

CLAY MINERALS OF LAKE ABERT, AN ALKALINE, SALINE LAKE

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Abstract—Mineralogical and chemical analyses of fine clay fractions from in and around Lake Abert, Lake County, Oregon, show that the pyroclastic rocks supplying detritus to the lake weather to a suite of layer silicate clay minerals varying from high-charge dioctahedral montmorillonite to montmorillonite/intergrade smectite-chlorite interstratifications. In the lake these clays extract K, Mg, and Si to form authigenic interstratified illite and a trioctahedral, Mg-rich mineral resembling stevensite in composition. Both the neoformed interstratifications contribute little unambiguously to X-ray powder diffraction patterns, which are dominated by the reflections of detrital clays. From limited data it appears that the illite occurs below 0.8 m depth in sediments of a possibly somewhat fresher (brackish) lake and the trioctahedral interstratification between 0.4 and 0.2 m depth in sediments of a lake of about the same size and salinity (about 30–90 g/kg) as that of the present lake.

Key Words—Chemical analysis, Chlorite, Illite, Interstratification, Montmorillonite, Saline lake, Stevensite, X-ray powder diffraction.

INTRODUCTION

Many studies have shown that the composition of clay minerals in a saline environment is modified by reaction with ions from the solution phase. For example, Millot (1949, 1964) recognized in ancient saline, lacustrine sediments an increase in silica and other cations relative to alumina in smectites from the basin margin to the center. More recent studies of the geochemical evolution of waters and sediments of alkaline, saline lakes suggest that reactions involving silica or silicates remove cations from solution and thus exert a significant effect on the solute budget of lake systems (Jones and Van Denburgh, 1966; Eugster and Jones, 1968, 1979; Jones *et al.*, 1969, 1977; Carmouze, 1976; Eugster and Maglione, 1979). In Lake Chad sediment Gac *et al.* (1977) and Pedro *et al.* (1978) reported the formation of authigenic smectite by an addition of Mg to suspended sediment or of silica to colloidal, iron-rich particulates. In addition, the illitization of detrital smectite with concomitant uptake of Mg was described by Singer and Stoffers (1980) for sediments from Lakes Albert and Manyara in East Africa, and Dyni (1976) and Tettendorst and Moore (1978) described authigenic stevensite from the Eocene Green River Formation in central Utah. Drever (1971, 1974) proposed the diagenetic alteration and Mg enrichment of smectite in anoxic marine sediments as an important control mechanism for the major cation composition of sea water.

A study of the solute budget of saline, alkaline Lake

Abert in south central Oregon (Figure 1) by Phillips and Van Denburgh (1971) and Van Denburgh (1975) showed a rapid and thorough depletion of solute Ca and Mg and a longer term loss of K on inflow to the lake. A concomitant silica loss was thought to be too large to be attributed to diatom activity alone, and it was suggested that whereas Ca formed calcite, K and Mg may have formed silicates in the bottom sediment.

Lake Abert is a remnant of a much larger pluvial lake, Lake Chewaucan. It lies on the downthrown side of a normal fault at the base of the Abert Rim, the scarp face of the adjacent upthrown block. Deike and Jones (1980) showed that the bulk of the fine sediment in the lake enters by mass movement off the steep slopes of the Abert Rim; however, some is the result of run-off from rocks surrounding the playa flats to the north and northwest. The source rocks are Miocene and Pliocene volcanics that range from basalt to rhyolite, but are mainly of intermediate composition.

The aim of the present work is to describe the clay minerals found in Lake Abert and, by comparison with the source rocks, to deduce the extent of the transformation or neoformation that has occurred in the saline waters of the lake.

EXPERIMENTAL PROCEDURE

Sample preparation

Sediment cores from the lake bottom and the playa flats north of Lake Abert (Figure 1) were sub-sampled

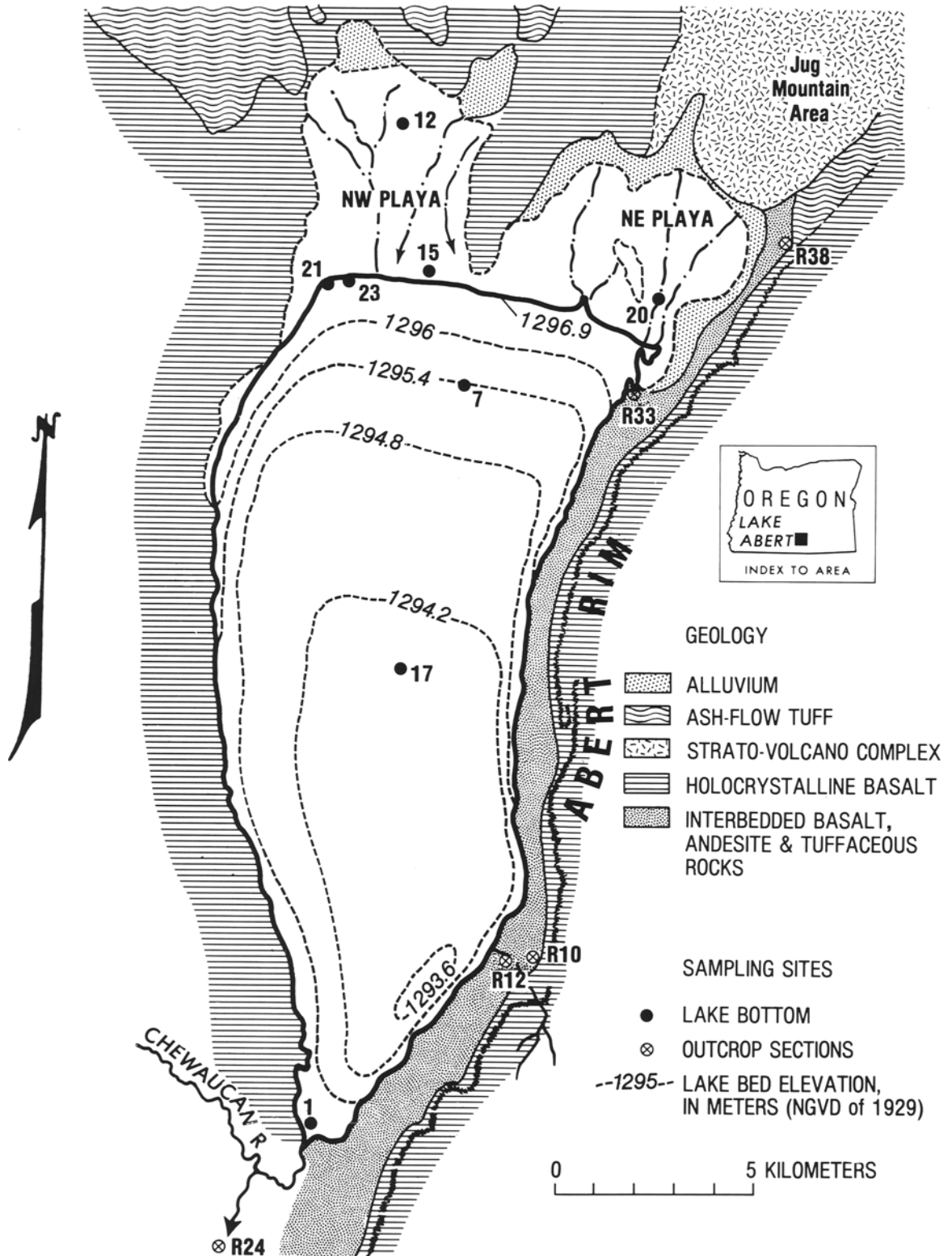


Figure 1. Map of Lake Abert, Oregon, and surrounding area showing the principal lithologies (adapted from Walker, 1963) and the location of sample sites.

