

Distribution and Genesis of
Authigenic Silicate Minerals
In Tuffs of Pleistocene
Lake Tecopa, Inyo County
California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 597



Distribution and Genesis of Authigenic Silicate Minerals In Tuffs of Pleistocene Lake Tecopa, Inyo County California

By RICHARD A. SHEPPARD and ARTHUR J. GUDE 3d

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*Zeolites, potassium feldspar, searlesite
and clay minerals formed during diagenesis
of rhyolitic vitric tuffs that were
deposited in a saline lake*



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DISTRIBUTION AND GENESIS OF AUTHIGENIC SILICATE MINERALS IN TUFFS OF PLEISTOCENE LAKE TECOPA, INYO COUNTY, CALIFORNIA

By RICHARD A. SHEPPARD and ARTHUR J. GUDE 3d

ABSTRACT

The deposits of Pleistocene Lake Tecopa cover about 90 square miles along the Amargosa River in southeastern Inyo County. These deposits consist chiefly of mudstone and interbedded rhyolitic vitric tuffs that interfinger marginward with coarser clastic sediments. A total of 12 tuffs, 2 inches to 13 feet thick, were recognized in the 220 feet of exposed section. They are mainly the result of ash falls directly into the lake, although the upper parts of some contain reworked material. This report summarizes the physical properties, chemistry, and areal distribution of those silicate minerals that formed in the tuffs during diagenesis.

Zeolites, monoclinic potassium feldspar, searlesite, clay minerals, and opal occur in the altered tuffs. The zeolites are mainly phillipsite, clinoptilolite, erionite, and in trace to minor amounts, analcime and chabazite. Clay minerals are nearly ubiquitous and occur in trace to major amounts associated chiefly with zeolites and potassium feldspar. Most beds contain two or more zeolites, but some beds are monomineralic. Potassium feldspar also locally forms monomineralic beds.

Zeolites are locally associated with relict glass; potassium feldspar and searlesite are locally associated with zeolites, but nowhere has potassium feldspar or searlesite been found associated with relict glass. Textural evidence shows that some potassium feldspar and searlesite replace phillipsite and suggests that all potassium feldspar and searlesite in the tuffs formed from phillipsite and other early diagenetic zeolites rather than directly from the rhyolitic glass.

Three diagenetic facies recognized in the tuffs have fresh glass, zeolite, and potassium feldspar or searlesite as their diagnostic constituents. The fresh-glass facies is along the lake margin and is succeeded basinward by the zeolite facies and then by the potassium feldspar facies in the central part of the basin. The boundary between the zeolite and potassium feldspar facies bulges basinward at the inlets to Lake Tecopa. Original textures and sedimentary structures are generally preserved in tuffs of the zeolite and potassium feldspar facies. Preservation of these features in altered tuffs that are laterally equivalent to tuffs of the fresh-glass facies is convincing evidence that the present differences in composition and mineralogy are due to postdepositional processes. Experimental work by other mineralogists indicates that the formation of zeolites and feldspar is favored over clay minerals by a relatively high alkali ion to hydrogen ion activity ratio. The distribution and the gradational character of the facies are undoubtedly due to a chemical zonation of the pore water during diagenesis. The pore water was "fresh" near the margin and inlets of the lake but increasingly alkaline and saline basinward. This zonation was probably inherited from the depositional environment. Water of Lake Tecopa was probably moderately to highly saline with a pH of 9 or higher, except near the lake margin.

Solution of the rhyolitic glass by alkaline and saline pore water provided the material necessary for formation of zeolites and, subsequently, potassium feldspar. The paragenesis of silicate minerals within the zeolite facies is attributed to variations in the $\text{Na}^+ + \text{K}^+ : \text{H}^+$ activity ratio, the activity of H_2O , the activity of SiO_2 and the $\text{K} : \text{Na} + \text{Ca} + \text{Mg}$ ratio in the pore water.

INTRODUCTION

LOCATION

Pleistocene Lake Tecopa is in southeastern Inyo County (fig. 1), Calif. mainly in Tps. 21 and 22 N., Rs. 6 and 7 E. It is about 20 airline miles east of the southern end of Death Valley. The nearest principal cities are Las Vegas, 60 airline miles to the east, and Barstow, 80 airline miles to the southwest. The desert towns of Shoshone and Tecopa lie within the lake basin and can be reached by paved State Route 127. The area is shown on the 15-minute Eagle Mountain, Shoshone, and Tecopa quadrangle topographic maps published by the U.S. Geological Survey.

GEOGRAPHY

Lake Tecopa is in the southern part of the Basin and Range physiographic province, just north of the Mojave Desert. This area comprises mainly isolated

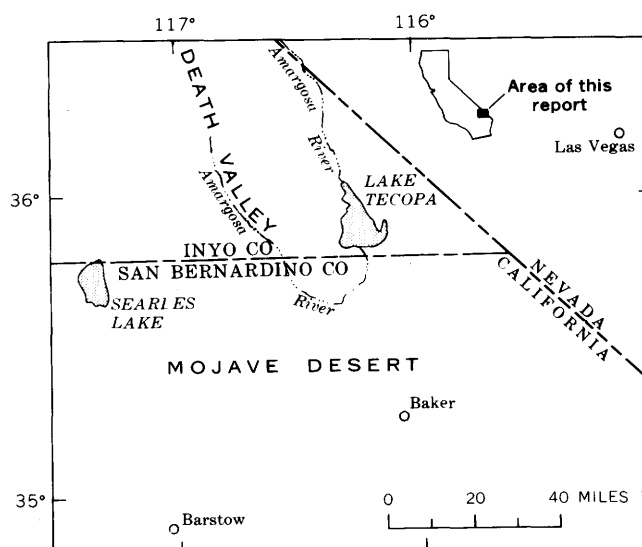


FIGURE 1.—Index map showing location of Lake Tecopa, Calif.

short mountain ranges separated by desert plains. The lake occupied an intermontane basin which lies between the southern parts of the Resting Spring and Nopah Ranges on the east and the southern part of the Greenwater Range, Dublin Hills, and Ibex Hills on the west. Most of the peaks surrounding the basin range in elevation from 3,000 to 4,000 feet; none rise as high as 5,000 feet.

The deposits of Lake Tecopa have a north-south extent along the Amargosa River of about 14 miles and an east-west extent at the widest part of about 11 miles, although the maximum extent of the beds cannot be determined, owing to erosion and concealment by alluvial fans of Recent age. The lake beds cover about 90 square miles. The lowest exposures of the beds lie at an elevation of about 1,300 feet near Tecopa. Along the sides of the surrounding hills, the uppermost beds lie at an elevation of about 1,800 feet.

PREVIOUS WORK

Most of the previous work on Lake Tecopa and vicinity was concerned with deposits of saline minerals or pumicite. The lake beds were briefly described by Bailey (1902) and Campbell (1902, p. 14-15) in connection with their studies of saline mineral deposits near Resting Spring. Short but comprehensive descriptions of the lake beds and a plausible history of the lake were given by Noble, Mansfield, and others (1922, p. 59-67) and Noble (1931, p. 62-71) as a consequence of their exploration of the Zabriskie nitrate field. Only small concentrations of nitrates were found in the caliche formed on the lake beds, and the beds were virtually barren.

Pumicite deposits just southwest of Shoshone were briefly described by Tucker (1920, p. 297), Norman and Stewart (1951, p. 109), Chesterman (1956, p. 68, 85), and Blanc and Cleveland (1961a, p. 6). The pumicite (locally referred to as "silica") was mined from a tuff unit in the lake deposits where the vitric material is free of alteration. Mining continued intermittently from 1920 to the late 1950's (Chesterman, 1956, p. 85). The same tuff unit was mined for bentonite just northwest of Shoshone where the tuff is altered to montmorillonite. Melhase (1926) studied the bentonite, which he termed "amargosite," and rightly attributed its formation to the alteration of vitric material by hot springs.

The general geology of Lake Tecopa and vicinity was summarized by Noble (1926) and Mason (1948). Lake Tecopa was briefly mentioned by Thompson (1929, p. 112-113, 572-575), Blackwelder (1936; 1954, p. 39-40), Hubbs and Miller (1948, p. 84-85), and Blanc and Cleveland (1961b, p. 5).

NAME OF THE LAKE

Bailey (1902, p. 10-17) and Campbell (1902, p. 14-15) seem to have recognized lacustrine rocks along the Amargosa River near Resting Spring about the same time. Bailey considered the lake to be Pleistocene in age and named it "Resting Springs Lake." He believed the lake to be one of many remnants of a much larger lake, Lake Aubury, which supposedly covered much of Inyo and San Bernardino Counties and parts of Kern, Los Angeles, and Riverside Counties. Bailey's map (between p. 32 and 33), showing the location and extent of Resting Springs Lake and other Pleistocene lakes in southern California, was so inaccurate that later workers have not followed his usage. We adopt the usage of Blackwelder (1936), who briefly described and formally named Lake Tecopa. Blackwelder did not publish a map showing the extent of Lake Tecopa, but such a map had been published earlier by Thompson (1929).

SCOPE OF INVESTIGATION

This investigation of Lake Tecopa is directed primarily at a study of the formation and distribution of zeolites and other authigenic silicate minerals in the tuffaceous beds. Although zeolites are common authigenic minerals in tuffaceous rocks of Cenozoic age throughout the desert regions of southeastern California (Sheppard and Gude, 1964), the tuffs of Lake Tecopa were chosen for detailed study for the following reasons: (1) the tuffs are relatively young and have been subjected to only very shallow burial, (2) the lacustrine rocks show slight or no deformation, (3) exposures are good and individual tuffs can be traced with ease throughout most of the basin, (4) the configuration of the basin is readily deciphered, and (5) reconnaissance in 1963 showed that fresh vitric tuffs could be traced laterally into completely altered tuffs.

Sampling was confined to surface outcrops and weighted heavily in favor of tuffs, although the other rock types were sampled sufficiently to obtain representative material. No cores were available to this investigation. This lack is not considered detrimental to the study except that the distribution and abundance of saline minerals probably could have been more meaningfully determined through study of cores, particularly from the central part of the basin.

LABORATORY METHODS

X-ray diffractometer patterns were made of all bulk samples of tuffs. The samples were first ground to a powder, packed in aluminum sample holders, and then exposed to nickel-filtered copper radiation. Relative abundances of authigenic minerals were estimated from

the diffractometer patterns. Estimates are probably less reliable for mixtures containing glass or opal because these materials yield a rather poor X-ray record. Optical studies using immersion oil mounts and thin sections supplemented the X-ray data and provided information on the age relationships of the minerals.

Most samples of altered tuff contained more than one authigenic mineral. In order to identify each mineral in the diffractometer patterns of bulk samples, the patterns were compared to a "sieve." The sieve, such as that illustrated in figure 2, was prepared from pure mineral separates at the same scale as the patterns of the bulk samples. One mineral at a time can be sieved from the bulk patterns until all lines are identified. This procedure served to render the identifications routine and to help the analyst recognize minor or trace amounts of constituents.

ACKNOWLEDGMENTS

Grateful appreciation is expressed to those in the Geological Survey who provided technical assistance during this study. Ellen S. Daniels, Elaine L. Munson, Harriet Neiman, and Christel L. Parker performed analyses. Paul D. Blackmon determined the clay mineralogy of representative mudstones and altered tuffs. Richard E. Van Loenen assisted in sample preparation during the early laboratory phase of the investigation. Melvin E. Johnson prepared thin sections of the altered tuffs—a feat that required exceptional patience and skill to preserve the delicate authigenic minerals.

We have benefited from discussions with Professor Richard L. Hay of the University of California on the genesis of zeolites in sedimentary rocks. We also are grateful to Professor Hay for his technical review of the manuscript.

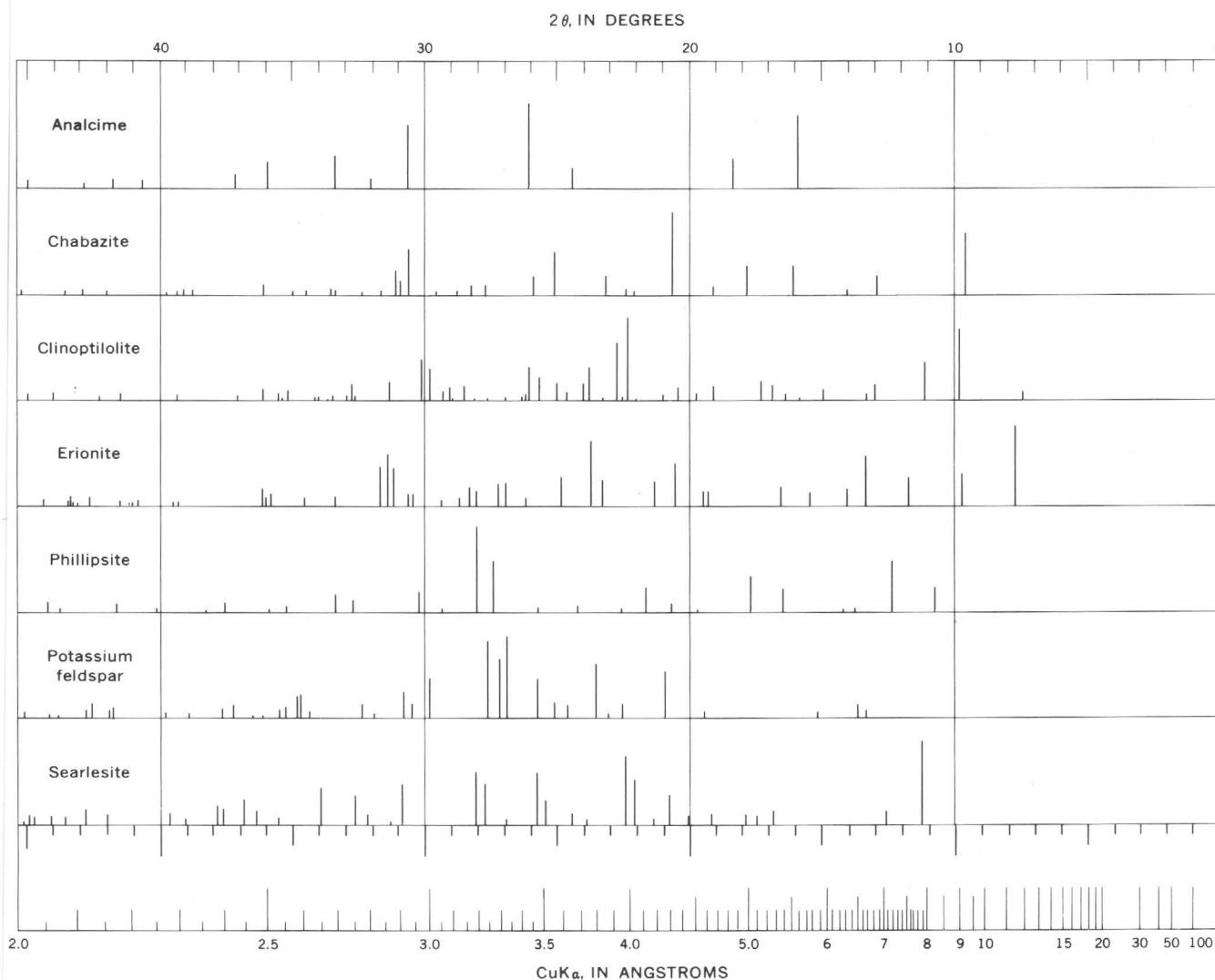


FIGURE 2.—Diagrammatic sketch showing X-ray diffractometer patterns of authigenic silicate minerals. Copper radiation with nickel filter. Relative intensities indicated by height of lines above base line. All samples are from Lake Tecopa except analcime and chabazite, which are from altered tuffs of the Barstow Formation, about 10 miles north of Barstow, Calif.

GEOLOGIC SETTING

The mountain ranges surrounding the Lake Tecopa basin are composed principally of sedimentary rocks of Cambrian age and volcanic and sedimentary rocks of Tertiary age (Noble, 1926, p. 65-67; Mason, 1948). Precambrian granitic gneiss crops out in two areas at the southern end of the Nopah Range. Sedimentary rocks of Precambrian age have been mapped along and east of the Amargosa River south of Tecopa (Mason, 1948, p. 340-341). Basalt flows of late Tertiary or early Pleistocene age are exposed just north of Shoshone, at several places in the southern part of Dublin Hills, and in Greenwater Valley.

The barrier behind which the waters of the Amargosa River were impounded to form Lake Tecopa lies south of Tecopa and is composed of alluvial fan deposits buttressed by older rocks. Water also entered Lake Tecopa from Greenwater Valley on the west, Chicago Valley on the southeast, and other minor drainages peripheral to the lake. As the basin filled with sediment the lake began to overflow and the river cut through the barrier. The lake was eventually drained, and the lake deposits subsequently dissected by the Amargosa River and its tributaries (Noble, 1926, p. 68).

Erosion and dissection of the lake deposits have proceeded to such a degree that now the area is characterized by badlands in the central part of the basin and

dissected gravel-capped pediments along the marginal parts of the basin. Alluvium-filled washes, tributary to the Amargosa River, transect both areas. The pediments slope gently toward the river and are capped with a veneer of gravel that generally is several inches to several feet thick. The gravel cap increases in thickness toward the mountain fronts and merges with the more steeply sloping alluvial aprons adjacent to the fronts.

Natural exposures of the lake deposits are restricted to the badlands area in the central part of the basin and to steep-sided bluffs along washes in the dissected pediment area. Even in the badlands area the best exposures are along washes (fig. 3) because most of the hills have a "popcorn" coating formed by weathering of the predominant montmorillonite-rich mudstones.

The only exposures of pre-Lake Tecopa rocks within the area of lake deposits are some low hills that once were islands in the lake (fig. 4); nowhere has the Amargosa River cut through the basal lake beds. The islands are composed of sedimentary rocks of Cambrian age except for an island a half mile north of Shoshone and another in the Greenwater Valley, about 1 mile south of Dublin Hills. Both of these are underlain by basalt of late Tertiary or early Pleistocene age. Most of the islands, particularly the smaller ones, probably were completely buried by lake sediment and now have been exhumed by erosion. However, at least two of the larger islands probably never were completely buried.



FIGURE 3.—Badlands underlain by mudstone with thin, interbedded tuffs. Details of the stratigraphy exposed only in the steep-sided bluffs along washes. Mountains in background underlain by pre-Lake Tecopa rocks. View looking southwest across central part of lake basin.

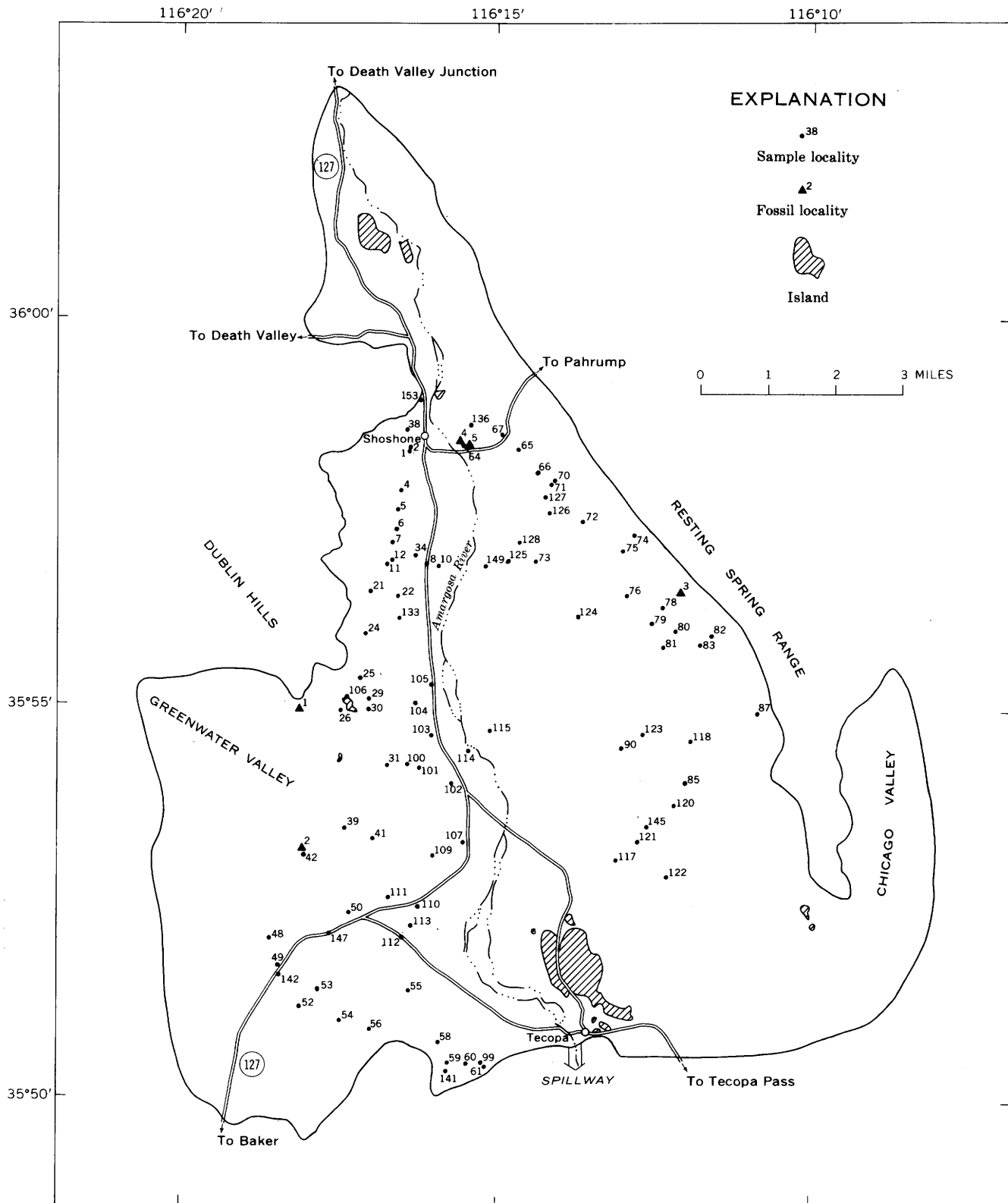


FIGURE 4.—Map of Lake Tecopa showing sample localities of tuffs and fossil localities. X-ray analysis of samples given in table 10.

One of these is 2 miles north of Shoshone and the other is 1 mile north of Tecopa.

At present the Amargosa River is dry except during brief periods following torrential rains. Short stretches maintain a feeble flow where fed by springs such as those near Shoshone and Tecopa. White efflorescent salts commonly coat marshy areas along the river within the lake basin. Burkeite ($2\text{Na}_2\text{SO}_4 \cdot \text{Na}_2\text{CO}_3$), the-nardite (Na_2SO_4), and halite (NaCl) were identified in samples collected just east of State Route 127, about 3.5 miles south of Shoshone. Borax ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$) also has been reported (Campbell, 1902, p. 14; Noble, 1926, p. 70), but was not identified in our samples.

