

PETROLOGY AND MINERALOGY OF THE MOUNT ROSA
AREA, EL PASO AND TELLER COUNTIES, COLORADO
III. LAMPROPHYRES AND MINERAL DEPOSITS¹

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ABSTRACT

Widely scattered dark gray lamprophyre dikes in the Mount Rosa area strike generally north-northwest and dip steeply. Outcrops of the lamprophyres, which can usually be traced for less than 500 feet, range in width from 2 to 25 feet. The lamprophyres are of two types, sodic syenites and sodic diorites. They intrude Pikes Peak granite, its variants, and Mount Rosa-type pegmatites. The lamprophyres are believed to be of late Precambrian age and their period of intrusion overlapped that of Mount Rosa-type pegmatites.

Veins of fluorite strike mainly north or northeast and dip steeply. These are probably of Tertiary age. Strongly radioactive altered zones in Mount Rosa granite contain uranothorite and thorogummite, which also occur as late hydrothermal minerals in Mount Rosa-type pegmatites.

INTRODUCTION

In this concluding article on the petrology and mineralogy of the Mount Rosa area, El Paso and Teller Counties, Colorado, we report the results of studies on nearly 50 fine-grained lamprophyre dikes and of the study of fluorite and barite veins and radioactive zones. Descriptions of the granites and pegmatites of the area have recently been presented (Gross and Heinrich, 1965, 1966). The presence of lamprophyres in this area was first recorded by Finlay (1916).

LAMPROPHYRES

Distribution. No general structural pattern of lamprophyre distribution appears from plotting the locations of the widely scattered outcrops. The predominant strike of the dikes is north-northwest with dips nearly vertical. A few dikes strike northeasterly and dip steeply northwest or southeast. Their outcrops can be traced for less than 500 feet, and the dikes range in thickness from 2 to 25 feet. A few small bodies, which appear, from outcrop, to be rectangular in outline, do not exceed 300 by 100 feet.

Small dikes occur along and adjacent to the Gold Camp Road near Wade Cutoff, on the south-facing slope of Kineo Mountain, and one particularly long dike can be traced from near Bruin Inn northward to Bear

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Creek (Fig. 2, Gross and Heinrich, 1965). The two rectangular lamprophyre bodies that occur in the area are north of Kineo Mountain and near Stove Mountain adjacent to the Gold Camp Road.

Petrology. The lamprophyres are dark gray to black, fine-grained rocks which are generally very resistant to erosion. Mafic minerals predominate, with scattered microphenocrysts of feldspar producing a spotted appearance. Rarely small clots of amphibole grains can be seen in

TABLE 1. MODES OF SELECTED LAMPROPHYRES, MOUNT ROSA AREA, COLORADO

No.	4-6	32-16	32-1A	60-8
Olivine (altered)	29.5			
Augite	32.0			
Titanaugite				22.0
Aegirine				10.0
Barkevikite		45.9		
Biotite		11.5	41.3	
Andesine (Ab62)	28.0			
Oligoclase (Ab70-72)		39.3	46.5	
Anorthoclase perthite				58.0
Accessory (magnetite)	10.5			10.0
Fluorite & magnetite			12.2	
Magnetite & apatite		3.3		
Johannsen No.	3212	3212	2212	2110
Classification	Olivine diorite	Meladiorite	Diorite	Sodic syenite

Locations:

- 4-6 At head of East Beaver Creek, Teller County.
- 32-16 One-half mile southeast of Kineo Mtn., El Paso County.
- 32-1A Near trail, North Cheyenne Creek, El Paso County.
- 60-8 One-fourth mile northwest of pegmatite 61-4, El Paso County.

the larger rectangular bodies. In many places the feldspar crystals are aligned sub-parallel to the trend of the dikes.

Thin section studies indicate that the lamprophyres belong to two major types: sodic syenites and sodic diorites.

a) *Sodic syenites:* Most commonly the phenocrysts are of anorthoclase which forms rounded single crystals or, less usually, glomeroporphyritic groups. This feldspar shows marginal replacement-type perthitization and moiré structure. The chief matrix feldspar is similar, except the grains are invariably more strongly perthitized, usually throughout their entirety.

The matrix texture most commonly is anhedral-granular with neither the feldspars nor the mafics showing any crystal boundaries. In a few, however, the matrix alkali feldspar forms euhedral tablets with the mafics in smaller, anhedral, interstitial grains and clusters. These feldspar tablets may have a criss-cross arrangement or show poorly developed flow structure (trachytoid).

The mafic species are aegirine, barkevikite, biotite ($\text{Fe}^{3+} \pm \text{Ti}$ -rich).

TABLE 2. CHEMICAL ANALYSIS OF A SODIC SYENITE

SiO ₂	61.46
Al ₂ O ₃	14.55
Fe ₂ O ₃	2.30
FeO	5.78
MgO	.50
CaO	2.74
Na ₂ O	4.71
K ₂ O	4.88
H ₂ O ⁺	.74
H ₂ O ⁻	.54
TiO ₂	1.07
P ₂ O ₅	.27
MnO	.25
BaO	.17
F	.14
S	.01
ZrO ₂	.02
	100.13

Cuts Pikes Peak granite, one-half mile east of Jones Park, Teller County. G. Steiger, Analyst. Finlay, 1916.

Mineralogy: Aegirine, barkevikite, biotite, anorthoclase-perthite; accessory zircon, quartz, allanite, fluorite.