Table 1. Rock and sediment samples from Lake Abert area, Oregon.

<i>Weathered rocks</i>	
R10	Light grey to buff, largely devitrified, layered pumiceous tuff underlying massive trachytic andesite, upper one third of Abert Rim.
R12d	Shallow soil developed in a red, scoriaceous, pyroclastic capping of an andesite flow, Lower Abert Rim.
R24	White, altered ash bed within mixed andesitic pyroclastic and flow unit. Crooked Creek at US Hwy. 395, south of the map area in Figure 1.
R33	White to buff ash bed beneath a basaltic andesite flow, 30 m above the lake surface at the base of Abert Rim.
R38	Grey, massive, partially devitrified pumiceous ash and tuff from the northern end of Abert Rim. Probably a rough correlative of the strata yielding sample R10.
<i>Lake bottom and playa sediments</i>	
1e	Dark green to black, faintly laminated clay from 0.43 m below the sediment-water interface, Lake Abert near the mouth of Chewaucan River. Clay content = 47% <2 μm , 6% <0.1 μm .
7q	Dark green, very plastic clay from 0.1 m below the sediment-water interface. Clay content = 60% <2 μm .
12b	Black, massive bottom sediment from a small brine pool on the playa 2 km northwest of the lake. Clay content = 20% <2 μm , 10% <0.1 μm .
15b	Buff to brown, indistinctly laminated, sand- and silt-rich sediment from 0.2 m below the playa surface. Clay content = 15% <2 μm , 2% <0.1 μm .
17i	Dark green to black, faintly laminated clay from 0.40 m below the sediment-water interface in the center of the lake. Clay content = 43% <2 μm .
20i	Green, massive clay from 1.52 m below the playa surface. Clay content = 50% <2 μm .
21cb	Light green, irregularly laminated sediment from 0.25 m below the playa surface close to the northwest lake margin. Clay content = 12% <2 μm , 1% <0.1 μm .
21jb	Light green, slightly banded clay from 0.8 m below the playa surface. Clay content = 53% <2 μm , 4% <0.1 μm .
21jc	Mottled green and black sediment from 1.05 m below the playa surface. Clay content = 37% <2 μm , 7% <0.1 μm .
23de	Dark green to black, massive clay from 2.15 m below the playa surface close to the northwest lake margin. Clay content = 40% <2 μm , 7% <0.1 μm .

to give materials from differing depths in the sediments. The samples were washed with distilled water until they dispersed, and the <2- μm fractions were collected. Preliminary X-ray powder diffraction (XRD) examination showed the presence in these fractions of non-crystalline material, either volcanic glass or diatom fragments, that gave an intense, broad, 4- \AA reflection, together with poorly oriented, expanding layer silicate minerals. Finer fractions (<0.1 μm) showed little evi-

dence of such noncrystalline material. Because the positions and shapes of the principal diffraction maxima were similar in both size fractions the "purer" <0.1- μm fractions were used throughout for the detailed study of the expanding layer silicates. They were separated by ultracentrifugation of suspensions made slightly alkaline with NaOH. The separated clays were then flocculated with NaCl, washed salt-free, dried, and stored in the Na-saturated form. Samples of source rocks and their weathering crusts were taken from the Abert Rim and elsewhere in the vicinity of the lake. Fine clay fractions of the weathering crusts were prepared as described above. Descriptions of all samples are listed in Table 1.

Analytical methods

X-ray powder diffraction (XRD) analyses were carried out using Philips diffractometers with $\text{CuK}\alpha$ or $\text{CoK}\alpha$ radiation either filtered or with a graphite crystal monochromator. Oriented samples were prepared by drying Na-saturated clay sols on rectangular glass plates. Samples were solvated with ethylene glycol vapor for 4 hr at 60°C or heated in air at various temperatures on a heating stage (Brown *et al.*, 1972). The 06l reflections were measured on powder specimens packed into cavity holders.

Infrared (IR) spectra were obtained with a Perkin Elmer 577 infrared spectrophotometer using 2 mg of clay mixed with 170 mg of KBr, pressed into discs, and dried at 150°C.

Major element chemical analyses were made on samples fused with lithium borate and dissolved in acid using adaptations by S. L. Rettig (U.S. Geol. Survey, Reston, Virginia, personal communication) of the methods of Shapiro (1975). Amounts of poorly crystalline material in the clays were measured by acid ammonium oxalate extraction (Schwertmann, 1964).

Particle size distributions were determined by pipette analysis and high-speed centrifugation.

RESULTS

Clay-size material (<2- μm) forms from 5 to 60% and averages 30% of the Lake Abert sediments. The largest clay contents were found in the most recently deposited lake-bottom sediments or in sediments from the playa at depths of >1 m (Deike and Jones, 1980). The <0.1- μm fraction represents 5–15% of the <2- μm clay.

X-ray powder diffractometry

Examination of <2- μm fractions showed a dominance of expanding layer silicates, with some plagioclase and clinoptilolite and minor phillipsite, mica, and kaolinite. Plagioclase, phillipsite, and mica were noted only in the 2- to 0.5- μm fraction, whereas clinoptilolite was found in fractions as fine as 0.25 μm . Kaolinite was detected in very small amounts in some of the <0.1- μm fractions.