AGE OF THE LAKE DEPOSITS

Previous reports on Lake Tecopa have alluded to finds of vertebrate fossils in the lake deposits (Bailey, 1902, p. 32; Noble, 1926, p. 70; Blackwelder, 1936), but most of the fossils seem to have escaped description and identification. One exception is a camel, *Camelops hesternus* (Leidy), that O. P. Hay (1927, p. 85) recorded; teeth and bones were found about 2 miles north of Tecopa.

During the present investigation, fragmentary vertebrate fossils were found at several localities, mainly near the lake margins. All these fossils occur in the upper part of the lake deposits. Fossils from the following localities were identified by G. E. Lewis:

Fossil locality 1

USGS fossil vertebrate catalog No. D 598; about $\frac{1}{4}$ mile south of Dublin Hills, SW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 14, T. 21 N., R. 6 E.

Equus sp., fragments of cheek tooth
Camelops sp., distal fragment of metapodial
Mammuthus sp., phalanx fragment

Fossil locality 2

USGS fossil vertebrate catalog No. D 598; Greenwater Valley, SW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 26, T. 21 N., R. 6 E.

Camelops sp., small fragments of cheek tooth and foot bones
Mammuthus sp., small fragments of laminae of cheek tooth

A tooth of an extinct muskrat was identified by C. A. Repenning from the following locality:

Fossil locality 3

USGS vertebrate locality M 1089; about $\frac{1}{2}$ mile southwest of Chappo Spring, NE $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 11, T. 21 N., R. 7 E.

Ondatra sp. cf. *O. kansasensis* Hibbard, right second lower molar

In addition to the vertebrate fossils, chara, diatoms, ostracodes, and snails were found in the upper part of the lake deposits. Ostracodes were identified by I. G. Sohn from the following localities:

Fossil locality 3

About $\frac{1}{2}$ mile southwest of Chappo Spring, NE $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 11, T. 21 N., R. 7 E.

Candona sp. 1
Candona sp. 2
Candoniella? sp.
Cyprideis? sp., smooth
Cypridopsis? sp.
Cyprois? sp.

Fossil locality 4

About $\frac{1}{2}$ mile east of Shoshone, SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 30, T. 22 N., R. 7 E.

Candona sp., different from that at locality 3
Cyprideis sp., differs from that at locality 3 in that adults are slightly shorter and the posterior of the female right valve is slightly smaller than the left in dorsal outline. Males do not have a node in the ventroposterior area.
Cypridopsis? sp., smaller than at locality 3
Darwinula sp.
Limnocythere sp.

A total of 42 species and varieties of diatoms were identified by K. E. Lohman from fossil locality 5. Relative abundance: R, rare; F, frequent; C, common; A, abundant.

Fossil locality 5

USGS diatom locality 5817; about 0.6 mile east-southeast of Shoshone, SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 30, T. 22 N., R. 7 E.

<i>Achnanthes coarctata</i> Brébisson	F
<i>Amphora ovalis</i> Kützing	R
<i>Anomoeneis costata</i> (Kützing) Hustedt	C
<i>sphaerophora</i> (Kützing) Pfitzer	F
<i>sphaerophora</i> var. <i>guntheri</i> Müller	F
<i>sphaerophora</i> var. <i>sculpta</i> (Ehrenberg) Müller	C
sp.	R
<i>Caloneis</i> sp.	R
<i>Campylodiscus</i> cf. <i>C. clypeus</i> Ehrenberg	C
<i>Cocconeis placentula</i> var. <i>euglypta</i> (Ehrenberg) Cleve	R
<i>Cymbella cymbiformis</i> (Kützing) Van Heurck	F
<i>cistula</i> (Hemprich) Grunow	F
<i>mexicana</i> (Ehrenberg) Cleve	F
<i>Denticula thermalis</i> Kützing	C
<i>Diploneis ovalis</i> (Hilse) Cleve	R
<i>Epithemia zebra</i> (Ehrenberg) Kützing	C
<i>zebra</i> var. <i>porcellus</i> (Kützing) Grunow	C
<i>Fragilaria brevistriata</i> Grunow	A
<i>construens</i> (Ehrenberg) Grunow	C

Fossil locality 5—Continued

USGS diatom locality 5817; about 0.6 mile east-southeast of Shoshone, SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 30, T. 22 N., R. 7 E.—Continued

<i>Gomphonema dubravicense</i> Pantocsek	F
<i>gracile</i> Ehrenberg	R
<i>intricatum</i> Kützing	F
<i>lanceolatum</i> var. <i>insignis</i> (Gregory) Cleve	F
<i>subclavatum</i> Grunow	R
sp. A	F
<i>Hantzschia</i> cf. <i>H. amphioxys</i> (Ehrenberg) Grunow	F
<i>Mastogloia elliptica</i> Agradh	F
<i>Navicula cuspidata</i> Kützing	F
<i>oblonga</i> Kützing	F
<i>peregrina</i> (Ehrenberg) Kützing	R
sp. A	F
<i>Neidium iridis</i> var. <i>vernalis</i> Reichelt	R
<i>Nitzschia amphibia</i> Grunow	F
<i>angulata</i> (Wm. Smith) Grunow	R
<i>tryblionella</i> Hantzsch	F
<i>Pinnularia microstauron</i> (Ehrenberg) Cleve	R
<i>streptoraphe</i> Cleve	R
<i>viridis</i> (Nitzsch) Ehrenberg	F
<i>Rhopalodia gibberula</i> (Ehrenberg) Müller	F
<i>gibberula</i> var. <i>baltica</i> Müller	F
<i>Surirella striatula</i> Turpin	F
<i>Synedra</i> cf. <i>S. ulna</i> (Nitzsch) Ehrenberg	F

Unfortunately none of these fossils is diagnostic for an accurate age determination. The horse, camel, and mammoth fossils are too fragmentary for positive specific identification. All probably are of middle or late Pleistocene age (G. E. Lewis, written commun., 1964). Although the fossil record of muskrats is not as complete as it is for many mammals, present knowledge indicates a middle Pleistocene age for the Lake Tecopa specimen (C. A. Repenning, written commun., 1965). Comparison of the Lake Tecopa diatom assemblage with assemblages from other Pleistocene lacustrine rocks of southern California and the fact that three Lake Tecopa species, *Gomphonema dubravicense*, *Gomphonema* sp. A, and *Navicula* sp. A, are extinct indicate a middle to late Pleistocene age (K. E. Lohman, written commun., 1965). All that can be said of the ostracodes is that they do not contradict a Pleistocene age (I. G. Sohn, written commun., 1965). The scanty fossil record, then, indicates that the upper part of the lake deposits is definitely Pleistocene and probably no older than middle Pleistocene.

STRUCTURAL FEATURES OF LAKE TECOPA

At most places the lake deposits are nearly horizontal and dip gently toward the central part of the basin. The structure contour map (fig. 5) shows that except for several small areas the contours are similar con-

centric and conform to the shape of the basin. Dips average 80–100 feet per mile along the marginal parts of the basin and 20–40 feet per mile in the central part of the basin. Dips of as much as 7° were measured on the flanks of small domes and basins in the northern part of the lake. Quaquaversal dips of several degrees are also common adjacent to islands. This relation is particularly well shown at the small island southeast of Dublin Hills in SW $\frac{1}{4}$ sec. 13, T. 21 N., R. 6 E.

The gentle basinward dips and the minor irregularities at the northern part of the basin probably were caused not by tectonic forces but by the effects of differential compaction superimposed on a slight depositional dip. Inasmuch as the sediments of Lake Tecopa are predominantly fine grained, they probably were capable of considerable compaction. Bradley (1964, p. A16–A17) calculated that differential compaction between the marginal and central parts of the Green River Basin may account for basinward dips of as much as 1°. The total amount of gravitational compaction probably is less above buried hills than above adjacent flats or topographic lows where the thickness of compactible sediments is greater. Possibly, then, the irregularities of the structure contours at the northern end of the basin can be explained by differential compaction over an irregular topography. Bradley (1964, p. A17) observed that in the Green River Basin, beds of the Green River Formation adjacent to flanks of buried hills dip 1°–8° more steeply than the general regional dip.

Throughout the lake-bed area there are sinks of various sizes, ranging from about 1 to 30 feet in diameter. Possibly the sinks formed by solution of water-soluble salts followed by collapse of an overlying competent bed such as an altered tuff. Perhaps some of the irregularities shown on the structure contour map at the northern part of the lake are due to solution rather than differential compaction.

Normal faults of slight displacement are common in the lake deposits at the southeastern part of the basin. Most of the faults dip southwest and generally have displacements of less than a foot. The maximum displacement observed was 5 feet. Some faults occur in areas where active slumping is common. Others, however, are not associated with slumped areas. The Trona sheet of the geologic map of California (California Div. Mines and Geology, 1963) shows a buried major fault along the western flank of the Resting Spring Range and suggests that the normal faults in the lake deposits are due to relatively recent movement along the buried fault.

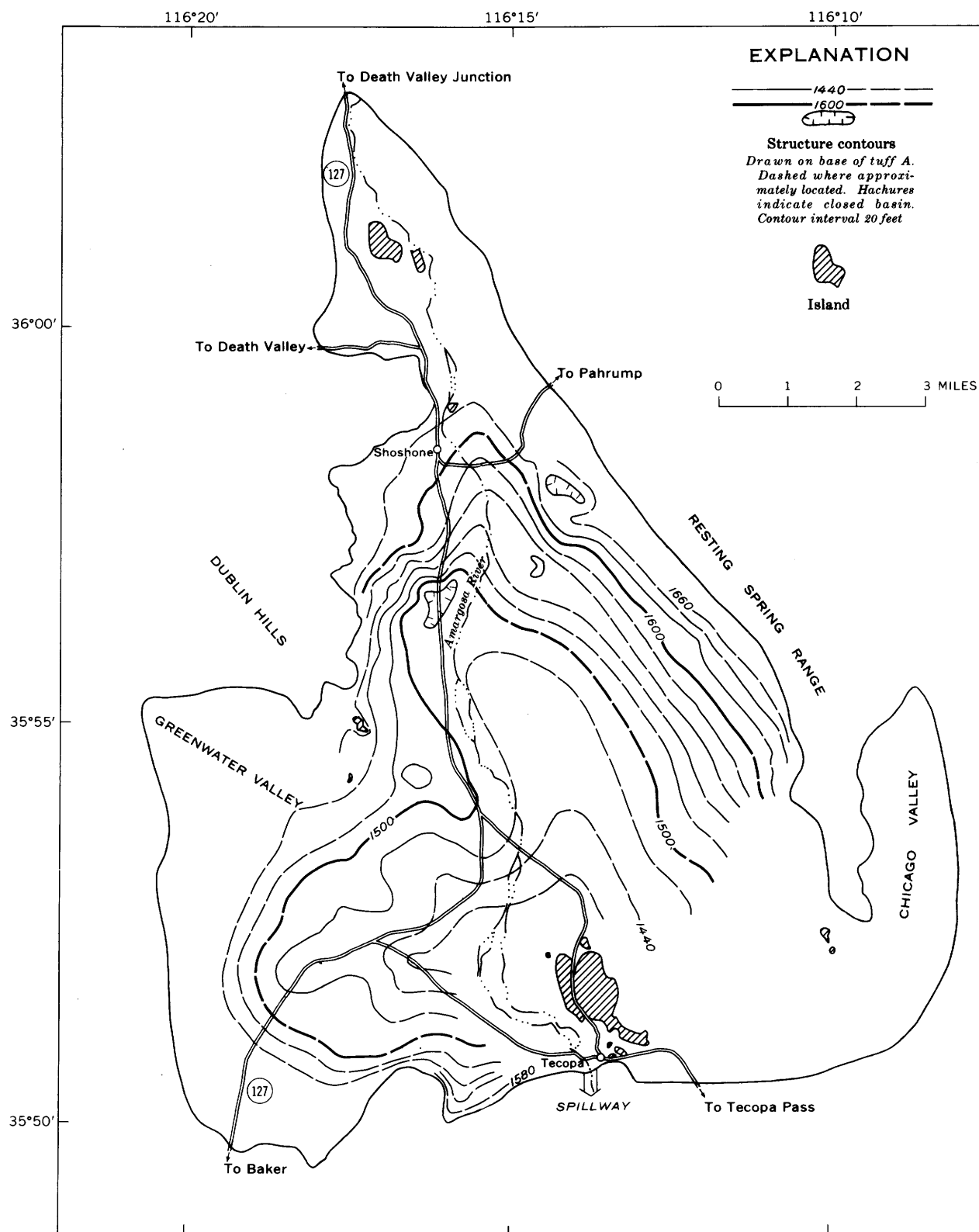


FIGURE 5.—Structure contour map of deposits of Lake Tecopa. No data for southeastern part of lake.

STRATIGRAPHY AND LITHOLOGY OF THE LAKE DEPOSITS

The stratigraphy of the deposits of Lake Tecopa (fig. 6) is known from several short measured sections that were pieced together by study of many other unmeasured sections. Correlation of outcrops between the measured sections was facilitated by tracing the distinctive tuffs. Because a vast volume of lake beds was eroded by the Amargosa River in the central part of the basin, only the lower beds crop out there. Nowhere, however, are the basal beds exposed. Only the upper beds crop out along the marginal parts of the basin where the uppermost beds locally grade laterally into and interfinger with coarse fluvialite rocks.

The dominant lithology of the deposits of Lake Tecopa is mudstone or a calcareous, silty, or sandy variant. These rocks grade marginward into siltstone and sandstone interbedded with conglomerate. Near the basin margin lacustrine rocks interfinger with the fluvialite rocks and commonly are difficult to differentiate. Calcareous rocks are common throughout the basin but are especially abundant and rich in calcite at the northern end of the lake, in the vicinity of Shoshone and northward. Evidently the calcium-bearing "fresh" waters of the ancestral Amargosa River precipitated their calcium as calcite upon coming in contact with the alkaline and saline lake water.

Several thin beds of dolomite are recognized in the Lake Tecopa deposits. The dolomite is white to light gray, very finely crystalline, and powdery. Commonly, the dolomite beds contain as much as 20 percent argillaceous impurities.

Tufa deposits are common near the margins of the lake, especially near Shoshone and along the western flank of the Resting Spring Range. The tufa is white to light tan, porous, and finely crystalline. Tufa is locally interbedded with the uppermost lake deposits, but elsewhere it cements younger alluvial fan material. Apparently the tufa was deposited by springs marginal to the lake. The springs evidently were active during the late stages of the lake and rather continuously for a period after the lake was drained. Inasmuch as some of the tufa deposits west of the Resting Spring Range are alined, the springs may have emerged along a fault bounding the range.

A well-developed soil occurs above tuff A in the abandoned "silica" quarry southwest of Shoshone. The soil is pale greenish yellow and 1.5-2.5 feet thick, and it grades into the underlying vitric tuff. Thin white veinlets of calcite are common throughout the soil but are especially abundant in the upper clayey part. This soil has not been recognized elsewhere in the lake deposits—perhaps because it is inconspicuous at natural expo-

sure, but more likely because it was formed locally near the lake margin.

The total exposed thickness of the lake deposits is about 220 feet. Even though erosion by the Amargosa River and its tributaries has produced a topographic

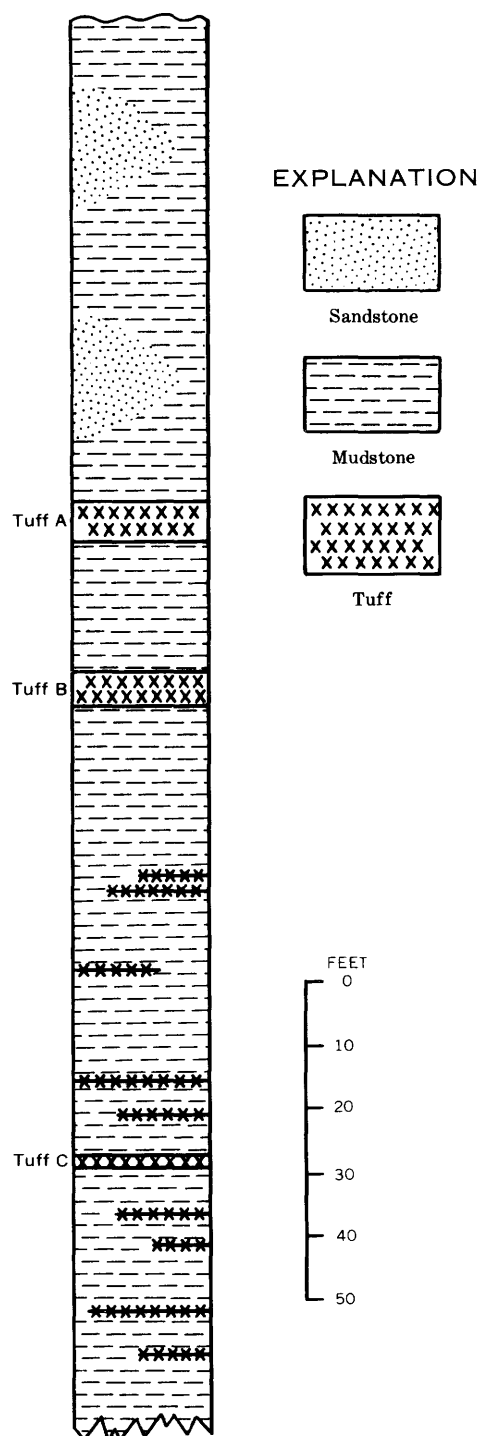


FIGURE 6.—Generalized stratigraphic section of the deposits of Lake Tecopa. Base of deposits is not exposed; top is eroded.

relief of about 500 feet in the lake deposits, the gentle basinward dip of the beds has reduced the thickness of the beds subjected to erosion. If the beds had been horizontal, the erosion would have exposed 500 feet of stratigraphic section. The total thickness of lake deposits in the basin cannot be estimated without subsurface data. Probably lacustrine rocks do not extend to the valley floor; alluvial fan deposits and valley-floor alluvium probably underline the lacustrine rocks.

CONGLOMERATE, SANDSTONE, AND SILTSTONE

Conglomerate, sandstone, and siltstone occur chiefly along the lake margin. These coarse clastic sediments interdigitate basinward with the predominant mudstone. Thin beds of siltstone, and rarely sandstone, occur locally in the central part of the basin.

Conglomerate generally is medium to thick bedded and poorly indurated except where locally cemented by calcite. Pebbles are angular to subrounded and generally less than 1 inch in diameter. The composition of the pebbles is variable from bed to bed and place to place, and reflects differences in the local source rocks. Some beds contain abundant limestone and dolomite pebbles.

Sandstone and siltstone is pale brown to greenish gray, thin to thick bedded, and generally poorly indurated. Cementation is local; the following cements occur, listed in approximate order of decreasing abundance: calcite, clay minerals, opal, and zeolite. Sedimentary structural features other than bedding are rare, but ripple marks and crossbedding are locally present.

The framework constituents of sandstone and siltstone consist of varying amounts of mineral grains and rock fragments. Sorting is poor and the clasts have an estimated roundness of 0.2–0.5. Matrix is less than 15 percent of the rock and is chiefly clay minerals. The detrital minerals are feldspar and quartz and lesser amounts of biotite, hornblende, clinopyroxene, muscovite, epidote, and zircon. Feldspar exceeds quartz, and plagioclase generally exceeds alkali feldspar. Rock fragments are chiefly volcanic, and there are lesser amounts of granitic rock, quartzite, chert, and low-grade metamorphic rocks. Sand and silt-sized shards or pseudomorphs of clinoptilolite or phillipsite are locally common. Following the classification of Pettijohn (1957, p. 291), these sandstones and siltstones are termed "arkose" or "subgraywacke," depending on whether feldspar or rock fragments predominate.

MUDSTONE

Mudstone is the predominant rock in the Lake Tecopa deposits. Mudstone has an earthy luster and is pastel shades of brown, gray, and green. Green mudstone is chiefly in the upper part of the exposed stratigraphic section and is volumetrically less than the brown or gray type. Most mudstones are even bedded and medium to thick bedded. Fresh mudstone breaks with a conchoidal or subconchoidal fracture, and the fractures commonly are filled or lined with gypsum or halite. Where weathered, the mudstone has a typical punky "popcorn" coating several inches thick.

Most mudstones contain, in addition to clay minerals, calcite, detrital silt and sand, and locally, soluble saline minerals or authigenic silicate minerals. The silt and sand fraction is rarely more than 25 percent of the rock but is commonly as much as 5 percent. Most of these relatively coarse grains are angular to subangular and include both mineral and rock fragments. Feldspar, quartz, biotite, and a variety of rock fragments compose most of this fraction. Actually, the mineralogic composition of the silt and sand fraction in the mudstones is similar to that of the siltstones and sandstones of Lake Tecopa. Vitroclastic textures are rare in the mudstones; however, pseudomorphs of potassium feldspar and zeolite after shards were recognized in three samples.

The mineral content of the finer than 2μ fraction for four mudstones is given in table 1. Standard X-ray techniques were used to determine the clay mineralogy. After disaggregation in water and complete removal of soluble salts, the finer than 2μ fraction was sedimented on tiles and oriented by suction. X-ray data was then obtained from untreated glycolated and heated (400°C and 550°C) samples. Montmorillonite and illite are consistently abundant and mixed-layer illite-montmorillonite, chlorite, and vermiculite (?) are in minor or trace amounts locally; kaolinite was not recognized.

TABLE 1.—*Mineral content of the finer than 2μ fraction of mudstones from Lake Tecopa*

[Analyst: Paul D. Blackmon. A, major; B, minor; T, trace; —, looked for but not found]

Mineral	Sample			
	1	2	3	4
Montmorillonite	A	A	A	A
Sepiolite	A	A	—	—
Illite (dioctahedral mica)	A	B	A	A
Mixed-layer illite-montmorillonite	—	—	B	—
Vermiculite(?)	T	—	—	—
Chlorite	—	—	T	T
Calcite	B	T	T	T
Dolomite	—	—	B	B
Erionite(?)	—	T	—	—
Quartz	T	T	—	—
Feldspar	B	B	B	A

The significance of sepiolite in two samples (1 and 2) is not fully understood. Sepiolite was not found by Droste (1961) or Kerr and Langer (1965) in their studies of the clay mineralogy of playas in the Mojave Desert and vicinity. Sepiolite is known to occur, however, in other saline lake deposits (Bradley, 1930; Milot, 1962; Regis, 1961). Except for sepiolite, the clay mineral suite of the mudstones is probably detrital. Sepiolite is presumably authigenic; however, additional sampling is necessary to show its distribution and relation to the other clay minerals.