Aegirine appears as rare rounded phenocrysts and as matrix granules; both are uralitized by the sodic amphibole. Less commonly titanian augite may also be present. The amphibole forms clots of larger grains in a few rocks but usually is confined to the matrix where some of it replaces aegirine. Uncommonly thin veinlets of barkevikite cut the syenites, attesting to the late development of the amphibole. Biotite is restricted to the matrix. Accessory minerals include riebeckite, allanite, zircon, apatite, magnetite and fluorite. In Table 1 (No. 60-8) is presented the mode of a pyroxene syenite lamprophyre. Table 2 gives the chemical analysis of a syenitic lamprophyre.

b) *Sodic diorites*: The dioritic lamprophyres show even greater mineralogical variability than their syenitic counterparts. Some contain the combination of augite and olivine (Table 1, No. 4-6); others have a sodic amphibole as the chief mafic species (Table 1, No. 32-16); whereas in a third type biotite is the sole mafic mineral (Table 1, No. 32-1A). The olivine is completely altered to an antigorite-calcite pseudomorph which retains the original olivine crystal outline. The plagioclase ranges from Ab₆₂ to Ab₇₂, with the more calcic varieties occurring in olivine-pyroxene rocks. Amphibole and biotite dioritic lamprophyres may contain accessory perthitic alkali feldspar.

In these rocks the bulk of mafics may appear as phenocrysts in a dominantly feldspathic matrix that is fine-grained and felted. Accessories are magnetite, allanite and abundant apatite.

Age relations to other intrusive rocks. The lamprophyre dikes transect the Pikes Peak granite and its variants. Contacts between the two are sharp with no apparent exo- or endomorphic effects. Although no lamprophyres have been found intruding the Mount Rosa granite, Mount Rosa pegmatites are cut by them. However, in one occurrence a Mount Rosa-type pegmatite cuts a very small lamprophyre. This indicates that although most of the Mount Rosa pegmatites had been emplaced prior to lamprophyre intrusion, initiation of the latter process began just before termination of the pegmatitic stage. Thus the age of the lamprophyres is Precambrian, post-Mount Rosa, or slightly younger than 1010-1080 my (Gross and Heinrich, 1965, 1966).

Other Colorado lamprophyres. Geological and petrological data on other Colorado lamprophyres are summarized in Table 3. The four Precambrian groups (Table 3, 1-3, plus that of this paper) all are apparently among the very youngest Precambrian rocks of the state. The others (Table 3) are Eocene to Miocene in age. Most of the swarms are spatially and genetically related to "central" igneous complexes (Table 3, Nos. 1, 2, 6, 7) that are somewhat to strongly alkalic. The Mount Rosa swarm is related at least in distribution and in time to an alkalic granite body and is unique in this respect among Colorado lamprophyre swarms. The three others (Table 3, Nos. 3, 4, 5) are not relatable to any "central" alkalic complex.

Discussion. Reviews of theories on the origin of lamprophyres have been published by Eskola (1954), Kaitaro (1956), and Turner and Verhoogen (1960). The state of our knowledge regarding their genesis can best be summarized by the statement of Turner and Verhoogen, 1960, p. 255, "It

must be admitted that no completely satisfactory explanation of the origin of lamprophyre has yet been proposed". Indeed most theories are highly unsatisfactory. This includes Barth's (1962, p. 193) explanation: ". . . much evidence supports the view that lamprophyres are diabases that have been altered by metasomatic processes." In Colorado diabases and lamprophyres occur side by side (*e.g.*, the Lookout Mountain area), but the diabases are older and no transitional rocks nor relict features exist even to suggest that lamprophyres are derived by the alteration of diabases.

Turner and Verhoogen (1960, p. 254) state also that "Today any direct comagmatic relation between granite and associated lamprophyres is generally denied". The Mount Rosa lamprophyres are perhaps somewhat unusual in the following ways:

1. They are syenitic to meladioritic; gabbroic, peridotitic and feldspathoidal types are absent.
2. Feldspars are not confined to the rock matrixes.
3. CaCO_3 is not abundant; in fact, it is rare to absent in most varieties.
4. They show a temporal relationship to terminal stages of Mount Rosa igneous activity.

That the lamprophyre magma is a late derivative of the Mount Rosa magma is not suggested by any observational data. It seems rather that the former was intruded, from a genetically separate source, along fractures in Pikes Peak granite that were formed in response to stresses related to the emplacement of the Mount Rosa sheet.

MINERAL DEPOSITS

Fluorite veins. A few scattered breccia zones containing fluorite have been prospected in the St. Peters Dome district. All of these veins dip steeply and transect Pikes Peak granite, mostly near fayalite granite bodies.

Only one of the larger breccia zones has been mined for fluorite (the Hughes Boss claim); this zone can be traced for more than two miles and has been named the St. Peters Dome fault (Boos and Boos, 1957). The mineralized zone has a thickness of more than 6 feet and is well exposed at a caved drift near Rock Creek Canyon. The vein strikes N. 55° E. and dips 56° SE. Northward the strike of the fracture zone changes to N. 15° W., and the dip to 76° SW., and it increases in thickness. At the summit of the ridge the fluorite vein is 4 to 6 feet thick and trends N. 30° W. Near Duffield the vein strikes N. 22° E. where exposed in a shaft. Many small offsets along the fracture zone cause changes in strike. Pinch-and-swell structure is common. The wall rock is normally Pikes Peak granite, but at one spot the vein cuts fayalite granite.

