American Mineralogist, Volume 60, pages 235–239, 1975

Authigenic Albite and Potassium Feldspar in the Green River Formation, Colorado and Wyoming

GEORGE A. DESBOROUGH

U.S. Geological Survey, Denver, Colorado 80225

Abstract

Authigenic albite occurs as the major mineral constituent in a prominent tuff in the upper part of the Tipton Member of the Eocene Green River Formation in Wyoming. Minor amounts of analcime and quartz are associated with the albite, and the tuff is enclosed in rich oil shale. Authigenic albite and K-feldspar as crystal aggregates and subhedral to euhedral crystals, mostly less than 10 μm in size, are ubiquitous minor constituents in oil shale in the Piceance Creek basin, Colorado. In terms of their intermediate structural state and cell parameters, these authigenic albites are similar to synthetic albites. The K-feldspars are disordered and similar to those reported for other closed-basin deposits.

Introduction

Authigenic albite and K-feldspar have been identified in oil shale and tuffs of the Eocene Green River Formation of Colorado and Wyoming. Low-temperature authigenic varieties of these two minerals have been reported as constituents of thin altered pyroclastic beds (Hay, 1966; Iijima and Hay, 1968; Surdam and Parker, 1972; Goodwin, 1973) and in oil shale (Hay, 1966; Smith and Milton, 1966; Hite and Dyni, 1967; Brobst and Tucker, 1973). Hay (1966) pointed out that the 3-mm-long albite crystals from the Green River Formation, reported by Moore (1950), had refractive indices incompatible with albite, and, furthermore, no albite grains that large or of that crystal form have subsequently been identified (Milton *et al,* 1960).

This report presents new compositional and structural data on authigenic albite and K-feldspar, and new information about the distribution of these minerals in the Green River Formation. Recognition of the widespread occurrence of these feldspars in oil shale provides additional data on the composition of these rocks for which oil extraction processes are being studied.

Methods of Study

Specimens used in this study are from drill cores in the Green River basin of Wyoming and the Piceance Creek basin of Colorado. They were selected on the basis of stratigraphic significance as well as their occurrence in oil-shale sequences of high economic potential. In contrast, Milton *et al* (1960) studied specimens, atypical of much of the oil shale, for purposes of topical mineralogical studies.

Because of the small (less than 5–10 μm) size of mineral grains in these rocks and the semi-opacity of the abundant organic component, standard petrographic thin sections were not of much value for mineral identification. Polished surfaces or polished thin sections are very useful, however, and these have been prepared as intact slabs for more than 100 samples of oil shale. Reflected light microscopy of these polished surfaces and polished thin sections, integrated with quantitative and qualitative electron microprobe analysis and secondary electron microscopy, provides the essential information concerning composition, morphology, occurrence, and associated minerals for albite and K-feldspar. X-ray diffractometer studies were conducted on intact rock slabs, crushed bulk samples, HCl-leached concentrates, ashed samples, and 10- 40-mg powders drilled from 1- 3-mm-thick intervals of polished rock slabs with miniature bits. Concentration of the feldspars for both X-ray diffraction and polished-grain-mount studies was increased by use of concentrated HCl on crushed samples.

Some polished surfaces of intact slabs were also subjected to concentrated HCl to remove analcime, Ca-Mg-Fe carbonates, and dawsonite. Apparently quartz, albite, and K-feldspar are not noticeably affected by this HCl treatment.

Albite Replacement of Pyroclastic Beds

Albite is the major constituent that replaced the original constituents of a 5-inch (12.7-cm)-thick tuff (DACO-3-1604.7, Table 1) in Wyoming. The tuff is underlain and overlain by rich oil shale, and is below the main saline zone. This is the first reported occur-

TABLE 1. Specimen Localities and Descriptions of Albites and K-Feldspars in the Green River Formation, Colorado and Wyoming