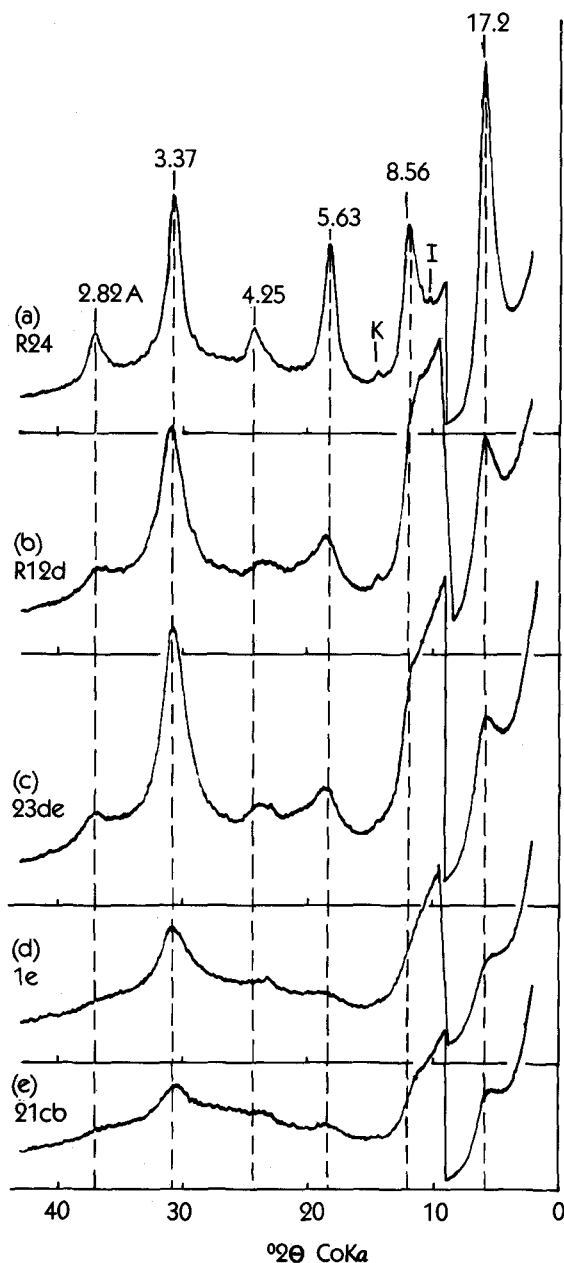


Figure 2. X-ray powder diffractometer traces of Na-saturated, ethylene glycol-solvated, $<0.1\text{-}\mu\text{m}$ fractions of weathered rocks and sediments from the Lake Abert area. K = kaolinite, I = illite. There is a scale change at about $8^\circ 2\theta$ ($\text{CoK}\alpha$).

XRD data for the $<0.1\text{-}\mu\text{m}$ fractions of selected samples are given in Table 2 and Figures 2 to 7. Figure 2a illustrates the XRD pattern of an ethylene glycol solvated smectite, with six orders of the $17.0\text{-}\text{\AA}$ basal reflection, from sample R24, weathered ash of Abert Rim. The most dissimilar pattern to that of sample R24 given by a weathered rock sample is that of sample R12d (Figure 2b). The reflections are less well resolved than those shown in Figure 2a, particularly the second, fourth, and

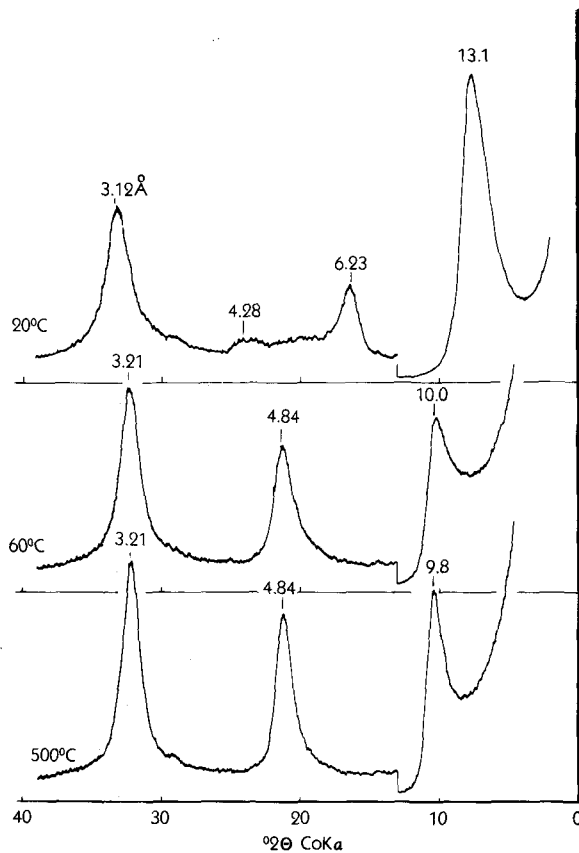


Figure 3. X-ray powder diffraction traces of a Na-saturated, $<0.1\text{-}\mu\text{m}$ fraction of sample R24 heated in air. There is a scale change at about $13^\circ 2\theta$ ($\text{CoK}\alpha$).

sixth reflections. Figures 2c to 2e illustrate the range in patterns observed for the lake-bottom and playa samples. The pattern with the best resolved reflections, that of sample 23de, is similar to that of sample R12d, whereas sample 21cb gave poorly resolved reflections throughout. The reflection positions are almost identical for the five traces, but the resolution of the reflections is different. The differences among the samples are therefore not likely due to large variations in the nature of interstratified units because such variations would cause the reflections to migrate from the smectite positions. The results of the ethylene glycol treatment alone (see Table 2 for samples not illustrated in Figure 2) suggests that the samples are smectites or interstratified minerals with a large proportion of smectite layers. A decrease in the numbers of layers in the diffracting units could account for the observed decrease in resolution of the reflections.

The XRD patterns of sample R12d and most of the sediment samples have a $5\text{-}\text{\AA}$ reflection in addition to smectite reflections (Table 2). These $5\text{-}\text{\AA}$ reflections are weak and very poorly resolved and can be attributed to either the second order of the $10\text{-}\text{\AA}$ illite reflection, for

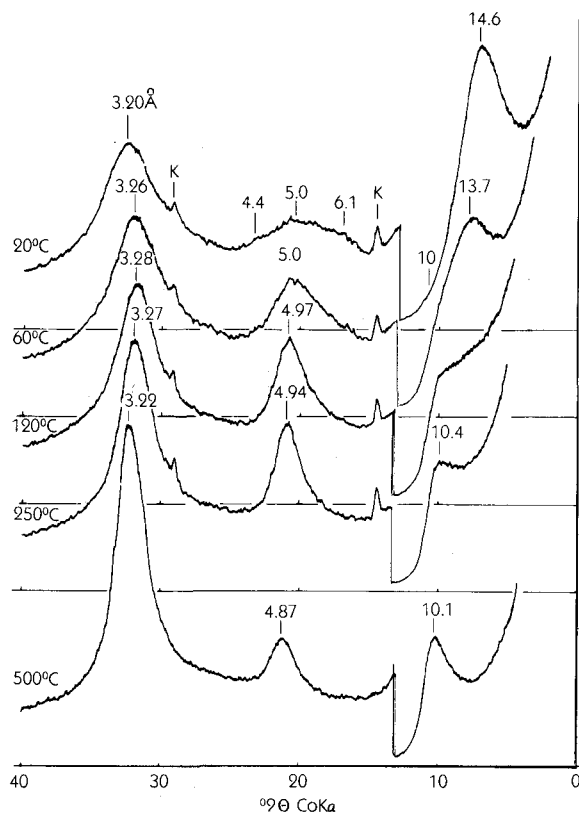


Figure 4. X-ray powder diffraction traces of a Na-saturated, $<0.1\text{-}\mu\text{m}$ fraction of sample R12d heated in air. K = kaolinite. There is a scale change at about $13^\circ 2\theta$ (CoK α).

which the first order reflection cannot be resolved from the smectite second order reflection, or to the third order of a 15-Å intergrade phase for which the other orders cannot be distinguished. XRD patterns of Na-saturated samples heated in air (Figures 3 to 7) show that

