Siltstone and ash . Siltstone: light greenish-white both surfaces, calcareous, structureless, becomes argillaceous near top of unit. Wood Chop A ash bed: white both surfaces, vuggy in places. Ash occurs at base of unit and as thin discontinuous bands through lower half of unit. Ash has been mixed with surrounding siltstone.. Unit weathers to popcorn slope. Contact sharp with 18. Sample #970713B collected of ash. 2.1

Unit 16 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 17. 1.5

Unit 15 - Sandy micritic limestone (marl): white both surfaces, matrix supported sand, bed is undulatory, structureless. Unit weathers to break in slope. Contact sharp with 16. Sample #970713A. 0.05

Unit 14 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to popcorn slope. Upper surface is undulatory and unit pinches out laterally. Contact sharp with 15. 0.08

Unit 13 - Claystone: light yellow olive green fresh surface, light pale yellow greenish-white weathered surface, very calcareous, laminated, shaley habit. Unit weathers to popcorn slopes. Contact sharp with 14. 2.6

Unit 12 - Claystone: olive green with red patches fresh surface, light yellowish-green weathered surface, contains abundant iron-oxide staining, very calcareous, structureless, blocky fracture. Iron-oxide stains on weathered surface are very prominent. Unit weathers to popcorn slopes. Contact gradational with 13 noted by lack of red clay and change to laminated habit.	2.1
Unit 11 - Claystone: olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact gradational with 12 noted by appearance of red clays and iron-oxide staining.	0.2
Unit 10 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 11.	0.06
Unit 9 - Claystone: olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 10.	0.03
Unit 8 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 9.	0.3
Unit 7 - Claystone: olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 8.	0.8
Unit 6 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 7.	0.14
Unit 5 - Silty claystone: olive green fresh surface, light greenish-white weathered surface, contains iron-oxide staining basal 2 m, very calcareous, sparkles, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 6.	3.8
Unit 4 - Siltstone: light olive green white fresh surface, light greenish-white weathered surface, slightly argillaceous, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 5.	1.7
Unit 3 - Siltstone: light pinkish-tan both surfaces, sightly argillaceous, calcareous, structureless. Unit weathers to popcorn slope. Contact gradational with 4 noted by color change and increase in clay content.	0.5
Unit 2 - Silty claystone: olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 3.	1.1
Unit 1 - Siltstone: light pinkish-tan both surfaces, sightly argillaceous, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 2.	NM

member 2

Base of the formation not exposed

Total thickness measured 73.48

Appendix B-14

Location 14 on Figure 2.2 (Red Clay Mesa section)

Measured by Jacob staff and tape measure on July 11, 1997

Field Assistant: Amy Morrison

Location: Navajo Reservation, Indian Wells 7.5' Quadrangle, N 35° 28.992' by W 110° 01.943' Southeast side of mesa, northeast of corrals, just west of straight cliff face.

Outcrop Attitude: N30E 8NW measured from unit number 6

Measured bottom up

#14 Red Clay Mesa	Meters
Top of mesa, no further exposure	
Unit 20 - Mafic lava: black both surfaces, aphanitic, thins to the east. Unit weathers to cliff.	NM (est. ~5)
Unit 19 - Mafic tuff: brownish-green both surfaces, fine to coarse lapilli, clast supported, calcareous, slightly normal graded, thin to thick planar-tabular bedded. Unit weathers to large cliff. Contact sharp with 20.	NM (est. ~15)
Unit 18 - Tuff sandstone: greenish-brown both surfaces, very fine-grained at base but coarsens upwards, mafic, contains accidental clasts (Wingate Fm and lower Bidahochi units), calcareous, finely wavy laminated, some lenticular beds, trough and planar cross-bedded, contains antidunes and bomb sags. Unit weathers to cliff. Contact sharp with 19.	1.7
Unit 17 - Silty claystone and sandy siltstone. Silty claystone: light greenish-white both surfaces, very calcareous, structureless. Sandy siltstone: brownish-green both surfaces, volcaniclastic, contains mafic Hopi Buttes material, calcareous, structureless. Two small sandy siltstone layers occur at 1.5 and 2.1 m. Near top of unit silty claystone contains patchy areas of Hopi Buttes volcanic material. Unit weathers to popcorn slopes. Contact sharp with 18.	4.3
contact members 4/5 - 1.5 m from base of unit 17	
Unit 16 - Siltstone: light pinkish-tan both surfaces, calcareous, moderately indurated, structureless. Unit weathers to small ledge. Contact sharp with 17.	0.75
Unit 15 - Silty claystone: light greenish-white both surfaces, very calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 16.	0.3
Unit 14 - Siltstone: light pinkish-orange tan fresh surface, light pinkish-tan weathered surface, calcareous, structureless. Unit weathers to calcified slopes. Contact sharp with 15.	1.9
Unit 13 - Silty claystone, light pink fresh surface, light pinkish-red weathered surface, very calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 14. Sample #970711.	3.3
Unit 12 - Siltstone: light pinkish-tan both surfaces, slightly argillaceous, calcareous, structureless. Unit weathers to calcified slopes. Contact sharp with 11.	0.1

Unit 11 - Silty claystone, light olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 12.	0.09
Unit 10 - Siltstone: light pinkish-tan both surfaces, slightly argillaceous, calcareous, structureless. Unit weathers to calcified slopes. Contact sharp with 11.	1.3
Unit 9 - Claystone: dark olive green fresh surface, light greenish-white weathered surface, very calcareous, laminated, slightly shaley habit. Unit weathers to popcorn slope. Contact sharp with 10. Sample #970711I collected near base.	1.6
Unit 8 - Siltstone: light olive green fresh surface, light greenish-white weathered, contains red streaked areas on fresh surfaces and has iron-oxide staining on weathered surfaces, calcareous, structureless. Unit becomes argillaceous near top. Unit weathers to slopes. Contact gradational with 9 noted by a dominance of claystone. Sample #970711H collected near base.	0.8
contact members 3/4	
Unit 7 - Siltstone: light pinkish-tan both surfaces, calcareous, weakly thin to medium planar-tabular bedded. At 10.8 m siltstone is more indurated. Unit weathers to calcified slopes then cliff. Contact sharp with 8.	15.7
Unit 6 - 13.71 Ma ash bed: light grayish-white, fine-grained, felsic, vitric, calcareous, wavy laminated. Unit weathers to prominent ledge. Contact gradational with 7 due to reworked upper surface of ash bed. Sample #970427A collected east of this location on south side of Triplets Mesa .	0.28
Unit 5 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified slopes. Contact sharp with 6.	2.15
Unit 4 - Claystone: light olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 5. Sample #970711G collected near base.	1.35
Unit 3 - Siltstone and ash beds. Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Blue-gray #1 and 2 ash beds: blue-gray both surfaces, very fine-grained, entire bed is very wavy (20 cm amplitude). Two ash beds occur at 6.1 and 6.7 m. Unit weathers to calcified slope. Contact sharp with 4. Sample #970711F collected at 6.8 m. Sample #970711L of upper ash bed. Sample #970711K of lower ash bed.	6.9
Unit 2 - Siltstone: light greenish-white both surfaces, calcareous, sparkles, structureless. Unit weathers to popcorn slope. Contact gradational with 3 noted by a color change.	0.1
Unit 1 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to popcorn slope. Contact gradational with 2 noted by a color change.	NM
Base of the formation not exposed	
Total thickness measured	**42.62**

Appendix B-15

Location 15 on Figure 2.2 (Shonto Butte Canyon section)

Measured by Jacob staff and tape measure on August 3, 1997

Field Assistant: Tara Krapf

Location: Navajo Reservation, Dilkon 7.5' Quadrangle, N 35° 25.094' by W 110° 21.888' Located north of yellow butte on the southeast end of Shonto Butte in a deep canyon cut back into mesa. Section is accessed via a small jeep trail that cuts up canyon. Section begins in draw where white ash is exposed in road and proceeds upstream to where mounds of pink siltstone are located. Section then goes north up through sediments.

Outcrop Attitude: N80E 10NW measured from unit number 18. Units 9-18 were measured horizontal and then corrected for apparent dip of unit 18. Attitude changed at base of 25 to N60E 4NW.

Measured bottom up

#15 Shonto Butte Canyon	**Meters**
Edge of lava filled maar rim	
Unit 37 - Mafic lava: N1 black both surfaces, porphyritic - small crystals of olivine and pyroxene/amphibole. Unit weathers cliff.	6+
Unit 36 - Volcaniclastic sandstone and siltstone. Sandstone: 10 R 5/4 pale reddish brown fresh surface, fine- to coarse-grained, angular, contains mafic clasts up to boulder size of Hopi Buttes material, calcareous, planar-tabular bedded. Siltstone: 10YR 8/2 very pale orange fresh surface, calcareous, structureless. Unit is at angular discordance with lower units (N20W 68NE) and dips toward maar crater. Unit weathers to ledge. Contact sharp with 37.	2.1
Unit 35 - Claystone: 10Y 6/2 pale olive fresh surface, slightly silty, very calcareous, structureless. Unit contains breccia blocks of siltstone and mafic aphanitic rock that appear to be out of place and jumbled with claystone. Unit covered by mafic colluvium. Contact scour with 36.	3.2
Unit 34 - Silty micritic limestone (marl): N9 white both surfaces, sparkles, laminated to structureless, contains ostracods. Unit weathers to break in slope. Contact sharp with 35. Sample 970803B.	0.3
Unit 33 - Claystone: 10Y 6/2 pale olive fresh surface, weathered surface covered, slightly silty, very calcareous, sparkles, structureless. Unit weathers to popcorn slope. Contact sharp with 34.	0.65
Unit 32 - Interbedded claystone and silty claystone. Claystone: 5Y 5/2 light olive gray fresh surface, 5Y 6/2 yellowish-olive gray weathered surface, very calcareous, weakly laminated. Silty claystone: 5Y 7/2 yellowish-gray both surfaces, calcareous, structureless, blocky fracture. Unit is more clay-rich at base and more silt-rich near top. Unit weathers to popcorn slope and is partially covered by mafic colluvium. Contact sharp with 33.	7.0
Unit 31 - Silty claystone: 5Y 7/2 yellowish-gray both surfaces, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 32.	3.4
Unit 30 - Claystone: 5Y 5/2 light olive gray fresh surface, 5Y 6/2 yellowish-olive gray weathered surface, very calcareous, weakly laminated. Unit weathers to popcorn slope. Contact sharp with 31.	1.05

Unit 29 - Silty micritic limestone (marl): 5Y 7/1 pale green yellow both surfaces, sparkles, structureless, contains ostracods. Unit weathers to break in slope. Contact sharp with 30. Sample 970803A.	0.45
Unit 28 - Silty claystone: 5Y 7/2 yellowish-gray both surfaces, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 29.	3.5
Unit 27 - Sandstone: 5Y 8/1 yellowish-gray both surfaces, fine-grained, moderately sorted, subangular, calcareous, structureless, contains ostracods. Unit weathers to break in slope. Contact sharp with 28. Sample #980418B.	0.09
contact members 2/5	
Unit 26 - Silty claystone: 5Y 7/2 yellowish-gray both surfaces, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 27.	4.2
Unit 25 - Claystone: 5Y 5/2 light olive gray fresh surface, 5Y 6/2 yellowish-olive gray weathered surface, very calcareous, laminated defined by red (oxidized) partings. Unit weathers to popcorn slope. Contact gradational with 26 noted by color change and increase in silt.	2.65
Unit 24 - Siltstone: 5Y 8/1 yellowish-gray both surfaces, calcareous, moderately indurated, sparkles, structureless. Unit weathers to ledge. Contact sharp with 25.	0.4
Unit 23 - Claystone: 5Y 7/2 yellowish-gray both surfaces, slightly silty, very calcareous, structureless, blocky fracture. Unit very silty at base and top. Unit weathers to popcorn slope. Contact gradational with 24 noted by dominance of silt.	1.25
Unit 22 - Argillaceous siltstone: 10YR 7/2 pale grayish-yellow orange both surfaces, calcareous, moderately indurated, structureless. Unit weathers to popcorn slope. Contact sharp with 23.	2.4
Unit 21 - Sandstone: 10YR 7/2 pale grayish-yellow orange both surfaces, very fine-grained, contains mafic minerals, calcareous, poorly indurated, laminated, contains ostracods and mollusk fragments. Unit weathers to small ledge. Contact sharp with 22. Sample 980418A.	0.14
Unit 20 - Claystone: 5Y 5/2 light olive gray fresh surface, 5Y 6/2 yellowish-olive gray weathered surface, very calcareous, laminated. Unit weathers to popcorn slope. Contact sharp with 21.	1.0
Unit 19 - Argillaceous siltstone: 10YR 7/2 pale grayish-yellow orange both surfaces, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 20.	0.65
Unit 18 - Claystone: 5Y 5/2 light olive gray fresh surface, 5Y 6/2 yellowish-olive gray weathered surface, very calcareous, laminated. Unit weathers to popcorn slope. Contact sharp with 19.	0.49
Unit 17 - Siltstone: 5Y 8/1 yellowish-gray both surfaces, calcareous, sparkles, single bed. Unit weathers to ledge. Contact sharp with 18.	0.15
Unit 16 - Claystone with siltstone interbeds. Claystone: 5Y 7/2 yellowish-gray both surfaces, very calcareous, structureless, blocky fracture. Siltstone: 10YR 7/2 pale grayish-yellow orange both surfaces, calcareous, structureless. Siltstone interbeds vary from 5-10 cm thick and occur above 0.5 m from the base. Unit weathers to popcorn slopes with break in slopes. Contact sharp with 17.	2.46

Unit 15 - Argillaceous siltstone: 10YR 7/2 pale grayish-yellow orange both surfaces, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 16.	0.49
contact members 1/2	
Unit 14 - Claystone: 5Y 7/2 yellowish-gray both surfaces, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 15.	2.07
Unit 13 - Argillaceous siltstone and siltstone. Argillaceous siltstone: 10YR 7/2 pale grayish-yellow orange both surfaces, calcareous, structureless. Siltstone: 10YR 7/2 pale grayish-yellow orange both surfaces, calcareous, laminated. Laminated siltstone bed (7 cm thick) occurs 0.7 m from base. Unit weathers to popcorn slope and break in slope. Contact sharp with 14.	2.95
Unit 12 - Claystone: 5Y 8/1 yellowish-gray both surfaces, slightly silty, very calcareous, sparkles, structureless, very blocky fracture. Unit weathers to popcorn slope. Contact sharp with 13.	0.49
Unit 11 - Argillaceous siltstone and silty claystone. Argillaceous siltstone: 10YR 7/2 pale grayish-yellow orange both surfaces, structureless. Claystone: 5Y 8/1 yellowish-gray both surfaces, slightly silty, very calcareous, sparkles, structureless, very blocky fracture. Claystone bed (10 cm thick) occurs at 1.2 m from base. Unit weathers to popcorn slope. Contact sharp with 12.	2.66
Unit 10 - Claystone: 5Y 8/1 yellowish-gray both surfaces, slightly silty, very calcareous, sparkles, structureless, very blocky fracture. Unit weathers to popcorn slope. Contact sharp with 11.	1.18
Unit 9 - Silty claystone: 10YR 7/2 pale grayish-yellow orange both surfaces, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 10.	0.69
Unit 8 - Covered slope	~0.2
Unit 7 - Claystone: 5Y 8/1 yellowish-gray fresh surface, 5Y 7.5/1 yellowish-gray weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 8.	0.5
Unit 6 - Ash bed: N9 white both surfaces, felsic, partially bentonized, calcareous, structureless. Unit weathers to ledge. Contact gradational with 7 due to reworked upper surface of ash. Sample 970809A.	0.06
Unit 5 - Claystone: 5Y 8/1 yellowish-gray fresh surface, 5Y 7.5/1 yellowish-gray weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 6.	0.85
Unit 4 - Argillaceous siltstone: 10YR 7/2 pale grayish-yellow orange both surfaces, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 5.	0.35
Unit 3 - Tuffaceous claystone: N 8.5 light gray white both surfaces, contains ash from unit below, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 4.	0.65
Unit 2 - Echo Spring Mountain ash bed: N9 white both surfaces, felsic, partially bentonized, calcareous, well indurated, structureless. Unit weathers to ledge. Contact gradational with 3 due to reworked upper surface of ash. Sample 970803C.	0.3

Unit 1 - Claystone: 10YR 6.5/3 pale yellowish-brown both surfaces, slightly silty, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 2.	NM

Base of the formation not exposed

Total thickness measured	**56.97**

Appendix B-16

Location 16 on Figure 2.2 (SW Wood Chop Mesa Section)

Measured by Jacob staff and tape measure on July 19, 1997

Field Assistant: Bo Burgess

Location: Navajo Reservation, Indian Wells 7.5' Quadrangle, N 35° 25.454' by W 110° 02.427' Located along the southwestern side of Wood Chop mesa. A small dirt trail leads to a flat terrace just east of section location. This terrace is the first one west of the Clark houses in the valley. Walk down to red hill located at the base of second point projecting from the mesa.

Outcrop Attitude: N80W 8NE measured from unit number 51

Measured bottom up

#16 SW Wood Chop Mesa	**Meters**
Cliff to top of mesa, no further exposure	
Unit 65 - Mafic lava: N 1 black both surfaces, slightly rubbley base. Unit weathers to cliff.	NM (~20 m)
Unit 64 - Interbedded tuff sandstone and siltstone: Tuff sandstone: 10YR 5/6 yellowish-orange brown both surfaces, medium- to coarse-grained, poorly to moderately sorted, subangular, calcareous, well indurated, thin- to medium-bedded. Tuff siltstone: 10YR 5/6 yellowish-orange brown both surfaces, calcareous, moderately indurated, structureless. Unit weathers to cliff. Contact sharp with 65.	1.1
Unit 63 - Mafic tuff: 10YR 5/4 moderate yellowish-brown both surfaces, fine- to medium lapilli, little or no matrix, clast supported, abundant biotite noted, calcareous, medium bedded, weakly welded. Unit weathers to cliff. Contact sharp with 64.	0.33
Unit 62 - Interbedded tuff sandstone and siltstone: Tuff sandstone: 10YR 5/6 yellowish-orange brown both surfaces, medium- to coarse-grained, poorly to moderately sorted, subangular, mafic, calcareous, well indurated, weakly normal graded, thin- to medium-bedded. Tuff siltstone: 10YR 5/6 yellowish-orange brown both surfaces, mafic, calcareous, moderately indurated, structureless. Unit weathers to cliff. Contact sharp with 63.	0.9
contact member 4/5	

Unit 61 - Siltstone fining upwards to claystone. Siltstone: 10Y 8/2 pale greenish-yellow fresh surface, 5GY 9/1 pale light greenish-gray weathered surface, contains iron oxide staining at base, calcareous, structureless. Claystone: 10Y 8/2 pale greenish-yellow fresh surface, 5GY 9/1 pale light greenish-gray weathered surface, very calcareous, compacted, structureless, blocky fracture. Unit fines to claystone by 1.2 m from base. Unit weathers to slope and cliff due to overlying resistant beds. Contact scour with 62. Sample #980419E of claystone 0.5 m from top of unit. 2.3

contact member 3/4

Unit 60 - Siltstone with ash bed. Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, slightly argillaceous, calcareous, moderately indurated, structureless. Ash bed: N6 gray both surfaces, friable, single discontinuous bed. Ash bed occurs at 2.2 m from base. Unit weathers to calcified slope. Contact sharp with 61. 3.0

Unit 59 - Claystone: 10Y 7/4 moderate greenish-yellow fresh surface, 10Y 8/3 greenish-yellow weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 60. 0.55

Unit 58 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, slightly argillaceous, calcareous, moderately indurated, structureless. Unit weathers to calcified slope. Contact sharp with 59. 2.0

Unit 57 - Claystone: 10Y 7/4 moderate greenish-yellow fresh surface, 10Y 8/3 greenish-yellow weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 58. 0.32

Unit 56 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, slightly argillaceous, calcareous, moderately indurated, structureless. Unit weathers to calcified slope. Contact sharp with 57. 3.4

Unit 55 - Claystone: 10Y 7/4 moderate greenish-yellow fresh surface, 10Y 8/3 greenish-yellow weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 56. 0.16

Unit 54 - Siltstone and sandy siltstone. Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, no clay noted, calcareous, moderately indurated, structureless. Sandy siltstone: 10YR 8/4 grayish-yellow orange both surfaces, calcareous, well indurated, one bed. Sandy bed occurs at 3.5 m from base. Unit weathers to cliff. Contact sharp with 55. 5.2

Unit 53 - Stan Butte ash bed: 5B 9/1 bluish-white both surfaces, fine-grained, felsic, vitric, weakly calcareous, wavy laminated. Unit weathers to ledge. Contact gradational with 54 due to reworked upper surface of ash bed. Sample #971004L. 0.18

Unit 52 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, no clay noted, calcareous, moderately indurated, structureless. Unit weathers to cliff. Contact sharp with 53. 1.05

Unit 51 - 13.71 Ma ash bed: N9 white both surfaces, fine-grained, felsic, vitric, weakly calcareous, wavy laminated. Unit weathers to prominent ledge. Contact gradational with 52 due to reworked upper surface of ash bed. Sample #971004K. 0.30

Unit 50 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, no clay noted, calcareous, moderately indurated, structureless. Unit weathers to cliff. Contact sharp with 51. 2.0

Unit 49 - Claystone: 10Y 7/4 moderate greenish-yellow fresh surface, 10Y 8/3 greenish-yellow weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 42.	1.5
Unit 48 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, no clay noted, calcareous, moderately indurated, structureless. Unit weathers to cliff. Contact sharp with 49.	3.5
Unit 47 - Tuffaceous siltstone: 5Y8/1 yellowish-gray both surfaces, tuffaceous, calcareous, single undulatory bed. Unit appears to contain some glass material. Unit weathers to cliff. Contact sharp with 46. (Blue-gray #2 ash bed?)	0.05
Unit 46 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, no clay noted, calcareous, moderately indurated, structureless. Unit weathers to cliff. Contact sharp with 47.	1.6
Unit 45 - Tuffaceous siltstone: 5Y 8/1 yellowish-gray both surfaces, calcareous, single undulatory bed. Unit weathers to cliff. Contact sharp with 46.	0.05
Unit 44 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, no clay noted, calcareous, moderately indurated, structureless. Unit weathers to cliff. Contact sharp with 45.	1.15
Unit 43 - Tuffaceous siltstone: 5Y 8/1 yellowish-gray both surfaces, calcareous, single undulatory bed. Unit weathers to cliff. Contact sharp with 44.	0.05
Unit 42 - Siltstone: 10YR 8/4 grayish-yellow orange both surfaces, no clay noted, calcareous, moderately indurated, structureless. Unit weathers to cliff. Contact sharp with 43.	1.4
contact member 2/3	
Unit 41 - Interbedded claystone and micritic limestone (marl). Claystone: 10Y 7/4 moderate greenish-yellow fresh surface, 10Y 8/3 greenish-yellow weathered surface, very calcareous, structureless at base but laminated otherwise, blocky fracture. Micritic limestone: 10Y 7/4 moderate greenish-yellow fresh surface, 10Y 8/3 greenish-yellow weathered surface, structureless. Unit weathers to popcorn slope. Contact sharp with 42. Sample #980419D of micritic limestone 30 cm from base.	1.1
Unit 40 - Blue-gray #3 ash bed: N9 white fresh surface, felsic, vitric, weakly calcareous, poorly indurated, laminated. Unit weathers to ledge. Contact gradational with 41 due to reworked upper surface of ash bed. Samples #970719F, 971004J.	0.09
Unit 39 - Silty claystone: 10Y 7/4 moderate greenish-yellow fresh surface, 10Y 8/3 greenish-yellow weathered surface, very calcareous, structureless, blocky fracture. At 1.1 m unit is very blocky with weak to strong lamination defined by alternating shades of green. Unit weathers to popcorn slope. Contact sharp with 40.	3.1
Unit 38 - Siltstone: 10YR 7.5/6 pale yellowish-orange fresh surface, 10YR 8/4 grayish-yellow orange weathered surface, slightly argillaceous, calcareous, structureless. Unit weathers to slope. Contact sharp with 39.	3.6
Unit 37 - Claystone: 5Y 5/2 light olive gray fresh surface, 10YR 8/4 grayish-yellow orange weathered surface, very calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 38.	0.26
Unit 36 - Siltstone: 10YR 7.5/6 pale yellowish-orange fresh surface, 10YR 8/4 grayish-yellow orange weathered surface, slightly argillaceous, calcareous, structureless. Unit weathers to slope. Contact sharp with 37.	0.6

Unit 35 - Claystone: 5Y 5/2 light olive gray fresh surface, 10YR 8/4 grayish-yellow orange weathered surface, no selenite noted, very calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 36. 0.2

Unit 34 - Siltstone: 10YR 7.5/6 pale yellowish-orange fresh surface, 10YR 8/4 grayish-yellow orange weathered surface, calcareous, structureless. Unit weathers to slope. Contact sharp with 35. 2.1

Unit 33 - Claystone: 5Y 5/2 light olive gray fresh surface, 10YR 8/4 grayish-yellow orange weathered surface, selenite abundant, contains iron oxide staining, very calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 34. 2.7

Unit 32 - Wood Chop D ash bed: 5GY 7.5/1 light greenish-gray fresh surface, biotite noted, calcareous, sparkles, wavy laminated. Unit weathers to ledge. Contact gradational with 29 due to reworked upper surface of ash bed. Samples #970719E, 971004I. 0.09

