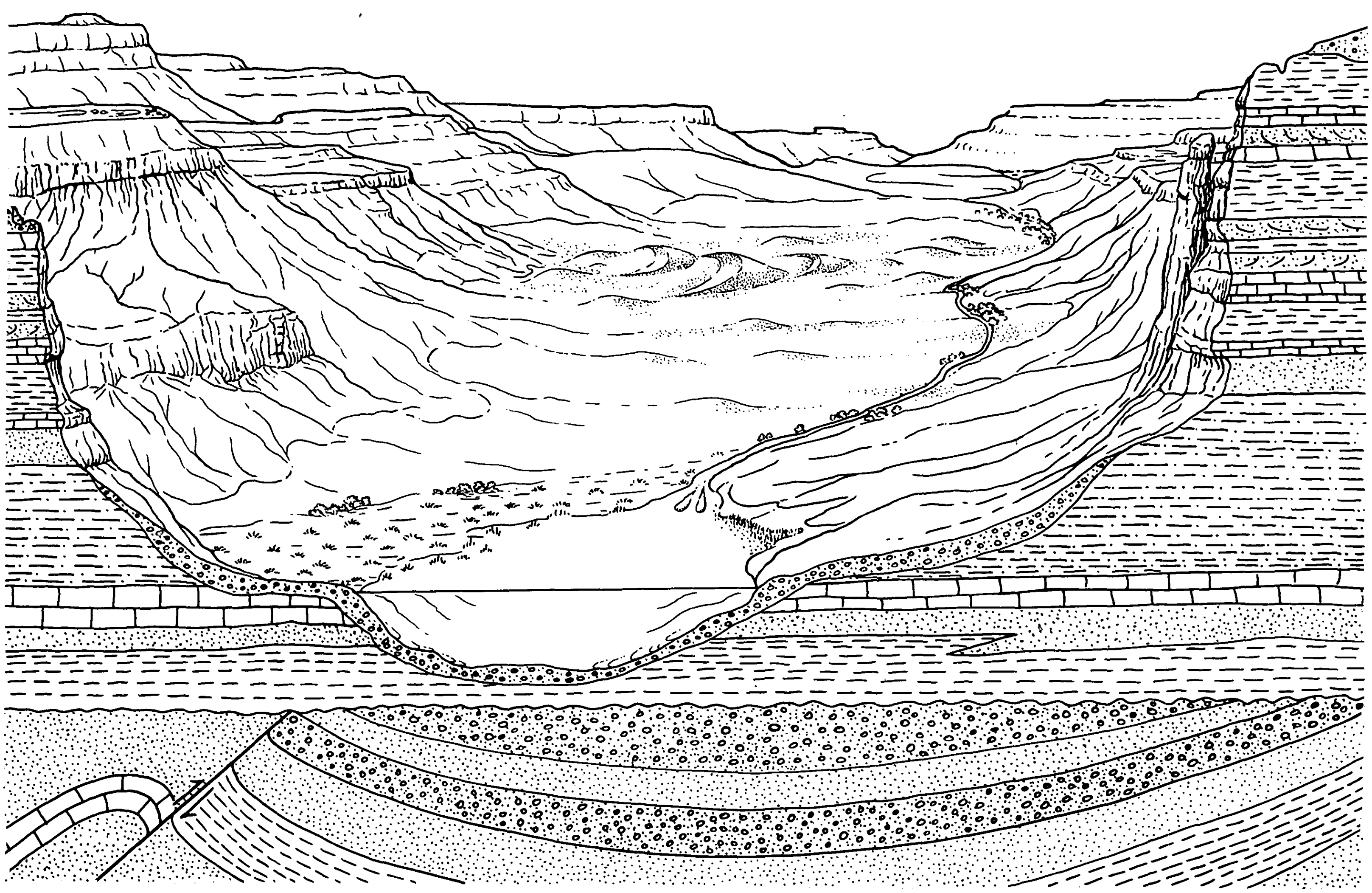
X-Ray Diffraction Studies of the <0.5-μm Fraction from the Brushy Basin Member of the Upper Jurassic Morrison Formation, Colorado Plateau

U.S. GEOLOGICAL SURVEY BULLETIN 1808–G



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Chapter G

X-Ray Diffraction Studies of the <0.5-μm Fraction from the Brushy Basin Member of the Upper Jurassic Morrison Formation, Colorado Plateau

By DOUGLASS E. OWEN, CHRISTINE E. TURNER-PETERSON, and NEIL S. FISHMAN

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1808

EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
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To convert from	To	Multiply by
Feet (ft)	Meters (m)	0.3048
Miles (mi)	Kilometers (km)	1.609
Pounds (lb)	Kilograms (kg)	0.4536
Degrees Fahrenheit (°F)	Degrees Celsius (°C)	Temp °C = (temp °F–32)/1.8

EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

X-ray Diffraction Studies of the <0.5-μm Fraction from the Brushy Basin Member of the Upper Jurassic Morrison Formation, Colorado Plateau

By Douglass E. Owen, Christine E. Turner-Peterson, *and* Neil S. Fishman

Abstract

Studies of the <0.5-μm fraction of samples from tuffaceous beds of ancient Lake T'oo'dichi', a large saline, alkaline lake complex in the Brushy Basin Member of the Upper Jurassic Morrison Formation, Colorado Plateau, reveal an interesting trend in the distribution of clay minerals. In the outer part of the lake the clay mineral population is dominated by smectitic mixed-layer illite/smectite, whereas in the inner part of the lake the clay mineral population is predominantly illitic mixed-layer illite/smectite. Mixed-layer clay minerals in the area between the outer and inner parts exhibit a high degree of variability. Vertically adjacent beds may contain very different mixed-layer clay populations. Chlorite generally is present where illitic mixed-layer clay minerals are common.

The distribution of mixed-layer illite/smectite in the lacustrine units did not result from depositional processes because most of the samples were from tuff beds that contain little admixed detrital material. Furthermore, the absence of illitic clays in the outer margin of the lake system precludes a detrital origin for illitic clays farther basinward because the illitic clays would necessarily have crossed the smectitic zone in transit. The distribution of mixed-layer clays also cannot be explained by the Gulf Coast model of illitization—progressive illitization due to burial and attendant heating. The Gulf Coast model cannot be used to explain vertically adjacent beds in the Brushy Basin Member that contain very different mixed-layer clay populations because these beds would undoubtedly have experienced a similar burial and thermal history. Instead, the trend of increasingly illitic mixed-layer clays toward the center of Lake T'oo'dichi' can more readily be attributed to changes in pore-water chemistry. In fact, the trend in clay-mineral composition coincides with the hydrogeochemical gradient of increasing salinity and alkalinity associated with the saline, alkaline lake; hence, pore-water chemistry alone appears to have controlled clay composition in the lacustrine sediments of Lake T'oo'dichi'.

Manuscript approved for publication, May 26, 1989.

INTRODUCTION

Certain mineral transformations are used as geothermometers to provide evidence for minimum temperatures in the host rock at their time of formation. The conversion of smectite to illite-rich mixed-layer illite/smectite is widely used in this manner; this conversion is commonly thought to begin at approximately 90 °C (Burst, 1969; Hower and others, 1976; Freed, 1980; Milliken and others, 1981; Pollastro and Scholle, 1986). Because this conversion can be related to temperature, it commonly is used to determine if a sedimentary sequence has been heated to sufficient temperatures to generate hydrocarbons (Gautier and others, 1985). The conversion also is used to obtain information on the thermal and burial history of sedimentary basins, and, as such, it is critical to know if exceptions to the paradigm exist.

Pore-water chemistry is assumed to be an important constraint in the illitization of smectite because a source of potassium is required (Hower and others, 1976; Johnston and Miller, 1984). It is not generally thought, however, that pore-water chemistry alone can drive the reaction in the absence of elevated temperatures. There are clues, however, to indicate that illitic mixed-layer clay may form under synsedimentary conditions. Illitic clays believed to be authigenic have been reported in modern lake sediments in Africa

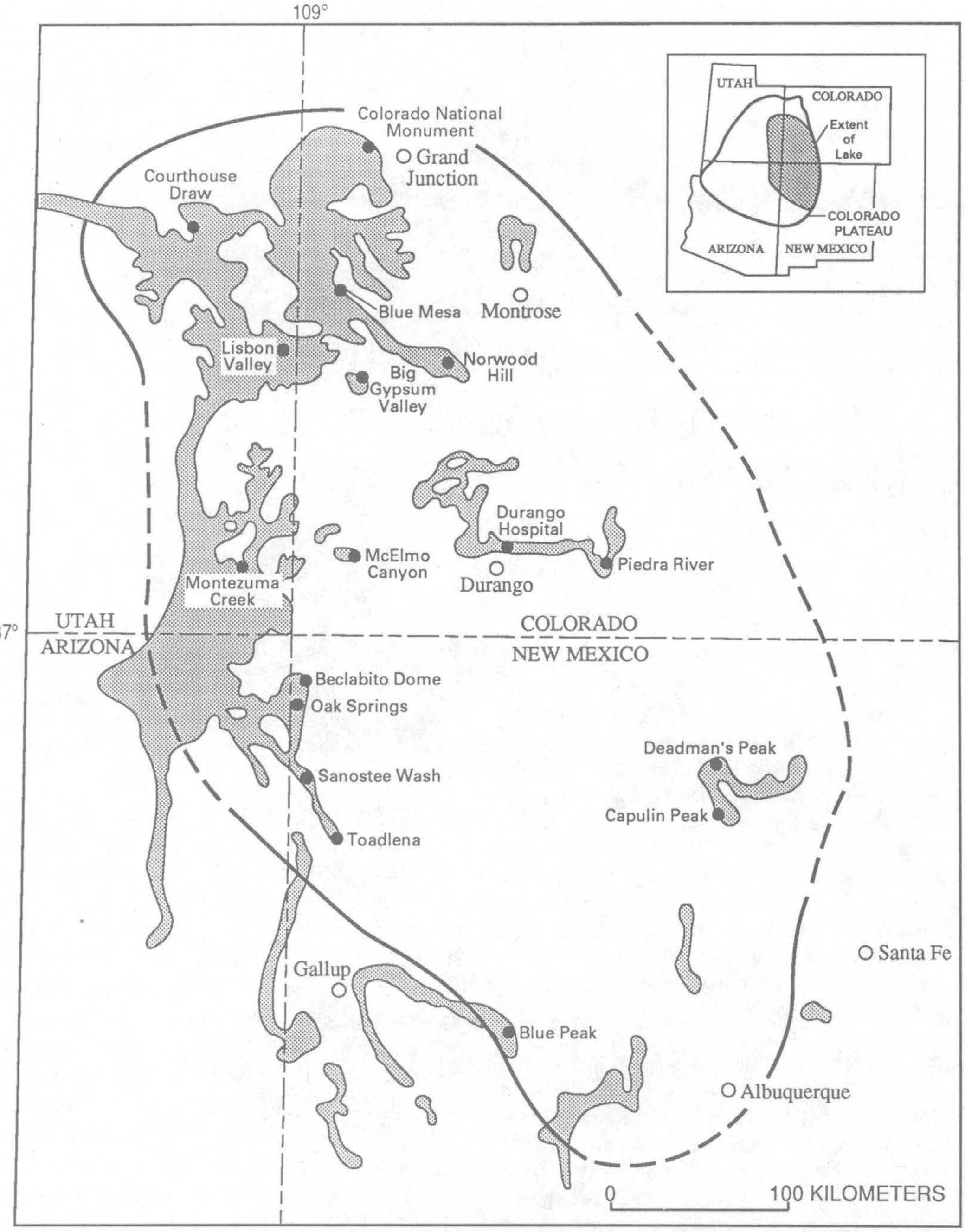

Figure 1. Extent of ancient Lake T'oo'dichi' (solid and dashed line) in Brushy Basin Member of the Morrison Formation, eastern Colorado Plateau. Dashed line indicates where boundary of lake is uncertain. Sample localities (circles) and outcrop areas of Morrison Formation (pattern) are also shown. Modified from Turner-Peterson (1987).

(Singer and Stoffers, 1980) and are thought to be a predictable consequence of the extreme pore-water chemistry in the lake sediments. Thus, saline, alkaline lakes appear to be convenient natural laboratories in which to test the hypothesis that pore-water chemistry alone can facilitate the formation of authigenic illitic clays.