Specimen Name or Number (mineralogy)	Location	Depth	Member	Description and Reference
DACO-3-757 (K-feldspar)	Diamond Alkali Co., No. 3 core hole, sec. 8, T. 18 N., R. 108 W., Sweetwater Co., Wyoming	757 ft (230.7 m)	Wilkins Peak	tuff, 4 inches (10.2 cm) thick, uppermost tuff in columnar section No. 6 of Culbertson (1961, Fig. 348.2).
DACO-3-1604.7	do.	1,604.7 ft (489.1 m)	Tipton	tuff, 5 inches (12.7 cm) thick, uppermost tuff in Tipton Member, about 20 ft (6.1 m) below base of columnar section No. 6 of Culbertson (1961, Fig. 348.2)
Main tuff (K-feldspar>analcime, quartz>>albite)	Stauffer Mine, sec. 18, T. 20 N., R. 109 W., Sweetwater Co., Wyoming	-	Wilkins Peak	tuff, 1-2 ft (0.3-0.6 m) thick (Figs. 8, 10, Deardorff and Mannion, 1971)
C154Mb (quartz, albite, dolomite>calcite)	Wolf Ridge Minerals Corp. Savage 24-1 core hole sec. 24, T. 1 S., R. 98 W. Rio Blanco., Colorado	1,436 ft (437.7 m)	Parachute Creek	Mahogany bed, rich oil shale (Desborough et al, 1974)
C230 Mb	Colony Development Corp. No. 1-2, core hole sec. 1, T. 5 S., R. 96 W., Garfield Co., Colorado	540 ft (164.6 m)	Parachute Creek	Mahogany bed, rich oil shale (Desborough et al, 1974)

rence of authigenic albite constituting as much as 60 wt percent of any bed occurring in the Green River Formation and is exceptionally high for sedimentary deposits. K-feldspar is apparently absent, and analcime and quartz are the major associated minerals detected by X-ray diffraction and electron microprobe analysis. Secondary electron microscopy on HCl-leached fragments of albite grain aggregates at magnifications between 1,425× and 5,000× revealed that the largest crystal was approximately 10 μm across and that most grains have very poorly developed crystal form. Iijima and Hay (1968), Surdam and Parker (1972), and Goodwin (1973) reported K-feldspar as the principal authigenic feldspar replacing the tuffs in the Green River Formation of Wyoming. Iijima and Hay (1968) recognized authigenic albite in tuffaceous rocks, whereas Surdam and Parker (1972, p. 693) "have not confirmed the occurrence of authigenic albite in the tuffs." Goodwin (1973, p. 98) stated that "much, if not all, of the albite in the Green River Formation probably was deposited either directly as clastic material, or formed by albitization of more calcic plagioclase." The source of the clastic albite was not indicated.

The X-ray powder pattern of the authigenic albite replacing the tuff bed (Table 2) is very similar to that of synthetic albite (MacKenzie, 1957, Fig. 5) or synthetic analbite (Bambauer *et al,* 1967, Fig. 1), except that the *220* and *020* peaks are not clearly resolved. The *(131)*–*(1$\bar{3}$1)* separation is 1.46° *2θ* Cu*Kα* or 0.135 Å, corresponding to a non-ordered albite. Cell parameters and constants, determined by the refinement of X-ray diffractometer data using the U. S.

TABLE 2. X-Ray Powder Diffraction Data of Authigenic Albite, Wyoming*

hkl	d_{calc}** (Å)	d_{obs} (Å)	Int.	hkl	d_{calc}** (Å)	d_{obs} (Å)	Int.
020	6.38	6.38	12	$\bar{1}32$	2.645	2.648	4
001	6.37			$\bar{2}\bar{4}1$	2.542	2.540	10
$\bar{1}\bar{1}1$, $11\bar{1}$	5.88	5.89	4	$2\bar{2}1$	2.513	2.516	4
$\bar{1}11$	5.62	5.61	7	$\bar{2}41$	2.471	2.469	4
$\bar{2}01$	4.042	4.042	56				
$1\bar{1}1$	3.868	3.868	11	$\bar{1}50$	2.420	2.420	4
				240	2.389	2.388	4
111	3.763	3.768	23	$\bar{1}42$	2.301	2.301	3
130	3.659	3.664	21	060	2.129	2.129	8
$\bar{1}\bar{1}2$, $11\bar{2}$	3.495	3.498	7	$\bar{2}\bar{6}1$	1.906	1.905	2
031	3.436	3.430	7	222	1.882	1.881	2
$\bar{1}12$	3.374	3.374	11***	$\bar{3}\bar{5}2$	1.848	1.848	6
				$0\bar{6}2$***	-	-	-
040	3.193	3.198	100	113	1.798	1.798	4
002	3.187			$\bar{2}04$	1.7816	1.7815	8
220	3.156	3.153	19				
$1\bar{3}1$	2.987	2.984	10				
$0\bar{4}1$	2.934	2.934	22				
$0\bar{2}2$	2.931						
131	2.846	2.849	8				
022	2.779	2.776	1				