Unit 31 - Claystone: 5Y 5/2 light olive gray fresh surface, 10YR 8/4 grayish-yellow orange weathered surface, slightly silty, selenite abundant, contains iron oxide staining, very calcareous, laminated defined by silty iron oxide layers. Unit weathers to popcorn slope. Contact sharp with 32. 0.6

Unit 30 - Siltstone with tuffaceous siltstone. Siltstone: 5YR 6.5/2 grayish-orange pink both surfaces, calcareous, structureless. Tuffaceous siltstone (Wood Chop C ash bed): N9 white fresh surface, structureless. Tuffaceous bed is basal 9 cm of unit. Unit weathers to ledge and slope. Contact sharp with 31. Sample #971004H of tuffaceous bed. 0.4

Unit 29 - Claystone: 5Y 5/2 light olive gray fresh surface, 10YR 8/4 grayish-yellow orange weathered surface, has a brown cast to upper layers, slightly silty, very calcareous, laminated defined by silt-rich partings. Unit weathers to popcorn slope. Contact sharp with 30. 1.5

Unit 28 - Wood Chop B ash bed: N9 white fresh surface, calcareous, sparkles, weakly laminated. Unit weathers to ledge. Contact gradational with 29 due to reworked upper surface of ash bed. Samples #970719D, 971004G. 0.17

Unit 27 - Claystone: 5Y 5/2 light olive gray fresh surface, 10YR 8/4 grayish-yellow orange weathered surface, slightly silty, gypsum common, very calcareous, laminated defined by silt-rich partings. Unit weathers to popcorn slope. Contact sharp with 28. 1.0

Unit 26 - Siltstone: 5YR 6.5/2 grayish-orange pink surfaces, no selenite noted, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 27. 0.16

Unit 25 - Claystone: 5Y 5/2 light olive gray fresh surface, 10YR 8/4 grayish-yellow orange weathered surface, very little selenite noted, slightly silty, contains iron oxide staining bottom half of unit, very calcareous, laminated defined by silty iron oxide layers. Unit weathers to popcorn slope. Contact sharp with 26. 2.4

Unit 24 - Wood Chop A ash bed: N9 white fresh surface, calcareous, sparkles, structureless. Unit weathers to slope. Contact gradational with 25 due to reworked upper surface of ash bed. Sample #971004F. 0.05

Unit 23 - Siltstone: 5YR 6.5/2 grayish-orange pink surfaces, selenite common, little or no clay present, calcareous, structureless. Unit has vertical fractures that have iron oxide staining. Unit weathers to break in slope. Contact sharp with 24. 0.6

Unit 22 - Claystone: 5Y 5/2 light olive gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, selenite abundant, slightly silty, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 23.	0.1
Unit 21 - Siltstone: 5YR 6.5/2 grayish-orange pink surfaces, selenite common, little or no clay present, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 22.	0.08
Unit 20 - Claystone with tuffaceous zone. Claystone: 5Y 5/2 light olive gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, selenite common, slightly silty, very calcareous, structureless, blocky fracture. Tuffaceous zone (~12 cm): N9 white fresh surface, contains some glass shards, sparkles, structureless. Tuffaceous zone occurs in center of unit. Unit weathers to popcorn slope with tuffaceous bed forming break in slope. Contact sharp with 17. Sample #980419B of tuffaceous unit.	0.35
Unit 19 - Siltstone: 5YR 6.5/2 grayish-orange pink surfaces, selenite common, little or no clay present, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 20.	0.7
Unit 18 - Claystone: 5Y 5/2 light olive gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, selenite common, slightly silty, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 19.	0.5
Unit 17 - Siltstone: 10R 4/4 reddish-brown fresh surface, 10R 8/4 orange pink weathered surface, selenite common, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 18.	0.1
Unit 16 - Claystone with tuffaceous bed. Claystone: 5Y 5/2 light olive gray fresh surface, 10YR 8/4 grayish-yellow orange weathered surface, selenite abundant, slightly silty, very calcareous, laminated defined by silty iron oxide stained layers. Unit has abundant iron oxide staining but becomes less abundant last ~2 m. Tuffaceous bed: N9 white fresh surface, contains some glass shards, sparkles, structureless. Unit weathers to popcorn slope with tuffaceous bed forming break in slope. Contact sharp with 17. Sample #980419C of tuffaceous unit.	5.7
Unit 15 - Siltstone: 10R 4/4 reddish-brown fresh surface, 10R 8/4 orange pink weathered surface, selenite common, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 16.	0.4
Unit 14 - Claystone: 5Y 5/2 light olive gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, selenite common, slightly silty, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 15.	0.2
Unit 13 - Argillaceous siltstone: 10R 4/4 reddish-brown fresh surface, 10R 8/4 orange pink weathered surface, selenite common, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 12.	0.25
Unit 12 - Claystone: 5Y 5/2 light olive gray fresh surface, 10YR 8/4 grayish-yellow orange weathered surface, selenite abundant especially at top, slightly silty, very calcareous, structureless, blocky fracture. Unit has abundant iron oxide staining 50 cm from base which becomes less abundant last ~2 m. Unit weathers to popcorn slope. Contact sharp with 13.	5.9
Unit 11 - Argillaceous siltstone :10R 4/4 reddish-brown fresh surface, 10R 8/4 orange pink weathered surface, selenite common, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 12.	0.6

Unit 10 - Claystone: 5Y 5/2 light olive gray fresh surface, 5Y 7/2 yellowish-gray weathered surface, selenite abundant especially at top, slightly silty, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 11. 0.35

Unit 9 - Argillaceous siltstone:10R 4/4 reddish-brown fresh surface, 10R 8/4 orange pink weathered surface, selenite abundant especially at base, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 10. 4.55

Unit 8 - Sandy siltstone with ash fines upward into silty micritic limestone (marl). Sandy siltstone: 10Y 7/2 greenish-yellow olive fresh surface, 5Y 7/2 yellowish-gray weathered surface, contains medium-grained chert and quartz clasts, calcareous, structureless with middle of unit weakly wavy laminated. East point biotite ash bed: N9 white fresh surface, contains abundant biotite, mixed with sandy siltstone. Silty micritic limestone: 10Y 7/2 greenish-yellow olive fresh surface, 5Y 7/2 yellowish-gray weathered surface, contains quartz and chert clasts, selenite common, structureless. Unit changes into micritic limestone 60 cm from base. Unit weathers to slope and ledge. Contact sharp with 9. Samples #980419A and 971004E of ash, #970719C of micritic limestone. 1.6

contact member ½

Unit 7 - Interbedded claystone and silty claystone with one siltstone layer. Claystone: 10R 4/4 reddish-brown fresh surface, 10R 6/4 reddish-orange weathered surface, selenite abundant crystals and roses with crystals up to 2 cm long, calcareous, partially laminated, some portions appear to have microstructures - small spherical balls and wavy lines. Silty claystone: 10R 4/4 reddish-brown fresh surface, 10R 6/4 reddish-orange weathered surface, calcareous, laminated. Silty claystone: 5Y 7/2 yellowish-gray fresh surface, very calcareous, structureless. Green silty claystone occurs as one 6 cm bed 80 cm from base. Siltstone: 10R 6/4 reddish-orange both surfaces, calcareous, structureless, occurs as one 12 cm bed 2.6 m from base. Gypsum tends to occur in more claystone rich layers but is not restricted to one bedding plane but crosses bedding and has no preferred orientation. Entire unit is thin bedded to laminated and varies due to silt content. Unit weathers to popcorn slope with small breaks in slope. Contact sharp with 8. Sample #980318A collected of claystone with spherical nodules. 4.1

Unit 6 - Claystone grading into silty claystone. Claystone: 10R 4/4 fresh surface, 10R 6/4 reddish-orange weathered surface, selenite abundant crystals and roses with crystals up to 2 cm long, calcareous, partially laminated. Silty claystone: 5Y 7/2 yellowish-gray fresh surface, very calcareous, structureless. Unit grades to silty claystone at 0.37 m. Unit weathers to popcorn slope. Contact gradational with 7 noted by a color change. 0.4

Unit 5 - Argillaceous siltstone: 10R 5/4 pale reddish-brown fresh surface, 10R 6/4 reddish-orange weathered surface, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 6. 1.9

Unit 4 - Siltstone: 5YR 7/2 grayish-orange pink both surfaces, no clay present, contains some very fine sand, slightly calcareous, poorly indurated, structureless. Unit weathers to popcorn slope. Contact gradational with 5 noted by appearance of clay. 0.29

Unit 3 - Echo Spring Mountain ash bed: 5Y 8/1 yellowish-gray fresh surface, N9 white weathered surface, felsic, extensively bentonized, weakly laminated. Unit weathers to small ledge. Contact gradational with 4 due to reworked upper surface of ash bed. Sample #970719B. 0.12

Unit 2 - Bidahochi Formation - Siltstone and sandstone. Siltstone: 10R 5/4 pale reddish-brown fresh surface, 10R 6/4 reddish-orange weathered surface, contains small pebbles of quartz and chert at the base, contains isolated (matrix supported) coarse-sand grains, calcareous, structureless. Sandstone: 5YR 7/4 grayish-orange pink both surfaces, very fine-grained, laminated to ripple laminated. Sandstone occurs as thin (1-7 cm thick) beds and lenses throughout unit with an increase of beds at 11 m. Unit weathers to popcorn slope and ledges. Contact sharp with 3. Sample #970719A collected of siltstone, #971004D of pebbles.	14.45
contact Wingate Formation/member 1 Bidahochi Formation	
Unit 1 - Wingate Formation - Siltstone: 10YR 7/6 yellowish-gray orange both surfaces, calcareous, well indurated, structureless. Unit is mottled and oxidized at upper surface. Unit weathers to calcified slopes. Contact disconformity with 2. Sample #971004C.	NM
Total thickness measured	**95.45**

Appendix B-17

Location 17 on Figure 2.2 (East of Martinez Spring Section)

Measured by Jacob staff and tape measure on July 12, 1997

Field Assistant: Amy Morrison

Location: Navajo Reservation, Greasewood Spring 7.5' Quadrangle, N 35° 26.428' by W 109° 58.252' On the east side of mesa across from the spring, on the north side of canyon

Attitude: N12E 5NW measured from unit number 11

Measured bottom up

#17 East of Martinez Spring	Meters
Top of mesa, no further exposure	
Unit 19 - Mafic lava: black both surfaces, aphanitic, appears granular with lots of white specks?, rounded surfaces, appears bedded, apparent pillow structures. Unit weathers to cliff.	NM
contact member 4/5	
Unit 18 - Silty claystone: brown fresh surface, light pinkish-brown weathered surface, very calcareous, structureless, blocky fracture. Unit varies in thickness due to contact with lava. Unit weathers to popcorn slope. Contact scour with 19.	0.5
Unit 17 - Silty claystone: light olive green fresh surface, light greenish-white weathered surface, iron-oxide staining at base, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact gradational with 18 noted by color change.	2.3
contact member 3/4	
Unit 16 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified slopes. Contact sharp with 17.	5.1

Unit 15 - Silty claystone: light olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 16.	0.6
Unit 14 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified slopes. Contact sharp with 15.	6.85
Unit 13 - Claystone: light olive green fresh surface, light greenish-white weathered surface, slightly silty, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 14.	0.06
Unit 12 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified slopes. Contact sharp with 13.	1.0
Unit 11 - 13.71 Ma ash bed: light grayish-white with bottom 6 cm more gray cast, fine-grained, felsic, vitric, calcareous, wavy laminated. Unit weathers to prominent ledge. Contact gradational with 12 due to reworked upper surface of ash bed. Sample #970712C collected above 6 cm. Sample #970712D collected lower 6 cm.	0.28
Unit 10 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified slopes. Contact sharp with 11.	2.1
Unit 9 - Claystone: light olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 10.	1.1
Unit 8 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified slopes. Contact sharp with 9.	3.1
Unit 7 - Blue-gray #1 ash bed: blue-gray both surfaces, vitric, weakly laminated, undulatory bed. Unit weathers to small ledge. Contact gradational with 8 due to reworked upper surface of ash bed. Sample #970712B collected at base.	0.06
Unit 6 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified slopes. Contact sharp with 7.	1.0
Unit 5 - Blue-gray #2 ash bed: blue-gray both surfaces, vitric, weakly laminated, undulatory bed. Unit weathers to break in slope. Contact gradational with 6 due to reworked upper surface of ash bed. Sample #970712A collected at base.	0.07
Unit 4 - Siltstone: light pinkish-tan both surfaces, slightly argillaceous, calcareous, structureless. Unit weathers to calcified slopes. Contact sharp with 5.	4.5
Unit 3 - Claystone: light olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 4.	1.6
Unit 2 - Siltstone: light olive green fresh surface, light greenish-white weathered surface, calcareous, sparkles, structureless. Unit weathers to popcorn slope. Contact sharp with 3.	1.0
Unit 1 - Siltstone: light pinkish-tan both surfaces, slightly argillaceous, calcareous, structureless. Unit weathers to popcorn slopes. Contact gradational with 2 noted by a color change.	1.4

Base of the formation not exposed

Total thickness measured	**32.62**

Appendix B-18

Location 18 on Figure 2.2 (Greasewood anticline section A):

Measured by Jacob staff and tape measure on July 04, 1997.

Field Assistant: Elizabeth Tyack

Location: Navajo Reservation, Arrowhead Butte NE 7.5' Quadrangle, N 35^0 26.998', W 109^0 51.389' Section is accessible from small trail that leads to abandon house northeast of anticline knob. Walk 1 km to north side of knob. Upper portion is measured on the northwest side of the second projection to the north. The lower portion (N 35^0 26.231', W 109^0 52.215') of the section is 2 km to the southwest and can be accessed via this route or from entering the area from the west. This section is measured at small cliff that faces westward.

Outcrop attitude: N80E 07SE measured from unit 28 at the eastern outcrop location and N35W 05SW measured from unit 14 at the western outcrop location

Measured bottom up

#18 Greasewood anticline composite	**Meters**
Unit 33 - Quaternary fill - unconsolidated conglomerate and siltstone. Cobble conglomerate: light tan to orange, well rounded, contains percussion marks, matrix composed of medium to coarse sand, subrounded, contains clasts of chert, many varieties of quartz and well indurated sandstone clasts of member 6. Siltstone: reddish-orange, arenaceous, mottled, lenticular. Unit weathers to loose hummocky slopes.	1.5
Unit 32 - Claystone: light olive green fresh surface, light greenish white weathered surface, calcareous, iron-oxide staining common near base, structureless. Red claystone unit occurs above this green one a few m to the east (NM or included here). Unit weathers to popcorn slopes. Contact disconformity with 33.	0.4
contact members 3/4	
Unit 31 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 32.	0.35
Unit 30 - Ash bed: greenish-gray both surfaces, calcareous, moderately indurated, structureless. Unit weathers to small ledge. Contact gradational with 31. Sample number 970704G.	0.06
Unit 29 - Siltstone, claystone, and ash bed. Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Claystone: olive gray fresh surface, greenish-white weathered surface, calcareous, structureless. Satan Butte ash bed: grayish-white both surfaces, calcareous, structureless, discontinuous. The 3 cm thick ash bed occurs 70 cm from base of unit. The 30 cm thick green claystone occurs 5.6 m from the base of unit. Unit weathers to calcified crusted slopes with small ledge. Contact sharp with 30. Sample #980420B of ash bed.	7.0

Unit 28 - 13.71 Ma ash bed: white, fine grained, felsic, vitric, calcareous, wavy laminated. Unit weathers to prominent ledge. Contact gradational with 29. Sample #970704F.	0.31
Unit 27 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 28.	1.0
Unit 26 - Siltstone fining upwards into claystone. Siltstone: light greenish-white both surfaces, calcareous. Claystone: light olive green fresh surface, light greenish-white weathered surface, very calcareous, slightly tuffaceous. Unit weathers to popcorn slopes. Contact gradational with 27 noted by a color change.	0.4
Unit 25 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact gradational with 26 noted by color change.	2.2
Unit 24 - Blue-gray #1 ash bed: grayish-white, calcareous, poorly indurated, structureless, bed is undulatory. Unit weathers to small ledge. Contact gradational with 25 due to reworked upper surface of ash bed. Sample #970704E.	0.08
Unit 23 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 24.	0.8
Unit 22 - Blue-gray #2 ash bed: blue-gray both surfaces, calcareous, poorly indurated, weakly laminated, bed is undulatory. Unit weathers to small ledge. Contact gradational with 23. Sample #970704D.	0.115
Unit 21 - Sandstone and siltstone. Siltstone: light pinkish-tan both surfaces, slightly arenaceous, calcareous, well indurated in areas of heavy calcification. Sandstone: light pinkish-tan both surfaces, very fine-grained, calcareous, structureless. Unit fines to siltstone 0.5 m from base. Unit weathers to calcified crusted slopes. Contact sharp with 22.	2.0
Unit 20 - Siltstone fining upwards into claystone. Siltstone: yellowish-green fresh surface, light greenish-white weathered surface, very calcareous, structureless. Claystone: olive gray fresh surface, greenish-white weathered surface, slightly tuffaceous, calcareous, structureless. Unit fines to claystone 30 cm above the base. Unit weathers to popcorn slopes. Contact gradational with 21 noted by color change.	2.3
contact members 2/3	
Unit 19 - Siltstone and ash bed. Siltstone: light orangish-tan both surfaces, arenaceous lower half - fines upward, very calcareous, structureless. Blue-gray #3 ash bed: light blueish-gray both surfaces, friable, wavy laminated. The 5 cm thick ash bed occurs 5.95 m above base. Unit weathers to calcified crusted slopes with ash bed forming small ledge. Contact gradational with 20 noted by color change. Sample #970704C of ash bed.	6.3
Unit 18 - Siltstone fining upwards into claystone. Siltstone: yellowish-green fresh surface, light greenish-white weathered surface, iron-oxide staining at base, very calcareous, structureless. Claystone: olive gray fresh surface, greenish-white weathered surface, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 19.	1.1
Unit 17 - Siltstone and ash bed. Siltstone: tan fresh surface, light tan weathered surface, arenaceous lower third - fines upwards, very calcareous, structureless. Wood Chop D ash bed: N9 white fresh surface, weathered surface covered, calcareous, mixed with surrounding siltstone, one 5 cm thick bed. Ash bed occurs 0.6 m above base. Unit weathers to calcified crusted slopes with a small ledge. Contact gradational with 18 noted by color change. Sample #980420A of ash bed.	1.2

Unit 16 - Wood Chop C ash bed: light grayish-white both surfaces, slightly calcareous, poorly indurated, weakly laminated, reworked with light brown siltstone. Unit weathers to small ledge. Contact gradational with 17 due to reworked upper surface of ash bed. Sample #970704B. 0.2

Unit 15 - Sandstone fining upward to siltstone. Sandstone: light brownish-tan fresh surface, light tan weathered surface, very fine-grained, very calcareous, very silty, structureless. Siltstone: light brown fresh surface, whitish-brown weathered surface, arenaceous, calcareous, structureless. Unit fines to siltstone 0.5 m from base. Unit weathers to calcified crusted slopes. Contact sharp with 16. 1.6

transfer northeast along ash bed to upper section location

Unit 14 - Wood Chop B ash bed: grayish-white both surfaces, slightly calcareous, poorly indurated, finely laminated at base but reworked above with light brown siltstone similar to unit 1. Unit weathers to small ledge. Contact gradational with 15. Sample #970704A. 0.2

Unit 13 - Siltstone: light brownish-tan fresh surface, light tan weathered surface, arenaceous, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 14. 0.5

Unit 12 - Claystone: dark olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 13. 0.7

Unit 11 - Siltstone: light brownish-tan fresh surface, light tan weathered surface, arenaceous, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 12. 0.55

Unit 10 - Claystone: light olive green fresh surface, light greenish-white weathered surface, very calcareous, iron-oxide staining abundant especially at base, structureless to slightly shaley near top of unit. Unit weathers to popcorn slopes. Contact sharp with 11. 2.8

contact members 1/2

Unit 9 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 10. 1.9

Unit 8 - Claystone: light brownish-olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 9. 0.85

Unit 7 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 8. 0.85

Unit 6 - Volcaniclastic sandstone: light brownish-green fresh surface, light greenish-brown weathered surface, very fine-grained, contains abundant mafic clasts, calcareous, one bed. Unit weathers to small ledge. Contact sharp with 7. Sample #970704I. 0.07

Unit 5 - Interbedded claystone and siltstone: Claystone: reddish-brown fresh surface, light reddish-brown weathered surface, calcareous, structureless, blocky fracture. Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Claystone occurs at base and then alternates with siltstone - measured subunits are: 1.4 m, 0.35 m, 0.2 m, 0.28 m, 0.33 m, 0.4 m, 0.4 m, 0.2 m, 0.65 m, 1.15 m, 0.7 m, 1.5 m, and 1.1 m. Unit weathers to popcorn and calcified crusted slopes. Contact sharp with 6. 8.66

Unit 4 - Claystone: light olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless. Unit weathers to popcorn slopes. Contact gradational with 5 noted by a color change. 0.2

Unit 3 - Sandstone fining upward into siltstone. Sandstone: light brown fresh surface, light tan weathered surface, very calcareous, structureless. Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified crusted slope. Contact sharp with 4.	0.25
Unit 2 - Echo Spring Mountain (?) ash bed: light grayish-white fresh surface, light greenish-white weathered surface, silty, calcareous, well indurated, shaley. Unit weathers to small ledge. Contact gradational with 3 due to reworked upper surface of ash bed. Sample #970704H.	0.08
Unit 1 - Siltstone: light reddish-brown fresh surface, very light reddish-brown weathered surface, argillaceous, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 2.	3.8+
Base of formation not exposed	
Total Bidahochi thickness measured	**48.825**

Appendix B-19

Location 19 on Figure 2.2 (Greasewood Mesa South):

Measured by Jacob staff and tape measure on July 05, 1997.

Field Assistant: Elizabeth Tyack

Location: Navajo Reservation, Arrowhead Butte NE 7.5' Quadrangle, N 35^0 28.228', W 109^0 50.015' Lower portion is located near Y in road at badlands area. Upper portion (N 35^0 28.833', W 109^0 49.333' - topo estimation) is back against mesa to the east on north side of westward projection.