In order to evaluate the role of pore-water chemistry in the formation of mixed-layer illite/smectite, we studied the mineralogy and distribution of authigenic clays in tuffaceous beds of ancient Lake T'oo'dichi', a large saline, alkaline lake in the Brushy Basin Member of the Upper Jurassic Morrison Formation, eastern Colorado Plateau (Turner-Peterson, 1987) (fig. 1). The ancient lake sequence consists of saline, alkaline lake deposits, as thick as 100 m, that are characterized by thick intervals of altered silicic volcanic ash. Differential alteration of the ash reflects the lateral hydrogeochemical gradient in a saline, alkaline lake complex and resulted in the development of concentrically zoned authigenic mineral facies (Bell, 1986; Fishman and others, 1986; Turner-Peterson and others, 1986; Turner-Peterson, 1987). Our hypothesis is that the distribution of authigenic illite/smectite reflects the same hydrogeochemical gradient that is reflected in the distribution of authigenic aluminosilicate minerals across the lake.

The lacustrine deposits of Lake T'oo'dichi' in the Brushy Basin Member of the Morrison Formation are particularly suitable to our purposes for several reasons. First, in a study of the Brushy Basin Member, Keller (1962) noted a west-east change in clay-mineral composition, from smectitic mixed-layer clays in eastern Utah to illitic mixed-layer clays in western Colorado. The lateral trends noted by Keller coincide with lateral trends in authigenic aluminosilicate minerals in tuff beds in the same area (Turner-Peterson, 1987). Thus, the Brushy Basin Member seems a good natural laboratory in which to test our hypothesis relating lateral trends in clay authigenesis to lateral changes in pore-water chemistry. In addition, the abundance of tuff beds in Lake T'oo'dichi' increases the likelihood of obtaining an authigenic, rather than a detrital, suite of clay minerals; most of the tuff beds contain abundant relict shards that attest to the air-fall origin of much of the material.

In this report, we present the results of the first phase of our study, the goal of which was to document the occurrence and distribution of clay minerals in ancient Lake T'oo'dichi'. Our studies of the diagenetic history of Lake T'oo'dichi' continue, and, ultimately, we plan to evaluate the distribution of authigenic clay minerals with respect to the authigenic aluminosilicate minerals in the lacustrine complex and to model the pore-water chemistry during formation of all these authigenic minerals.

Acknowledgments.—We owe special thanks to Gene Whitney, who trained us to use laboratory equipment to process our samples, to make slides and to use the X-ray diffractometer, on which we ultimately ran more than 1,000 slides of clay separates. He also provided many hours of consultation and help with interpretation. We also owe special thanks to Rick Mahrt, who was always helpful and willing to demonstrate how to use the lab equipment and many times made quick repairs or adjustments to the instruments that saved us much time and maintained the quality of the data; and to Ken Esposito who generated the publication-quality diffractograms included in this report. Charles Pierson and Gene Whitney reviewed the paper and provided many helpful suggestions and criticisms. This study was entirely funded by the Gilbert Fellowship Program of the U.S. Geological Survey.

GEOLOGIC SETTING

The Brushy Basin Member is the uppermost member of the Upper Jurassic Morrison Formation and covers an area of approximately 150,000 km² in the eastern Colorado Plateau (fig. 1). In the study area, the Brushy Basin conformably overlies the fluvial Westwater Canyon, Recapture, or Salt Wash Members of the Morrison, and is unconformably overlain by either the Lower Cretaceous Burro Canyon Formation or the Upper Cretaceous Dakota Sandstone. The Brushy Basin Member is recognized from the southern margin of the San Juan basin in New Mexico northward to near Grand Junction, Colo. (fig. 1). North and east of Grand Junction, the Morrison Formation is not subdivided into members, and thus, the Brushy Basin Member is not formally recognized. At the type section near Blanding, Utah, the Brushy Basin is 137 m thick (Gregory, 1938); elsewhere on the Colorado Plateau it is locally thicker. North of the Colorado–New Mexico State line, beyond the depositional pinchout of the Westwater Canyon Member, beds equivalent to the Brushy Basin Member in New Mexico rest directly on beds that are equivalent to the Recapture Member of the Morrison Formation (Turner-Peterson, 1987). The name Recapture is not extended much beyond the pinchout of the Westwater Canyon, and the entire interval above the Salt Wash Member is mapped as the Brushy Basin Member in this region (fig. 2).

For this study, it was important to distinguish beds within the Brushy Basin Member that are equivalent to the Recapture Member farther south from those equivalent to the vertically more restricted Brushy Basin Member in New Mexico. The lower part of the Brushy Basin Member and the upper part of the Brushy Basin Member are used, respectively, to make this distinction (Turner-Peterson, 1987) (fig. 2) and are hereafter referred to as lower Brushy Basin Member and upper Brushy Basin Member.

The lower Brushy Basin Member was deposited dominantly by alluvial processes that involved delivery of detrital material, including detrital clay, from a heterogeneous source area several hundred kilometers to the southwest. The dominantly clastic lower Brushy Basin Member is only locally punctuated by tuff beds of air-fall origin. In contrast, the upper Brushy Basin Member originated chiefly as airborne volcanic ash that erupted in an arc region to the southwest and was carried northeastward by prevailing winds to the depositional basin. This interval is interpreted as a saline, alkaline lake, Lake T'oo'dichi'. Interbedded with the tuffs in the upper Brushy Basin Member are fluvial sandstone beds that represent episodic flooding of clastic material across a playa surface (Turner-Peterson, 1987). The distinction between the two intervals within the member is readily

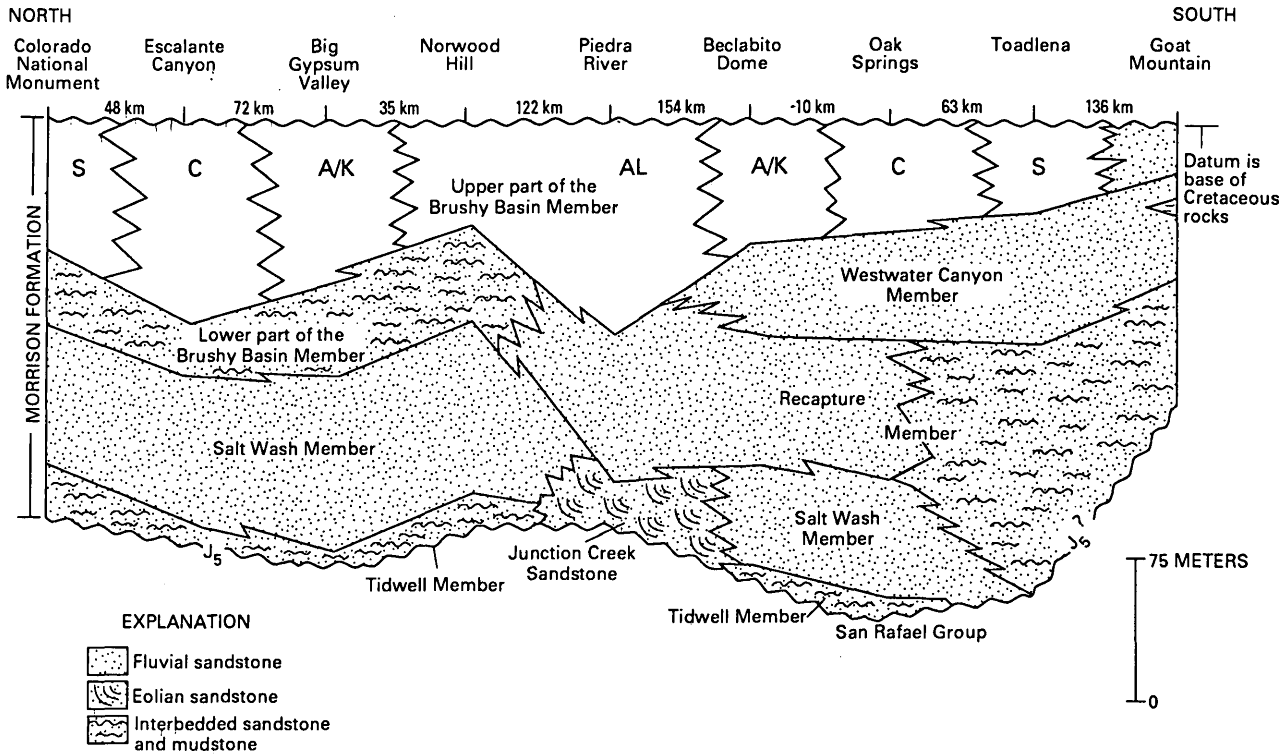

Figure 2. Schematic cross section showing stratigraphy of the Morrison Formation from the southern margin of the San Juan basin northward to the Colorado National Monument (fig. 1). The upper part of the Brushy Basin Member of the Morrison Formation is defined by the saline, alkaline lake deposits; lithofacies include smectite (S), clinoptilolite (C), analcime ±potassium feldspar (A/K), and albite (AL). The lower part of the member consists chiefly of fluvial sandstone and floodplain mudstone and claystone. J_5 marks the unconformity that separates the Morrison Formation from underlying rocks; queried where questionable. Horizontal scale variable. Modified from Turner-Peterson (1987).

apparent at most localities. The lower Brushy Basin Member consists chiefly of fluvial sandstone and floodplain mudstone and claystone, whereas the saline, alkaline lake deposits of Lake T'oo'dichi', chiefly altered volcanic tuff, are restricted to and help define the upper Brushy Basin Member (fig. 2). The lateral change in authigenic mineralogy in the lacustrine beds of the Brushy Basin Member shown in figure 2 reflects a hydrogeochemical gradient in a saline, alkaline lake. Water levels fluctuate considerably in these lakes, and the composition of pore waters in the underlying lake sediments reflects these fluctuations. During periods of high lake levels, all sediments are exposed to relatively fresh water and minerals reflecting this fresher water form at this time; during low stands, pore waters of increased salinity and alkalinity in the central part of the lake alter minerals formed during high stands to minerals that reflect the increased salinity and alkalinity. The net effect of these fluctuations is a distribution of authigenic minerals that reflects an overall hydrogeochemical gradient (fig. 2).

The upper contact of the Brushy Basin Member can be difficult to determine where the member is overlain by the Lower Cretaceous Burro Canyon Formation. Both units contain mudstone, and suspected mudstone-on-mudstone contact at many localities make the contact difficult to establish with certainty. Tuffaceous mudstone, which exhibits a characteristic "popcorn" weathering, is confined to the Brushy Basin Member. Mudstone in the Burro Canyon Formation commonly does not exhibit "popcorn" weathering; thus the nature of the weathering commonly is a useful criterion in distinguishing the two units. This study demonstrates, however, that tuffaceous mudstone in the Brushy Basin Member locally contains illitic rather than smectitic mixed-layer illite/smectite and does not exhibit "popcorn" weathering and is thus not readily distinguished from the mudstone of the overlying Burro Canyon Formation. Color is locally a useful criterion because mudstone in the Burro Canyon typically is red and green, whereas mudstone in the Brushy Basin is commonly green and brown.

Pebbles in conglomeratic sandstone beds within the mudstone slopes in question also provide clues that help to distinguish the Burro Canyon Formation from the Brushy Basin Member of the Morrison Formation. The Burro Canyon Formation typically contains only white, gray, or black chert pebbles. In contrast, the Brushy

Basin Member contains a heterogeneous suite of pebbles, most notably a distinctive suite of green and red chert pebbles. The contact between the two units typically is determined on the basis of a combination of criteria listed herein, but placement of the contact is not always certain. Despite these difficulties, error in placing the contact probably does not exceed 12 m at any locality.

METHODS

Our goal was to test the role of pore-water chemistry in the formation of authigenic clays in a saline, alkaline lake setting, and most of our samples were collected from lacustrine deposits of ancient Lake T'oo'dichi'. Samples were collected from throughout the Brushy Basin Member in the southern part of the study area, but chiefly from the upper Brushy Basin Member in the northern part of the study area (fig. 2). In addition, locally, samples were collected from units of the lower Brushy Basin Member and from the lowermost mudstones of the Burro Canyon Formation so that these clay minerals could be contrasted with clay minerals in units of the upper Brushy Basin Member. In all, 441 samples were collected from 17 outcrop localities (fig. 1): most samples (323) were collected from tuff beds and the others from mudstone (67) and claystone (51). Most, if not all, of the claystone samples are tuffaceous.