* DACO-3-1604.7, albite in Diamond Alkali Co. No. 3 core hole at depth of 1604.7 feet (489.1 m), Tipton Member, Green River Formation, Sweetwater County, Wyoming.

** Indices and d(calc) from least squares analysis of X-ray powder data using the computer program of Appleman and Evans (1973).

*** Interference from quartz.

Geological Survey FORTRAN IV computer program (Appleman and Evans, 1973) are, with standard errors in parentheses: $a = 8.164(9)$ Å, $b = 12.804(6)$ Å, $c = 7.143(4)$ Å; $\alpha = 93°55.4(3.7)'$, $\beta = 116°34.9(2.8)'$, $\gamma = 88°51.5(3.12)'$; $V = 666.2(6)$ Å^3; $\alpha^* = 86°11.1(3.7)'$, $\gamma^* = 89°18.8(3.0)'$. These cell parameters, as well as the positions of the *$\bar{2}01$, $\bar{2}04$,* and *060* X-ray spacings (Table 2), also indicate that the albite is non-ordered (Wright, 1968; Wright and Stewart, 1968).

A diamond-paste-polished slab and a grain mount of this albite were analyzed with the electron microprobe using feldspar standards (8 kV operating voltage, 10 nA specimen current, 4 μm diameter beam). The elements Na, Al, Si, K, and Ca were analyzed simultaneously. Because quartz occurs dispersed throughout many of the albite grains and grain aggregates, many analyses were rejected. Although all grains in the grain-mount specimen had been leached with concentrated HCl to remove analcime, several of the 85 analyses were rejected because minute grains of analcime remained within the polished albite grains and aggregates. From 42 acceptable analyses, the ranges and mean values (with calculated standard deviations in parentheses) are, in weight percent: Na_2O, 10.3 to 12.3, mean 11.4(3); CaO, <0.05 to 0.20, mean <0.05; K_2O, <0.05 to 0.58, mean 0.06(5). For CaO, only 5 of the 42 analyses showed 0.10–0.20 wt percent, all others being less than 0.05. For 33 of the 85 analyses, the amount of K_2O in wt percent was less than 0.05; the remaining 52 analyses had 0.05 to 0.58 wt percent K_2O (mean 0.13 wt percent). Atomic absorption analyses by G. D. Shipley and Claude Huffman, Jr., on the HCl-leached albite concentrate that contained minor quartz, indicated that the content of lithium was less than 30 ppm. Analyses for boron by Leon A. Bradley, using the 6-step semiquantitative spectrographic method on a fraction of the same material, indicated only 20 ppm. These data and the electron microprobe data illustrate that the albite is pure $NaAlSi_3O_8$.

The albite concentrate was also heated at 775°C for 3 days in an attempt to further disorder the mineral, but no measurable change in the *(131)–(1$\bar{3}$1)* spacing was detected.

Albite also occurs as a minor constituent in specimens of the main tuff (Table 1) from the Stauffer Trona mine. This rock is principally K-feldspar and quartz, but minor albite was detected by X-ray diffraction studies. Sixteen electron microprobe analyses of this albite revealed a mean Na_2O content of 11.7 (±0.10) wt percent and a mean K_2O content of less than 0.10 wt percent. The content of CaO for these 16 albite grains was less than 0.05; therefore, the mean K_2O content, 0.10, may be due in part to small inclusions of K-feldspar in the albite. Both albite and K-feldspar adjoin or replace grains of what is, probably, pyroclastic or epiclastic sanidine.

