SEPIOLITE IN THE AMBOSELI BASIN OF KENYA: A NEW INTERPRETATION

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ABSTRACT

The Sinya Beds of Kenya (lower? Pleistocene) are spring-related deposits of the Amboseli Lake Basin. They contain both bedded waxy sepiolite and meerschaum, a massive lightweight porous sepiolite. The meerschaum deposits are largely restricted to the crestal area of the Sinya Dome, which is about 760 x 215 m in areal extent. Here the Sinya Beds consist of 1.5 - 5 m of dolomitic caliche breccia, mostly in the form of dome- and mound- shaped masses, overlain by 1-3 m of intensely folded and fractured waxy bedded sepiolite. Meerschaum occurs as irregular pockets and small veins, most of which are in the caliche breccias.

The meerschaum-bearing part of the Sinya Beds originated as follows. First, sepiolite and carbonate were precipitated along the southeast margin of the lake basin, which was fed by springs from Kilimanjaro. This sepiolite is of the bedded, waxy variety. Slight uplift of the Sinya Dome raised the crestal deposits above the water table. The caliche breccias were formed within the sepiolitic clays by evaporation of ground water in the vadose zone. Precipitation of carbonate was localized over permeable zones (fractures?), resulting in caliche-breccia mounds and domes, the growth of which folded and fractured the overlying clays. Meerschaum was precipitated from ground water in the caliche breccias and overlying clays, very likely following a rise in the water table.

INTRODUCTION

Scope and Purpose

The oldest Pleistocene deposits of the Amboseli Basin contain two varieties of sepiolite. That of economic importance is meerschaum, a massive, pure, lightweight form used for the manufacture of high-quality pipes. More common is a denser, waxy bedded sepiolite that has not been utilized economically. Dolomite is the host rock for most of the meerschaum. The Kenya deposits have been studied by geologists of the Kenya Geological Survey (Williams, 1972) and by R. K. Stoessell (Stoessell, 1977; Stoessell and Hay, 1978). The senior author visited these deposits only briefly in 1975 with Stoessell. Stoessell discovered kerolite, a hydrated disordered variety of talc, and proposed a geochemical and hydrologic explanation for the origin of the sepiolite, kerolite, and dolomite.

New insight on the origin of the Amboseli deposits arose in the course of studies on Mg-silicate clays and carbonates in the Amargosa Desert of Nevada and California (Hay et al., 1980; Teague, 1981). The present paper is essentially a reinterpretation of the field data already established by Williams (1972) and Stoessell and Hay (1978).

Geologic Setting

The Amboseli Basin is semiarid and covers an area of about 400 km^2 on the Kenya-Tanzania border. The western half is dominated by a playa, Lake Amboseli, which bears water only during the rainy season. The basin (Fig. 1) is bordered on the north by hills of Precambrian metamorphic rock and on the south by Mt. Kilimanjaro, which consists largely of alkaline lavas, principally olivine basalts. Mt. Kilimanjaro is a major source of water, which flows into the basin as streams and ground water.

