

# Trioctahedral Smectite in the Green River Formation, Duchesne County, Utah

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 967





# Trioctahedral Smectite in the Green River Formation, Duchesne County, Utah

By JOHN R. DYNI

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*An X-ray-diffraction study of clay minerals  
in some lacustrine rocks of Eocene age exposed  
in the southwestern part of the Uinta Basin*



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# TRIOCTAHEDRAL SMECTITE IN THE GREEN RIVER FORMATION, DUCHESNE COUNTY, UTAH

By JOHN R. DYNI

## ABSTRACT

Abundant trioctahedral smectite of probable authigenic origin and smaller amounts of discrete illite comprise a simple assemblage of clay minerals in a basin-edge sequence of lacustrine claystones and oil shales in the Eocene Green River Formation, southwest Uinta Basin, Duchesne County, Utah. Small amounts of chlorite and mixed-layer clay are present in a few samples; kaolinite is absent.

The smectite is well crystallized and has a high expandable-layer content. Chemical analysis of partly purified material suggests an iron-bearing hectorite which contains notable quantities of zinc (740 ppm (parts per million)), lithium (670 ppm), copper (175 ppm), and fluorine (0.85 percent).

No significant differences were noted in the clay-mineral content of the claystones and oil shales. However, of the associated carbonate minerals, calcite predominates in the oil shales, whereas dolomite strongly predominates in the claystones. This relationship suggests that the interstitial waters of the claystones during deposition and (or) lithification were more saline than those of the oil shales. The trioctahedral smectite evidently formed in a magnesium-rich lacustrine environment and appears to be part of a basin edge-to-center series of clay mineral facies—mixed detrital clay minerals to smectite to illite.

## INTRODUCTION

This report presents the results of an X-ray-diffraction study of 17 samples of oil shale and claystone collected from a sequence of lacustrine rocks in the Eocene Green River Formation, which is exposed on the southwest side of the Uinta Basin, Duchesne County, Utah. The objective of this study was to identify the clay and associated minerals in some claystones and oil shales, and to determine the differences, if any, in the mineralogy of the two rock types.

Earlier studies (Hite and Dyni, 1967; Hosterman and Dyni, 1972) suggest that several major lithofacies of the Green River Formation and associated Tertiary rocks in Colorado and Utah have characteristic assemblages of clay minerals. For example, in the deeper part of the Piceance Creek basin, east of the Uinta Basin, in western Colorado, the oil-shale facies of the Green River Formation contains moderate to sparse amounts of illite, abundant dolomite, and sodium carbonate minerals, whereas an underlying lithofacies composed of dark

kerogenaceous shale contains abundant illite and lesser amounts of carbonate minerals. Older fluvial mudstones and associated rocks of the Wasatch Formation on the margins of the basin contain a mixed assemblage of kaolinite, illite, and mixed-layer clay. Overlying the oil-shale facies, a thick sequence of chiefly fine-grained clastic rocks contains smectite and illite. These data suggest the possibility that clay mineral assemblages in a time-stratigraphic sequence of rocks of the Green River Formation change progressively from a shoreward fluvial environment to a saline lacustrine environment at basin center. With this idea in mind, a sequence of lacustrine rocks was picked for study that was thought to represent shallow-water basin-margin sediments (claystones) that alternate with deeper water anoxic lacustrine sediments (oil shales).

*Acknowledgment.*—The capable assistance of Robert W. Brown and Jerry D. Tucker in the sample preparation and X-ray work is gratefully acknowledged.

## GEOLOGIC SETTING

The sequence of rocks studied includes most of the Parachute Creek Member of the Eocene Green River Formation as used by Dane (1955) in the southwestern part of the Uinta Basin, Utah. These rocks were described and sampled by the author and W. B. Cashion in 1969 (unpub. data) at two localities (fig. 1) near Utah Highway 33 in the vicinity of the divide between the Price River drainage to the southeast and the Strawberry River drainage to the north, about 25 miles (40 km) southwest of the village of Duchesne. In this area, the Parachute Creek Member forms a belt of outcropping rocks several miles wide that dip 2°–4° NE. beneath younger Eocene rocks into the Uinta Basin. The member forms a moderately rugged topography of steep shaly slopes and thin laterally persistent ledges of resistant oil shale.

The composite section of rocks exposed at the two localities is 416 feet (126.8 m) thick (fig. 2). At the base is an asphaltic sandstone which forms the uppermost part of the delta facies of Bradley (1931). The top of



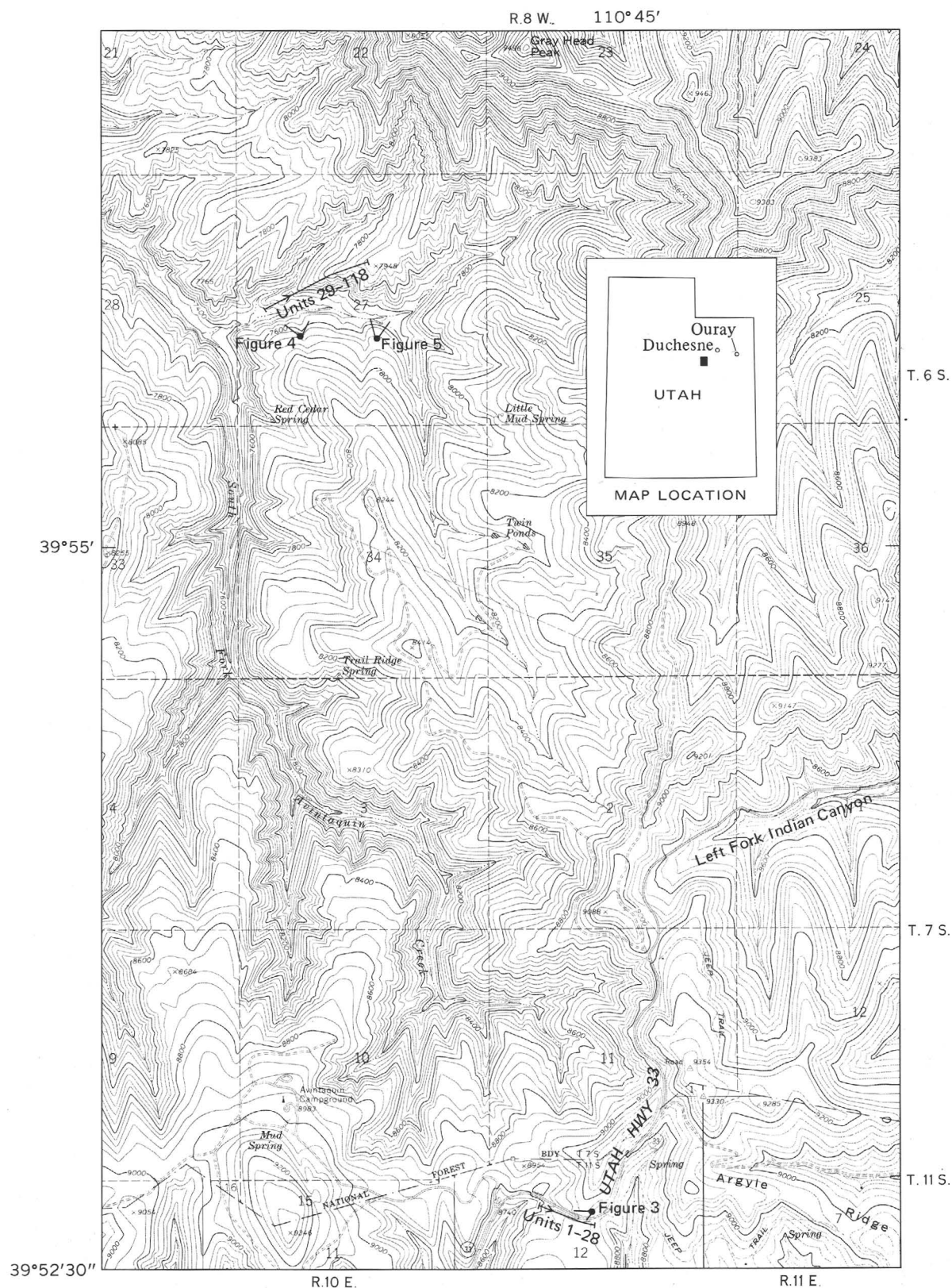


FIGURE 1.—Localities of composite measured section in southwest Duchesne County, Utah. Localities photographed in figures 3, 4, and 5 are shown by  $\bullet$ . Base from U.S. Geological Survey Gray Head Park and Jones Hollow topographic quadrangles, scale 1:24,000, 1969 and 1968.