The breccia zone consists of many ramifying veinlets of fluorite from

TABLE 3. EXAMPLES OF OTHER COLORADO LAMPROPHYRES

Location	Petrology	Consanguineous alkalic complex and related rocks	Geological age	References
1. McKinley Mtn. area, Northern Wet Mtns., Custer and Fremont Cos.	"lamprophyres" phenocrysts of augite, hornblende or biotite in a fine-grained dark gray matrix.	Democrat Gulch gabbro-syenite-breccia complex. Other dikes are 1) syenites, 2) dark syenites, 3) andesites, andesite porphyries, basalts, 4) gabbros. Lamprophyres may be youngest dikes.	youngest Precambrian rocks of the area, 595 my.	Christman <i>et al.</i> , 1959; Heinrich and Dahlem, 1966
2. Lookout Mtn. area, Fremont Co.		McClure Mtn.-Iron Mtn. gabbro-syenite-nepheline syenite-ijolite complex. Dike sequence is: 1. Olivine gabbro and Iherzolite 2. nepheline syenite 3. augite-barkevikite spessartite 4. plagioclase spessartite 5. vogesite 6. trachyte 7. carbonatite	Part of youngest Precambrian rock group in the area, possibly also 595 my.	Dahlem, 1965; Heinrich and Dahlem, 1966

TABLE 3—(Continued)

3. Northern Sawatch Range	"resemble minette, vogesite and spessartite"	None indicated. Occur in gneiss and granite, have been metamorphosed to amphibolite facies.	Their intrusion constitutes almost the youngest Precambrian event of the area.	Pearson, 1959
4. Front Range, Boulder Co.	limburgite	Dikes of monzonite porphyry, diorite porphyry; latite breccia	Last event in Tertiary intrusive and mineralization sequence; Probably Eocene.	Lovering and Goddard, 1950. E. N. Goddard, pers. comm.
5. South Park, Park Co. Secs. 20, 21, T. 11S., R. 75W.	Two composite bodies (one dike, one sill) of older analcite trachydolerite and younger analcite syenite	none known	Post-cretaceous, Pre-Oligocene	Jahns, 1938; Stark <i>et al.</i> , 1949
6. Raton Mesa region, south-central Colo.	syenite lamprophyre, olivine gabbro lamprophyre, foidal gabbro lamprophyre	West Spanish Peak of syenodiorite porphyry. Lamprophyres are in "subparallel group" of dikes which is younger than radial dike swarm.	Late Eocene to Early Oligocene	Knopf, 1936; Johnson, 1960, 1961, 1964.
7. Cripple Creek district, Teller Co.	trachydolerite, vogesite, monchiquite	Latite-phonolite "Basin breccia," syenite phonolite	Miocene	Cross, 1897; Lindgren and Ransome, 1906

less than an inch to several feet thick. Locally along the zone the breccia blocks have been chloritized and silicified. The vein minerals are chiefly fluorite, quartz and chlorite with minor amounts of sphalerite and galena. Gold in pyrite and small quantities of chalcopyrite and barite have been reported by Stevens (1949), who states that the ore is known to continue to a depth of at least 600 feet.

A few other small prospects in the vicinity contain fluorite and chlorite or barite. These deposits show considerable brecciation of Pikes Peak granite and weak sulfide mineralization.

Within the Mount Rosa area these mineralized breccia zones are found cutting Pikes Peak granite, fayalite granite, and the lamprophyres, all Precambrian rocks. As no younger rocks are present in the area, the breccia veins can only be dated crudely by comparison with fluorite deposits in adjoining regions. Stevens states that the Mount Rosa veins resemble structurally and mineralogically the Cripple Creek fluorite deposits and thus may be of Miocene age.

Nine samples of fluorite ores from six deposits were analyzed for Be, with generally negative results. The highest value was 5 ppm Be in a gray-green fluorite from a narrow vein on the north trending spur of Cookstove Mountain, north of the Duffield area, a prospect not described by Stevens (1919).

Radioactive deposits. Many pegmatites and one small area of altered Mount Rosa granite were uncovered as the result of prospecting for radioactive minerals. The radioactivity stems from zircon and thorite, less commonly from pyrochlore, microlite or thorongumite. These deposits have a high concentration of thorium but are low in uranium.

The radioactive pegmatites are composed primarily of quartz, microcline, riebeckite and zircon. Radial fracturing of quartz around metamict zircon and thorongumite is common. In a few pegmatites, olive-green euhedra of pyrochlore are associated with zircon, and the border zones of some pegmatites contain a few yellow-orange crystals of radioactive microlite. Secondary uranium minerals are rare, although uranophane has been identified from a pegmatite containing zircon, thorite and pyrochlore. None of the radioactive pegmatites have proved to be of any commercial value.

A small area three miles northeast of Rosemont on the Summit Wye Road contains two trenches from which were shipped 500 tons of radioactive ore. Core drilling indicated variable amounts of radioactive ore at a depth of 100 feet in Mount Rosa granite. Assays indicated thorium exceeded uranium in the ore, which contained thorongumite (Carl Quinn, pers. comm.). The ore bodies are irregular-shaped pods within the Mount

Rosa granite along a northeast-trending ridge. A radiometric survey with scintillation counter indicated that most of the bodies are elongate, trending northeast.

At the Rosa No. 1 trench nearest the Summit Wye Road, fayalite granite is bleached light gray and the highly radioactive Mount Rosa granite is stained red-violet by hematite. The mineralized Mount Rosa granite is composed of altered feldspar, quartz and riebeckite, some of which has been converted to biotite or chlorite. Uranophane coats most of the individual grains, and small grains of thorite are disseminated through the rock. A highly radioactive brownish-black vitreous coating of uranothorite less than 3/8 inch thick occurs along fractures. Fluorescent pale-green opal is visible along some fractures. Page (1956, p. 630) states that ". . . small stocks, sills, and dikes of alkalic and fluorine-rich intrusives showing abundant deep-red to purplish-red oxides are guides to possible deposits of thorium."

The Mount Rosa granite of the altered area is radioactive owing chiefly to thorogummite and uranothorite. Much hematite is also present along with supergene uranophane and uraniferous opal.

Thorite in the pegmatites formed in an "intermediate to late period in the hydrothermal replacement stage" (Gross and Heinrich, 1966). It seems probable that the deposits of thorite in fracture zones in Mount Rosa granite on the Summit Wye Road represent time and genetic equivalents of their pegmatitic dimorphs but which were formed by the late-stage hydrothermal solutions that had migrated beyond their usual pegmatitic boundaries.