Feldspar in the finer than 2μ fraction of the mudstones is chiefly monoclinic potassium feldspar. The small crystal size suggests an authigenic origin; furthermore, authigenic potassium feldspar was recognized as shard pseudomorphs in some mudstones. X-ray diffraction data of bulk samples of mudstones indicate that as much as 30 percent of some mudstones is potassium feldspar. Mudstones richest in feldspar generally have some evidence of vitroclastic texture, although vitroclastic texture is apparently absent in other mudstones containing as much as 20 percent feldspar. Rhyolitic vitric glass or an early diagenetic potassium-rich zeolite is a logical source of potassium for the feldspar. Authigenic potassium feldspar forms as much as 20 percent of non-tuffaceous clays in Searles Lake. Hay and Moiola (1963, p. 329) suggested that enough potassium could have been derived from the original clay minerals and pore fluid of the sediment in Searles Lake to account for about 20 percent authigenic potassium feldspar.

TUFF

Tuffs in the Lake Tecopa deposits make up about 8–12 percent of the exposed stratigraphic section and are the most conspicuous and continuous strata. The tuffs are mainly the result of ash falls directly into the lake. Twelve tuffs are recognized, and they range in thickness from 2 inches to 13 feet. Generally the thicker tuffs are more continuous than the thinner ones. Thin tuffs generally are single beds, but tuffs more than several inches thick commonly consist of multiple beds. The individual strata of multiple-bedded tuffs are 1/16–30 inches thick but generally are 4–12 inches thick.

Fresh tuff (fig. 7) is white to light gray and has a characteristic vitreous luster. It is very friable and easily disaggregated with the fingers. Natural exposures are poor; therefore, thin fresh tuffs could easily be overlooked. Where cemented by calcite the tuff is resistant and commonly forms a ledge. The lower contact of a tuff generally is sharp, whereas the upper contact commonly is gradational into the overlying rock, regardless of lithology. Most tuffs are even bedded, but beds of some thick multiple-bedded tuffs channel into lower

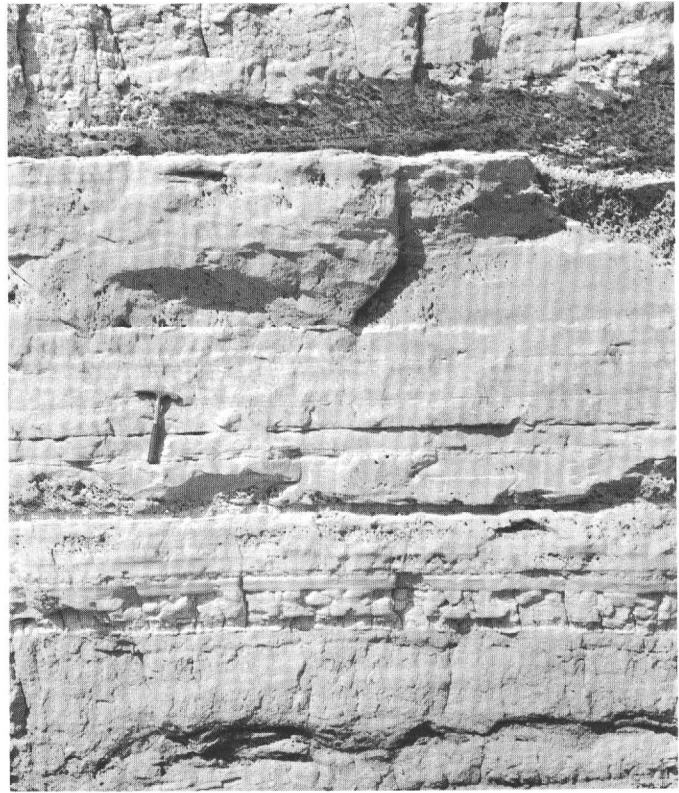


FIGURE 7.—Tuff A at abandoned pumicite workings about 0.3 mile southwest of Shoshone. Tuff is friable and multiple bedded and consists of fresh glass. Note the abundant borings by wasps in the soft tuff. Calcareous siltstone underlies tuff.

beds as much as several inches. Ripple marks or ripple laminations are present but not common. Individual beds of either single-bedded or multiple-bedded tuffs are commonly graded, being coarser at the base. Some tuffs show contorted laminations that were formed after deposition by internal flowage.

The tuffs are vitric but contain varying amounts of crystal and rock fragments. Most are very fine to fine grained, although some are medium grained. The vitric particles are of two types: (1) platy bubble-wall shards formed from the walls of relatively large broken bubbles (fig. 8A), and (2) pumice shards that contain small elongated bubbles (fig. 8B). Most tuffs are composed of both types; however, one type generally is greatly predominant. The shard type and other characteristics for the three consistently thick tuffs in the deposits of Lake Tecopa are given in table 2. The index of refraction of unaltered shards ranges from 1.494 to 1.498.

The crystal and rock fragments in the tuffs are generally angular and range from less than 1 to 25 percent of the rock. These fragments more commonly compose less than 1–5 percent of the rock (table 2). The crystals are chiefly plagioclase (An_{18-30}), sanidine, quartz,

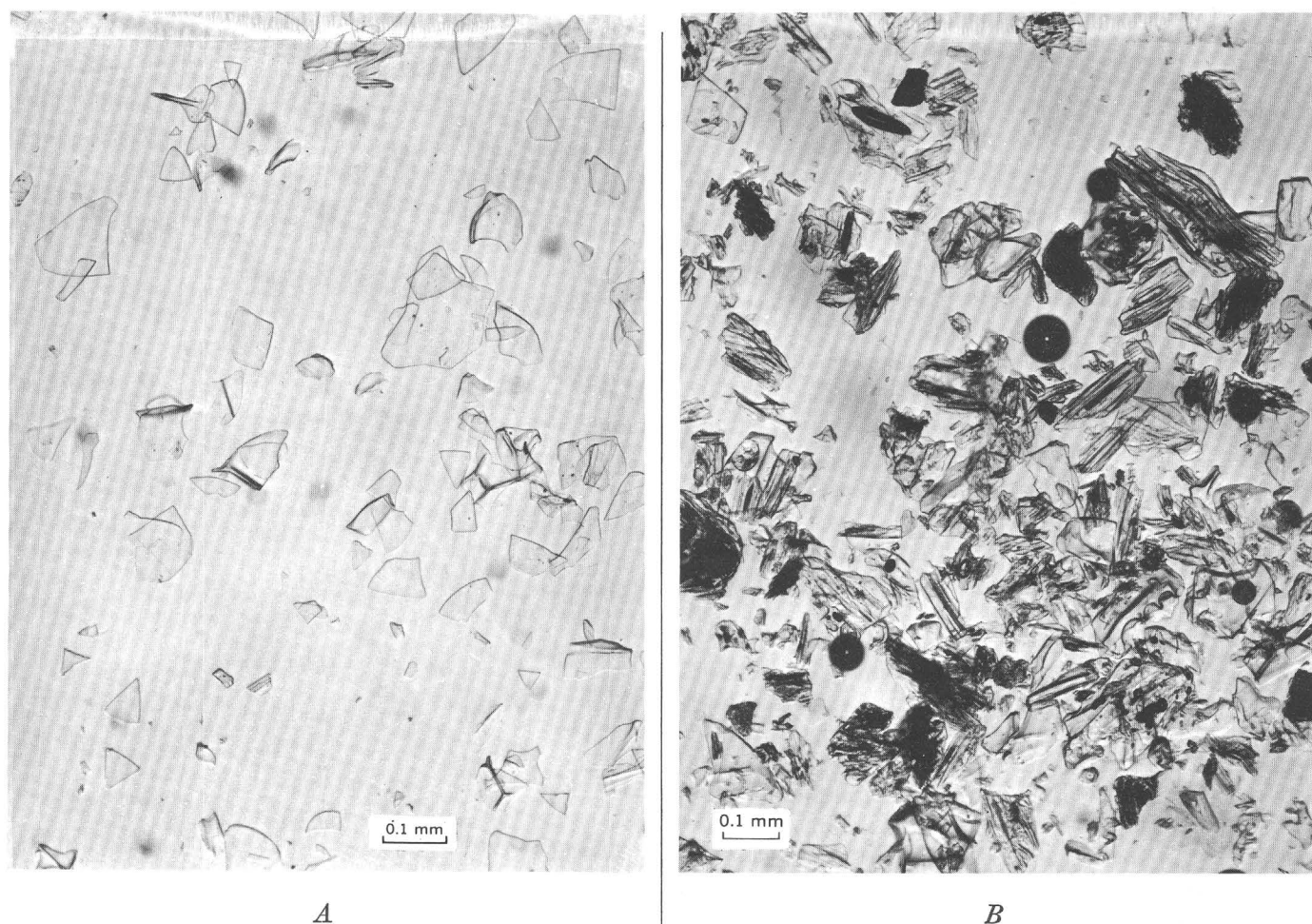


FIGURE 8.—Shard types in tuffs of Lake Tecopa. *A*, platy bubble-wall shards formed from the walls of relatively large broken bubbles. *B*, pumice shards that contain small elongated bubbles. Dark circles with light interiors are bubbles in mounting medium.

TABLE 2.—Characteristics of three consistently thick tuffs in the Lake Tecopa deposits

Characteristic	Tuff A	Tuff B	Tuff C
Range in thickness...feet...	2-13	1-11	1-2.5
Common thickness...feet...	4-8	3-6	2
Multiple bedding.....	Yes	Yes	Generally no
Range in percentage of crystal and rock fragments.	<1-3	1-25	1-5
Common percentage of crystal and rock fragments.	<1	1-10	1-3
Predominant shard type...	Platy bubble-wall.	Pumice	Platy bubble-wall.
Index of refraction of shards.	1.497-1.498	1.495	—
Presence of chevkinite....	Yes	No	No

and biotite and minor amounts of any or all the following: hornblende, clinopyroxene, zircon, apatite, and

chevkinite. All can locally be found with glass attached and are therefore considered pyrogenic.

Spherulitic and hyalopilitic lava are the most common recognizable rock fragments in the tuffs. These fragments presumably were derived from the vent area from which the vitric ash erupted. Other grains such as granite, polycrystalline quartz, epidote, and microcline probably are of local derivation. Some transport other than by air is indicated inasmuch as most show some rounding. Perhaps some were carried to the lake by influent streams. Others could have blown into the lake after rounding during stream transport or by wave action along the lakeshores.

Chemical analyses of unaltered shards from two tuffs indicate a rhyolitic composition (tables 3, 4). Before analysis, the shards were separated from the other constituents of the tuffs by disaggregation followed by flotation in a heavy liquid mixture of bromoform and

acetone. Although no other tuffs in the Lake Tecopa deposits have been analyzed, all are presumed to be rhyolitic because of the low index of refraction (1.494–1.498) of shards and the associated phenocrystic minerals as described above. Analyses 1 and 2 (table 3) are of shards from tuff A; analysis 3 is of shards from tuff B. The shards are very similar in composition, and all are hydrated. Total water ranges from 4.07 to 4.73 weight percent. The $K_2O:Na_2O$ ratio ranges from 1.65 to 1.80. Inasmuch as the shards are hydrated, this ratio probably has been increased over the original ratio by leaching of Na_2O in the postdepositional environment (Lipman, 1965, p. D22; Truesdell, 1966, p. 119–121).

TABLE 3.—Chemical analyses of unaltered shards from tuffs of Lake Tecopa deposits

[Analyst: Christel L. Parker]

	1	2		3
		a	b	
SiO ₂ -----	72.78	70.96	72.17	71.83
Al ₂ O ₃ -----	11.89	11.43	11.63	11.88
Fe ₂ O ₃ -----	.55	.68	.69	.56
FeO-----	.99	.92	.94	.38
MgO-----	.22	.87	.88	.55
CaO-----	.55	1.31	.49	.47
Na ₂ O-----	3.03	3.10	3.15	2.94
K ₂ O-----	5.31	5.12	5.21	5.30
H ₂ O+-----	3.86	3.87	3.94	4.28
H ₂ O-----	.21	.38	.39	.45
TiO ₂ -----	.12	.13	.13	.09
P ₂ O ₅ -----	.01	.01	.01	.01
MnO-----	.04	.04	.04	.04
CO ₂ -----	.01	.65	—	.01
Cl-----	.12	.12	.12	.07
F-----	.15	.21	.21	.09
Subtotal-----	99.84	99.80	100.00	98.95
Less O-----	.09	.12	.12	.06
Total-----	99.75	99.68	99.88	98.89

1. Tuff A, laboratory No. D100749. Locality 1 (fig. 4), NW $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 31, T. 22 N., R. 7 E.
2. Tuff A, laboratory No. D100751. Locality 82 (fig. 4), NE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 11, T. 21 N., R. 7 E. a. Uncorrected analysis. b. Analysis corrected for CO₂ and equivalent CaO to make calcite.
3. Tuff B, laboratory No. D101150. Locality 67 (fig. 4), SE $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 29, T. 22 N., R. 7 E.

AUTHIGENIC MINERALS

ANALCIME

Analcime, commonly referred to as analcite, is one of the more abundant zeolites in sedimentary rocks. Since its early recognition in the Green River Formation (Bradley, 1928) and in lacustrine tuffs near Wikieup, Ariz. (Ross, 1928), analcime has been reported in rocks of diverse ages, lithologies, and sedimentary environments (Deer and others, 1963, p. 346–347). Analcime has an ideal formula of $NaAlSi_2O_6 \cdot H_2O$, but the anal-

TABLE 4.—Semiquantitative spectrographic analyses of unaltered shards from tuffs¹ of Lake Tecopa deposits

Results are reported in percent to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, etc.; which represent approximate midpoints of group data on a geometric scale. The assigned group for semiquantitative results will include the quantitative value about 30 percent of the time. Symbols used: 0, looked for but not detected. <, with number means less than number shown—here usual detectabilities do not apply; +, presence of lithium obtained by the 6-step spectrographic method cannot be evaluated until present techniques are modified. The following elements were looked for but not found: Ag, As, Au, Bi, Cd, Co, Ge, Hf, Hg, In, Ni, Pd, Pt, Re, Sb, Sc, Ta, Te, Th, Tl, U.

[Analyst: Harriet Neiman]

	1	2	3
B-----	0	0.003	0.006
Ba-----	.015	.015	.005
Be-----	.0005	.0005	.0003
Ce-----	.01	.01	0
Cr-----	<.0001	.0015	.0003
Cu-----	.0007	.0015	.0015
Ga-----	.002	.002	.002
La-----	.01	.01	0
Li-----	0	+	0
Mo-----	.005	.0015	.0007
Nb-----	.003	.003	.0015
Pb-----	.002	.0015	.003
Sn-----	.005	.002	0
Sr-----	.003	.01	.003
V-----	0	.002	0
Y-----	.007	.007	.0015
Yb-----	.0007	.0007	.00015
Zr-----	.015	.02	.005

¹ Samples are same as those in table 3.

cime of sedimentary rocks is generally more siliceous (table 5). Coombs and Whetten (1967) recently studied the composition of analcimes from sedimentary and low-grade metamorphic rocks by utilizing cell size as an indicator of composition (Saha, 1959, p. 304), and they determined a range in Si:Al ratio from 2.0 to about 2.7. Analcimes in altered rhyolitic tuffs of saline lake deposits commonly have a Si:Al ratio in the higher part of this range.

Analcime is a rare zeolite in the Lake Tecopa deposits. Generally it makes up 10 percent or less of the altered tuffs, although as much as 20 percent has been found in one sample. Analcime commonly is associated with one or more of the following authigenic silicates: clay minerals, potassium feldspar, and searlesite (table 6).

TABLE 5.—Formulas of selected alkalic zeolites

[Formulas are standardized in terms of a sodium end member that has one aluminum atom. All formulas are taken from Hay (1966a, p. 7); however, formulas for chabazite and erionite are modified by unpublished data]

Name	Dominant cations	Formula
Analcime-----	Na	$NaAlSi_2O_6 \cdot 0.2-0.8H_2O$
Chabazite-----	Na, Ca	$Na_4Al_3Si_3O_{14} \cdot 0.4-0.6H_2O$
Clinoptilolite----	Na, K, Ca	$Na_4Al_3Si_3O_{14} \cdot 0.4-0.6H_2O$
Erionite-----	Na, K, Ca	$Na_4Al_3Si_3O_{14} \cdot 0.4-0.6H_2O$
Phillipsite-----	Na, K, Ca	$Na_4Al_3Si_3O_{14} \cdot 0.4-0.6H_2O$

TABLE 6.—*Checklist of associated authigenic silicate minerals in tuffs of Lake Tecopa*

[X, mineral pair associated; O, mineral pair not associated]

	Analcime	Chabazite	Clay minerals	Clinoptilolite	Erionite	Opal	Phillipsite	Potassium feldspar	Searlesite
Analcime.....	—	O	X	X	O	X	X	X	X
Chabazite.....	O	—	X	X	X	O	X	O	O
Clay minerals.....	X	X	—	X	X	X	X	X	X
Clinoptilolite.....	X	X	X	—	X	X	X	X	X
Erionite.....	O	X	X	X	—	X	X	X	O
Opal.....	X	O	X	X	X	—	X	X	X
Phillipsite.....	X	X	X	X	X	X	—	X	X
Potassium feldspar.....	X	O	X	X	X	X	X	—	X
Searlesite.....	X	O	X	X	O	X	X	X	—

Analcime has not been recognized in thin sections of the tuffs from Lake Tecopa probably because of its very small crystal size. Identification is based solely on X-ray diffractometer powder data (fig. 2) of bulk samples. Study of various size fractions of two analcime-bearing tuffs indicates that most of the analcime is in the less than 2μ fraction.

CHABAZITE

Chabazite is not a commonly reported zeolite in diagenetically altered tuffs. Chabazite was recently described from altered tuffs in lacustrine deposits near Bowie, Ariz. (Sand and Regis, 1966), and Barstow, Calif. (Gude and Sheppard, 1966). In physical properties and chemistry, these chabazites differ from the common chabazite that occurs in cavities and fractures of basic igneous rocks. Chabazite has an ideal formula of $\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$, but natural chabazites show considerable variation in cation content and Si:Al ratio (table 5). The meager available data indicate that chabazite from altered rhyolitic vitric tuffs contains more alkalis and silica than chabazite from nonsedimentary environments.

Chabazite is one of the less abundant zeolites in the Lake Tecopa deposits. Generally it occurs in trace amounts and only rarely makes up as much as 10 percent of the tuff. The chabazite commonly is associated with two or more of the following authigenic silicates: clinoptilolite, erionite, phillipsite, and clay minerals.

Chabazite has not been identified in thin section because of either its fine crystallinity or its poorly formed crystals. Identification is based solely on X-ray diffractometer powder data of bulk samples. Table 7 gives the d spacings and corresponding intensities for those chabazite peaks that could be culled from diffractometer patterns of bulk samples consisting of several authigenic minerals. The d values are lower than those generally reported for nonsedimentary chabazites but are very similar to those of an alkali- and silica-rich chabazite from an altered rhyolitic vitric tuff in the Barstow Formation (Gude and Sheppard, 1966).

TABLE 7.—*X-ray powder data for chabazite from tuff B*

[Diffractometer: copper radiation, nickel filter. Intensity: s, strong; m, moderate; w, weak]

d spacing	Intensity
9.3.....	m
6.83.....	m
5.52.....	w
4.97.....	w
4.26.....	s
3.55.....	m
2.88.....	w

CLAY MINERALS

Most of the altered tuffs of Lake Tecopa contain authigenic clay minerals, and some consist predominantly of clay minerals. Thin-section study is useful for determining the paragenetic relations of the clay minerals to the other authigenic silicate minerals, but other methods are necessary for positive identification of the clay minerals. The clay mineralogy of the less than 2μ fraction for eight samples was determined by P. D. Blackmon using the standard X-ray techniques described previously. Montmorillonite and illite are in all samples, commonly with trace amounts of one or more of the following: vermiculite, sepiolite, and mixed-layer illite-montmorillonite. Montmorillonite is dominant in some samples and illite is dominant in others. Montmorillonite is generally the dominant clay mineral reported in altered tuffs; however, the other clay minerals listed above are known from tuffs subjected only to diagenesis (Schultz, 1963).

CLINOPTILOLITE

Clinoptilolite is a member of the heulandite structural group. Although there is still disagreement on the distinction between these closely related zeolites, most workers agree that clinoptilolite is the silica-rich (Hey and Bannister, 1934; Mumpton, 1960) and alkali-rich (Mason and Sand, 1960) member (table 5). Indices of refraction (Mason and Sand, 1960, p. 350) and response to thermal treatment (Mumpton, 1960, p. 359–61; Shepard and Starkey, 1964) have also been used to distinguish clinoptilolite from heulandite.

Clinoptilolite in the altered tuffs of Lake Tecopa generally is associated with one or more of the following authigenic silicates: chabazite, erionite, phillipsite, clay minerals, opal, potassium feldspar, and searlesite. Only rarely is clinoptilolite found in monomineralic beds. Clinoptilolite occurs as laths or plates that range from 0.006 to 0.03mm in length. Most are about 0.01 mm long.

Indices of refraction for clinoptilolite are fairly constant and within the range suggested by Mason and Sand (1960, p. 350) for distinguishing clinoptilolite

from heulandite. The mean index ranges from 1.477 to 1.480 and the birefringence is low, about 0.003. All clinoptilolites examined have parallel or nearly parallel extinction and are length slow.

An analysis of clinoptilolite from Lake Tecopa is given in table 8. The clinoptilolite was separated from a nearly monomineralic part of tuff A by disaggregation followed by flotation in a heavy liquid mixture of bromoform and acetone. The analysis was recalculated into atoms per unit cell, on the basis of 72 oxygen atoms, and

TABLE 8.—*Chemical analyses of zeolites from tuff A of Lake Tecopa*

[a, uncorrected analysis; b, analysis corrected for CO₂ and equivalent CaO to make calcite. Analyst of clinoptilolite, erionite, and phillipsite 1: Ellen S. Daniels. Analyst of phillipsite 2: Elaine L. Munson]

	Clinoptilolite		Erionite		Phillipsite 1	Phillipsite 2
	a	b	a	b	a	a
SiO ₂ -----	60.13	65.10	59.37	60.67	57.48	56.84
Al ₂ O ₃ -----	10.21	11.06	12.62	12.90	14.29	14.82
Fe ₂ O ₃ -----	1.37	1.48	1.32	1.35	.78	.52
FeO-----	.07	.08	.09	.09	.00	.00
MgO-----	.99	1.07	1.07	1.09	.22	.10
CaO-----	4.28	.22	1.53	.65	.01	.00
Na ₂ O-----	4.75	5.14	4.30	4.39	4.51	5.42
K ₂ O-----	2.71	2.94	4.00	4.09	6.55	5.81
H ₂ O ⁺ -----	6.65	7.20	7.52	7.69	8.67	8.92
H ₂ O ⁻ -----	5.11	5.53	6.79	6.94	7.00	7.01
TiO ₂ -----	.11	.12	.09	.09	.10	.13
P ₂ O ₅ -----	.03	.03	.02	.02	.00	.01
MnO-----	.03	.03	.03	.03	.00	.01
CO ₂ -----	3.20	—	.70	—	—	—
Total-----	99.64	100.00	99.45	100.00	99.61	99.59
Molecular SiO ₂ :Al ₂ O ₃ -----		10.00		7.98	6.82	6.51
Molecular K ₂ O:Na ₂ O-----		.38		.61	.95	.71

Clinoptilolite, laboratory No. D100796. Locality 60 (fig. 4), NW¼NW¼ sec. 17, T. 20 N., R. 7 E.