Series	Fm.	Member	Cumulative thickness, in feet (and metres)		Unit	Thickness		Lithologic description
						Feet	Metres	
E O C E N E	Green River Formation	Parachute Creek Member (Dane, 1955)	Tuff zone of the Parachute Creek Member (Dane, 1955)		118	1.7	0.52	Tuff
					115-117	6.6	2.01	Oil shale
					114	2.0	0.61	Limestone
					113	4.3	1.31	Claystone
					112	11.5	3.51	Limestone and claystone, interbedded
					111	6.0	1.83	Claystone
					110	1.6	0.49	Limestone
					109	13.3	4.05	Claystone
					108	1.2	0.37	Oil shale
					107	12.0	3.66	Claystone
					105-106	3.4	1.04	Oil shale and claystone
					104	0.8	0.24	Oil shale
					102-103	8.4	2.56	Dolomite, siltstone, and claystone
					99-101	5.4	1.65	Mostly claystone
					98	8.4	2.56	Siltstone and claystone
					97	9.0	2.74	Claystone
					96	1.0	0.30	Dolomite
					95	17.0	5.18	Claystone
					87-94	5.2	1.59	Mostly oil shale; several thin tuffs
					86	18.6	5.67	Siltstone and claystone, interbedded
					85	12.8	3.90	Claystone and marlstone
					83-84	4.8	1.46	Oil shale
					82	4.9	1.49	Claystone and marlstone
					80-81	4.8	1.46	Oil shale
					79	0.2	0.06	Tuff
					76-78	5.3	1.62	Marlstone and claystone
					75	0.5	0.15	Oil shale
					72-74	10.0	3.05	Marlstone
					66-71	4.9	1.49	Oil shale (68)
					65	2.4	0.73	Marlstone
					64	4.0	1.22	Claystone
					63	0.7	0.21	Oil shale
					62	8.4	2.56	Claystone
					61	0.02	0.006	Tuff
					60	12.0	3.66	Claystone
					58-59	3.8	1.16	Claystone, marlstone, and oil shale
					55-57	6.6	2.01	Siltstone; 0.3 ft (9.1 cm) tuff in middle
					54	4.3	1.31	Claystone
					51-53	5.9	1.80	Siltstone, claystone and oil shale
					50	8.6	2.62	Claystone
					49	0.8	0.24	Oil shale
					48	2.3	0.70	Marlstone
					47	2.0	0.61	Claystone
					46	0.8	0.24	Tuff
					45	10.7	3.26	Claystone
					44	2.5	0.76	Limestone
					43	2.5	0.76	Concealed
					42	10.9	3.32	Siltstone
					40-41	5.1	1.55	Siltstone, dolomite, and claystone
					39	7.0	2.13	Claystone
					38	0.2	0.061	Tuff
					37	7.0	2.13	Claystone
					36	0.1	0.031	Tuff
					35	3.3	1.01	Claystone
					33-34	4.8	1.46	Dolomite and limestone
					32	9.4	2.87	Claystone
					31	0.8	0.24	Oil shale
					30	0.1	0.031	Tuff
					29	20.0	6.10	Claystone
					28	0.6	0.18	Tuff
					27	0.3	0.091	Oil shale
					26	5.0	1.52	Dolomite, clayey
					25	8.6	2.62	Claystone
					24	0.3	0.091	Tuff
					22-23	6.2	1.89	Claystone, marlstone, and oil shale
					20-21	1.3	0.40	Claystone and oil shale
					19	5.5	1.68	Siltstone
					18	16.0	4.88	Dolomite, clayey
					17	0.7	0.21	Oil shale
					16	2.2	0.67	Dolomite and marlstone
					14-15	4.6	1.40	Claystone
					13	1.0	0.30	Oil shale
					10-12	4.1	1.25	Dolomite; 0.1 ft (3.0 cm) tuff in middle
					9	2.0	0.61	Claystone
					8	5.7	1.74	Limestone, clayey
					7	0.1	0.031	Oil shale
					2-6	16.8	5.12	Dolomite
					1	2.0	0.61	Siltstone, asphaltic
		Delta facies of Bradley (1931)	0			6.7 +	2.04 +	Sandstone, asphaltic

FIGURE 2.—Composite measured section of part of the Green River Formation. Units 1–28 were measured in a roadcut along Utah Highway 33 near the top of the divide between the drainages of Willow Creek and Left Fork Indian Canyon in the NE¼SW¼ sec. 12, T. 11 S., R. 10 E., Duchesne County, Utah. Units 29–118 were measured near South Fork Avintaquin Creek in sec. 27, T. 6 S., R. 8 W., Duchesne County. The section was measured and described by J. R. Dyni and W. B. Cashion in 1969 (unpub. data). The circled numbers indicate the units that were studied during the present investigation.

the section is a bed of volcanic tuff, 1.7 feet (0.52 m) thick, which is the basal unit of the tuff zone of the Parachute Creek Member (Dane, 1955). The composite section of rocks consists of claystone and marlstone in beds commonly 2–20 feet (0.6–6.1 m) thick; scattered siltstone beds of similar thickness; limestone and dolomite, especially in the lower 55 feet (16.8 m) of the section; and scattered thin ledge-forming beds of dark oil shale commonly a few tenths of a foot to a few feet thick. Throughout the section are many thin beds of orange-weathering tuff. The rocks exposed at the two localities are shown in figures 3–5.

### METHOD OF INVESTIGATION

Seventeen fist-size samples of selected beds of oil shale and claystone collected at the two localities shown in figure 1 were prepared for X-ray-diffraction analysis as follows: One-half of the sample was ground to minus-60 mesh in a hammermill. A 5-g (gram) portion of this material was pelletized at 20,000 lb/in<sup>2</sup> (pounds per square inch) in a hydraulic press and analyzed by conventional X-ray-diffraction methods. Another 15-g portion was prepared for clay-mineral analysis of the  $<2\text{-}\mu\text{m}$  (micrometre) fraction by the methods of Jackson (1973), which were modified as necessary to shorten sample preparation time. The  $<2\text{-}\mu\text{m}$  fraction of each sample was treated in several ways to obtain specimens that were (1) magnesium saturated, (2) magnesium saturated and glycolated, (3) potassium saturated, and (4) potassium saturated and heated at 525°C. X-ray-diffraction traces were made of these specimens oriented on glass slides and of randomly oriented magnesium-saturated speci-



FIGURE 3.—Units 3–18 exposed in roadcut along the south side of Utah Highway 33 in sec. 12, T. 11 S., R. 10 E., Duchesne County, Utah. Units measured here but not shown in the photograph are equally well exposed in the same roadcut.