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UMIAT BENTONITE: AN UNUSUAL MONTMORILLONITE FROM UMIAT, ALASKA

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ABSTRACT

Numerous bentonite clays interbedded with shale and coal are exposed in the interfingering, Cretaceous sediments along the Colville River and its tributaries in northern Alaska. Two bentonite beds of high purity, ten to twelve inches thick are conveniently accessible at Umiat Mountain, four miles northeast of Umiat, Alaska. X-ray diffraction, x-ray fluorescence and other diagnostic techniques revealed the bentonite to be nearly pure montmorillonite with certain beidellitic characteristics. It is proposed that this clay be known as Umiat bentonite.

INTRODUCTION

Numerous extensive bentonite beds have been reported in northern Alaska (Detterman *et al.*, 1963). These bentonites, some of which are interbedded with coal, are well exposed in interfingering Cretaceous sediments along the Colville River and its tributaries. Accurate field descriptions have been given, and stratigraphic relationships seem to be well understood, but as yet a systematic mineralogical characterization has not been reported. The present work was undertaken to provide this information and to uncover possible correlations between clay mineralogy and depositional environment.

Preliminary reconnaissance revealed that two bentonite beds of high purity, ten to twelve inches thick, are conveniently accessible on the south face of Umiat Mountain, about 4 miles northeast of Umiat, Alaska. These two beds and several others of lesser thickness lie in the basal portion of the Seabee formation (Whittington, 1956). The south face of Umiat Mountain consists of black, fissile shale with intercalated bentonites. The sequence is capped by a poorly consolidated subgraywacke. The outcrop is typical of Cretaceous sediments in this area. The rocks are semilithified and are folded into broad open structures. Post depositional lithological changes apparently have been minimal.

Field specimens of the Umiat bentonite are dark green on fresh fractures but cream to buff on weathered surfaces. Biotite flakes are abundant and more or less randomly distributed. The material had an *in situ* water content of about 20%. The beds fracture conchoidally and appear to be mineralogically homogeneous; no definite stratification within the beds is visible.

About 100 pounds of bentonite were collected from the two large beds shown in Fig. 1. Portions of this material were studied by *x*-ray diffraction, electron microscopy and other techniques selected for the purpose of fully characterizing the clay fraction.

EXPERIMENTAL METHODS

Preparation of clays. The calcium clay for *x*-ray analysis was prepared as follows: Approximately 10 g of material was soaked in 1 liter of deionized



FIG. 1. Photograph of bentonite beds. Arrow drawn to bed sampled. Light-colored beds are bentonite.

water and dispersed with a laboratory stirrer. The suspension was allowed to settle 20 cm for 16 hours in order to obtain the $<2\mu$ e.s.d. fraction. The clay fraction was then passed dropwise through a column containing calcium-saturated Amberlite IR-120 exchange resin. Oriented specimens were prepared by repeated centrifugation after the method of Kinter and Diamond (1956). Oriented mounts of lithium-saturated clay were prepared in a manner similar to that described above. The clay was first passed through a mixed bed (Fisher 903525) cation-anion exchange resin that removed soluble salts and converted the clay to the hydrogen form.

Then the suspension was immediately passed dropwise through a lithium-saturated column of Amberlite IR-120 resin.

X-ray diffraction analysis. A General Electric XRD-5 diffractometer equipped with a copper-target tube was used for the diffraction studies. The detector system utilized a G.E. No. 6 proportional counter. Peak intensities were obtained by multiplying peak heights, scaled from diffraction charts, by peak widths at half-height. Calcium-saturated oriented aggregates and randomly oriented powder specimens were analyzed in the dry and glycolated conditions over the angular range $2\theta = 2$ to 100° . A lithium-saturated oriented aggregate was heated for 12 hours at 250° C., and for 12 hours in glycerol at 85° C. (*cf.* Greene-Kelly, 1955). A diffraction pattern was obtained from this aggregate over the range $2\theta = 2$ to 35° .

Electron microscopy. Electron photomicrographs were obtained with an RCS-3F electron microscope operated at an accelerating voltage of 100 KV. The $<2\mu$ e.s.d. raw clay suspension was first passed through a hydrogen-saturated cation exchange resin; a drop of the suspension was then removed and placed on a collodion film supported by a 200 mesh copper grid. The suspension was evaporated to dryness and introduced into the interior of the microscope. During preparation and subsequent handling, the mount was protected against dust contamination.

Exchange capacity. The $<2\mu$ e.s.d. fraction of raw Umiat bentonite was passed through a hydrogen saturated Rohm and Haas IR-120 cation exchange resin and through a hydroxyl saturated Rohm and Haas IRA-400 anion exchange resin. This treatment removed the dissolved electrolytes present in the raw clay and left the hydrogen saturated Umiat clay suspended in deionized water. A suspension of hydrogen-saturated Wyoming bentonite was prepared in the same manner to serve as a standard for comparison. Nearly complete exchange was accomplished by restricting the total amount of raw clay passed through the resins to 10% of the total capacity of the exchange column before column regeneration. The hydrogen clay suspensions were titrated conductimetrically with 0.1 N NaOH; both suspensions were 0.6% clay by weight. The resulting data were plotted and the two points of inflection were interpreted as representing titratable hydrogen and aluminum. The second inflection point represents the exchange capacity of the clay (Low, 1955). From a knowledge of the titer at this point and the weight of clay in the titrated suspension, the exchange capacity was computed. A $<2\mu$ e.s.d. sample was also analyzed by the ammonium acetate method (Jackson, 1958). The

eluted cations present in the raw clay were determined by the normal spectrophotometric methods.