Outcrop attitude: N18E 04SE measured from unit 12

Measured bottom up

#19 Greasewood Mesa South	**Meters**
Unit 47 - Sandstone: light tan both surfaces, fine-grained, well sorted, rounded, quartzose, contains some mafic volcanic clasts and areas of white ash material, calcareous, poorly indurated, high-angle planar cross-bedded. Unit weathers to loose slopes.	7.8
Unit 46 - Siltstone: light pinkish-tan fresh surface, light tan weathered surface, arenaceous, calcareous, structureless. Unit weathers to cliff. Contact sharp with 47.	1.5
Unit 45 - Sandstone: light tan fresh surface, light grayish-tan weathered surface, very fine-grained to medium grained, poorly sorted, subangular to rounded, contains abundant mafic volcanic clasts, calcareous, planar cross-bedded. Unit weathers to cliff. Contact sharp with 46.	0.21
Unit 44 - Volcaniclastic siltstone: banded white and tan weathered surface, contains abundant matrix supported sand sized euhedral pyroxene and other mafic volcanic clasts, calcareous, moderately indurated, structureless. Unit weathers to cliff. Contact sharp with 45.	0.81

Unit 43 - Sandstone: light tan fresh surface, light grayish-tan weathered surface, very fine-grained to medium grained, poorly sorted, subangular to rounded, contains abundant coarse mafic volcanic clasts, calcareous, planar and trough cross-bedded, convoluted bedding, contains minor siltstone lamina. Paleocurrent reading of 205 from axial plane of a 18 cm thick trough. Unit weathers to cliff. Contact sharp with 44. 0.83

contact members 5/6

Unit 42 - Claystone: light olive green fresh surface, light greenish-white weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 43. 0.8

Unit 41 - Claystone: light brown fresh surface, tan weathered surface, slightly silty, calcareous, structureless. Unit weathers to popcorn slopes. Contact gradational with 42 noted by color change. 1.0

Unit 40 - Siltstone: light pinkish-tan fresh surface, light tan weathered surface, arenaceous with abundant volcanic material, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 41. 0.5

Unit 39 - Sandstone: pinkish-brown fresh surface, light pinkish-tan weathered surface, fine-grained, well sorted, subrounded to rounded, calcareous, laminated with small beds of volcanic material, trough cross-bedded. Unit weathers to calcified crusted slopes. Contact sharp with 40. 1.7

Unit 38 - Arenaceous siltstone: light pinkish-tan both surfaces, calcareous, weakly laminated, more sandy near top. Unit weathers calcified crusted slopes. Contact gradational with 39 noted by a structural change. 0.75

Unit 37 - Claystone: light brown fresh surface, tan weathered surface, slightly silty, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 38. 1.85

Unit 36 - Sandstone and claystone. Sandstone: pinkish-brown fresh surface, light pinkish-tan weathered surface, fine-grained, well sorted, subrounded to rounded, calcareous, laminated with small beds of volcanic material, planar cross-bedded at base. Claystone: light brown fresh surface, tan weathered surface, slightly silty, calcareous, structureless. Claystone bed 40 cm thick occurs 65 cm from base. Unit weathers to calcified crusted slopes. Contact sharp with 37. 1.3

Unit 35 - Claystone: light olive green fresh surface, light greenish-white weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 36. 0.07

Unit 34 - Volcaniclastic siltstone interbedded with claystone. Volcaniclastic siltstone: greenish-white fresh surface, light tan weathered surface, medium-grained, poorly sorted, rounded to subangular, contains abundant matrix supported sand sized euhedral pyroxene and other mafic volcanic clasts, calcareous, moderately indurated, structureless. Claystone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to calcified crusted slopes and ledges. Contact sharp with 35. 1.33

Unit 33 - Claystone: light olive green fresh surface, light greenish-white weathered surface, silty, calcareous, structureless, blocky fracture. Red silt rich layers occur near top of unit. Unit weathers to popcorn slopes. Contact sharp with 34. 2.45

Unit 32 - Claystone: light brown fresh surface, tan weathered surface, slightly silty, calcareous, structureless. Unit weathers to popcorn slopes. Contact gradational with 33 noted by color change. 0.55

Unit 31 - Silty claystone: light olive green fresh surface, light greenish-white weathered surface, more silty near top, calcareous, structureless. Silt content varies throughout unit with fining upward cycles apparent. Unit weathers to popcorn slopes. Contact gradational with 32 noted by color change. 7.15

Unit 30 - Volcaniclastic sandstone: greenish-white both surfaces, medium-grained, poorly sorted, rounded to subangular, contains abundant euhedral pyroxene and other mafic volcanic clasts, fines upward, calcareous, moderately indurated, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 31. 0.6

Unit 29 - Silty claystone: light olive green fresh surface, light greenish-white weathered surface, contains class shards? and volcanic material, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 30. 0.4

Unit 28 - Argillaceous siltstone , light tan fresh surface, light pinkish-tan weathered surface, very calcareous, moderately indurated, blocky fracture. Unit weathers to small ledge. Contact sharp with 29. 0.26

Unit 27 - Volcaniclastic siltstone interbedded with claystone. Volcaniclastic siltstone: greenish-white both surfaces, medium-grained, poorly sorted, rounded to subangular, contains abundant matrix supported sand sized euhedral pyroxene and other mafic volcanic clasts, calcareous, moderately indurated, structureless. Claystone: light greenish white both surfaces, calcareous, structureless. Claystone occurs as two small cm thick beds 15 and 17 cm from base. Unit weathers to calcified crusted slopes and ledges. Contact gradational with 28 noted by a color change. Sample number 970705A. 0.35

contact members 4/5

Unit 26 - Siltstone fining upwards to claystone. Siltstone: light olive green fresh surface, light greenish-white weathered surface, calcareous, iron-oxide staining abundant, structureless. Claystone: light olive green fresh surface, light greenish-white weathered surface, calcareous, structureless, blocky fracture. Unit fines upward to claystone 22 cm above base. Unit weathers to popcorn slopes. Contact sharp with 27. 1.85

Unit 25 - Conglomerate, sandstone, and claystone. Granule conglomerate: grayish-red fresh surface, light reddish-brown weathered surface, consist primarily of chert, quartz, and petrified wood clasts, sandy matrix, calcareous, trough cross-bedded, fines upward. Sandstone: light tan both surfaces, fine to medium grained**,** poorly sorted, well rounded, calcareous, thin bedded, undulatory beds, laterally interfingers with conglomerate. Claystone, reddish-brown both surfaces, calcareous, interbedded with channel material and sandstone beds. Unit weathers to pebble strewn slopes and ledges. Contact sharp with 26. Sample number 971004A. 0.55

Unit 24 - Claystone interbedded with siltstone and sandstone. Claystone: brick red fresh, red weathered, very calcareous, structureless, blocky fracture. Siltstone: red both surfaces, calcareous. Sandstone, red both surfaces, very fine-grained, calcareous. Siltstone and sandstone occur every 1.5 to 2.5 m throughout unit with a 1 meter thick siltstone unit 16 m above the base. Interbedded siltstone and sandstone give unit appearance of thick bedding. Unit weathers to popcorn slopes with small breaks in slope caused by silt and sand layers. Contact gradational with 25. 35.7

Unit 23 - Siltstone: light brown both surfaces, calcareous, moderately indurated, structureless. Unit weathers to small ledge. Contact sharp with 24.	0.2
Unit 22 - Claystone: brick red fresh, red weathered, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 23.	0.6
Unit 21 - Arenaceous siltstone: light brown both surfaces, calcareous, moderately indurated, structureless. Unit weathers to small ledge. Contact sharp with 22.	0.5
Unit 20 - Siltstone fining upwards to claystone. Siltstone: light olive green fresh surface, light greenish-white weathered surface, calcareous, iron oxide staining abundant, structureless. Claystone: light olive green fresh surface, light greenish-white weathered surface, calcareous, structureless, blocky fracture. Unit fines to claystone 40 cm above base. Unit changes color to light brown upper 10 cm. Unit weathers to popcorn slopes. Contact sharp with 21.	4.3
contact members 3/4	
Unit 19 - Siltstone: light pinkish-tan both surfaces, arenaceous, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact gradational with 20 noted by color change.	3.7
Unit 18 - Claystone: light olive green fresh surface, light greenish-white weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 19.	0.1
Unit 17 - Siltstone: light pinkish-tan both surfaces, arenaceous, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 18.	3.0
Unit 16 - Claystone: light olive green fresh surface, light greenish-white weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 17.	0.4
Unit 15 - Siltstone: light pinkish-tan both surfaces, arenaceous, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 16.	4.0
Unit 14 - Ash bed: grayish white both surfaces, calcareous, moderately indurated, structureless, reworked with siltstone. Unit weathers to small ledge. Contact gradational with 15 due to reworked upper surface of ash bed.	0.08
Unit 13 - Siltstone coarsens upwards into sandstone. Siltstone: light pinkish-tan both surfaces, slightly arenaceous, calcareous, structureless. Sandstone light pinkish-tan both surfaces, very fine-grained, quartzose, moderately to well indurated, structureless. Unit changes to dominantly sandstone 1.8 m from base. Unit weathers to calcified crusted slopes. Contact sharp with 14.	6.7
transfer east to edge of mesa where ash bed is exposed at base of outcrop	
Unit 12 - 13.71 Ma ash bed: white, fine grained, felsic, vitric, calcareous, wavy laminated. Unit weathers to prominent ledge. Contact gradational with 13. Sample number 970628A.	0.28
Unit 11 - Siltstone: 10YR 7/2 pale grayish orange both surfaces, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 12.	1.05
Unit 10 - Claystone: 10Y 6/2 pale olive fresh surface, 10Y 7/2 pale yellowish olive weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 11.	0.6

Unit 9 - Siltstone: 10Y 7/3 greenish yellow fresh surface, 10Y 8/2 pale greenish yellow weathered surface, slightly argillaceous, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact gradational with 10 noted by increased clay content.	0.1
Unit 8 - Siltstone: 10YR 7/2 pale grayish orange both surfaces, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 9.	2.2
Unit 7 - Blue-gray #1 ash bed: 5B 8/1 pale blue both surfaces, friable, laminated. Unit weathers to small ledge. Contact gradational with 8 due to reworked upper surface of ash bed. Sample #970628B.	0.12
Unit 6 - Siltstone: 10YR 7/2 pale grayish orange both surfaces, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 7.	0.8
Unit 5 - Blue-gray #2 ash bed: 5PB 7/2 pale blue both surfaces, friable, laminated. Unit weathers to small ledge. Contact gradational with 6 due to reworked upper surface of ash bed. Sample #970315D.	0.18
Unit 4 - Siltstone: 10YR 7/2 pale grayish orange both surfaces, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 5.	3.5
Unit 3 - Claystone: 10Y 6/2 pale olive fresh surface, 10Y 7/2 pale yellowish olive weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 4.	1.6
moved along slope to location below ash beds	
Unit 2 - Siltstone: 10Y 7/3 greenish yellow fresh surface, 10Y 8/2 pale greenish yellow weathered surface, slightly argillaceous, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 3.	0.5
Unit 1 - Siltstone: 10YR 7/2 pale grayish orange both surfaces, slightly argillaceous, calcareous, structureless. Unit weathers to calcified crusted slopes. Contact sharp with 2.	NM
member 3	
Base of formation not exposed	
Total thickness measured	**104.82**

Appendix B-20

Location 20 on Figure 2.2 (Elephant Butte section)

Measured by Jacob staff and tape measure on July 31, 1997

Field Assistant: Tara Krapf

Location: Navajo Reservation, Montezumas Chair 7.5' Quadrangle, N 35° 21.884' by W 110° 30.539' Located on the east side of butte in a large ravine cut into side. Section starts above the Entrada/Cretaceous cross-bedded sandstone units.

Outcrop Attitude: Measured using N50E 10 NW from Entrada Fm? this is probably not the attitude of Bidahochi Fm - very difficult to determine contact or attitude measurement.

Measured bottom up

#20 Elephant Butte	Meters
Cliff to top of butte, no further exposure	
Unit 17 - Mafic lava: N1 black both surfaces, porphyritic - large crystals of pyroxene, amphiboles, and olivine, columnar jointed. Unit weathers cliff.	NM
Unit 16 - Colluvium covered slope.	NM
Unit 15 - Siltstone: 10R 3/4 dark reddish-brown, fresh surface, 10R 8/4 orange pink weathered surface, slightly argillaceous, calcareous, structureless. Unit weathers to calcified slopes. Contact covered with 16.	0.4
Unit 14 - Argillaceous siltstone: 10Y 7/2 pale greenish olive fresh surface, 10Y 8/2 pale greenish-yellow weathered surface, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 15.	0.45
Unit 13 - Sandstone fining upwards to siltstone. Sandstone: 5Y 8/1 yellowish-gray both surfaces, medium-grained, poorly sorted, subrounded, very calcareous, planar cross-bedded. Siltstone: 5Y 8/1 yellowish-gray both surfaces, argillaceous, calcareous, structureless. At 4.1 m unit fines to siltstone. Unit weathers to break in slope and slope. Contact sharp with 14.	5.6
Unit 12 - Interbedded siltstone and claystone. Siltstone: 10YR 8/4 pale yellowish orange fresh surface, 5YR 7/1 yellowish gray weathered surface, calcareous, structureless. Claystone: red and green colored - 10Y 6/4 greenish olive and 5YR 4/4 moderate brown fresh surfaces, very calcareous, structureless. Siltstone is dominant lithology with claystone beds only 2-3 cm thick. Unit weathers to calcified slope. Contact sharp with 13.	2.2
Unit 11 - Sandstone: 5Y 8/1yellowish-gray both surfaces, very fine-grained, slightly silty, calcareous, structureless. Silty component concentrated near base. Unit weathers to slope. Contact sharp with 12.	2.5
Unit 10 - Interbedded siltstone and sandstone. Siltstone: 5YR 3/2 grayish-brown fresh surface, 10R 3/6 dark reddish-brown weathered surface, calcareous, structureless. Sandstone: N9 white both surfaces, very fine-grained, calcareous, structureless. Sandstone beds are 2-3 cm thick at base and increase in thickness near top. Unit weathers loose slopes. Contact sharp with 11.	2.1
Unit 9 - Silty claystone: banded 5R 2/6 very dark red and 10Y 6/2 pale olive fresh surfaces, weathered surface covered, calcareous, structureless. Unit weathers to slope. Contact sharp with 10.	0.1
Unit 8 - Interbedded siltstone and sandstone then coarsens upwards to sandstone. Siltstone: 5YR 5/6 light brown both surfaces, structureless, blocky fracture. Sandstone: 5YR 5/6 light brown both surfaces, very fine-grained, calcareous, planar cross-bedded. At 4.5 m unit coarsens into sandstone: 10R 3/6 dark reddish-brown fresh surface, 5YR 4/6 moderate brown weathered surface, fine-grained, well sorted, rounded, calcareous, low-angled planar cross-bedded. Unit weathers to calcified slopes. Contact sharp with 9.	11.6
Unit 7 - Siltstone: 10YR 7/4 grayish-orange fresh surface, 10YR 7/2 pale yellowish orange weathered surface, contains abundant white patchy areas, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 8.	2.3

Unit 6 - Sandstone: 10YR 7/4 grayish-orange fresh surface, 10YR 7/2 pale yellowish orange weathered surface, fine-grained, poorly sorted, subrounded, quartzose, friable, high-angled planar cross-bedded. Paleocurrent reading of 115 from 0.8 m forset bed near base. Unit weathers to slopes. Contact gradational with 7.	0.8
Unit 5 - Siltstone: 5YR 5/6 light brown fresh surface, 5YR 6/6 light brown weathered surface, slightly argillaceous, calcareous, thin to laminated bedded. Clay content varies within unit - areas of clay-rich green sparkly siltstone. Unit weathers to slope. Unit contains green and white mottled looking areas. Contact sharp with 6. Sample #970731A of green siltstone.	0.6
Contact Mesozoic units / Bidahochi Fm member 1	
Unit 4 - Entrada Fm? - Sandstone: 5YR 7/4 orange brown fresh surface, 5Y 8/2 gray yellow weathered surface, fine- to very fine-grained, moderately sorted, subangular to subrounded, quartzose, mafic minerals common, silty, calcareous, poorly indurated, planar cross-bedded. Unit weathers to slopes. Contact sharp with 5.	15.7
Unit 3 - Entrada Fm? - Sandstone: 5Y 8/2 gray yellow fresh surface, 10YR 7/2 pale grayish-orange brown weathered surface, fine-grained, moderately sorted, subangular to subrounded, quartzose, mafic minerals common, very calcareous, well indurated, laminated, high-angled planar cross-bedded. Paleocurrent reading of 122 from 2.15 m forset bed at 7.8 m from base. Unit weathers to cliffs and ledges. Contact gradational with 4 noted by a change in induration. Sample #971003A.	31.5
Unit 2 - Entrada Fm? - Siltstone: 5GY 7/1 greenish-gray both surfaces, calcareous, structureless. Unit weathers beneath cliff of unit above. Contact sharp with 3.	0.12
Unit 1 - Wingate Fm - Sandy siltstone: 10YR 6.5/6 dark yellowish-orange both surfaces, very calcareous, well indurated, structureless, nodular. Unit weathers to cliffs and slopes. Contact sharp with 2.	NM
Total thickness measured	**75.97**
Total determined Bidahochi Fm	**28.65**

Appendix B-21

Location 21 on Figure 2.2 (Lee Windmill section)

Measured by Jacob staff and tape measure on July 25, 1997

Field Assistant: Carey Lang

Location: Navajo Reservation, Na Ah Tee Canyon 7.5' Quadrangle, N 35° 23.512' by W 110° 12.012' Located along the slope below and to the south of the windmill tower. Section starts in red units in long flat ravine where ash outcrops are visible.

Outcrop Attitude: No suitable attitude was obtainable - according to orientation of units appears horizontal.

Measured bottom up

#21 Lee Windmill	**Meters**
Top of outcrop, no further exposure	

Unit 28 - Quaternary alluvium - Loosely consolidated sand and silt: orange, tan, and yellow colored with speckled black grains, contains abundant Hopi Buttes volcanic material and clasts of Wingate and Bidahochi units, clasts are generally rounded and weathered. Unit is trough cross-bedded. Unit weathers to calcified slopes with soil profile at top. 10

contact member 2 and Quaternary alluvium

Unit 27 - Silty claystone: N9 white both surfaces, contains some sand-sized material, very calcareous, structureless. Unit weathers to popcorn slope. Contact disconformity with 28. 0.07

Unit 26 - Claystone: 5Y 3/3 olive gray fresh surface, 10Y 6/2 pale olive weathered surface, slightly silty, very calcareous, structureless, blocky fracture. Top of unit contains abundant silt. Unit weathers to popcorn slope. Contact sharp with 27. 1.7

Unit 25 - Silty claystone: 10YR 7/4 grayish-orange fresh surface, 10YR 8/4 pale grayish-orange weathered surface, calcareous, structureless. Unit weathers to popcorn slope. Contact gradational with 26 but easily noted by a sharp color change. 0.5

Unit 24 - Interbedded claystone and argillaceous siltstone. Claystone: 5Y 7/2 yellowish-gray fresh surface, 10YR 6/2 pale yellowish-brown weathered surface, slightly silty, calcareous, structureless, blocky fracture. Argillaceous siltstone: 10YR 7/2 orange yellowish-brown both surfaces, calcareous, structureless. Siltstone beds are 10-20 cm thick and make unit medium bedded. Unit weathers to popcorn slope with small breaks in slope. Contact gradational with 25. 1.8

Unit 23 - Claystone: 5Y 4/2 olive gray brown and 10R 3.5/4 dark reddish-brown fresh surfaces, 10YR 6/3 yellowish-orange brown weathered surface, calcareous, laminated defined by pink and green bands, blocky fracture. Iron-oxide staining abundant in partings of laminated clays. Red coloration diminishes up through unit. Unit weathers to popcorn slope. Contact gradational with 24. Sample 970725E of red claystone. 1.8

Unit 22 - Claystone: 5Y 4/2 olive gray brown fresh surface, 10YR 6/2 pale yellowish-brown weathered surface, calcareous, laminated, blocky fracture. Iron-oxide staining abundant in partings of laminated clays. Unit weathers to popcorn slope. Contact gradational with 23. 2.2

Unit 21 - Claystone: 5Y 7/2 yellowish-gray fresh surface, 10YR 6/2 pale yellowish-brown weathered surface, slightly silty, calcareous, laminated, blocky fracture. Basal 40 cm weathers to same color as fresh surface. Unit weathers to popcorn slope. Contact gradational with 22. 3.35

Unit 20 - Argillaceous siltstone: 10YR 7/2 orange yellowish-brown both surfaces, calcareous, structureless. Unit weathers to break in slope. Contact gradational with 21. 0.25

Unit 19 - Claystone: 5Y 7/2 yellowish-gray fresh surface, 10YR 6/2 pale yellowish-brown weathered surface, slightly silty, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact gradational with 20. 2.35

Unit 18 - Argillaceous siltstone: 10YR 7/2 orange yellowish-brown both surfaces, calcareous, structureless. Unit weathers to break in slope. Contact gradational with 19. 0.1

Unit 17 - Claystone: 5Y 7/2 yellowish-gray fresh surface, 5YR 7/2 grayish-orange pink weathered surface, slightly silty, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact gradational with 18. 1.1

Unit 16 - Argillaceous siltstone: 10YR 7/2 orange yellowish-brown both surfaces, calcareous, structureless. Unit weathers to break in slope. Contact gradational with 17. 0.2

Unit 15 - Claystone: 5Y 7/2 yellowish-gray fresh surface, 5YR 7/2 grayish-orange pink weathered surface, slightly silty, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact gradational with 16.	0.95
Unit 14 - Siltstone: 10YR 7/4 grayish-orange fresh surface, 5YR 7/4 light brown orange pink weathered surface, calcareous, structureless. Unit weathers to calcified slope. Contact sharp with 15.	0.45
Unit 13 - Silty claystone: 5Y 7/2 yellowish-gray fresh surface, 10Y 8/2 pale greenish-yellow, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 14.	0.65
Unit 12 - Siltstone: 10YR 7/4 grayish-orange fresh surface, 5YR 7/4 light brown orange pink weathered surface, calcareous, structureless. Unit weathers to calcified slope. Contact sharp with 13.	0.4
Unit 11 - Claystone: 5Y 7/2 yellowish-gray fresh surface, 5Y 8/1 yellowish-gray, slightly silty, very calcareous, structureless, slightly shaley. Unit weathers to popcorn slope. Contact sharp with 12.	1.55
contact members 1/2	
Unit 10 - Interbedded siltstone and silty claystone with ash bed. Siltstone: 10YR 7.5/4 grayish-orange both surfaces, calcareous, structureless. Silty claystone: 10R 5/5 reddish-brown both surfaces, structureless, blocky fracture. East point biotite ash bed: N9 white, biotite abundant, contains black clay-like material, structureless, discontinuous. Ash bed (10 cm thick) occurs 0.3 m from base. Unit weathers breaks in slope and slopes. Contact sharp with 11. Sample 970725C of ash bed.	2.55
Unit 9 - Tuffaceous siltstone: N9 white both surfaces, calcareous, structureless. Unit weathers to ledge. Contact gradational with 10 due to reworked upper surface. Sample #970725B.	0.12
Unit 8 - Silty claystone: 10R 5/5 reddish-brown both surfaces, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 9.	0.35
Unit 7 - Siltstone: 10YR 7.5/4 grayish-orange both surfaces, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 8.	0.53
Unit 6 - Silty claystone: 10R 5/5 reddish-brown both surfaces, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 7.	1.1
Unit 5 - Siltstone: 10YR 7.5/4 grayish-orange both surfaces, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 6.	0.32
Unit 4 - Silty claystone: 10R 5/5 reddish-brown both surfaces, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 5.	1.0
Unit 3 - Siltstone: 10R 8/3 grayish orange pink both surfaces, contains patches of ash from unit below, calcareous, structureless. Unit weathers to ledge. Contact gradational with 4 noted an increase in clay content.	0.3
Unit 2 - Echo Spring Mountain ash bed: N9 white both surfaces, partially bentonized, structureless to slightly wavy laminated. Unit weathers to ledge. Contact gradational with 3 due to reworked upper surface of ash bed. Sample #970725A.	0.4

Unit 1 - Argillaceous siltstone coarsening upward to siltstone. Argillaceous siltstone: 10R 5/6 reddish-brown fresh surface, 5YR 6/4 light brown, weathered surface, calcareous, structureless. Siltstone: 10YR 7.5/4 grayish-orange, calcareous, structureless. At 2.4 m unit contains green clay rich patches that sparkle. Unit coarsens to siltstone at 3.5 m. Unit weathers to slope. Contact sharp with 2.	3.8+
Base of the formation not exposed	
Total thickness measured	**39.89**

Appendix B-22

Location 22 on Figure 2.2 (East point Section)

Measured by Jacob staff and tape measure on July 12, 1997

Field Assistant: Amy Morrison

Location: Navajo Reservation, Greasewood Spring 7.5' Quadrangle, N 35° 23.335' by W 109° 57.032' On the eastern most point of mesa, started in eastward flowing ravine where 2 ash beds are exposed

Outcrop Attitude: N45E 2NW measured from unit number 51

Measured bottom up

#22 East point	**Meters**
Top of mesa, no further exposure	
Unit 57 - Mafic lava: black both surfaces, porphyritic, contains phenocrysts of olivine and pyroxene up to 5 mm long, slightly rubbley base. Unit weathers to cliff.	3+
Unit 56 - Mafic tuff: brownish-green both surfaces, clast supported, calcareous, medium bedded. Unit not always present between mafic lava and unit 55. Unit weathers to cliff. Contact sharp with 57.	1.65
Contact members 4/5	
Unit 55 - Claystone: olive green tan fresh surface, light greenish-white weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 56.	4.4
Unit 54 - Siltstone: light pinkish-tan both surfaces, calcareous, moderately indurated, structureless. Unit weathers to calcified slopes. Contact sharp with 55.	0.4
Unit 53 - Claystone: olive green tan fresh surface, light greenish-white weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 54.	0.4
contact members 3/4	
Unit 52 - Siltstone: light pinkish-tan both surfaces, calcareous, moderately indurated, structureless. Unit weathers to calcified slopes. Contact sharp with 53.	6.3

Unit 51 - 13.71 Ma ash bed: white both surfaces, fine-grained, felsic, vitric, calcareous, wavy laminated. Unit weathers to prominent ledge. Contact gradational with 52 due to reworked upper surface of ash bed. Sample #970712O collected of ash bed.	0.32
Unit 50 - Siltstone: light pinkish-tan both surfaces, calcareous, moderately indurated, structureless. Unit weathers to calcified slopes. Contact sharp with 51.	1.3
Unit 49 - Claystone: olive green tan fresh surface, light greenish-white weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 50.	1.05
Unit 48 - Siltstone: light greenish-white both surfaces, tuffaceous, calcareous, structureless. Unit weathers to calcified slopes. Contact sharp with 49.	0.5
Unit 47 - Siltstone: light pinkish-tan both surfaces, calcareous, moderately indurated, structureless. Unit weathers to calcified slopes. Contact gradational with 48 noted by a color change.	1.7
Unit 46 - Blue-gray #1 ash bed: blue-gray both surfaces, calcareous, weakly laminated, undulatory bed, pinches in and out. Unit covered in slope. Contact gradational with 47 due to reworking of ash bed. Sample #970712N collected at base.	0.03
Unit 45 - Siltstone: light pinkish-tan both surfaces, calcareous, moderately indurated, structureless. Unit weathers to calcified slopes. Contact sharp with 46.	0.4
Unit 44 - Blue-gray #2 ash bed: blue-gray both surfaces, felsic, vitric, very friable, weakly laminated, undulatory bed. Unit covered in slope. Contact gradational with 45 due to reworked upper surface of ash bed. Sample #970712M collected at base.	0.12
Unit 43 - Siltstone: light pinkish-tan both surfaces, calcareous, moderately indurated, structureless. Unit weathers to calcified slopes. Contact sharp with 44.	3.4
Unit 42 - Claystone: light brownish-green fresh surface, light greenish white weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 43.	1.0
Unit 41 - Siltstone: light tanish-white both surfaces, tuffaceous, very calcareous, well indurated, structureless. Unit weathers to ledge. Contact sharp with 42.	0.12
Unit 40 - Claystone: light brownish-green fresh surface, light greenish white weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 41.	0.4
Unit 39 - Siltstone: light greenish-white both surfaces, calcareous, moderately indurated, structureless. Unit weathers to break in slope. Contact sharp with 40.	0.5
Unit 38 - Siltstone: light pinkish-tan both surfaces, slightly sandy, calcareous, structureless. Unit weathers to break in slope. Contact gradational with 39 noted by color change.	1.6
Unit 37 - Blue-gray #3 ash bed: blue-gray both surfaces, felsic, vitric, calcareous, wavy laminated. Unit weathers to ledge. Contact gradational with 38 due to reworked upper surface of ash bed. Sample # 970712L of ash.	0.07
Unit 36 - Siltstone: light pinkish-tan both surfaces, slightly sandy, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 37.	2.45