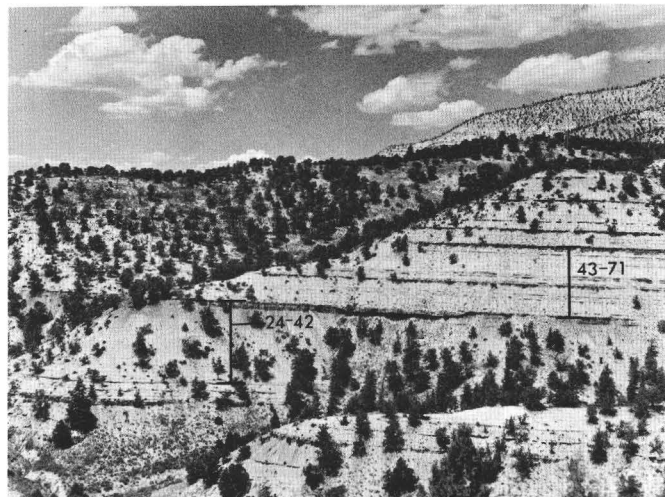


FIGURE 4.—Exposures of units 24-71 on the north side of an unnamed valley tributary to South Fork Avintaquin Creek in sec. 27, T. 6 S., R. 8 W., Duchesne County, Utah. Most of the thin laterally persistent dark ledges are oil shale.

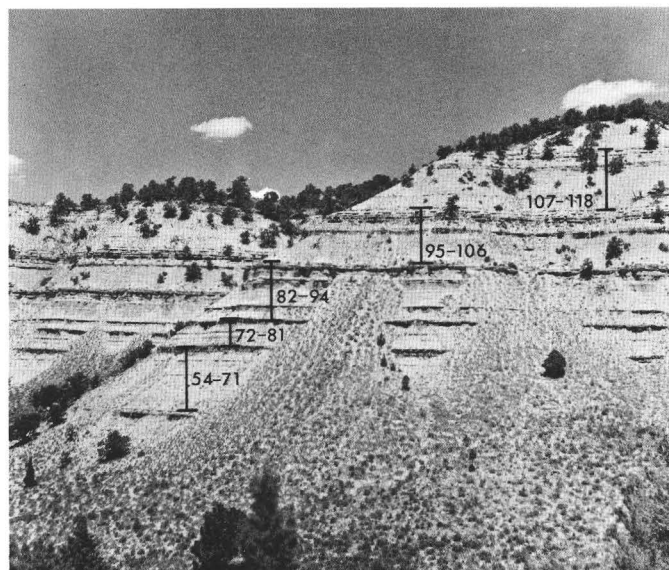


FIGURE 5.—Exposures of units 54-118 on the north side of an unnamed valley tributary to South Fork Avintaquin Creek in sec. 27, T. 6 S., R. 8 W., Duchesne County, Utah. Most of the thin laterally persistent dark ledges are oil shale.

mens. The  $<2\text{-}\mu\text{m}$  fraction of sample 17 was additionally tested for trioctahedral smectite by the method of Greene-Kelly (described by MacEwan, in Brown, 1961, p. 190) and was semiquantitatively analyzed for major elements by X-ray spectrometer.

The instrumental conditions for X-ray diffraction were nickel-filtered  $\text{CuK}\alpha$  radiation generated at 34 kilovolts and 18 milliamperes with  $1^\circ$  scatter and divergence slits, 0.010-inch receiving slit, a  $2\theta$  scan speed of  $2^\circ$  per minute, scintillation detector, and a counting rate of 3,000 counts per second.

TABLE 1.—*Qualitative mineralogy of oil-shale and claystone samples from Duchesne County, Utah*  
[A, abundant; ×, moderate to small amount; Tr., trace; ?, doubtfully present; . . . , absent]

Sample No.	Clay minerals (determined in 2-μm fraction)				Other minerals (determined in whole-rock fraction)								
	Smectite-to-illite ratio				Chlorite	Mixed layer	Quartz	Potassium feldspar	Sodium feldspar	Analcime	Dolomite-to-calcite ratio		
	Method A		Method B										
Oil shale													
7 . . . . .	85	15	86	14	...	...	A	×	?	...	80	20	
13 . . . . .	89	11	92	8	...	...	A	×	...	×	50	50	
17 . . . . .	80	20	96	4	...	×	A	×	...	...	55	45	
27 . . . . .	84	16	87	13	...	...	A	×	...	...	21	79	
49 . . . . .	91	9	91	9	...	...	A	×	...	...	28	72	
63 . . . . .	79	21	79	21	...	...	A	×	...	...	14	86	
68 . . . . .	80	20	74	26	...	...	A	×	×	...	21	79	
80 . . . . .	82	18	80	20	...	...	A	×	×	...	22	78	
104 . . . . .	86	14	76	24	...	...	A	×	×	...	62	38	
Claystone													
9 . . . . .	77	23	92	8	×	...	A	×	×	×	27	73	
15 . . . . .	96	4	96	4	...	×	A	...	Tr.	...	100	0	
25 . . . . .	79	21	90	10	...	×	A	×	×	...	80	20	
37 . . . . .	87	13	88	12	...	...	A	×	×	...	89	11	
60 . . . . .	89	11	90	10	...	...	A	Tr.	Tr.	...	73	27	
64 . . . . .	79	21	92	8	...	...	A	Tr.	Tr.	...	72	28	
95A . . . . .	95	5	92	8	...	...	A	×	Tr.	...	100	0	
109 . . . . .	81	19	90	10	...	?	A	×	×	...	72	28	

<sup>1</sup> Mixed-layer clay computed with smectite and illite.

<sup>2</sup> Chlorite computed with smectite.

## MINERALOGY

The X-ray mineralogy of the 17 samples of oil shale and claystone is summarized in table 1. The clay minerals were determined in the <2- $\mu$ m fraction, whereas the remaining minerals were determined from X-ray-diffraction analyses of the whole-rock sample.

### CLAY MINERALS

Trioctahedral smectite and illite are the principal clay minerals found in both rock types. Figures 6 and 7 show X-ray-diffraction patterns of the <2- $\mu$ m fraction of typical samples of oil shale and claystone which were magnesium saturated, magnesium saturated and glycolated, potassium saturated, and potassium saturated and heated to 525°C. The smectites in both rock types behave similarly with various treatments; the basal 001 reflection of magnesium-saturated specimens expands from 14 Å to 17 Å on glycolation, and the potassium-saturated specimens show a 001 reflection at 12.1–12.6 Å, which collapses to about 10 Å on heating to 525°C.

Applying the method of Reynolds and Hower (1970), the smectite was found to contain expandable 17 Å layers ranging from 70 percent to usually in excess of

85 percent.<sup>1</sup> The smectite in most samples shows good crystallinity, judging from the sharpness of the 001 reflection.

The smectite was determined to be trioctahedral by its 060 reflection, which is close to 1.53 Å in most samples (figs. 6, 7, and lower pattern of fig. 8), and by reexpansion of the basal 001 spacing to 17 Å after heating and glycolation of a lithium-saturated specimen (fig. 8, upper pattern). This technique (Greene-Kelly, 1953) shows that lithium-saturated trioctahedral smectites and beidellite will reexpand to 17 Å on glycolation after they have been heated between 200° and 300°C; lithium-saturated dioctahedral montmorillonites collapse irreversibly on heating and will not reexpand on glycolation. The trioctahedral smectites of this study are distinguished from beidellite by the 060 reflection; for beidellite, this reflection has a spacing of about 1.49–1.50 Å.