Specific surface area. The specific surface area of the untreated field specimen was determined by nitrogen adsorption; a similar determination was made on untreated Wyoming bentonite for comparison. This method gives an estimate of external surface area only, since nitrogen does not penetrate into the interlamellar space. The total specific surface, assuming all lamellae are expandable, may be computed from the lattice parameters of montmorillonite to be about 800 m²/g. Thus a nitrogen adsorption surface area permits an estimate of the approximate number of lamellae per packet of platelets in the natural state.

Differential thermal analysis. The DTA curves for the untreated Umiat and Wyoming bentonites were obtained with an Aminco differential thermoanalyzer programmed to heat at 8° C. per minute. The reference sample was 40 to 140 mesh Al₂O₃; the analysis was done under air in an Inconel sample block.

Pore size distributions in the naturally occurring clays were obtained using the Aminco-Winslow mercury porosimeter operated to 15,000 psi corresponding to a calculated equivalent capillary radius of about 0.01 μ .

X-Ray fluorescence analysis. Quantitative analyses of Sr, Mn and Ti in the bulk clay and <2 μ fraction were performed using x-ray fluorescence methods. For this work, the spectrometer was equipped with a molybdenum tube, a lithium fluoride analyzing crystal, and a helium path. Ten thousand counts were accumulated on each peak and adjacent background; the resulting peak intensity, corrected for background, was compared with similar measurements obtained from the rock standards G-1 and W-1. Corrections were made to compensate for the matrix differences among samples and standards.

Dr. John Hower kindly did a major element analysis of the <2 μ fraction by x-ray fluorescence. Details of the procedure are given by Hower *et al.* (1964).

RESULTS

Figure 2 shows the x-ray diffraction pattern of a glycolated, oriented aggregate of the <2 μ fraction of the Umiat bentonite, calcium-saturated. The exceeding regularity of the clay-organic complex is indicated by (a) the sharp diffraction maxima, (b) the presence of intense reflections through the 0014, and (c) the rational sequence of the 00l series; the standard deviation of d_{001} is ± 0.03 Å, based on reflections from the 005 through the 0014. In this respect Umiat bentonite is equivalent to Wyo-

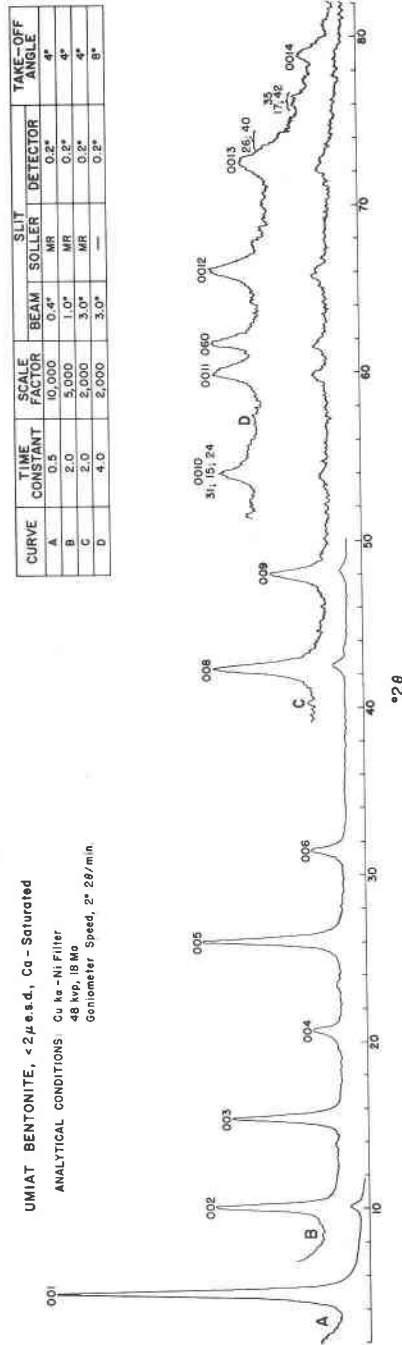


FIG. 2. X-ray diffraction pattern of 2μ, glycolated, calcium-saturated, Umiat bentonite.

ming (Clayspur) bentonite, when studied by similar procedures (Reynolds, 1965).

The d-spacing of the 060 reflection ($d=1.500 \text{ \AA}$) indicates that the Umiat bentonite is dioctahedral. This distinction is of some importance, for data given below indicate that, for some conditions, the dehydration characteristics of the lithium-saturated and heated clay are typical of beidellite and saponite. The dioctahedral character of the Umiat clay precludes classifying the Umiat bentonite as saponite.

Greene-Kelly (1955) has pointed out that some montmorillonoids lose their ability to expand in glycerol after lithium-solvation and heating.

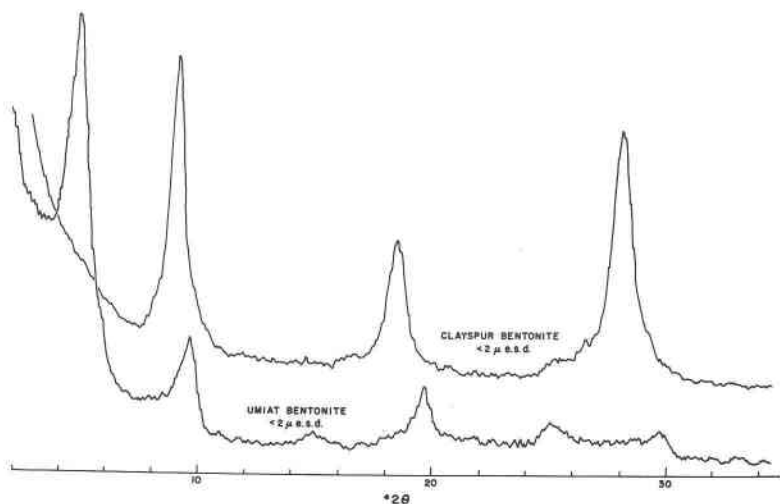


FIG. 3. X-ray diffraction patterns of glycolated Umiat bentonite and Wyoming bentonite after lithium solvation and heating to 275°C .