Unit 35 - Sandstone: light pinkish-tan both surfaces, medium-grained, moderately sorted, well rounded to subangular, contains mafic sand-sized clasts, calcareous, weakly trough cross-bedded. Unit varies in thickness due to scour contact. Unit weathers to ledge. Contact sharp with 36. 0.3-0.8

Unit 34 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to break in slope. Contact scour with 35. 1.9

contact members 2/3

Unit 33 - Silty claystone: olive green fresh surface, weathered surface covered, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 34. 0.15

Unit 32 - Wood Chop D ash bed: brown and white layers both surfaces, calcareous, well indurated, lamination defined by brown claystone within white ash. Unit weathers to ledge. Contact gradational with 33 due to reworked nature of ash bed. Sample #970712K of ash rich layers. 0.2

Unit 31 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 32. 0.25

Unit 30 - Claystone: light olive green fresh surface, light greenish-white weathered surface, contains iron-oxide staining, very silty and slightly tuffaceous at base, very calcareous, sparkles, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 31. 0.4

Unit 29 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 30. 2.1

Unit 28 - Claystone: light olive green fresh surface, light greenish-white weathered surface, contains iron-oxide staining, very calcareous, sparkles, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 29. 0.5

Unit 27 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 28. 0.4

Unit 26 - Silty claystone and two ash beds. Silty claystone: light olive green fresh surface, light greenish-white weathered surface, contains iron-oxide staining especially at base, very calcareous, sparkles, structureless, blocky fracture. Ash beds: olive green fresh surface, grayish-white weathered surface, calcareous, structureless, mixed with surrounding claystone. Wood Chop B ash bed (12 cm thick) is 0.7 m from base. Wood Chop C ash bed (6 cm thick) is 1.8 m from base. Unit weathers to popcorn slopes. Contact sharp with 27. Sample #980118F of Wood Chop B ash bed. Sample #980118G of Wood Chop C ash bed. 2.7

Unit 25 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 26. 0.6

Unit 24 - Silty claystone: light olive green fresh surface, light greenish-white weathered surface, very calcareous, sparkles, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 25. 1.5

Unit 23 - Silty claystone and ash bed. Silty claystone: light olive greenish-brown fresh surface, light greenish-white weathered surface, calcareous, sparkles, structureless, blocky fracture. Wood Chop A ash bed: grayish-white, felsic, calcareous, structureless. Ash bed (6cm thick) is 0.5 m from base. Unit weathers to popcorn slopes with ash forming break in slope. Contact gradational with 24 noted by color change. Sample #980118E collected of ash bed. 0.75

Unit 22 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 23. 0.6

Unit 21 - Claystone: yellowish-olive green fresh surface, light yellow greenish-white weathered surface, contains iron-oxide staining especially at base, very calcareous, weakly laminated, shaley. Unit weathers to popcorn slopes. Contact sharp with 22. 2.2

Unit 20 - Siltstone: light pinkish-tan both surfaces, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 21. 0.7

Unit 19 - Claystone: yellowish-olive green fresh surface, light yellow greenish-white weathered surface, contains iron-oxide staining, very calcareous, weakly laminated, shaley. Unit weathers to popcorn slopes. Contact sharp with 20. Sample #970712J. 3.5

Unit 18 - Silty claystone: light olive green fresh surface, light greenish-white weathered surface, contains 50 cm iron-oxide stain at base, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact gradational with 19 noted by structural change. Sample #970712I collected near base. 1.3

contact members ½

Unit 17 - Siltstone: light reddish-brown fresh surface, light pinkish-tan weathered surface, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 18. 0.9

Unit 16 - Claystone: olive green fresh surface, light greenish-white weathered surface, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 17. 1.2

Unit 15 - Siltstone: light reddish-brown fresh surface, light pinkish-tan weathered surface, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 16. 1.3

Unit 14 - Volcaniclastic sandstone: light tanish-gray both surfaces, very fine-grained, biotite and mafic minerals noted, calcareous, single bed. Unit weathers to small ledge. Contact sharp with 15. Sample #970712H. 0.2

Unit 13 - Siltstone: light reddish-brown fresh surface, light pinkish-tan weathered surface, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 12. 1.7

Unit 12 - Silty claystone: light reddish-brown fresh surface, light pinkish-brown weathered surface, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 13. 1.0

Unit 11 - Siltstone: light reddish-brown fresh surface, light pinkish-tan weathered surface, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 12. 0.9

Unit 10 - Covered slope 3.2

Unit 9 - Silty claystone: light reddish-brown fresh surface, light pinkish-brown weathered surface, calcareous, structureless. Unit weathers to popcorn slopes. Contact covered. 3.0

Unit 8 - Siltstone: light reddish-brown fresh surface, light pinkish-tan weathered surface, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 9.	0.6
Unit 7 - Claystone: brick red fresh surface, light pinkish-red weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 8. Sample #970712G.	1.8
Unit 6 - Siltstone: light reddish-brown fresh surface, light pinkish-tan weathered surface, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 7.	0.6
Unit 5 - Claystone: dark olive green with red patches and layers fresh surface, light pinkish-tan and greenish-white weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 6.	0.7
Unit 4 - Siltstone: light reddish-brown fresh surface, light pinkish-tan weathered surface, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 5.	0.4
Unit 3 - East point biotite ash bed: light green at base and pinkish-white fresh surface, whitish-gray weathered surface, biotite abundant, poorly calcareous, structureless. Crystal rich layer at base. Unit weathers to small ledge. Contact gradational with 4 due to reworked upper surface of ash bed. Sample #970712F, 980118C collected at base.	0.09
Unit 2 - Claystone: reddish-brown fresh surface, light pinkish-brown tan weathered surface, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 3.	0.9
Unit 1 - Echo Spring Mountain ash bed: white lower portion and green upper portion fresh surface, tanish-white weathered surface, felsic, poorly calcareous, structureless. Unit weathers to small ledge. Contact gradational with 2 due to reworked upper surface of ash bed. Sample #970712E, 980118D collected at base.	0.12
Base of the formation not exposed	
Total thickness measured	**70.27**

Appendix B-23

Location 23 on Figure 2.2 (East Twin Butte Composite Section)

Measured by Jacob staff and tape measure on July 18 and August 7, 1997

Field Assistants: Anthony Burgess and Tracey Fitzner

Location: Navajo Reservation, Greasewood Spring 7.5' Quadrangle, N 35° 24.118' by W 109° 53.834' (eastern portion), N 35° 24.101' by W 109° 53.666' Composite section: lower section is exposed where stream valley cuts up into butte. Section starts on south bank of stream valley in a small tributary below the exposed slope under cliff. The upper portion is measured on a erosional scarp cut into northeastern part of the eastern butte.

Outcrop Attitude: measured flat - essentially zero dip measured on unit 38

measured bottom up

#23 East Twin Butte Composite	Meters
Cliff to top of mesa, no further exposure	
Unit 45 - Mafic lava: N 1 black both surfaces, aphanitic, slightly glassy. Unit scours into claystone below. Unit weathers to cliff.	NM
contact members 4/5	
Unit 44 - Claystone: 10Y 8/1 pale greenish-yellow both surfaces, very calcareous, structureless, blocky fracture. Unit weathers to cutback under cliff above. Contact scour with 45.	2 to 4
contact members 3/4	
Unit 43 - Siltstone: 10YR 7/4 grayish orange both surfaces, very little or no clay present, calcareous, wavy thin-to medium-bedded. Unit weathers to calcified slope. Contact sharp with 44.	1.7
Unit 42 - Claystone: 10Y 6.5/2 pale olive fresh surface, slightly silty, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 43.	1.9
Unit 41 - Siltstone: 10YR 7/4 grayish orange both surfaces, very little or no clay present, calcareous, wavy thin-to medium-bedded. Unit weathers to calcified slope. Contact sharp with 42.	4.1
Unit 40 - Claystone: 10Y 6.5/2 pale olive fresh surface, slightly silty, calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 41.	0.5
Unit 39 - Siltstone: 10YR 7/4 grayish orange both surfaces, very little or no clay present, calcareous, wavy thin-to medium-bedded. Unit weathers to calcified slope. Contact sharp with 40.	5.5
Unit 38 - 13.71 Ma ash bed: N9 white both surfaces, fine-grained, felsic, vitric, calcareous, wavy laminated. Unit weathers to prominent ledge. Contact gradational with 39 due to reworked upper surface of ash bed. Sample #970718H.	0.32
Unit 37 - Siltstone: 10YR 7/4 grayish orange both surfaces, very little or no clay present, calcareous, wavy thin-to medium-bedded. Unit weathers to calcified slope. Contact sharp with 38.	1.35
Unit 36 - Claystone: 10Y 8/2 pale greenish-yellow both surfaces, slightly silty, tuffaceous (?), calcareous, wavy bedded (30 cm amplitude), blocky fracture. Unit weathers to popcorn slope. Contact sharp with 37.	1.0
Unit 35 - Siltstone: 10YR 7/4 grayish orange both surfaces, very little or no clay present, calcareous, wavy thin-to medium-bedded. Unit weathers to calcified slope. Contact sharp with 36.	5.7
Unit 34 - Tuffaceous siltstone fining upwards into claystone. Tuffaceous siltstone: 10Y 8/1 pale greenish-yellow both surfaces, calcareous, structureless. Claystone: 10Y 8/1 pale greenish-yellow both surfaces, calcareous, structureless. Unit fines to claystone 35 cm from base. Unit weathers to break in slope. Contact gradational with 35 due to mixing of two units.	0.95
Unit 33 - Silty claystone: 10Y 8/2 pale greenish-yellow both surfaces, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 34.	0.65

Unit 32 - Siltstone: 10YR 7/4 grayish orange both surfaces, very little or no clay present, mafic grains common, calcareous, planar-tabular thin-bedded. Unit weathers to calcified slope. Contact sharp with 33. 1.45

Unit 31 - Blue-gray #3 ash bed: 5Y 7/1 yellowish-olive gray both surfaces, felsic, calcareous, wavy bedded. Unit weathers to small ledge. Contact gradational with 32 due to reworked upper surface of ash bed. Sample #970807H. 0.12

Unit 30 - Siltstone coarsening to sandstone. Siltstone: 10YR 7/4 grayish orange both surfaces, slightly argillaceous, calcareous, structureless. Sandstone; 10YR 6/2 pale yellowish-brown both surfaces, fine-grained, moderately sorted, round with some euhedral grains, contains abundant black mafic grains, calcareous, thin bedded, low-angled trough cross-bedded and laminated planar-tabular bedded. At 4.85 m unit changes to sandstone with interbeds of siltstone. Unit weathers to break in slopes and ledges. Contact sharp with 31. Sample #970807G of abundant mafic mineral component. 7.7

contact members 2/3

Unit 29 - Claystone: 10Y 7/2 greenish-yellow olive fresh surface, 10Y 6/2 pale olive weathered surface, slightly silty, very calcareous, structureless, blocky fracture. Unit weathers to slopes. Contact sharp with 30. 0.22

Unit 28 - Siltstone: 10YR 7/4 grayish orange both surfaces, slightly argillaceous, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 29. 0.19

Unit 27 - Claystone: 10Y 7/2 greenish-yellow olive fresh surface, 10Y 6/2 pale olive weathered surface, slightly silty - reworked ash from below, very calcareous, structureless, blocky fracture. Unit weathers to slopes. Contact sharp with 28. 0.4

Unit 26 - Wood Chop C ash bed: 5Y 7/1 yellowish-olive gray both surfaces, medium-grained, calcareous, structureless. Unit weathers to small ledge. Contact gradational with 27 due to reworked upper surface of ash bed. Sample #970807F. 0.05

Unit 25 - Claystone: 10Y 7/2 greenish-yellow olive fresh surface, 10Y 6/2 pale olive weathered surface, slightly silty - reworked ash from below, very calcareous, structureless, blocky fracture. Unit weathers to slopes. Contact sharp with 26. 0.8

Unit 24 - Wood Chop B ash bed: 5Y 7/1 yellowish-olive gray both surfaces, medium-grained, calcareous, thin bedded. Unit weathers to ledge. Contact gradational with 25 due to reworked upper surface of ash bed. Sample #970807E. 0.17

Unit 23 - Claystone: 10Y 7/2 greenish-yellow olive fresh surface, 10Y 6/2 pale olive weathered surface, silty at base, very calcareous, sparkles, structureless, blocky fracture. Unit weathers to slopes. Contact sharp with 24. 0.55

Unit 22 - Sandstone: 10YR 7/4 grayish orange both surfaces, very fine-grained, quartzose, calcareous, trough cross-bedded. Unit weathers to ledge. Contact sharp with 23. 1.75

Unit 21 - Claystone: 10Y 7/2 greenish-yellow olive fresh surface, 10Y 6/2 pale olive weathered surface, slightly silty, very calcareous, structureless, blocky fracture. Unit weathers to slopes. Contact wavy with 22. 0.3

Unit 20 - Siltstone: 10YR 6/2 pale yellowish-brown both surfaces, slightly argillaceous, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 21. 0.3

Unit 19 - Member 2 felsic ash bed: N9 white both surfaces, felsic, vitric, calcareous, weakly laminated to structureless. Unit weathers to ledge. Contact gradational with 20 due to reworked upper surface of ash bed. Sample #970807D. 0.17

Unit 18 - Siltstone: 10YR 6/2 pale yellowish-brown both surfaces, slightly argillaceous, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 19. 0.5

Unit 17 - Claystone: 10Y 7/2 greenish-yellow olive fresh surface, 10Y 6/2 pale olive weathered surface, slightly silty, very calcareous, structureless, blocky fracture. Unit is very silty, basal 10 cm. Unit weathers to slopes. Contact sharp with 18. 1.2

Unit 16 - Siltstone: 10YR 6/2 pale yellowish-brown both surfaces, slightly argillaceous, calcareous, structureless. Unit weathers to break in slope. Contact sharp with 17. 0.8

Unit 15 - Claystone: 10Y 7/2 greenish-yellow olive fresh surface, 10Y 6/2 pale olive weathered surface, slightly silty, iron-oxide staining abundant, selenite abundant, very calcareous, structureless, blocky fracture. Unit is very silty at top. Unit weathers to slopes. Contact sharp with 16. 3.7

Unit 14 - Siltstone: 10YR 6/2 pale yellowish-brown both surfaces, slightly argillaceous, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 15. 2.3

Unit 13 - Claystone: 10Y 7/2 greenish-yellow olive fresh surface, 10Y 6/2 pale olive weathered surface, slightly silty, iron-oxide staining occurs as blotchy patches, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slopes. Contact sharp with 14. 2.2

transfer section to north

Unit 12 - Argillaceous siltstone, claystone, and siltstone. Argillaceous siltstone: 10R 5/6 reddish-brown fresh surface, 10R 7/2 grayish-orange pink weathered surface, calcareous, structureless to slightly shaley. Claystone: 10R 4/4 reddish-brown fresh surface, 10R 5/4 pale reddish-brown weathered surface, calcareous, structureless, blocky fracture. Siltstone: 10R 5/6 reddish-brown fresh surface, 10R 7/2 grayish-orange pink weathered surface, calcareous, structureless. At 6 m unit is predominantly siltstone with minor clay content. At 11.5 m unit is interbedded siltstone and claystone with siltstone the dominant lithology over small 8-15 cm thick claystone interbeds. Unit weathers to popcorn slopes but is partially and completely covered in some areas by mafic scree. Contact sharp with 13. 12.7

contact? members 1/2 at 11.5 m from base of unit 12

Unit 11 - Claystone: 10Y 7/2 pale greenish-olive fresh surface, weathered surface covered, calcareous, weakly laminated. Unit is tuffaceous at top with a zone of N9 white color. Unit weathers to popcorn slopes. Contact sharp with 12. 0.2

Unit 10 - Silty claystone: 10R 4/4 reddish-brown fresh surface, 10R 5/4 pale reddish-brown weathered surface, calcareous, structureless, blocky fracture. Gypsum common in scree but not observed in-situ. Unit weathers to popcorn slopes. Contact sharp with 11. 0.4

Unit 9 - Siltstone: 10R 6/4 orange reddish-brown fresh surface, 10R 7/4 moderate orange pink weathered surface, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 10. 1.65

Unit 8 - Silty claystone: 10R 4/4 reddish-brown fresh surface, 10R 5/4 pale reddish-brown weathered surface, calcareous, structureless. Unit weathers to popcorn slopes. Contact sharp with 9.	0.3
Unit 7 - Siltstone: 10R 6/4 orange reddish-brown fresh surface, 10R 7/4 moderate orange pink weathered surface, slightly argillaceous, arenaceous in upper half, calcareous, structureless. Gypsum common in scree but not observed in-situ. Unit weathers to popcorn slope. Contact sharp with 8.	5.9
Unit 6 - Silty claystone and sandstone. Silty claystone: 10R 4/4 reddish-brown fresh surface, 10R 5/4 pale reddish-brown weathered surface, gypsum common, calcareous, structureless. Sandstone: 10YR 7/6 yellowish-orange both surfaces, medium-grained, moderately sorted, rounded, calcareous, lenticular. Sandstone occurs as small lenses throughout unit. At 3 m unit contains abundant gypsum as fracture fillings. Unit weathers to popcorn slope. Contact sharp with 7.	6.25
Unit 5 - Sandstone: 5YR 6/6 light brown both surfaces, very fine-grained, contains rip-up clasts of mudstone, argillaceous at top, calcareous, structureless. Unit weathers to slope. Contact sharp with 6.	1.7
Unit 4 - Siltstone: 10R 3/4 dark reddish-brown fresh surface, 10R 5/6 reddish-brown weathered surface, calcareous, structureless. Unit weathers to slope. Contact sharp with 5.	0.55
Unit 3 - Sandstone: 10YR 7/6 yellowish-orange both surfaces, medium-grained, moderately sorted, rounded, calcareous, structureless. Unit weathers to slope. Contact sharp with 4.	0.3
Unit 2 - Bidahochi Fm - Conglomerate: 10YR 7/6 yellowish-orange both surfaces, consists of pebbles of chert, quartz, and petrified wood, structureless. Unit weathers to ledge. Contact sharp with 3. Sample #971003X	0.07
contact Wingate Fm/Bidahochi member 1	
Unit 1 - Wingate Fm - Argillaceous siltstone: 10R 4/4 gray reddish-brown fresh surface, 5YR 5/6 light brown weathered surface, contains veins of gypsum, calcareous, moderately to well indurated, medium to thick bedded. Unit weathers to calcified slope. Contact disconformity with 2.	NM
Total thickness measured	**82.14**

Appendix B-24

Location 24 on Figure 2.2 (Echo Spring Mountain Section)

Measured by Jacob staff and tape measure on August 7, 1997

Field Assistant: Tracy Fitzner

Location: Navajo Reservation, French Butte 7.5' Quadrangle, N 35° 18.017' by W 110° 20.133' Located along the western cliff exposure of the mesa. A small jeep trail leads out to mesa just south of the former Castle Butte Trading Post. The section was measured in the valley on the south side of the projection that meets trail. Measuring continues to the south in next canyon starting at unit 17.

Outcrop Attitude: measured flat - essentially zero dip measured on unit 5

Measured bottom up

#24 Echo Spring Mountain	Meters
Top of mesa, no further exposure	
Unit 32 - Mafic lava: N 1 black with white spots both surfaces, aphanitic with some small phenocrysts of olivine, amygdulized. Unit weathers to cliff.	NM
contact members 2/5 in covered slope?	
Unit 31 - Covered slope - colluvium. Contact difficult to determine with 32.	31.5
Unit 30 - Claystone: 10Y 6/2 pale olive fresh surface, 10Y 8/2 pale yellowish gray weathered surface, very calcareous, weakly laminated, blocky fracture. Unit weathers to slope. Contact colluvial with 31 noted by slump blocks and rotated bedding.	~7
Unit 29 - Interbedded sandstone and silty claystone. Sandstone: 10Y 8/2 pale greenish-yellow both surfaces, very fine-grained, contains some fine sand-sized grains, calcareous. Silty claystone: 10Y 8/2 pale greenish-yellow both surfaces, very calcareous, structureless. Sandstone beds occur at base and top of unit. Lower sandstone is 10 cm thick and structureless. Upper bed is 15 cm thick, fine-grained, moderately sorted, rounded, quartzose, calcareous, rippled laminated, wavy contact with underlying claystone. Unit weathers to slopes and popcorn slopes. Contact sharp with 30.	0.55
Unit 28 - Siltstone: 10YR 7/2 pale orange yellowish brown both surfaces, argillaceous lower third of unit, calcareous, structureless. At 1.0 meter unit becomes arenaceous. Unit weathers to calcified slope. Contact sharp with 29.	1.7
Unit 27 - Sandstone: 10Y 8/2 pale greenish-yellow both surfaces, very fine-grained, poorly sorted - contains medium sand-sized grains of quartz, chert, and some mafic minerals, very calcareous, structureless. Some areas have concentration of mafic minerals. Unit weathers to ledge. Contact sharp with 28. Sample #9805027B of mafic concentrated area.	0.15
Unit 26 - Silty claystone: 10YR 7/2 pale orange yellowish brown both surfaces, calcareous, structureless. Unit weathers to calcified slope. Contact sharp with 27.	0.45
Unit 25 - Claystone: 10YR 4/2 dark yellowish-brown fresh surface, 10YR 5/4 moderate yellowish-brown weathered surface, calcareous, structureless. Unit weathers to popcorn slope. Contact gradational with 26 noted by a color change.	1.5
Unit 24 - Silty claystone: 10Y 8/2 pale greenish-yellow both surfaces, very calcareous, structureless. Unit changes color at 20 cm from base to 10YR 7/2 pale orange yellowish brown. Unit weathers to calcified slope. Contact gradational with 25 noted by a color change.	1.6
Unit 23 - Ash bed: N9 white both surfaces, mica minerals noted, partially bentonized, calcareous, structureless. Unit weathers to ledge. Contact sharp with 24.	0.12
Unit 22 - Siltstone: 10YR 7/2 pale orange yellowish brown both surfaces, arenaceous, calcareous, ripple laminated. Unit weathers to break in slope. Contact sharp with 23.	0.24

Unit 21 - Silty claystone: 10Y 8/2 pale greenish-yellow both surfaces, very calcareous, structureless, blocky fracture. Unit weathers to slope. Contact gradational with 22 noted by lose of clay content.	0.18
Unit 20 - Siltstone: 10YR 7/2 pale orange yellowish brown both surfaces, arenaceous, calcareous, basal 0.7 m is ripple laminated, upper beds are medium to thick bedded. Unit weathers to break in slope. Contact sharp with 21.	2.7
Unit 19 - Siltstone fining upwards into claystone. Siltstone: 10Y 6/2 pale olive both surfaces, calcareous, structureless. Claystone: 10Y 6/2 pale olive both surfaces, contains some biotite and mafic minerals in partings, very calcareous, laminated, shaley. Unit fines to claystone at 0.2 m from base. Iron-oxide staining common in partings. At 1.4 m unit has red bands of claystone. At 1.8 m unit changes color to 10YR 4/2 dark yellowish-brown. Unit weathers to popcorn slope. Contact sharp with 20.	4.45
Unit 18 - Claystone: 10YR 7/2 pale orange yellowish brown both surfaces, calcareous, structureless, blocky fracture. Unit has red blotchy areas at top. Unit weathers to popcorn slope. Contact sharp with 19.	0.9
Unit 17 - Siltstone: 10YR 7/4 pale orange yellowish brown both surfaces, arenaceous, calcareous, structureless. Unit weathers to ledge. Contact gradational with 18 noted by a grain size change.	0.4
Unit 16 - Silty claystone: 10YR 7/2 pale orange yellowish-brown fresh surface, 10YR 6.5/3 pale yellowish-brown weathered surface, mafic minerals common, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope with small breaks in slope. Contact gradational with 17 noted by a color change.	2.8
Unit 15 - Argillaceous siltstone fining upwards into claystone. Argillaceous siltstone: 5Y 7/2 yellowish-gray fresh surface, 5Y 7.5/1 yellowish-gray weathered surface, calcareous, structureless. Claystone: 5GY 6/1 greenish-gray fresh surface, 5Y 6/1 light olive gray weathered surface, calcareous, laminated. Iron-oxide staining common in partings. Unit weathers to popcorn slope. Contact sharp with 16.	4.45
Unit 14 - Silty claystone and sandstone. Silty claystone: 10YR 7/2 pale orange yellowish-brown fresh surface, 10YR 6.5/3 pale yellowish-brown weathered surface, contains mafic minerals, calcareous, structureless, blocky fracture. Sandstone: 10YR 7/2 pale orange yellowish-brown fresh surface, 10YR 6.5/3 pale yellowish-brown weathered surface, very fine-grained, calcareous, lenticular. Silt is concentrated in some beds. Sandstone lense occurs near top of unit. Iron-oxide staining common. Unit weathers to popcorn slope with small breaks in slope. Contact sharp with 15. Sample #970807C.	2.3
Unit 13 - Silty claystone and siltstone. Silty claystone: 10YR 5.5/3 yellowish-brown fresh surface, 10YR 6/2 pale yellowish-brown weathered surface, selenite nodules abundant, calcareous, structureless. Siltstone: 5YR 8/2 gray orange fresh surface, 5YR 7/3 grayish-orange pink weathered surface, slightly argillaceous, selenite roses and booklets abundant, calcareous, structureless. Siltstone bed (20 cm thick) occurs at 3.5 m. Unit weathers to popcorn slopes and break in slope. Contact sharp with 14.	4.7
Unit 12 - Argillaceous siltstone: 5Y 7/2 yellowish-gray light brown fresh surface, slightly sandy - contains some mafic minerals, calcareous, sparkles, structureless. Unit weathers to slope. Contact sharp with 13.	0.12