Erionite, laboratory No. D100797. Locality 61 (fig. 4), NE¼NW¼ sec. 17, T. 20 N., R. 7 E.

Phillipsite 1, laboratory No. D100552. Locality 8 (fig. 4), NE¼SW¼ sec. 6, T. 21 N., R. 7 E.

Phillipsite 2, laboratory No. D101552. Locality 49 (fig. 4), NW¼SW¼ sec. 2, T. 20 N., R. 6 E.

is given in table 9. Monovalent cations exceed divalent ones and the Si:Al+Fe³⁺ ratio is 4.60. Sodium is in excess of potassium, as is generally true for clinoptilolite; however, potassium-rich clinoptilolites have been reported from other areas (Minato, 1964; Sheppard and others, 1965, p. 247).

ERIONITE

Erionite was considered an extremely rare mineral prior to the work of Deffeyes (1959a, b) and Regnier (1960, p. 1207), who showed it to be a common alteration product of rhyolitic vitric tuffs in north-central Nevada. Since then, erionite has been recognized in altered tuffs from many of our Western States.

The Lake Tecopa erionite occurs as monomineralic beds or in association with one or more of the following authigenic silicates: clinoptilolite, chabazite, phillipsite, clay minerals, potassium feldspar, searlesite, and rarely, opal. Unlike the woolly-appearing erionite from the type locality at Durkee, Oreg. (Eakle, 1898), the Lake

TABLE 9.—*Composition of unit cell of zeolites from tuff A of Lake Tecopa*

[Fe²⁺, Ti, P, and Mn were omitted in calculation of the unit cell]

	Atoms per unit cell			
	Clinoptilolite	Erionite	Phillipsite 1	Phillipsite 2
Si-----	29.27	28.19	12.26	12.16
Al-----	5.86	7.06	3.59	3.74
Fe ³⁺ -----	.50	.47	.13	.08
Mg-----	.72	.75	.07	.03
Ca-----	.11	.32	.00	.00
Na-----	4.48	3.95	1.87	2.25
K-----	1.68	2.42	1.78	1.59
H ₂ O ⁺ -----	10.80	11.90	6.17	6.36
H ₂ O ⁻ -----	8.29	10.76	4.98	5.00
O-----	72.00	72.00	32.00	32.00
Si+Al+Fe ³⁺ -----	35.63	35.72	15.98	15.98
Si:Al+Fe ³⁺ -----	4.60	3.74	3.30	3.18

Tecopa erionite has a prismatic or acicular habit (fig. 9). Erionite generally forms a network of unoriented crystals, although aggregates of radiating crystals are locally common. The erionite rarely pseudomorphs shards; hence, relict vitroclastic texture commonly is



FIGURE 9.—Photomicrograph of zeolitic tuff A showing network of prismatic erionite. Unpolarized light.

absent in tuffs consisting mainly of this zeolite. Individual crystals range from 0.01 to 0.12 mm in length, but most are 0.03–0.04 mm long.

Indices of refraction of Lake Tecopa erionite are: $n_o = 1.455$ – 1.461 and $n_e = 1.459$ – 1.465 . These indices are lower than generally reported (Deer and others, 1963, p. 398) and may be due to the relatively high silica content of the erionite. Birefringence is about 0.004, higher than that of the other Lake Tecopa zeolites. Erionite has parallel extinction and is length slow.

A chemical analysis of Lake Tecopa erionite is given in table 8. The erionite was separated from a nearly monomineralic part of tuff A by disaggregation followed by flotation in a heavy liquid mixture of bromoform and acetone. The analysis was recalculated into atoms per unit cell, on the basis of 72 oxygen atoms, and is given in table 9. Monovalent cations exceed divalent ones and sodium exceeds potassium. Erionite from sedimentary deposits generally contains more sodium than potassium; however, a notable exception was reported by Eberly (1964, p. 33) for an erionite from

Rome, Oreg. The Si: Al + Fe⁺³ ratio for the Lake Tecopa erionite is 3.74, which is slightly higher than generally reported (table 5) and intermediate between the analyzed clinoptilolite and phillipsite.

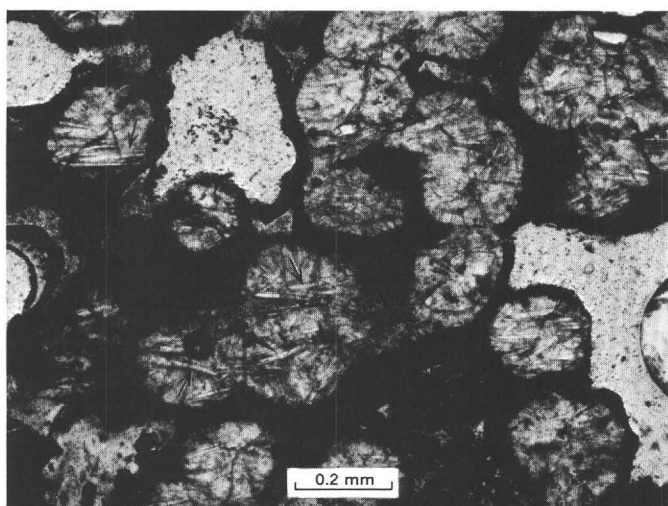
OPAL

Opal is difficult to recognize in altered tuffs because of its isotropic and nondescript character. Opal is colorless to pale brown in thin section and has an index of refraction between 1.420 and 1.426. Most identifications of opal in the tuffs at Lake Tecopa are based on X-ray diffractometer powder data of bulk samples. Opal has characteristically broad peaks at the following d spacings: 4.24 Å, 4.10 Å, 3.32 Å, 2.98 Å, and 2.50 Å. Opal is commonly associated with potassium feldspar and clay minerals, less commonly associated with clinoptilolite, and only rarely associated with erionite and phillipsite. Segregations containing as much as 80 percent opal are locally common.

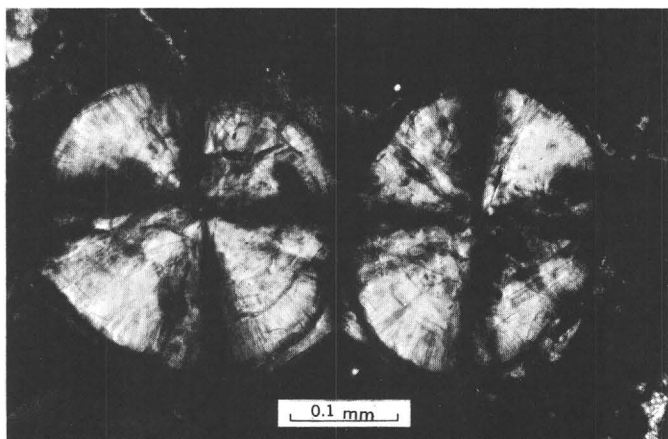
PHILLIPSITE

Phillipsite is the most abundant zeolite in the tuffs of Lake Tecopa and occurs in monomineralic beds or in association with one or more of the following authigenic silicates: clinoptilolite, chabazite, erionite, clay minerals, opal, potassium feldspar, or searlesite. The crystal habit and size are variable. The habit is generally spherulitic or some variant of prismatic. Spherulites range in diameter from 0.05 to 0.5 mm, although most are 0.1–0.2 mm (fig. 10). Clusters of several mutually interfering spherulites are common. Where tuff A is altered to zeolites, the lower 1/8–4 inches is characteristically spherulitic phillipsite. The prismatic variety is of two types: (1) stubby crystals with a length-to-width ratio of 1.5–2 (fig. 11) and (2) elongated crystals with a length-to-width ratio of 4–8. Crystals of both prismatic types range from 0.002 to 0.08 mm in length, but most are about 0.02 mm long. Vitroclastic textures are generally better preserved by the elongated crystals than by the stubby ones.

Indices of refraction for phillipsite vary considerably, more so than for any other zeolite in the Lake Tecopa deposits. The mean index ranges from 1.458 to 1.480 and the birefringence is very low, about 0.002. Most of the phillipsite crystals have a mean index of refraction between 1.460 and 1.472. Although there is some overlap, stubby crystals commonly have a mean index in the low part of this range, whereas elongated crystals have a mean index in the high part of the range. Both spherulites and individual crystals commonly are zoned; the marginal parts, whether of spherulites or of individual crystals, invariably have a higher index. A



A



B

FIGURE 10.—Photomicrographs of spherulitic phillipsite. *A*, light circular areas are spherulites of phillipsite. Relict platy shards (arrows), outlined by a clay mineral, show similar orientation from spherulite to spherulite. Unpolarized light. *B*, radially oriented fibers of phillipsite in spherulites show extinction cross under crossed nicols. Clay mineral film surrounds spherulites.

difference in index of as much as 0.018 between interior and margin has been measured. All phillipsite crystals examined have parallel or nearly parallel extinction and are length slow.

These indices of refraction for the Lake Tecopa phillipsite are similar to those of phillipsite from other saline lakes (Hay, 1964, p. 1374), but are much lower than those of phillipsite from other environments. Deer, Howie, and Zussman (1963, p. 386) reported a range of 1.483–1.514 for presumably nonsedimentary phillipsite. Even phillipsite in sediments of the deep-sea floor generally has a mean index of about 1.484 (Hay, 1964, p.

1376). The high silica content of the Lake Tecopa phillipsite as contrasted to that of phillipsites having different origins probably accounts for the relatively low indices of refraction.

Two chemical analyses of phillipsite from Lake Tecopa are given in table 8. The phillipsite was separated from nearly monomineralic parts of tuff A by disaggregation followed by flotation in a heavy liquid mixture of bromoform and acetone. The analyses were recalculated into atoms per unit cell, on the basis of 32

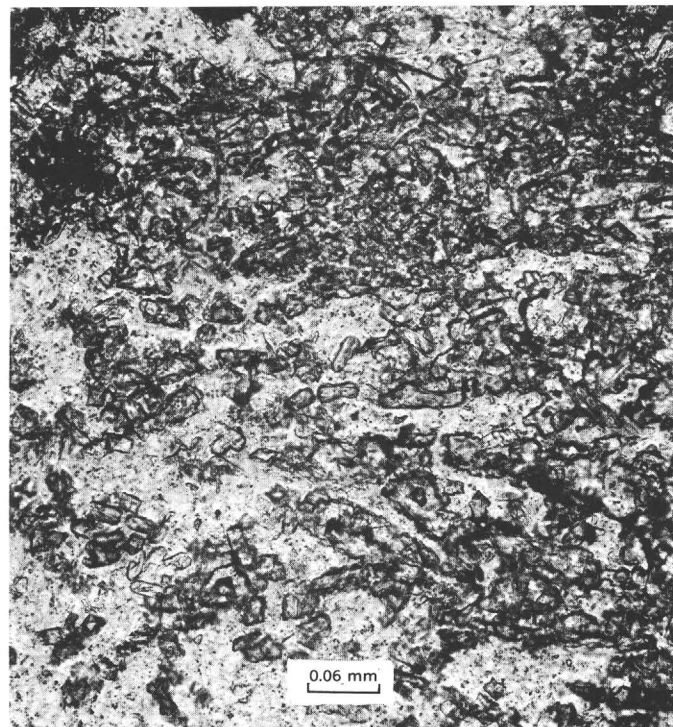


FIGURE 11.—Photomicrograph of stubby, prismatic crystals of phillipsite. Unpolarized light.

oxygen atoms, and are given in table 9. Monovalent cations greatly exceed divalent ones; calcium, in particular, is negligible or absent. The sodium content exceeds the potassium content for both samples of phillipsite from Lake Tecopa, although the sodium content of phillipsite 1 is only slightly in excess. The Si:Al+Fe⁺³ ratios (3.18 and 3.30) are much higher than the range of 1.3–2.2 indicated by Deer, Howie, and Zussman (1963, p. 393) for phillipsite (table 5).

The high potassium plus sodium and silica contents of the Lake Tecopa phillipsite set it apart from phillipsites of other origins. However, the analyses of this phillipsite are very similar to analyses of phillipsite from altered rhyolitic tuffs that occur in saline lake deposits elsewhere in southern California (Hay, 1964, p. 1375) and southeastern Oregon (Regis and Sand,

1966). The relatively high alkali and silica contents of these philipsites are due, at least in part, to the rhyolitic composition of the parent material.

POTASSIUM FELDSPAR

Potassium feldspar occurs as an authigenic mineral in sedimentary rocks that are diverse in lithology, depositional environment, and age (Hay, 1966a). The authigenic potassium feldspar is a pure or nearly pure potassium variety and occurs as authigenic crystals, overgrowths on detrital and pyrogenic feldspar, and replacements of detrital and pyrogenic plagioclase. In tuffs of the Lake Tecopa deposits, authigenic potassium feldspar occurs mainly as authigenic crystals and only very rarely as marginal replacements of detrital or pyrogenic plagioclase. The feldspar occurs in monomineralic beds or with one or more of the following authigenic silicates: analcime, clinoptilolite, erionite, phillipsite, clay minerals, opal, and searlesite.

The potassium feldspar in the altered tuffs forms rather nondescript low-birefringent aggregates of irregular crystals that range from less than 0.002 to 0.010 mm. The aggregates superficially resemble chert; however, they are identical to authigenic potassium feldspar from sediments of Searles Lake (Hay and Moiola, 1963, p. 323) and altered tuffs in the Barstow Formation of southern California (Sheppard and Gude, 1965, p. 3-4). The 1.518 mean index of refraction suggests nearly pure potassium feldspar. Other optical constants could not be measured from the very small crystals. The feldspar is interpreted to be monoclinic inasmuch as X-ray diffraction patterns show only the (131) peak rather than the pair, (131) and $(\bar{1}\bar{3}1)$, the criterion suggested by Goldsmith and Laves (1954, p. 3) for distinguishing monoclinic from triclinic potassium feldspar.

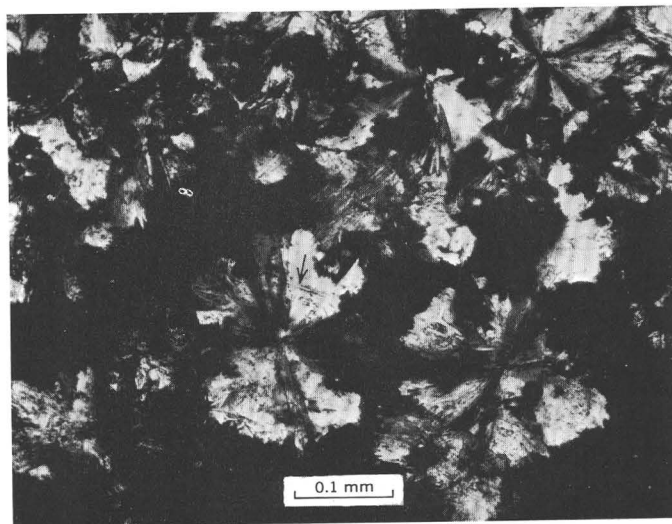
SEARLESITE

Searlesite ($\text{NaBSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$) was first described by Larsen and Hicks (1914) from the saline deposits of Searles Lake, Calif. Since then, searlesite has been reported from similar deposits elsewhere in southern California (Hay, 1966a) and in Nevada (Foshag, 1934) and Wyoming (Fahey, 1950).

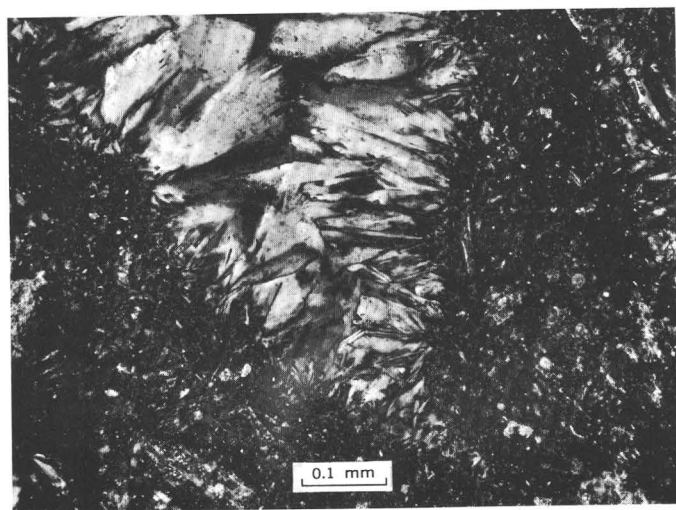
Searlesite in the altered tuffs of Lake Tecopa is associated with one or more of the following authigenic silicates: analcime, clinoptilolite, erionite, phillipsite, clay minerals, and potassium feldspar. Searlesite and potassium feldspar are most commonly associated. Nowhere have monomineralic beds of searlesite been recognized. Searlesite generally makes up 10-20 percent of the altered tuff, but locally it may make up as much as 70 percent of the tuff. The habit of searlesite is generally

prismatic or platy and only rarely spherulitic (fig. 12A). Individual crystals range from 0.02 to 0.5 mm in length but commonly are about 0.1 mm long. Spherulites range from 0.1 to 0.6 mm in diameter. Cavities commonly are lined with relatively large searlesite crystals (fig. 12B), many of which show terminal crystal faces.

Searlesite is readily identified in thin section by its relatively coarse crystallinity, high indices of refraction,



A



B

FIGURE 12.—Photomicrographs of searlesite in tuffs of the potassium feldspar facies. A, ragged spherulites of searlesite with interstitial, weakly birefringent potassium feldspar. Vague relicts (arrow) of shards within the spherulites are outlined by a clay mineral. Crossed nicols. B, large crystals of platy searlesite line cavity. Matrix is finely crystalline searlesite and potassium feldspar. Searlesite adjacent to cavity is finer crystalline than that in interior of cavity. Crossed nicols.

and high birefringence. Indices of refraction are: $\alpha = 1.515-1.518$, $\beta = 1.529-1.530$, and $\gamma = 1.533-1.534$; birefringence is 0.016-0.018.

DIAGENETIC FACIES

DISTRIBUTION

Three diagenetic facies are recognized in the tuffs of the Lake Tecopa deposits. Tuffs nearest the lake margins are characterized by fresh glass and are herein termed the "fresh-glass facies." Tuffs in the central part of the lake basin are characterized by potassium feldspar and (or) searlesite and are termed the "potassium feldspar facies." Those tuffs intermediate in position between the fresh-glass facies and the potassium feldspar facies and characterized by zeolite are termed the "zeolite facies."

The boundaries between the facies are laterally gradational and difficult to recognize in the field. Tuffs of the fresh-glass facies generally can be distinguished from those of the zeolite facies in the field, but tuffs of the zeolite facies almost never can be distinguished from those of the potassium feldspar facies. X-ray diffractometer powder data (fig. 2) of bulk samples, coupled with thin section study, are considered to be essential for positive identification and placement in the proper facies.

Maps showing the diagenetic facies for tuff A, tuff B, and all other tuffs stratigraphically below tuff B are given in figures 13-15, respectively. The boundary between the fresh-glass facies and the zeolite facies was placed at the first appearance of zeolite; however, tuff A was considered in the fresh-glass facies even though the basal $\frac{1}{4}$ - $\frac{1}{2}$ inch was altered to phillipsite. This concession was necessary because of difficulties found in sampling the base. The boundary between the zeolite facies and the potassium feldspar facies was placed at the first appearance of potassium feldspar or searlesite. The distribution of potassium feldspar and searlesite is similar throughout the basin; commonly the two minerals are associated.

Tuffs A and B are the only tuffs that can be traced from the fresh-glass facies, through the zeolite facies, and into the potassium feldspar facies. The first two tuffs below tuff B (fig. 6) can be traced from the fresh-glass facies into the zeolite facies, and the remainder of the tuffs lower in the section can be traced from the zeolite facies into the potassium feldspar facies or are exposed only in the potassium feldspar facies. These lower tuffs are not exposed along the marginal parts of the basin because the tributaries of the Amargosa River have not yet cut down to them. It is assumed that if the tuffs were completely exposed, they would

show the same transition from fresh glass, through zeolites, to potassium feldspar as shown by tuffs A and B.

In a general way the fresh glass-zeolite facies boundary and the zeolite-potassium feldspar facies boundary parallel the shape of the lake basin in plan. A notable exception is at the north end of the basin near Shoshone where the boundaries are flattened toward the central part of the basin. A similar basinward projection of the facies is also recognized near Greenwater Valley at the western margin and Chicago Valley at the southeastern margin of the basin. These three localities were the main inlets of relatively fresh water for saline Lake Tecopa. The zeolite facies is generally 0.5-1.0 mile wide except near the Amargosa River inlet at the north end of the basin, where the facies is broadened to 1.25-1.75 miles. These features indicate that the chemical depositional environment affected, if not controlled, the distribution of the diagenetic facies.

FIELD DESCRIPTION

Tuffs of the fresh-glass facies are typically pale gray and friable (fig. 7); shards have a distinct vitreous luster. Altered tuffs generally are white or pastel shades of green, yellow, orange, or brown, relatively hard, and dull or earthy. Unlike tuffs of the fresh-glass facies, altered tuffs are resistant and ledge forming (fig. 16). Even those altered parts of otherwise fresh tuffs stand out in natural exposures. Calcite-cemented fresh tuffs also are ledge formers, but the vitreous character of the shards is obvious under the hand lens. Original textures and sedimentary structures, such as ripple marks (fig. 17), are generally preserved in the altered tuffs. Preservation of these features in altered tuffs that are laterally equivalent to tuffs of the fresh-glass facies is convincing evidence that the present differences in composition and mineralogy are due to postdepositional processes.

The authigenic silicate minerals in tuffs of the zeolite and potassium feldspar facies cannot be positively identified in the field because of the very small size of the crystals. Where the altered tuff is nearly monomineralic, certain gross physical aspects of the rock may aid field identification. Altered tuffs consisting chiefly of phillipsite are pastel shades of yellow, orange, or green; they are punky and break with an irregular fracture. Phillipsite is the only zeolite in the Lake Tecopa deposits that occurs as spherulites. Tuffs replaced mainly by clinoptilolite are pale gray or yellow and relatively dense, and they break with a blocky or conchoidal fracture. Tuffs mainly of erionite are white, pale orange, or tan, and porous, and they break with a blocky fracture (fig. 18).

