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ORIGIN OF MAGNESIUM CLAYS FROM THE AMARGOSA DESERT, NEVADA

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Abstract—Deposits of sepiolite, trioctahedral smectite (mixed-layer kerolite/stevensite), calcite, and dolomite, found in the Amargosa Flat and Ash Meadows areas of the Amargosa Desert were formed by precipitation from nonsaline solutions. This mode of origin is indicated by crystal growth patterns, by the low Al content for the deposits, and by the absence of volcanoclastic textures. Evidence for low salinity is found in the isotopic compositions for the minerals, in the lack of abundant soluble salts in the deposits, and in the crystal habits of the dolomite. In addition, calculations show that modern spring water in the area can precipitate sepiolite, dolomite, and calcite following only minor evaporative concentration and equilibration with atmospheric CO_2. However, precipitation of mixed-layer kerolite/stevensite may require a more saline environment. Mineral precipitation probably occurred during a pluvial period in shallow lakes or swamps fed by spring water from Paleozoic carbonate aquifers.

Key Words—Dolomite, Kerolite, Mixed layer, Precipitation, Sepiolite, Smectite, Stevensite.

INTRODUCTION

Unusual and economically important clay deposits of Plio-Pleistocene age have been found in the Ash Meadows and Amargosa Flat areas of the Amargosa Desert, Nye County, southern Nevada (Figures 1 and 2). Sepiolite occurs in beds as much as 1.2 m thick. Large deposits of a trioctahedral smectitic clay (mixed-layer kerolite/stevensite) are associated with the sepiolite and with nearby travertine deposits. Papke (1970) first reported the smectitic clay, which he identified as saponite, and suggested that it formed by the alteration of volcanic glass in an alkaline lake. Papke (1972) also first described the sepiolite and indicated that it formed by precipitation from an evaporating saline lake. Post (1978) supported this chemical origin, but Regis (1978) proposed that the sepiolite formed by alteration of Tertiary volcanic sediments by hot, magnesium-rich water. The mixed-layer kerolite/stevensite component of the clay deposits was described by Eberl *et al.* (1982). The present contribution discusses the origin of the Amargosa clays and associated minerals.

GEOGRAPHIC AND GEOLOGIC SETTING

The study area forms a part of the Ash Meadows and Lathrop Wells 15-minute quadrangles and can be divided into the Amargosa Flat (or Dry Lake) area and the Ash Meadows area (Figure 1). Both areas are surrounded by mountains and were covered by a large pluvial lake during the late Pliocene and Pleistocene. This lake probably was divided into smaller lakes as the lake level fluctuated with climatic changes (Smith, 1976: Dudley and Larson, 1976).

Amargosa Flat is now a playa. It is often covered by thin salt encrustations that give it a whitish color. These encrustations indicate that evaporation removes water from this area; however, the playa is not completely enclosed, and occasionally abundant surface runoff drains by an intermittent stream into the Ash Meadows area, and then into the Amargosa River (Figure 1). Ash Meadows is characterized by 20 flowing springs in or near the area. Discharge from these springs was estimated by Walker and Eakin (1963) to be about 17,000 acre-feet/yr. The springs are fed by Paleozoic limestone and dolomite aquifers that are recharged in carbonate rock highlands to the east and north; surrounding hills do not receive enough precipitation to produce such a discharge. Temperatures of the springs range between 21° and 34°C. The present climate of the Amargosa Desert is dry (precipitation = 8–10 cm/yr) and warm (mean annual temperature = 18°C). Evaporation reaches 250 cm/yr (Dudley and Larson, 1976).

The geology and stratigraphy of the study area were discussed by Denny and Drews (1965), Burchfiel (1966), and Naff (1973). The Cambrian Bonanza King Formation, a series of highly fractured carbonate rocks, is the most important aquifer at Ash Meadows.

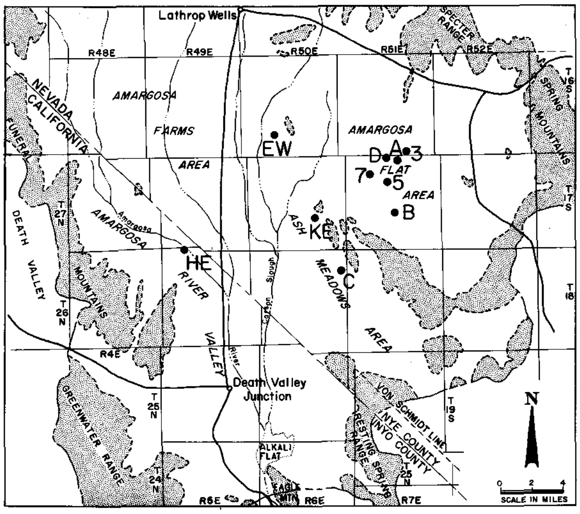

Figure 1. Location of the holes and pits in the study area. The numbers refer to pits; the single letters to holes. KE and EW are the Kinney and Ewing bentonite deposits; HE is the Hectorite-Whiting pit.

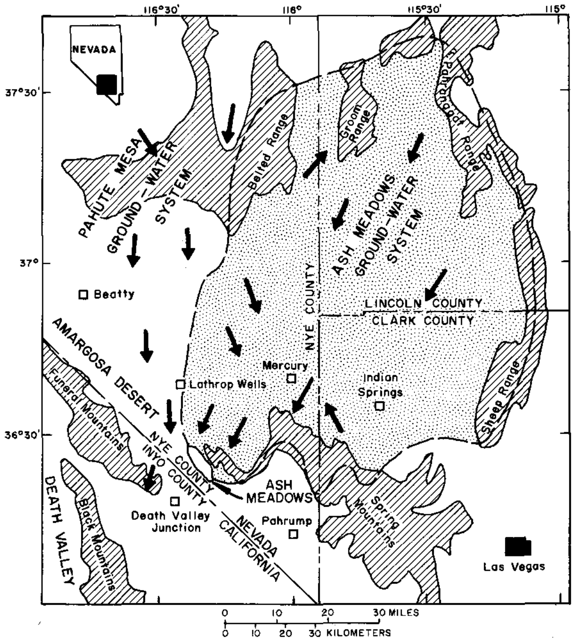

Figure 2. Generalized hydrogeology of the Ash Meadows and part of the Pahute Mesa regional water systems (Dudley and Larson, 1976).