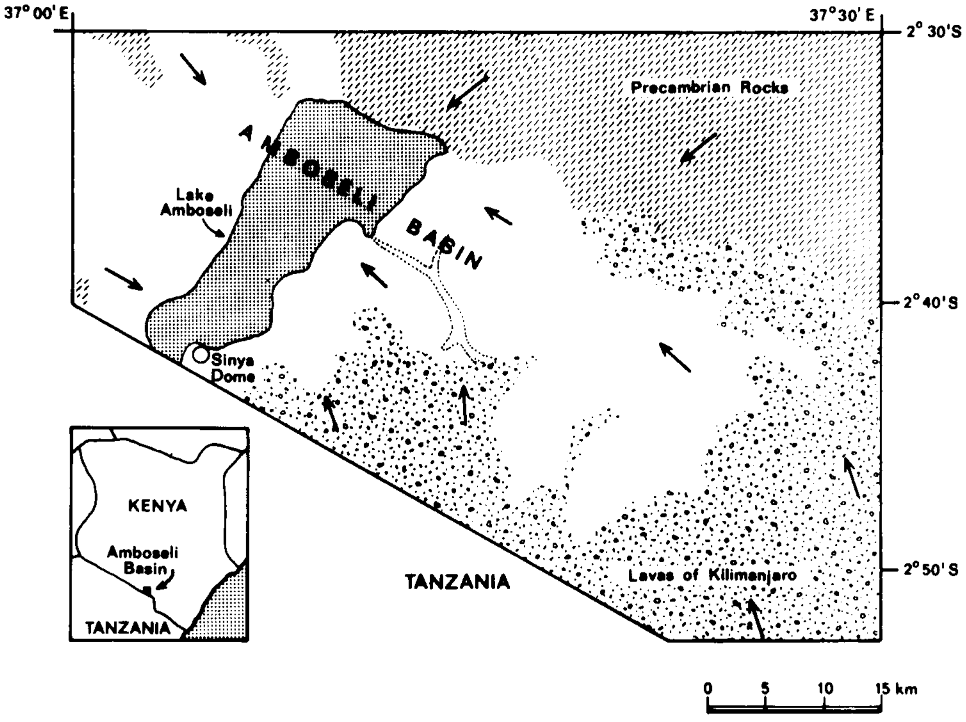

Fig. 1. Map of the Amboseli Basin in Kenya, after Williams (1972) and Stoessell (1977). Arrows indicate regional flow pattern of surface and subsurface water.

Lake sediments of Pleistocene Age comprise three stratigraphic units (Williams, 1972). The lowest is the Sinya Beds, which are exposed principally on the crest of an anticline named the Sinya Dome, near the southern edge of the basin. The maximum known thickness of these beds, penetrated by drilling, is 18 m. The Amboseli Clays unconformably overlie the Sinya Beds in the vicinity of the Sinya Dome and underlie the present lake basin at shallow depth. A maximum thickness of about 60 m was estimated by Williams (1972). These are sepiolitic clays with authigenic calcite, dolomite, gaylussite, and K-feldspar. Illitic clay is widespread and may be detrital, authigenic, or both. The Ol Tukai Beds are the youngest Pleistocene unit. These comprised silts, clays, clay-clast aggregates and caliches. The formation is found in the southern part of the basin and has a maximum thickness of about 8 m. Authigenic minerals include sepiolite, analcime, opal, and calcite.

THE SINYA BEDS

The Sinya Beds are found in both Kenya and Tanzania, but only the Kenya deposits are considered in this paper. They are exposed principally in excavations on the crest of the Sinya Dome, which is about 760 m long and 215 m wide (Williams, 1972). Here the exposed beds consist of about 1.5 - 5 m of nodular and brecciated dolomite, mostly in the form of elongate mounds or domes, overlain by 1-3 m of statified waxy sepiolite that is intensely folded and fractured. Dolomite breccia characteristically forms the cores of anticlines (Fig. 2) and may occur as irregular masses within deformed sepiolite. Dolomite masses are in places thrust over crumpled beds of sepiolite. The pattern of folding is highly variable, but Williams (1972) noted some evidence that minor flexures radiate out from the core of the Sinya Dome.

Meerschaum occurs as irregular masses and small veins, most commonly filling the space between nodules and blocks of dolomite. It forms lenticles and veins along fractures in the waxy sepiolite. The meerschaum is generally undeformed, although Williams (1972) noted fracture-filling meerschaum with lineated surfaces suggesting movement after deposition. The amount of meerschaum is small relative to the dolomite and waxy sepiolite, and J. Walsh (in Williams, 1972) has estimated 7.3 kg of meerschaum per cubic m of host rock. Kerolite locally occurs around the sepiolite, separating it from the dolomite (Stoessell and Hay, 1978).