The species of trioctahedral smectite in the samples studied could not be determined from the X-ray data alone. The diffraction pattern of an unoriented composite specimen of the <2- $\mu$ m fraction free of nonclay impurities, which was prepared from oil-shale

<sup>1</sup>In table 3 of Reynolds and Hower (1970, p. 34), the d spacing for the 003 reflection for 100-percent expandable 17 Å layers in the randomly stratified in the IM-ordered columns should read 5.67 Å instead of 5.61 Å, according to J. B. Hayes, Marathon Oil Co. (oral commun., 1973).

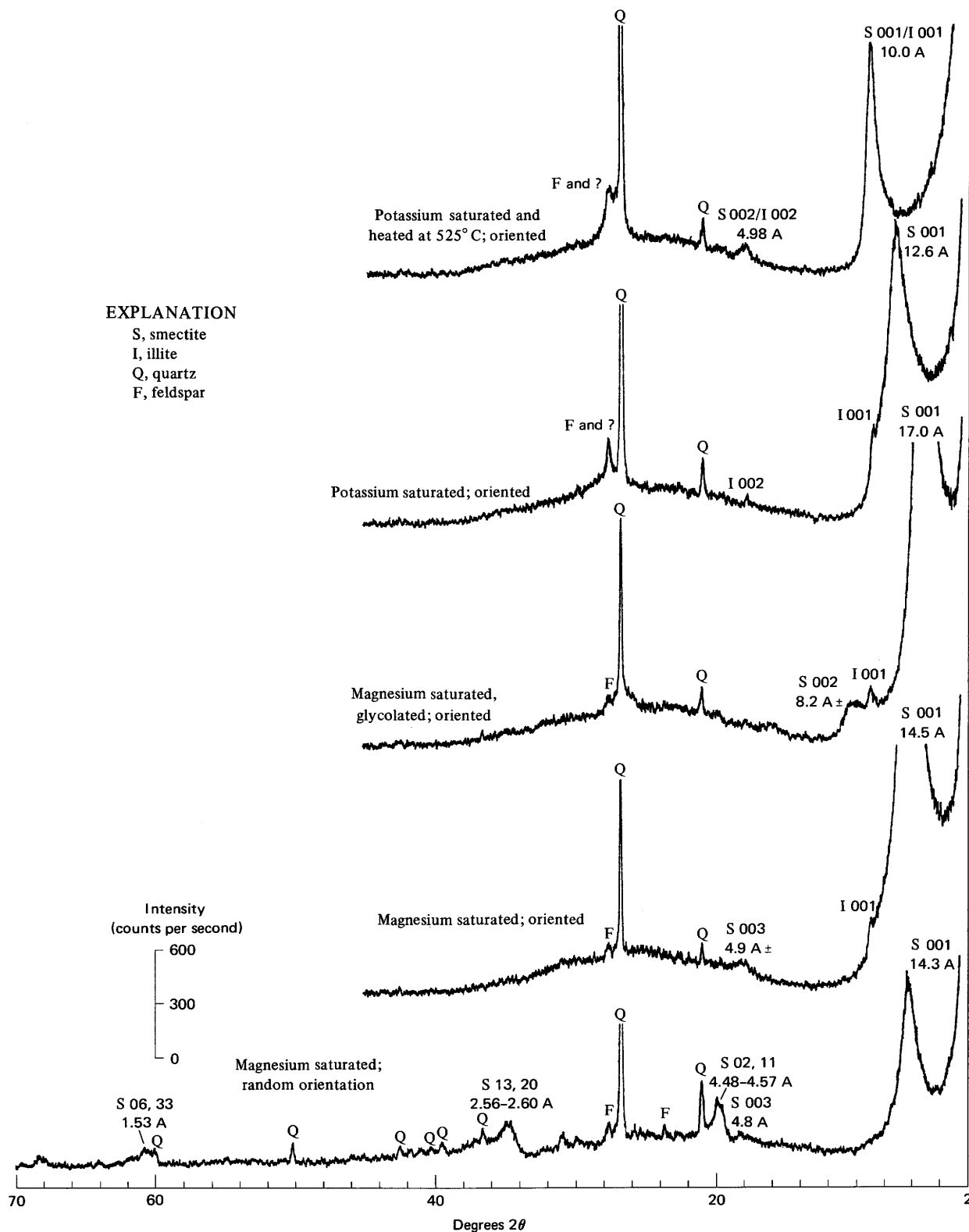


FIGURE 6.—X-ray diffraction patterns of 2-μm fraction of oil-shale sample 49 treated in several ways.

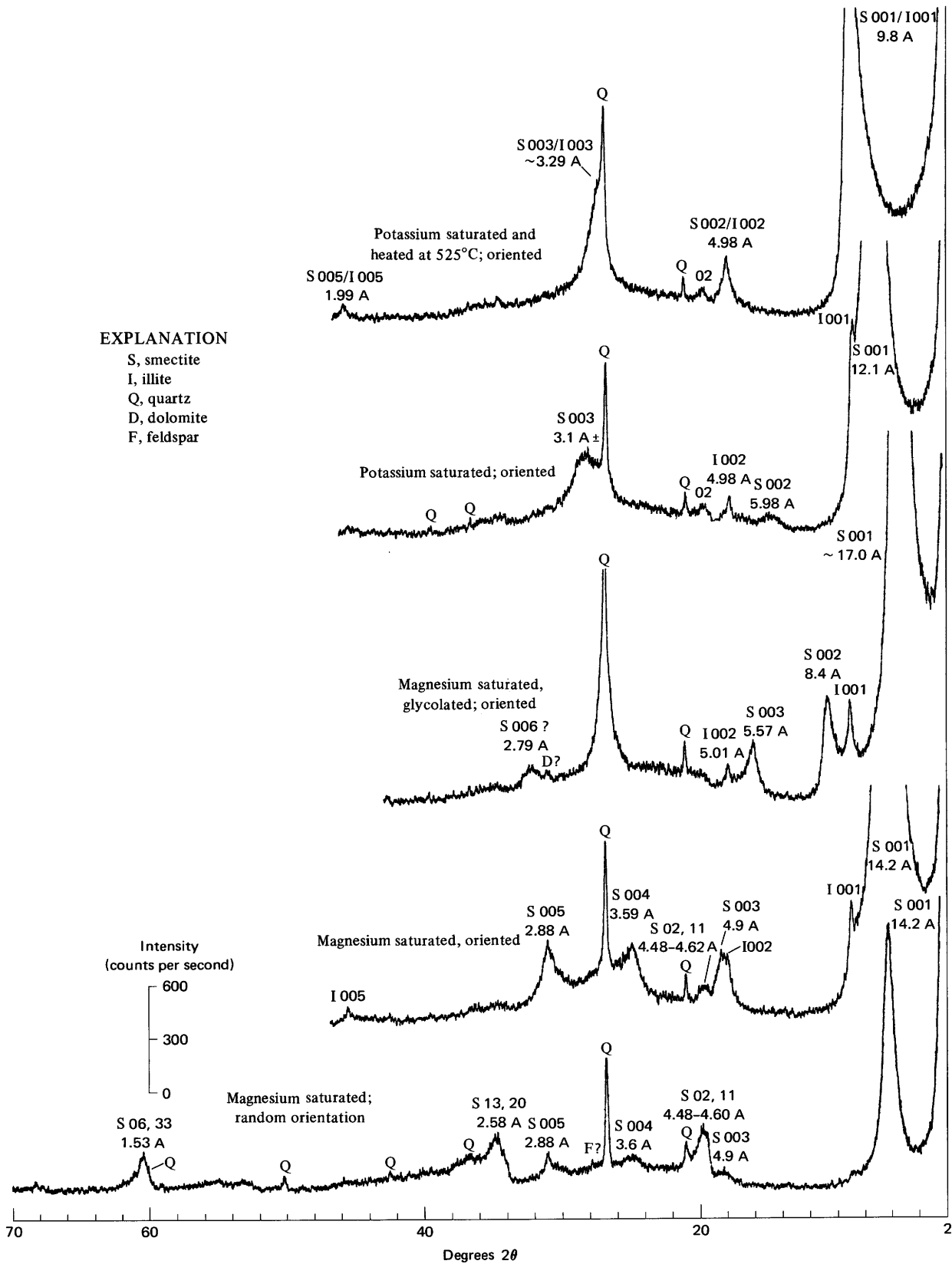


FIGURE 7.—X-ray diffraction patterns of <2-μm fraction of claystone sample 64 treated in several ways.