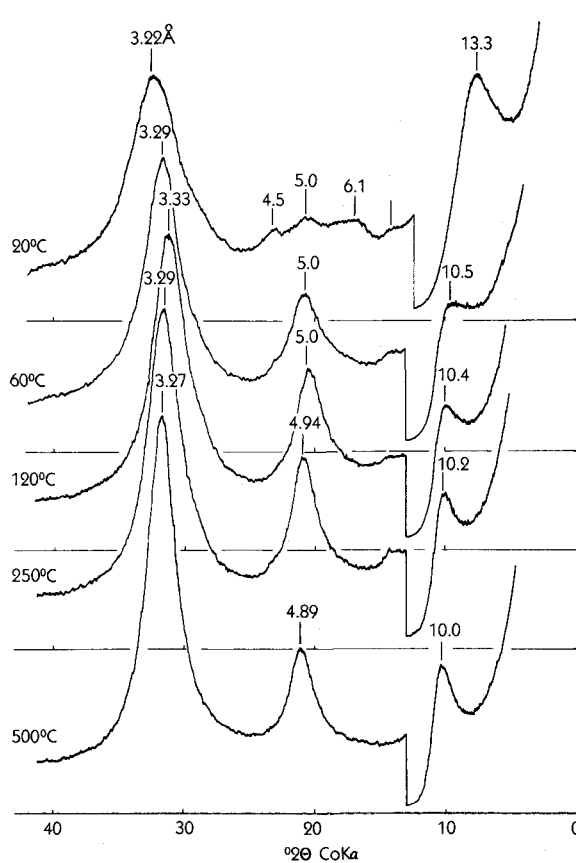


Figure 5. X-ray powder diffraction traces of a Na-saturated, $<0.1\text{-}\mu\text{m}$ fraction of sample 23de heated in air. There is a scale change at about $13^\circ 2\theta$ (CoK α).

only sample R24 collapses like smectite on heating. At 20°C and 50% RH, sample R24 showed an interlayer complex of one layer of water molecules. On heating to

Table 2. Peak positions of $<0.1\text{-}\mu\text{m}$ fractions of rock and sediment samples from the Lake Abert area, Oregon.

Sample	Basal reflections (Å)							General reflection (06)
	Air	Ethylene glycol						
	001	001	002	003	004	005	006	
R10	13.9	16.9	(8.75)	5.62	4.28	3.37	2.84	1.500
R12d	14.1	16.9	8.70	5.57 ¹	4.33	3.35	2.80	1.512
R24	13.0	16.8	8.56	5.63	4.25	3.37	2.82	1.500
R33	14.2	18.0	8.66	5.62	4.34	3.36	2.83	1.507
R38	13.0	16.8	8.45	5.55	4.25	3.23	2.80	1.501
1e	15.8	18.3	(9.3)	5.58 ¹	4.46	3.38	2.86	1.512
7q	15.9	18.6	9.09	5.62 ¹	4.43	3.37	2.84	1.515
12b	16.3	18.4	11.4	5.56 ¹	4.45	3.38	2.85	1.517
17i	16.0	18.3	(9.68)	5.58 ¹	4.46	3.37	2.86	1.515
20i	15.3	17.8	9.1	5.55	4.38	3.37	2.85	1.515
21cb	14.9	17.9	8.78	5.62 ¹	4.45	3.36	2.82	1.517
21jc	12.8	17.5	8.93	5.55 ¹	4.36	3.37	2.83	1.510
23de	13.2	17.4	8.63	5.57 ¹	4.35	3.37	2.83	1.505

The samples were Na-saturated, and either dried in air at 20°C or solvated with ethylene glycol vapor at 60°C.

¹ A broad, 5-Å reflection corresponding to the 003 of a 10-Å segregation was also noted.

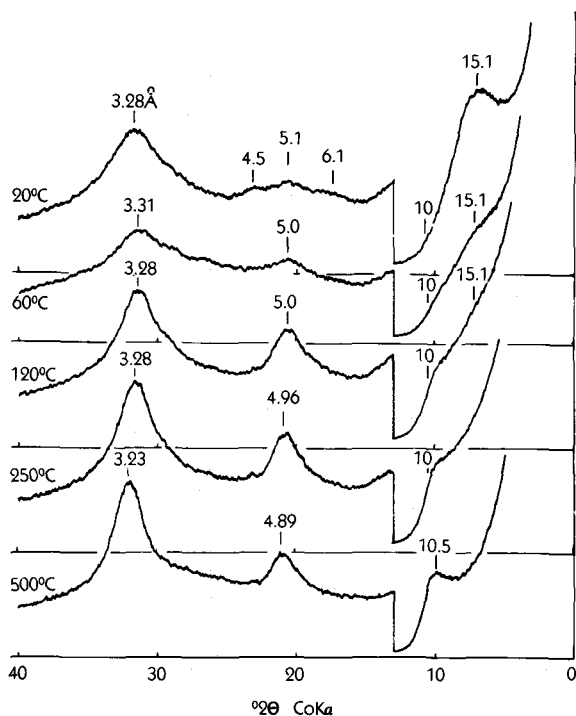


Figure 6. X-ray powder diffraction traces of a Na-saturated, $<0.1\text{-}\mu\text{m}$ fraction of sample 1e heated in air. There is a scale change at about $13^\circ 2\theta$ (CoK α).

60°C most of the water was expelled and the structure collapsed to a spacing near 10.0 Å. Heating to 250°C collapsed a few more layers, sharpening the reflections and reducing the spacing to 9.8 Å. Additional heating, to 500°C, caused little further change.

Sample R12d differs from sample R24 in that at 20°C its XRD pattern has poorly resolved reflections at 6.1 and 4.4 Å, but none at 13.1 or 3.12 Å (Figure 4). Instead a strong reflection at 14.6 Å, a poorly resolved reflection at 5 Å, and a reflection at 3.20 Å are present. On heating the sample to 120°C, where Ca- or Mg-saturated smectites lose their last layer of water molecules, the 13.7-Å reflection disappeared and the 10- and 5-Å reflections were further strengthened. Heating the sample to 250°C and 500°C progressively increased the resolution of all three reflections and slightly decreased the basal spacing. Thus, sample R12d contains some Na-saturated smectite layers that collapse at 60°C, some layers that behave like smectite saturated with divalent cations and that collapse at 120°C, and some layers that collapse between 120° and 500°C. The last two types of layers can be referred to as intergradient or intergrade smectite-chlorites (Brown *et al.*, 1978, p. 133) because their "hindered" collapse is intermediate between the free collapse of smectites and the zero collapse of chlorites. Of the other weathered rocks examined, sample R38 contains a smectite similar to that found in sample R24 whereas samples R10, R12c, and R33 contain phases

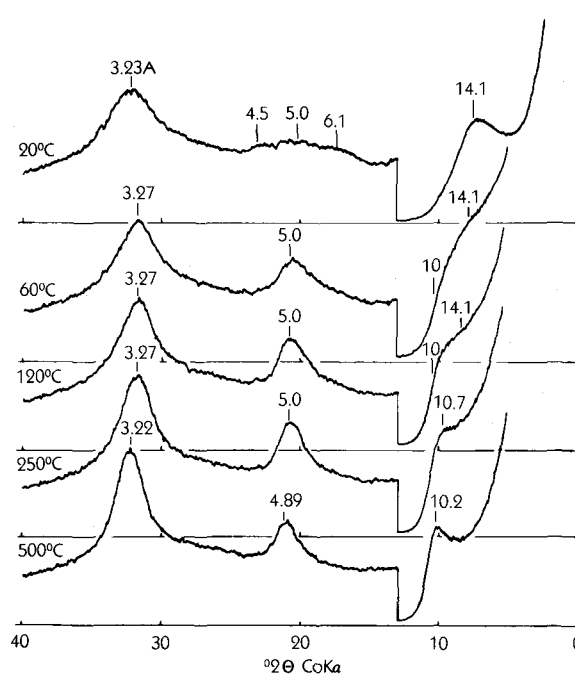


Figure 7. X-ray powder diffraction traces of Na-saturated, $<0.1\text{-}\mu\text{m}$ fraction of sample 21cb heated in air. There is a scale change at about $13^\circ 2\theta$ (CoK α).

of intermediate composition with more smectite layers and fewer intergrade layers than sample R12d.