It is overlain by Ordovician, Silurian, and Devonian dolomite and limestone. Tertiary rocks consist of fanglomerates, limestones, siltstones, and fine-grained sandstones. Tertiary tuffs are rare in the study area, but outcrop to the south and west. Tertiary volcanic rocks dip beneath the investigated lake deposits, but they were not encountered in the deepest auger hole (35 m). Quaternary sediments in the area are composed of the travertine and playa deposits investigated in this study. Borehole samples from Ash Meadows (Maxey and Kaufmann, 1972) showed that the playa beds are irregularly deposited in lenses and stringers of relatively limited extent.

HYDROLOGY

Two ground-water basins converge in the southern part of the Amargosa Desert: the Ash Meadows and the Pahute Mesa systems (Maxey and Kaufmann, 1972). The Ash Meadows system discharges water into the Ash Meadows-Carson Slough area, and the Pahute Mesa system discharges into the central and northwestern Amargosa Desert. Winograd and Thordarson (1975) found that the highly permeable Paleozoic carbonate rocks of the study area control the regional movement of the Ash Meadows ground water, funneling it into the major springs at Ash Meadows. Using deuterium as a tracer, Winograd and Friedman (1972) suggested that 65% of this water comes from the Spring Mountains and Sheep Range, 50 to 100 km to the east, and 35% comes from underflow from the Pahranagat Valley, 150 km northeast of Ash Meadows. Tertiary tuffaceous rocks are the principal aquifers for the Pahute Mesa system (Blankennagel and Weir, 1973); general movement of water in both systems is shown in Figure 2.

Winograd and Thordarson (1975) and Winograd and Pearson (1976) found Ash Meadows water to be a calcium-magnesium-sodium bicarbonate type with a pH of 7.4, an alkalinity of 5.04 meq/liter, and a uniform isotopic composition. Pahute Mesa water is characterized by high silica and sodium contents. Its silica content is 60 ppm in the central part of the Amargosa Desert and may be as much as 82 ppm (Naff *et al.*, 1974). The chemistry of well water and springs in the study area was summarized by Dudley and Larson (1976); Table 1 presents compositions from their data for both water systems.

Table 1. Average chemical analyses of water from the study area (after Dudley and Larson, 1976).

Constituent	Ash Meadows System (mean mg/liter)	Pahute Mesa System (mg/liter)
SiO_2	24.6	66.0
Ca	49.8	14.6
Mg	24.3	3.4
Na	75.4	80.3
K	9.4	5.9
Li	0.1	0.1
B	0.4	0.2
NO_3	2.6	8.2
HCO_3	291.6	136.6
SO_4	78.7	28.8
Cl	20.2	6.7
F	2.1	2.5

TECHNIQUES

Channel samples were taken over 15-cm intervals from open pit walls that were exposed during mining, and from auger cores. The locations of pits and auger holes are shown in Figure 1. Most of the holes (A, B, C, D) and pits (3, 5, 7) are in the Ash Meadows groundwater system. The Hectorite-Whiting Pit (HE), however, is probably in the Pahute Mesa ground-water system. Points labeled KE (Kinney) and EW (Ewing) indicate the location of Tertiary bentonite beds that may dip beneath the investigated deposits. All of these deposits were being mined by Industrial Mineral Ventures at the time of the study.

Laboratory techniques included thin section study, X-ray powder diffraction (XRD) analysis, scanning electron microscopy (SEM), and electron microprobe analysis of bulk samples. Eighty thin sections were made from various lithologic units to determine the presence or absence of volcanic glass, the type of non-clay minerals present, and the textural relationship between clay and non-clay minerals. Specimens were impregnated with epoxy before being cut, because the clays (except for a few sepiolite samples) disintegrated in water. Sections were cut without regard to specific orientation.

One hundred samples were examined by XRD analysis. Powdered whole-rock samples were X-rayed from 2° to 65°2θ, using CuKα radiation and a Norelco diffractometer[1] with a scanning speed of 1°2θ/min. Oriented, <2-μm size fractions of these samples were sedimented on glass slides or porous plates and X-rayed from 2° to 32°2θ under the same conditions. The <0.1-μm size fraction of 20 samples was also separated by centrifugation for more detailed mineralogical and chemical investigation.

Semiquantitative mineralogical data were obtained from whole rock samples by comparing their XRD patterns with standards prepared by mixing non-clay minerals and purified clay minerals from the study area. Calibration curves for quartz (using the intensity of the 101 reflection), calcite (104 reflection), dolomite (104 reflection), and sepiolite (110 reflection) were prepared for this comparison. The amount of micaceous material was calculated theoretically from chemical analyses by assigning all of the K_2O to muscovite.

One hundred samples were analyzed chemically with an ARL three-channel microprobe. Polished glass beads were prepared from fused samples by the method of Gulson and Loverings (1968). At least 8 spots were analyzed per sample. Machine conditions were: 20 kV acceleration, 0.20 μA beam current, 2 μm bean diameter, and a counting time of 20 sec/reading. The readings showed high homogeneity for each sample. Volatile content was determined by loss on ignition. Standards from the U.S. Geological Survey and National Bureau of Standards were prepared and exam-