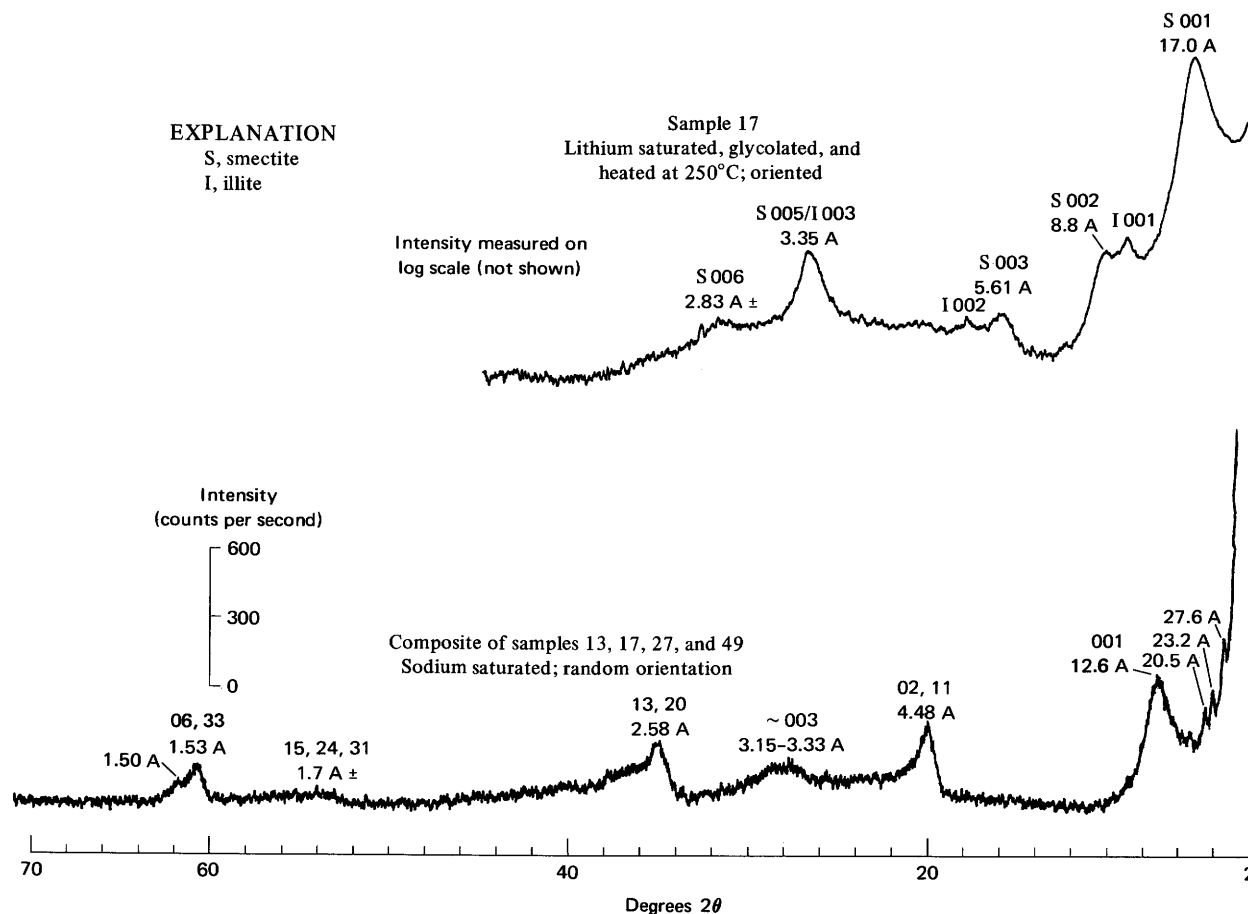


FIGURE 8.—X-ray diffraction patterns of purified <2- $\mu$ m clay fractions of several oil-shale samples.

samples 13, 17, 27, and 49, is shown in figure 8 (lower pattern). Several low-angle reflections at  $3^{\circ}$ – $5^{\circ}$   $2\theta$  suggest some mixed-layer clay. The X-ray pattern resembles in a general way some patterns for high-magnesium- and low-aluminum-bearing trioctahedral smectites (hectorite and stevensite) reported by Faust, Hathaway, and Millot (1959). The low-angle reflections just mentioned suggest the possible presence of stevensite; however, the d spacings for the 060 reflections published by the aforementioned authors are consistently lower (1.52 Å) than for the smectites reported here (1.53 Å). According to X-ray data given by MacEwan (in Brown, 1961, p. 192) for some trioctahedral smectites, other possibilities include aluminous and iron-rich saponite. The possibility of more than one species of trioctahedral smectite cannot be ruled out as suggested by the broadness (multiple peaks?) of the 02 reflection in many X-ray patterns. (See the patterns for the unoriented magnesium-saturated specimens in figs. 6 and 7.)

A chemical analysis of a partly purified sodium-saturated specimen of the <2- $\mu$ m fraction of oil-shale sample 17 is given in table 2, and an emission

spectrographic analysis of a portion of the same specimen is given in table 3.

Assuming that all of the  $K_2O$  (potassium oxide) in the chemical analysis of sample 17 is in mixed-layer and discrete illite, and assuming an average composition of illite as determined by Weaver and Pollard (1973, table 3, p. 9), about 20 percent of the chemically analyzed specimen is illite and the remainder is trioctahedral smectite and probably some silicate impurities. (See ratios of smectite to illite for sample 17 in table 1.)

The amounts of silica, lithium oxide, and fluoride in the calculated chemical composition of the illite-free smectite (table 2, rightmost col.) are close to the values reported for these constituents in stevensite by Bradley and Fahey (1962, table 1). However, the amounts of iron oxide and alumina reported here are considerably higher than the amounts found by Bradley and Fahey.