The samples were crushed to granule size in a jaw crusher and placed in 250-mL beakers. The beakers were then filled with distilled water and the samples sonified for 3 minutes. Flocculation of the clay suspensate was rare. When flocculation occured, the suspension was diluted; if flocculation remained a problem, a dispersant (sodium hexametaphosphate) was added. The suspended clays were placed in 10-cm-high centrifuge bottles and spun at 1,000 rpm for 33 minutes to settle the >0.5-μm fraction, the time being determined by Stokes' Law. The <0.5-μm fraction, which remained in suspension, was selected for two reasons: (1) Examination of several size fractions on representative samples indicated that the <0.5-μm size fraction gave the most easily interpreted data and the least interference from quartz. (2) This size fraction was less likely to contain detrital clays.

The <0.5-μm fraction for each sample was suctioned onto 0.45-μm-pore filters and then transferred to two glass slides; this method for producing slides of oriented clay minerals is as described by Drever (1973) and modified by Pollastro (1982). One slide was heated at 550 °C (1,022 °F) for 1 hour, and the second slide was placed over a reservoir of ethylene glycol in an oven at 60 °C (140 °F) overnight. The slides were then X-rayed by using Cu Kα radiation and scanning from 2° to 35° 2θ or from 2° to 52° 2θ at 3° 2θ/min. The resulting X-ray diffractograms were interpreted by using the techniques described in Brown and Brindley (1980) and Reynolds (1980).

Identified clay minerals include smectite, mixed-layer illite/smectite, chlorite, and kaolinite. The term smectite is used to refer to clays that swell upon glycolation to ~17 Å, exhibit integrally spaced peaks, and collapse to ~10 Å upon heating. To determine the expandability (percent smectite layers) of mixed-layer illite/smectite, the position of the illite/smectite peaks found between 8.52 and 10.16 Å and between 5.62 and 5.01 Å was noted; both peak positions were compared with table 4.5A in Reynolds (1980) to determine amount of smectite (in percent). Smectitic mixed-layer illite/smectite is used to refer to clays having a high percentage of smectite, and illitic mixed-layer illite/smectite refers to clays having a low percentage of smectite. If only one peak was used to determine the percentage of smectite, it is noted in the data tables (appendix). The percent smectite listed in the tables should be considered as approximate rather than absolute (see Srodon, 1980). Although the percentages are approximate, the data set is internally consistent and certainly suitable for comparison of one outcrop locality with another. Diffractograms for a highly expandable or smectitic mixed-layer clay having integrally spaced peaks are shown in figure 3, and diffractograms for a low expandable or highly illitic mixed-layer clay are shown in figure 4.

The presence of chlorite or kaolinite was determined by the presence of a peak between 7.1 and 7.2 Å (12.5–12.3° 2θ) and a more diagnostic peak between 3.5 and 3.6 Å (25.5–24.7° 2θ) on the diffractogram from the glycolated sample. Figure 5 shows diffractograms for a sample containing abundant chlorite. Chlorite was distinguished from kaolinite by the presence of a peak at ~6° 2θ (13.9 Å) on the diffractogram of the heated sample; at 550 °C, chlorite collapses to one peak at this position and kaolinite disappears. Other minerals were also determined by using peak positions. A subjective ranking by abundance was made based on relative peak intensity for minerals other than mixed-layer illite/smectite, and the abundance of these minerals was categorized as trace, present, or abundant.

Interpretations for all of the X-ray patterns are shown in the appendix (tables 1–17). The percentage of smectite layers in either smectite or mixed-layer illite/-smectite for each sample and the relative abundance of the other minerals in each sample are given. Sample elevations are in feet and meters above the base of the Brushy Basin Member of the Morrison Formation. A brief megascopic description of each sample is also given and includes the color and rock type.

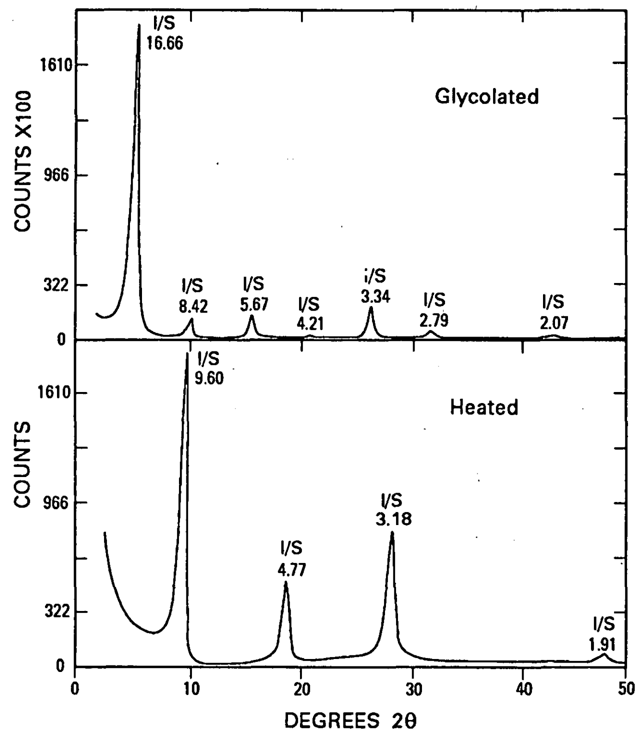

Figure 3. X-ray diffractograms of highly smectitic mixed-layer clay from Toadlena locality (fig. 1). Note integral spacing of reflections. I/S, illite/smectite; all peaks labeled in angstroms.

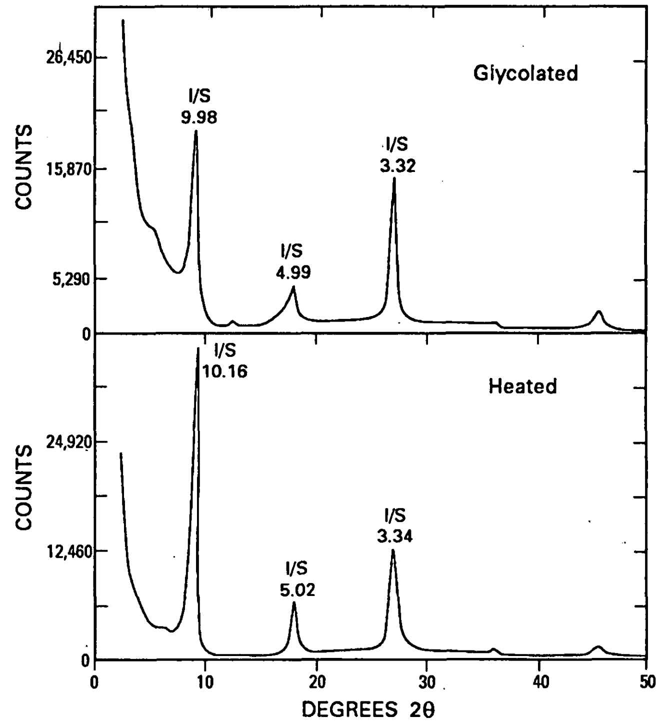

Figure 4. X-ray diffractograms of highly illitic mixed-layer clay from Blue Mesa locality (fig. 1). I/S, illite/smectite; all peaks labeled in angstroms.

RESULTS

Distribution of Clays

Our chief interest was the distribution of mixed-layer illite/smectite in ancient Lake T'oo'dichi', which includes all of the Brushy Basin Member in New Mexico and the upper Brushy Basin Member elsewhere. Smectitic or highly expandable clays predominate in ancient Lake T'oo'dichi' at Blue Peak, Capulin Peak, Colorado National Monument, Courthouse Draw, Lisbon Valley, Montezuma Creek, Sanostee Wash, and Toadlena (figs. 1, 6–13). At Colorado National Monument and Lisbon Valley (figs. 1, 8, 10), the persistence of highly smectitic mixed-layer illite/smectite in the upper Brushy Basin Member contrasts markedly with the more illitic (Colorado National Monument) or more variable mixed-layer illite/smectite clays (Lisbon Valley) of the lower Brushy Basin Member. Chlorite or kaolinite is in some samples and quartz is commonly present in trace amounts (appendix). Some localities, such as Blue Peak (fig. 6), are dominantly, though not completely, smectitic.

Clays from Beclabito Dome, Big Gypsum Valley, Deadman's Peak, McElmo Canyon, and Oak Springs (figs. 1, 14–18) are highly variable from one sample horizon to another. At these localities, smectitic mixed-layer clays are present, but many tuff beds also contain mixed-layer clays having only 10–20 percent smectite layers. Chlorite or kaolinite and trace amounts of quartz are in most samples from these localities (appendix). Figure 5 shows a representative X-ray pattern for a sample from the McElmo Canyon locality that contains abundant chlorite.

Clays from Blue Mesa, Durango Hospital, Norwood Hill, and Piedra River are dominantly illitic mixed-layer illite/smectite (figs. 1, 19–22). At all of these localities, smectitic mixed-layer illite/smectite is rare to absent. At Piedra River, for instance, only 3 of 77 samples contain a highly smectitic mixed-layer clay (fig. 22). Chlorite is present in almost all of the samples from the four localities; a few samples contain kaolinite (see appendix). The samples also contain trace amounts of quartz.

Discussion

The distribution of mixed-layer illite/smectite clays with respect to the outline of ancient Lake T'oo'dichi' as shown in figure 1 reveals a significant basinward trend. That part of the Brushy Basin Member deposited in the outer part of the saline, alkaline lake contains

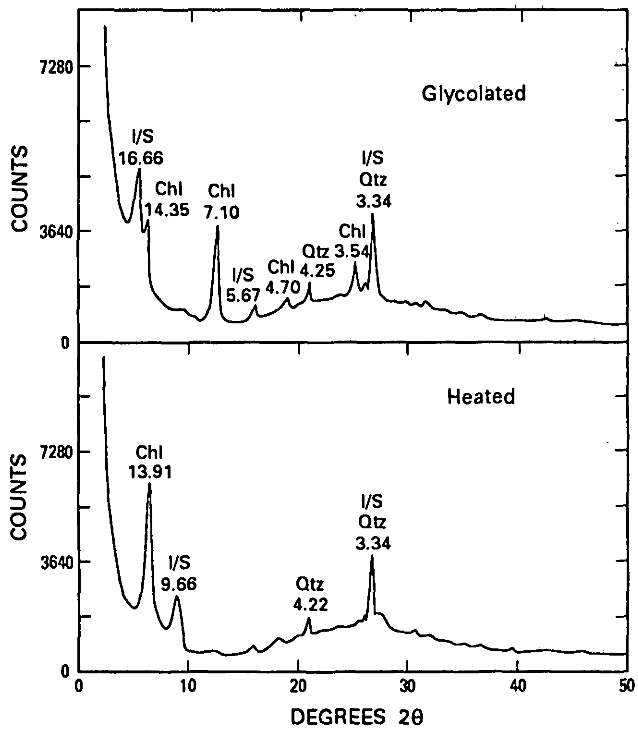

Figure 5. X-ray diffractograms of chlorite-rich sample from McElmo Canyon locality. Chl, chlorite; I/S, illite/smectite; Qtz, quartz; all peaks labeled in angstroms.

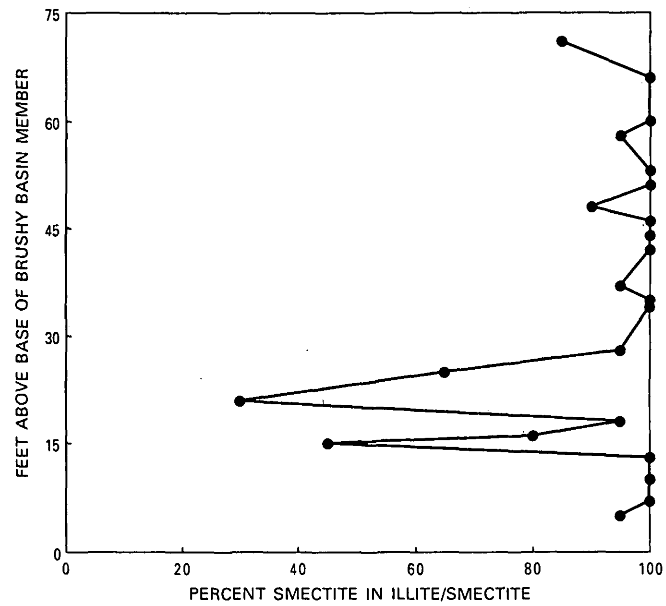

Figure 6. Amount of smectite in some mixed-layer clays in samples from Blue Peak locality (fig. 1). Complete set of data in appendix (table 4).