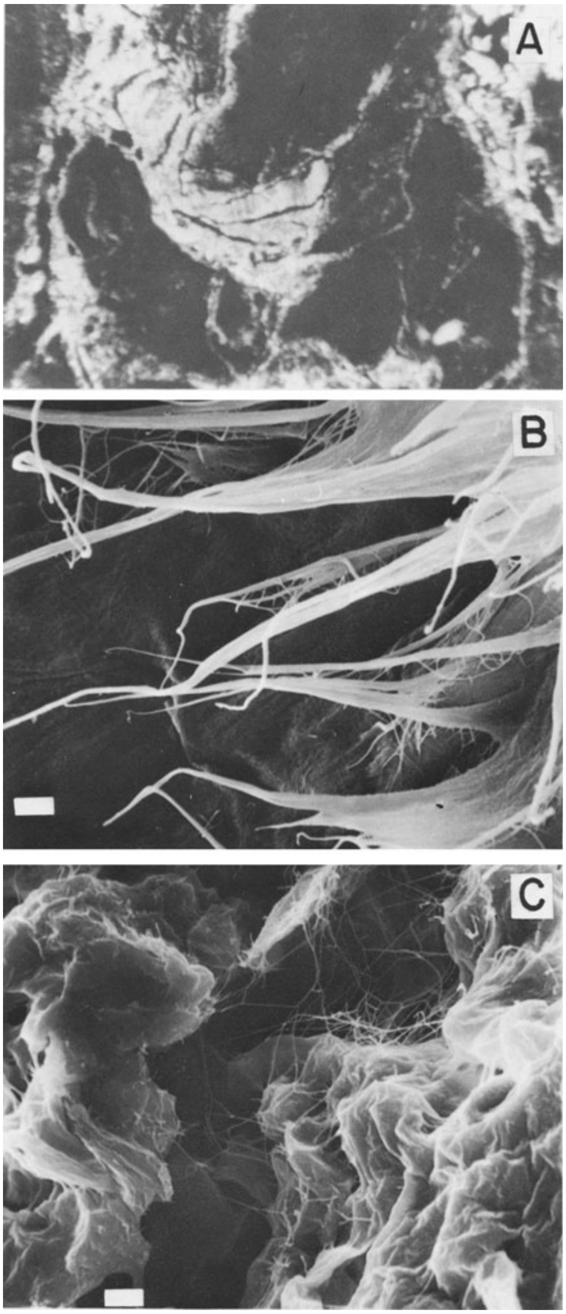

Figure 3. Textures from the sepiolite assemblage. A. Photomicrograph of sepiolite with desiccated and recrystallized texture from pit 2. B. Scanning electron micrograph of parallel to subparallel, long sepiolite fibers from pit 1 (bar = 2 μm). C. Scanning electron micrograph showing desiccation in sepiolite with secondary long, subparallel fibers from pit 2 (bar = 2 μm).

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[1] Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

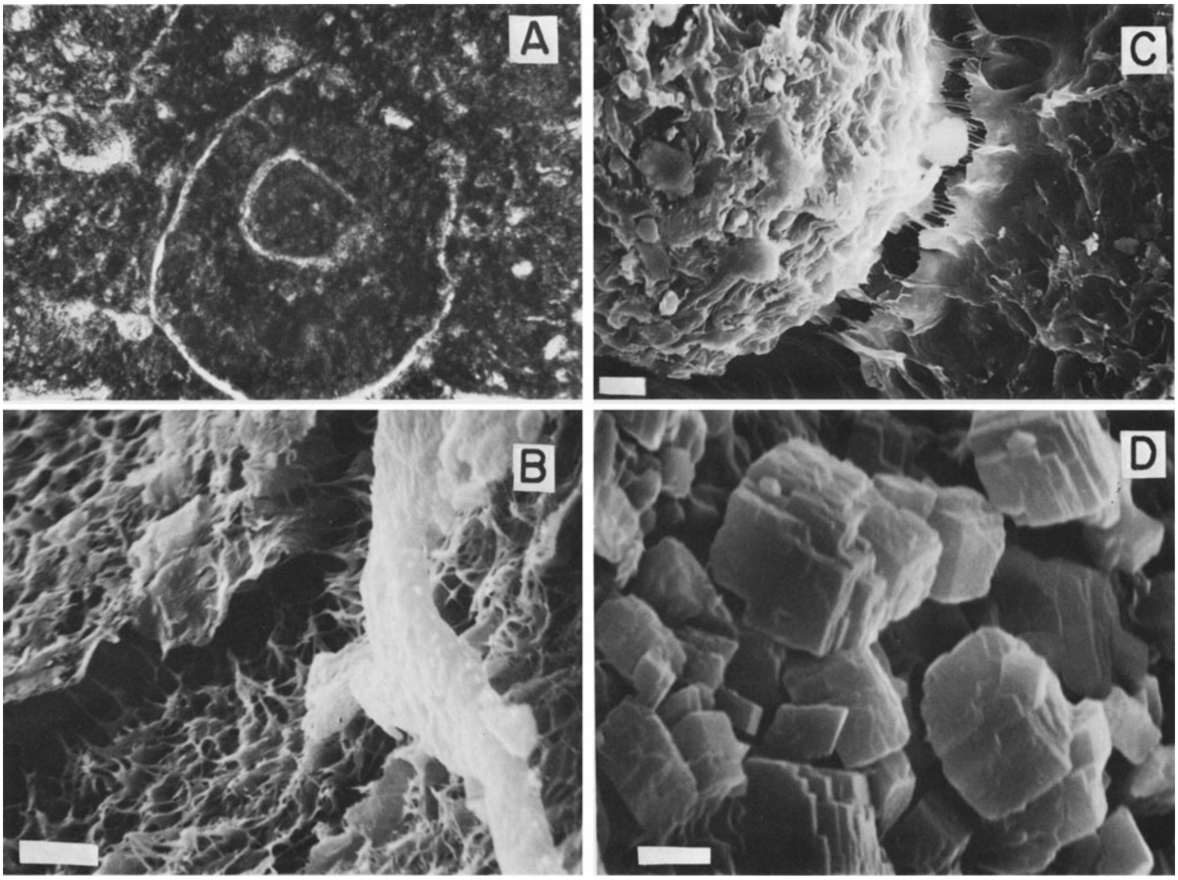

Figure 4. Textures from the smectite-sepiolite assemblage. A. Photomicrograph of desiccated mixed-layer kerolite/stevensite from hole D. Sepiolite (white) fills the cracks and is intermixed with the matrix. B. Scanning electron micrograph showing short fibers of sepiolite intermixed with mixed-layer kerolite/stevensite from hole D (bar = 2 μm). C. Scanning electron micrograph of sepiolite growth along the desiccation planes of mixed-layer kerolite/stevensite from hole D (bar = 4 μm). D. Scanning electron micrograph of euhedral dolomite from pit 5 (bar = 2 μm).

ined under identical conditions. Initial data for standards and samples were corrected for drift and dead-time effects. Calibration curves prepared from the standards for each oxide served as a basis for quantitative analysis of the unknowns. Matrix and background corrections proved to be unnecessary. A few duplicate samples analyzed by the Illinois Geological Survey and the U.S. Geological Survey in Reston, Virginia, showed that the method was accurate.