A structural formula for the smectite calculated from the data in table 2 (rightmost col.) gave

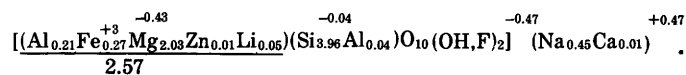




TABLE 2.—*Chemical analysis of a partly purified sodium-saturated specimen of the < 2- $\mu$ m fraction of oil-shale sample 17*

[Chemical analysis by Wayne Mountjoy, Violet Merritt, Johnnie Gardner, and G.T. Burrow]

Oxide	Percent	Oxides from first column assignable to illite <sup>1</sup> (percent)	Calculated composition of smectite free of illite (percent)
SiO <sub>2</sub> .....	53.4	9.79	54.4
Al <sub>2</sub> O <sub>3</sub> .....	7.5	5.18	2.9
Total Fe as Fe <sub>2</sub> O <sub>3</sub> ..	5.00	.98	4.99
MgO .....	15.5	.54	18.7
CaO .....	.17	.06	.14
Na <sub>2</sub> O .....	2.55	...	3.18
K <sub>2</sub> O .....	1.38	1.38	...
F .....	.85	...	1.06
ZnO .....	.09	...	.11
Li <sub>2</sub> O .....	.14	...	.17
CuO .....	.02	...	.02
Loss on ignition ....	13.2	1.69	14.4
Total .....	99.8	...	100.1

<sup>1</sup>Composition of illite is based on the average of chemical analyses of 24 illites calculated by Weaver and Pollard (1973, table 3, p. 9).

TABLE 3.—*Emission spectrographic analysis of a portion of the < 2- $\mu$ m fraction of oil-shale sample 17*

[Semiquantitative six-step spectrographic analysis by Nancy M. Conklin]

Element	Percent	Element	Parts per million	Element	Parts per million
Si .....	10	Zn .....	700	Ni .....	20
Al .....	5	Li .....	1,500	Pb .....	70
Fe .....	3	Cu .....	150	Sc .....	7
Mg .....	10	Mn .....	70	Sr .....	70
Ca .....	.15	Ag .....	1	V .....	150
Na .....	3	B .....	150	Y .....	10
K .....	3	Ba .....	70	Zr .....	30
Ti .....	.1	Be .....	1	Ga .....	20
		Co .....	10	Yb .....	1
		Cr .....	70		

NOTE.—Looked for, but not found: As, Au, Bi, Cd, La, Mo, Nb, Pd, Pt, Sb, Sn, Te, U, W, P, Ce, Ge, Hf, In, Re, Ta, Th, Tl, Eu.

Because of the likelihood of impurities in the smectite and because of the lack of data for ferric and ferrous iron, the preceding formula should be treated circumspectly. Despite these limitations, the formula shows that the amount of aluminum substitution in the tetrahedral sheet is small and that occupancy of cation sites in the octahedral sheet is low. If these relationships are true, they indicate a stevensite-hectorite smectite rather than a saponite, which has considerably more aluminum substituting for silicon in the tetrahedral sheet and, consequently, also has a higher negative tetrahedral charge of about 0.25 to 0.85 (fig. 9). Saponite also differs from stevensite and hectorite by generally having a positive octahedral charge and a cation occupancy of the octahedral sheet close to 3.00. The occupancy of the octahedral sites as shown by the formula seems unusually low, although a value as low as 2.30 for a zincian trioctahedral smectite (sauconite) was reported by Weaver and Pollard (1973, table 40, analysis 3).

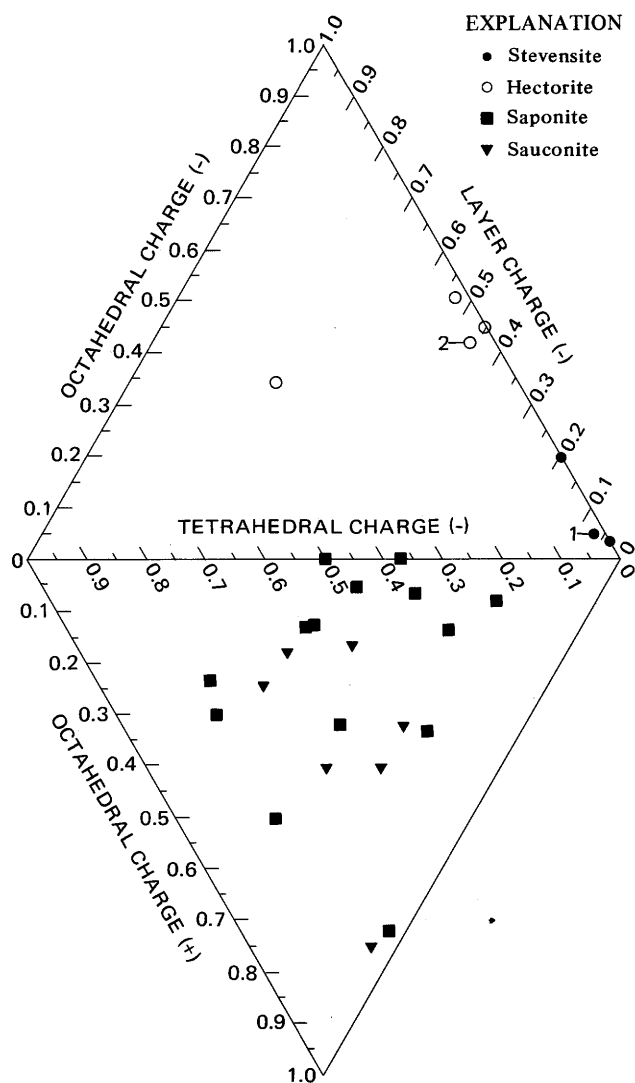


FIGURE 9.—Distribution of structural charge for some trioctahedral smectites. The data were compiled from published analyses. 1, Stevensite of Bradley and Fahey (1962); 2, smectite of this report.

Faust, Hathaway, and Millot (1959) have shown that stevensite and hectorite are closely related species of trioctahedral smectite but that they differ in chemical composition, in structural charge, and in other properties. Stevensite is essentially a magnesium silicate and has a low negative layer charge owing to a small deficiency of divalent octahedral cations. Hectorite is similar in composition to stevensite, but it also contains essential amounts of lithium, aluminum, and fluorine. Hectorite has a larger negative layer charge than stevensite because of substitution of lithium for divalent octahedral cations and because of a deficiency of octahedral cations as in stevensite (fig. 9). The distinction between the two minerals becomes less clear when the occurrence of stevensite in the

Green River Formation reported by Bradley and Fahey (1962) is considered. This smectite contains appreciable aluminum, lithium, and fluorine, like hectorite, but it has a structural layer charge of only  $-0.06$ , which is typical of stevensite. The relatively high layer charge ( $-0.47$ ) for the smectite of this study, as well as the presence of lithium, aluminum, and fluorine, suggest closer affinities to hectorite than to stevensite. It is concluded, therefore, that the smectite of this study is probably a hectorite.

The nonexpandable layer clay mineral having a basal 001 spacing of 10 Å is identified here as illite. The few broad reflections suggest that most of this material is illite in the sense of Hower and Mowatt (1966), but some of it may be a true mica, possibly biotite, which is commonly found in many of the thin beds of volcanic tuff scattered through the composite measured section (J. R. Dyni, unpub. data, 1972).

The relative abundance of illite to smectite was determined in two ways. In the first method (table 1, method A) the ratio of the relative intensity of the 001 reflection of 100-percent illite to 100-percent smectite in the glycolated magnesium-saturated specimens was assumed to be 1:4.5. A similar ratio was used indirectly by Schultz (1964, p. C11) to calculate the proportions of aluminous illite and aluminous montmorillonite in the Pierre Shale. A similar 001 peak-height ratio was found in X-ray-diffraction analysis of some synthetic mixtures of illite, montmorillonite, and kaolinite by Jarvis, Dragsdorf, and Ellis (1957, fig. 1). In the second method (table 1, method B), adopted from Droste (1961, p. 13, 15), the intensity of the 001 reflection of illite at 10 Å is assumed to remain unchanged after heating to 525°C. (Droste heated his samples to 400°C.) The intensity of the reflection at 10 Å is assumed to increase in proportion to the amount of smectite present when its crystal structure collapses to a basal spacing of about 10 Å on heating. The percentage of illite is calculated from the ratio of the area of the 10 Å reflection of the glycolated specimen (which provides maximum separation of the 001 reflections of illite and smectite) to the area of the same reflection after heating to 525°C multiplied by 100. In both methods smectite was calculated as the difference between 100 percent and the calculated percentage of illite. The results (table 1) show the preponderance of smectite, commonly 80 percent or more, in the clay mineral fraction in most samples.