Disseminated Albite in Oil Shale

Brobst and Tucker (1973) recognized albite as a ubiquitous mineral in oil shales and associated rocks in the Green River Formation, Piceance Creek basin, Colorado. The occurrence of albite in rocks containing analcime and/or dawsonite has been widely recognized in X-ray diffraction studies of bulk samples. In the present study, albite was examined in the rich, laterally persistent Mahogany oil shale bed (C154Mb and C230Mb, Table 1) of the Piceance Creek basin in Colorado, which contain 20–25 wt percent of kerogen and yield oil upon heating to about 500°C. Quartz, dolomite, and calcite, with lesser amounts of dawsonite, analcime, K-feldspar, and siderite are commonly associated with this albite, which generally exhibits a subhedral-to-euhedral square or rectangular shape with a maximum dimension of about 20 μm. Concentrates with a high content of albite have been obtained by heating crushed material to 525°C for 12 hours in atmosphere, or to 480°C for 1 hour, and then leaching with concentrated HCl to remove carbonates. X-ray diffraction studies reveal that the pattern is nearly identical to that of the albite in Wyoming. The separation of the *(131)–(1$\bar{3}$1)* spacing is 1.28–1.30° 2θ Cu$K\alpha$ or 0.120 Å, and no difference is noted for material heated at 480°C for 1 hour or for that heated at 525°C for 12 hours. The mean Na_2O content for 43 albite grains in two drill-core specimens from different localities is 11.7(2) wt percent and the mean K_2O content is 0.10(10) wt percent. The CaO content is 0.05–0.20 wt percent. Thus, these albites in oil shale are of moderately high purity. Only 2 of the 43 albite grains analyzed in oil shale are attached to or replace sanidine of probable detrital origin.

Potassium Feldspar Replacement of Pyroclastic Beds

Potassium feldspar is the main constituent in tuffs in the Wilkins Peak Member of the Green River Formation in Wyoming, according to Surdam and Parker (1972, Fig. 2). One of the most prominent of these is the main tuff which is exposed in the Stauffer Trona mine (Table 1). This is the bed containing the

K-feldspar for which Goodwin (1973) reported the cell parameters that Sheppard and Gude had determined. A sample from this bed, examined in the present study, consists mainly of K-feldspar with an X-ray diffraction pattern essentially identical to that illustrated by Sheppard and Gude (1973, Fig. 3). However, quartz is also a major constituent, and the *$\bar{2}01$* peak of albite is conspicuous even though albite is a distinctly minor component as shown by electron microprobe analyses previously discussed.

Analyses of the K-feldspar in the main tuff are not satisfactory due to the fine grain size (less than 5 μm) and the intergrowth with quartz and minor albite. The 15 best analyses showed 0.2–0.4 wt percent Na_2O. The average K_2O content for these 15 analyses is 16.3 wt percent, compared with 16.9 for ideal K-feldspar. A concentrate of about 50 wt percent K-feldspar and 50 wt percent quartz, analyzed using atomic absorption methods, showed less than 30 ppm lithium. Semiquantitative spectrographic analyses of a similar concentrate indicated 300 ppm boron; thus up to 600 ppm of boron is present in this K-feldspar. The boron is apparently a significant trace constituent of this K-feldspar. The K-feldspar is therefore similar to those reported by Sheppard and Gude (1973, Table 2) to contain from 500 to 5,000 ppm. The boron value of 600 ppm, however, is not necessarily typical of authigenic K-feldspar in the Green River Formation. K-feldspar from a K-feldspar bed from the Wilkins Peak Member (DACO-3-757, Table 1) contained only 70 ppm of boron (semiquantitative spectrographic analysis). Lithium was not detected (less than 30 ppm). The bed did not contain detectable quartz or albite as indicated by X-ray diffraction methods, but pyrite was present in minor concentrations. The X-ray diffractometer pattern and X-ray spacings of this K-feldspar are identical with those of the K-feldspar in the main tuff of the Green River Formation.