Eighty samples were examined with a JSM U3 scanning electron microscope. Undisturbed samples were lightly coated with gold prior to examination. Purified clays were also studied to insure that each sample was monomineralic for chemical analysis.

Oxygen and carbon isotopes were determined on carbonates from the <2-μm and the 2–0.2-μm size fractions. Measurements of oxygen and deuterium were carried out on whole rock specimens of high-purity sepiolite. Details of this work will be described in a later paper.

TEXTURES

Three major assemblages of minerals were recognized from holes and pits: (1) A sepiolite assemblage that predominates in the thick, relatively pure sepiolite beds from the Amargosa Flat and Ash Meadows areas; (2) a smectite-sepiolite assemblage that is common in beds underlying and overlying the pure sepiolite beds; and (3) a smectite-travertine assemblage in samples from one of the ancient spring mounds in the area, the Hectorite-Whiting Pit.

Sepiolite assemblage

Petrographic examination showed that intraclasts of sepiolite make up from <5 to 80% of the major sepiolite beds in the study areas. The intraclasts vary from a few micrometers to more than 10 mm in size; in places, laminated intraclasts are embedded in a sepiolite groundmass. Laminated intraclasts of sepiolite fill cavities in the major sepiolite beds. Sepiolite intraclasts are generally subangular to angular, and show a distinct desiccation texture that in places is filled with recrystallized sepiolite (Figure 3A).

Other minerals identified with the petrographic microscope are quartz, biotite, chlorite, sericite, dolomite, and opaque minerals. Their abundance is minor, usually <3% of the samples. The biotite is almost entirely altered to chlorite. The K-feldspar grains are almost all altered to sericite and clay minerals; plagioclase is generally less altered. Non-clay minerals are subangular, and broken crystals are common, suggesting a detrital origin.

The groundmass of the sepiolite rocks is massive and fibrous on a microscopic scale and is characterized by a desiccated texture. Plant rootlets are abundant in all samples, with the exception of the laminated varieties of sepiolite, and the rootlets are commonly filled with quartz, clay minerals, and iron oxides. Glass shards and relict volcanic textures are absent, but rhyolitic rocks most likely supplied the fine, broken, non-clay crystals that were carried into the deposits by streams and by the wind.

SEM of whole rock samples shows two varieties of sepiolite: a long-fiber variety (Figure 3B) that occurs in the thick sepiolite beds, and a short-fiber type (Figure 4B) that is mixed with the trioctahedral smectitic clay. The long-fiber variety occurs in a parallel-to-subparallel pattern, which, with the general intergrowth pattern of the crystals and the lack of a precursor clay mineral, suggests an authigenic origin in which sepiolite precipitated directly from solution. Long, curved fibers also occur along and across desiccated surfaces, suggesting growth from secondary solution (Figure 3C).

Smectite-sepiolite assemblage

Textures of the smectite-sepiolite assemblage are almost the same as those of the sepiolite assemblage. Intraclasts are mostly sepiolite and/or trioctahedral smectite. Some are silty; others are clayey. Some clasts are subrounded to rounded, whereas others form flat pebbles. The clasts vary in size from a few micrometers to 8 mm. Their abundance ranges between 0 and 70% of the major smectite-sepiolite beds.

Monomineralic, detrital grains are similar to those in the sepiolite beds and do not exceed 4% of the whole rock. They consist of partly corroded feldspars and quartz, biotite altered to chlorite, and some muscovite, sericite, and opaque minerals, with a preponderance of broken crystals. The cementing material is mostly calcite and/or dolomite. In some samples, dolomite is more abundant than the Mg-silicate minerals. Calcite also occurs intermixed with the matrix.

As in the massive sepiolite beds, plant rootlets are abundant, pelletoidal texture is not uncommon, and desiccation cracking is evident. Secondary sepiolite fills fractures and concentric desiccation cracks (Figure 4A) and is intermixed with the Mg-smectites. Volcanic glass shards and volcanoclastic textures were not found.

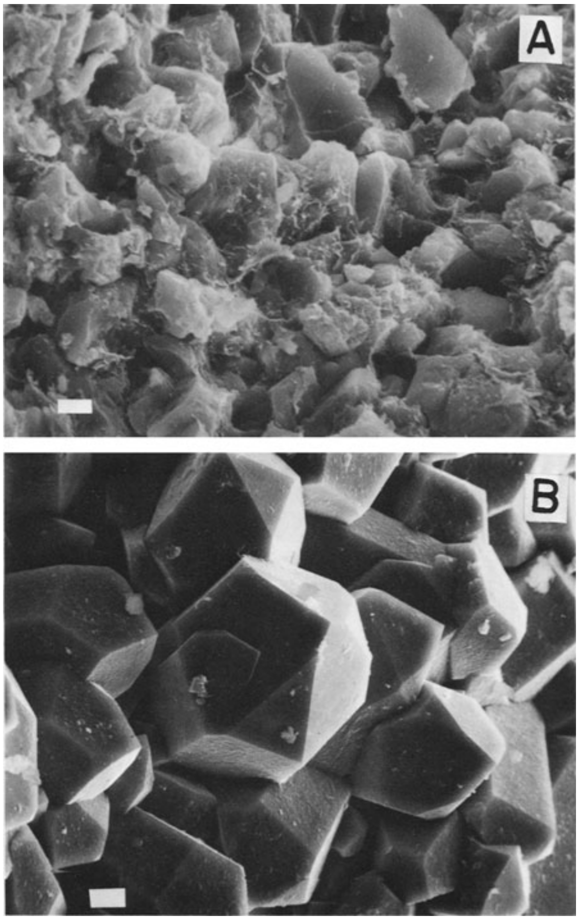

Figure 5. Textures from the smectite-travertine assemblage. A. Scanning electron micrograph of mixed-layer kerolite/stevensite fibers coating calcite rhombs and plates from the Hectorite-Whiting pit (bar = 2 μm). B. Scanning electron micrograph of euhedral quartz filling cavities in the Hectorite-Whiting pit (bar = 4 μm).