Mixed-layer clay was detected in a few samples. Because the mixed-layer clay collapsed to 10 Å on heating to 525°C, all of it can be assumed to be mixed-layer illite-smectite. Chlorite was noted in one sample. Kaolinite was not detected in any of the samples.

## OTHER MINERALS

Quartz is relatively abundant in all of the samples. Potassium feldspar and, in lesser amounts, sodium feldspar are present in small to trace amounts in many of the samples. Analcime was detected in two samples.

Dolomite and calcite are major mineral components of the oil shales and claystones. Their relative abundance to each other was calculated by the method of Royse, Wadell, and Petersen (1971) by using peak heights as measured on the diffraction trace rather than by fixed time. Calcite is relatively more abundant in the oil shales than in the claystones; in five of nine samples of oil shale, calcite exceeds dolomite in abundance. Conversely, dolomite is more abundant in the claystones than in the oil shales; in all but one sample of claystone, dolomite greatly exceeds calcite in abundance.

## ORIGIN OF SMECTITE

Trioctahedral smectite, which is considered to be sparse in sedimentary rocks (Weaver, 1967, p. 43), may be more abundant in sediments of continental closed basins than has been previously suspected. Papke (1970, 1972) described playa deposits of saponite at Ash Meadows, Nev., and sepiolite and associated saponite in Amargosa Desert, southern Nevada. Droste (1961) found smectite and illite to be the principal clay minerals in sediments from many playa lakes in the Mojave Desert, southern California. Although Droste (1961, p. 15) noted the presence of both dioctahedral and trioctahedral smectite, he did not distinguish between them but inferred that the latter type comprised a substantial part of the clay fraction at least in a few playas. Saponite in dry-lake sediments in western Australia was reported by Graham (1953), and hectorite from some Tertiary lake beds in eastern Morocco was described by Millot (1949) and Jeanette (1952). (Also see Faust, and others, 1959, p. 343.)

In the Green River Formation, stevensite, first reported by Bradley and Fahey (1962), occurs in widely spaced thin layers through the saline facies of the Wilkins Peak Member in southwest Wyoming (Bradley and Eugster, 1969, p. B16). Tank (1969) reported abundant smectite and illite in oil shales and shales of the underlying Tipton Shale Member of the Green River Formation in the same area, but he did not distinguish between types of smectite. Considering these occurrences and the occurrences described in this report, trioctahedral smectite may be much more abundant in the formation than has been recognized.

The trioctahedral smectite in the rocks studied may

be authigenic. Magnesium-rich interstitial water, as evidenced by the presence of abundant (and probably authigenic) dolomite, may be an important factor in the origin of the smectite, as it seems to be for sepiolite and probably for associated saponites in a playa deposit described by Papke (1972, p. 213–214). The simple clay-mineral assemblage of smectite and illite, with the virtual exclusion of other clay minerals, might suggest an authigenic origin, although lack of clay minerals can be explained several ways. Therefore, it would be of value to know whether the discrete illite is also trioctahedral, which, if it is, would suggest a common origin or precursor.

If the smectite is allogenic, its origin is problematic inasmuch as large quantities of trioctahedral smectite in probable source rocks are not known. Cretaceous marine shales and younger rocks on the San Rafael Swell are likely source rocks, but these probably contained dioctahedral smectite and other clay minerals, as they do elsewhere in the Rocky Mountain region (Schultz, 1964, p. C6; Weaver, 1961). Volcanic ash is a probable source for some of the smectite; however, the ash beds present in the composite section amount to only 1 or 2 percent of the total sequence. Even if the entire hydrographic basin of the Tertiary lake occupying the Uintah Basin is considered, the total amount of ash that could have been contributed to the lake by streams, plus that deposited directly in the lake, probably would not amount to more than two or three times the amount of ash now present in the composite section.

Unless a source area which contained unusually large amounts of trioctahedral smectite is found, it becomes necessary to consider the formation of the smectite by reactions with other minerals or possibly by transformation of dioctahedral to trioctahedral smectite.

Levinson and Vian (1966) synthesized probable trioctahedral smectite by reacting dolomite, quartz, kaolinite, and water at moderate temperatures, and Graham (1967) subsequently proposed that saponite in a surficial playa deposit near Marchagee, Western Australia, was formed by this method at ambient temperature and pressure. Transformation of dioctahedral to trioctahedral smectite has not, to the author's knowledge, been demonstrated experimentally, but it would be worth trying.

## STRATIGRAPHIC MINERALOGY

In Indian Canyon in the Uinta Basin, the sequence of rocks overlying unit 118 of the measured section in figure 2 to the base of the Horse Bench Sandstone Bed in the upper part of the Green River Formation is 324 feet (98.8 m) thick and consists predominantly of

lacustrine claystones, thin beds of oil shale, and associated rock types similar to those of the measured section. The X-ray mineralogy of the rocks in this 324-foot-thick (98.8-m-thick) sequence, similar to that of the measured section, consists of dolomite, calcite, feldspars, quartz, illite, and abundant smectite. The smectite is probably trioctahedral, but this was not confirmed by X-ray analysis. Minor amounts of other clay minerals are also present.

The smectite in the entire 740-foot-thick (225.6-m-thick) sequence of rocks from the base of the measured section to the base of the Horse Bench Sandstone Bed can be divided, with few exceptions, into five distinct units, on based on the spacing of the 001 reflection of the smectite, as follows:

<i>Feet (metres in parentheses) above base of total sequence</i>	<i>Average spacing (A) of 001 reflection of smectite</i>
Base of Horse Bench Sandstone Bed.	
721–740 (219.8–225.6) .....	14.7
540–721 (164.6–219.8) .....	12.6
299–540 (91.1–164.6) .....	14.7
173–299 (52.7–91.1) .....	12.6
0–173 (0–52.7) .....	14.7

The change in spacing in the basal reflection of smectite, if real, may reflect several episodic changes in the major interlayer cation vertically through the above sequence of rocks—that is, from calcium (?) smectite with a basal spacing of 14.7 Å to sodium smectite with a spacing of 12.6 Å. Possibly, this alternation in spacing may have been in response to changes in the salinity of the lake waters. As salinity increased, the dominant exchangeable cation became sodium, and as salinity decreased, calcium became the dominant cation.

The sequence of rocks between the probable Mahogany oil-shale bed (units 80–81 of the measured section in fig. 2, according to W. B. Cashion, oral commun., 1971) and the base of the Horse Bench Sandstone Bed is 484 feet (147.5 m) thick in Indian Canyon and can be traced in the subsurface in oil and gas test wells eastward to the vicinity of Ouray, Utah. This sequence of rocks, which contains abundant smectite and illite in Indian Canyon, thins and grades laterally into a lithofacies composed entirely of oil shale that contains no smectite, little or no illite, and, locally, abundant nahcolite and shortite. The Horse Bench Sandstone Bed thins eastward and is absent in the Ouray area; however, its approximate position in wells can be determined from geophysical well logs.