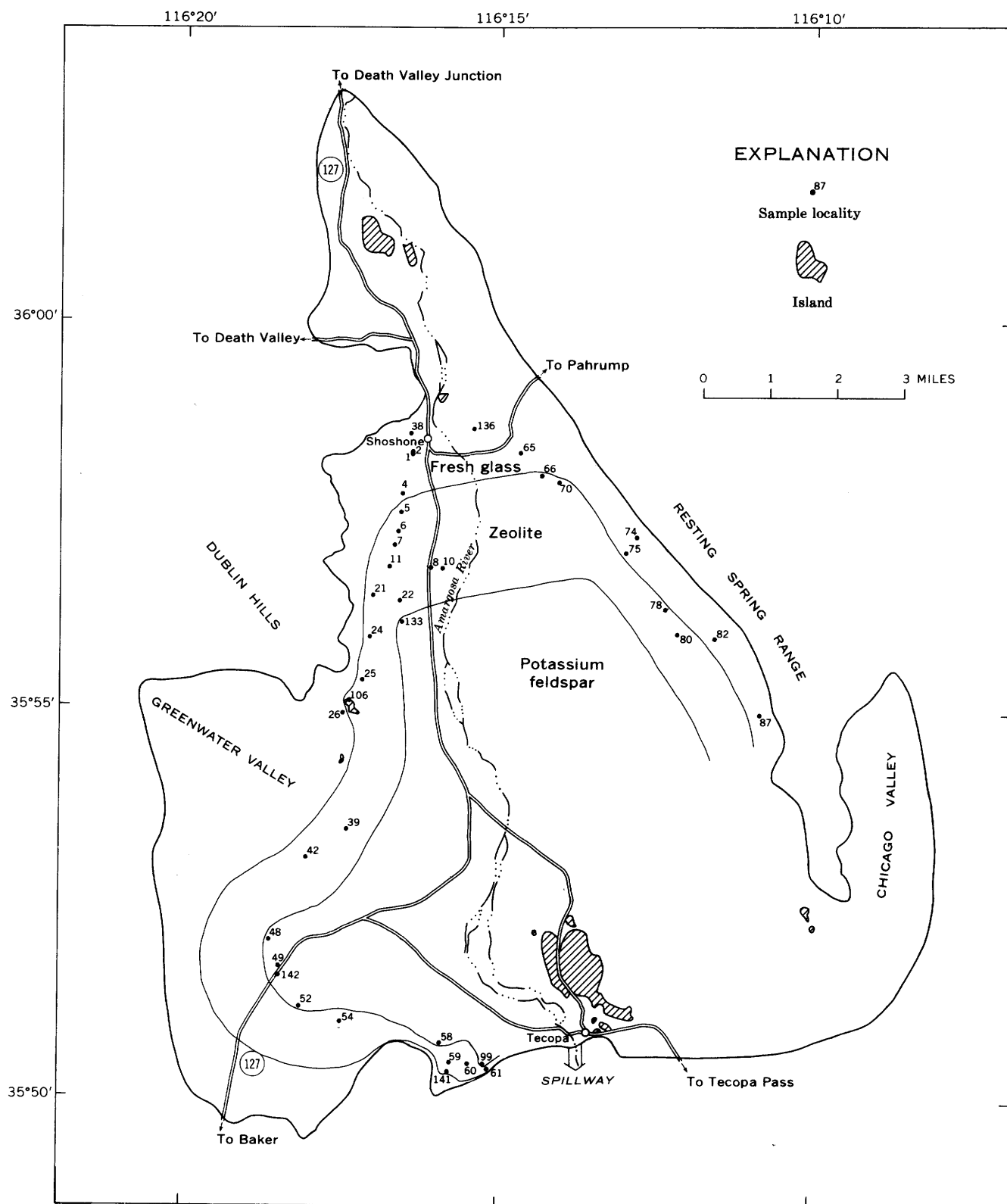


FIGURE 13.—Map of Lake Tecopa showing diagenetic facies for tuff A. X-ray analysis of samples given in table 10.

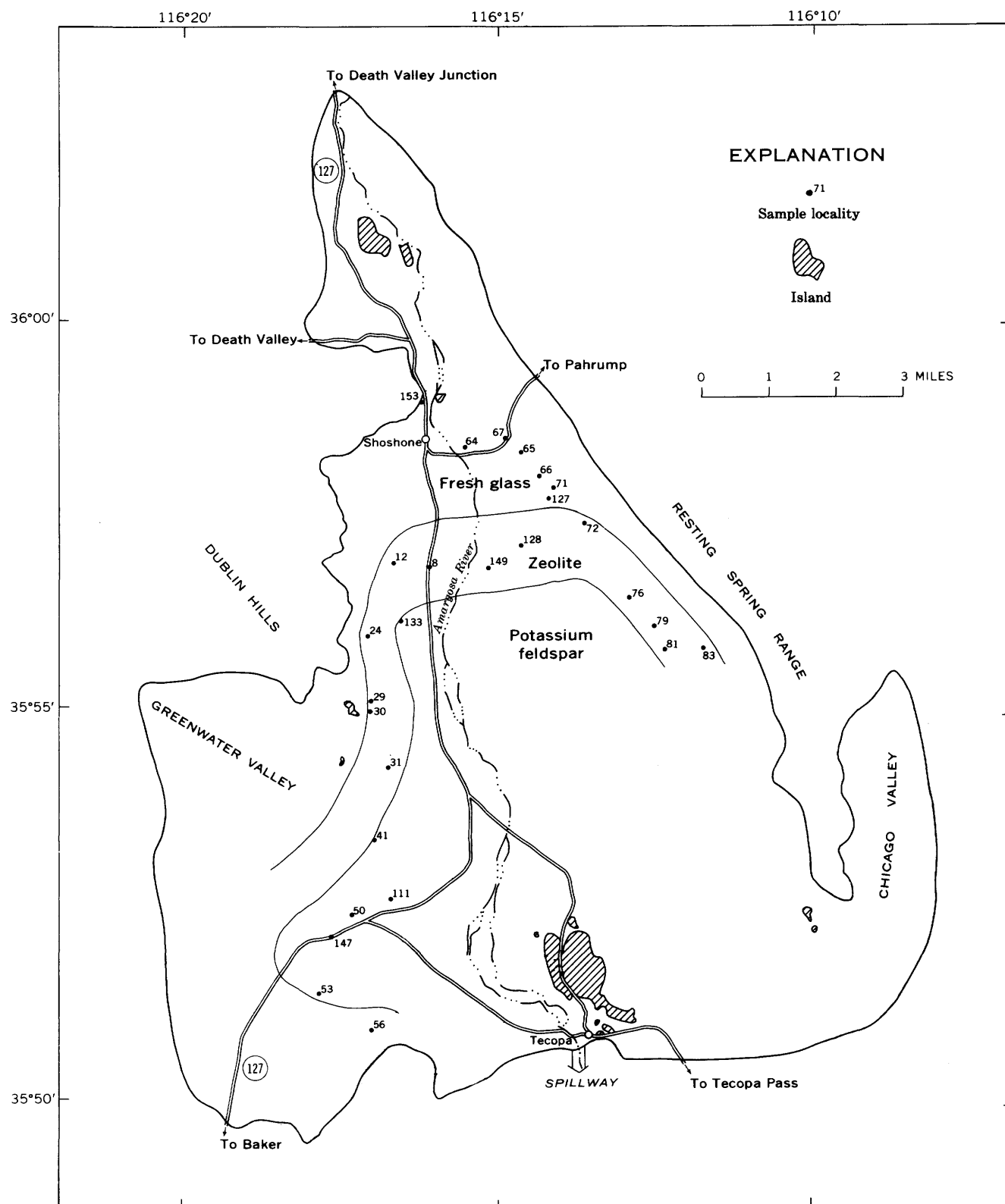


FIGURE 14.—Map of Lake Tecopa showing diagenetic facies for tuff B. X-ray analysis of samples given in table 10.

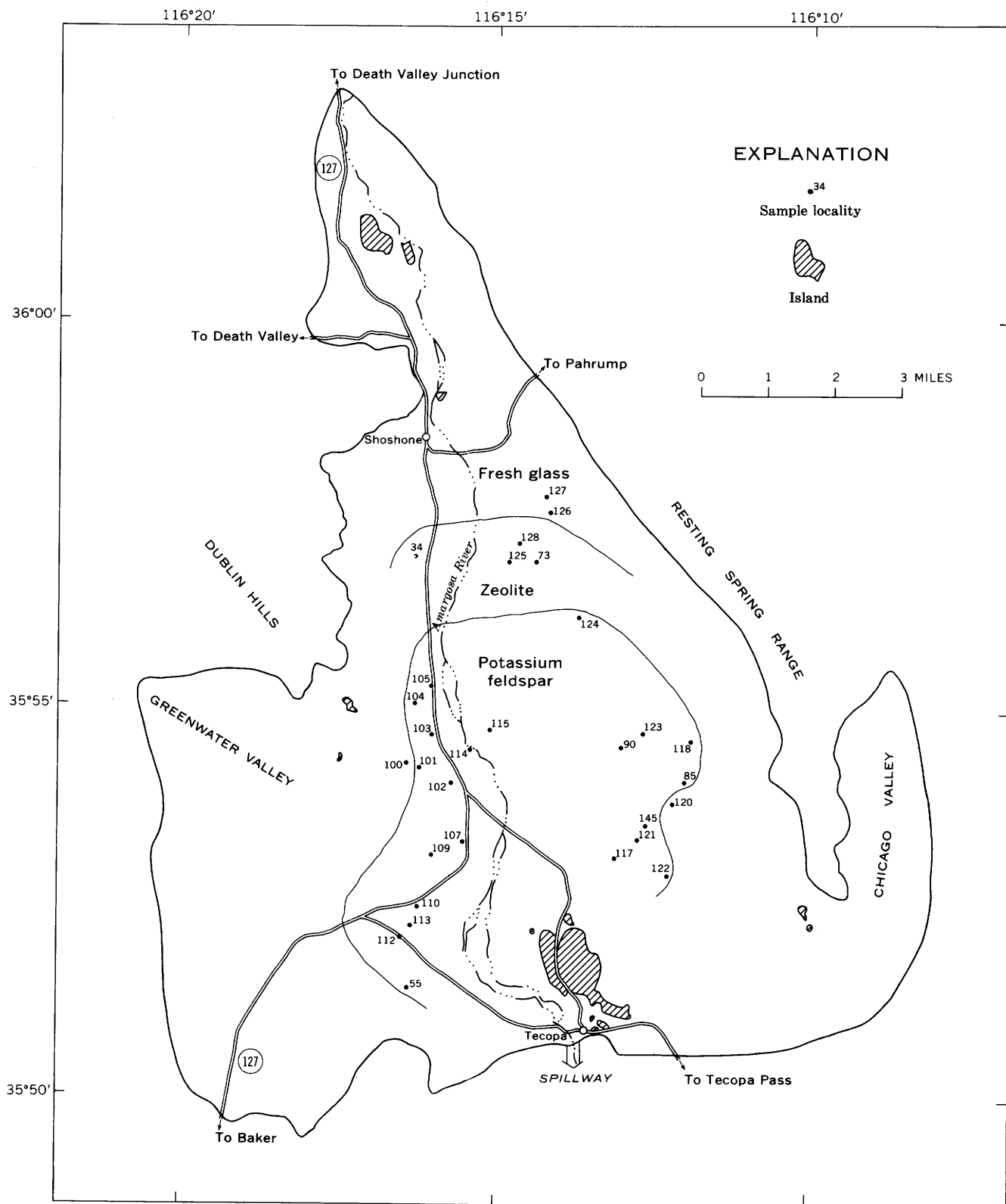
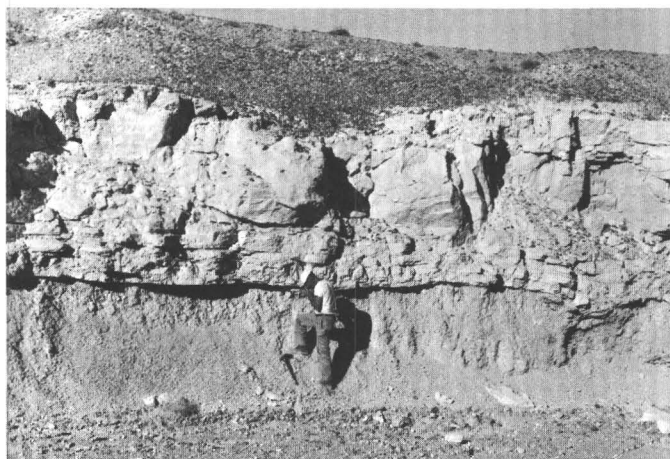


FIGURE 15.—Map of Lake Tecopa showing diagenetic facies for all tuffs stratigraphically below tuff B. X-ray analysis of samples given in table 10.



A



B

FIGURE 16.—Natural exposures of resistant zeolitic tuff. A, tuff A along wash about 2 miles south of Shoshone. B, tuff B forms canyon lip about 5 miles south of Shoshone. In background are the Dublin Hills.

Inasmuch as erionite-rich tuff can be sawed and nailed, it was used as a building stone in certain parts of central Nevada by the early settlers (R. H. Olson, oral commun., 1964).

Tuffs in the potassium feldspar facies are variable in appearance, probably because they generally consist of more than one authigenic mineral. If the tuff is chiefly potassium feldspar, it commonly is white, friable, and punky and breaks with an irregular fracture. If much searlesite occurs with the feldspar, the tuff is hard and relatively dense. Vitroclastic texture is generally better preserved in the zeolite facies than in the potassium feldspar facies.

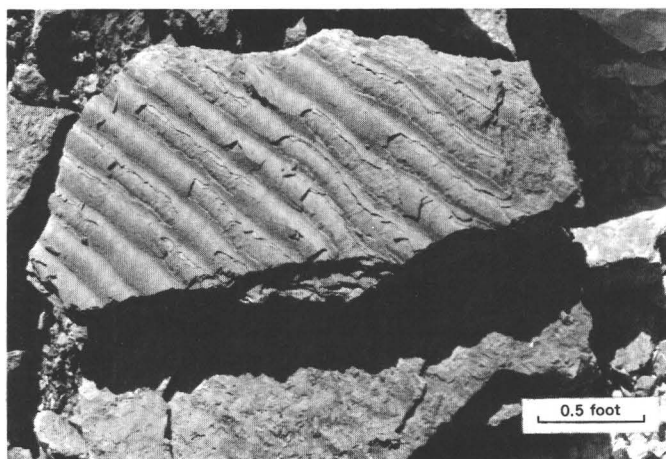


FIGURE 17.—Ripple marks preserved on a bed from the lower part of tuff A, about 2 miles south of Shoshone. Bed consists chiefly of phillipsite and clinoptilolite.



FIGURE 18.—Erionite-rich upper part of tuff A, about 3 miles south of Shoshone. Note typical blocky fracture.

PETROGRAPHY

The mineralogy of the altered tuffs was determined mainly by study of X-ray diffractometer powder data of bulk samples (table 10), supplemented by thin-section study. Thin sections were especially useful for determining the age relationships of the authigenic minerals, but were not examined until the mineralogy of the altered tuffs was known by X-ray methods. Optical identification of the zeolites is difficult because of their small crystal size and similar optical properties and habits. Inasmuch as analcime and chabazite could not be identified in thin section, their age relationships to the other authigenic minerals is unknown.

The tuffs show gradational changes in mineralogy from the lake margins to the central part of the basin.

These changes are from fresh glass or glass with incipient montmorillonite(?) alteration to relict glass and zeolites; to zeolites; to zeolites, potassium feldspar, and (or) searlesite; and then to potassium feldspar and searlesite. Calcite and authigenic clay minerals occur in tuffs throughout the basin regardless of facies. Opal is recognized in only the zeolite and potassium feldspar facies.

Crystal fragments in the tuffs generally are unaltered; however, plagioclase locally shows marginal replacement by potassium feldspar in the potassium feldspar facies; hornblende, apatite, and, rarely clinopyroxene show marginal solution in both zeolite and potassium feldspar facies. Hay and Moiola (1963, p. 325) found that grains of plagioclase, quartz, and clinopyroxene are intensively etched below a depth of 220 feet in the deposits of saline Searles Lake. As much as 75 percent of some plagioclase and clinopyroxene grains had been dissolved.

FRESH-GLASS FACIES

Descriptions of tuffs from the fresh-glass facies have been given in a previous section entitled "Tuff," and need not be repeated here. In general, the shards in the tuffs are fresh except that they are hydrated. A thin film of montmorillonite(?) surrounds the shards, particularly pumice shards, of some samples.

ZEOLITE FACIES

Vitric material in tuffs of the zeolite facies is replaced by zeolites, clay minerals, and, locally, opal. All zeolites except analcime are locally associated with relict glass. Chabazite, through rarely identified in the tuffs, occurs only where there is relict glass and always near the boundary of the fresh-glass and zeolite facies. Analcime occurs only within the potassium feldspar facies but near the zeolite-potassium feldspar boundary. Inasmuch as analcime is commonly associated with potassium feldspar or searlesite, analcime probably forms in a chemical environment that differs from that in which the other alkali zeolites form.

Thick tuffs generally contain two or more zeolites in addition to the nearly ubiquitous authigenic clay minerals; however, thin tuffs generally are nearly monomineralic. Phillipsite is the principal zeolite in these thin tuffs. Samples from thick tuffs consist very commonly of two zeolites, less commonly of three zeolites, and rarely of four zeolites. Those associations of zeolites recognized in the tuffs of Lake Tecopa are:

Zeolite associations		
[Ch, chabazite; Cl, clinoptilolite; E, erionite; P, phillipsite]		
2 zeolites	3 zeolites	4 zeolites
Cl+P	P+Cl+Ch	Ch+Cl+E+P
Cl+E	P+Cl+E	
Cl+Ch	Ch+Cl+E	
E+P		

The most common associations of two and three zeolites are clinoptilolite plus phillipsite and phillipsite plus clinoptilolite plus erionite, respectively. Four zeolites have been recognized in only one sample. The absence of other seemingly possible zeolite associations may be in part due to our inability to identify small percentages of a constituent by optical or X-ray techniques.

The vitroclastic texture is preserved in most tuffs of the zeolite facies. However, altered tuffs that lack authigenic clay minerals or that are coarsely crystalline commonly lack relict texture or have only vague "ghosts" of shards. Typical pseudomorphs after platy bubble-wall shards consist of a thin marginal film of clay (presumably montmorillonite), several microns thick, succeeded inwardly by crystals of one or more zeolites. The pseudomorphs may be either solid or hollow; commonly both types can be seen in the same thin section. The larger pseudomorphs generally are the hollow ones. Hollow pseudomorphs characteristically consist of the marginal film of clay succeeded inwardly by a single layer of phillipsite crystals oriented perpendicular to the shard wall (fig. 19). The solid pseudo-

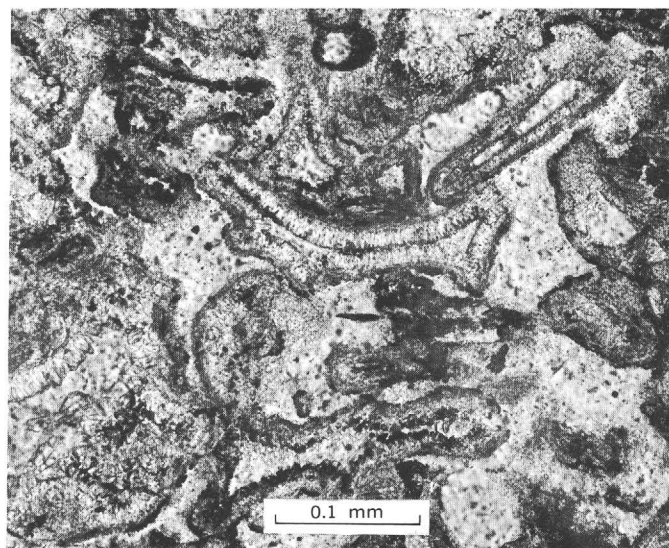


FIGURE 19.—Photomicrograph of zeolitic tuff showing hollow phillipsite pseudomorphs of shards. A single layer of prismatic phillipsite grew perpendicular to shard wall and adjacent to marginal film of montmorillonite(?). Unpolarized light.