For comparative purposes, boron-bearing K-feldspar from the Barstow Formation (Sheppard and Gude, 1973, Table 2) was X-rayed and analyzed with the electron microprobe. X-ray diffractometer patterns of this material are essentially identical with those of the two K-feldspars described above. This material was also simultaneously analyzed for Na, Al, Si, K, and Ca with the electron microprobe using feldspar standards. Totals for these oxides were generally 96.0–99.0 wt percent, and thus it might appear that there is loss of X-ray intensity due to decomposition. An electron beam defocussed to 4 μm diameter and a specimen current of 10 nA were used at an operating voltage of 10 kV. Rather than mineral decomposition, it is suspected that the very small size of individual grains results in "open space" along grain boundaries and thus, unlike the standards, a small part of the area being analyzed is not solid. For 30 analyses, the mean contents are: K_2O, 15.88; Na_2O, 0.4; and CaO, <0.05–0.10 wt percent. The Na_2O content ranges from 0.30 to 0.50 wt percent for all 30 analyses, whereas CaO was detected in the 0.05–0.10 wt percent range in only 4 of the 30 analyses. These results are very similar to those for a bulk sample of the same material (Sheppard and Gude, 1965, Table 1, Analysis 5).

Potassium Feldspar Disseminated in Oil Shale

Oil shale having both high and low organic content contains K-feldspar as a common mineral, making up as much as 10 wt percent. Because of the relatively low intensity of X-ray diffraction peaks for K-feldspar, amounts less than about 5 wt percent may not be detected. However, electron microprobe analyses of many oil shales, rich or lean, confirm the presence of single grains and aggregates of K-feldspar in samples where K-feldspar is not detected by X-ray diffraction analyses of bulk samples.

Ordering of Authigenic Feldspars

The most recent comprehensive studies of authigenic feldspars in carbonate rocks have been carried out by Kastner (1971). These feldspars occur in concentrations up to 2 wt percent and are low albite and microcline. They are high-purity end members containing less than 1 mole percent of $KAlSi_3O_8$ in albite and less than 1 mole percent of $NaAlSi_3O_8$ in microcline. Kastner (1971) has strongly emphasized that all authigenic albites are well ordered and has suggested (p. 1424) that the exception reported by Baskin (1956) was due to a systematic error in cell parameters or to the presence of admixed detrital feldspars. The present study shows that the authigenic albites of the Green River Formation are not well ordered, according to the separation of the *131* and *$1\bar{3}1$* peaks. The powder patterns resemble analbite, and the values of α^* and γ^* are intermediate between high and low albite. These results for the authigenic albite in the Green River Formation are consistent with the interpretations of MacKenzie (1957) and Martin (1968). The more recent studies of Trembath (1973) clearly illustrated the effect of aqueous NaOH on obliquity in albite.

The authigenic K-feldspar from the Green River

Formation of Wyoming has the same anomalous cell parameters as K-feldspar from other saline-lake deposits, as shown by Sheppard and Gude (1973).

The present study of authigenic albite and K-feldspar in the Green River Formation illustrates that the conclusions of Kastner (1971) for authigenic albite and K-feldspar in limestones and dolomites do not particularly apply to closed-basin occurrences of these minerals in fine-grained calcite and dolomite-bearing oil shales or in altered tuffaceous rocks.

Acknowledgments

Thanks are extended to G. D. Shipley and Claude Huffman, Jr., for lithium analyses using atomic absorption methods, and to Leon Bradley for boron analyses using the 6-step semiquantitative spectrographic method. R. A. Sheppard and A. J. Gude, 3d, are thanked for providing the K-feldspar specimen from the Barstow Formation in California and for critical comments.

References

APPLEMAN, D. E., AND H. T. EVANS, JR. (1973) Job 9214: Indexing and least-squares refinement of powder diffraction data. *U.S. Dep. Commerce, Nat. Tech. Inform. Serv.* **PB216188.**

BAMBAUER, H. U., M. CORLETT, E. EBERHARD, AND K. VISWANATHAN (1967) Diagrams for the determination of plagioclases using X-ray powder methods. *Schweiz. Mineral. Petrogr. Mitt.* **57**, 333–349.

BASKIN, YEHUDA (1956) A study of authigenic feldspars. *J. Geol.* **64**, 132–155.