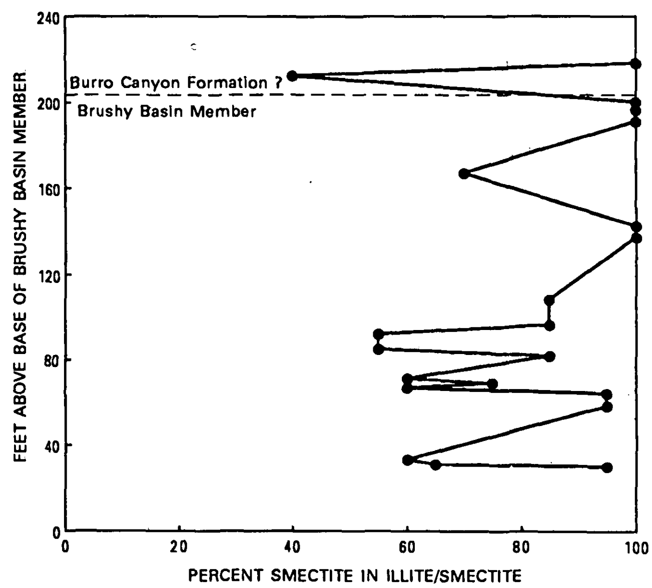

Figure 7. Amount of smectite in some mixed-layer clays in samples from Capulin Peak locality (fig. 1). Complete set of data in appendix (table 5).

predominantly smectitic clays (figs. 6-13), whereas the part deposited in the inner part of the lake contains predominantly illitic clays (figs. 19–22). Between these two zones, mixed-layer illite/smectite varies greatly (figs. 14–18).

A detrital origin for the illitic mixed-layer clays in Lake T'oo'dichi' can be ruled out. (1) The majority of beds sampled are tuff beds, which frequently contain volcanic ash of airfall origin and little admixed detrital material. (2) If a detrital illite component had been added to the airfall material, it would necessarily have crossed the smectitic zone in transit; the absence of illitic clays in the smectite zone around the outer margins of the lake system precludes a detrital origin for the illitic clays farther basinward.

The Gulf Coast model for illitization—illitization by progressive burial and attendant heating—also cannot be applied to the Brushy Basin Member because it does not explain the interbedding of tuff beds that contain variable compositions of mixed-layer clays, from almost pure smectite to almost pure illite, over vertical distances on the order of a few meters or less. Examples of this vertical variability are at the Beclabito Dome, Big Gypsum Valley and Deadman's Peak localities. These patterns cannot be explained by the Gulf Coast model because adjacent beds would undoubtedly have experienced a similar burial and thermal history. Localized potential heat sources also cannot explain the observed vertical variation in clay distribution.

The distribution of mixed-layer clays in Lake T'oo'dichi' is similar to that reported in similar depositional environments and probably reflects the pore-water chemistry at the time of diagenesis in the

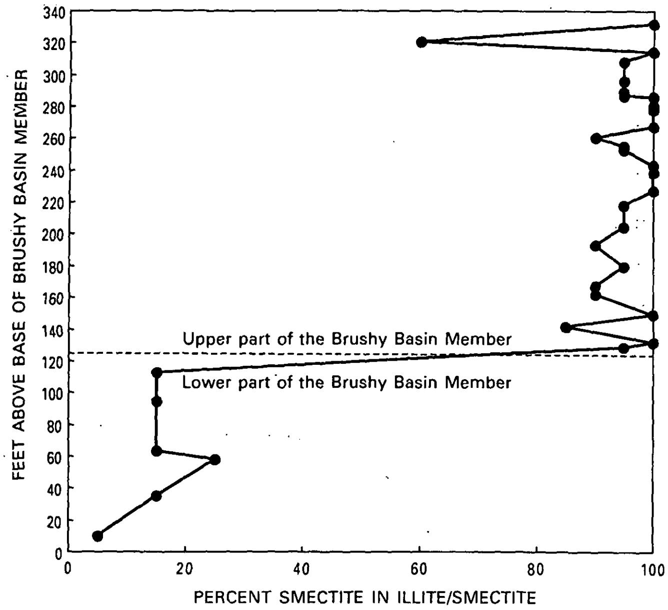

Figure 8. Amount of smectite in some mixed-layer clays in samples from Colorado National Monument locality (fig. 1). Complete set of data in appendix (table 6). Note dramatic difference between the amount of smectite in mixed-layer clays in the lower and upper parts of the Brushy Basin Member.

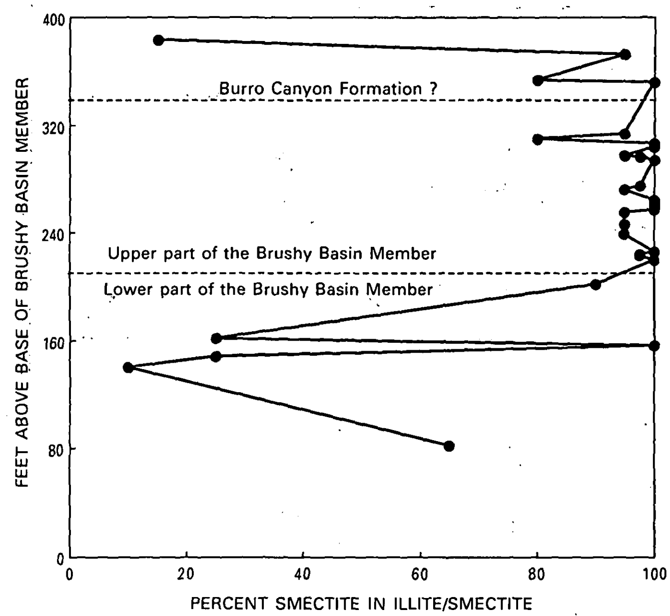

Figure 10. Amount of smectite in some mixed-layer clays in samples from Lisbon Valley locality (fig. 1). Complete set of data in appendix (table 10). Note dramatic difference between the amount of smectite in mixed-layer clays in both lower part of Brushy Basin Member and Lower Cretaceous Burro Canyon Formation, and the upper part of Brushy Basin Member.

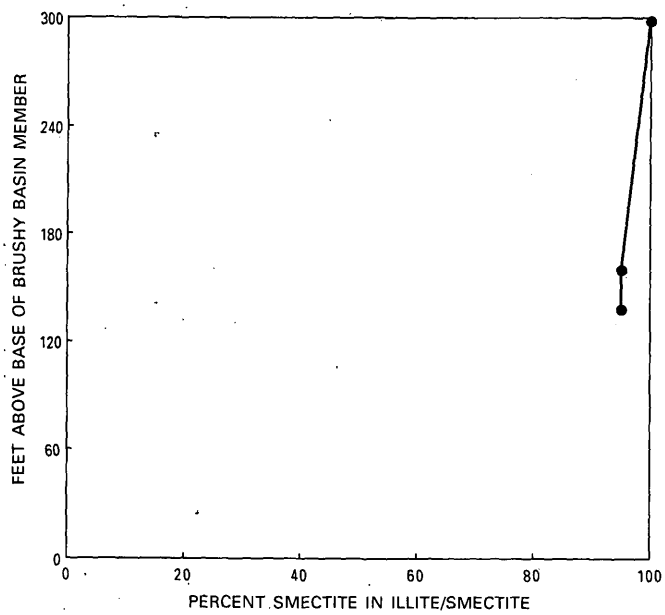

Figure 9. Amount of smectite in some mixed-layer clays in samples from Courthouse Draw locality (fig. 1). Complete set of data in appendix (table 7).

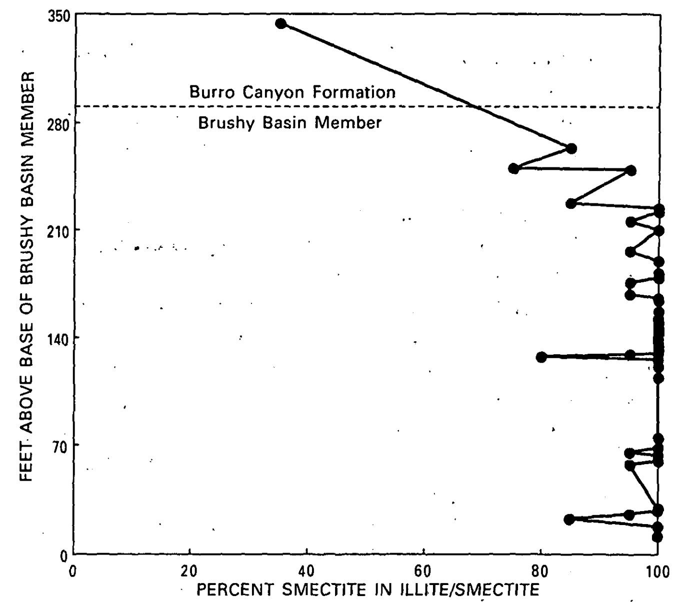

Figure 11. Amount of smectite in some mixed-layer clays in samples from Montezuma Creek locality (fig. 1). Complete set of data in appendix (table 12).

lacustrine sediments. In studies of lake deposits in the Green River Formation, Surdam and Parker (1972) observed that montmorillonite (smectite) is associated with units interpreted to have been deposited in relatively fresh water, an observation consistent with what we observe in the Brushy Basin Member. Smectite occurs in tuff beds around the outer edge of ancient Lake T'oo'dichi', an area where there would have been an

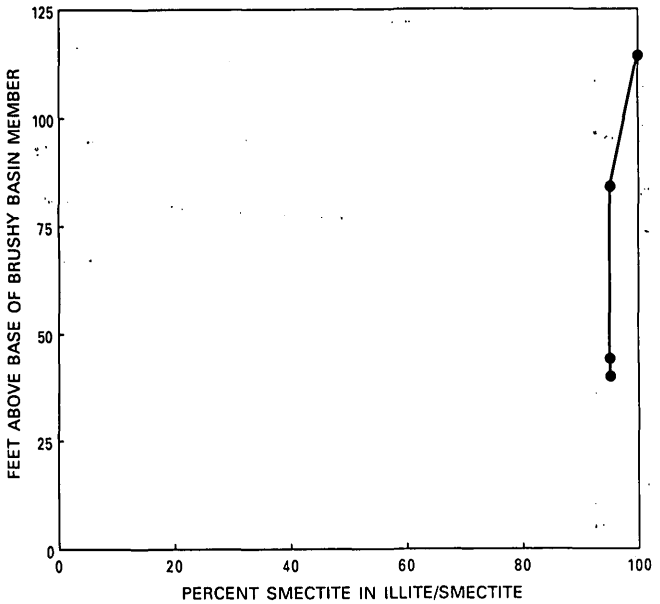

Figure 12. Amount of smectite in some mixed-layer clays in samples from Sanostee Wash locality (fig. 1). Complete set of data in appendix (table 16).

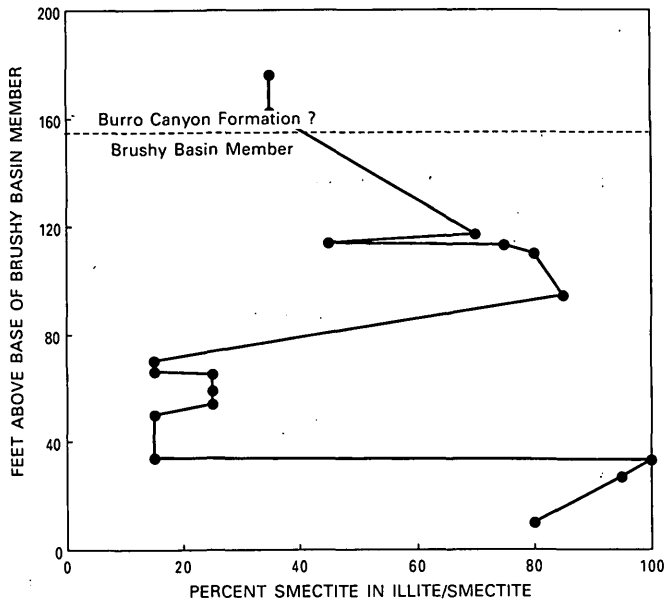

Figure 14. Amount of smectite in some mixed-layer clays in samples from Beclabito Dome locality (fig. 1). Complete set of data in appendix (table 1).