TABLE 10.—*Mineralogic composition of tuffs of Lake Tecopa as estimated from X-ray diffractometer patterns of bulk samples*

[—, looked for but not found; Tr., trace. Clay, 10A: Authigenic illite and pyrogenic biotite. Other: Chiefly pyrogenic or detrital quartz and plagioclase. Sample E from locality 66 and sample A from locality 83 also contain less than 1 part dolomite]

Locality	Sample	Sample taken—	X-ray analysis (parts of ten)												
			Glass	Clay, 14A	Clay, 10A	Chabazite	Phillipsite	Erionite	Clinoptil- olite	Analcime	Potassium feldspar	Searlesite	Opal	Calcite	Halite
Tuff A (figure 13)															
1	A	36 in. above base.....	10	—	—	—	—	—	—	—	—	—	—	—	—
	B	At base.....	10	—	—	—	Tr.	—	—	—	—	—	—	—	—
2	A	12 in. above base.....	5	5	—	—	—	—	—	—	—	—	—	—	—
4	E	74 in. above base.....	10	—	—	—	—	—	—	—	—	—	Tr.	—	—
	D	40 in. above base.....	10	—	—	—	—	—	—	—	—	—	—	—	Tr.
5	C	6 in. above base.....	10	—	—	—	—	—	Tr.	—	—	—	—	—	—
	B	At base.....	—	—	—	—	10	—	—	—	—	—	—	—	—
5	E	130 in. above base.....	6	—	—	—	1	—	3	—	—	—	—	—	—
	D	126 in. above base.....	8	—	—	—	—	—	2	—	—	—	—	—	Tr.
6	C	65 in. above base.....	8	—	—	—	1	—	1	—	—	—	Tr.	—	Tr.
	B	6 in. above base.....	10	—	—	—	Tr.	—	—	—	—	—	—	—	—
6	A	At base.....	—	—	Tr.	—	10	—	—	—	—	—	—	—	—
	E	At top.....	6	—	—	—	3	—	Tr.	—	—	—	1	—	Tr.
7	D	48 in. above base.....	10	—	—	—	—	Tr.	Tr.	—	—	—	—	—	Tr.
	C	24 in. above base.....	7	—	2	—	—	—	Tr.	—	—	—	1	—	Tr.
7	B	16 in. above base.....	3	—	1	—	3	—	3	—	—	—	—	—	—
	A	At base.....	—	—	1	—	9	—	—	—	—	—	—	—	—
7	K	104 in. above base.....	—	—	2	—	6	—	1	—	—	—	—	—	1
	J	50 in. above base.....	3	1	2	—	2	—	2	—	—	—	Tr.	—	Tr.
8	H	39 in. above base.....	5	2	2	—	—	—	1	—	—	—	Tr.	—	Tr.
	G	38 in. above base.....	3	2	2	—	1	Tr.	1	—	—	—	1	—	Tr.
8	F	28 in. above base.....	8	Tr.	—	—	1	1	Tr.	—	—	—	Tr.	—	—
	E	21 in. above base.....	3	1	—	—	3	—	3	—	—	—	—	—	—
8	D	16 in. above base.....	6	1	—	1	Tr.	Tr.	2	—	—	—	—	—	—
	C	6 in. above base.....	2	—	—	—	6	—	2	—	—	—	—	—	—
8	B	At base.....	—	—	—	—	10	—	Tr.	—	—	—	—	—	—
	T5-1-11B	At top.....	—	—	—	—	3	—	3	—	—	2	—	—	2
8	10C	95 in. above base.....	—	—	1	—	—	Tr.	Tr.	—	—	9	Tr.	—	—
	10B	89 in. above.....	—	—	2	—	8	—	Tr.	—	—	—	—	—	Tr.
8	10A	80 in. above base.....	—	—	2	—	2	1	5	—	—	—	—	—	—
	9B	75 in. above base.....	—	Tr.	—	—	—	10	—	—	—	—	—	—	—
8	9A	65 in. above base.....	—	Tr.	1	—	—	1	3	—	—	5	—	—	—
	8	58 in. above base.....	—	—	—	—	2	3	5	—	—	—	—	—	—
8	7B	52 in. above base.....	—	4	2	—	1	—	3	—	—	—	Tr.	—	Tr.
	7A	46 in. above base.....	—	1	—	—	2	1	6	—	—	—	—	—	Tr.
8	6	42 in. above base.....	—	4	1	—	1	—	2	—	—	—	2	—	Tr.
	4B	32 in. above base.....	—	3	Tr.	—	Tr.	Tr.	7	—	—	—	Tr.	—	Tr.
8	4A	20 in. above base.....	—	3	2	—	—	Tr.	2	—	—	—	Tr.	—	3
	3	8 in. above base.....	—	1	—	—	4	—	5	—	—	—	—	—	Tr.
8	2	At base.....	—	Tr.	Tr.	—	10	—	—	—	—	—	Tr.	—	—
	A	do.....	—	—	Tr.	—	10	—	Tr.	—	—	—	—	Tr.	—
11	B	At upper part.....	—	—	3	—	4	—	1	—	—	—	1	—	1
21	A	48 in. above base.....	—	5	4	—	1	—	Tr.	—	—	—	Tr.	—	—
	C	At top.....	—	—	2	—	—	—	8	—	—	—	Tr.	—	—
22	B	At middle.....	—	4	2	—	3	—	1	—	—	—	—	—	Tr.
	A	At base.....	—	Tr.	—	—	10	—	—	—	—	—	—	—	—
22	C	At top.....	—	1	Tr.	—	1	—	8	—	—	—	—	—	—
	B	At middle.....	—	4	2	—	1	1	2	—	—	—	Tr.	—	Tr.
22	A	At base.....	—	—	Tr.	—	9	1	—	—	—	—	—	—	—

DIAGENETIC FACIES

TABLE 10.—Mineralogic composition of tuffs of Lake Tecopa as estimated from X-ray diffractometer patterns of bulk samples—Continued

Locality	Sample	Sample taken—	X-ray analysis (parts of ten)													Other
			Glass	Clay, 14A	Clay, 10A	Chabazite	Phillipsite	Erionite	Clinoptil- olite	Analcime	Potassium feldspar	Searlesite	Opal	Calcite	Halite	
Tuff A (figure 13)—Continued																
24	C	60 in. above base.....	—	4	—	—	5	—	Tr.	—	—	—	—	—	—	—
	B	30 in. above base.....	5	—	Tr.	—	2	Tr.	3	—	—	—	—	—	—	—
	A	At base.....	—	—	—	—	10	—	Tr.	—	—	—	—	—	—	—
25	A	do.....	—	2	—	—	8	—	—	—	—	—	—	—	—	—
26	D	At top.....	6	1	3	—	—	—	—	—	—	—	—	—	—	Tr.
	C	36 in. above base.....	6	3	1	—	—	—	—	—	—	—	—	—	—	Tr.
38	B	At base.....	10	—	—	Tr.	Tr.	—	Tr.	—	—	—	—	—	—	—
	C	At upper part.....	9	1	—	—	—	—	—	—	—	—	—	—	—	—
	B	52 in. above base.....	9	Tr.	—	—	1	—	—	—	—	—	—	—	—	—
39	A	At base.....	6	4	—	—	—	—	—	—	—	—	—	—	—	—
	C	At top.....	5	1	Tr.	—	3	—	Tr.	—	—	—	—	—	—	—
	B	At middle.....	3	1	—	—	2	Tr.	4	—	—	—	—	—	—	—
42	A	At base.....	—	2	—	—	8	—	Tr.	—	—	—	—	—	—	—
	B	At top.....	—	2	3	—	Tr.	3	2	—	—	—	—	—	—	Tr.
	A	At base.....	—	1	1	—	8	Tr.	Tr.	—	—	—	—	—	—	Tr.
48	S4-1B	At upper part.....	—	—	3	—	2	1	—	—	4	—	—	—	—	Tr.
	1C	At middle.....	—	1	1	—	—	—	Tr.	—	Tr.	—	8	—	—	Tr.
	1A	At base.....	—	1	1	—	6	—	1	Tr.	—	1	—	—	—	Tr.
49	C	At upper part.....	—	1	2	—	3	—	—	—	1	—	3	—	—	—
	B	do.....	—	Tr.	—	—	—	—	10	—	—	—	—	—	—	—
	A	At base.....	—	1	1	—	8	Tr.	—	—	—	—	—	—	—	—
52	A	At lower part.....	—	Tr.	1	—	8	—	—	—	1	—	—	—	—	—
54	A	At middle.....	—	1	1	—	3	—	5	—	—	—	—	—	—	—
58	D	At top.....	—	3	3	—	1	—	1	—	1	—	1	—	—	—
	C	32 in. above base.....	—	2	4	—	2	—	1	—	1	—	—	—	—	—
	B	10 in. above base.....	—	—	4	—	4	—	2	—	—	—	—	—	—	—
59	A	At base.....	—	1	—	—	9	—	—	—	—	—	—	—	—	—
	F	At top.....	—	2	2	—	4	—	—	—	—	—	Tr.	—	—	—
	E	72 in. above base.....	3	1	2	—	2	Tr.	2	—	—	—	—	—	—	Tr.
60	D	40 in. above base.....	5	—	—	—	—	—	5	—	—	—	—	Tr.	—	—
	C	20 in. above base.....	10	—	—	Tr.	Tr.	—	Tr.	—	—	—	—	Tr.	—	—
	B	6 in. above base.....	10	—	—	—	Tr.	—	—	—	—	—	—	—	—	—
61	A	At base.....	2	—	1	—	7	—	Tr.	—	—	—	—	—	—	—
	C	At upper part.....	2	—	—	—	—	Tr.	8	—	—	—	Tr.	—	—	—
	B	At lower part.....	1	Tr.	Tr.	—	5	—	4	—	—	—	—	—	—	—
65	A	At base.....	—	—	1	—	9	—	—	—	—	—	—	—	—	—
	B	At upper part.....	2	Tr.	1	—	Tr.	3	4	—	—	—	Tr.	—	—	—
	140A	At lower part.....	3	—	—	—	—	7	—	—	—	—	Tr.	—	—	—
66	A	At base.....	2	—	—	—	3	2	3	—	—	—	—	—	—	—
	C	At upper part.....	9	Tr.	1	—	Tr.	—	—	—	—	—	Tr.	—	—	—
	B	do.....	4	1	2	—	2	—	1	—	—	—	—	—	—	—
70	A	do.....	4	1	1	—	1	—	3	—	—	—	Tr.	—	—	—
	D	3 in. above base.....	—	1	2	—	7	—	—	—	—	—	—	—	—	—
	B	At base.....	—	Tr.	Tr.	—	10	—	—	—	—	—	—	—	—	Tr.
74	A	At middle.....	—	—	1	—	6	—	3	—	—	—	—	—	—	—
	A	At base.....	1	—	1	—	7	—	1	—	—	—	—	—	—	—
	A	Near base.....	9	—	Tr.	—	—	—	—	—	—	—	—	5	—	—
75	A	At middle.....	5	—	—	—	—	—	—	—	—	—	—	—	—	—
78	A	At upper part.....	5	1	1	—	3	—	Tr.	—	—	—	—	—	—	—

DISTRIBUTION AND GENESIS OF AUTHIGENIC SILICATE MINERALS

80	B	At middle.....	2	4	3	—	Tr.	—	—	—	—	—	—	—	1
	A	At base.....	—	1	1	—	8	—	—	—	—	—	—	Tr.	—
82	B	Near top.....	7	—	Tr.	—	—	—	—	—	—	—	3	—	—
	A	At middle.....	10	Tr.	Tr.	—	—	—	—	—	—	—	Tr.	—	—
87	A	At lower part.....	5	—	—	—	—	—	—	—	—	—	5	—	—
99	F	At top.....	—	2	1	—	Tr.	1	4	—	—	—	—	—	2
	E	24 in. above base.....	—	1	—	—	1	—	8	—	—	—	—	—	—
	D	12 in. above base.....	—	1	—	—	3	—	6	—	—	—	—	—	—
	C	6 in. above base.....	—	Tr.	—	—	8	—	1	—	—	1	—	—	—
	B	4 in. above base.....	—	—	—	—	3	—	5	—	—	2	—	—	—
	A	At base.....	—	Tr.	Tr.	—	8	—	1	—	Tr.	1	—	—	—
106	D	At top.....	—	3	4	—	2	1	—	—	—	—	—	—	—
	C	At middle.....	10	—	—	—	—	Tr.	—	—	—	—	—	—	—
	B	At base.....	—	—	2	—	8	Tr.	—	—	—	—	Tr.	—	—
133	C	At upper part.....	—	—	—	—	—	10	—	—	—	—	—	—	—
	A	At base.....	—	1	—	—	7	—	Tr.	—	Tr.	2	—	—	—
136	A	do.....	9	Tr.	Tr.	—	1	—	—	—	—	—	—	—	—
141	B	76 in. above base.....	—	—	3	—	2	—	—	—	—	—	1	—	4
142	C	12 in. above base.....	—	2	—	—	1	Tr.	Tr.	—	2	—	5	—	—
	B	6 in. above base.....	—	—	—	—	4	—	4	—	Tr.	—	2	—	—
	A	At base.....	—	—	2	—	8	—	Tr.	—	—	—	—	—	—

Tuff B (figure 14)

8	D	At top.....	—	2	6	—	Tr.	—	Tr.	—	—	—	—	1	—	1
	C	40 in. above base.....	—	6	2	—	1	—	Tr.	—	—	—	—	Tr.	—	1
	B	14 in. above base.....	—	2	4	—	2	—	Tr.	—	—	—	—	Tr.	—	1
12	A	Near middle.....	—	5	4	—	Tr.	—	Tr.	—	—	—	—	Tr.	—	1
24	F	66 in. above base.....	—	—	5	—	Tr.	—	1	—	—	—	—	1	—	3
	E	36 in. above base.....	—	3	1	—	6	—	Tr.	—	—	—	—	—	—	—
	D	At base.....	—	1	1	—	8	—	—	—	—	—	—	—	—	—
29	B	At upper part.....	4	2	2	Tr.	—	—	2	—	—	—	—	—	Tr.	—
	A	At base.....	4	2	2	Tr.	—	Tr.	2	—	—	—	—	—	Tr.	—
30	A	At middle.....	5	1	3	—	—	—	Tr.	—	—	—	—	—	Tr.	—
31	C	At top.....	2	—	1	—	Tr.	Tr.	7	—	—	—	—	—	Tr.	—
	B	66 in. above base.....	1	—	—	—	—	1	8	—	—	—	—	—	Tr.	—
	A	At base.....	1	Tr.	2	—	2	—	4	—	—	—	—	—	Tr.	—
41	D	At upper part.....	—	2	Tr.	—	Tr.	—	1	—	2	—	5	—	—	—
	C	do.....	—	2	1	—	Tr.	—	1	—	3	—	3	—	—	—
	B	At middle.....	—	—	—	—	—	—	—	Tr.	—	10	Tr.	—	—	—
	A	At base.....	—	1	1	—	7	—	—	—	1	—	—	—	—	—
50	B	At middle.....	—	2	1	—	—	—	—	2	3	—	1	Tr.	—	—
	A	At lower part.....	—	—	1	—	7	—	—	—	—	2	Tr.	—	—	—
53	A	12 in. above base.....	—	—	2	—	6	—	Tr.	—	2	—	—	—	—	—
56	A	do.....	—	2	1	—	5	—	—	—	—	—	—	—	—	2
64	A	At middle.....	5	1	2	—	—	—	—	—	—	—	1	—	—	1
65	B	do.....	5	—	—	—	—	—	—	—	—	—	5	—	—	—
66	E	Near middle.....	5	2	Tr.	—	—	—	—	—	—	—	1	—	1	—
67	A	At base.....	8	—	1	—	—	—	—	—	—	—	—	—	—	1
71	A	Near base.....	8	—	1	—	—	—	—	—	—	—	—	—	—	1
72	A	do.....	2	—	Tr.	—	8	—	—	—	—	—	—	—	Tr.	—
76	B	At middle.....	—	—	2	—	8	Tr.	—	—	—	—	—	—	—	—
	A	At base.....	—	—	Tr.	—	10	—	—	—	—	—	—	—	—	—
79	A	56 in. above base.....	4	—	—	—	6	Tr.	Tr.	—	—	—	—	—	—	—
81	A	At base.....	—	—	1	—	9	—	—	—	—	—	—	—	—	—
83	A	At upper part.....	—	8	—	—	Tr.	—	—	—	—	—	1	—	—	1
111	A	18 in. above base.....	—	—	3	—	2	—	—	—	5	—	—	—	—	—
127	A	At lower part.....	3	4	Tr.	—	—	—	—	—	—	—	3	—	Tr.	—
128	D	At top.....	—	—	1	—	9	—	—	—	—	—	—	—	Tr.	—
	C	At middle.....	10	—	—	—	—	—	—	—	—	—	—	—	—	—

DIAGENETIC FACIES

TABLE 10.—Mineralogic composition of tuffs of Lake Tecopa as estimated from X-ray diffractometer patterns of bulk samples—Continued

Locality	Sample	Sample taken—	X-ray analysis (parts of ten)													
			Glass	Clay, 14A	Clay, 10A	Chabazite	Phillipsite	Erionite	Clinoptil- olite	Analcime	Potassium feldspar	Searlesite	Opal	Calcite	Halite	Other
Tuff B (figure 14)—Continued																
128	B	At lower part.....	10	—	—	—	—	—	—	—	—	—	—	Tr.	—	—
	148M	At base.....	6	—	2	—	2	—	—	—	—	—	—	—	—	Tr.
133	E	54 in. above base.....	—	2	—	—	7	—	—	—	Tr.	1	—	—	—	—
	D	At lower part.....	—	1	1	—	7	—	Tr.	—	—	1	—	Tr.	—	—
147	B	18 in. above base.....	—	—	2	—	—	—	—	—	1	4	3	Tr.	—	—
	A	At base.....	—	—	2	—	—	—	—	—	3	—	5	Tr.	—	—
149	A	Near middle.....	—	1	2	—	4	—	1	—	—	—	2	Tr.	—	Tr.
153	A	At lower part.....	8	Tr.	—	—	—	—	—	—	—	—	—	—	—	2
Tuffs below tuff B (figure 15)																
34	B	25 ft below tuff B, at top..	5	—	—	—	—	—	—	—	—	—	—	5	—	Tr.
	A	25 ft below tuff B, at base.....	—	1	Tr.	—	9	—	—	—	—	—	—	Tr.	—	Tr.
55	A	10–15 ft above tuff C.....	—	1	—	—	1	—	—	—	8	—	—	—	—	Tr.
73	A	30 ft below tuff B.....	—	—	Tr.	—	10	—	—	—	—	—	—	—	—	Tr.
85	119A	6 ft above tuff C.....	—	2	1	—	5	—	—	—	1	—	—	Tr.	1	—
	85B	From tuff C, at middle....	—	2	Tr.	—	8	—	Tr.	—	—	—	—	—	—	—
	A	From tuff C, at base.....	—	Tr.	—	—	10	—	Tr.	—	—	—	—	—	—	—
	119B	7 ft below tuff C.....	—	3	1	—	1	—	—	—	2	—	—	1	—	2
	144C	19 ft below tuff C, at upper part.....	—	4	1	—	Tr.	—	—	—	1	—	1	1	—	2
	B	19 ft below tuff C, at lower part.....	—	Tr.	Tr.	—	10	—	—	—	—	—	—	—	—	Tr.
	119D	25 ft below tuff C.....	—	2	5	—	Tr.	—	—	—	—	—	—	2	—	1
90	C	5 ft above tuff C.....	—	1	2	—	—	—	—	—	5	2	—	—	—	—
	B	From tuff C, at middle....	—	—	2	—	—	—	—	—	8	—	—	—	—	—
	A	From tuff C, at base.....	—	1	Tr.	—	Tr.	—	—	—	8	1	—	—	—	—
100	A	29 ft above tuff C.....	—	Tr.	1	—	6	Tr.	3	—	—	—	—	—	—	Tr.
101	B	29 ft above tuff C, at upper part.....	—	—	—	—	—	—	—	—	2	—	8	Tr.	—	—
	A	29 ft above tuff C, at base.....	—	2	—	—	—	—	—	—	8	—	—	Tr.	—	—
102	ST-3-11B	From tuff C, at top.....	—	Tr.	2	—	—	—	—	—	8	—	—	—	—	—
	A	From tuff C, at base.....	—	Tr.	1	—	—	—	—	—	4	5	—	—	—	—
103	A	From tuff C, at lower part.....	—	—	2	—	—	—	—	—	4	—	4	—	—	—
104	A	Between tuffs B and C, at upper part.....	—	—	3	—	—	—	—	—	3	—	4	—	—	—
105	B	From tuff C, at top.....	—	—	2	—	—	—	—	—	5	2	—	1	—	—
	A	From tuff C, at base.....	—	Tr.	2	—	—	—	—	—	6	2	—	Tr.	—	—
107	A	From tuff C, near base....	—	—	2	—	—	—	—	—	7	1	—	—	—	—
109	B	From tuff C, at top.....	—	—	1	—	—	—	—	—	6	2	—	1	—	—
	A	From tuff C, at base.....	—	—	Tr.	—	—	—	—	—	8	2	—	—	—	—
110	A	Between tuffs B and C....	—	—	—	—	—	—	—	—	—	7	—	—	—	3
112	A	10–15 ft above tuff C....	—	—	1	—	—	—	—	—	7	2	—	—	—	—
113	A	do.....	—	Tr.	2	—	—	—	—	—	6	2	—	Tr.	—	—
114	A	From tuff C, near top....	—	2	2	—	—	—	—	—	5	1	—	Tr.	—	—
115	A	From tuff C.....	—	1	3	—	—	—	—	—	4	2	—	Tr.	—	—

DISTRIBUTION AND GENESIS OF AUTHIGENIC SILICATE MINERALS

117	C-----	28 ft below tuff C, near top.	—	—	1	—	6	—	—	—	2	—	—	—	1	—
	B-----	28 ft below tuff C, 1 in. above base.	—	—	1	—	4	—	—	—	5	—	—	—	—	—
	A-----	28 ft below tuff C, at base.	—	1	Tr.	—	4	—	—	—	1	—	—	—	4	—
118	A-----	6 ft above tuff C-----	—	—	—	—	—	—	—	—	10	—	—	Tr.	—	Tr.
120	C-----	From tuff C, at top-----	—	3	1	—	6	—	—	—	—	—	—	Tr.	—	—
	B-----	From tuff C, at middle---	—	2	—	—	8	—	Tr.	—	—	—	—	—	—	—
	A-----	From tuff C, at base-----	—	2	—	—	7	—	Tr.	—	—	—	—	—	—	1
121	146D-----	8 ft below tuff C, at top---	—	4	4	—	1	—	—	—	1	—	—	Tr.	—	—
	C-----	8 ft below tuff C, 5 in. above base.	—	3	4	—	1	—	—	—	1	—	—	1	Tr.	—
	B-----	8 ft below tuff C, 2 in. above base.	—	2	2	—	4	—	—	—	2	—	—	—	—	—
	A-----	8 ft below tuff C, at base---	—	—	2	—	2	—	—	—	5	—	—	—	1	—
121E-----		13 ft below tuff C, at upper part.	—	2	Tr.	—	2	—	—	—	1	—	—	Tr.	3	2
	D-----	13 ft below tuff C, at base.	—	1	1	—	3	—	—	—	2	—	—	Tr.	3	—
	C-----	23 ft below tuff C, at base.	—	Tr.	4	—	6	—	—	—	—	—	—	—	—	Tr.
	A-----	30 ft below tuff C-----	—	Tr.	1	—	4	—	—	—	5	—	—	—	—	Tr.
122	C-----	From tuff C, at top-----	—	—	5	—	4	—	—	—	—	Tr.	—	—	1	—
	B-----	From tuff C, at middle---	—	—	1	—	3	—	—	—	—	—	—	—	6	—
	A-----	From tuff C, at base-----	—	1	1	—	8	—	—	—	—	—	—	Tr.	—	—
123	B-----	From tuff C, at upper part.	—	—	1	—	—	—	—	—	—	2	3	—	4	—
	A-----	From tuff C, at lower part.	—	—	Tr.	—	—	—	—	—	10	—	—	—	—	—
124	A-----	25 ft below tuff B-----	—	1	2	—	—	—	—	—	7	—	—	—	—	—
125	A-----	28 ft below tuff B, lower part.	—	—	3	—	4	—	—	—	—	—	—	Tr.	—	3
126	A-----	do-----	8	—	2	—	—	—	—	—	—	—	—	—	—	Tr.
127	E-----	do-----	7	—	—	—	—	—	—	—	—	—	—	2	—	1
128	148E-----	25 ft below tuff B-----	—	—	1	—	9	—	—	—	—	—	—	—	—	Tr.
	C-----	28 ft below tuff B, at top.	—	—	—	—	10	—	—	—	—	—	—	—	—	Tr.
	B-----	28 ft below tuff B, at middle.	—	—	1	—	9	—	—	—	—	—	—	—	—	—
	A-----	28 ft below tuff B, at base.	—	1	1	—	8	—	—	—	—	—	—	Tr.	—	Tr.
145	D-----	From tuff C, at top-----	—	—	1	—	2	—	—	—	1	—	3	2	1	—
	C-----	From tuff C, 5 in. above base.	—	1	1	—	1	—	—	—	Tr.	—	—	—	7	—
	B-----	From tuff C, 3 in. above base.	—	—	1	—	6	—	—	—	1	—	2	—	—	—
	A-----	From tuff C, at base-----	—	—	1	—	3	—	—	—	6	—	—	—	—	—

DIAGENETIC FACIES

morphs are of two types: (1) those in which the phillipsite crystals of the single layer simply grew until they joined in the center and (2) those which resemble hollow pseudomorphs except that the central cavity is filled with relatively large randomly oriented crystals of clinoptilolite or erionite. This latter type is more common in the larger pseudomorphs.