SEM reveals a plate-like morphology for the trioctahedral smectite (Eberl *et al.*, 1982). Short fibers of sepiolite appear to have grown from the smectite on desiccation surfaces (Figure 4B and 4C), suggesting that this type of sepiolite possibly formed by the dissolution and recrystallization of trioctahedral smectitic clay.

Authigenic dolomite occurs throughout the deposits, but is most abundant in the smectite-sepiolite assemblage. The authigenic dolomite is white, free from organic material, and may be distinguished by its color from dark detrital dolomite. The latter was derived from the surrounding mountains and is abundant in surface soils. It also occurs as a very minor constituent in the clay deposits.

Authigenic dolomite crystals are distinctly rhombo-

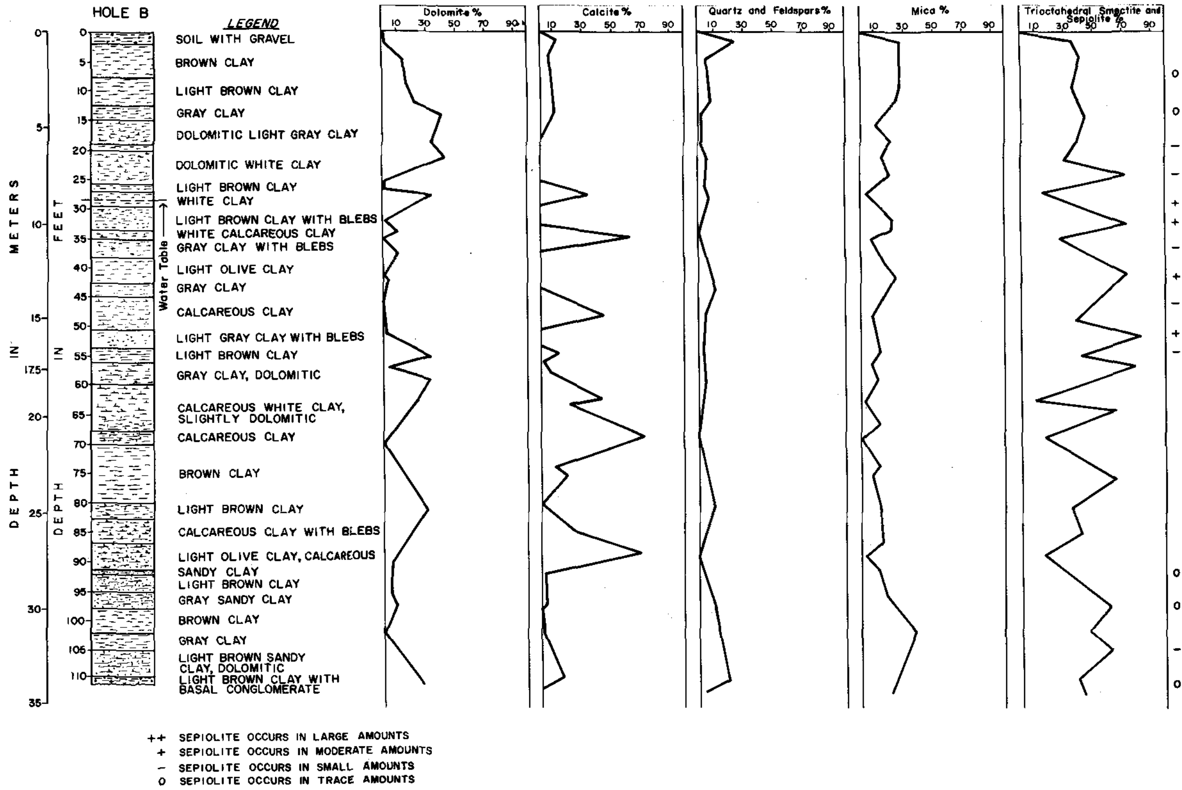

Figure 6. Lithology and mineral distribution in core B.

hedral (Figure 4D), and range in size from <2 μm to 10 mm. Rhombohedral crystals are mixed with and embedded in the Mg-silicate matrix; some occur as rhombohedral clusters with interpenetrating crystal faces. Fine rhombohedral dolomite results from slow crystallization from a highly dilute solution (Folk and Land, 1975). Coarse varieties show evidence of layer-by-layer growth, which, according to Weaver (1975) results from precipitation under near-surface conditions from dilute water in a schizohaline environment, i.e., an environment in which hypersaline water is diluted with fresh water (Folk and Siedlecka, 1974). Calcite also occurs in euhedral crystals.

Smectite-travertine assemblage

Microcrystalline, massive calcite is the major constituent of the smectite-travertine assemblage from the Hectorite-Whiting Pit. Clay minerals occur intermixed with calcite, and/or as cavity-filling material (Figure 5A) with chalcedony and quartz (Figure 5B). Chalcedony and quartz also replace calcite. The travertine appears to have formed by direct chemical precipitation from a previously active spring, with subsequent filling of fractures by silica and clay minerals. SEM reveals that the trioctahedral smectitic clay in this group has a fibrous habit, although XRD studies show that its crystal structure is nearly identical with that of the plate-like trioctahedral smectitic clay found in the smectite-sepiolite assemblage (Eberl *et al.*, 1982).