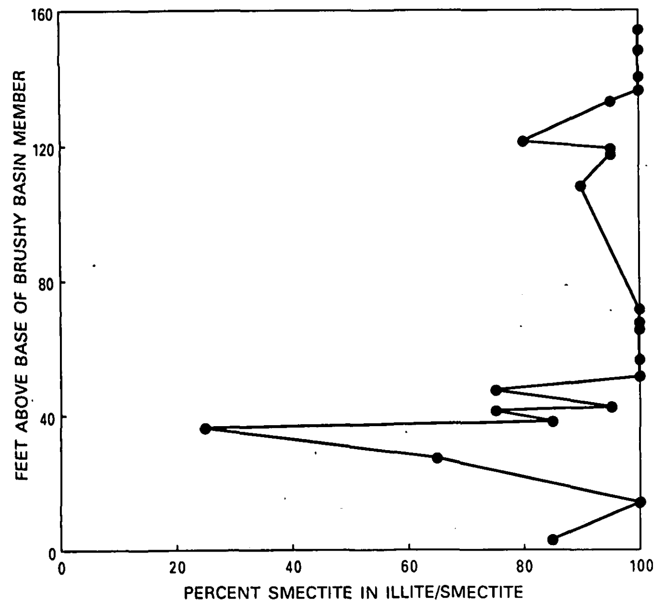

Figure 13. Amount of smectite in some mixed-layer clays in samples from Toadlena locality (fig. 1). Complete set of data in appendix (table 17).

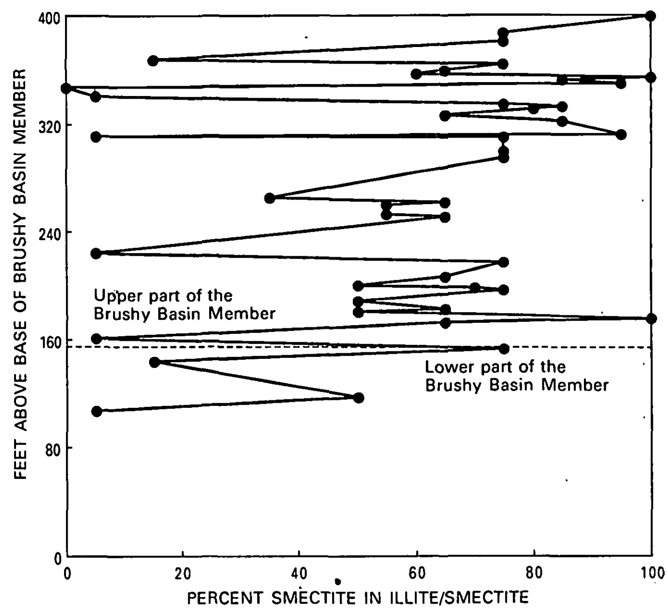

Figure 15. Amount of smectite in some mixed-layer clays in samples from Big Gypsum Valley locality (fig. 1). Complete set of data in appendix (table 2).

influx of fresh water. The illite in the center of Lake T'oo'dichi' probably reflects the more saline, alkaline porewater in the center of the lake. Singer and Stoffers (1980) examined mixed-layer illite/smectite clays in two cores from two saline lakes in Africa and observed a similar pattern.

CONCLUSIONS

The distribution of mixed-layer illite/smectite in tuffaceous beds of ancient Lake T'oo'dichi', a large saline, alkaline lake complex in the Brushy Basin Member of the Upper Jurassic Morrison Formation, can

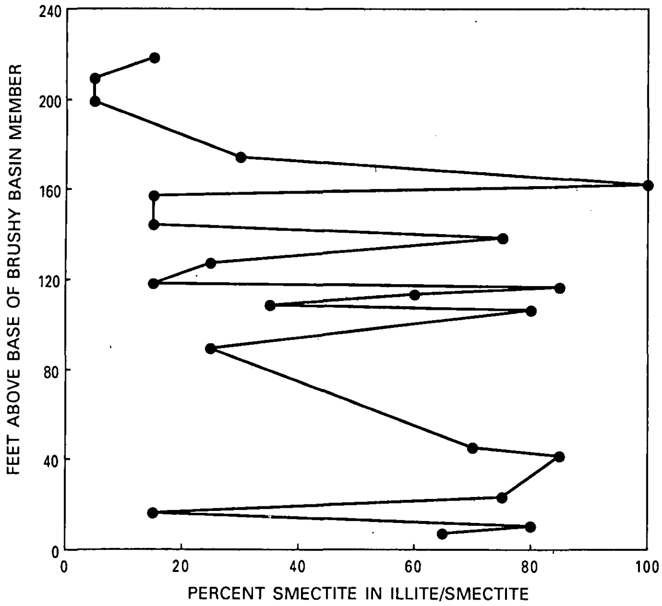

Figure 16. Amount of smectite in some mixed-layer clays in samples from Deadman's Peak locality (fig. 1). Complete set of data in appendix (table 8).

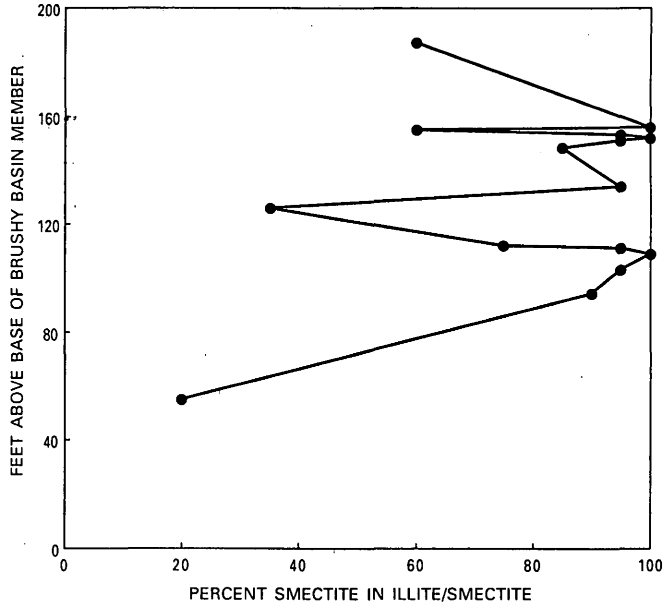

Figure 18. Amount of smectite in some mixed-layer clays in samples from Oak Springs locality (fig. 1). Complete set of data in appendix (table 14).

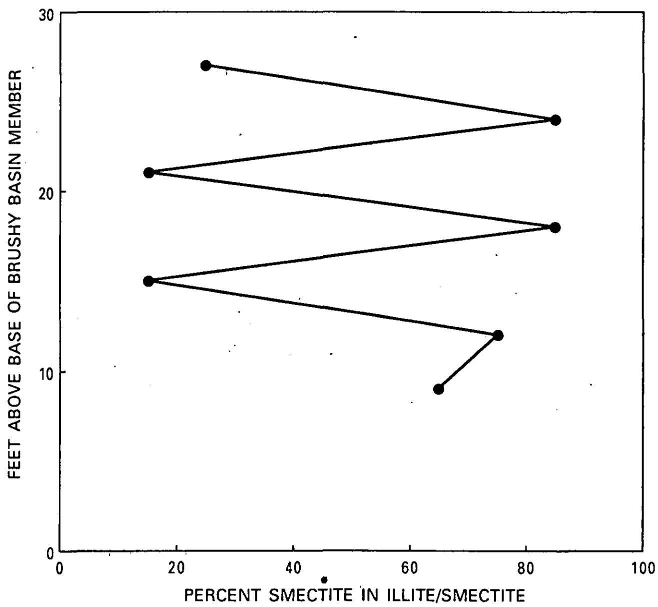

Figure 17. Amount of smectite in some mixed-layer clays in samples from McElmo Canyon locality (fig. 1). Complete set of data in appendix (table 11).

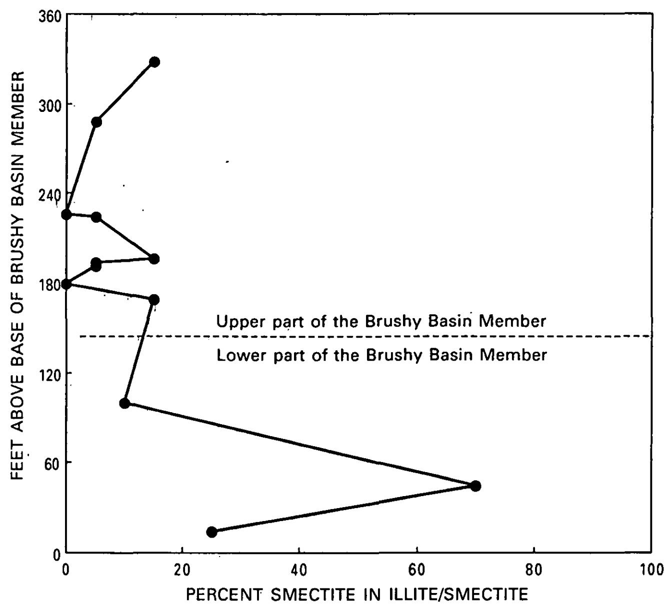

Figure 19. Amount of smectite in some mixed-layer clays in samples from Blue Mesa locality (fig. 1). Complete set of data in appendix (table 3).

more readily be attributed to changes in pore-water chemistry than to any other factor. We can rule out other possible explanations, such as the introduction of detrital illite or the conversion of smectite to illite with increasing temperature associated with burial. The trend of increasingly illitic clays toward the center of Lake T'oo'dichi' coincides with the hydrogeochemical gradient of increasing salinity and alkalinity associated with the lake. Thus, pore-water chemistry, rather than increased temperature associated with increased depth of burial,

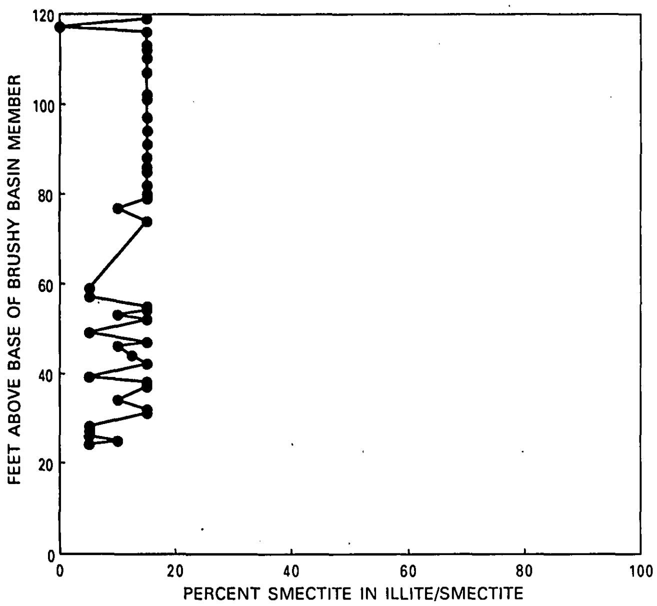

Figure 20. Amount of smectite in some mixed-layer clays in samples from Durango Hospital locality (fig. 1). Complete set of data in appendix (table 9).

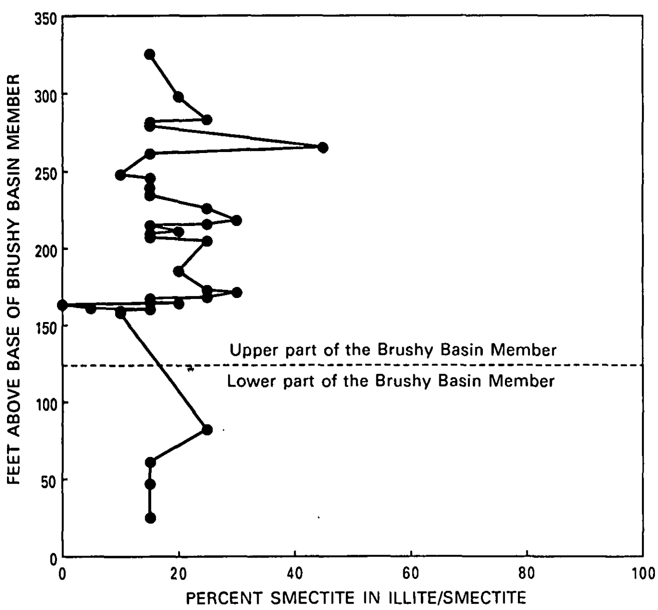

Figure 21. Amount of smectite in some mixed-layer clays in samples from Norwood Hill locality (fig. 1). Complete set of data in appendix (table 13).

was probably the more critical factor in controlling clay composition. The results of this study demonstrate formation of low-temperature illite in a saline, alkaline lake environment. Additional studies, including radiometric dating of the clays, are currently underway to test this conclusion.