He suggests that lithium migrates into vacant octahedral lattice sites and neutralizes the lattice charge producing a nonexpandable pyrophyllite-like material. His work would indicate that normal montmorillonite (*i.e.*, minerals in which the site of the charge is octahedral) undergoes this irreversible collapse, whereas beidellite (of tetrahedral charge) does not. Greene-Kelly's technique has therefore been regarded as a useful means of distinguishing between montmorillonite and beidellite.

Clay-sized fractions of Umiat and Clayspur bentonite were treated according to the Greene-Kelly procedure and x-ray diffraction patterns shown in Fig. 3 were obtained. The chemical composition of Clayspur bentonite (Kerr *et al.*, 1950) indicates that it is a normal montmorillonite, and accepting the Greene-Kelly criteria, the diffraction pattern of

Fig. 3 is consistent with this view; Clayspur bentonite remained collapsed to a $d(001)$ of 9.7 \AA in the presence of hot glycerol. The Umiat bentonite, on the other hand, expanded to a normal $d(001)$ of 17.7 \AA . On the basis of these data and the Greene-Kelly criteria, one could, therefore, conclude that the clay-sized fraction of the Umiat bentonite consists predominantly of beidellite.

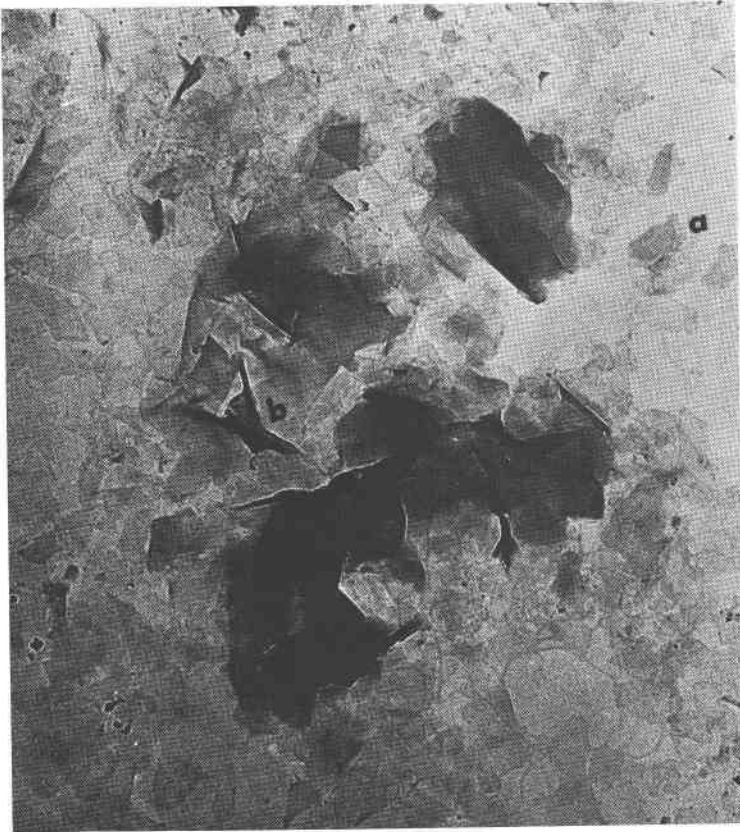


FIG. 4. Electron photomicrograph of Umiat bentonite.

An electron photomicrograph of the Umiat Bentonite is presented in Fig. 4. The mica-like nature of the thin clay particles is clearly evident. Individual lamellae cannot be distinguished but evidence of recently cleaved packets is clearly seen at (a); a good example of the crumpled and folded structures is located at (b). Except for the basal plane no well defined cleavage planes appear; this is characteristic of the 2:1 lattice clay minerals.

The cation exchange capacity of the $<2\mu$ fraction of raw Umiat bentonite was found by the ammonium acetate method to be 109 me/100 g dry clay. Of this 0.3 me was lithium, 102 me was sodium, 1.3 me was potassium and 5.6 me was calcium in the natural state. Thus it appears that the exchange complex is predominantly sodium saturated and the

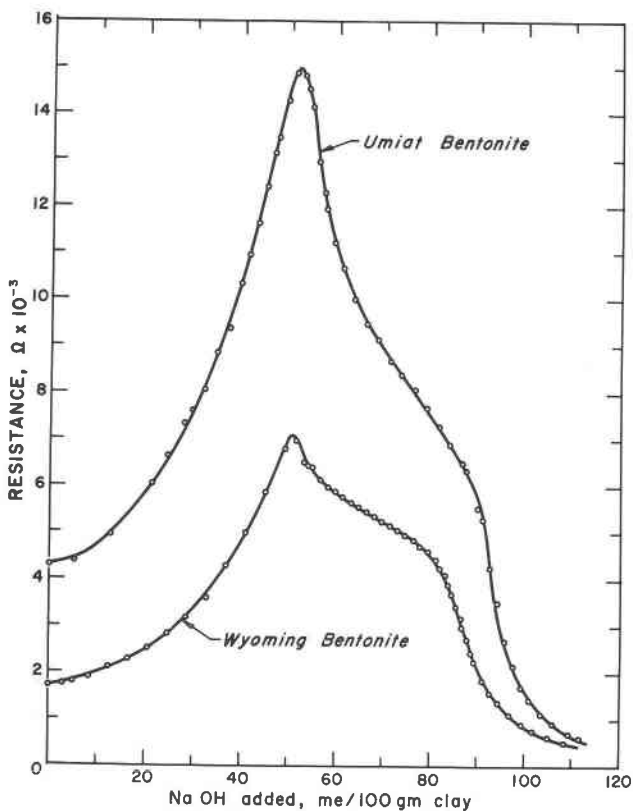


FIG. 5. Titration curves of H-saturated Umiat bentonite compared to that of Wyoming bentonite.