The waxy, bedded sepiolite is green or greenish gray, locally rootmarked, and contains thin veins of dolomite and calcite. The sepiolite is in places surrounded by thin sheets of waxy kerolite, which is pale grey to pastel green. The contact may be gradational over a distance of 1 or 2 cm, and the kerolite may well be an alteration product of the sepiolite (Stoessell, 1977;

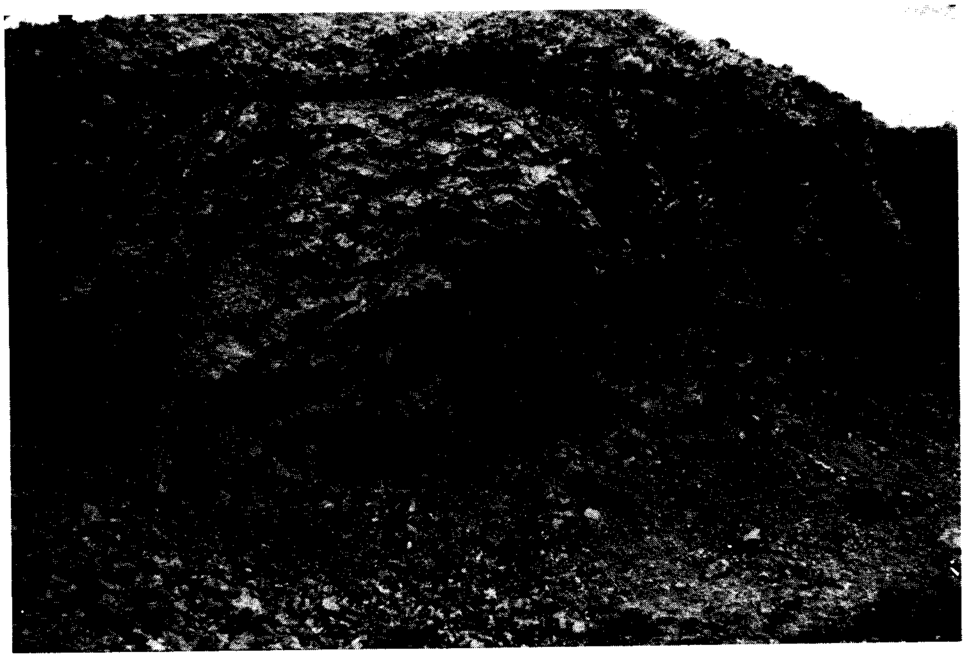

Fig. 2. Exposure of the Sinya Beds in an excavation on the crest of the Sinya Dome. In center of photograph is a caliche breccia dome forming the core of an anticline and flanked by intensely deformed clays. At top a layer of rubble overlies the Sinya Beds. This exposure of the Sinya Beds is about 3 m high.

Stoessell and Hay, 1978).

The meerschaum, waxy green sepiolite, and kerolite are relatively pure Mg-silicate clays (Table 1). Bulk samples of meerschaum have 0.2 to 1.8 percent Al_2O_3 and 0.5 to 1.0 percent FeO + Fe_2O_3 (Williams, 1972; Stoessell and Hay, 1978). A sample of waxy green sepiolite has 1.8 percent Al_2O_3 and 0.1 to 0.7 percent FeO + Fe_2O_3. The amount of K_2O ranges from 0.2 to 1.0 percent and roughly correlates with the amounts of aluminum and iron. This relation suggests the presence of a small amount of clay mica, possibly phengitic illite.

The dolomitic breccias consist of angular blocks and irregular to subrounded nodules as much as 30 cm in average diameter. Their surfaces commonly have a reticulate pattern of surface cracks, which may be filled by meerschaum (Stoessell and Hay, 1978). Adjacent blocks and nodules generally fit together, indicating only slight displacement. Shearing is widespread and widely parallels the margins of the breccia domes giving the appearance of

TABLE 1.

Chemical Composition of Sediments of the Sinya Beds[b]

	s.d.[a]	1	2	3	4
SiO_2	0.09	53.70	53.17	54.51	3.66
TiO_2	0.01	0.12	0.17	0.03	0.01
Al_2O_3	0.04	1.15	1.76	0.49	0.18
Fe_2O_3	0.02	0.64	0.99	0.10	0.09
FeO		0.02	0.04		
MnO		0.00	0.01	0.00	0.00
NiO		0.000	0.000	0.000	0.0005
MgO	0.05	23.31	24.70	28.01	20.11
CaO	0.02	0.03	0.23	0.52	31.48
Na_2O	0.02	0.67	0.45	0.85	0.06
K_2O	0.03	0.61	0.97	0.26	0.01
P_2O_5		0.02	0.04	0.03	0.06
$H_2O^+ + CO_2$		9.83	8.29	7.97	44.78
H_2O^-		9.76	8.79	7.18	0.38
Total		99.86	99.61	99.95	100.83

a. Standard deviations were computed from duplicate analyses of major oxides on all samples.

b. R. Stoessell did the analyses using a modified procedure of Shapiro and Brannock (1962). Totals of H_2O^+ and CO_2 were computed using ignition loss with a correction for FeO.