The same sequence of rocks in the Western Oil Shale Corp. core hole EX–1, in the SW $\frac{1}{4}$ SE $\frac{1}{4}$  sec. 36, T. 9 S., R. 20 E., Uintah County, about 57 miles (92 km) east of Indian Canyon, has thinned to 448 feet

(136.6 m) and lies between the depths of about 1,854 and 2,302 feet (565.1 and 701.6 m). Smith, Trudell, and Robb (1972), who studied in detail the lithology and mineralogy of the core from this well, found that the sequence consists entirely of oil shale. They reported that throughout the sequence, as at Indian Canyon, dolomite, calcite, potassium feldspar, sodium feldspar, and quartz are abundant but, significantly, that smectite is absent and illite evidently is present only in the lower 250 feet (76.2 m) of the sequence. The last reported occurrence of illite upward in the sequence coincides roughly with the first appearance of nahcolite as in the Piceance Creek basin in Colorado (Hite and Dyni, 1967, fig. 4). Nahcolite becomes locally abundant in the nodules, masses, and thin beds in the upper 120 feet (36.6 m) of the sequence. Some shortite ( $\text{Na}_2\text{CO}_3 \cdot 2\text{CaCO}_3$ ) and sparse neighborite  $\text{NaMgF}_3$  and searlesite ( $\text{NaBSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$ ) are also found in the nahcolite-bearing part of the sequence. The top of the nahcolite- and shortite-bearing oil shale extends several tens of feet higher than the sequence of rocks considered here.

The eastward change from claystones and associated rocks to oil shale is reflected by increasing resistivities on electric logs of wells that penetrate these rocks (fig. 10). The predominantly claystone sequence in the vicinity of Indian Canyon shows a shale-like response on electric logs (Gulf 1 Indian Canyon well, in fig. 10), averaging about 20 ohms or less. The resistivity increases gradually eastward toward the Western Oil Shale Corp. core hole EX-1, and in the Sun 1 South Ouray well, a few miles to the northwest, the average apparent resistivity of these rocks has increased to about 156 ohms. This increase in resistivity is attributed to decreasing clay mineral content with a corresponding increase in kerogen and carbonate minerals.

The area of the oil shale and associated sodium minerals marks a chemical depocenter of Lake Uinta during Green River time, which is younger than nahcolite-bearing oil-shale deposits in the Piceance Creek basin in Colorado and older than another saline sequence of lacustrine rocks at the base of the Uinta Formation near Duchesne, Utah.

Cook (1973) and Vine and Tourtelot (1969) have noted that the amounts of many of the trace elements found in oil shale from the Green River Formation are less than would be expected for an organic-rich sedimentary rock. On the other hand, a few elements, including lithium, beryllium, and fluorine, show a twofold to tenfold increase over crustal abundance. The distribution and abundance of some trace elements found in oil shale may be controlled in part by basin lithofacies and the geochemical conditions of

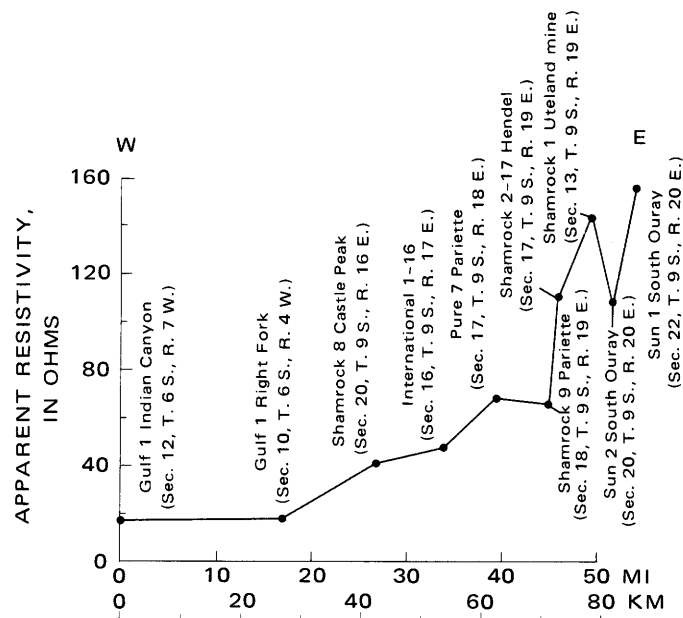


FIGURE 10.—Diagram showing the eastward increase of the averaged resistivity determined from the 16-inch normal curve for the sequence of Green River rocks between the Mahogany oil-shale bed and the Horse Bench Sandstone Bed in 10 wells between Indian Canyon and Ouray, Utah.

their depositional environments. As noted earlier, trioctahedral smectite contains notably large amounts of lithium, zinc, and copper. These elements, and others, may have been trapped during the formation and deposition of the smectite before they could migrate basinward into the oil-shale facies. This could explain why copper and zinc are found in quantities less than anticipated in the oil shale. For example, zinc in the whole-rock fraction of the 17 samples listed in table 1 ranges from 32 to 121 ppm (table 4), a threefold to ninefold increase in abundance over that of pyrolyzed Green River oil shale analyzed by Cook (1973). If smectite served as a chemical trap for selected metals, perhaps such elements could be

TABLE 4.—Semiquantitative X-ray fluorescence analysis of zinc in whole-rock samples of oil shale and claystone [Analyses by J. R. Dyni]

Oil Shale		Claystone	
Sample No.	Zinc (ppm)	Sample No.	Zinc (ppm)
7	102	9	108
13	38	15	32
17	88	25	36
27	75	37	55
49	43	60	42
63	71	64	54
68	121	95A	41
80	59	109	76
104	74		

Environment	Fluvial	Near-shore lacustrine	Offshore lacustrine	Chemical depocenter
Salinity of sediment waters	Fresh	Fresh to moderately saline	Saline	Hypersaline
Eh	Oxidizing	Mildly reducing	Moderately to strongly reducing	Strongly reducing
Rock type	Variegated mudstone, siltstone, and drab sandstone	Green claystone, some marlstone, and thin beds of oil shale	Kerogenaceous marlstone and oil shale	Oil shale and evaporites
Clay minerals	Various smectite, illite, mixed-layer chlorite and kaolinite	Smectite (trioctahedral) and illite	Illite	Little illite or no clay minerals
Principal authigenic matrix minerals	Calcite(?)	Mixed dolomite and calcite	Dolomite	Dolomite, dawsonite and quartz

FIGURE 11.—Schematic cross section of rock types and associated clay and authigenic matrix minerals found in the Green River Formation and related rocks, Uinta and Piceance Creek basins, Utah and Colorado.

concentrated in economic amounts. In this regard, there are a number of units of high electrical conductivity in rocks above and below the Mahogany bed in several wells between Indian Canyon and Ouray. For example, in the Shamrock 2 Walton well, in the NW $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 14, T. 9 S., R. 16 E., Duchesne County, several such conductive zones are present between the depths of 2,420 and 3,130 feet (737.6 and 954.0 m). The top of the Mahogany bed in this well is at a depth of 2,769 feet (844.0 m). Perhaps these high conductivities are attributable to metal-bearing smectites or possibly to sulfide minerals, although sulfide minerals did not seem especially abundant in a few samples of rotary cuttings of one conductive unit that were examined.

## BASIN LITHOFACIES

Regardless of the process responsible for the large quantities of trioctahedral smectite in the Green River Formation, the fact remains that this study, together with other published data, suggests a zonation of clay minerals from basin edge to center (fig. 11). The clay facies shown in figure 11 are not necessarily synchronous; the cross section simply shows their relative positions in the basin as they are now known.

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