Concretions are locally abundant near the middle of zeolitic tuff A. The concretions (fig. 20) are spherical or ellipsoidal and generally 0.25–0.5 inch in diameter. Each concretion consists of a porous phillipsite core and an outer clinoptilolite rind. Where the concretions are close together, a single rind may envelop two or more cores. The concretions are set in a matrix of clinoptilolite and erionite, and both concretions and matrix show relict vitroclastic texture. Thin-section study indicates that the contacts between core and rind and between rind and matrix are not sharp, but are gradational through about 0.5 mm.

In some tuffs or parts of tuffs the zeolite occurs as a dense network of unoriented relatively large crystals. This occurrence is especially common for monomineralic or nearly monomineralic samples consisting of erionite (fig. 9) and less common for those consisting of clinoptilolite. A film of clay outlines the relict shards and reveals the vitroclastic texture. If no clay is present, vitroclastic texture is vague or nonexistent.

Thin sections of partly altered tuffs clearly show that the finer glass particles alter before the coarser ones. Large glassy shards, enclosed by a clay film, are set in a matrix of zeolite and clay minerals. A more altered

variant consists of ragged remnants of shards “floating” in a matrix of zeolite and clay. Pumice shards commonly are altered to a greater degree than platy bubble-wall shards of comparable size, probably because of their greater porosity and surface exposure.

Thin layers of spherulitic phillipsite are characteristic of the basal part of tuff A in the zeolite facies. Spherulitic phillipsite is gradational upward into prismatic phillipsite through a 2- to 3-mm-thick zone where the spherulites are small and malformed. The spherulites resemble oolites except that they have a radial internal structure (fig. 10B) rather than a concentric structure so characteristic of oolites. The spherulites lack nuclei; however, some apparently have engulfed scattered pyrogenic minerals during their growth. Most spherulites enclose “ghosts” of shards that are outlined by montmorillonite(?). Individual fibers of phillipsite extend undistorted through these relict shards. The same alinement of relict shards persists within all spherulites of a layer (fig. 10A) and attests to the formation of the spherulites during diagenesis rather than by direct precipitation of phillipsite on the lake bottom. Small clusters of radiating erionite crystals are locally perched on the spherulites and project into the interstices. An orange or yellowish-green clay mineral—presumably illite—commonly coats the exposed parts of spherulites and erionite clusters.

Petrographic evidence, then, indicates that at least some of the zeolite pseudomorphs formed by crystallization of the zeolite(s) in cavities from which the glass had been dissolved. The hollow pseudomorphs are difficult to explain in any other way. Other zeolite replacements probably were contemporaneous with solution of the glass, but convincing evidence is lacking. The montmorillonite(?) that occurs as a marginal film on pseudomorphs or that outlines “ghosts” of shards evidently was the earliest authigenic silicate mineral to form. In many coarsely crystalline zeolitic tuffs and spherulitic replacements, this film of montmorillonite(?) is the only clue to the vitroclastic nature of the rock. Those parts of the zeolitic tuffs that are coarsely crystalline and lack relict vitroclastic texture may represent sites of recrystallization.

POTASSIUM FELDSPAR FACIES

Tuffs of the potassium feldspar facies are characterized by authigenic potassium feldspar and (or) searlesite. These constituents generally are associated and occur in trace to major amounts of the altered tuff. Neither potassium feldspar nor searlesite is associated with relict glass. Potassium feldspar and searlesite can locally be found associated with each of the zeolites

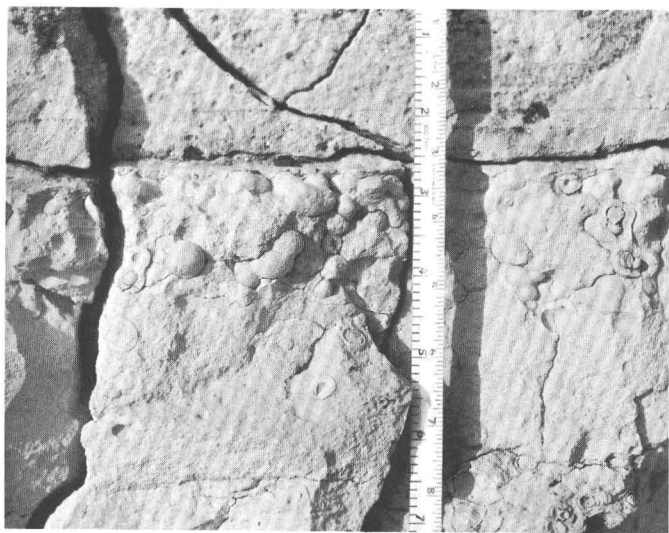


FIGURE 20.—Concretions in a matrix of clinoptilolite and erionite, near the middle of zeolitic tuff A, about 2 miles south of Shoshone. Concretions consist of a phillipsite core and a clinoptilolite rind.

except chabazite. Tuffs consisting of potassium feldspar and phillipsite are especially common near the boundary between the zeolite and potassium feldspar facies.

Authigenic potassium feldspar generally occurs as a mosaic of anhedral crystals of minute size. The relict vitroclastic texture is vague or nonexistent in those tuffs or parts of tuffs where there is abundant feldspar. Locally, remnants of a marginal clay film serve to outline relict shards and identify the texture. Samples collected near the zeolite facies commonly show potassium feldspar replacement of phillipsite pseudomorphs after shards and of phillipsite spherulites. Where replacement is complete, the relict textures are obliterated.

Marginal replacements of detrital or pyrogenic plagioclase by potassium feldspar are rare in the altered tuffs. Where replacements are found, though, the potassium feldspar forms an optically continuous sheath, about 10μ thick, that surrounds the plagioclase. Twinning of the plagioclase does not extend through the potassium feldspar replacement.

Searlesite has three modes of occurrence in tuffs of the potassium feldspar facies: (1) cavity linings or fillings, (2) irregular replacement patches, and (3) spherulites. The cavities in which searlesite crystallized are of two types: (1) hollow phillipsite pseudomorphs after shards and (2) relatively large, as much as 7 mm, irregular cavities that must have formed in the tuff subsequent to deposition. One or more anhedral crystals of searlesite fill the central cavity of the phillipsite pseudomorphs (fig. 21). There is no evidence of replacement of the prismatic phillipsite by the searlesite. Large irregular cavities commonly are lined with platy searlesite crystals that grew nearly normal to the cavity walls and either terminated in an unfilled central cavity or grew until opposing crystals joined to form a solid filling (fig. 12B). Some large cavity fillings show two layers of searlesite crystals—a layer of small crystals adjacent to the cavity walls and, inward, a layer of much larger crystals. Rarely, the searlesite occurs as mutually interfering clusters of crystals that radiate from many points around the cavity walls. All these varieties of searlesite fillings in large irregular cavities can be seen in a single thin section.

Tuffs collected near the zeolite facies commonly consist of phillipsite pseudomorphs after shards and irregular patches of searlesite. Unlike the searlesite in cavity fillings, this searlesite shows no preferred orientation with respect to the boundary of the patch. Remnants of phillipsite pseudomorphs are rarely seen in these patches, but where they are found they definitely indicate localization of searlesite by replacement rather than by cavity filling.



FIGURE 21.—Searlesite (light) fills hollow phillipsite (dark) pseudomorphs of shards in tuff of the potassium feldspar facies. Crossed nicols.

Isolated spherulites of searlesite occur in a matrix of finely crystalline potassium feldspar in tuff C from the central part of the lake basin. Vague relict shards are outlined by a nearly opaque, irresolvable material in both searlesite spherulites and feldspar matrix.

Saline minerals or molds of saline minerals are most abundant in tuffs and mudstones of the potassium feldspar facies although they also occur in tuffs and mudstones of the zeolite facies. Tuffs in the potassium feldspar facies commonly contain 10–20 percent halite, which occurs as disseminated cubes about 10μ in size. Fractures of some tuffs and mudstones are locally coated with anhedral halite and indicate late formation of some halite. Even the small cubes of halite probably were not precipitated directly from the lake water but were deposited from pore solutions during diagenesis.

Trona ($\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3 \cdot 2\text{H}_2\text{O}$) has been recognized at a single locality in the potassium feldspar facies, about 2.7 miles south of Shoshone and 0.5 mile west of State Route 127, where it occurs as a lens as much as 2

feet thick in the central part of tuff A. The lens is white and powdery and consists of very small acicular crystals of trona.

Molds of gaylussite ($\text{CaCO}_3 \cdot \text{Na}_2\text{CO}_3 \cdot 5\text{H}_2\text{O}$) and (or) pirssonite ($\text{CaCO}_3 \cdot \text{Na}_2\text{CO}_3 \cdot 2\text{H}_2\text{O}$) occur in tuffs and mudstones of both the potassium feldspar and zeolite facies. The molds are disseminated and euhedral and are commonly 1–5 mm in size. Locally the molds are filled or partly filled with aggregates of subhedral calcite. Molds in some tuffs and mudstones are distorted, probably by compaction subsequent to solution of the saline minerals.

PARAGENESIS OF AUTHIGENIC MINERALS

Age relationships can be determined for some of the authigenic minerals in the tuffs by study of the sequence of filling of cavities and shard molds, replacement relations, and the gradational change in mineralogy from the margin to the center of the lake basin.

A clay mineral that in thin section looks most like montmorillonite seems to have been the earliest authigenic silicate mineral to form in the tuffs. A thin film of montmorillonite(?) locally surrounds glassy shards in tuffs of the fresh-glass facies; however, montmorillonite(?) outlines relict shards in zeolite pseudomorphs and phillipsite spherulites of the zeolite facies. A film or remnants of a film of montmorillonite(?) also outline relict shards in parts of tuffs replaced by potassium feldspar and searlesite.

Another authigenic clay mineral, presumably illite on the basis of X-ray data, must have formed after phillipsite and erionite because it coats phillipsite spherulites and erionite crystals that are perched on the spherulites.

Zeolites were deposited after montmorillonite(?) and, at least locally, before potassium feldspar and searlesite. Successive fillings of shard molds that were rimmed by montmorillonite(?) indicate that phillipsite preceded searlesite. Both potassium feldspar and searlesite locally replace phillipsite. Potassium feldspar and searlesite may also replace other zeolites, but such relationships were not observed in thin section.

The order of emplacement of the zeolites is difficult to ascertain because the individual minerals commonly cannot be recognized in thin section. However, filling of shard molds consistently shows that phillipsite formed before erionite and clinoptilolite. Erionite perched on phillipsite spherulites and projecting into interstices between the spherulites confirms the earlier formation of phillipsite. The mineralogy of thick tuffs in the zeolite facies also suggests that phillipsite formed before erionite and clinoptilolite because the basal parts of mostly fresh tuffs generally are altered to phillipsite,

whereas completely altered tuffs consist of phillipsite at the base but of erionite and clinoptilolite, with or without phillipsite, in the upper layers. This transition in tuff A is illustrated in the many washes 0.5 mile west of State Route 127, from about 0.7 mile south of Shoshone to about 2 miles south of Shoshone (fig. 13, table 10). Replacement of one zeolite by another in the zeolite facies was not recognized although more than one zeolite commonly occurs in the same specimen. Apparently, an early-formed zeolite is stable or perhaps metastable in the changing chemical environment that produces subsequent zeolites.

GENESIS OF THE AUTHIGENIC SILICATE MINERALS

Throughout the world, zeolites of authigenic origin occur in sedimentary rocks of diverse lithologies, depositional environments, and ages (Hay, 1966a). Zeolites are especially abundant in altered rhyolitic vitric tuffs of Cenozoic age. The zeolites and associated authigenic silicate minerals form during diagenesis by reaction of the volcanic glass with interstitial water (Deffeyes, 1959a), which may have originated as either meteoric water (Hay, 1963a) or connate water of a saline lake (Hay, 1964). Recently, zeolites have also been found in the saline soils developed on nephelinite ash of Olduvai Gorge, Tanzania (Hay, 1963b).

In his excellent review of zeolites and zeolitic reactions, Hay (1966a) discussed the following factors that may control the formation and distribution of zeolites and associated authigenic silicate minerals in sedimentary rocks: temperature, pressure, chemistry of the pore water, metastable crystallization, and composition, permeability, and age of the host rock. Inasmuch as all the authigenic silicate minerals in the Lake Tecopa deposits occur within a given tuff, differences in composition, permeability, and certainly age cannot explain their distribution pattern. The deposits of Lake Tecopa were subjected to only very shallow burial; therefore, the temperature and pressure during diagenesis must have been low. The youngest tuff, tuff A, probably never was buried more than 100 feet, equivalent to a pressure of about 10 bars. Even though the potassium feldspar facies of the tuffs is in the structurally low part of the basin, the slight increase in temperature and pressure due to the increased amount of burial seems insufficient to account for the observed pattern of the diagenetic facies. The differences in mineralogy of the tuffs, then, probably reflect differences in the chemistry of the pore water.

Experimental work indicates that the activity ratio of alkali ions to hydrogen ions and the activity of silica are the major chemical parameters of the solutions that control whether clay minerals, zeolites, or feldspars will

be formed at conditions that approximate surface temperatures and pressures (Hemley, 1959, 1962; Garrels and Christ, 1965, p. 359-370; Hess, 1966). Formation of zeolites and feldspars rather than clay minerals is stimulated by relatively high alkali-ion to hydrogen-ion activity ratios and by relatively high silica activities. The high alkali-ion to hydrogen-ion activity ratio necessary for the formation of zeolites in a tuff can be attained in the depositional environment of a saline, alkaline lake (Hay, 1964) or in the postdepositional environment, as a result of solution and hydrolysis of rhyolitic vitric material by subsurface water (Hay, 1963a, p. 237-242).

EVIDENCE OF SALINE, ALKALINE WATER IN LAKE TECOPA

Several criteria suggest strongly that much of Lake Tecopa was a saline and alkaline lake, at least during the time represented by the exposed deposits. The most obvious indication is the occurrence of saline minerals. The lens of trona in tuff A and the occurrence of halite and molds of gaylussite or pirssonite throughout the stratigraphic section in the central part of the basin indicate a saline, alkaline depositional environment. The common occurrence of sinks, particularly in mudstones of the central part of the basin, suggests that soluble saline minerals are even more abundant than outcrop sampling indicates. Experimental work by others suggests a minimum salinity of 22 percent as indicated by trona (Freeth, 1923) and 14 and 21 percent as indicated by gaylussite and pirssonite, respectively (Bury and Redd, 1933).

Indirect evidence of salinity comes from the abundant calcite in the deposits at the north end of the lake, where the Amargosa River entered. The calcite seems best explained as precipitates formed near the points where inflowing calcium-bearing "fresh" water mixed with saline water. G. I. Smith (1966, p. 173-174) recently described a similar "chemical delta" of calcium carbonate in the upper Wisconsin sediments at the inlet to saline Searles Lake.

The distribution of fossils can also be interpreted to indicate an abnormal salinity for that part of the lake where fossils are absent. At Lake Tecopa, fresh-water diatoms (K. E. Lohman, written commun., 1965) and ostracodes (I. G. Sohn, written commun., 1965) have been found only in sediments near the inlets of the lake or very close to shore.

A saline, alkaline depositional environment can be inferred by the occurrence of certain authigenic silicate minerals found by other investigators to indicate saline waters. The abundant phillipsite is especially indicative

inasmuch as it is rare in rhyolitic tuffs deposits outside the saline, alkaline environment (Hay, 1964, p. 1384). Searlesite, too, is indicative of high salinity, according to Hay (1966a, p. 103), who found it to be the only authigenic silicate mineral of common occurrence that is restricted to a highly saline nonmarine environment.

EVIDENCE OF AREAL VARIATION IN CHEMICAL ENVIRONMENT

Not only was Lake Tecopa probably a saline lake, but there is a strong correlation between the inferred areal variation in this salinity and the distribution of authigenic silicate minerals in tuffs. Tuffs still represented by the fresh-glass facies probably were deposited in fresh water near shore and near the major inlets; farther basinward, these same tuffs are represented by the zeolite and potassium feldspar facies because they were deposited in saline, alkaline water. Fresh-water diatoms and ostracodes occur only with the unaltered glass facies. In contrast, halite, trona, and molds of gaylussite or pirssonite occur only in tuffs and associated sediments of the zeolite and potassium feldspar facies, and seem notably concentrated in the potassium feldspar facies.

Studies of altered tuffs in other Pleistocene and Recent saline lake deposits also show a strong correlation between salinity and authigenic silicate mineralogy (Hay, 1966a). Recent rhyolitic ash beds apparently are presently altering to zeolites in Teels Marsh, Nev. (Hay, 1964, p. 1367-1368; Cook and Hay, 1965; Hay, 1966a, p. 32-34). Water samples from pits and auger holes range in salinity from 0.5 to 17 percent but have a constant pH of 9.4. The uppermost ash at a depth of less than a foot is altered to zeolites only in that part of the playa which is covered with a trona crust and where the salinity is therefore highest. Lower ash beds also vary from fresh glass to completely zeolitized tuff, and the degree of alteration increases with increasing salinity of the interstitial water. Searlesite occurs locally in some of the altered beds.

Authigenic silicate minerals in rhyolitic tuffs of late Quaternary Owens, China, and Searles Lakes, Calif. show a distribution pattern that can be correlated with salinity (Hay and Moiola, 1964; Hay, 1966a, p. 34-36). Water from the eastern slopes of the Sierra Nevada fed Owens River and flowed into Owens Lake. During much of late Quaternary time, the three lakes were connected, and water spilled from Owens Lake to China Lake and then to Searles Lake (Smith and Pratt, 1957, p. 1-3). The water was progressively evaporated and enriched in salts from Owens Lake through China Lake to Searles Lake. A variety and an abundance of saline minerals occur in Searles Lake (Smith and Haines,

1964); gaylussite is commonly sparsely disseminated but locally abundant in a core from China Lake (Smith and Pratt, 1957, p. 14-25); saline minerals are absent in Owens Lake except at the surface, where they formed after diversion of the Owens River in 1913 (Hay, 1964, p. 1369). Rhyolitic glass has been altered to phillipsite, potassium feldspar, and searlesite in Searles Lake and to phillipsite, clinoptilolite, erionite, and searlesite in China Lake. Glass is fresh in Owens Lake except in an interval where it is replaced by phillipsite, clinoptilolite, and erionite (Hay and Moiola, 1964). Apparently the zeolites in Owens Lake represent an episode when the lake was moderately saline and alkaline. The abundance of potassium feldspar in Searles Lake and the absence of feldspar and the abundance of zeolites in China Lake can be attributed to differences in salinity. Brine permeating the upper and lower salt bodies at Searles Lake has a salinity of 34-36 percent (Haines, 1959, p. 146), whereas waters from wells at China Lake have salinities of 0.7-23 percent (Moyle, 1963, p. 142-158). Waters from both lakes show about the same range in pH, 9.1-9.4 for Searles Lake and 9.1-9.6 for China Lake.

The sequence of authigenic silicate minerals in Lake Tecopa from margin to the central part of the basin also parallels the sequence of authigenic silicate minerals from Owens Lake to China Lake to Searles Lake. In a general way, the fresh-glass facies at Lake Tecopa corresponds to the common unaltered glass at Owens Lake, the zeolite facies corresponds to the predominant zeolite authigenesis at China Lake, and the potassium feldspar facies corresponds to the predominant potassium feldspar authigenesis at Searles Lake.

The distribution of the diagenetic facies in tuffs of Lake Tecopa and the gradational character of the facies are attributed chiefly to differences in pH and salinity of the water trapped in the tuffs during deposition. Water of Lake Tecopa was probably moderately to highly saline with a pH of at least 9, except near the lake margin. Runoff and influent springs and small streams probably kept the salinity and pH at lower levels along the margin. Relatively fresh water also prevailed near the Amargosa River inlet and the inlets of streams that occupied Greenwater Valley on the west and Chicago Valley on the east. The volume of fresh water that entered the lake at these inlets apparently was large enough to maintain relatively low salinities in the lake water, even at an appreciable distance basinward.

Although the chemical zonation of the pore water in the tuffs is assumed to have been inherited from the lake water at the time of deposition, the zonation could have developed after deposition. Perhaps Lake Tecopa was uniformly alkaline and moderately or highly saline

rather than fresh near the margin and inlets and increasingly alkaline and saline basinward. This alkaline and saline water, trapped in the tuffs as pore water during deposition, may have been "freshened" along shore by the encroachment of fresh water after deposition. Such a mechanism was recently suggested by Eugster and Smith (1965, p. 518) to explain the distribution of saline minerals in certain units of the Lower Salt at Searles Lake.

CHEMICAL FACTORS AFFECTING FORMATION OF ZEOLITES

The paragenetic relationships as shown by the authigenic silicate minerals in the zeolite facies of Lake Tecopa suggest that the following factors are responsible for the observed mineralogy: activity of SiO_2 , activity of H_2O , $\text{Na}^+ + \text{K}^+ : \text{H}^+$ activity ratio, and $\text{K} : \text{Na} + \text{Ca} + \text{Mg}$ ratio. Age relationships as observed in thin sections indicate that the sequence of formation was montmorillonite, phillipsite, and then erionite or clinoptilolite.

The tuffs of Lake Tecopa are interbedded with relatively impermeable mudstones and after deposition may have behaved as closed systems, consisting of rhyolitic glass and the connate water. The early formation of montmorillonite probably was favored by a relatively low $\text{Na}^+ + \text{K}^+ : \text{H}^+$ activity ratio (Hemley, 1962). This activity ratio would have been at its lowest level at the time of deposition. Subsequent solution of glass or the formation of montmorillonite by an initial marginal hydrolysis of the glass would cause an increase in the pH and the concentration of alkali ions (Hay, 1963a, p. 240); the increase would raise the $\text{Na}^+ + \text{K}^+ : \text{H}^+$ activity ratio of the pore water and provide an environment more suitable for the formation of zeolites than of additional montmorillonite.