Amongst the lake-bottom and playa samples, the layer silicate mineral in sample 23de is most smectite-like (Figure 5). Most of its layers collapsed at 60°C, and further heating caused minor sharpening of the reflections and shifts in the basal spacing. The spacing does not become less than 10 Å, however, reflecting the presence of non-exchangeable K ions in interlayer positions (see Table 4). Samples 21jb and 21jc resemble sample 23 de, but all the other playa and lake-bottom samples show collapse properties intermediate between those of sample R12d and samples 1e or 21cb, i.e., collapse was very hindered so that traces of a 14-Å component were detected after heating above 120°C.

At 20°C the smectite and smectite-chlorite intergrade components of the samples are segregated, at least partially, as shown by the coexistence of 6-, 5-, and 4-Å reflections in the traces. This segregation was less clear with ethylene glycol-solvated samples, however, as a poorly resolved 5-Å reflection, but no separate 15-Å reflections were noted. Presumably ethylene glycol molecules penetrated the intergrade regions sufficiently to give most of the layers a spacing near to 17 Å. Further, random interstratification of smectite with either illite or intergrade smectite-chlorite layers cannot be extensive. Comparison of Figure 2 and the spacings in Table 2 with traces simulated by Reynolds (1980, p. 289) indicates that the Lake Abert clays cannot contain more

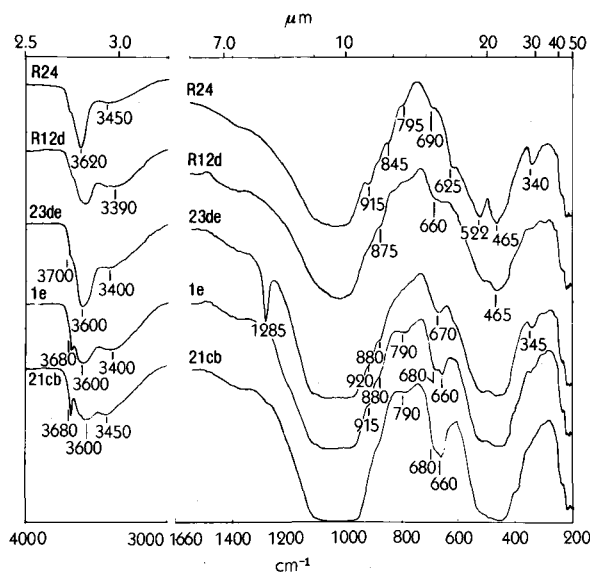


Figure 8. Infrared spectra of Na-saturated, $<0.1\text{-}\mu\text{m}$ fractions of weathered rock and sediments from the Lake Abert area. Samples were pressed in KBr discs and dried at 150°C .

than 20% of either illite or chlorite layers interstratified with $17\text{-}\text{\AA}$ layers.

The values of $d(06l)$ (Table 2) varied from 1.500 to 1.512 \AA for the weathered rock samples, the spacings increasing with the iron content of the specimens. Amongst the lake bottom and playa clays the spacings increase from 1.505 \AA for sample 23de to 1.517 \AA for the Mg-rich sample 21cb. This spacing decreased slightly, to 1.514 \AA , when the sample was treated with acid ammonium oxalate solution and much of its Mg dissolved (Table 7). Thus, the clays from the weathered rocks are all dioctahedral, the range observed being consistent with the iron contents of the specimens. The slightly larger $06l$ spacings of the high-Mg clays, coupled with their smaller iron contents, indicates the probable presence of a trioctahedral component.

Infrared spectroscopy

Infrared (IR) spectra of the $<0.1\text{-}\mu\text{m}$ clay fractions from the weathered rock and lake clays are illustrated in Figure 8. The spectrum of sample R24 is that of a dioctahedral smectite. Those of samples 23de and R12d are similar, but not identical, to that of sample R24. In contrast, samples 1e and 21cb show prominent absorption peaks at 3680 , 680 , and 660 cm^{-1} , which can be attributed to Mg ions in trioctahedral coordination (Farmer, 1974). The 3680-cm^{-1} band is due to OH-stretching and the band at 660 cm^{-1} , to OH-bending. These absorptions are similar to those observed for the trioctahedral silicates talc, saponite, and the hydrated talc mineral, kerolite, but not to trioctahedral chlorite. IR measurements on heated samples showed that the trioctahedral, Mg-rich phases are all stable to 350°C , and the phase in sample 21cb is stable to at least 550°C . Removal of Mg ions by extraction with acid ammonium oxalate or sodium acetate solutions diminished these absorptions.

Chemical analysis

Rock samples. The chemical compositions of fine clay fractions from weathered rocks are given in Table 3, together with the compositions of two unweathered rock samples. As the clays were Na-saturated and contained no Ca, all of the compositions were recalculated for easy comparison on a water and CaO-free basis. Table 3 shows that when the dacitic tuff weathered to smectite (sample R24), the Al concentration did not change, but Fe and Mg increased relative to Si and K. Alteration of the basaltic andesite scoria into the interstratified smectite/intergrade smectite-chlorite of sample R12 did not significantly affect the Si concentration, but increased Fe, Mg, and K relative to Al. The other clay fractions from weathered rocks have chemical compositions intermediate between those of samples R24 and R12d, their Al and Fe concentrations grading between the two, but their Si, Mg, and K concentrations being more similar to that of R24.

Table 3. Chemical composition of crushed, unweathered rocks and clay fractions of weathered rocks from Abert Rim, Oregon.

Sample	Total anhydrous oxides (wt. %)	Major oxides recalculated to total 100%					
		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O
<i>Unweathered rocks, <1 mm</i>							
R24	79.5 (+1.0 CaO)	71.4	19.4	3.5	2.1	1.3	2.3
R12	82.6 (+9.8 CaO)	56.4	22.9	12.1	4.3	3.5	0.8
<i>Clay fractions, <0.1 μm, Na-saturated</i>							
R24	78.3	65.7	19.5	6.4	4.1	4.1	0.1
R33	79.0	62.4	17.9	9.1	5.0	4.0	0.7
R38	74.9	63.5	16.6	9.2	5.3	4.3	0.7
R10	79.2	62.1	16.7	10.1	5.5	4.4	0.5
R12d	76.2	55.3	15.0	15.6	8.5	3.4	1.4

Analyst: S. L. Rettig.

Table 4. Unit formulae set to 22 charges (1) and 4 Si ions (2) for Na-saturated, <0.1 μm , weathered rock clay fractions, Abert Rim, Oregon.