MINERALOGY

XRD data indicate that mineralogy of the Amargosa Flat and Ash Meadows areas (holes A, B, C, D and pits 3, 5, 7) is very different from that of the Kinney and Ewing bentonites (KE and EW in Figure 1). These bentonites exhibit volcanoclastic textures and are composed primarily of dioctahedral smectite (Khoury and Eberl, 1979, 1981). In contrast, the holes and pits contain trioctahedral smectite, sepiolite, dolomite, and calcite, which (as discussed above) exhibit textures that suggest precipitation from solution. Qualitatively, the mineralogy of core B (Figure 6) is representative of that found in the other holes and pits. It was not possible, however, to correlate mineralogical distributions between holes.

The trioctahedral smectite mineral is mixed-layer kerolite/stevensite (Eberl *et al.*, 1982). Kerolite is a disordered form of talc, and stevensite is a smectite that derives its layer charge mainly from octahedral vacancies. The proportion of kerolite and stevensite layers in the mixed-layer mineral was determined by modeling the structure with a modified version of the computer

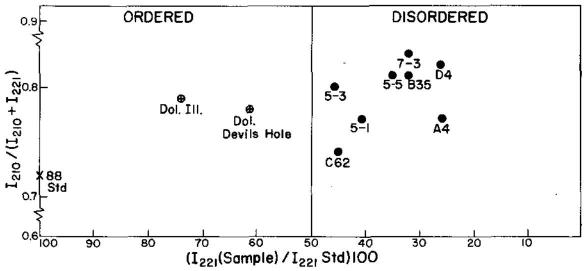

Figure 7. Order-disorder X-ray powder diffraction reflection ratios showing the degree of ordering of dolomite from the study area. Dolomite from the holes and pits lies in the disordered region. Ordered dolomite from the U.S. Bureau of Standards (Std. 88), from Thornton, Illinois (Dol. Ill.), and from Paleozoic rock at Devil's Hole are shown for comparison.

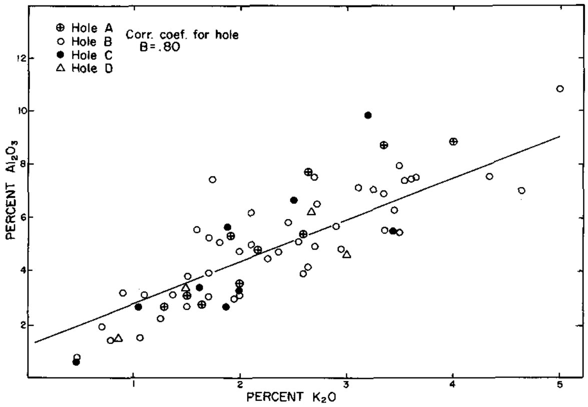

Figure 8. Relationship between Al_2O_3 and K_2O for whole-rock samples.

program of Reynolds and Hower (1970). Some variation in the proportions of kerolite and stevensite was found, but no obvious pattern was noted between kerolite content and depth or areal distribution.

Intraclasts, which are common in core B, have the same mineralogy as the rest of the core. The micaceous mineral in this core is probably detrital because residue from the acid-insoluble residue of Paleozoic carbonates in the study area is chiefly illite. The surface sediment where this hole was drilled is encrusted by efflorescent thenardite, the only quantitatively important soluble salt found in the study area.

The dolomite from the core has a disordered structure. The degree of disorder was calculated by comparing the intensities of the 221 and 210 reflections (Bathurst, 1975). An ordered dolomite (sample 88) from the National Bureau of Standards was used for comparison. Two Paleozoic dolomite samples, one from the study area (Devil's Hole) and one from Thornton (Cook County, Illinois), were also X-rayed (Figure 7). The degree of ordering for dolomite from the core ranges between 26 and 46%, values which are appreciably less than that for Paleozoic dolomite from the study area (63%); these data support the contention that disordered dolomite from the core was not derived from erosion of the surrounding Paleozoic carbonates; but, that it is authigenic.

CHEMISTRY

The distribution of whole-rock chemistry with depth was reported by Khoury (1979). No obvious patterns were noted, except for an inverse relationship between CaO and other oxides that corresponds to an inverse relationship between calcite and other minerals. The chemical data, however, support a nonvolcanic origin for the clays. According to Eberl *et al.* (1982) the purified trioctahedral smectite and sepiolite contain little or no aluminum, suggesting a nonvolcanic origin for the deposits because other deposits in the area that, based on textural criteria, were derived from volcanic ash, have a relatively high Al_2O_3 content. Examples are the two thin, unaltered ash layers found in pit 3 and the Kinney and Ewing bentonites. The ash layers contain 12% Al_2O_3, and the Kinney and Ewing bentonites contain ~15%. The average Al_2O_3 content for core B, even without correction for detrital components, is only 5%. If the clays were formed from volcanic ash, large amounts of Al_2O_3 would have had to have been leached out of the deposit, while at the same time more soluble elements were left behind. It is difficult to reconcile a volcanic origin for the mixed-layer kerolite/stevensite with the presence of the unaltered ash layers in pit 3 that are totally surrounded by the mixed-layered clay.

The linear relationship between the Al_2O_3 and K_2O contents of the cores (Figure 8) suggests that both oxides are present in the same mineral or minerals. XRD data suggest that the dominant Al-K-bearing phase is an illite-like mineral which, as discussed above, is most likely detrital. The presence of small smounts of feldspar lends some scatter to the data in Figure 8.

Chemically, the trioctahedral smectite from travertine deposits at the Hectorite-Whiting Pit is similar to the smectites from the Ash Meadows and Amargosa Flat areas, except that it has about twice the F^- and Li^+ content (Eberl *et al.*, 1982), suggesting that it formed in a solution of a different chemical composition from those that precipitated the lake clays. The presence of authigenic quartz and the deposit's geographic location suggest precipitation from silica-rich Pahute-Mesa water rather than from Ash-Meadows water.