Sample 1 is fracture-filling massive white sepiolite (meerschaum); 2, massive green sepiolite of the bedded clays; 3, gray kerolite; 4, dolomite. Samples 1 and 3 represent the purest specimens collected of sepiolite and kerolite, respectively. The computed formula for the white sepiolite (no. 1), based on 8 oxygens to balance all cations except H^+, is

$$(Mg_{1.90}Na_{0.07}K_{0.04})\ (Si_{2.94}Al_{0.08}Fe_{0.03})O_{7.5}(OH).3.07H_2O.$$

Similarly, the computed formula for the kerolite (no. 3), based on 11 oxygens, is

$$(Na_{0.12}K_{0.03}Ca_{0.04})\ (Mg_{2.29})\ (Si_{3.91}Al_{0.04}Fe_{0.01})O_{10}(OH)_2.2.62H_2O.$$

Fe in the formulas refers to Fe^{3+}.

anticlinal folding. Some of the blocks and nodules of dolomite contain rounded, sharp-margined masses of waxy sepiolite as much as a cm in diameter. The dolomite also contains finely disseminated Mg-silicate clay. The one sample studied in detail contains 10 percent of a trioctahedral smectite. This smectite is very likely stevensite (Mg smectite) in view of the very small amounts of Al and Fe in the analyzed dolomite Table 1, no. 4).

As shown by drill cores, the Sinya Beds on the flanks and away from the dome consist principally of clay and mudstone, much of which contains carbonate (dolomite?), and at least some of which is sepiolitic (Williams, 1972). Meerschaum was found in a single drill hole away from the crest of the dome. The dolomitic breccias are apparently restricted to the crest of the dome.

GEOCHEMISTRY

At temperatures and pressures corresponding to near earth-surface conditions, the initial formation of magnesium silicates is determined by reaction kinetics rather than chemical stabilities. Preliminary stability relations between Amboseli cryptocrystalline sepiolite and kerolite were reported by Stoessell (1977) from 25°C and 1 bar. These hydrolysis experiments lasted 13 months for sepiolite and 6 months for kerolite. For each mineral, experiments were run in 5 solutions with starting compositions ranging from acidic to basic. The results implied equilibration with kerolite in solutions having a final pH less than 8 and equilibration with sepiolite in more basic solutions. The thermodynamic log K values for sepiolite ($Mg_2Si_3O_{7.5}(OH).3H_2O$) and kerolite ($Mg_3Si_4O_{10}(OH)_2.nH_2O$) were 15.50 ± 0.21 and 23.54 ± 0.19, respectively, for the following reactions:

$$\text{sepiolite} + 4H^+ = 2Mg^{2+} + 3SiO_2 + 5.5H_2O$$

$$\text{kerolite} + 6H^+ = 3Mg^{2+} + 4SiO_2 + (4+n)H_2O$$

The value for sepiolite is thermodynamically consistent with the 1 bar solubility data at 51° and 90°C reported by Christ, Hostetler, and Siebert (1973). We know of no other experimental data for kerolite. These results are tentative, and final experimental data (8 year equilibrations) will be reported later by the junior author.

The K values imply sepiolite is metastable with respect to kerolite, and both are metastable with respect to talc. Sepiolite is stable with regard to serpentine at aqueous silica activities greater than quartz saturation. Only at very high silica activities (greater than amorphous silica saturation) does sepiolite become more stable than kerolite and talc. The rather common low temperature formation of sepiolite must then be due to kinetic inhibitions in the formation of other magnesium silicates.