Unit 11 - Siltstone fining upwards into silty claystone. Siltstone: 5YR 8/2 gray orange fresh surface, 5YR 7/3 grayish-orange pink weathered surface, slightly argillaceous, selenite roses and booklets abundant, calcareous, structureless. Silty claystone: 10YR 5.5/3 yellowish-brown fresh surface, 10YR 6/2 pale yellowish-brown weathered surface, selenite nodules abundant, calcareous, structureless. Unit grades to silty claystone at ~ 2.3 m. Unit weathers to popcorn slope. Contact sharp with 12. 5.3

Unit 10 - Silty claystone: 5Y 7/1 yellow gray both surfaces, calcareous, structureless to medium bedded. Unit varies in silt content throughout. Unit weathers to popcorn slope. Contact sharp with 11. 0.9

Unit 9 - Sandstone: 5YR 8/2 gray orange pink both surfaces, very fine-grained, poorly sorted - contains medium sand-sized grains, calcareous, single bed, wavy surfaces. Unit weathers to slope. Contact sharp with 10. 0.1

Unit 8 - Claystone: 5Y 7/2 yellowish-gray fresh surface, weathered surface covered in slope, very calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 9. 1.0

Unit 7 - Silty claystone: N9 white both surfaces, contains mafic minerals, calcareous, laminated, discontinuous. Unit weathers to discontinuous ledge. Contact sharp with 8. Sample # 970807B. 0.15

contact members 1/2

Unit 6 - Silty claystone: 5YR 8/2 gray orange pink fresh surface, 5YR 7/3 grayish-orange pink, calcareous, structureless, weakly blocky fracture. Unit is silty at base. Clay rich areas have slight color variance of 10YR 8/3 pale grayish orange. Unit weathers to break in slope and popcorn slope. Contact sharp with 7. 6.5

Unit 5 - Echo Spring Mountain ash bed: N9 white fresh surface, 5YR 8/2 gray orange pink weathered surface, felsic, bentonized, silty, calcareous, lower third of unit is structureless - rest is laminated bedded. Upper 2/3 of unit is reworked with silty claystone. Unit weathers to prominent ledge. Contact gradational with 6 due to reworked upper surface of ash bed. Sample #970617A. 0.6

Unit 4 - Silty claystone: 5YR 5/6 light brown fresh surface, 5YR 5/5 light brown weathered surface, calcareous, structureless. At 1.5 m, a 60 cm thick area changes color to 5Y 8/1 yellowish-gray. Unit weathers to popcorn slope. Contact scour with 5. 2.75

Unit 3 - Silty micritic limestone (marl): N9 white both surfaces, structureless, discontinuous. Unit weathers to discontinuous ledge. Contact gradational with 4 due to discontinuous nature. Samples #970807A, 980418C. 0.16

Unit 2 - Bidahochi Formation - Argillaceous siltstone, silty claystone, and sandstone. Argillaceous siltstone: 5YR 5/6 light brown fresh surface, 5YR 5/5 light brown weathered surface, sandy at the base, calcareous, structureless. Silty claystone: 5YR 5/6 light brown fresh surface, 5YR 5/5 light brown weathered surface, calcareous, structureless. Sandstone: calcareous, fine-grained, moderately sorted, rounded, quartzose, weakly trough cross-bedded. Lower 60 cm of unit is mottled. Just above the base unit grades into silty claystone. At 2 m a 10 cm thick sandstone bed occurs. At 6.7 m a bed (9 cm thick) of silty claystone changes color to 5GY 8/1 light greenish-gray fresh surface and is mottled looking. Small selenite crystals are observed in this unit. Unit weathers to popcorn slopes and ledges. Contact sharp with 3. 9.9

contact Entrada Formation/member 1 Bidahochi Formation

Unit 1 - Entrada Formation - Siltstone: 5YR 6/4 light brown fresh surface, 5YR 5/5 light brown weathered surface, calcareous, moderately to well indurated, planar cross-bedded. Unit weathers to cliffs and slopes. Contact disconformity with 2 noted by a white sandstone layer.	NM
Total thickness measured	**95.17**

Appendix B-25

Location 25 on Figure 2.2 (Vertical Cliff Section)

Measured by Jacob staff and tape measure on July 23, 1997

Field Assistant: Carey Lang

Location: Navajo Reservation, Sunflower Butte 7.5' Quadrangle, N 35° 20.037' by W 110° 12.658' Located along the cliff to the northeast of Sunflower Butte. The section was measured below the small vent just west of where the mesa projects towards Sunflower Butte. The locality can be entered from above and access is along dirt trails from highway 15.

Outcrop Attitude: N60W 3NE measured from a clay parting

Measured bottom up

#25 Vertical Cliff near Sunflower Butte	**Meters**
Top of mesa, no further exposure	
Unit 46 - Mafic lava: N1 black both surfaces, contains small phenocrysts of olivine, slightly rubbley base. Unit weathers to cliff.	2+
Unit 45 - Mafic tuff: 10 YR 5/2 yellowish-brown both surfaces, coarse lapilli, clast supported, contains abundant euhedral pyroxene, amphibole, and wall rock lithologies, has calcite amygdules, very calcareous, structureless. Unit weathers to ledge. Contact scour with 46.	1.2
Unit 44 - Interbedded tuff sandstone and siltstone: Tuff sandstone: 5YR 6/2 yellowish-olive gray both surfaces, medium- to coarse-grained, poorly to moderately sorted, subangular, mafic, contains granule-sized clasts, calcareous, well indurated, thin- to medium-bedded. Tuff siltstone: 5YR 6/2 yellowish-olive gray both surfaces, mafic, calcareous, moderately indurated, structureless. Unit weathers to cliff. Contact sharp with 45.	1.2
Unit 43 - Siltstone: 10R 6/4 reddish-orange brown fresh surface, 10R 7/6 reddish-orange pink weathered surface, calcareous, well indurated, single bed, displays soft-sediment deformation. Unit weathers to cliff. Contact sharp with 44.	0.08
Unit 42 - Interbedded tuff sandstone and siltstone: Tuff sandstone: 5YR 6/2 yellowish-olive gray both surfaces, medium- to coarse-grained, poorly to moderately sorted, subangular, mafic, contains granule-sized clasts, calcareous, well indurated, thin- to medium-bedded. Tuff siltstone: 5YR 6/2 yellowish-olive gray both surfaces, mafic, calcareous, moderately indurated, structureless. Unit weathers to cliff. Contact sharp with 43.	3.5

Unit 41 - Interbedded claystone and siltstone. Claystone: 10Y 7/2 pale olive yellow fresh surface, 5Y 8/2 pale yellowish gray weathered surface, slightly silty, very calcareous, structureless, blocky fracture. Siltstone: 10YR 6/4 gray yellowish orange fresh surface, calcareous, structureless. Unit contains some matrix-supported, sand-sized mafic volcanic clasts throughout. Unit weathers to slope. Contact sharp with 42. 0.62

Unit 40 - Interbedded tuff sandstone and siltstone: Tuff sandstone: 10YR 5/6 yellowish-orange brown both surfaces, medium- to coarse-grained, poorly to moderately sorted, subangular, mafic, contains mafic clasts up to 13 cm long near top, calcareous, well indurated, weakly normal graded at base, trough cross-bedded above 70 cm. Tuff siltstone: 10YR 5/6 yellowish-orange brown both surfaces, mafic, calcareous, moderately indurated, structureless. Tuff siltstone occurs as small lenticular beds (<2cm thick) and at the upper 10 cm of unit. Unit weathers to ledge. Contact sharp with 41. 1.5

Unit 39 - Mafic tuff: 10 YR 5/2 yellowish-brown both surfaces, coarse lapilli, clast supported, contains abundant euhedral pyroxene, amphibole, and wall rock lithologies, has calcite amygdules, very calcareous, structureless. Unit weathers to ledge. Contact sharp with 40. 0.44

Unit 38 - Claystone: 10Y 7/2 pale olive yellow fresh surface, 5Y 8/2 pale yellowish gray weathered surface, slightly silty, very calcareous, sparkles, structureless to laminated in areas, some blocky fracture. At 1.65 m unit contains matrix-supported, sand-sized, mafic clasts from the Hopi Buttes volcanic field. Volcanic material increase towards top of unit. Unit weathers to slope. Contact scour with 39. 2.5

contact member 2/5 at 1.65 m from base of unit 38

Unit 37 - Argillaceous siltstone: 10YR 6/4gray yellowish orange fresh surface, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 38. 0.5

Unit 36 - Claystone: 10Y 7/2 pale olive yellow fresh surface, 5Y 8/2 pale yellowish gray weathered surface, slightly silty, very calcareous, sparkles, structureless to laminated in areas, some blocky fracture. Unit weathers to slope. Contact sharp with 37. 0.4

Unit 35 - Argillaceous siltstone: 10YR 6/4gray yellowish orange fresh surface, calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 36. 0.25

Unit 34 - Claystone: 10Y 7/2 pale olive yellow fresh surface, 5Y 8/2 pale yellowish gray weathered surface, slightly silty, very calcareous, sparkles, structureless to laminated in areas, some blocky fracture. Unit very contains abundant siltstone (like unit 33) in basal 50 cm. Unit weathers to slope. Contact sharp with 35. 1.25

Unit 33 - Argillaceous siltstone: 10YR 6/4 gray yellowish orange fresh surface, calcareous, structureless. Unit weathers to popcorn slope. Contact gradational with 34 noted by appearance of claystone. 0.65

Unit 32 - Claystone and silty micritic limestone (marl). Claystone: 10Y 7/2 pale olive yellow fresh surface, 5Y 8/2 pale yellowish gray weathered surface, slightly silty, very calcareous, sparkles, structureless to laminated in areas, some blocky fracture. Silty micritic limestone (marl): N9 white weathered surface, structureless. Limestone bed (20 cm thick) occurs at base. Unit weathers to ledge then popcorn slope. Contact sharp with 33. Sample #980418H of limestone bed. 2.1

Unit 31 - Sandstone: 5YR 7/6light orange brown both surfaces, fine-grained, poorly sorted, rounded, mafic minerals common, weakly calcareous, structureless. Unit weathers to break in slope. Contact sharp with 32. 0.3

Unit 30 - Interbedded argillaceous siltstone and claystone. Argillaceous siltstone: 5YR 7/3 grayish-orange pink fresh surface, 10YR 8/3 pale grayish-orange weathered surface, calcareous, structureless. Claystone: 10Y 7/2 pale olive yellow fresh surface, 5Y 8/2 pale yellowish gray weathered surface, slightly silty, very calcareous, sparkles, structureless. Unit is thin bedded defined by continuous repeating of two units. Unit weathers to slope. Contact sharp with 31. 2.85

Unit 29 - Claystone and silty micritic limestone (marl). Claystone: 10Y 7/2 pale olive yellow fresh surface, 5Y 8/2 pale yellowish gray weathered surface, slightly silty, very calcareous, sparkles, structureless. Silty micritic limestone (marl): N9 white, discontinuous, structureless. Marl occurs at base. At 1.1 m claystone changes color to 10Y 5/2 light grayish olive fresh surface, 10Y 6/2 pale olive weathered surface, and is laminated and shaley. Unit weathers to popcorn slope. Contact gradational with 30 noted by a color change and increase in silt content. Sample # 980418G of silty micritic limestone. 3.35

Unit 28 - Argillaceous siltstone: 5YR 7/3 grayish-orange pink fresh surface, 10YR 8/3 pale grayish-orange weathered surface, calcareous, structureless. Unit weathers to slope. Contact sharp with 29. 2.25

Unit 27 - Claystone: 10Y 7/2 pale olive yellow fresh surface, 5Y 8/2 pale yellowish gray weathered surface, slightly silty, very calcareous, sparkles, structureless. Unit weathers to popcorn slope. Contact gradational with 28 noted by a color change and increase in silt. 2.8

Unit 26 - Argillaceous siltstone and ash bed. Argillaceous siltstone: 5YR 7/3 grayish-orange pink fresh surface, 10YR 8/3 pale grayish-orange weathered surface, calcareous, structureless. Wood Chop C ash bed: N9 white weathered surface, massive, structureless. Ash bed (3cm thick) occurs at base and is mixed with surrounding siltstone. Unit weathers to slope and break in slope. Contact sharp with 27. Sample #980418F of ash bed. 1.6

Unit 25 - Silty claystone: 5Y 8/2 pale yellowish gray fresh surface, 10YR 7/3 pale grayish-orange weathered surface, some areas with abundant bands 10R 7.5/4 moderate orange pink fresh surface, very calcareous, structureless to weakly laminated. Unit has iron oxide staining which appears to be from red colored silt-rich partitions. Unit weathers to popcorn slope. Contact sharp with 26. 2.9

Unit 24 - Wood Chop B ash bed: N9 white fresh surface, calcareous, sparkles, structureless. Unit weathers to break in slope. Contact gradational with 25 due to reworked upper surface of ash bed. Sample #970723K. 0.04

Unit 23 - Silty claystone: 5Y 8/2 pale yellowish gray fresh surface, 10YR 7/3 pale grayish-orange weathered surface, some areas with abundant bands 10R 7.5/4 moderate orange pink fresh surface, very calcareous, structureless to weakly laminated. Unit has iron oxide staining which appears to be from red colored silt-rich partitions. Unit weathers to popcorn slope. Contact sharp with 24. 4.35

Unit 22 - Silty claystone: 10Y 6.5/2 pale olive fresh surface, 10YR 8/3 pale grayish-orange weathered surface, abundant color bands 10R 7.5/4 moderate orange pink fresh surface, no gypsum noted, very calcareous, laminated, sparkles, shaley habit. Unit has iron oxide staining which appears to be from red colored silt-rich partitions. Unit weathers to popcorn slope. Contact gradational with 23 noted by decrease in red color especially between partings. 3.25

Unit 21 - Sandstone: 10YR 6/2 pale yellowish brown both surfaces, medium- to coarse-grained, moderately sorted, rounded, consists entirely of platy claystone rip-up clasts, calcareous, structureless. Upper surface of unit contains ripple structures. Unit weathers to cliff. Contact sharp with 22. Sample #970723I.	0.04
Unit 20 - Silty claystone and siltstone. Silty claystone: 10Y 6.5/2 pale olive fresh surface, 10Y 7/2 pale olive yellow weathered surface, selenite common, very calcareous, weakly thin-bedded, blocky fracture. Siltstone: 10Y 6.5/2 pale olive fresh surface, 10Y 7/2 pale olive yellow weathered surface, volcaniclastic, very calcareous, moderately indurated, weakly thin-bedded, blocky fracture. Siltstone occurs at 1.8 m (30 cm thick bed) and 2.25 m (40cm thick bed) from the base. Unit weathers to cliffs and slopes. Contact sharp with 21.	3.4
Unit 19 - Silty claystone: 10Y 6.5/2 pale olive fresh surface, 10Y 7/2 pale olive yellow weathered surface, contains biotite and mafic minerals, selenite common, very calcareous, laminated, shaley habit. Unit has iron oxide staining which appears to be from red colored silt-rich partitions. Unit is laminated lower third and structureless rest of unit. Red staining occurs in lower two-thirds. Unit is very silty upper third. Unit weathers to popcorn slope then cliff. Contact gradational with 20 noted lack of red staining and structural change.	1.95
Unit 18 - Silty claystone: 10Y 6.5/2 pale olive fresh surface, 10Y 7/2 pale olive yellow weathered surface, contains biotite and mafic minerals, selenite common, very calcareous, laminated, shaley habit. Unit has iron oxide staining which appears to be from silt-rich partitions. Unit weathers to popcorn slope. Contact gradational with 19 noted by increase in red color especially between partings.	1.05
Unit 17 - Sandstone: 10Y 8/3 pale greenish-yellow both surfaces, very fine-grained, calcareous, weakly wavy laminated, contains ostracods. Unit weathers to small ledge. Contact sharp with 18. Sample #980418E.	0.04
Unit 16 - Claystone: 10YR 6/2 pale yellowish-brown both surfaces, gypsum only noted in scree, slightly silty, very calcareous, structureless. Unit changes color to 10Y 6.5/2 pale olive fresh surface, 10Y 7/2 pale olive yellow weathered surface, at 2.9 m. Unit weathers to popcorn slope. Contact sharp with 17. Sample #970723H.	3.35
Unit 15 - Argillaceous siltstone: 5YR 7/2 grayish-orange pink both surfaces, calcareous, structureless. Unit weathers to slope. Contact sharp with 16.	0.16
Unit 14 - Claystone: 10YR 4.5/2 dark yellowish brown fresh surface, 10Y 7.5/2.5 pale greenish-yellow weathered surface, becomes more green at top, selenite nodules common, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 15.	1.65
Unit 13 - Argillaceous siltstone: 5YR 7/2 grayish-orange pink both surfaces, calcareous, structureless. Unit weathers to slope. Contact sharp with 14.	0.18
Unit 12 - Claystone: 10YR 4.5/2 dark yellowish brown fresh surface, 10Y 7.5/2.5 pale greenish-yellow weathered surface, calcareous, structureless, blocky fracture. Unit does not appear to have gypsum in brown claystone but has lenses of green claystone (like unit 11) and gypsum mixture. Unit weathers to popcorn slope. Contact sharp with 13. Sample #970723G.	4.15
Unit 11 - Claystone: 10Y 5/2 grayish-pale olive fresh surface, contains abundant selenite, very calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact gradational with 12 noted by a color change.	0.1

Unit 10 - Siltstone: 10YR 6.5/4 grayish orange both surfaces, calcareous, structureless. Unit weathers to slope. Contact sharp with 11. 0.13

Unit 9 - Claystone: 10Y 5/2 grayish-pale olive fresh surface, contains abundant selenite especially at top, very calcareous, structureless, blocky fracture. 11 cm from top claystone is more brownish-red and contains satin spar in the color change zone. Unit weathers to popcorn slope. Contact sharp with 10. Sample #970723F. 0.6

Unit 8 - Claystone: 5YR 4/4 moderate brown fresh surface, weathered surface covered in slope, calcareous, structureless, blocky fracture. Unit weathers to popcorn slope. Contact gradational with 9 noted by a color change. Sample #970723E. 0.15

Unit 7 - Siltstone: 10YR 6.5/4 grayish orange both surfaces, calcareous, structureless. Unit weathers to slope. Contact sharp with 8. 0.22

Unit 6 - Tuffaceous claystone, marl, and claystone. Tuffaceous claystone: N9 white both surfaces, contains mafic minerals, calcareous, structureless. Marl: 5Y 8/1 yellowish gray fresh surface, structureless. Claystone: 10Y 6/2 pale olive, has red blotchy areas, very calcareous, structureless. Tuffaceous claystone mixed with marl in lower portion with concentration near the base. Unit grades to green claystone near top. Unit weathers to ledge. Contact sharp with 7. Sample #970723D of ash near base. 1.3

contact members 1/2

Unit 5 - Siltstone: 5YR 6/4 light brown fresh surface, 5YR 6.5/4 light pinkish brown weathered surface, slightly argillaceous, slightly sandy, selenite common, calcareous, trough cross-bedded noted by 2 mm thick clay rich layers, blocky fracture. Unit weathers to calcified slope. Contact sharp with 6. 4.3

Unit 4 - East point biotite ash bed: 10Y 8/2 pale greenish yellow both surfaces, contains abundant biotite, silty, wavy laminated. Unit weathers to small ledge. Contact gradational with 5 due to reworked upper surface of ash bed. Sample #970723C. 0.06

Unit 3 - Siltstone: 5YR 6/4 light brown fresh surface, 5YR 6.5/4 light pinkish brown, slightly argillaceous, selenite common, calcareous, weakly trough cross-bedded noted by clay rich layers, blocky fracture. Unit weathers to popcorn slope. Contact sharp with 4. 1.4

Unit 2 - Bidahochi Formation - Siltstone, claystone, and ash. Siltstone: 5YR 5.5/4 light brown both surfaces, contains small pebbles of quartz and chert at the base, slightly sandy, calcareous, structureless. Claystone: green both surfaces, very calcareous, structureless. Claystone: bright red both surfaces, calcareous, structureless. Echo Spring Mountain ash bed: N9 white, felsic, friable, extensively bentonized, structureless, discontinuous. Green claystone occurs as lenses and blotchy areas at 6.3 m from the base and above. Also at this horizon the siltstone becomes argillaceous. At 7.8 m have small patches of ash mixed with claystone. Red claystone occurs at 11.45 m. A small 10 cm thick ash bed occurs at 12 m. Selenite crystals and nodules occur in units above ash bed. Unit weathers to popcorn slopes. Contact gradational with 3 noted by decrease in clay content and structural change. Sample #970723A collected of red claystone, #970723B of ash bed. 13.35

contact Wingate Formation/member 1 of Bidahochi Formation

Unit 1 - Wingate Formation - Siltstone: 5YR 5/5 light brown both surfaces, calcareous, moderately to well indurated, structureless, nodular. Unit weathers to cliffs and slopes. Contact disconformity with 2. NM

Total thickness measured 79.46

Appendix B-26

Location 26 on Figure 2.2 (616 Section)

Measured by Jacob staff and tape measure on June 16, 1997

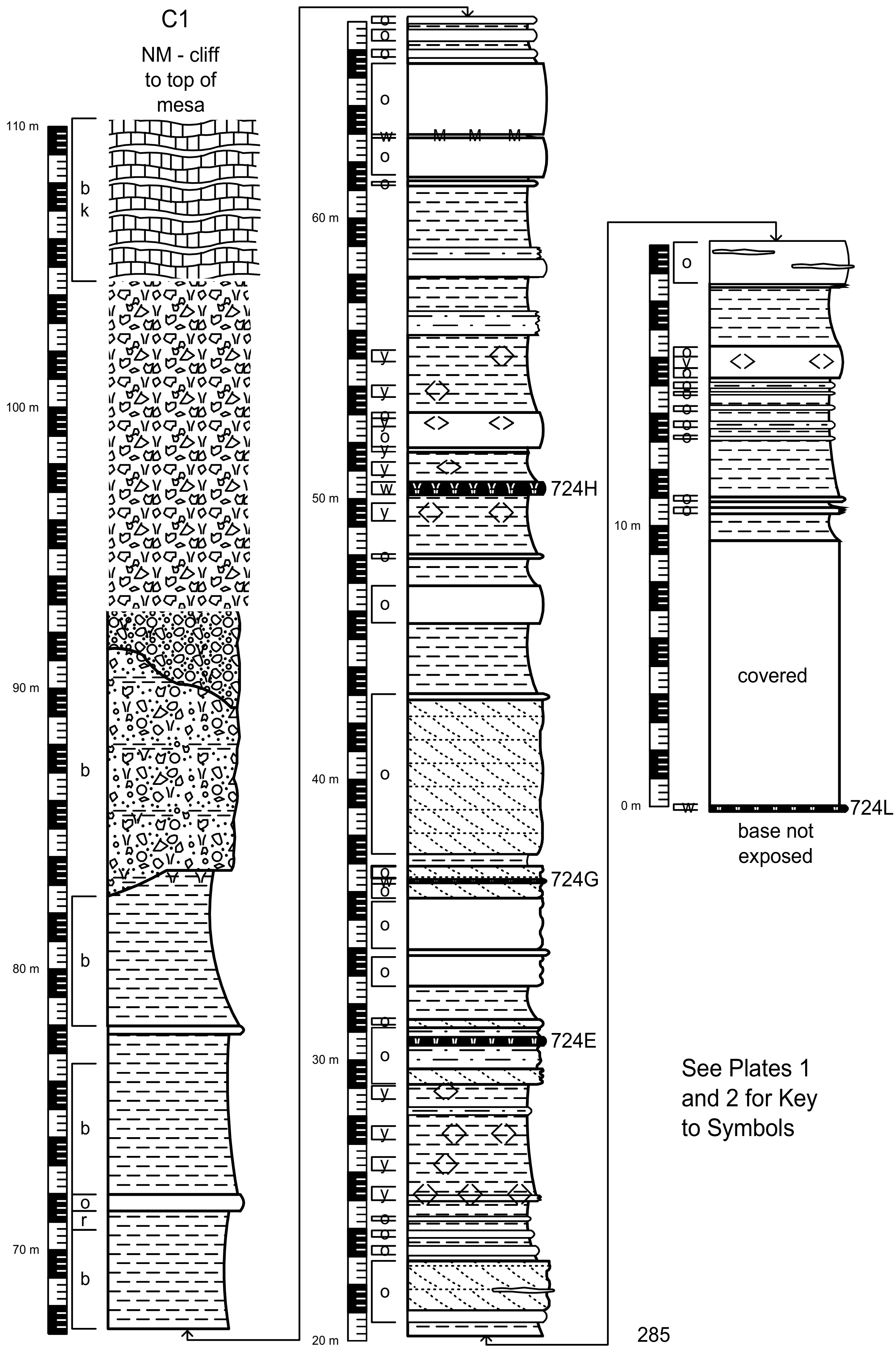
Location: Navajo Reservation, French Butte 7.5' Quadrangle, N 35° 19.151' by W 110° 17.535' Located on west end of unnamed butte NW or Sunflower Butte. A small outcrop is visible from the dirt road that connects east-west dirt road with north-south paved highway 60.