ratio of sodium to calcium is about 18 me to one. For comparison, the exchange capacity for Wyoming bentonite was determined by the same method to be 92 me/100 g clay. The titration curves of the two 0.6% hydrogenated clay suspensions are shown in Fig. 5. As has been shown by Low (1955), the first point of inflection corresponds to titratable hydrogen or hydronium ions whereas the second signifies the end point for the titratable aluminum ions present. The cation exchange capacity is, therefore, determined from the abscissa at the second point of inflection. For

Wyoming bentonite it is seen to be about 82 me/100 g clay, in general agreement with previously published values (Low, 1955). The end point for the Umiat bentonite, however, is seen to be about 91 me/100 g clay. The discrepancy between the values determined by the two methods should not be alarming, for this determination is sensitive and known to depend critically upon the methods employed. The significant point is that by either method the cation exchange capacity of Umiat bentonite was found to be about 10 to 15 me/100 g greater than that of Wyoming bentonite.

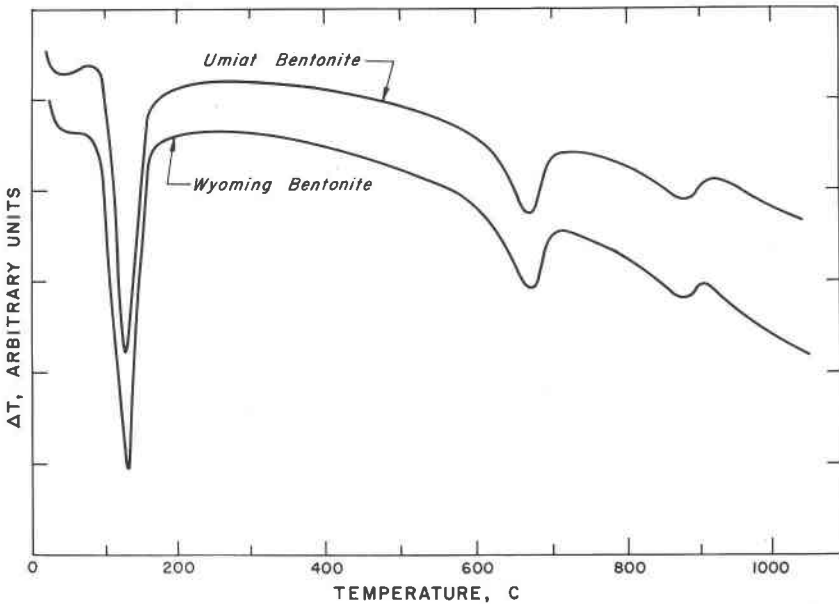


FIG. 6. Differential thermal analysis of Umiat bentonite and Wyoming bentonite.

The specific surface area (external area) by nitrogen adsorption was found to be about 17.5 and 18.0 m²/g (± 0.1 ; average of two determinations) for Umiat bentonite and Wyoming bentonite, respectively. In this respect there is no significant difference between the two clays. Since the total specific surface of 2:1 expanding lattice clays is known from unit cell dimensions to be about 800 m²/gm, both appear to contain on the average about 50 lamellae per packet. This estimate is consistent with the appearance of electron photomicrographs.

Differential thermograms for the two clays are shown in Fig. 6, and pore size distributions obtained by mercury intrusion (0.400 g, dried, field samples) are shown in Fig. 7. The result of the differential thermal

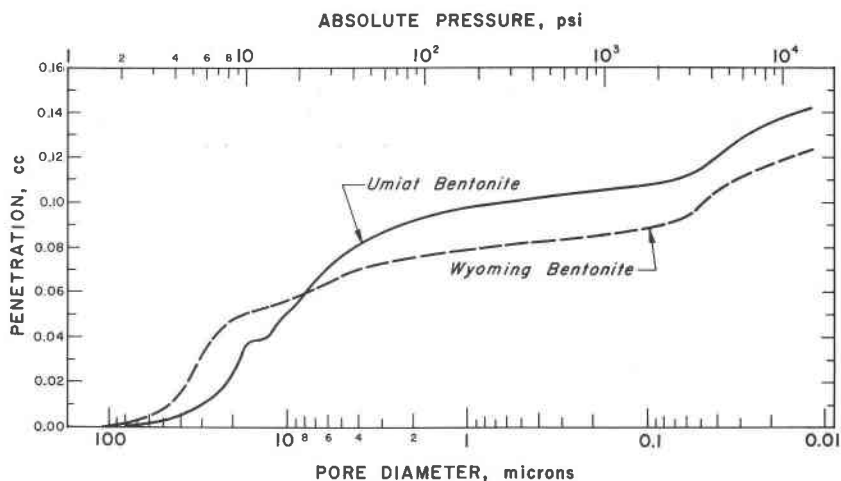


FIG. 7. Pore size distribution of Umiat bentonite compared with that of Wyoming bentonite by mercury intrusion of 0.400 g dried field samples.

TABLE 1. RESULTS OF X-RAY FLUORESCENCE ANALYSIS OF UMIAT BENTONITE

Element	Amount (ppm)	
	<2 μ fraction	Bulk sample
Titanium	824	1046
Manganese	96	157
Strontium	225	367

TABLE 2. MAJOR ELEMENT ANALYSIS OF UMIAT BENTONITE (<2 μ)

Oxide	wt. %
SiO ₂	55.99
TiO ₂	0.15
Al ₂ O ₃	18.92
Fe ₂ O ₃ } FeO }	3.38
MgO	3.08
CaO	1.61
Na ₂ O	not determined
K ₂ O	0.08

Assuming the C.E.C. to be 100 me /100 g, the formula can be shown as (X_{0.42}) (Al_{1.48} Fe_{0.15}³⁺ Mg_{0.32}) (Si_{3.92} Al_{0.08}) O₁₀ (OH)₂.

analyses shows no differences between the two bentonites, and both curves exhibit only those features normally expected from a 2:1 expanding lattice clay. The porosity data reveal that in the natural state the Umiat bentonite has a somewhat larger number of 5 to 10 μ and a smaller number of 20 to 50 μ (equivalent cylindrical diameter) pores than does the Wyoming bentonite; otherwise the pore size distributions are also remarkably similar.