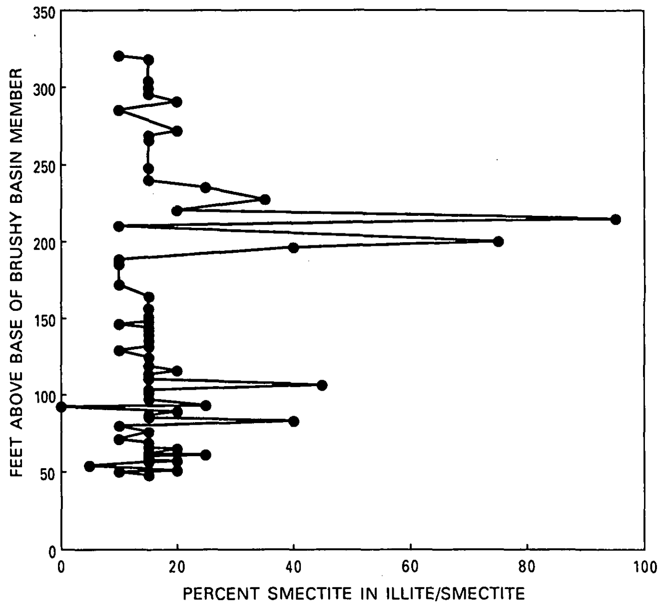

Figure 22. Amount of smectite in some mixed-layer clays in samples from Piedra River locality (fig. 1). Note that only 3 of 77 samples contain highly smectitic mixed-layer clays. Complete set of data in appendix (table 15).

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APPENDIX

Table 1. X-ray identification of <0.5-μm fraction, Beclabito Dome

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates identification uncertain]

Sample no.	Elevation (ft)	Elevation (m)	Megascopic description	Percent smectite	Other minerals
			Brushy Basin Member		
2	10	3.0	Green tuff	80	Chlorite-trace to present
3	27	8.2	Green tuff	90-100	Chlorite-present
4	33	10.0	Green tuff	100	Chlorite-present to abundant; quartz-trace
5	34	10.4	Green tuff	10-20	Chlorite-abundant to present; quartz-trace
6	50	15.2	Green tuff	10-20	Chlorite-abundant to present; quartz-trace
7	54	16.5	Green tuff	20-30	Chlorite-present; quartz-trace
8	59	18.0	Green tuff	20-30	Chlorite-present to abundant; quartz-trace
10	65	19.8	Green tuff	20-25	Chlorite-present to abundant; quartz-trace
11	66	20.1	Green tuff	10-20	Chlorite-present; quartz-trace?
12	70	21.3	Green tuff	10-20	Chlorite/kaolinite?-present; quartz-trace
13	94	28.6	Green tuff	80-90	Chlorite-present; quartz-trace; mica/feldspar?
14	110	33.5	Green tuff	80 (1 peak)	Chlorite-present to abundant; quartz-trace
15	113	34.4	Green tuff	≈75	Chlorite-present; quartz-trace
16	114	34.8	Green tuff	40-50	Chlorite-present
17	117	35.7	Green tuff	≈70 (1 peak)	Chlorite-trace
			Burro Canyon Formation?		
18	162	49.4	Brown mudstone	30-40	None observed
20	176	53.6	White claystone	30-40	None observed

Table 2. X-ray identification of <0.5-μm fraction, Big Gypsum Valley

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates identification uncertain]

Sample no.	Elevation (ft)	Elevation (m)	Megascopic description	Percent smectite		Other minerals
			Lower part of Brushy Basin Member			
4	107	32.6	Green claystone	0-10		Chlorite-present
5	117	35.7	Green mudstone	≈50	(1 peak)	Chlorite-present
7	144	43.9	Green mudstone	0-10		Chlorite?-present
8	153	46.6	Green mudstone	70-80	(1 peak)	Chlorite-present; quartz-trace
			Upper part of the Brushy Basin Member			
9	161	49.1	Blue tuff	0-10		Chlorite-present; quartz-trace
10	172	52.4	Pink tuff	60-70	(1 peak)	None observed
11	175	52.4	Green tuff	100		Chlorite-present to abundant
13	180	54.9	Green mudstone	50	(1 peak)	None observed
14	182	55.5	Green mudstone	60-70		Chlorite-trace
15	188	57.3	Mottled red/green mudstone	≈50		Chlorite-present
16	196	57.3	Green claystone	70-80	(1 peak)	Chlorite-present to abundant
17	198	60.4	Green tuff	70	(1 peak)	Chlorite-present; quartz-trace
18	200	61.0	Green claystone	≈50		None observed
19	206	62.8	Green tuff	60-70	(1 peak)	Chlorite to abundant
21	217	66.1	Green tuff	70-80	(1 peak)	Chlorite-present to abundant; quartz-trace
22	224	68.3	Green tuff	0-10		Chlorite-trace; quartz-trace
25	251	76.5	White tuff	60-70		None observed
26	253	77.1	Red tuff	50-60	1 peak)	None observed
27	260	79.3	Gray tuff	50-60		Chlorite-trace
28	262	79.9	Gray tuff	60-70		None observed
29	265	80.8	Brown claystone	30-40		Quartz-trace
33	295	89.9	Green tuff	70-80	(1 peak)	Chlorite-present; quartz-trace
34	299	91.1	Blue tuff	70-80	(1 peak)	Chlorite-present; quartz-trace
35	310	94.5	Orange tuff	70-80	(1 peak)	Chlorite-present; quartz-trace
36	311	94.8	Green tuff	0-10		Chlorite-present
37	312	95.1	Green tuff	90-100	(1 peak)	Chlorite-present to abundant; quartz-trace
39	321	97.8	Orange tuff	80-90		None observed
40	326	99.4	Green tuff	60-70	(1 peak)	Chlorite?-trace; quartz-trace
41	330	100.6	Green tuff	80	(1 peak)	Chlorite-present; quartz-trace
42	332	101.2	Green tuff	80-90	(1 peak)	Chlorite-present
43	334	101.8	Orange tuff	70-80	(1 peak)	Chlorite-present; quartz-trace
44	340	103.6	Blue tuff	0-10		Chlorite-present to abundant; quartz-trace
47	346	105.5	Blue tuff	0		Chlorite-present to abundant
48	349	106.4	Green tuff	90-100		Chlorite-present
49	352	107.3	Green tuff	80-90	(1 peak)	Chlorite-trace; quartz-trace
50	354	107.9	Green tuff	100	(1 peak)	Chlorite-present to abundant
51	356	108.5	Orange tuff	60	(1 peak)	Chlorite-present; quartz-trace
52	359	109.4	Brown mudstone	60-70	(1 peak)	Chlorite-present; quartz-trace
53	363	110.6	Brown tuff	70-80		Chlorite-present; quartz-trace
54	367	111.9	Brown tuff	10-20		Kaolinite?-trace to present
55	380	115.8	Orange tuff	70-80	(1 peak)	Chlorite-trace; quartz-trace
56	387	118.0	Blue tuff	70-80		Quartz-trace
57	399	121.6	Blue tuff	100		Quartz-trace

Table 3. X-ray identification of <0.5-µm fraction, Blue Mesa

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates identification uncertain]

Sample no.	Elevation (ft)	Elevation (m)	Megascopic description	Percent smectite		Other minerals
			Lower part of the Brushy Basin Member			
2+14	14	4.3	Red mudstone	20-30		None observed
3+19	44	13.4	Gray-green mudstone	≈70		Chlorite-abundant; quartz-trace
5+32	100	30.5	Red mudstone	≈10		Chlorite-trace; quartz-trace; feldspar?-trace
			Upper part of the Brushy Basin Member			
10+3	169	51.5	Green mudstone	10-20		Chlorite-trace; quartz-trace
10+13	179	54.6	Green tuff	0		None observed
10+25	191	58.2	Blue tuff	0-10		None observed
10+28	194	59.2	Blue-green tuff	0-10		Chlorite-trace; quartz-trace
10+30	196	59.7	Blue-green tuff	10-20		Chlorite-present; quartz-trace
12+12	224	68.3	Green tuff	0-10		Chlorite-trace; quartz-trace?
12+14	226	68.9	Green tuff	0		Chlorite-present
12+76	288	87.8	Green tuff	0-10	(1 peak)	None observed
14+17	328	100.0	Green tuff	10-20		Quartz-trace?

Table 4. X-ray identification of <0.5-µm fraction, Blue Peak

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates identification uncertain]

Sample no.	Elevation (ft)	Elevation (m)	Megascopic description	Percent smectite	Other minerals
1	5	1.5	Green mudstone	90-100	None observed
2	7	2.1	Green mudstone	100	None observed
3	10	3.0	Green mudstone	100	None observed
4	13	4.0	Green mudstone	100	Chlorite-present
5	15	4.6	Green mudstone	40-50	None observed
6	16	4.9	Green mudstone	80	None observed
7	18	5.5	Red mudstone	≈95	None observed
8	21	6.4	Green mudstone	≈30	None observed
9	25	7.6	Green mudstone	60-70	None observed
10	28	8.5	Green mudstone	90-100	Chlorite/kaolinite?-trace
11	34	10.4	Green claystone	100	None observed
12	35	10.7	Green claystone	100	None observed
13	37	11.3	Green claystone	90-100	None observed
14	42	12.8	Green claystone	100	None observed
15	44	13.4	Green claystone	100	None observed
16	46	14.0	Green mudstone	100	None observed
17	48	14.6	Yellow claystone	≈90	None observed
18	51	15.5	Green mudstone	100	None observed
19	53	16.2	Green mudstone	100	None observed
20	58	17.7	Green claystone	90-100	None observed
21	60	18.3	Green mudstone	100	None observed
22	66	20.1	Green claystone	100	None observed
23	71	21.6	Green claystone	80-90	None observed

Table 5. X-ray identification of <0.5-µm fraction, Capulin Peak

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates identification uncertain]

Sample no.	Elevation (ft)	Elevation (m)	Megascopic description	Percent smectite		Other minerals
			Brushy Basin Member			
1	30	9.1	Orange tuff	90-100		Chlorite?-trace; quartz-trace
2	31	9.4	Green claystone	60-70		Mica?
3	33	10.1	Orange tuff	≈60		Kaolinite-present
4	58	17.7	Green tuff	90-100		Kaolinite?-trace; mica?
5	64	19.5	Orange tuff	90-100		Kaolinite-trace; quartz-trace; clinoptilolite?-trace
6	67	20.4	Orange tuff	≈60		Kaolinite-trace; quartz-trace; clinoptilolite?-trace
7	69	21.0	Gray tuff	70-80	(1 peak)	Clinoptilolite?-present
8	71	21.6	Brown claystone	≈60		Quartz-trace
9	82	25.0	Orange tuff	80-90	(1 peak)	Kaolinite-present; clinoptilolite?-present
10	85	25.9	Orange tuff	50-60		Kaolinite-trace; quartz-trace
11	92	28.0	Orange tuff	50-60	(1 peak)	Clinoptilolite?-trace
12	96	29.3	Orange tuff	80-90	(1 peak)	Kaolinite-present; clinoptilolite?
13	108	32.9	Orange tuff	80-90		Kaolinite-present
15	137	41.8	Yellow claystone	≈100		None observed
16	142	43.3	Green tuff	≈100		Kaolinite-present; mica?-trace; quartz-trace
17	167	50.9	Orange tuff	≈70	(1 peak)	Kaolinite-abundant; quartz-trace
18	191	58.2	Yellow claystone	100		kaolinite-abundant-present
19	196	59.7	Green mudstone	100		Kaolinite-abundant
20	200	61.0	Gray mudstone	100		Kaolinite-present to abundant; quartz-trace
			Burro Canyon Formation?			
21	212	64.6	Green mudstone	≈40		Kaolinite-abundant; quartz-trace to present
23	218	66.4	Green tuff	100		Kaolinite-abundant; quartz-trace to present

Table 6. X-ray identification of <0.5-μm fraction, Colorado National Monument

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates identification uncertain]