Outcrop Attitude: N50E 5 SE from unit 3

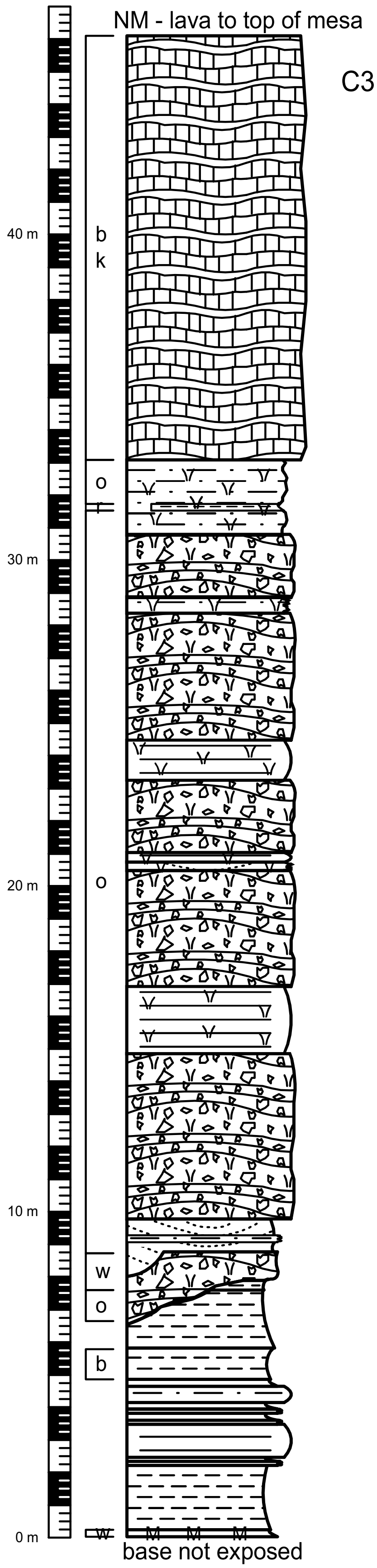
Measured bottom up

#26 616 Section	Meters
Toreva block, no in-situ outcrop available	
Unit 8 - Mafic lava: N1 black fresh surface, brownish-red weathered surface, porphyritic - large phenocrysts of pyroxene and amphibole. Unit is a Toreva block and is not in-situ.	NM
Unit 7 - Interbedded claystone and siltstone. Claystone: light olive green fresh surface, gray weathered surface, very calcareous, structureless, blocky fracture. Siltstone: orangish-tan both surfaces, calcareous, structureless. Claystone is dominant lithology with siltstone beds up to 60 cm thick throughout. Unit weathers to popcorn slope. Colluvial contact with 8.	7.5
Unit 6 - Siltstone: white with yellow iron-oxide streaks fresh surface, grayish-white weathered surface, calcareous, sparkles, structureless. Unit becomes arenaceous, dark brown, and weakly laminated 2 m from base. Unit weathers to popcorn slope. Contact sharp with 7.	7.7
Unit 5 - Mudstone: dark brown fresh surface, light reddish-brown weathered surface, very calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 6.	6.1
Contact members ½	
Unit 4 - Ash bed: N9 white fresh surface, orangish-tan weathered surface, felsic, slightly bentonized, calcareous, lower 20 cm is laminated ash - upper 40 cm is ash mixed with silt - structureless. Unit pinches out to southwest and is not apparent where section was measured - occurs nearby in next small ravine - sits on mudstone beds of unit 3. Unit weathers to ledge. Contact gradational with 5 due to reworked upper surface of ash bed. Sample #970616A.	0.6
Unit 3 - Mudstone: dark brown fresh surface, light reddish-brown weathered surface, very calcareous, structureless. Unit weathers to popcorn slope. Contact sharp with 4.	1.1
Unit 2 - Bidahochi Formation - conglomerate: purplish-white both surfaces, consists of granules and pebbles, clast supported, contains quartz, chert, petrified wood, metavolcanics, and rare fossiliferous dolostone clasts, trough cross-bedded, lenticular and pinches-out to the northwest. Unit weathers to ledge. Contact sharp with 3. Samples #971005B of conglomerate, #980418D of fossiliferous dolostone clast.	0.4

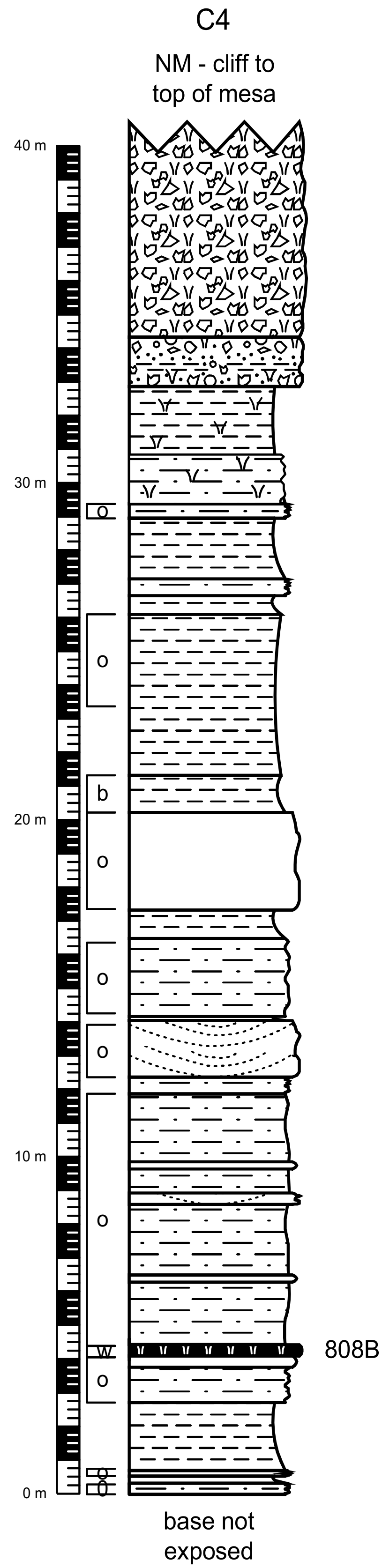
Unit 1 - Wingate Formation - Siltstone: orangish-brown weathered surface, calcareous, moderately to well indurated, nodular. Extensive orange colored weathered horizon at top of unit. Unit weathers to slope. Contact disconformity with 2.	NM
Total thickness measured	**23.4**

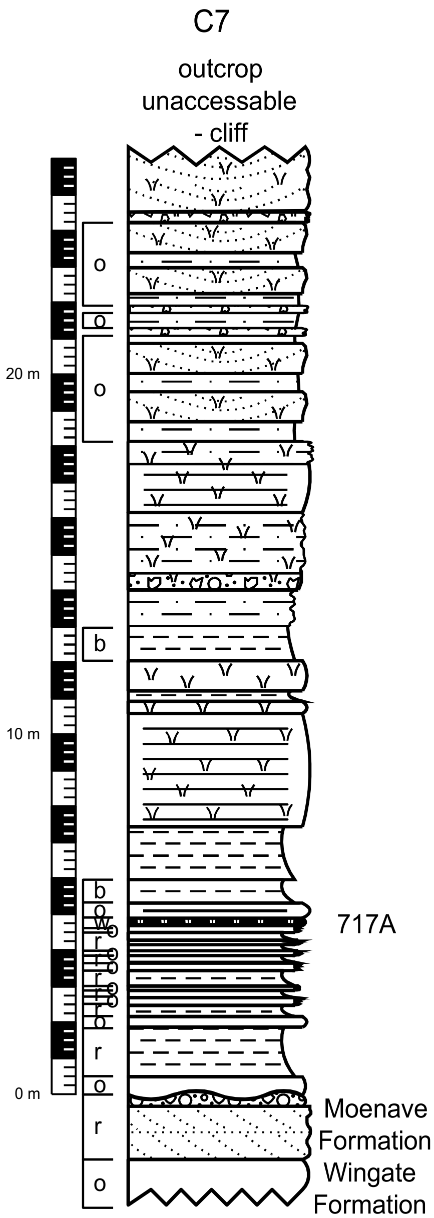


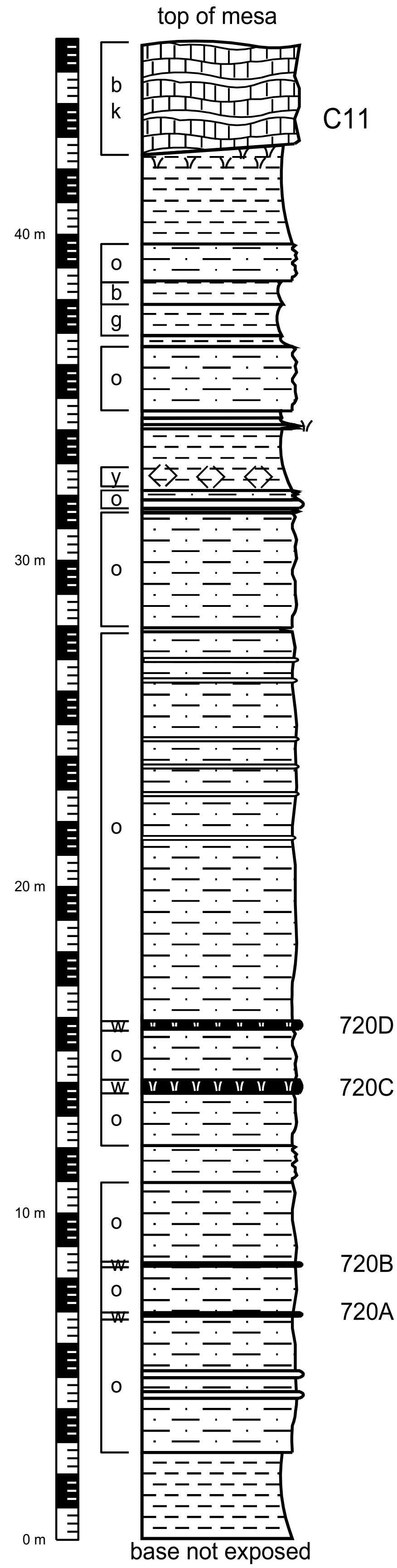
See Plates 1 and 2 for Key to Symbols



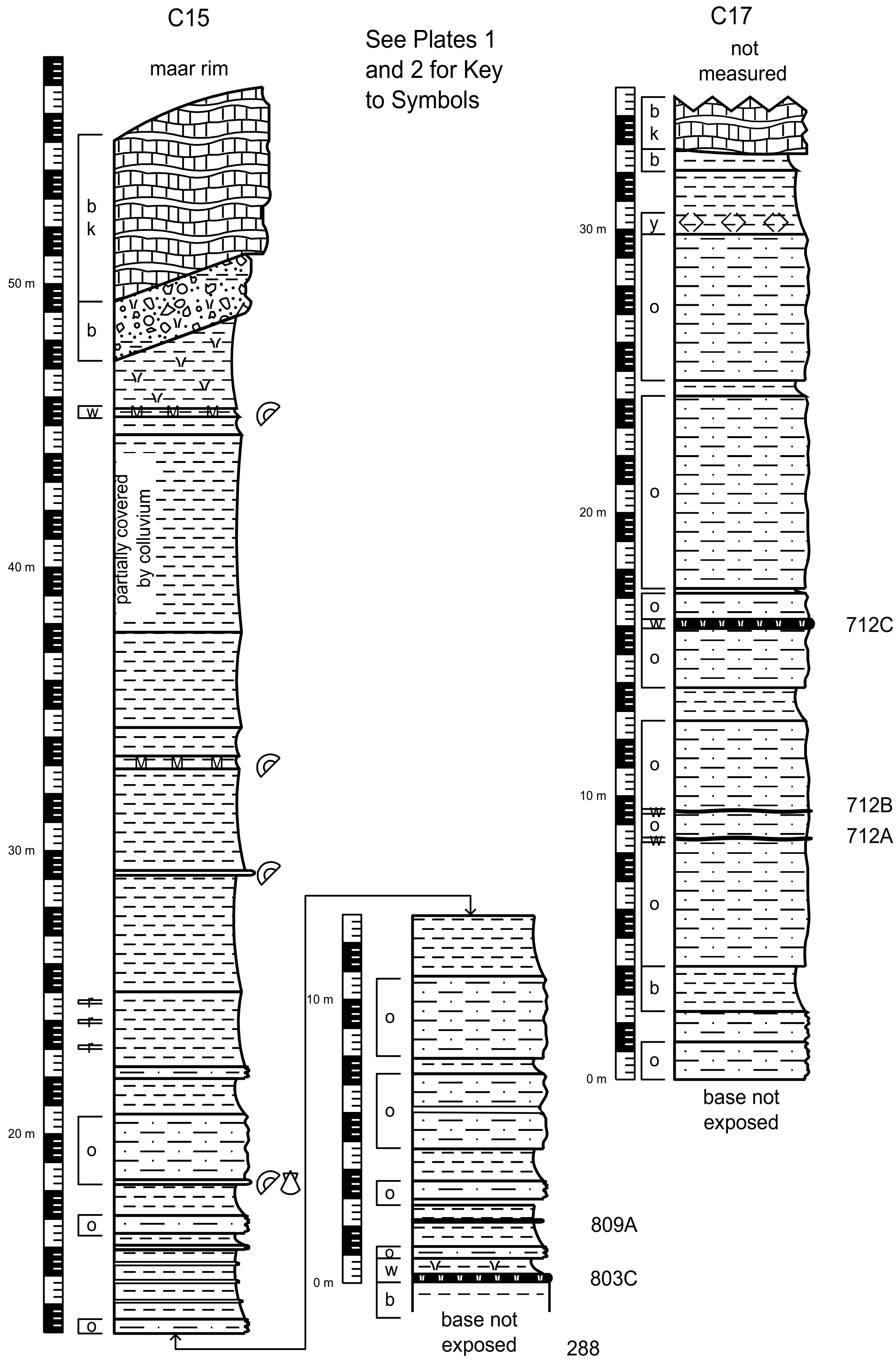
See Plates 1 and 2 for Key to Symbols







See Plates 1 and 2 for Key to Symbols


C15
maar rim
See Plates 1 and 2 for Key to Symbols
C17
not measured
b
k
b
y
o
w
partially covered by colluvium
712C
712B
712A
809A
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30 m
20 m
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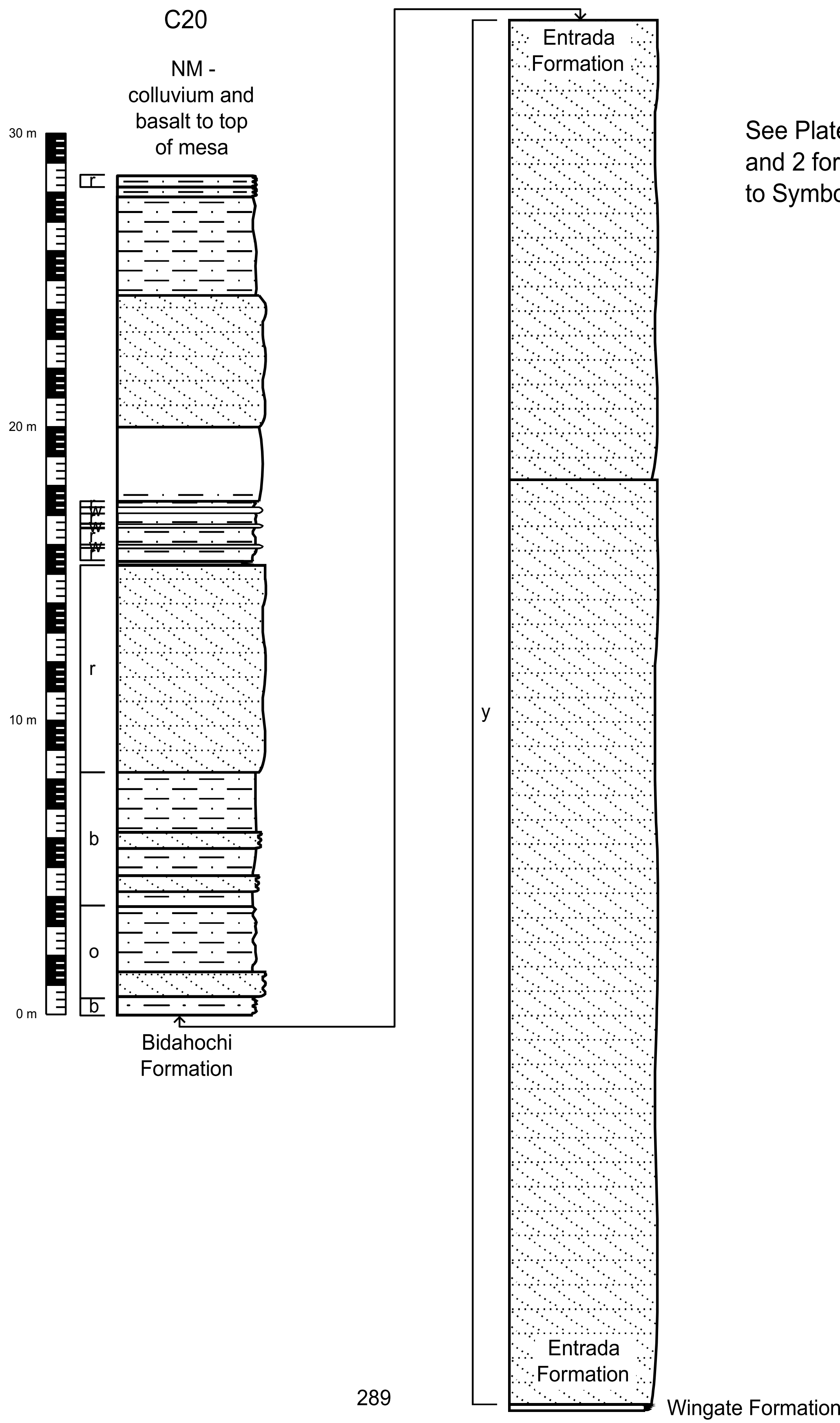
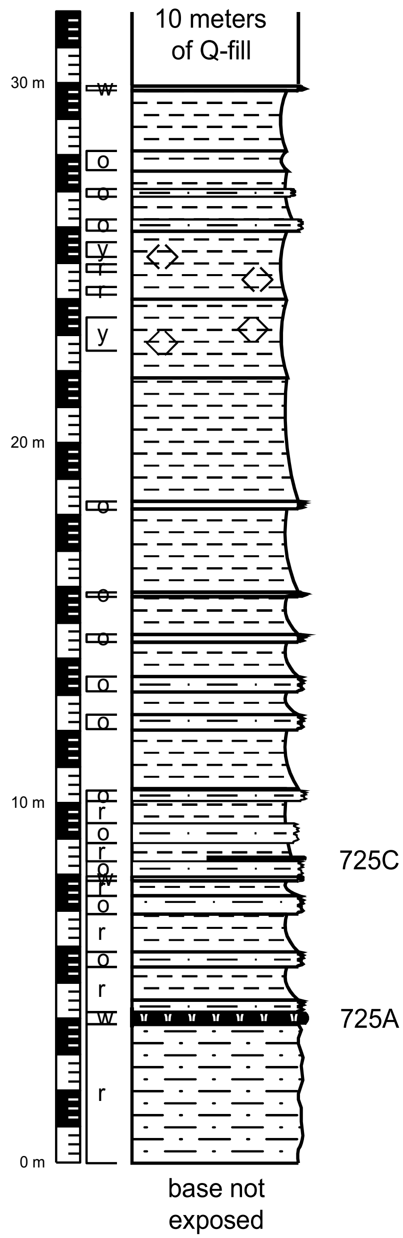
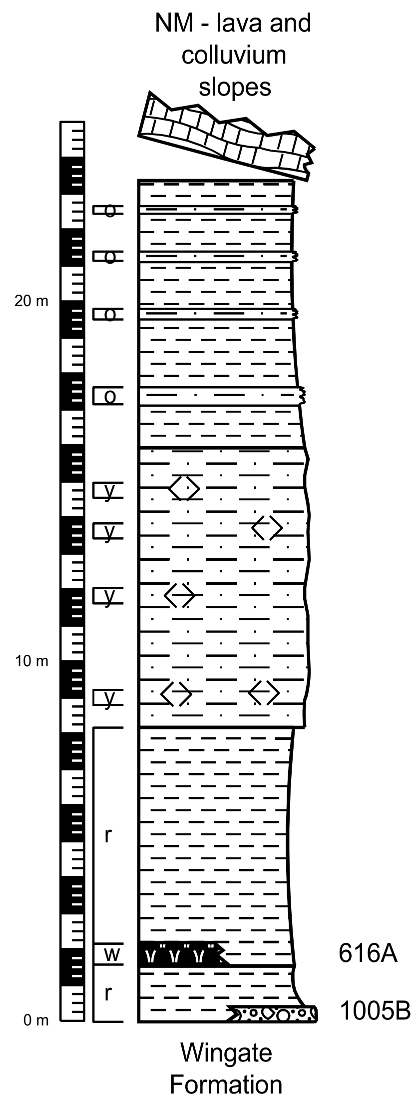


See Plates 1 and 2 for Key to Symbols

C21



C26



See Plates 1
and 2 for Key
to Symbols

Appendix C - Ar-Ar Analyses

The following tables and graphs are the reported the ^{40}Ar-^{39}Ar analyses data from New Mexico Geochronological Research Laboratory. Notes for first three tables follow Table C.4 and after Table C.6 for last two tables .

Table C.1 Analytical Methods:

Sample preparation and irradiation:
Mineral phases concentrated by dissolving glass and matrix from the crushed rock in 15% HF.
K-feldspar and biotite separates were prepared using standard heavy liquid, Franz magnetic separation, and hand-picking techniques.
Samples irradiated in machined A1 discs for 7 hours in D-3 position, Nuclear Science Center, College Station, TX.
Neutron flux monitor Fish Canyon Tuff sanidine (FC-1). Assigned age = 27.84 Ma (Deino and Potts, 1990) relative to Mmhb-1 at 520.4 Ma (Sampson and Alexander, 1987).

Instrumentation:
Mass Analyzer Products 215-50 mass spectrometer on line with automated all-metal extraction system.
Feldspar crystals were fused by a 10 watt Synrad CO_2, laser.
Reactive gases removed during a 2 minute reaction with 2 SAES GP-50 getters, 1 operated at ~450°C and 1 at 20°C. Gas also exposed to a W filament operated at ~2000°C and a cold finger operated at -140°C.
Biotite samples were step-heated for 8 minutes in a Mo double-vacuum resistance furnace.
Reactive gases removed by a reaction with 3 SAES GP-50 getters, 2 operated at ~450°C and 1 at 20°C. Gas also exposed to a W filament operated at ~2000°C.

Analytical parameters:
Electron multiplier sensitivity averaged $1x10^{-16}$ moles/pA for the furnace and $5x10^{-17}$ moles/pA for the laser.
Total systems blanks and background averaged 684, 73, 1.8, 2.5, $2.6x10^{-18}$ moles for the furnace for temperatures <1300°C and 306, 3.5, 0.9, 0.2, $1.0x10^{-18}$ moles for the laser at masses 40, 39, 38, 37, and 36, respectively.
J-factors determined to a precision of ±0.1% by $C0_2$ laser-fusion of 4 single crystals from each of a 6 radial positions around the irradiation tray.
Correction factors for interfering nuclear reactions were determined using K-glass and CaF_2 and are as follows: $(^{40}Ar/^{39}Ar)_K$ = 0.00020±0.0003; $(^{36}Ar/^{37}Ar)_{Ca}$ = 0.00026±0.00002; and $(^{39}Ar/^{37}Ar)_{Ca}$ = 0.00070±0.00005.

Age calculations:

Furnace:
Total gas ages and errors calculated by weighting individual steps by the fraction of ^{39}Ar released.
Plateau ages calculated by weighting each step by the inverse of the variance.
Plateau age errors calculated using the method of Taylor (1982).
MSWD values are calculated for n-1 degrees of freedom for plateau.
Isochron ages, $^{40}Ar/^{36}Ar_i$ and MSWD values calculated from regression results obtained by the methods of York (1969).

Decay constants and isotopic abundances after Steiger and Jäger (1977).
All final errors reported at ±2 , unless otherwise noted.
Laser:
Weighted mean age calculated by weighting each age analysis by the inverse of the variance.
Weighted mean error calculated using the method of Taylor (1982).
MSWD values calculated for n-1 degrees of freedom.

Table C.2 Furnace ^{40}Ar-^{39}Ar analyses of biotite sample 970712F. Age spectra and isochron graphs follow tables.