The results of the analysis of Umiat bentonite for trace elements by *x*-ray fluorescence appear in Table 1. The amounts of titanium, strontium and manganese reported in Table 1 are comparable to those reported for the API reference montmorillonite clay minerals (Kerr *et al.*, 1950).

The major element analysis (neglecting H₂O) of the calcium-saturated <2 μ fraction is shown in Table 2.

DISCUSSION

The nomenclature of the montmorillonite clay minerals is now reasonably well defined. A comprehensive modern survey and bibliography has been published by MacEwan (1961). Definitions and terms used herein are in accord with his usage. The most common variety of montmorillonite has a dioctahedral structure and a lattice charge imbalance derived from the diadochic substitution of divalent cations for octahedral aluminum or ferric ions. Stoichiometrically, however, it is possible to derive a montmorillonite formula in which there are 4 octahedrally coordinated aluminum or (ferric ions) per unit cell and some substitution of silicon by tetrahedral aluminum; consequently, the site of lattice charge is tetrahedral. Variations between end member structures of this type comprise the beidellite-nontronite series. Many of the older identifications of beidellite are in doubt (Ross, 1960), but recent work by Greene-Kelly (1955) and Weir (1960) has clearly demonstrated the existence of beidellite as defined above. Beidellite is probably of rare occurrence. The only clearly identified specimens are material from the type locality at Beidell, and the sample from Black Jack Mine, Idaho (Greene-Kelly, 1955).

Umiat bentonite re-expanded after lithium solvation, heating and glyceration; Wyoming bentonite treated in the same manner did not expand. Thus it is evident that this treatment was capable of producing irreversible collapse in montmorillonite (Wyoming bentonite) but not in the Umiat clay. According to Greene-Kelly's criteria, it then appears that the Umiat bentonite may be either (1) beidellite, (2) nontronite, or (3) saponite. The iron content (Table 1) is insufficient for nontronite, and the occurrence of a typical dioctahedral 060 d-spacing clearly precludes identification as saponite. Therefore, according to the Greene-Kelly criteria, Umiat bentonite must be classified as beidellite. The data of

Fig. 5 support this identification. The higher electrical resistance of a suspension of Umiat bentonite compared to a similar suspension of Wyoming bentonite, for all increments of NaOH added indicates a lower exchangeable ion activity for Umiat bentonite. This effect is anticipated in a suspension containing a clay having its electrical charge imbalance in the tetrahedral layer compared to one of octahedral charge, for in the former the exchangeable ions can reside closer to the site of electrical charge and may thus be more tightly held and, consequently, less dissociated.

The results of the Greene-Kelly treatment and the titration curve suggest that the Umiat Bentonite is beidellite. However, the major element analysis provides a formula corresponding to montmorillonite. Moreover, the infrared spectra of the Umiat and Wyoming bentonites are essentially identical, and Russell and Farmer have shown that beidellite and montmorillonite gives distinctive infrared absorption curves.¹ The silica/alumina ratio obtained from a major element analysis is considered to be the best single criterion for distinguishing beidellite from montmorillonite. Unfortunately, if the analysis is done by *x*-ray fluorescence one cannot correct the results for the possible presence of amorphous silica. An attempt was made to resolve these contradictions, therefore, by a re-examination of the results obtained with the Greene-Kelly technique. The experimental conditions described above were duplicated and identical results were obtained. Then the procedure was altered slightly. The dispersed lithium-clay was flocculated with LiCl, centrifuged and dried. The slight excess of Li present as LiCl was not considered significant. When this material was heated to 250°, it changed from a gray-green to a distinct ferric oxide red. Glycerol solvation produced no expansion of this material.

Six other bentonites from the Umiat area, which we had tentatively identified as beidellite, were also re-examined after drying with excess LiCl. Each showed a marked color change with heating and a complete failure to expand upon glyceration. It appears that, for these clays, the dehydration characteristics are critically dependent on the presence of excess Li ions during heating. Wyoming bentonite showed no such behavior; no expansion with glycerol was noted for samples that were heated after column saturation, or after flocculation with LiCl.

It must be concluded from the chemical analysis and other data, that the Umiat bentonite is probably best classified as a montmorillonite but it differs significantly from Wyoming bentonite. The difference is manifested by a less dissociated ion exchange complex and a sensitivity to the presence of excess lithium ion when subjected to the Greene-Kelly treat-

¹ James D. Russell (priv. comm.).

ment. If the latter property is found to be characteristic of other bentonites, then the Greene-Kelly criterion ought to be further investigated and used with caution. The distinct color change upon heating suggests that at high temperatures excess lithium may displace ferrous or ferric ions from the octahedral layer. This behavior is not understood at present, but is being studied further.

SUMMARY

Major element, differential thermal, infrared, and *x*-ray diffraction data indicate that the Umiat bentonite is similar in most respects to Wyoming bentonite, and is, therefore, best classified as a montmorillonite. Titration curves indicate less dissociation of the exchange complex for the Umiat Bentonite, suggesting some structural and/or chemical difference between Umiat and Wyoming bentonite. The Umiat bentonite shows anomalous dehydration characteristics. Columnated lithium-clays subjected to the Greene-Kelly treatment show complete re-expansion with glycerol. If the lithium-clay is heated with excess LiCl, however, the dried material shows a marked color change and a complete loss of expandibility in glycerol.

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