Water chemistry data for 23 samples taken within Amboseli Basin were reported by Stoessell and Hay (1978). The water samples range in solutes from 60 to 7,000 parts per million (ppm). These data show a general increase in $a_{Mg^{2+}}/(a_{H^+})^2$ and a_{SiO_2} in water moving towards the lake bed. Two parallel trends were observed, one for surface water and one for ground water. Twelve of the samples were supersaturated with respect to both sepiolite and kerolite. Significant formation of Mg silicates appeared to occur at pH values greater than 7.9 as shown by reversals in activity trends. This supports the experimental observation by Siffert (1962) that a pH of at least 8 is necessary to nucleate sepiolite.

Field relations at Amboseli imply kerolite formed later than waxy sepiolite and sometimes as a sepiolite alteration product. The present-day ground water compositions in the Sinya Beds have high concentrations of Mg (> 10 ppm) and SiO_2 (> 60 ppm), pH between 7.9 and 8.3, and total dissolved solid contents below 1000 ppm. The experimental data of Stoessel (1977) are consistent with kerolite nucleation below a pH of 8. For these reasons, we would hypothesize kerolite forming in contact with slightly basic waters of low salinity. These waters contain Mg and SiO_2 derived from leaching the olivine basalts of Mt. Kilimanjaro. The lack of Al in detrital material within the predominantly carbonate Sinya Beds prevents the formation of saponites or palygorskite, resulting in relatively pure magnesium silicates.

We want to emphasize that the formation of Mg silicates at Amboseli is a problem of reaction kinetics, not chemical stability. Waters in the basin become supersaturated as a result of normal weathering processes. Because kerolite is more stable than sepiolite, increases in $a_{Mg^{2+}}$, a_{SiO_2}, and pH will increase the thermodynamic potential to transform sepiolite into kerolite. However, thermodynamics tell us only the reaction direction, not the reaction kinetics. We do know that to precipitate kerolite directly requires very high supersaturation (Jones, 1982). This is probably not the case for transformation from a precursor such as sepiolite or stevensite. The nature of the precursor will have an important effect on the reaction kinetics.

The kinetic importance of pH in the formation of Mg silicates is not yet understood. The effect of pH on kerolite formation may have to do with the kinetics of transformation of the precursor. In the hydrolysis experiments of Stoessell (1977), the reaction kinetics decreased significantly with increases in pH. Our conclusion that a high pH is not necessary to form significant amounts of kerolite is based on preliminary experimental results, the present-day ground water chemistry within the Sinya Beds, and the assumption that kerolite is presently forming in these beds. Other researchers might disagree. Khoury, Eberl, and Jones (1982) believe kerolite formed in the Amargosa Desert deposits in waters of higher pH and salinity than those presently found in the Sinya Beds at Amboseli. Those conclusions are based on the experimental observation by Siffert (1962) that talc can be precipitated with a trioctahedral smectite at a pH above 9, together with an observed association of small amounts of halite with kerolite and stevensite in the Amargosa Desert deposits. Jones (1982) points out that kerolite is often the result of a reaction between Mg interlayers in a preexisting smectite with aqueous SiO_2. Kerolite in the Amargosa Desert deposits is interstratified with stevensite and may represent an alteration of a preexisting smectite; whereas, at Amboseli, kerolite appears to have often had a sepiolite precursor. These differences in precursors should necessitate different solution compositions to overcome different kinetic contraints.

ORIGIN OF SINYA BEDS

Previous interpretation

The origin of the Sinya Beds is inferred by Stoessell and Hay (1978) as follows.

1. Sepiolite was precipitated along the southern, spring-fed margin of the lake. Water level fluctuated, and at times of low level the sepiolite dehydrated, producing desiccation cracks, and developing a brecciated, nodular texture.
2. The waxy bedded sepiolite which now overlies the dolomite was precipitated in the lake following a rise in level.
3. The lower, fractured sepiolite was dolomitized during a drop in lake level. It was suggested that this ground water was low in silica and derived from recharge areas in Precambrian carbonate rocks to the north. The Mg and SiO_2 released into solution by dolomitization were precipitated as sepiolite in open spaces around the carbonate blocks. The small, rounded masses of waxy sepiolite in some of the dolomite were considered unreplaced relicts of the primary sepiolite. The sharp contact between the dolomite and overlying bedded sepiolite was believed to represent the water table at the time of dolomitization.
4. Doming and intense, smaller-scale deformation were attributed to tectonic activity following deposition of the Sinya Beds.
5. Kerolite was formed from sepiolite by a lowering of pH, essentially as a weathering product.