Sample no.	Elevation (ft)	Elevation (m)	Megascopic description	Percent smectite		Other minerals
Lower part of the Brushy Basin Member						
1	10	3.0	Red mudstone	0-10		None observed
2	35	10.7	Red mudstone	10-20		None observed
3	58	17.7	Red claystone	20-30		None observed
4	63	19.2	Red mudstone	10-20		None observed
6	94	28.6	Brown mudstone	10-20	(1 peak)	Chlorite-trace
7	112	34.1	Brown mudstone	10-20		Quartz-trace
Upper part of the Brushy Basin Member						
8	128	39.0	Green mudstone	90-100		Mica/feldspar?-trace
9	131	39.9	Green mudstone	≈100		None observed
10	141	43.0	Green mudstone	80-90		None observed
12	149	45.4	Green mudstone	100		None observed
13	162	49.4	Green mudstone	≈90		None observed
14	167	50.9	Green mudstone	≈90		Quartz-trace
16	179	54.6	Green mudstone	90-100		None observed
18	193	58.8	Green mudstone	90		None observed
19	204	62.2	Yellow claystone	90-100		None observed
20	218	66.5	Gray mudstone	90-100		None observed
21	227	69.2	Brown mudstone	100		Mica?-trace
22	238	72.5	Green mudstone	100		None observed
23	243	74.1	Green mudstone	100		None observed
24	253	77.1	Yellow claystone	90-100		None observed
25	255	77.7	Green tuff?	90-100		Chlorite-present; quartz-trace
26	260	79.2	Green claystone	90		None observed
28	267	81.4	Brown mudstone	100		None observed
29	278	84.7	Green tuff	100		None observed
30	280	85.3	Green claystone	100		None observed
31	281	85.6	Blue tuff	100	(1 peak)	Kaolinite-present
32	286	87.2	Brown tuff	100		Chlorite-present to abundant; quartz-trace
33	287	87.5	Green claystone	90-100		None observed
34	289	88.1	Purple tuff	90-100		None observed
35	296	90.2	Green claystone	90-100		None observed
36	308	93.9	Blue tuff	90-100		Kaolinite/chlorite?-present to trace
37	314	95.7	Green claystone	100		Kaolinite-trace; quartz-present; mica?
38	320	97.5	Brown mudstone	60	(1 peak)	Chlorite-present to abundant
39	332	101.2	Green mudstone	100		None observed

Table 7. X-ray identification of <0.5-μm fraction, Courthouse Draw

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates identification uncertain]

Sample no.	Elevation (ft)	Elevation (m)	Megascopic description	Percent smectite	Other minerals
5+19A	138	42.1	Orange tuff	90-100	Clinoptilolite/mica?-present; quartz-trace; chlorite/kaolinite?-trace
5+41	160	48.8	Orange tuff	90-100	Clinoptilolite?-trace to present; quartz-trace
5+179	298	90.8	Green tuff	100	Mica?-present

Table 8. X-ray identification of <0.5-μm fraction, Deadman's Peak

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates identification uncertain]

Sample no.	Elevation (ft)	Elevation (m)	Megascopic description	Percent smectite		Other minerals
2	7	2.1	Green tuff	60-70	(1 peak)	Chlorite-present
3	10	3.0	Brown tuff	≈80	(1 peak)	Chlorite-trace; quartz-trace
6	16	4.9	Green tuff	10-20		Chlorite-trace
8	23	7.0	Green tuff	70-80	(1 peak)	Kaolinite-present to trace
13	41	12.5	Green tuff	80-90	(1 peak)	Kaolinite?-trace; quartz-trace
14	45	13.7	Green tuff	≈70	(1 peak)	Kaolinite-trace; quartz-trace
17	89	27.1	Green tuff	20-30		Chlorite-trace; quartz-trace
19	106	32.3	Green tuff	≈80	(1 peak)	Kaolinite-trace; quartz-trace
21	108	32.9	Green tuff	30-40	(1peak)	Chlorite/kaolinite?-present
23	113	34.4	Green tuff	≈60	(1 peak)	Quartz-trace
24	116	35.4	Green tuff	80-90		None observed
25	118	36.0	Orange tuff	10-20	(1 peak)	Chlorite-trace; quartz-trace
30	127	38.7	Green tuff	20-30	(1 peak)	Kaolinite-trace; quartz-trace
33	138	42.1	Green tuff	70-80	(1 peak)	Kaolinite-abundant; quartz-trace; mica-trace
35	144	43.9	Green tuff	10-20	(1 peak)	Kaolinite-trace; quartz-trace
38	157	47.8	Green tuff	10-20		Kaolinite-abundant; quartz-trace
39	162	49.4	Green tuff	100		Chlorite-abundant; quartz-trace
43	174	53.0	Green tuff	≈30		Kaolinite-abundant; quartz-trace
46	199	60.7	Blue tuff	0-10		Kaolinite-abundant; quartz-trace
49	209	63.7	Blue tuff	0-10		Kaolinite-present to abundant; quartz-trace
52	218	66.4	Green tuff	10-20	(1 peak)	Kaolinite-present to abundant; quartz-trace

Table 9. X-ray identification of <0.5-µm fraction, Durango Hospital

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates identification uncertain]

Sample no.	Elevation (ft)	Elevation (m)	Megascopic description	Percent smectite		Other minerals
3	24	7.3	Blue tuff	0-10		None observed
4	25	7.6	Green tuff	≈10		Quartz-trace
5	26	7.9	Green tuff	0-10		None observed
6	27	8.2	Green tuff	0-10		Quartz-trace
7	28	8.5	Green tuff	0-10		None observed
8	31	9.4	Blue tuff	10-20		None observed
9	32	9.8	Green tuff	10-20		None observed
10	34	10.4	Green tuff	≈10	(1 peak)	Quartz-trace
11	37	11.3	Green tuff	10-20		Quartz-trace
12	38	11.6	Green tuff	10-20		None observed
13	39	11.9	Gray tuff	0-10		Quartz-trace
14	42	12.8	Blue tuff	10-20		None observed
15	44	13.4	Brown tuff	10-15		None observed
16	46	14.0	Brown tuff	≈10		Chlorite/kaolinite?-trace
17	47	14.3	Green tuff	10-20		Quartz-trace
18	49	14.9	Blue tuff	0-10		None observed
20	52	15.8	Gray tuff	10-20		Kaolinite?-trace
21	53	16.2	Green tuff	≈10		Chlorite-trace
22	54	16.5	Green tuff	10-20		None observed
23	55	16.8	Green tuff	10-20	(1 peak)	Quartz-trace
24	57	17.4	Blue tuff	0-10		None observed
25	59	18.0	Green tuff	0-10		None observed
28	74	22.6	Green mudstone	10-20		None observed
29	77	23.5	Blue tuff	≈10		Chlorite-trace to present; quartz-trace
30	79	24.1	Green tuff	10-20		Chlorite?-trace
31	80	24.4	Green tuff	10-20		Chlorite-trace; quartz-trace
32	82	25.0	Green tuff	10-20		Chlorite-present; quartz-trace
33	85	25.9	Gray tuff	10-20		Quartz-trace
34	86	26.2	Green tuff	10-20		Chlorite-present to abundant; quartz-trace
35	88	26.8	Green tuff	10-20		Chlorite-present; quartz-trace
36	91	27.7	Green tuff	10-20		Chlorite-present; quartz-trace
37	94	28.6	Blue tuff	10-20	(1 peak)	None observed
38	97	29.6	Blue tuff	10-20		Chlorite-present; quartz-trace
39	101	30.8	Blue tuff	10-20		Chlorite-present; quartz-trace
40	102	31.1	Blue tuff	10-20		Chlorite-abundant; quartz-trace
41	107	32.6	Green tuff	10-20		Chlorite-abundant; quartz-trace
42	110	33.5	Green tuff	10-20		Chlorite-present; quartz-trace
43	112	34.1	Blue tuff	10-20		Chlorite?-trace
44	113	34.4	Green tuff	10-20		Chlorite-present to abundant
45	116	35.4	Blue tuff	10-20		Chlorite-trace to present
46	117	35.7	Purple tuff	0		Chlorite/kaolinite?-trace
47	119	36.3	Brown tuff	10-20		None observed

Table 10. X-ray identification of <0.5-μm fraction, Lisbon Valley

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates identification uncertain]

Sample no.	Elevation (ft)	Elevation (m)	Megascopic description	Percent smectite	Other minerals
Lower part of the Brushy Basin Member					
3	82	25.0	Brown mudstone	60-70	None observed
6	140	42.7	Brown claystone	≈10	None observed
7	148	45.1	Purp claystone	20-30	None observed
8	156	47.6	Green tuff	100	Quartz-trace
9	162	49.4	Brown claystone	20-30	None observed
10	202	61.6	Brown claystone	90	None observed
Upper part of the Brushy Basin Member					
13	220	67.1	Green tuff	100	None observed
14	223	68.0	Gray tuff	95-100	None observed
15	224	68.3	Orange tuff	95-100	None observed
16	226	68.9	Green tuff	100	Chlorite-present to abundant; quartz-trace
18	239	72.8	Orange tuff	90-100	None observed
19	246	75.0	Brown tuff	90-100	None observed
20	255	77.7	Green tuff	90-100	None observed
21	257	78.3	Green tuff	100	Quartz-trace
22	260	79.2	Green tuff	100	Quartz-trace
23	262	79.9	Green tuff	100	Quartz-trace
24	264	80.5	Green tuff	100	None observed
25	272	82.9	Green tuff	90-100	None observed
26	275	83.8	Orange tuff	95-100	None observed
28	294	89.6	Green tuff	100	Quartz-trace
29	296	90.2	Purple tuff	95-100	None observed
30	297	90.5	White tuff	90-100	Quartz-trace
31	304	92.7	Purple tuff	100	Quartz-trace
32	306	93.3	Purple tuff	100	None observed
33	310	94.5	Brown mudstone	75-85	None observed
34	313	95.4	Blue tuff	90-100	Kaolinite?-trace
Burro Canyon Formation?					
36	352	107.3	Green tuff	100	Kaolinite?-trace; quartz-trace
37	354	107.9	Brown mudstone	80	Kaolinite/chlorite?-trace
38	372	113.4	Green mudstone	90-100	None observed
39	383	116.7	Red claystone	10-20	Kaolinite?-trace

Table 11. X-ray identification of <0.5-μm fraction, McElmo Canyon

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates amount unknown]

Sample no.	Elevation (ft)	Elevation (m)	Megascopic description	Percent smectite	Other minerals
1	3	0.9	Green tuff	?	None observed
2	6	1.8	Green tuff	?	Chlorite-present
3	9	2.7	Green tuff	60-70 (1 peak)	Chlorite-present; quartz-trace
4	12	3.7	Green tuff	70-80 (1 peak)	Chlorite-abundant; quartz-trace
5	15	4.6	Green tuff	10-20 (1 peak)	Chlorite-present to abundant; quartz-trace
6	18	5.5	Green tuff	80-90 (1 peak)	Chlorite-present; quartz-trace
7	21	6.4	Green tuff	10-20 (1 peak)	Chlorite-present; quartz-trace
8	24	7.3	Green tuff	80-90 (1 peak)	Chlorite-present; quartz-trace
9	27	8.2	Green tuff	20-30 (1 peak)	Chlorite-present

Table 12. X-ray identification of <0.5-μm fraction, Montezuma Creek

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates identification uncertain]

Sample no.	Elevation (ft)	Elevation (m)	Megascopic description	Percent smectite		Other minerals
			Brushy Basin Member			
2	12	3.7	Green tuff	100		Kaolinite?-trace; quartz-trace
4	18	5.5	Green tuff	100		Chlorite-trace to present
6	23	7.0	Green tuff	80-90		None observed
7	26	7.9	Green tuff	90-100		None observed
8	28	8.5	Green tuff	100		Chlorite-present
9	30	9.1	Green tuff	100		Chlorite-present
10	58	17.7	Orange tuff	90-100		Chlorite-present; quartz-trace; clinoptilolite?
11	60	18.3	Green tuff	≈100		Kaolinite-present
13	64	19.5	Green tuff	100		Chlorite-trace
14	66	20.1	Orange tuff	90-100		Chlorite-present
15	69	21.0	Blue tuff	100		Chlorite-present
17	75	22.9	Orange tuff	100		Chlorite-present-trace
18	114	34.8	Green tuff	100	(1 peak)	Chlorite-present
20	121	36.9	Green tuff	100		None observed
22	126	38.4	Pink tuff	100		Mica?-trace
23	127	38.7	Green tuff	80		Chlorite-present to abundant
25	129	39.3	Pink tuff	90-100		None observed
24	130	39.6	Green tuff	100		Chlorite-trace to present
26	132	40.2	Pink tuff	100		None observed
27	134	40.8	Green tuff	100		Chlorite-present
28	137	41.8	Green tuff	100		Chlorite-present
29	139	42.4	Green tuff	100		Chlorite-present
30	142	43.3	Green tuff	100		Chlorite-present to abundant; quartz-trace
31	144	43.9	Green tuff	100		None observed
32	146	44.5	Orange tuff	100		None observed
33	149	45.4	Orange tuff	100		None observed
34	151	46.0	Green tuff	100		Chlorite-present to trace; quartz-trace
35	152	46.3	Green tuff	100		None observed
36	157	47.8	Pink tuff	100		None observed
37	164	50.0	Green and orange tuff	100		Quartz-trace
38	166	50.6	Green tuff	100		None observed
39	168	51.2	Brown tuff	90-100		None observed
42	176	53.6	Pink tuff	90-100		None observed
43	179	54.6	White tuff	100		None observed
44	182	55.5	Purple tuff	100		None observed
45	190	57.9	Purple tuff	100		None observed
46	196	59.7	White tuff	90-100		Feldspar?-trace
47	210	64.0	Purple tuff	100		None observed
48	216	65.8	Pink tuff	90-100		None observed
50	222	67.7	Pink tuff	100		None observed
51	224	68.3	Purple tuff	≈100		None observed
52	227	69.2	Pink tuff	80-90		None observed
54	249	75.9	Green claystone	90-100		None observed
55	250	76.2	Green tuff	70-80	(1 peak)	Chlorite-present
56	263	80.2	Green tuff	80-90	(1 peak)	Chlorite-trace to present
			Burro Canyon Formation?			
59	344	104.8	Green tuff	30-40	(1 peak)	Kaolinite-abundant