Solution of the rhyolitic glass by moderately alkaline and saline pore water provides the materials necessary for formation of the zeolites. Deffeyes (1959a, p. 607) emphasized that zeolites form during diagenesis—not by devitrification of the shards but by solution of the shards and subsequent precipitation of zeolite from the solution. Solutions of shards by the pore water is dependent upon the size and surface area of the shards. Small or pumice shards dissolve before large or platy shards. Some zeolites in the tuffs at Lake Tecopa precipitated in cavities formed by complete solution of shards (fig. 19), but other zeolites apparently formed contemporaneously with solution of the shards. Relict glass is common in those zeolitized tuffs near the outer margin of the zeolite facies.

Inasmuch as the zeolites of Lake Tecopa differ noticeably in chemical composition (tables 8 and 9), the

following factors may influence which zeolite will form: activity of SiO_2 , activity of H_2O and the $\text{K} : \text{Na} + \text{Ca} + \text{Mg}$ ratio of the pore water. Where relationships are clear, petrographic evidence indicates that phillipsite consistently formed before erionite or clinoptilolite. Table 8 shows that phillipsite is higher in K_2O and H_2O and lower in SiO_2 than either erionite or clinoptilolite. Phillipsite, then, should be favored over erionite or clinoptilolite by a relatively high $\text{K} : \text{Na} + \text{Ca} + \text{Mg}$ ratio, high activity of H_2O , and (or) low activity of SiO_2 . Such conditions may have prevailed during early diagenesis in tuffs of the zeolite facies.

Continued solution of rhyolitic glass coupled with the early formation of phillipsite in a tuff probably would enrich the pore water in SiO_2 and $\text{Na} + \text{Ca} + \text{Mg}$. The activity of SiO_2 may thus increase, and the $\text{K} : \text{Na} + \text{Ca} + \text{Mg}$ ratio decrease, to levels suitable for the formation of erionite and clinoptilolite rather than phillipsite. This enrichment of SiO_2 and $\text{Na} + \text{Ca} + \text{Mg}$ probably can attain higher levels in thick rather than thin tuffs and may explain why thin tuffs commonly are chiefly phillipsite, whereas thick tuffs commonly contain erionite and clinoptilolite as well as phillipsite.

The presence of locally abundant concretions near the middle of tuff A supports this hypothesis. The concretions (fig. 20) consist of a porous phillipsite core and a clinoptilolite rind and are set in a matrix of clinoptilolite and erionite. Early crystallization of phillipsite to form the cores of concretions would thereby cause enrichment of SiO_2 and $\text{Na} + \text{Ca} + \text{Mg}$ in the pore water of the remainder of the tuff. Crystallization of clinoptilolite and erionite could then proceed in this more favorable environment. The clinoptilolite rind formed where the enrichment of SiO_2 and (or) $\text{Na} + \text{Ca} + \text{Mg}$ was greatest—adjacent to the phillipsite core.

Differences in the H_2O content of the analyzed zeolites (table 8) suggest that the activity of H_2O may exert some control on the formation of zeolites. All the analyzed Lake Tecopa zeolites are deficient in H_2O if the analyses are compared to the ideal formulas of the zeolites; so the progressive decrease in H_2O content from phillipsite to erionite, and then to clinoptilolite may be more apparent than real. Analyses of chabazite and analcime from Lake Tecopa are not available; however, analyses given by Deer, Howie, and Zussman (1963, p. 343, 395) show that the H_2O contents are about 20–22 percent for chabazite and about 8–9 percent for analcime. These values bracket those for phillipsite, erionite, and clinoptilolite. Although the occurrences of chabazite and analcime in Lake Tecopa are few, their areal distribution seems to bracket the other zeolites. Chabazite occurs near the fresh glass-

zeolite facies boundary and consistently occurs with abundant relict glass, whereas analcime occurs near the zeolite-potassium feldspar facies boundary and consistently occurs without relict glass. The salinity of the lake water probably increased basinward; therefore the activity of H_2O of the pore water trapped in the tuffs probably decreased basinward. Other factors may have exerted similar control on the distribution of zeolites, but the original salinity of the pore water may have been responsible, in part, for the observed pattern.

REACTION OF ZEOLITES TO FORM POTASSIUM FELDSPAR

Presumably, potassium feldspar and searlesite could form directly from materials dissolved from rhyolitic glass by the pore water; however, there is no petrographic evidence to suggest that this process was operative in the tuffs of Lake Tecopa. Thin sections of some tuffs, particularly those near the zeolite-potassium feldspar facies boundary, show replacement of phillipsite by potassium feldspar and searlesite, and attest to at least local formation from a zeolite precursor rather than directly from glass. The absence of associated glass and potassium feldspar or glass and searlesite suggests that the process was general at Lake Tecopa.

Formation of potassium feldspar from zeolite precursors in tuffs that were never deeply buried has been documented in recent studies and inferred in others (Hay, 1966a, p. 93–98). Analcime is replaced by potassium feldspar and albite in tuffs of the Green River Formation in Wyoming (Hay, 1965; 1966b), where the formation of feldspars can be correlated with high salinities of the depositional environment. Textural and field evidence also indicates that potassium feldspar formed from early diagenetic clinoptilolite and analcime in rhyolitic tuffs of the Barstow Formation, southern California (Sheppard and Gude, 1965, p. 4).

Zeolites, because of their open structure (Smith, J. V., 1963), would seem to be particularly susceptible to alteration in the diagenetic environment. The initially high salinity of the pore water in tuffs of the potassium feldspar facies probably was the major factor that controlled the alteration. A relatively high salinity would have the effect of lowering the activity of H_2O —a condition that would favor the formation of anhydrous potassium feldspar from hydrous phillipsite or other alkali-rich zeolites.

The $\text{K}^+ : \text{H}^+$ activity ratio and the activity of SiO_2 may also influence the crystallization of potassium feldspar (Hemley and Jones, 1964; Hess, 1966). Hydrolysis experiments by Garrels and Howard (1959, p. 87) indicate that potassium feldspar will form at 25°C in environments having a $\text{K}^+ : \text{H}^+$ activity ratio greater than

about $10^{9.5}$. However, Orville (1964) has shown that in a solution saturated with amorphous SiO_2 , potassium feldspar can form at near-surface conditions when the $\text{K}^+:\text{H}^+$ activity ratio is greater than about $10^{5.6}$. The common association of opal with feldspar in tuffs of the potassium feldspar facies indicates a high level of SiO_2 activity. This high activity of SiO_2 alone probably is not the driving force of the reaction of alkali zeolites to form potassium feldspar because the zeolites, except analcime, are much more siliceous than the feldspar. These zeolites, not feldspar, should be stable at high SiO_2 activities.

The potassium for the authigenic potassium feldspar in the tuffs probably was derived mainly from potassium-bearing zeolite precursors; however, the original source of potassium probably was the rhyolitic glass. Additional potassium may have been supplied by the saline pore water or even by potassium-bearing saline minerals, although there is no evidence for the latter.

Boron, necessary for formation of searlesite in the potassium feldspar facies, probably was derived from the pore water, unless it had been effectively concentrated from the minor amount in the rhyolitic glass (table 4). Inasmuch as borates occur in sedimentary rocks of Tertiary age along the western flank of the Resting Spring Range, about 3 miles northeast of Shoshone (Noble, 1926), boron could easily have been carried into the lake by tributaries of the Amargosa River. Neither borates nor molds or pseudomorphs after borate minerals were recognized in the Lake Tecopa deposits. Searlesite commonly lines or fills irregular cavities and fractures(?) in the tuffs, and, therefore, formed relatively late.

AGE OF ALTERATION

Zeolites can form rapidly from volcanic glass in a saline, alkaline lake. Their formation from rhyolitic glass probably is facilitated by the rapid rate of solution and high solubility of the glass at a pH above 9 (Hay, 1966a, p. 81). Rhyolitic tuffs near the surface of Teels Marsh, a saline, alkaline playa in western Nevada, are altered to zeolites and searlesite. Studies of Teels Marsh by Cook and Hay (1965) suggest that alteration of the uppermost tuff at a depth of less than a foot took 1,000 years or less. Authigenic phillipsite (Hay, 1964, p. 1380) occurs in thin rhyolitic tuffs at several levels in the "Parting Mud" of Searles Lake, which gave carbon-14 dates of about 10,000–23,000 years (Smith, G. I., 1962). Zeolites also have formed within the past 20,000 years in nephelinite tuffs at Olduvai Gorge, Tanzania (Hay, 1963b, p. 1284).

The age of the alteration of the tuffs of Lake Tecopa is not known, except within broad limits. Preservation of original textures and sedimentary structures in the

tuffs indicates alteration after burial. Fragments of zeolitized tuff A are locally common in the veneer of gravel that caps the pediment east of the Amargosa River. Thus, tuff A, as well as all other tuffs, was altered before erosion and incorporation in the gravel. The gravel veneer has since been extensively dissected by the Amargosa River and its tributaries in the most recent cycle of erosion.

REFERENCES

- Bailey, G. E., 1902, The saline deposits of California: California Div. Mines Bull., v. 24, p. 1–216.
- Blackwelder, Eliot, 1936, Pleistocene Lake Tecopa [abs.]: Geol. Soc. America Proc. for 1935, p. 333.
- 1954, Pleistocene lakes and drainage in the Mojave region, southern California, p. 35–40, in Chap. 5 of Jahns, R. H., ed., Geology of southern California: California Div. Mines and Geology Bull. 170.
- Blanc, R. P., and Cleveland, G. B., 1961a, Pleistocene lakes of southeastern California II: California Div. Mines and Geology Mineral Inf. Service, v. 14, no. 5, p. 1–6.
- 1961b, Pleistocene lakes of southeastern California—I: California Div. Mines and Geology Mineral Inf. Service, v. 14, no. 4, p. 1–8.
- Bradley, W. H., 1928, Zeolite beds in the Green River Formation: Science, v. 67, p. 73–74.
- 1930, The occurrence and origin of analcite and meerschaum beds in the Green River Formation of Utah, Colorado, and Wyoming: U.S. Geol. Survey Prof. Paper 158-A, p. 1–7.
- 1964, Geology of Green River Formation and associated Eocene rocks in southwestern Wyoming and adjacent parts of Colorado and Utah: U.S. Geol. Survey Prof. Paper 496-A, p. A1–A86.
- Bury, C. R., and Redd, R., 1933, The system sodium carbonate-calcium carbonate-water: Chem. Soc. [London] Jour., p. 1160–1162.
- California Division of Mines and Geology, 1963, Geologic map of California, Trona sheet.
- Campbell, M. R., 1902, Reconnaissance of the borax deposits of Death Valley and Mohave Desert: U.S. Geol. Survey Bull. 200, 22 p.
- Chesterman, C. W., 1956, Pumice, pumicite, and volcanic cinders in California: California Div. Mines and Geology Bull. 174, p. 3–97.
- Cook, H. E., and Hay, R. L., 1965, Salinity control of zeolite reaction rates in Teels Marsh, Nevada [abs.], in Abstracts for 1964: Geol. Soc. America Spec. Paper 82, p. 31–32.
- Coombs, D. S., and Whetten, J. T., 1967, Composition of analcime from sedimentary and burial metamorphic rocks: Geol. Soc. America Bull., v. 78, p. 269–282.
- Deer, W. A., Howie, R. A., and Zussman, J., 1963, Rock-forming silicates, v. 4, Framework silicates: New York, John Wiley and Sons Inc., 435 p.
- Deffeyes, K. S., 1959a, Zeolites in sedimentary rocks: Jour. Sed. Petrology, v. 29, p. 602–609.
- 1959b, Erionite from Cenozoic tuffaceous sediments, central Nevada: Am. Mineralogist, v. 44, p. 501–509.
- Droste, J. B., 1961, Clay minerals in sediments of Owens, China, Searles, Panamint, Bristol, Cadiz, and Danby Lake basins, California: Geol. Soc. America Bull., v. 72, p. 1713–1722.

- Eakle, A. S., 1898, Erionite, a new zeolite: *Am. Jour. Sci.*, v. 4, p. 66-68.
- Eberly, P. E., Jr., 1964, Adsorption properties of naturally occurring erionite and its cationic-exchanged form: *Am. Mineralogist*, v. 49, p. 30-40.
- Eugster, H. P., and Smith, G. I., 1965, Mineral equilibria in the Searles Lake evaporites, California: *Jour. Petrology*, v. 6, p. 473-522.
- Fahy, J. J., 1950, Searlesite from the Green River Formation of Wyoming: *Am. Mineralogist*, v. 35, p. 1014-1020.
- Foshag, W. F., 1934, Searlesite from Esmeralda County, Nevada: *Am. Mineralogist*, v. 19, p. 268-274.
- Freeth, F. A., 1923, The system $\text{Na}_2\text{O}-\text{CO}_2-\text{NaCl}-\text{H}_2\text{O}$, considered as two four-component systems: *Royal Soc. London Philos. Trans.*, ser. A, v. 223, p. 35-87.
- Garrels, R. M., and Christ, C. L., 1965, Solutions, minerals, and equilibria: New York, Harper and Row, 450 p.
- Garrels, R. M., and Howard, Peter, 1959, Reactions of feldspar and mica with water at low temperature and pressure, in Swineford, Ada, ed., *Clays and clay minerals: Proc. Sixth Natl. Conf. on Clays and Clay Minerals*, p. 68-88.
- Goldsmith, J. R., and Laves, Fritz, 1954, The microcline-sanidine stability relations: *Geochim. et Cosmochim. Acta*, v. 5, p. 1-19.
- Gude, A. J., 3d, and Sheppard, R. A., 1966, Silica-rich chabazite from the Barstow Formation, San Bernardino County, southern California: *Am. Mineralogist*, v. 51, p. 909-915.
- Haines, D. V., 1959, Core logs from Searles Lake, San Bernardino County, California: *U.S. Geol. Survey Bull.* 1045-E, p. 139-317.
- Hay, O. P., 1927, The Pleistocene of the western region of North America and its vertebrated animals: *Carnegie Inst. Washington Pub.* 322-B, 346 p.
- Hay, R. L., 1963a, Stratigraphy and zeolitic diagenesis of the John Day Formation of Oregon: *California Univ. Pubs. Geol. Sci.*, v. 42, p. 199-262.
- 1963b, Zeolitic weathering in Olduvai Gorge, Tanganyika: *Geol. Soc. America Bull.*, v. 74, p. 1281-1286.
- 1964, Phillipsite of saline lakes and soils: *Am. Mineralogist*, v. 49, p. 1366-1387.
- 1965, Pattern of silicate authigenesis in the Green River Formation of Wyoming [abs.], in *Abstracts for 1964: Geol. Soc. America Spec. Paper* 82, p. 88.
- 1966a, Zeolites and zeolitic reactions in sedimentary rocks: *Geol. Soc. America Spec. Paper* 85, 130 p.
- 1966b, Reactions of alkalic zeolites at low temperatures in sedimentary deposits [abs.], in *Abstracts for 1965: Geol. Soc. America Spec. Paper* 87, p. 74.
- Hay, R. L., and Moiola, R. J., 1963, Authigenic silicate minerals in Searles Lake, California: *Sedimentology*, v. 2, p. 312-332.
- 1964, Authigenic silicate minerals in three desert lakes of eastern California [abs.], in *Abstracts for 1963: Geol. Soc. America Spec. Paper* 76, p. 76.
- Hemley, J. J., 1959, Some equilibria in the system $\text{K}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$: *Am. Jour. Sci.*, v. 257, p. 241-270.
- 1962, Alteration studies in the systems $\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$ and $\text{K}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$ [abs.], in *Abstracts for 1961: Geol. Soc. America Spec. Paper* 68, p. 196.
- Hemley, J. J., and Jones, W. R., 1964, Chemical aspects of hydrothermal alteration with emphasis on hydrogen metasomatism: *Econ. Geology*, v. 59, p. 538-569.
- Hess, P. C., 1966, Phase equilibria of some minerals in the $\text{K}_2\text{O}-\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$ system at 25°C ., and 1 atmosphere: *Am. Jour. Sci.*, v. 264, p. 289-309.
- Hey, M. H., and Bannister, F. A., 1934, Studies on the zeolites. Part VII, "Clinoptilolite," a silica-rich variety of heulandite: *Mineralog. Mag.*, v. 23, p. 556-559.
- Hubbs, C. L., and Miller, R. R., 1948, The Great Basin, with emphasis on glacial and post-glacial times. II. The zoological evidence: Correlation between fish distribution and hydrographic history in the desert basins of western United States: *Utah Univ. Bull.*, v. 38, p. 18-166.
- Kerr, P. F., and Langer, A. M., 1965, Mineralogical features of Mojave Desert playa crusts, in Neal, J. T., ed., *Geology, mineralogy, and hydrology of U.S. playas: Air Force Cambridge Research Lab. Environmental Research Papers* 96, p. 31-72.
- Larsen, E. S., and Hicks, W. B., 1914, Searlesite, a new mineral: *Adm. Jour. Sci.*, v. 38, p. 437-440.
- Lipman, P. W., 1965, Chemical comparison of glassy and crystalline volcanic rocks: *U.S. Geol. Survey Bull.* 1201-D, p. D1-D24.
- Mason, Brian, and Sand, L. B., 1960, Clinoptilolite from Patagonia, the relationship between clinoptilolite and heulandite: *Am. Mineralogist*, v. 45, p. 341-350.
- Mason, J. F., 1948, Geology of the Tecopa area, southeastern California: *Geol. Soc. American Bull.*, v. 59, p. 333-352.
- Melchase, John, 1926, Mining bentonite in California: *Eng. Mining Jour.-Press*, v. 121, p. 837-842.
- Millot, Georges, 1962, Crystalline neoformation of clays and silica, in *Proc. Symposium Basic Sci. France and the U.S.*, New York Univ., 1960: New York Univ. Press, p. 180-191.
- Minato, Hideo, 1964, Two zeolites in zeolitic rocks in Japan (Potassium clinoptilolite and powdery mordenite) [abs.], in *Program of Zeolite Symposium, Internat. Mineralog. Assoc.*, New Delhi, India, 1964, p. 3.
- Moyle, W. R., Jr., 1963, Data on water wells in Indian Wells Valley area, Inyo, Kern, and San Bernardino Counties, California: *California Dept. Water Resources Bull.* 91-9, 243 p.
- Mumpton, F. A., 1960, Clinoptilolite redefined: *Am. Mineralogist*, v. 45, p. 351-369.
- Noble, L. F., 1926, Note on a colemanite deposit near Shoshone, California, with a sketch of the geology of a part of Amargosa Valley: *U.S. Geol. Survey Bull.* 785-D p. 63-73.
- 1931, Nitrate deposits in southeastern California, with notes on deposits in southeastern Arizona and southwestern New Mexico: *U.S. Geol. Survey Bull.* 820, 108 p.
- Noble, L. F., Mansfield, G. R., and others, 1922, Nitrate deposits in the Amargosa region, southeastern California: *U.S. Geol. Survey Bull.* 724, 99 p.
- Norman, L. A., Jr., and Stewart, R. M., 1951, Mines and mineral resources of Inyo County: *California Jour. Mines and Geology*, v. 47, p. 17-136.
- Orville, P. M., 1964, Is K-feldspar stable in a near-surface environment? [abs.], in *Abstracts for 1963: Geol. Soc. America Spec. Paper* 76, p. 126.
- Pettijohn, F. J., 1957, *Sedimentary rocks*, 2d ed.: New York, Harper and Brothers, 718 p.
- Regis, A. J., 1961, Sepiolite in the Green River Formation, Sweetwater County, Wyoming [abs.]: in *Program for Annual Meeting Geol. Soc. America, Cincinnati, Ohio, Nov. 1961*, p. 127A.
- Regis, A. J., and Sand, L. B., 1966, K-Na phillipsite, Crooked Creek, Oregon [abs.]: *Am. Mineralogist*, v. 51, p. 270.

- Regnier, Jerome, 1960, Cenozoic geology in the vicinity of Carlin, Nevada: *Geol. Soc. America Bull.*, v. 71, p. 1189-1210.
- Ross, C. S., 1928, Sedimentary analcite: *Am. Mineralogist*, v. 13, p. 195-197.
- Saha, Prasenjit, 1959, Geochemical and X-ray investigation of natural and synthetic analcites: *Am. Mineralogist*, v. 44, p. 300-313.
- Sand, L. B., and Regis, A. J., 1966, An unusual zeolite assemblage, Bowie, Arizona [abs.], in *Abstracts for 1965: Geol. Soc. America Spec. Paper 87*, p. 145-146.
- Schultz, L. G., 1963, Nonmontmorillonitic composition of some bentonite beds: in Bradley, W. F., ed., *Clays and clay minerals: Proc. Eleventh Natl. Conf. on Clays and Clay Minerals*, p. 169-177.
- Shepard, A. O., and Starkey, H. C., 1964, Effect of cation exchange on the thermal behavior of heulandite and clinoptilolite, in *Short papers in geology and hydrology: U.S. Geol. Survey Prof. Paper 475-D*, p. D89-D92.
- Sheppard, R. A., and Gude, A. J., 3d, 1964, Reconnaissance of zeolite deposits in tuffaceous rocks of the western Mojave Desert and vicinity, California, in *Geological Survey research 1964: U.S. Geol. Survey Prof. Paper 501-C*, p. C114-C116.
- , 1965, Potash feldspar of possible economic value in the Barstow Formation, San Bernardino County, California: *U.S. Geol. Survey Circ. 500*, 7 p.
- Sheppard, R. A., Gude, A. J., 3d, and Munson, E. L., 1965, Chemical composition of diagenetic zeolites from tuffaceous rocks of the Mojave Desert and vicinity, California: *Am. Mineralogist*, v. 50, p. 244-249.
- Smith, G. I., 1962, Subsurface stratigraphy of late Quarternary deposits, Searles Lake, California—a summary, in *Short papers in geology and hydrology: U.S. Geol. Survey Prof. Paper 450-C*, p. C65-C69.
- , 1966, Geology of Searles Lake—a guide to prospecting for buried continental salines: in Rau, J. L., ed., *Second Symposium on Salt: Northern Ohio Geol. Soc.*, v. 1, p. 167-180.
- Smith, G. I., and Haines, D. V., 1964, Character and distribution of nonclastic minerals in the Searles Lake evaporite deposit, California: *U.S. Geol. Survey Bull.* 1181-P, p. P1-P58.
- Smith, G. I., and Pratt, W. P., 1957, Core logs from Owens, China, Searles and Panamint Basins, California: *U.S. Geol. Survey Bull.* 1045-A, p. 1-62.
- Smith, J. V., 1963, Structural classification of zeolites: *Mineralog. Soc. America Spec. Paper 1*, p. 281-290.
- Thompson, D. G., 1929, The Mojave Desert region, California: *U.S. Geol. Survey Water-Supply Paper 578*, 759 p.
- Truesdell, A. H., 1966, Ion-exchange constants of natural glasses by the electrode method: *Am. Mineralogist*, v. 51, p. 110-122.
- Tucker, W. B., 1920, Los Angeles field division, Inyo County, California: *California Mining Bur. Rept.* 17, p. 273-305.