Revised Interpretation

This new interpretation of the meerschaum-bearing part of the Sinya Beds differs from the earlier one in the origin of the dolomitic breccia and meerschaum, and in the cause and timing of the intense folding of the clays above the dolomitic breccias. The interpretation is as follows.

1. Sepiolite and carbonate (dolomite?) were precipitated along the southern, spring-fed margin of the lake. This sepiolite includes the waxy sepiolite forming the upper part of the Sinya Beds.

2. Slight doming raised the crestal deposits of the Sinya Dome above the water table. Ground water from Kilimanjaro seeped upward through permeable zones, probably fractures, in the crestal area. Nodules of carbonate with disseminated stevensite were formed in evaporation of ground water at or above the water table and within the pre-existing sepiolite clays (Fig. 3). Continued evaporation resulted in the growth of new nodules below those already formed, pushing them upward and deforming the overlying clays. Fractures in the deformed clays would have aided evaporation and localized nodule growth, ultimately resulting in the dome-shaped masses of caliche breccia that form cores of anticlines. Mann and Horwitz (1979) have called upon this mechanism for the growth of steep-sided calcrete (=caliche) domes in western Australia. These domes, like some of the Amboseli domes, have structures engendered by shear and concentric folding due to upward growth pressure. Intense, upward small-scale deformation of the bedded clays is attributed to growth of the domes and irregular masses of caliche breccia. The small rounded masses of waxy sepiolite in some of the dolomite nodules and blocks are considered clasts of matrix clay incorporated during growth of the carbonate. As yet unresolved is whether the caliche breccias were formed directly as dolomite or by dolomitization of calcium carbonate.

3. Meerschaum filling space between dolomite blocks and fractures in folded clays was deposited after growth of the adjacent blocks and folding of the clays. Indeed, most or nearly all of the meerschaum may have been deposited after growth and uplift of the caliche breccias and deformation of the clays. The change in precipitation from carbonate (plus stevensite) to sepiolite may have been caused by a rise in the water table, with the meerschaum deposited from ground water less evaporated that the vadose water from which the caliche breccias were precipitated. Some, at least, of the meerschaum was probably deposited before growth of the caliche breccias had been completed, in view of the lineated (slickensided?) fracture-filling meerschaum noted by Williams. Meerschaum could have been deposited during growth of the caliche breccias as a result of a slight, temporary rise in the water table, followed by a lowering during which more caliche breccia was formed.

4. Doming continued following deposition of the Sinya Beds, and they were eroded in the area prior to deposition of the Amboseli clays. Seams of white sepiolite in the lower part of the Amboseli clays in the crestal area (Stoessel and Hay, 1978) were probably precipitated from ground water seeping along fractures, similar to precipitation of meerschaum in the Sinya Beds.