Table 13. X-ray identification of <0.5-µm fraction, Norwood Hill

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates identification uncertain]

Sample no.	Elevation (ft)	Elevation (m)	Megascopic description	Percent smectite	Other minerals
			Lower part of the Brushy Basin Member		
2	25	7.6	Green claystone	10-20	Chlorite-trace
4	47	14.3	Green mudstone	10-20	Chlorite-trace
7	61	18.6	Red claystone	10-20	Chlorite-present-trace; quartz-trace
12	82	25.0	Green claystone	20-30	Chlorite-present-trace
			Upper part of the Brushy Basin Member		
18	158	48.2	Green tuff	≈10	Chlorite-present; quartz-trace
19	159	48.5	Green claystone	≈10	Chlorite-present
20	160	48.8	Green tuff	10-20	Chlorite-present
21	161	49.1	Green tuff	0-10	Chlorite-present; quartz-trace
22	163	49.7	Green tuff	0	Chlorite-present to abundant
23	164	50.0	Green claystone	≈20	None observed
24	165	50.3	Green tuff	10-20 (1 peak)	Chlorite-present to abundant
25	167	50.9	Green tuff	10-20	Kaolinite?-present to abundant
26	168	51.2	Green tuff	20-30	Chlorite-abundant; quartz-trace
28	171	52.1	Orange tuff	≈30	Quartz-trace
29	173	52.7	Green tuff	20-30	Chlorite-present; quartz-trace
31	185	56.4	Brown claystone	≈20	Chlorite-present
34	205	62.5	Green tuff	20-30	Chlorite-trace to present; quartz-trace
36	207	63.1	Green tuff	10-20	Chlorite-trace to present; quartz-trace
37	209	63.7	Green tuff	10-20	Chlorite-trace; quartz-trace
38	211	64.3	Brown tuff	≈20?	Chlorite-trace; quartz-trace
40	215	65.5	Blue tuff	10-20	Chlorite-present; quartz-trace
41	216	65.8	Blue tuff	20-30	Chlorite-trace to present; quartz-trace
42	218	66.4	Green tuff	≈30	Chlorite-trace to present; quartz-trace
43	226	68.9	Green tuff	20-30	Quartz-trace
44	234	71.3	Brown tuff	10-20	Chlorite-present; quartz-trace
45	239	72.8	Green tuff	10-20	Chlorite-abundant; quartz-trace
47	245	74.7	Green tuff	10-20	Chlorite-present; quartz-trace
48	248	75.6	Green mudstone	≈10	Chlorite-trace to present; quartz-trace
49	261	79.6	Green tuff	10-20	Chlorite-abundant; quartz-trace
50	265	80.8	Green tuff	40-50	Chlorite-present to abundant, quartz-trace
51	279	85.0	Green tuff	10-20	Chlorite-present; quartz-trace
52	281	85.6	Green tuff	10-20	Chlorite-trace; quartz-trace
54	283	86.3	Green tuff	20-30	Chlorite-abundant; quartz-trace
55	298	90.8	Green tuff	≈20	Chlorite-abundant; quartz-trace
57	325	99.1	Green tuff	10-20	Kaolinite?-present; quartz-trace

Table 14. X-ray identification of <0.5-µm fraction, Oak Springs

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates identification uncertain]

Sample no.	Elevation (ft)	Elevation (m)	Megascopic description	Percent smectite	Other minerals
3	55	16.8	Green tuff	≈20 (1 peak)	Chlorite-abundant
4	94	28.6	Orange tuff	≈90	None observed
5	103	31.4	Orange tuff	90-100	None observed
6	109	33.2	Orange tuff	100	None observed
7	111	33.8	Green/orange tuff	90-100	Kaolinite?-trace
8	112	34.1	Green tuff	70-80	Chlorite-present; quartz-trace
9	126	38.4	Green tuff	30-40 (1 peak)	Quartz-trace
10	134	40.8	Orange tuff	90-100	None observed
12	148	45.1	Green tuff	80-90	Chlorite-abundant
13	151	46.0	Pink tuff	90-100	None observed
15	152	46.3	Pink tuff	100	None observed
17	153	46.6	Pink tuff	90-100	None observed
19	155	47.2	Gray tuff	≈60	Chlorite-present; quartz-trace
20	156	47.6	Gray tuff	100	None observed
21	187	57.0	Green tuff	≈60	Chlorite/kaolinite?-trace

Table 15. X-ray identification of <0.5-μm fraction, Piedra River

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates identification uncertain]

Sample no.	Elevation (ft)	Elevation (m)	Megascopic description	Percent smectite		Other minerals
6	48	14.6	Brown tuff	10-20	(1 peak)	Kaolinite?-trace
7	50	15.2	Green tuff	≈10		Chlorite-abundant-present; quartz-trace
8	51	15.5	Green tuff	≈20		Chlorite-present; quartz-trace
9	54	16.5	Green tuff	0-10		Chlorite-present; quartz-trace
10	56	17.1	Green tuff	10-20		Chlorite-present
11	57	17.4	Green tuff	≈20		Chlorite-trace to present
12	58	17.7	Green tuff	10-20		Chlorite-present to trace; quartz-trace
13	60	18.3	Orange tuff	10-20		Chlorite-trace;quartz-trace
14	61	18.6	Green tuff	20-30		Chlorite-present; quartz-trace
15	62	18.9	Green tuff	10-20	(1 peak)	Chlorite-present
17	65	19.8	Green tuff	≈20		Chlorite-present to abundant
18	66	20.1	Green tuff	10-20		Chlorite-abundant; quartz-trace
19	69	21.0	Gray tuff	10-20		Chlorite-present
20	71	21.6	Green tuff	≈10		Chlorite-trace to present; quartz-trace
21	76	23.2	Gray tuff	10-20		Chlorite-present to abundant; quartz-trace
22	80	24.4	Green tuff	≈10		Chlorite-present; quartz-trace
23	83	25.3	Green tuff	40		Chlorite/kaolinite?-trace
24	85	25.9	Brown tuff	10-20		Chlorite-trace; quartz-trace
25	87	26.5	Blue tuff	10-20		Chlorite-present; quartz-trace
26	89	27.1	Brown tuff	≈20		Chlorite-present; quartz-trace
27	92	28.0	Green tuff	≈0		Chlorite?-trace; quartz-trace
28	93	28.4	Green tuff	20-30	(1 peak)	Chlorite-present; quartz-trace
29	97	29.6	Green tuff	10-20		Chlorite-present; quartz-trace
30	101	30.8	Brown tuff	10-20		None observed
31	103	31.4	Brown tuff	10-20		Kaolinite/chlorite?-trace to present; quartz-trace
32	106	32.3	Green tuff	40-50		Kaolinite?-trace; quartz-trace
33	110	33.5	Green tuff	10-20		None observed
34	113	34.4	Brown tuff	10-20		Chlorite?-trace; quartz-trace
35	116	35.4	Orange tuff	≈20		Kaolinite?-trace
36	119	36.3	Green tuff	10-20		Chlorite-present; quartz-trace
37	124	37.8	Brown tuff	10-20		Kaolinite?-trace
38	129	39.3	Brown tuff	≈10		Chlorite-trace
39	131	39.9	Green tuff	10-20		None observed
40	135	41.2	Green tuff	10-20	(1 peak)	None observed
42	139	42.4	Green tuff	10-20		Quartz-trace
43	142	43.3	Green tuff	10-20		None observed
44	144	43.9	Green tuff	≈10-20		Quartz-trace
45	146	44.5	Green tuff	≈10		Quartz-trace
46	148	45.1	Green tuff	10-20	(1 peak)	None observed
47	151	46.0	Green tuff	10-20		Quartz-trace
48	156	47.6	Green tuff	10-20	(1 peak)	None observed
49	164	50.0	Green tuff	10-20	(1 peak)	Kaolinite/chlorite?-trace
51	172	52.4	Green tuff	≈10		Chlorite-trace to present; quartz-trace
53	185	56.4	Green tuff	10	(1 peak)	Quartz-trace
54	188	57.3	Brown tuff	≈10	(1 peak)	Chlorite-trace; quartz-trace
55	196	59.7	Brown tuff	≈40	(1 peak)	None observed
56	200	61.0	Green tuff	70-80	(1 peak)	Quartz-trace
58	210	64.0	Green tuff	≈10		Chlorite-abundant; quartz-trace
59	215	65.5	Green tuff	90-100		Chlorite-abundant-present;quartz-trace
61	220	67.1	Green tuff	≈20		Chlorite-present; quartz-trace
62	227	69.2	Green tuff	30-40		Chlorite-present
63	235	71.6	Green tuff	20-30		Chlorite-abundant; quartz-trace
64	240	73.2	Green tuff	≈100	(1 peak)	Chlorite-present
66	248	75.6	Green tuff	10-20	(1 peak)	Chlorite-present
67	266	81.1	Brown tuff	10-20		Chlorite-abundant; quartz-trace
68	269	82.0	Green tuff	10-20		Chlorite-abundant; quartz-trace
69	272	82.9	Green tuff	≈20		Chlorite-present; quartz-trace
70	285	86.9	Green tuff	≈10		Chlorite-present to abundant; quartz-trace
71	291	88.7	Green tuff	≈20		Chlorite-present to abundant; quartz-trace
73	295	89.9	Green tuff	10-20		None observed
74	299	91.1	Green tuff	10-20		Chlorite-abundant; quartz-trace
75	304	92.7	Green tuff	10-20		Kaolinite?-present
76	318	96.9	Green tuff	10-20		Kaolinite?-trace; quartz-trace
77	320	97.5	Gray tuff	≈10		Kaolinite-present; quartz-trace

Table 16. X-ray identification of <0.5-µm fraction, Sanostee Wash

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates identification uncertain]

Sample no.	Elevation (ft)	(m)	Megascopic description	Percent smectite	Other minerals
B-7	40	12.2	Orange mudstone	90-100	None observed
B-10	44	13.4	Orange tuff	90-100	Chlorite-present; quartz-present
B-15	84	25.6	Gray claystone	90-100	None observed
B-19	114	34.8	Green tuff	100	Kaolinite/chlorite?-trace

Table 17. X-ray identification of <0.5-µm fraction, Toadlena

[Locality shown in fig. 1. Elevation is height above base of Brushy Basin Member. Query (?) indicates identification uncertain]

Sample no.	Elevation (ft)	(m)	Megascopic description	Percent smectite	Other minerals
1	3	0.9	Gray mudstone	80-90	None observed
2	14	4.3	Green mudstone	100	None observed
3	27	8.2	Green claystone	60-70	None observed
4	36	11.0	Green/red mudstone	20-30	None observed
5	38	11.6	Green mudstone	80-90	None observed
6	41	12.5	Green claystone	70-80	None observed
7	42	12.8	Green mudstone	90-100	None observed
8	47	14.3	Red mudstone	70-80	None observed
9	51	15.5	Green claystone	100	None observed
10	56	17.1	Yellow claystone	100	None observed
11	65	19.8	Green claystone	100	None observed
12	67	20.4	Green claystone	100	None observed
13	71	21.6	Green mudstone	100	None observed
14	108	32.9	Purple mudstone	90	None observed
15	117	35.7	Green mudstone	90-100	None observed
16	119	36.3	Brown mudstone	90-100	None observed
17	121	36.9	Green claystone	80	None observed
18	133	40.5	Green claystone	90-100	Kaolinite-present; quartz-trace
19	136	41.5	Gray claystone	100	None observed
20	140	42.3	Gray claystone	100	None observed
21	148	45.1	Green claystone	100	None observed
22	154	46.9	Green claystone	100	None observed

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