		Sample					
		R24 (1)	R33 (1)	R38 (1)	R10 (1)	R12d	
						(1)	(2)
Tetrahedral	Si	3.94	3.85	3.90	3.85	3.55	4.00
	Al	0.06	0.15	0.10	0.15	0.45	0.00
	Σ	4.00	4.00	4.00	4.00	4.00	4.00
Octahedral	Al	1.32	1.15	1.11	1.07	0.68	1.28
	Fe^{3+}	0.29	0.42	0.42	0.47	0.75	0.11
	Mg	0.37	0.46	0.49	0.48	0.81	0.61
	Σ	1.98	2.03	2.02	2.02	2.24	2.00
Interlayer	Na	0.48	0.48	0.51	0.53	0.42	0.48
	K	0.01	0.06	0.05	0.04	0.11	0.13
	Fe^{3+}						0.73
	Mg						0.31
	O						1.42

Unit formulae, based on the half unit cell with 22 positive and negative charges, of the clay fractions from weathered rocks (columns 2–6 of Table 4) show that samples R24 and R38 are high-charge, dioctahedral montmorillonites in which the interlayer charge is mostly balanced by substitution of Mg for Fe^{3+} or Al. Samples R10 and R33, that contain some intergrade layers, are of similar composition. Sample R12d differs from the others in that when calculated as a 2:1 layer silicate it has 2.24 octahedral ions, intermediate between a di- and trioctahedral mineral. Possibly some of the excess octahedral ions are in brucite-like units in interlayer positions. Making this assumption, the unit formula for sample R12d was recalculated. The sample has too much Si to fit a unit formula containing 28 charges, so it was calculated instead on the basis of 4 Si ions (version (2)). Table 3 shows that in version (2), 1.42 O ions, in the hydrated form equivalent to 0.47 units of the type $(\text{Mg}_{0.66}\text{Fe}^{3+}_{1.57})(\text{OH})_6$, would be in interlayer positions. To obtain this result, enough Mg to balance Na and K was assigned to 2:1 octahedral positions, Al and Fe were added to make the 2:1 unit exactly dioctahedral, and the remaining Fe and Mg were put into interlayer brucite positions. The allocation of ions is to some extent arbitrary, and it is possible to make the 2:1 unit of sample R12d look very similar to that of sample R38 by minor adjustments (it is assumed throughout that all the iron is in the Fe^{3+} form). It is improbable that the interlayer brucite unit is uncharged as shown in Table 4, because on heating, sample R12d behaves partly like chlorite, but also like a smectite with divalent cations. Therefore, we postulate that some of the Mg ions are exposed at the edges of the units and are hydrated in the same manner as exchangeable cations and that sample R12d has a composition intermediate between those of versions (1) and (2), i.e., some of the surplus octahedral cations of version (1) are hydrated in interlayer positions.

Table 5. Chemical composition of Na-saturated, <0.1- μm fractions of sediments from Lake Abert, Oregon.

Sample	Total anhydrous oxides (%)	Major oxides recalculated to total 100%					
		SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O
23de	84.1	58.1	17.2	13.8	4.5	3.7	2.7
21jc	86.5	57.3	14.3	13.7	6.7	3.0	3.8
21jb	86.7	58.4	11.9	11.9	9.7	2.9	4.2
1e	77.6	61.6	11.2	8.5	13.3	3.3	1.6
17i	81.8	63.2	7.2	5.7	17.9	3.7	1.8
15b	77.6	64.0	6.6	5.4	18.6	3.6	1.3
21cb	78.0	62.9	6.6	6.3	20.0	2.2	1.4

Analyst: S. L. Rettig.

Lake bottom and playa samples. Chemical compositions of Na-saturated, fine clay fractions are given in Table 5. Comparison with Table 3 shows that the lake-bottom and playa clays contain on average more Si, Mg, and K than the weathered rocks and less Al and Na. Unit formulae in both versions (1) and (2) are given in Table 6. The version (2) formula of sample 23de was found to be unsatisfactory and is omitted because the analysis contains insufficient Mg to balance interlayer Na and K and the total of octahedral cations would have to be reduced to 1.73 to balance the charges. All of the others can be calculated in version (2) form, although sample 15b contains so much Si that only 0.11 ions can be assigned to interlayer brucite-like units.

Samples 1e, 17i, 15b, and 21cb have K contents similar to that of sample R12d, whereas samples 23de, 21jc, and 21jb contain two to three times as much. The interlayer charge holding (Na + K) ions on the clays from the weathered rocks varies from 0.49 to 0.57 (version (1)). These values are large for smectites but not impossibly so. Those for samples 1e and 15b are in the same range, that for sample 21cb is smaller, and that for sample 17i is slightly larger, but the values for samples 23de, 21jc, and 21jb (0.67, 0.68, and 0.70, respectively) are much larger, too large in fact for smectites. Thus, for these three samples the addition of K, presumably from the lake water, has been into clays with the overall chemical composition of dioctahedral vermiculites.

The other major difference between the clays from the weathered rocks and the lake playa is the enhanced Mg in the latter. An enhancement of Mg was noted for samples 21jb, 1e, 17i, 15b, and 21cb, but not for samples 23de and 21jc, whose Mg concentrations fall within the range observed for the clays from the weathered rocks. Sample 21jb can be represented as a dioctahedral clay with 0.73 oxygen ions in interlayer brucite units (version (2)). Samples 1e, 17i, 15b, and 21cb contain much Si, however, and even with the transfer of the maximum number of ions into brucite units, the totals of the remaining octahedral ions exceed 2.00. It appears, therefore, that with the addition of Mg a new trioctahedral phase was formed.

Table 6. Unit formulae set to 22 charges (1) and 4 Si ions (2) for Na-saturated, <0.1- μm fractions of Lake Abert sediments.

		Sample												
		21jc		21jb		1e		17i		15b		21cb		
		23de (1)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
Tetrahedral	Si	3.67	3.69	4.00	3.75	4.00	3.84	4.00	3.93	4.00	3.96	4.00	3.90	4.00
	Al	0.33	0.31	0.00	0.25	0.00	0.16	0.00	0.07	0.00	0.04	0.00	0.10	0.00
	Σ	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Octahedral	Al	0.95	0.78	1.18	0.65	0.96	0.66	0.86	0.45	0.54	0.44	0.49	0.39	0.49
	Fe ³⁺	0.66	0.66	0.11	0.57	0.29	0.40	0.41	0.27	0.27	0.25	0.25	0.30	0.30
	Mg	0.43	0.65	0.70	0.93	0.75	1.23	0.91	1.66	1.49	1.72	1.62	1.85	1.61
	Σ	2.04	2.09	1.98	2.15	2.00	2.29	2.18	2.38	2.30	2.41	2.36	2.54	2.40
Interlayer	Na	0.45	0.37	0.40	0.36	0.38	0.39	0.42	0.45	0.45	0.44	0.44	0.27	0.27
	K	0.22	0.31	0.34	0.74	0.37	0.12	0.13	0.14	0.15	0.10	0.10	0.11	0.11
	Al			0.00		0.00				0.00		0.00		0.00
	Fe ³⁺			0.60		0.32				0.00		0.00		0.00
	Mg			0.00		0.24				0.20		0.20		0.11
	O			0.91		0.73				0.20		0.20		0.11

Acid extraction. Table 7 shows the amounts of Si, Al, Fe, Mg, and K extracted from the lake and playa clays with 0.2 M ammonium oxalate solution adjusted to pH 3. Schwertmann (1964) proposed this extractant to separate noncrystalline iron oxides from crystalline goethite and lepidocrocite. With the Lake Abert clays it appears that the extractant dissolved the crystalline clays themselves, because in addition to Fe and Al, 14–66% of the original Mg and 11–63% of the original K contents of the samples were dissolved. The small amounts of Si removed probably reflect its relative insolubility in the acid solutions. With samples 1e and 21cb, part of the sample was destroyed, and the IR absorptions attributed to trioctahedral minerals were missing or diminished after the treatment.