BROBST, D. A., AND J. D. TUCKER (1973) X-ray mineralogy of the Parachute Creek member, Green River formation, in the Northern Piceance Creek Basin, Colorado. *U.S. Geol. Surv. Prof. Pap.* **803**, 53 p.

CULBERTSON, W. C. (1961) Stratigraphy of the Wilkins Peak Member of the Green River Formation, Firehole Basin quadrangle, Wyoming. In, *Short Papers in the Geologic and Hydrologic Sciences, U.S. Geol. Surv. Prof. Pap.* **424-D**, D170-D173.

DEARDORFF, D. L., AND L. E. MANNION (1971) Wyoming trona deposits. *Univ. Wyoming, Contrib. Geol.* **10**, 25–37.

DESBOROUGH, G. A., J. K. PITMAN, AND CLAUDE HUFFMAN, JR. (1974) Concentration and mineralogical residence of elements in rich oil shales of the Green River Formation, Piceance Creek basin, Colorado and the Uinta Basin, Utah: A Preliminary Report. *U.S. Geol. Surv. Open-File Rep.* **74-77**, 21 p.

GOODWIN, J. H. (1973) Analcime and K-feldspar in tuffs of the Green River formation, Wyoming. *Am. Mineral.* **58,** 93–105.

HAY, R. L. (1966) Zeolites and zeolitic reactions in sedimentary rocks. *Geol. Soc. Am. Spec. Pap.* **85,** 130 p.

HITE, R. J., AND J. R. DYNI (1967) Potential resources of dawsonite and nahcolite in the Piceance Creek basin, northwest Colorado. In, *Fourth Symposium on Oil Shale, Colo. Sch. Mines Q.* **62,** 25–38.

IIJIMA, AZUMA, AND R. L. HAY (1968) Analcime composition in tuffs of the Green River Formation of Wyoming. *Am. Mineral.* **53**, 184–200.

KASTNER, MIRIAM (1971) Authigenic feldspars in carbonate rocks. *Am. Mineral.* **56**, 1403–1442.

MACKENZIE, W. S. (1957) The crystalline modifications of $NaAlSi_3O_8$. *Am. J. Sci.* **255**, 481–516.

MARTIN, R. F. C. (1968) *Hydrothermal Synthesis of Low Albite, Orthoclase, and Non-Stoichiometric Albite.* PhD Thesis, Stanford University, 164 p.

MILTON, CHARLES, E. C. T. CHAO, J. J. FAHEY, AND M. E. MROSE (1960) Silicate mineralogy of the Green River Formation of Wyoming, Utah, and Colorado. *Int. Geol. Congr. 21st Session, Part* **21**, 171–184.

MOORE, F. E. (1950) Authigenic albite in the Green River oil shales. *J. Sed. Petrol.* **20**, 227–230.

SHEPPARD, R. A., AND A. J. GUDE, 3D (1965) Potash feldspar of possible economic value in the Barstow Formation, San Bernadino County, California. *U.S. Geol. Surv. Circ.* **500**, 7 p.

——— (1973) Boron-bearing potassium feldspar of authigenic origin in closed-based deposits. *U.S. Geol. Surv. J. Res.* **1**, 377–382.

SMITH, J. W., AND CHARLES MILTON (1966) Dawsonite in the Green River Formation of Colorado. *Econ. Geol.* **61**, 1029–1042.

SURDAM, R. C., AND R. D. PARKER (1972) Authigenic aluminosilicate minerals in the tuffaceous rocks of the Green River formation, Wyoming. *Geol. Soc. Am. Bull.* **83,** 689–700.

TREMBATH, L. T. (1973) Hydrothermal synthesis of albite: the effect of NaOH on obliquity. *Mineral. Mag.* **39**, 344–463.

WRIGHT, T. L. (1968) X-ray and optical study of alkali feldspar: II. An X-ray method for determining the composition and structural state from measurement of 2θ values for three reflections. *Am. Mineral.* **53**, 88–104.

———, AND D. B. STEWART (1968) X-ray and optical study of alkali feldspars. I. Determination of composition and structural state from refined unit-cell parameters and $2V$. *Am. Mineral.* **53**, 38–87.

Manuscript received, August 20, 1974; accepted for publication, October 29, 1974.