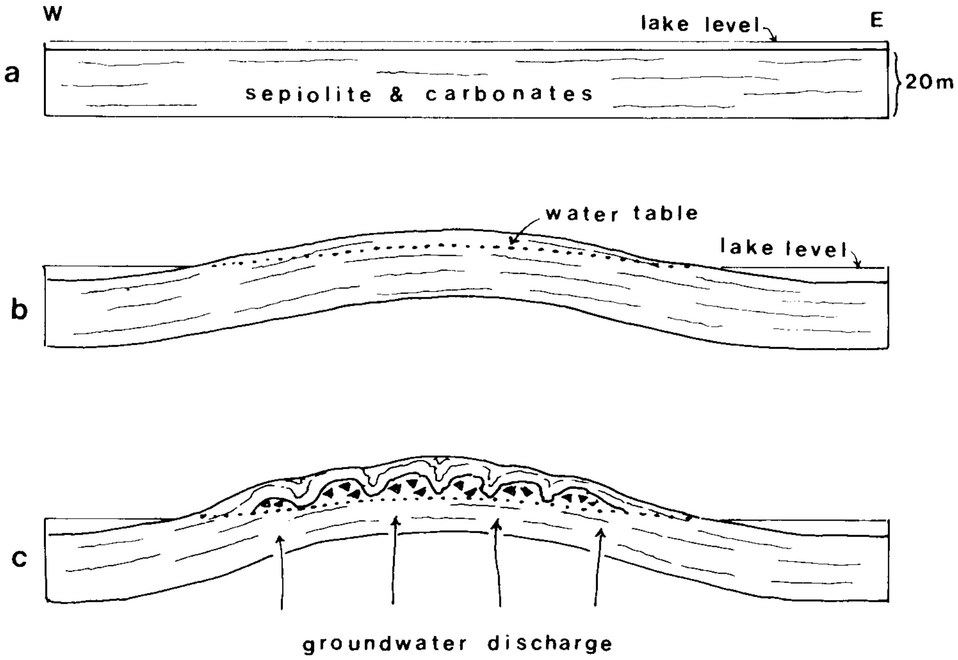

Fig. 3. Schematic east-west cross-section showing the development of the Sinya Dome and caliche breccia masses in the Sinya Beds. Section (a) shows the Sinya Beds prior to folding. Section (b) represents the early stages of doming, and Section (c) is of the dome after folding and shows caliche breccia mounds, which were formed at or above the water table following and possibly during doming. Bedded sepiolite and carbonates above the breccia mounds were deformed by their growth.

COMPARISON WITH AMARGOSA DEPOSITS

Deformation of beds by growth of caliche (= calcrete) from below have been reported by Price (1925), Jennings and Sweeting (1961), and Reeves (1976, p. 60-64). Reeves (1976, Fig. 3-14) and Horwitz and Mann (1979) figure caliche-breccia domes generally similar in texture and structure to those of the Sinya Beds. These domes are, however, smaller than those of the Sinya Beds, and associated Mg-silicate clays were not reported.

Some of the Pliocene and lower? Pleistocene deposits in the Amargosa Desert of southwestern Nevada and southeastern California are strikingly similar in most respects to the Sinya Beds on the crest of the Sinya Dome. The Amargosa Desert was a lake basin in the Pliocene and probably early Pleistocene. Springs supplied large amounts of water to the basin, resulting in large quantities of carbonates and Mg-silicate clays - principally sepiolite and stevensite with interlayered kerolite (Khoury, 1978). Most of the clays were deposited in playa and marshland environments.

Caliche-breccia masses comparable in size to those of the Sinya Beds. are widespread at two places in the desert (Teague, 1981). In the eastern part they form a narrow zone about 1 km long that appears to be localized along a pre-existing fault. Near the southwestern margin they underlie most of an area about 3 km long and 600 m wide. As seen in cross-section, the smaller, better-exposed caliche breccia masses form domes and mounds 2-3 m high and 4-6 m wide. The overlying and adjacent clays are deformed, commonly into anticlines with caliche breccia cores. Some of the caliche breccias form piercement structures. The largest masses, only incompletely exposed in excavations, have eroded tops and are at least 7 m thick. Shearing is common in the larger masses and some of the smaller ones.

The breccias consist of angular fragments and nodules many of which have reticulate surface cracks as in dolomite of the Sinya Beds. The carbonate in the Amargosa breccia can be dolomite, calcite or both. Field relationships suggest that the dolomite has replaced calcite. The carbonate rocks contain an average about 10 percent of disseminated Mg-silicate clay, principally kerolite-stevensite. Interstitial clay is principally kerolite-stevensite but can be sepiolite. With few exceptions the interstitial clay is deformed in folded and sheared zones, showing that most of it had been deposited before growth and displacement of the caliche breccias had been completed.

The Amargosa and Amboseli caliche breccias differ principally in the amount and mineral composition of the interstitial Mg-silicate clay. This may largely reflect a difference in the water composition, with that of the Amargosa deposits derived largely from recharge areas in carbonate rocks whereas that of Amboseli is from volcanic rocks. Hydrologic and climatic differences may have been additional factors, which cannot presently be evaluated.

ACKNOWLEDGEMENTS

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