DISCUSSION AND CONCLUSIONS

Deike and Jones (1980) showed that the principal source of detrital material to Lake Abert is weathered rock debris from the Abert Rim. The present study has shown that the rocks weather to give a range of layer silicate minerals from montmorillonite to montmorillonite/illite and montmorillonite/intergrade smectite-

chlorite interstratifications. Segregation was observed for both air-dried and ethylene glycol-solvated samples, but was less obvious with the latter, presumably because the organic molecules penetrated many of the intergrade interlayer positions. A unit formula of sample R12d was calculated that gives a maximum of 1.42 interlayer O ions, i.e., 47% of the three oxygen ions needed for a dehydrated brucite interlayer unit. The actual occupancy by intergrade units will be less than this because some of the metal ions are exposed and hydrated.

The non-exchangeable K of the clays from the weathered rock ranged between 0.01 and 0.11 K ions per unit formula. In clays containing intergrade smectite-chlorite, K ions may be located in dehydrated illite layers or blocked in hydrated smectite layers by islands of intergrade material. The fact that ethylene glycol penetrated many of these regions suggest that the former is the more probable locality. It is not possible to tell whether the illite layers represented by 0.11 K ions in sample R12d are randomly interstratified or segregated, because the expected reflection shift for random interstratification (Reynolds, 1980) is too small to be deter-

Table 7. Chemical composition of leachates of Na-saturated, <0.1- μm fractions of Lake Abert sediments.

Sample	Amounts extracted as % sample dry weight (90°C) ¹				
	Si	Al	Fe	Mg	K
23de	0.30 (1.4)	0.70 (9.6)	1.37 (1.76)	0.30 (13.6)	0.25 (13.8)
21jc	0.24 (1.1)	0.24 (3.7)	0.23 (2.8)	0.59 (16.8)	0.30 (10.9)
21jb	0.97 (4.1)	0.26 (4.8)	0.49 (6.8)	1.61 (31.6)	0.37 (12.3)
1e	0.64 (2.9)	0.93 (20.3)	1.25 (27.1)	4.15 (66.7)	0.25 (25.0)
17i	0.79 (3.3)	0.45 (14.5)	0.61 (18.6)	3.18 (36.0)	0.77 (62.6)
15b	1.07 (4.6)	0.21 (7.8)	0.24 (8.2)	4.12 (47.3)	0.24 (28.2)
21cb	0.82 (3.6)	0.44 (16.0)	0.46 (13.3)	3.19 (33.9)	0.17 (18.1)

Analyst: S. L. Rettig.

¹ Samples were extracted with acid (pH 3) 0.2 M ammonium oxalate solutions overnight at 25°C. Values in brackets are amounts extracted as % of original sample (values from Table 5).

mined and a 5-Å reflection from intergrade chlorite would mask a possible 5-Å reflection from segregated illite.

Clays and coarser weathered rock debris from the Abert Rim were transported and distributed over the bed of Lake Abert and the playa of former Lake Chewaucan. There the detrital clays were modified by reaction with lake waters enriched by ions dissolved from the rock debris or brought in by the Chewaucan River and other feeder streams. Apparently none of the detrital clays remained unmodified by this process as no pure montmorillonites similar to that in samples R24 or R38 have been separated from the lake sediments. Sample 23de resembles these montmorillonites most closely, but contains more K and occurs in smaller particles. It contains no intergrade smectite-chlorite and has the expanding properties of a smectite. It has the composition of a dioctahedral vermiculite, however, with an interlayer charge of 0.67 ions per formula unit, one third of which are satisfied by K. Hower and Mowatt (1966) confirmed that dioctahedral layer silicates of this composition are interstratified, with the K ions segregated into either K-rich illite layers or K-poor smectite layers. Sample 23de contains sufficient K for its illite layers to be detected by XRD whether they are randomly interstratified or segregated. The K ions are probably as tightly bound as they are in illite because the acid ammonia oxalate extraction, which removed all of the exchangeable Na ions, removed only 13% of the K ions. We therefore postulate that in samples 23de, 21jb, and 21jc, the K additional to that in the detrital clays is held in a neoformed illite phase. Sample 23de contains little or no intergrade smectite-chlorite and so its 5-Å reflection is probably caused by neoformed illite. A 10-Å reflection was not noted, however, and the 5-Å reflection is weak and broad, indicating that the diffracting units of the illite are very small.

The enhancement of the Lake Abert clays in K and Mg is similar to changes attributed by Singer and Stoffers (1980) to salinity increase resulting from climatic desiccation of the sediments of Lakes Albert and Man'ara in East Africa. In these lakes smectites were illitized by the incorporation of K ions released by transformation of K,Na-zeolite to analcime with the concomitant addition of Mg to the layer silicate. The K₂O contents of the African clays ranged from 1.5 to 7.3%, greater than those of Lake Abert, and the 10-Å illite reflections were greatly enhanced. The Lake Abert clays differ from the African clays in that zeolite transformation does not appear to be important; K- and Mg-containing clays are formed at different times and under different conditions, and although the additional K is strongly held, the new illite layers are so unevenly distributed that they contribute little to the XRD basal reflections.

Of the other Lake Abert clays described in detail, samples 1e, 17, 15b, and 21cb contain more Mg than any of the weathered rock clays. Their diffraction pat-

terns are similar to those of sample R12d, but their IR spectra show they contain varying amounts of a trioctahedral layer silicate. We therefore suggest that they consist of detrital clays mixed with a neoformed Mg-rich trioctahedral mineral. The most Si-rich, regular Mg phyllosilicate is the hydrous talc (kerolite), which has the formula Mg₃Si₄O₁₀(OH)₂·nH₂O (Brindley *et al.*, 1977). If sample 21cb contains 50% of material of this composition, the remainder recalculates to K_{0.22}Na_{0.54}(Mg_{0.70}Fe_{0.60}Al_{0.78})(Si_{3.80}Al_{0.20})O₁₀(OH)₂, a unit formula similar to that calculated for sample R10, but with more K. Thus, the lake clays with enhanced Mg, samples 21jb, 1e, 17i, 15b, and 21cb, probably contain an interstratified, trioctahedral phase resembling kerolite or stevensite, the nearly trioctahedral smectite (Brindley, 1980, p. 170), in composition. Brindley (1955) showed that natural stevensite may be interstratified, possibly with non-expanding, talc-like layers. The Lake Abert clays may also contain neoformed illite in addition, although Table 7 shows that K is not nearly as strongly held in sample 17i, for instance, as it is in samples 21jb, 21jc, or 23de. The XRD traces for all the lake sediment clays are dominated by reflections from detrital minerals.