ID	Temp (°C)	^{40}Ar-^{39}Ar	^{37}Ar-^{39}Ar	^{36}Ar-^{39}Ar (x 10^{-3})	$^{39}Ar_K$ (x 10^{-15} mol)	K/Ca	^{40}Ar*	^{39}Ar	Age (Ma)	±1 (Ma)
970712F G4:89, Biotite, 3.14 mg, J=0.000800428, D=1.00575, nm-89, Lab#=9194-01										
A	750	*869.3*	*0.0259*	*2870.7*	*4.75*	*19.7*	*2.4*	*19.5*	*30.1*	*6.0*
B	850	*137.1*	*0.0175*	*421.1*	*3.58*	*29.2*	*9.2*	*34.3*	*18.20*	*0.86*
C	950	82.77	0.0189	242.2	4.17	27.0	13.5	51.4	16.11	0.56
D	1000	49.55	0.0145	132.3	3.61	35.1	21.1	66.3	15.03	0.31
E	1050	45.56	0.0248	120.5	2.41	20.5	21.9	76.2	14.34	0.37
F	1100	43.23	0.0302	109.9	1.93	16.9	24.9	84.1	15.48	0.36
G	1150	35.06	0.0379	81.56	2.05	13.5	31.3	92.5	15.76	0.30
H	1200	20.69	0.0805	31.56	0.604	6.3	55.0	95.0	16.35	0.35
I	1250	*28.64*	*0.0064*	*34.75*	*0.133*	*79.3*	*64.2*	*95.6*	*26.34*	*0.95*
J	1300	*13.32*	*0.0000*	*13.80*	*0.082*	-	*69.4*	*95.9*	*13.29*	*0.98*
K	1650	*5.886*	*0.0000*	*5.853*	*0.995*	-	*70.6*	*100.0*	*5.99*	*0.12*
total	**gas age**		n=11		24.3	23.1			18.4	1.6
plateau	MSWD =	3.99**	n=6	steps C-H	14.8	23.9		60.8	**15.46**	**0.58***

Table C.3 Furnace ^{40}Ar-^{39}Ar analyses of biotite sample 970719E. Age spectra and isochron graphs follow tables.

ID	Temp (°C)	^{40}Ar-^{39}Ar	^{37}Ar-^{39}Ar	^{36}Ar-^{39}Ar (x 10^{-3})	$^{39}Ar_K$ (x 10^{-15} mol)	K/Ca	$^{40}Ar^*$	^{39}Ar	Age (Ma)	±1 (Ma)
970719E G5:89, Biotite, 3.00 mg, J=0.000802655, D=1.00575, nm-89, Lab#=9195-01										
A	750	213.8	0.0385	661.4	0.767	13.3	8.6	4.5	26.4	1.9
B	850	18.24	0.0063	14.40	2.52	80.6	76.7	19.1	20.13	0.11
C	950	19.49	0.0050	8.761	2.70	102.5	86.7	34.8	24.31	0.08
D	1000	14.75	0.0078	11.17	1.32	65.5	77.6	42.5	16.50	0.12
E	1050	12.99	0.0084	7.242	1.38	60.7	83.5	50.6	15.64	0.11
F	1100	13.04	0.0136	4.049	1.40	37.5	90.8	58.7	17.08	0.11
G	1150	11.32	0.0042	2.631	5.26	121.7	93.1	89.4	15.20	0.04
H	1200	11.19	0.0040	2.385	1.29	127.9	93.7	96.9	15.12	0.10
I	1250	8.025	0.0000	6.047	0.200	-	77.7	98.0	9.01	0.42
J	1300	9.574	0.0000	18.61	0.043	-	42.6	98.3	5.9	1.9
K	1650	13.50	0.0024	32.67	0.297	215.1	28.5	100.0	5.56	0.54
total	**gas age**		n=11		17.2	92.1			17.88	0.18

Table C.4 Furnace ^{40}Ar-^{39}Ar analyses of biotite sample 970118B. Age spectra and isochron graphs follow tables.

ID	Temp (°C)	^{40}Ar-^{39}Ar	^{37}Ar-^{39}Ar	^{36}Ar-^{39}Ar (x 10^{-3})	$^{39}Ar_K$ (x 10^{-15} mol)	K/Ca	^{40}Ar*	^{39}Ar	Age (Ma)	±1 (Ma)
970118B H1:89, Biotite, 4.34 mg, J=0.000800541, D=1.00575, nm-89, Lab#=9196-01										
A	750	218.9	5.580	721.8	0.420	0.091	2.7	1.2	8.7	2.5
B	850	12.02	0.0191	22.64	3.37	26.7	44.3	11.0	7.68	0.11
C	950	8.438	0.0057	10.54	7.45	88.8	63.1	32.7	7.67	0.06
D	1000	6.736	0.0049	4.668	4.10	104.3	79.5	44.6	7.72	0.05
E	1050	7.723	0.0098	8.157	2.88	52.3	68.8	52.9	7.66	0.06
F	1100	8.391	0.0081	10.10	3.30	63.1	64.4	62.5	7.79	0.06
G	1150	9.509	0.0066	13.49	3.11	77.7	58.1	71.6	7.96	0.09
H	1200	8.628	0.0100	10.72	3.97	51.0	63.3	83.1	7.87	0.08
I	1250	6.960	0.0060	5.678	4.90	85.0	75.9	97.3	7.61	0.04
J	1300	6.491	0.0077	4.179	0.816	66.2	81.0	99.7	7.58	0.12
K	1650	25.04	0.0266	69.88	0.101	19.2	17.6	100.0	6.3	1.2
total	**gas age**		n=11		34.4	71.3			7.74	0.10
plateau	MSWD =	2.08**	n=11	steps A-K	34.4	71.3		100.0	**7.71**	**0.06***

Notes:
Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interfering reactions.
Individual analyses show analytical error only; plateau, total gas age errors include error in J and irradiation parameters.
Analyses in italics are excluded from final age calculations.
n=number of heating steps
k/Ca = molar ratio calculated from reactor produced $^{39}Ar_K$ and $^{37}Ar_{ca}$.
D = 1 A.M.U. mass discrimination
* 2 error
** MSWD outside of 95% confidence interval

Table C.5 Laser ^{40}Ar-^{39}Ar analyses of sanidine sample 970315C. Ideogram follows tables.

ID	^{40}Ar-^{39}Ar	^{37}Ar-^{39}Ar	^{36}Ar-^{39}Ar (x 10^{-3})	$^{39}Ar_K$ (x 10^{-15} mol)	K/Ca	%$^{40}Ar^*$	Age (Ma)	±1 (Ma)
970315C A5:89, single crystal sanidine, J=0.000797707, D=1.00513, nm-89, Lab#=9150								
07	9.833	0.0419	0.8496	1.52	12.2	97.5	13.74	0.05
15	9.717	0.0389	0.2741	8.28	13.1	99.2	13.82	0.03
13	9.761	0.0401	0.4030	4.75	12.7	98.8	13.83	0.04
14	9.742	0.0402	0.3333	7.94	12.7	99.0	13.83	0.03
11	9.796	0.0382	0.4667	4.14	13.3	98.6	13.85	0.03
10	9.888	0.0400	0.7745	3.28	12.8	97.7	13.85	0.04
09	9.783	0.0377	0.4169	3.33	13.5	98.8	13.85	0.04
01	10.90	0.0388	4.060	2.99	13.2	89.0	13.91	0.05
03	9.791	0.0394	0.2992	5.38	13.0	99.1	13.91	0.03
02	9.920	0.0412	0.7321	2.14	12.4	97.8	13.92	0.05
05	*9.903*	*0.0400*	*0.4895*	*8.49*	*12.8*	*98.6*	*13.99*	*0.02*
12	*9.903*	*0.0399*	*0.2537*	*4.96*	*12.8*	*99.3*	*14.09*	*0.04*
08	*10.23*	*0.0433*	*0.4332*	*3.76*	*11.8*	*98.8*	*14.48*	*0.04*
06	*10.58*	*0.0407*	*0.6647*	*3.34*	*12.5*	*98.2*	*14.89*	*0.03*
04	*11.04*	*0.0369*	*0.5240*	*8.34*	*13.8*	*98.6*	*15.60*	*0.03*
weighted	**mean**	MSWD = 1.59	N=10		12.9	± 0.4	**13.85**	**0.02***

Table C.6 Laser ^{40}Ar-^{39}Ar analyses of sanidine sample 970705C. Ideogram follows tables.

ID	^{40}Ar-^{39}Ar	^{37}Ar-^{39}Ar	^{36}Ar-^{39}Ar (x 10^{-3})	$^{39}Ar_K$ (x 10^{-15} mol)	K/Ca	%^{40}Ar*	Age (Ma)	±1 (Ma)
970705C E16:91, multiple crystals sanidine, J=0.000802812, D=1.00253, nm-89, Lab#=9184								
03	16.94	0.1789	22.62	0.660	2.9	60.6	14.81	0.16
12	16.76	0.0552	15.22	1.03	9.2	73.0	17.64	0.12
02	22.13	0.1417	28.54	0.363	3.6	61.9	19.74	0.30
10	18.91	0.1359	8.405	0.905	3.8	86.9	23.65	0.12
11	23.85	0.0745	18.78	0.985	6.9	76.6	26.29	0.14
05	24.64	0.1627	16.08	0.306	3.1	80.8	28.59	0.29
06	40.37	0.1939	63.32	0.407	2.6	53.7	31.13	0.37
01	27.16	0.1659	12.95	0.147	3.1	86.0	33.51	0.67
07	30.01	0.0542	22.09	0.198	9.4	78.2	33.66	0.49
04	38.88	0.0667	23.96	0.591	7.6	81.7	45.45	0.24
09	41.56	0.1547	17.33	1.43	3.3	87.7	52.04	0.14
08	54.31	0.1203	12.26	0.800	4.2	93.3	71.98	0.23

Notes:
n=number of analyses used for weighted mean calculation
Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interfering reactions.
Individual analyses show analytical error only; plateau, total gas age errors include error in J and irradiation parameters.
Analyses in italics are excluded from final age calculations.
K/Ca = molar ratio calculated from reactor produced $^{39}Ar_K$ and $^{37}Ar_{ca}$.
* 2 error

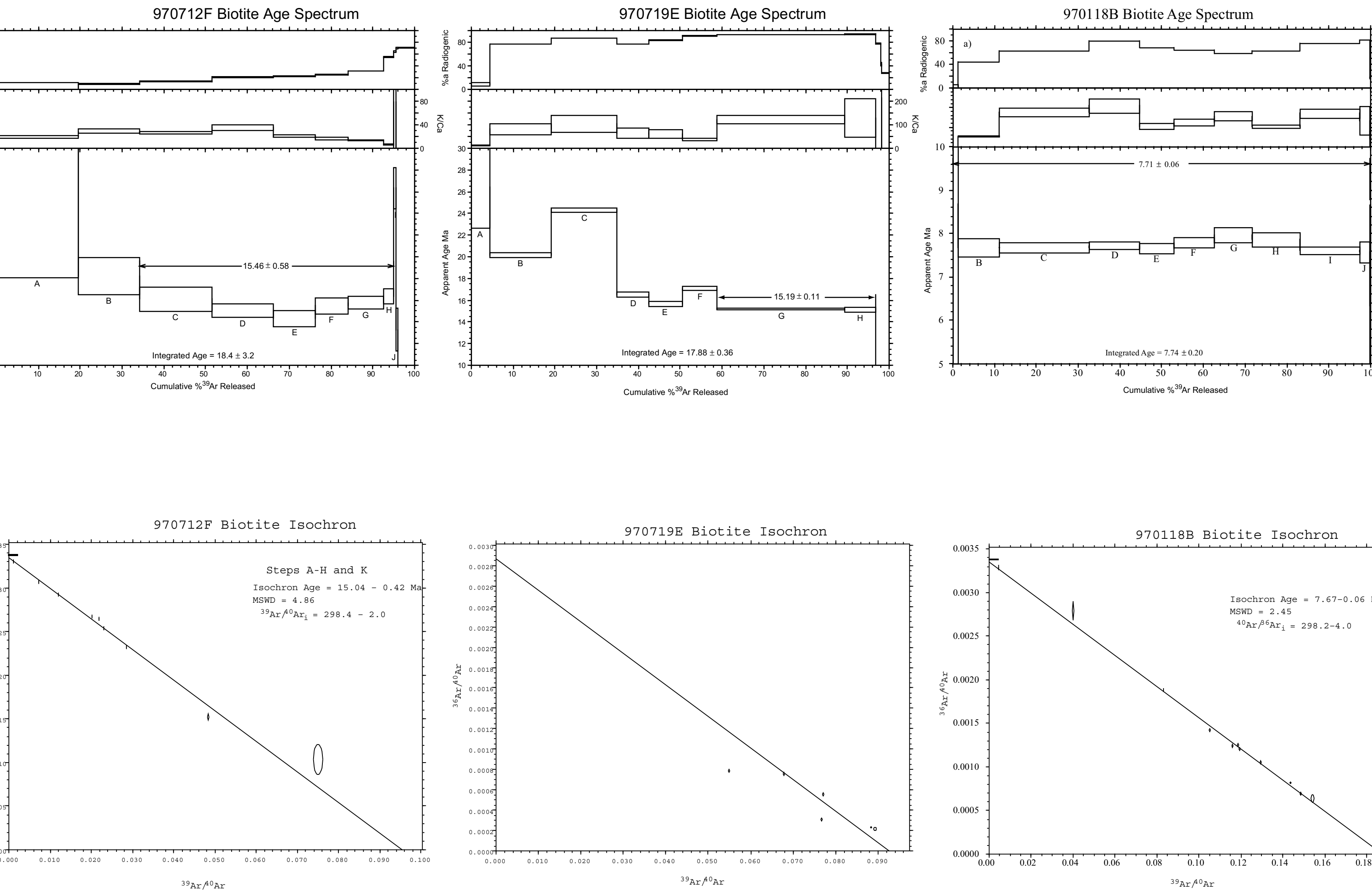
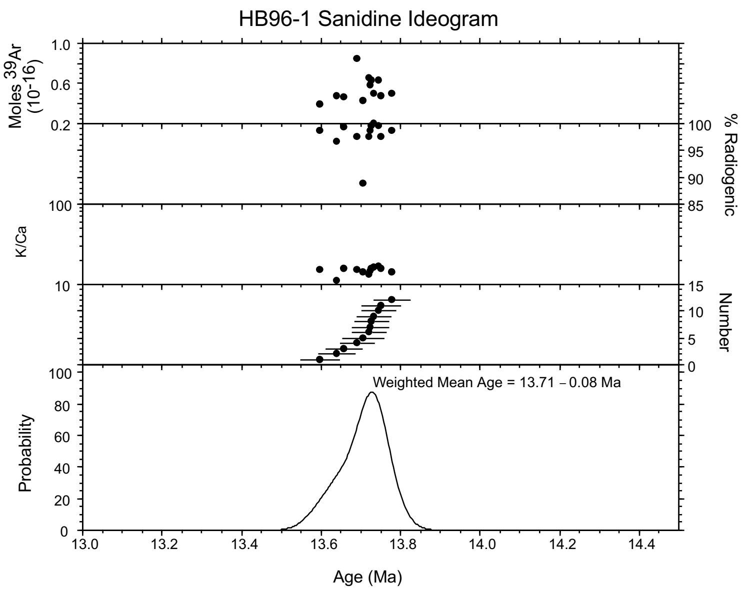
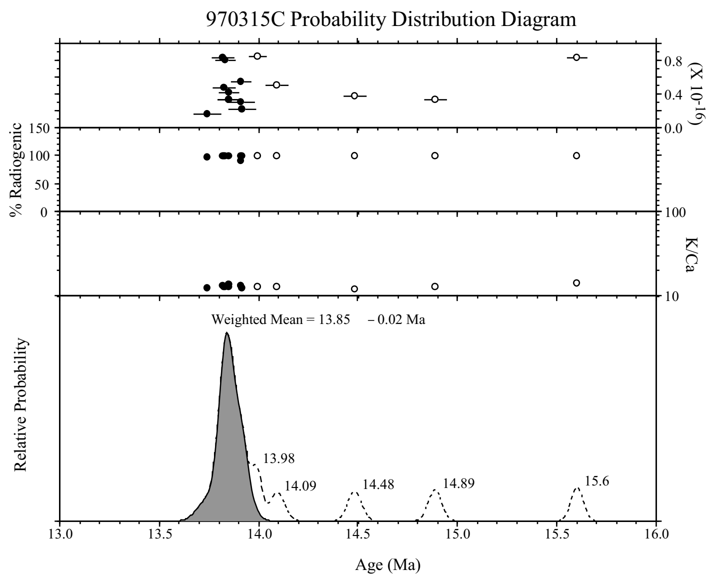


Figure C.1 Biotite age spectra.





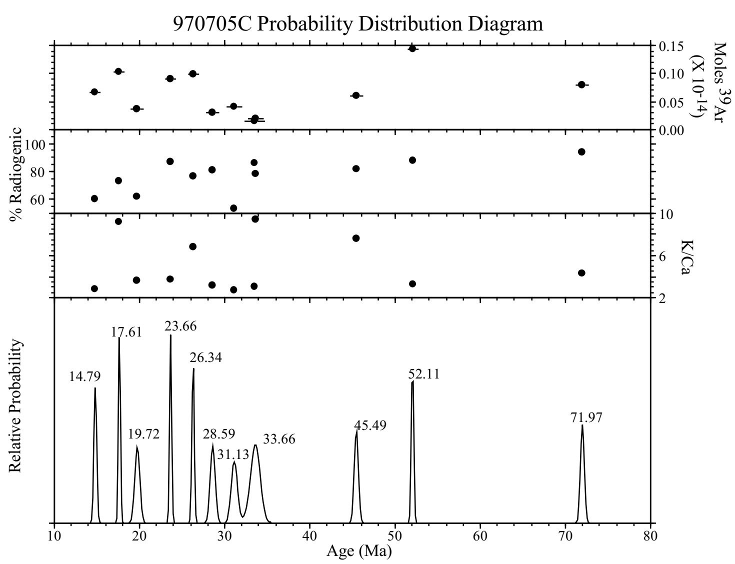


Figure C.2 Sanidine age spectra.

Appendix D - Geochemical Analyses of Glass Shards from the Bidahochi Formation

Appendix D Geochemical Analyses of Glass Shards from the Bidahochi Formation

Individual Shard Analyses - oxides reported in wt-%

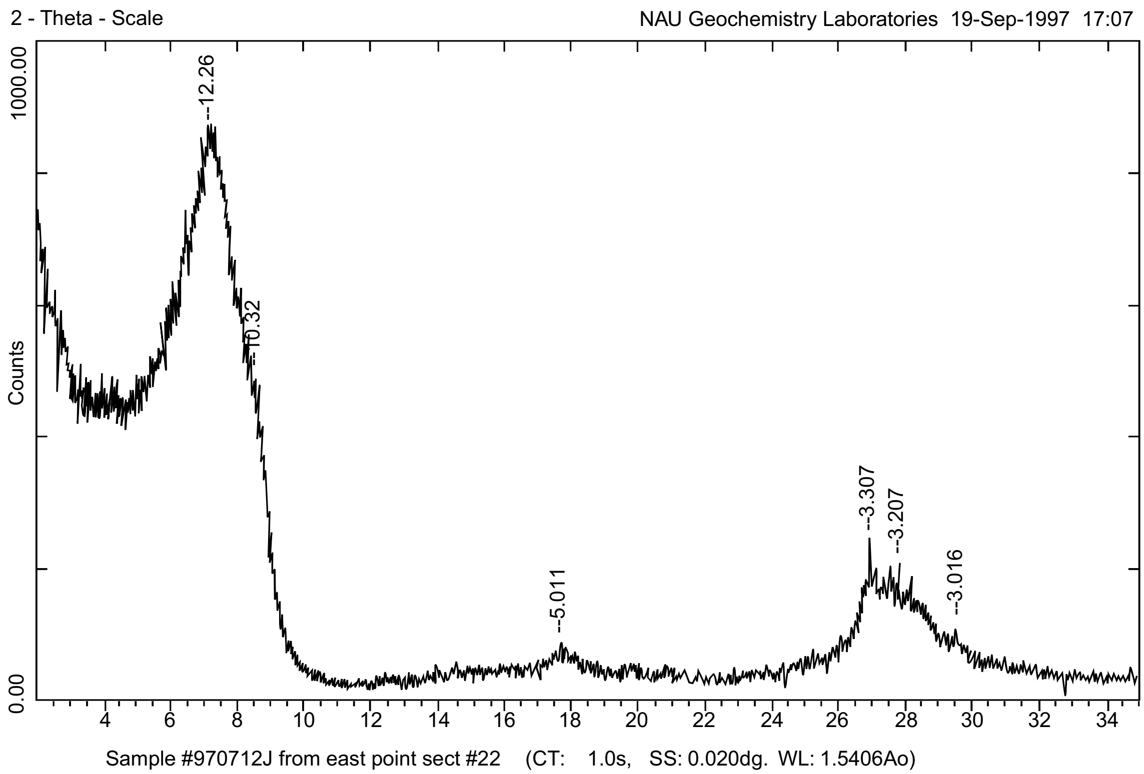
Sample	Mode	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	BaO	Na2O	K2O	Cl	F	sum	H2O	--O	Total
13.71 Ma ash bed																	
970427A	I	75.3	0.060	12.2	1.27	0.060	0.030	0.420	0.040	3.3	4.5	0.200	0.39	97.8	3.2	0.21	100.8
970427A	I	74.4	0.080	12.1	1.29	0.040	0.040	0.440	0.000	3.2	4.4	0.200	0.36	96.6	4.6	0.19	101.0
970427A	I	75.1	0.160	12.1	1.29	0.070	0.040	0.440	0.040	3.5	4.4	0.180	0.45	97.8	3.2	0.23	100.7
970427A	I	75.0	0.060	12.0	1.32	0.060	0.040	0.440	0.080	3.5	4.4	0.200	0.41	97.5	3.5	0.22	100.8
970427A	I	75.1	0.090	11.9	1.33	0.050	0.030	0.430	0.040	3.6	4.4	0.190	0.44	97.6	3.3	0.23	100.7
970427A	I	74.8	0.060	12.0	1.33	0.070	0.020	0.420	0.040	3.3	4.5	0.170	0.40	97.1	3.9	0.21	100.8
970427A	I	74.6	0.070	12.0	1.33	0.080	0.020	0.460	0.040	3.4	4.3	0.180	0.47	97.0	4.0	0.24	100.7
970427A	I	74.7	0.060	12.2	1.33	0.050	0.020	0.450	0.090	3.3	4.6	0.190	0.49	97.5	3.6	0.25	100.8
970427A	I	74.2	0.090	12.0	1.34	0.110	0.030	0.440	0.030	3.4	4.7	0.180	0.40	96.9	4.1	0.21	100.8
970427A	I	74.6	0.110	11.9	1.34	0.070	0.030	0.390	0.010	3.4	4.5	0.190	0.38	96.9	4.0	0.20	100.7
970427A	I	74.8	0.030	12.0	1.36	0.060	0.040	0.430	0.020	3.2	4.3	0.200	0.44	96.9	4.2	0.23	100.9
970427A	I	74.6	0.060	12.1	1.36	0.060	0.050	0.430	0.000	3.4	4.3	0.190	0.41	97.0	3.9	0.22	100.6
970427A	I	74.2	0.090	12.1	1.37	0.060	0.040	0.420	0.020	3.2	4.2	0.190	0.52	96.4	4.8	0.26	101.0
970427A	I	74.5	0.120	12.0	1.39	0.070	0.030	0.430	0.010	3.1	4.1	0.190	0.47	96.4	4.6	0.24	100.8
970427A	I	74.9	0.100	12.0	1.39	0.030	0.020	0.420	0.020	3.1	4.6	0.190	0.42	97.2	3.7	0.22	100.7
970427A	I	74.9	0.070	12.1	1.39	0.030	0.040	0.410	0.030	3.3	4.6	0.180	0.40	97.5	3.5	0.21	100.7
970427A	I	74.6	0.060	12.0	1.40	0.060	0.040	0.400	0.020	3.1	4.4	0.190	0.40	96.7	4.3	0.21	100.8
970427A	I	74.5	0.120	12.0	1.42	0.080	0.020	0.410	0.050	3.4	4.4	0.210	0.39	97.0	3.9	0.21	100.7
970427A	I	74.9	0.090	12.1	1.42	0.060	0.030	0.430	0.010	3.3	4.7	0.180	0.37	97.6	3.3	0.20	100.7
970427A	I	75.0	0.060	12.0	1.43	0.060	0.020	0.430	0.000	3.2	4.3	0.180	0.41	97.1	3.9	0.21	100.8
970427A	II	72.7	0.160	13.3	1.50	0.060	0.060	0.560	0.030	3.6	4.6	0.100	0.16	96.8	4.0	0.09	100.7
970427A	III	71.0	0.200	14.2	1.99	0.080	0.140	0.730	0.080	3.9	4.7	0.090	0.18	97.3	3.5	0.10	100.7
blue-gray #1 ash bed																	
971107L	I	75.1	0.140	11.7	1.61	0.020	0.030	0.590	0.000	2.9	4.3	0.100	0.38	96.9	5.0	0.19	101.7
971107L	I	74.7	0.130	11.7	1.65	0.060	0.000	0.570	0.000	2.7	4.3	0.100	0.39	96.3	5.6	0.19	101.7
971107L	I	75.7	0.130	11.7	1.66	0.060	0.020	0.570	0.000	3.0	4.4	0.110	0.38	97.7	4.9	0.18	102.5