ISOTOPIC COMPOSITION

Details of isotopic work in the study area will be presented in a later paper. The following sumarizes results that pertain to the origin of the deposits.

Dolomite is isotopically enriched in O^{18} and C^{13} with respect to calcite. The mean δO^{18} for dolomite is +24.2‰, and the mean δC^{13} is +0.7‰; whereas, the mean δO^{18} for calcite is +19.51‰, and the δC^{13} is −1.38‰. In a sample in which dolomite and calcite coexist (sample B46, taken at a depth of 9.30–9.45 m from core B), δO^{18} is enriched by 3.5‰ and δC^{13} by 4.5‰ in dolomite with respect to calcite. The enrichment for δO^{18} lies within the range (3–4‰) which has been determined experimentally for the protodolomite-calcite system by Fritz and Smith (1970). The enrichment for δC^{13} (4.5‰) is similar to a value reported by Clayton *et al.* (1968) for coexisting authigenic dolomite and calcite in Deep Springs Lake. Hence, the isotopic data suggest that calcite and dolomite in the study area are authigenic and may have precipitated in isotopic equilibrium.

The isotopic composition of sepiolite is slightly different in the Amargosa Flat and Ash Meadows areas. The mean δO^{18} of sepiolite is +15.7‰ in Amargosa Flat, and +17.0‰ in Ash Meadows. The mean δD is −102‰ in Amargosa Flat and −86‰ in Ash Meadows, a variation that suggests that sepiolite formed under slightly different conditions in the two areas, and that the areas may sometimes have been isolated from each other.

Marine and saline lake minerals are heavier in δO^{18} and δC^{13} than are the average dolomites, calcites, and sepiolites from the study area, suggesting that water in the study area was not saline or hypersaline during mineral precipitation. For example, marine calcite and Deep Springs dolomite have δO^{18} and δC^{13} values of +29.4 and +2.00‰, and +32.95 and +4.00‰, respectively (Clayton *et al.*, 1968). Marine sepiolite reported in Savin (1970) has a δO^{18} value of +32.5‰.

The isotopic composition of water from which the calcite, dolomite, and sepiolite precipitated can be estimated from the appropriate mineral-water fractionation factors by assuming a temperature for precipitation. At 25°C, δO^{18} for the water would be −8.3‰. A model for steady-state evaporation in which half of modern Ash Meadows water is lost by evaporation and half by outflow would yield such an isotopic composition, assuming an isotopic composition for present-day Amargosa water given by Winograd and Pearson (1976), and kinetic isotopic fractionation of this water (oral communication, T. Anderson, Department of Geology, University of Illinois, Urbana, Illinois). If mineral precipitation took place at lower temperature, less evaporation would suffice to yield the −8.3‰ lake water.

DISCUSSION

Considering the present climate, it is surprising that minerals in the Amargosa deposits precipitated from solutions that did not undergo extensive evaporation. The question arises whether these minerals can precipitate from present-day spring water without strong evaporation.

Approximate saturation indices were obtained for the minerals using ion activities calculated from the data in Table 1 with the Debye-Huckel equation at a calculated ionic strength of 0.011, and the thermochemical data found in Garrels and Christ (1965) and Tardy and Garrels (1974). Saturation index is defined as the activity product of a mineral divided by its solubility constant. A saturation index of less than 1.0 indicates that the solution is undersaturated with respect to the mineral. A saturation index greater than 1.0 indicates that the mineral will precipitate, given favorable reaction kinetics.

Calculations for present-day Ash Meadows water at the measured pH of 7.4 for spring water when it leaves the ground gives a saturation index of 0.8 for calcite, 3.48 for dolomite, and 1.5×10^{-3} for sepiolite. Thus, dolomite is the only mineral that should form under present conditions. Extensive evaporation is required to precipitate sepiolite. However, for spring water equilibrated with atmospheric CO_2, the initial pH becomes 8.4, and calcite should precipitate. If the Ca^{2+} and $CO_3{}^{2-}$ activities and pH are controlled by calcite precipitation and the Mg^{2+} activities by dolomite formation, the saturation index for sepiolite increases to 0.8. Such a solution requires only about 10% evaporation to precipitate sepiolite. Alternately, 5% Pahute-Mesa water could be mixed with Ash-Meadows water to exceed sepiolite's solubility product, but such a mixing seems unlikely given the presence of a major ground-water barrier between the two basins (Winograd and Thordarson, 1975, Figure 34, plate 1); or the composition of Ash Meadows water could have been altered as it passed through tuffaceous Tertiary aquitards that lie between the aquifers and the lake deposits, thereby yielding sepiolite without evaporation.

Dolomite is very slow to crystallize at 25°C, but recent experiments (Gaines, 1980) reveal that the rate of dolomite formation is increased by seed crystals, by the presence of small amounts of Li^+, by a Mg^{2+}/Ca^{2+} activity ratio for the solution close to 1.0, and by an oxidizing environment that destroys organic material that inhibits crystallization. These conditions would be met in Ash Meadows water, provided that seed crystals were supplied by the Paleozoic dolomite, because the Mg^{2+}/Ca^{2+} activity ratio calculated from Table 1 is 0.85, the environment is oxidizing, and the authigenic Mg-silicates that occur with the dolomite contain significant lithium (Eberl *et al.*, 1982).