The samples examined are too few to comment fully on the spatial distribution of the two neoformed phases within the lake sediments. All samples appear to be enhanced in K, but strongly bound K that we refer to as occurring in neoformed illite (Deike and Jones, 1980, have shown no adequate source of a detrital 10-Å phase) is only proved at sites 21 and 23 at depths of 0.8 m or more in uniformly fine sediment of perhaps a fresher lake. With regard to Mg enrichment, only samples 21jc and 23de appear to have no extra Mg, sample 21jb from 0.8 m depth has some, but not enough to give a trioctahedral phase detectable by IR. In contrast, sample 21cb from 0.2 m depth at the same site has the best developed Mg phase of all the samples examined. Elsewhere, this phase is found widely distributed in the lake beds from sites 1 to 15 at depths between 0.4 and 0.2 m. In these shallow and therefore recent lake and playa deposits the sequence of increasing Mg is from south to north—in the same direction as increasing salinity. Because of the proximity of the principal inflow from the Chewaucan River at the south end, Lake Abert dries from north to south. Sites on the outer fringes of the northwest playa (21cb) will dry before the center (15b), accounting for the differences in Mg-content and degree of impeded collapse between the playa clays.

The neoformed Mg-rich Abert clays show marked similarities to the stevensite of the Green River Formation described by Dyni (1976) and Tettenhorst and Moore (1978). The chemical composition given by Dyni (1976, p. 9), when corrected for its illite content, is similar to that of sample 1e from Lake Abert. Dyni showed that the Green River basin deposits are zoned from edge to center and suggested that the smectites alter from ditto trioctahedral with increasing salinity. Such a zona-

tion and alteration sequence is also envisaged as the present-day process of clay transformation in Lake Abert, although high Mg concentrations are not reached in the pore fluid because Mg is continuously extracted, presumably by adsorption onto suspended detritus, diatoms, or other organic remains.

Tettenhorst and Moore (1978, p. 592) gave a chemical composition for stevensite oolites from the Green River Formation that is rich in Si, even when corrected for 3% quartz. This mineral expanded like a smectite when solvated with ethylene glycol, but showed impeded collapse on heating. Tettenhorst and Moore (1978) suggested that interlayer organic matter impeded collapse. Otherwise, the Green River clays resemble the randomly interstratified kerolite/stevensite described by Eberl *et al.* (1982). An alternative explanation for the impeded collapse given by Tettenhorst and Moore (1978) was that the additional Si was an integral part of the structure, possibly in inverted tetrahedra.

The neoformed, high-Mg Lake Abert clays resemble the Green River Formation stevensite in that they have high Si contents, contain organic matter, and expand with ethylene glycol, but they show impeded collapse on heating. The expansion and impeded collapse also characterize clays from the weathered volcanics contributing fine sediment to the lake. Thus, the most probable explanation for the high Mg clays in Lake Abert itself is that they are dioctahedral/trioctahedral interstratifications similar to those of the Green River clays described above. This would account for the observation that whereas the impeded collapse of the clay from weathered rock sample R12 can be explained satisfactorily by conventional chloritization, that of lake clay samples 17i, 15b, and 21cb cannot. The expanding properties are similar, but chemical compositions are very different, reflecting the differences (as emphasized by Millot, 1964) between sub-aerial weathering (leaching) and neof ormation (additions) in an alkaline-saline lake.

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Резюме—Минералогические и химические анализы мелких фракций глин, взятых изнутри и из окрестности озера Аберт в дистрикте Озеро в Орегоне, указывают, что пирокластические породы (которые доставляют детритус в озеро) выветриваются и образуют слоистые силикатовые глинистые минералы, отличающиеся по составу от заряженных двухоктаэдрических монтмориллонитов до переслаиваний монтмориллонит-сметит-хлорит. В озере эти глины извлекают из воды K, Mg, и Si для образования аутигенных переслаивающихся иллитов и триоктаэдрического, Mg-обогащенного минерала, напоминающего по составу стевенсит. Оба свежееобразованные переслаивания способствуют частично недвусмысленно рентгеновским порошковым диффрактограммам, в которых доминируют отражения детритовых глин. На основании ограниченных данных кажется, что иллит находится ниже глубины 0,8 м в осадках немного пресного озера (солончатого), а триоктаэдрические переслаивания проявляются на глубине между 0,4 и 0,2 м в осадках озера примерно такого же самого размера и солёности (около 30–90 г/кг), как существующего в настоящее время озера. [E.G.]

Resümee—Mineralogische und chemische Analysen von feinen Tonfraktionen aus dem Innern und vom Rand des Lake Abert, Lake County, Oregon, zeigen, daß pyroklastische Gesteine Gesteinsschutt in den See liefern, der zu einer Abfolge von Tonmineralen verwittert, die von stark beladenem dioktaedrischem Montmorillonit bis Montmorillonit/Smektit-bzw. Montmorillonit/Chlorit-Wechselagerungen variieren. Im See extrahieren diese Tone K, Mg, und Si, um autigene Illit-Wechselagerungen und ein trioktaedrisches Mg-reiches Mineral, das in der Zusammensetzung mit Stevensit vergleichbar ist, zu bilden. Beide neugebildeten Wechselagerungen tragen wenig eindeutige Reflexe zur Röntgenpulveraufnahme bei, die vor allem die Reflexe der detritischen Tone zeigt. Aus den begrenzten Daten geht hervor, daß der Illit unter 0,8 m Tiefe in den Sedimenten eines möglicherweise etwas frischeren (brackischen) Sees auftreten und die trioktaedrischen Wechselagerungen zwischen 0,4 und 0,2 m Tiefe in Sedimenten eines Sees, der etwa die gleiche Größe und die gleiche Salinität aufweist (etwa 30–90 g/kg) wie der gegenwärtige See. [U.W.]

Résumé—Des analyses minéralogiques et chimiques de fractions d'argile fines provenant de l'intérieur et d'autour du Lac Abert, Lake County, Oregon, montrent que les roches pyroclastiques fournissant du détritit au lac s'altèrent en une suite de minéraux argileux silicates variant de montmorillonite dioctaédrale à haute charge à des interstratifications montmorillonite/smectite-chlorite intergrade. Dans le lac, ces argiles extraient K, Mg, et Si pour former de l'illite authigénique interstratifiée et un minéral riche en Mg ressemblant à la stevensite. Ces deux interstratifications nouvellement formées contribuent peu sans ambiguïté aux clichés de diffraction poudrée des rayons-X, qui sont dominés par les réflexions des argiles détritiques. A partir de données limitées il semble que l'illite se trouve sous une profondeur de 0,8 m dans les sédiments d'un lac possiblement à eau plus fraîche (saumure), et que l'interstratification trioctaédrale se trouve entre 0,4 et 0,2 m de profondeur dans les sédiments d'un lac d'à peu près la même taille et de même salinité (~30–90 g/kg) que celles du lac présent. [D.J.]