Sample	Mode	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	BaO	Na2O	K2O	Cl	F	sum	H2O	--O	Total
971107L	I	75.0	0.090	11.7	1.67	0.060	0.020	0.600	0.000	2.9	4.2	0.110	0.39	96.7	5.4	0.19	102.0
971107L	I	75.2	0.090	11.8	1.71	0.030	0.020	0.580	0.000	2.9	4.4	0.100	0.37	97.2	5.6	0.18	102.6
971107L	I	74.8	0.130	11.7	1.74	0.050	0.000	0.590	0.000	2.8	4.6	0.100	0.35	96.9	4.8	0.17	101.5
971107L	I	74.8	0.100	11.7	1.75	0.070	0.030	0.610	0.020	2.8	4.3	0.110	0.36	96.7	5.8	0.17	102.3
971107L	I	74.7	0.120	11.5	1.75	0.000	0.000	0.600	0.000	2.9	4.4	0.110	0.32	96.4	6.0	0.16	102.2
971107L	I	74.6	0.150	11.7	1.77	0.070	0.030	0.590	0.000	2.9	4.3	0.080	0.38	96.6	5.4	0.18	101.8
971107L	I	74.9	0.160	11.8	1.81	0.020	0.010	0.600	0.000	2.8	4.3	0.080	0.36	96.8	5.9	0.17	102.6
971107L	I	74.5	0.180	11.7	1.84	0.030	0.020	0.630	0.000	2.6	4.2	0.070	0.28	96.1	5.7	0.13	101.6
971107L	I	74.4	0.180	11.8	1.86	0.030	0.010	0.610	0.000	2.7	4.4	0.070	0.31	96.4	5.6	0.15	101.8
971107L	I	74.6	0.180	11.5	1.88	0.040	0.010	0.640	0.000	2.7	4.2	0.090	0.34	96.2	5.5	0.16	101.5
971107L	I	74.9	0.140	11.6	1.91	0.030	0.030	0.610	0.000	2.6	4.2	0.090	0.31	96.4	5.0	0.15	101.3
971107L	I	74.7	0.210	11.7	2.04	0.000	0.030	0.660	0.000	2.5	4.1	0.070	0.24	96.3	6.1	0.12	102.2
971107L	I	74.4	0.140	11.7	2.05	0.020	0.040	0.650	0.000	2.5	4.1	0.070	0.30	96.0	6.1	0.14	101.9
971107L	I	74.6	0.130	11.6	2.05	0.010	0.030	0.690	0.000	2.6	4.3	0.080	0.26	96.4	5.6	0.13	101.8
971107L	II	74.4	0.160	11.6	2.10	0.050	0.020	0.640	0.000	2.6	4.4	0.080	0.30	96.4	6.2	0.14	102.4
971107L	II	74.2	0.160	11.7	2.10	0.030	0.030	0.660	0.000	2.6	4.3	0.070	0.29	96.1	6.0	0.14	102.0
971107L	II	74.5	0.170	11.6	2.11	0.000	0.020	0.680	0.000	2.4	4.4	0.080	0.27	96.2	5.1	0.13	101.2
971107L	III	74.6	0.220	11.7	2.38	0.030	0.040	0.770	0.010	2.8	4.8	0.070	0.17	97.6	3.8	0.09	101.3
971107L	III	74.4	0.220	11.6	2.43	0.050	0.020	0.760	0.000	2.6	4.4	0.070	0.31	96.9	5.8	0.15	102.5
blue-gray #2 ash bed																	
970712M	I	72.6	0.170	10.9	3.64	0.210	0.000	0.250	0.000	3.0	4.0	0.130	0.31	95.2	6.8	0.16	101.9
970712M	I	73.3	0.270	11.0	3.65	0.200	0.000	0.240	0.000	3.0	4.0	0.100	0.29	96.1	6.6	0.15	102.5
970712M	I	73.7	0.200	10.8	3.69	0.210	0.010	0.220	0.000	3.1	4.1	0.130	0.28	96.4	5.5	0.15	101.8
970712M	I	73.0	0.190	11.0	3.70	0.190	0.010	0.240	0.000	2.4	3.8	0.120	0.34	95.0	7.3	0.17	102.1
970712M	I	72.3	0.210	10.9	3.71	0.160	0.010	0.230	0.000	2.9	3.8	0.120	0.32	94.7	7.6	0.16	102.1
970712M	I	73.0	0.210	11.0	3.71	0.170	0.000	0.230	0.000	2.7	3.9	0.120	0.30	95.3	6.7	0.15	101.9
970712M	I	70.5	0.230	11.0	3.71	0.170	0.000	0.260	0.000	2.6	3.8	0.110	0.32	92.7	8.5	0.16	101.0
970712M	I	73.1	0.260	10.9	3.73	0.190	0.000	0.230	0.000	2.6	4.2	0.130	0.36	95.7	7.1	0.18	102.6
970712M	I	73.4	0.220	10.9	3.73	0.190	0.010	0.230	0.000	3.1	4.0	0.150	0.28	96.2	6.1	0.15	102.2
970712M	I	70.4	0.210	10.9	3.74	0.150	0.020	0.240	0.000	2.4	3.9	0.120	0.37	92.5	8.9	0.18	101.2
970712M	I	73.7	0.210	11.0	3.76	0.180	0.010	0.230	0.000	2.7	4.1	0.130	0.30	96.3	6.3	0.16	102.5
970712M	I	71.8	0.210	10.9	3.76	0.160	0.020	0.230	0.000	2.4	3.6	0.120	0.37	93.6	8.1	0.18	101.5

Sample	Mode	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	BaO	Na2O	K2O	Cl	F	sum	H2O	--O	Total
970712M	I	73.3	0.180	10.9	3.76	0.180	0.000	0.270	0.000	2.7	3.9	0.130	0.31	95.6	6.6	0.16	102.1
970712M	I	73.2	0.220	11.0	3.77	0.170	0.020	0.230	0.000	2.9	3.9	0.130	0.30	95.8	6.4	0.16	102.1
970712M	I	71.7	0.210	11.0	3.77	0.160	0.020	0.240	0.000	3.1	4.1	0.130	0.36	94.8	7.3	0.18	101.9
970712M	I	72.7	0.240	11.0	3.77	0.190	0.020	0.220	0.000	2.8	3.8	0.120	0.31	95.2	7.1	0.16	102.1
970712M	I	73.8	0.220	11.0	3.77	0.180	0.000	0.240	0.010	3.3	4.0	0.120	0.28	96.9	6.1	0.15	102.9
970712M	I	73.9	0.230	11.0	3.82	0.190	0.010	0.250	0.000	2.6	4.2	0.130	0.34	96.7	7.1	0.17	103.6
970712M	I	71.0	0.240	11.1	3.82	0.150	0.020	0.240	0.000	2.7	4.0	0.130	0.34	93.7	7.5	0.17	101.1
970712M	I	72.6	0.200	10.9	3.84	0.180	0.010	0.240	0.000	2.7	3.8	0.130	0.36	95.0	6.9	0.18	101.7
970712M	I	73.9	0.210	11.0	3.89	0.150	0.010	0.220	0.000	3.3	4.1	0.130	0.32	97.2	5.3	0.16	102.4

Appendix E - X-ray Diffraction Data

This appendix contains the X-ray diffraction patterns that were used in this study. See Appendix A for methods of analysis and text for interpretation of results.



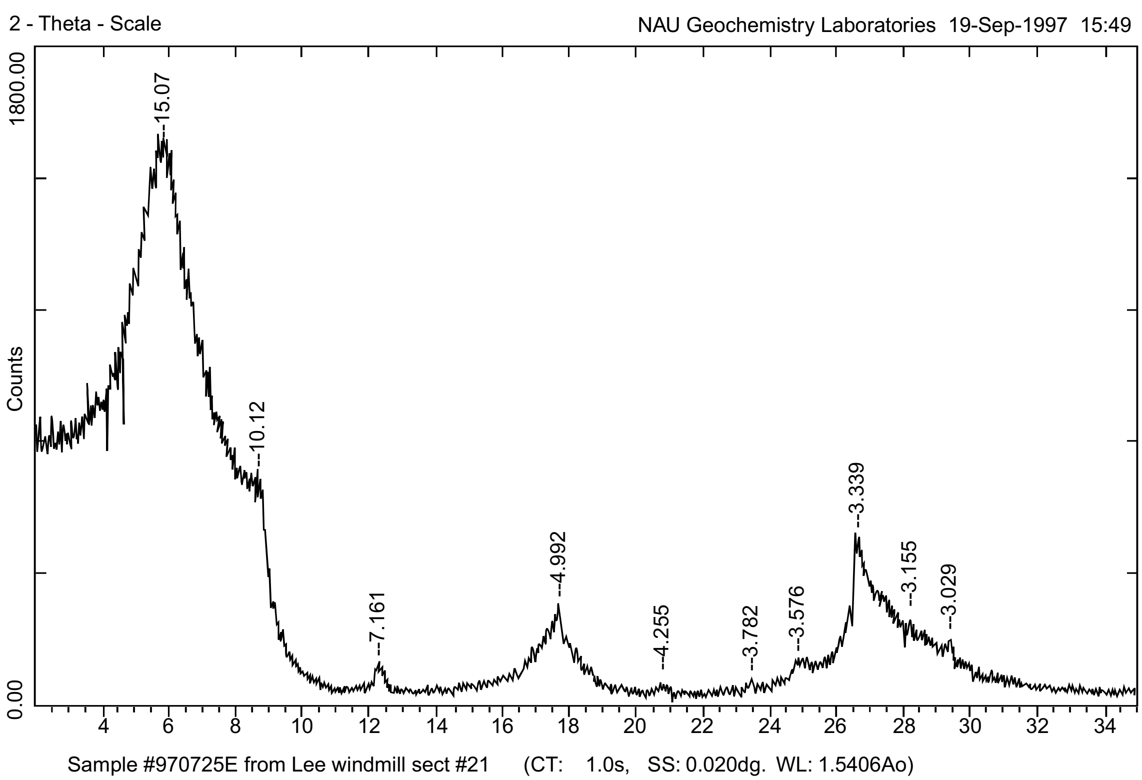


Figure E.1 X-ray diffraction patterns.

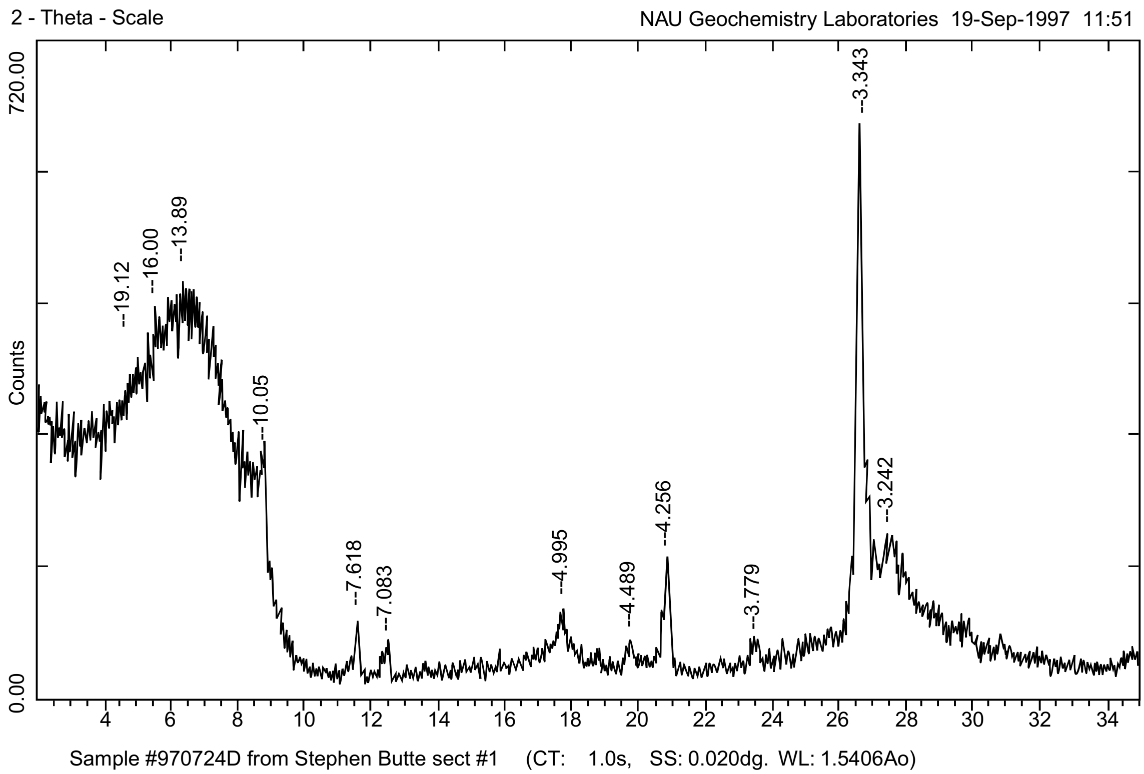
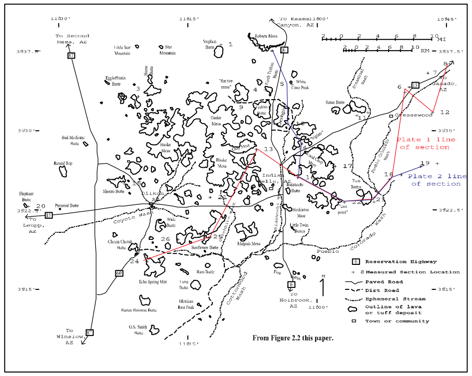


Figure E.2 X-ray diffraction patterns

Plate 1

Southeast to Northwest Cross Section Correlation Diagram of the Bidahochi Formation

Dallegge, Todd A., 1999, Correlation and Chronology of the Miocene-Pliocene Bidahochi Formation, Navajo and Hopi Nations, Northeastern Arizona: Northern Arizona University


From Figure 2.2 this paper.

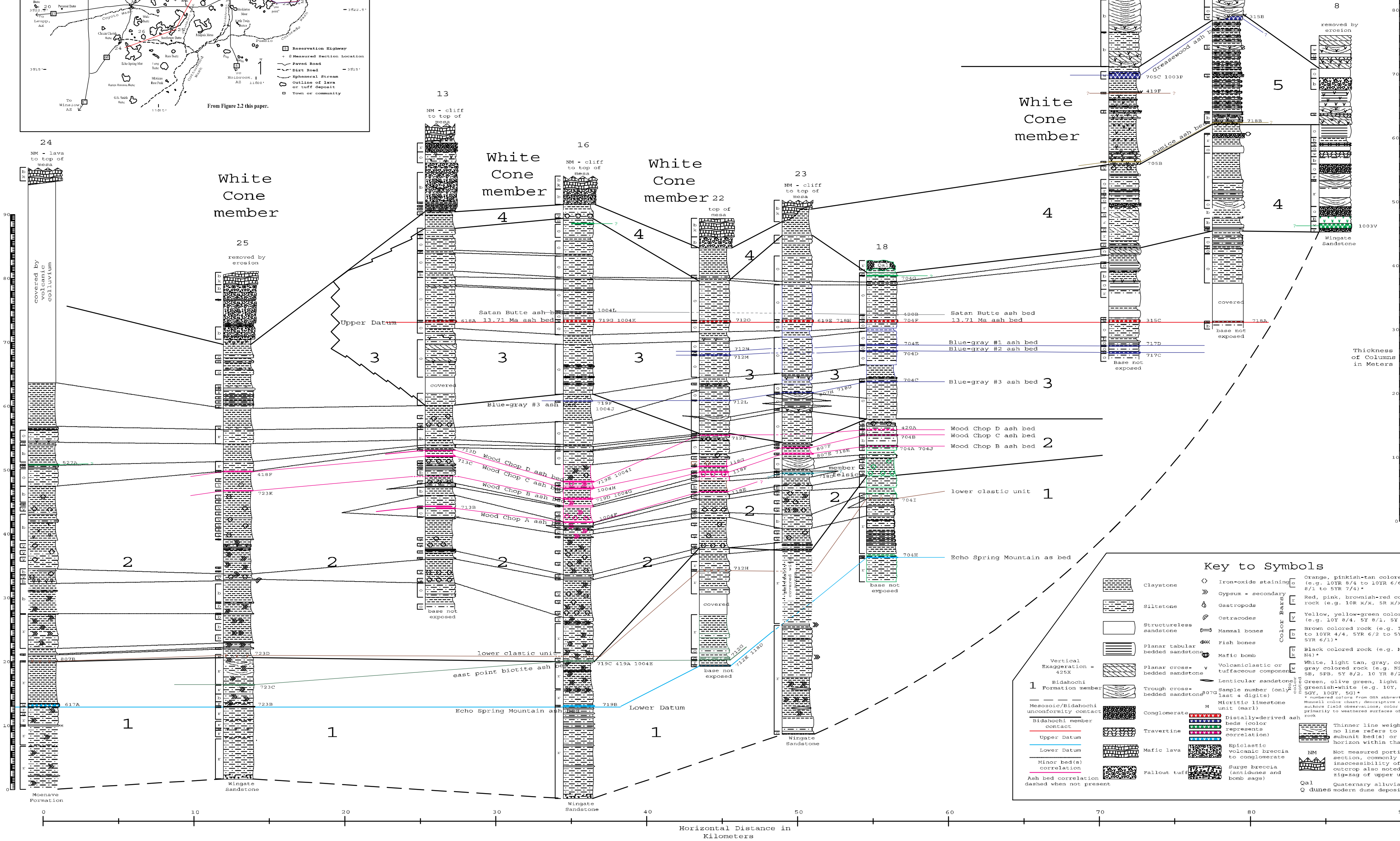


Plate 2

North to South to East Cross Section Correlation Diagram of the Bidahochi Formation

Dallegge, Todd A., 1999, Correlation and Chronology of the Miocene-Pliocene Bidahochi Formation, Navajo and Hopi Nations, Northeastern Arizona: Northern Arizona University

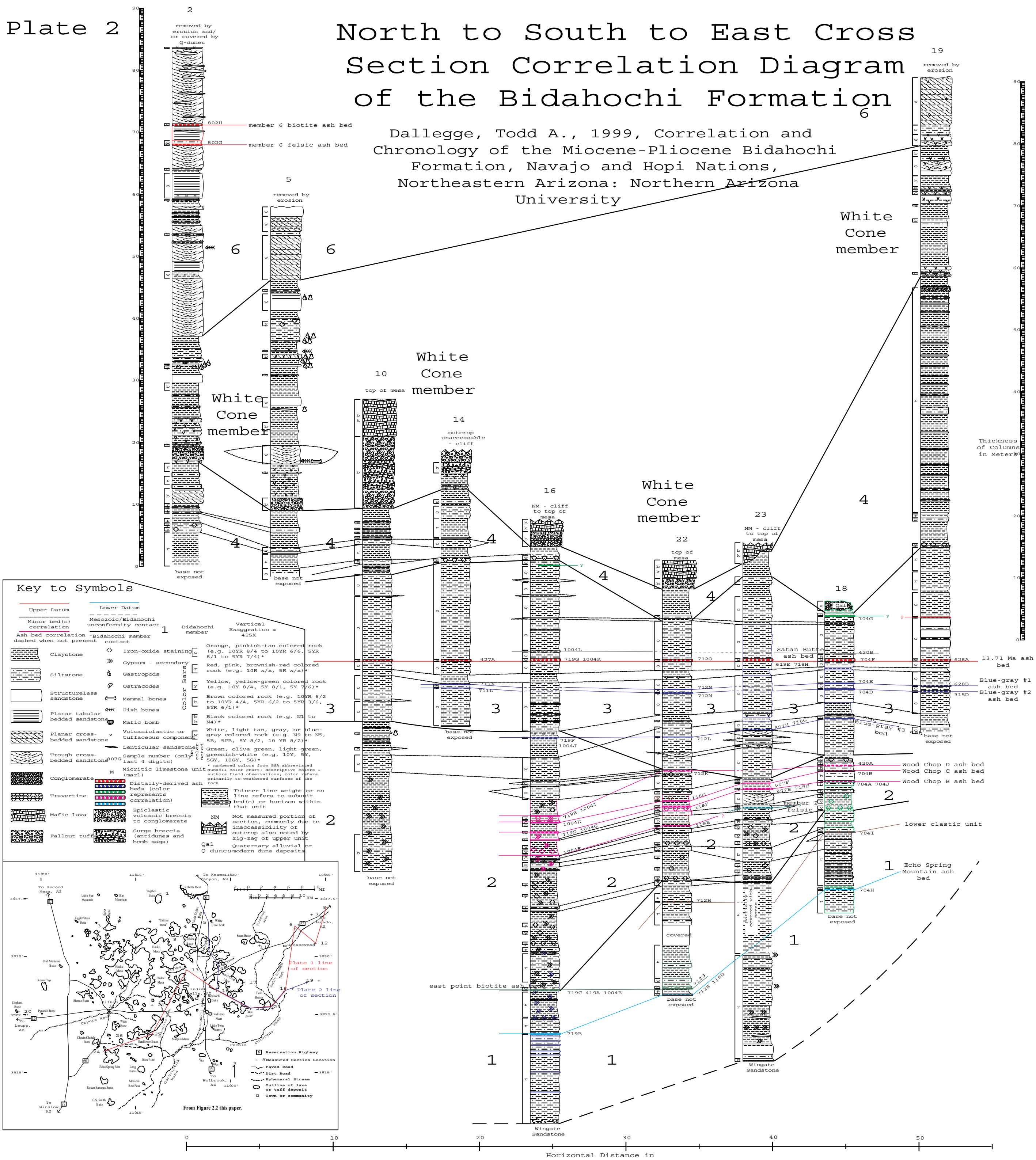
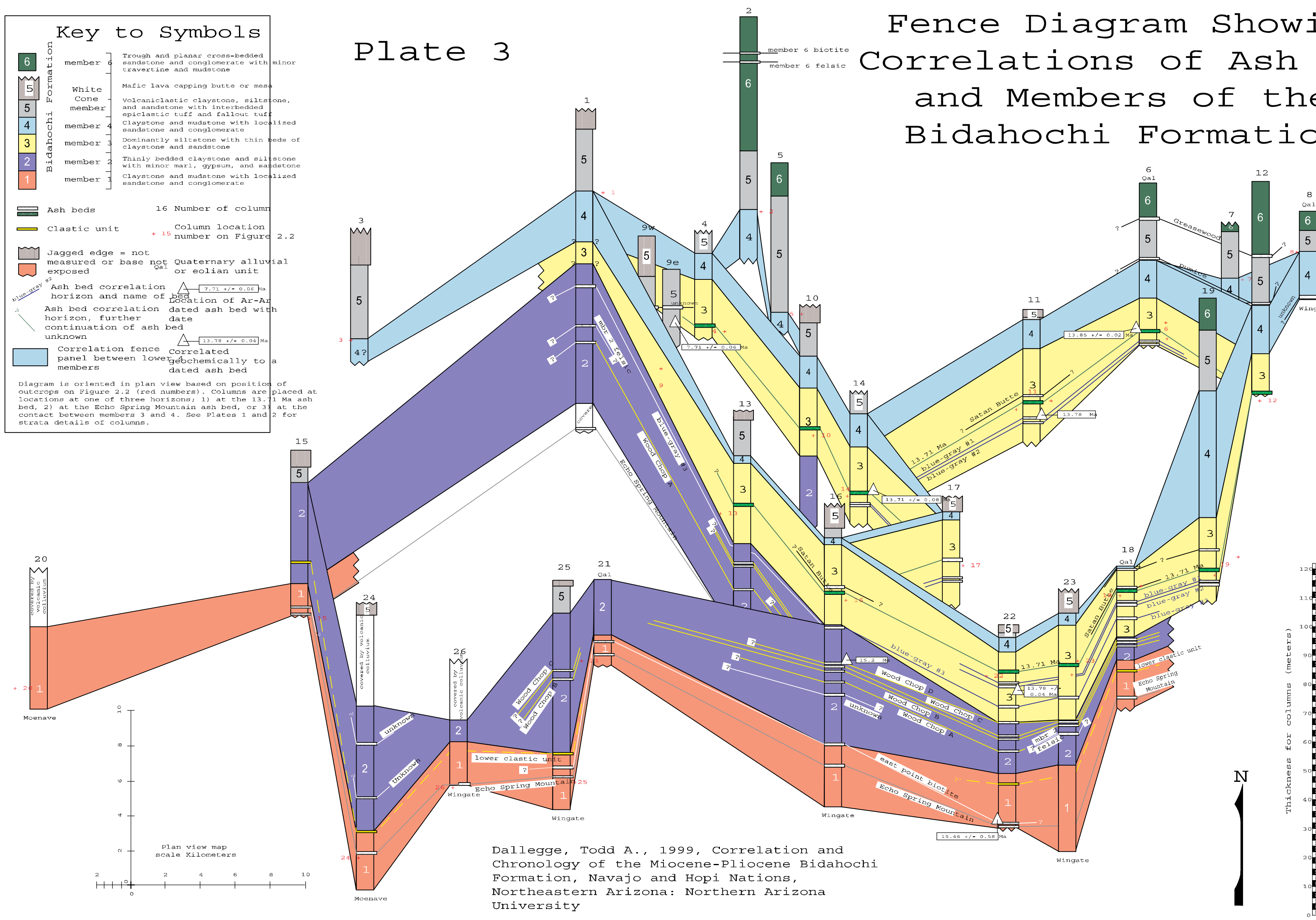


Plate 3

Fence Diagram Showing Correlations of Ash beds and Members of the Bidahochi Formation



Dallegge, Todd A., 1999, Correlation and Chronology of the Miocene-Pliocene Bidahochi Formation, Navajo and Hopi Nations, Northeastern Arizona: Northern Arizona University