A relationship between sepiolite and mixed-layer kerolite/stevensite is shown in the following reaction. Structural formulae for the minerals are calculated for a fixed anion content from chemical analyses of purified, <0.1-μm material (Eberl *et al.*, 1982). Interlayer cations are assumed to be either Na^+ or Li^+ for simplicity, and interlayer water is ignored:

$$\underline{\text{mixed-layer kerolite/stevensite}}$$

$$2.95(Mg_{2.72}Al_{0.07}Fe^{3+}{}_{0.03}Li_{0.09})(Si_{3.96}Al_{0.04})O_{10}(OH)_2Na_{0.21} + 2.6H_2O + 0.91H^+ \rightleftarrows$$

$$\underline{\text{sepiolite}}$$
$$Mg_{8.00}(Si_{11.68}Al_{0.23}Fe^{3+}_{0.08})O_{30}(OH)_4(OH_2)_4Na_{0.33}Li_{0.02} + 0.02Mg^{2+} + 0.10Al^{3+} + 0.01Fe^{3+} + 0.29Na^+ + 0.25Li^+.$$

Because mixed-layer kerolite/stevensite and sepiolite have nearly the same Mg/Si ratio, Si and most of the Mg are conserved in the solid phases in the above reaction, and the critical factor that determines the final product is the alkali/H^+ ratio of the solution. The above reaction shows that increased evaporation of lake water, with an accompanying increase in alkali activity and pH, would favor the formation of mixed-layer kerolite/stevensite. The importance of pH to this reaction has been established experimentally by Siffert (1962), who found that sepiolite precipitates at pH 8.5, that trioctahedral smectite forms in the same system at higher pH, and that talc precipitates with trioctahedral smectite at a pH higher than 9. Thus, the mixed-layer kerolite/stevensite may represent a more saline environment, a conclusion in harmony with the discovery of small amounts of halite associated with this phase (Eberl *et al.*, 1982). A reaction similar to the above also occurs during hydrothermal alteration of sepiolite (Güven and Carney, 1979).

Textural evidence indicates that sepiolite could not only be precipitated directly from solution, but that it could also be formed from dissolution of mixed-layer kerolite/stevensite. According to the above equation, a secondary solution, such as dilute ground water, which had a lower pH and sodium activity than the original water from which the kerolite/stevensite precipitated, would lead to the formation of secondary sepiolite.

SUMMARY

The study area is currently a desert, although the water table is close to the surface. This water comes from aquifers in Paleozoic rocks that surround and underlie the study area. During times of higher rainfall in the past, increased discharge gave rise to spring-fed lakes and/or swamps. Chemistry of this ancient ground water was probably not much different from that of modern springs, because it moved through the same carbonate aquifers. Thermochemical calculations confirm isotopic and textural evidence that calcite, dolomite, and sepiolite may precipitate from the spring water without strong evaporative concentration. Formation of mixed-layer kerolite/stevensite, however, may require more saline water, perhaps resulting from lake isolation or alteration of the spring water as it passed through tuffaceous Tertiary aquitards.

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Резюме—Отложения сепиолита, трехоктаэдрического смектита (смешанно-слойного керолита/стевенсита), кальцита, и доломита, найденные в районах Амаргоской низменности и пепловых лугов Амаргоской пустыни, были образованы путем осаждения из несоленых растворов. На этот способ происхождения указывают структуры роста кристаллов, низкое содержание Al в отложениях ш отсутствие вулканокластических текстур. Свидетельством низкой солености являются изотопные составы минералов, отсутствие обильных растворимых солей в отложениях и кристаллические черты доломита. Кроме того, расчеты показывают, что современная источниковая вода в районе может осаждать сепиолит, доломит и кальцит после незначительной испарительной концентрации и равновесия с атмосферическим CO_2. Однако, осаждение смешанно-слойного керолита/стевенсита может потребовать более соленой среды. Минеральные осаждения, вероятно, выступили в течение плювиального периода в мелких озерах или топях, питаемых источниковой водой из палеозойских карбонатных водоносных пластов. [E.C.]

Resümee—Ablagerungen von Sepiolith, trioktaedrischem Smektit (Wechsellagerung Kerolit/Stevensit), Calcit, und Dolomit, die in den Gebieten Amargosa Flat und Ash Meadows der Amargosa Wüste gefunden werden, bildeten sich durch Ausfällung aus nicht-salinen Lösungen. Diese Entstehungsart ergibt sich aus der Art des Kristallwachstums, dem niedrigen Al-Gehalt der Ablagerungen und durch das Fehlen von vulkanoklastischen Strukturen. Der Beweis für eine niedrige Salinität ergibt sich aus den einheitlichen Zusammensetzungen der Minerale, aus dem Fehlen überschüssiger löslicher Salze in den Ablagerungen und aus den Arten des Kristallhabitus von Dolomit. Außerdem zeigen Berechnungen, daß aus rezentem Quellwasser dieses Gebietes Sepiolith, Dolomit und Calcit ausfallen kann, was nur von einer geringen Konzentrierung durch Evaporation und von der Gleichgewichtseinstellung mit dem CO_2 der Luft abhängt. Die Ausfällung der Wechsellagerung Kerolit/Stevensit könnte jedoch höher saline Bedingungen erfordern. Diese Mineralausfällung geschah wahrscheinlich während einer pluvialen Periode in seichten Seen odor Mooren, die von Quellwasser aus paläozoischen, karbonathaltigen wasserführenden Schichten gespeist wurden. [U.W.]

Résumé—Des dépôts de sépiolite, de smectite trioctaèdre (kérolite/stevensite à couches melangées), de calcite, et de dolomite, trouvés dans les régions de l'Amargosa Flat et d'Ash Meadows du désert d'Amargosa ont été formés par la précipitation de solutions non-salines. Ce mode d'origine est indiqué par les dessins de croissance cristallographique, par le bas contenu en Al des dépôts, et par l'absence de textures volcanoclastiques. L'évidence pour la basse salinité est trouvée dans les compositions isotopiques pour les minéraux, dans le manque d'abondants sels solubles dans les dépôts, et dans les habitudes cristallographiques de la dolomite. De plus, des calculs montrent que de l'eau de source moderne dans la région peut précipiter la sépiolite, la dolomite, et la calcite suivant une concentration évaporative mineure et l'equilibration avec du CO_2 atmosphérique. La précipitation de kérolite/stevensite à couches melangées peut cependant exiger un environement plus salin. La précipitation des minéraux s'est probablement passée pendant une période pluviale dans des lacs peu profonds ou dans des marais nourris d'eau de source provenant des aquifères carbonates paléozoiques. [D.J.]