Potassium Feldspar in Weekeroo Station, Kodaikanal, and Colomera Iron Meteorites

Abstract. *Sodium plagioclase and small amounts of potassium feldspar are common constituents of silicate inclusions in the Weekeroo Station and Colomera iron meteorites; flamboyant x-ray antiperthite is unique to Kodaikanal silicate inclusions. Enrichment of potassium, sodium, silicon, and aluminum in these inclusions indicates a higher degree of chemical differentiation than in other meteorites.*

Preliminary x-ray diffraction work on minerals in silicate inclusions in the Kodaikanal iron meteorite (*1*) indicated the presence of a mixture of sodic plagioclase and K-feldspar. Electron-microprobe analyses indicated (*2*) the possible existence of K-feldspar in silicate inclusions of the Weekeroo Station iron meteorite. Utilizing x-ray diffraction and electron-microprobe analyses, we have confirmed the existence of abundant K-feldspar (present in x-ray antiperthite) in Kodaikanal, and of very small blebs of K-feldspar in the Weekeroo Station and Colomera meteorites (*3*).

Study of five Weekeroo Station silicate inclusions revealed a complex assemblage of minerals: bronzite, chromian augite, K-feldspar, oligoclase, cryptoperthite (?), tridymite, chlorapatite, whitlockite, chromite, ilmenite, rutile, schreibersite, troilite, nickel-iron, and native copper. Subhedral homogeneous crystals of oligoclase with albite twinning occur near the region of the inclusion–nickel iron matrix interface, and grade into an unusual massive spherulitic growth of oligoclase, cryptoperthite (?), and tridymite that accounts for more than 50 percent of the inclusion. Electron-beam scanning with the microprobe indicates that areas showing high potassium-K_α intensities are small in size ($< 5\ \mu$) and probably represent exsolved K-feldspar (cryptoperthite) in larger crystals of spherulitic oligoclase. Extremely thin lath-shaped crystals (up to 80 μ in length) of K-feldspar composition and of tridymite are found near the interface regions.

Kodaikanal silicate inclusions are commonly rounded or drop-like in two dimensions, and vary in longest dimension from 0.5 cm to several centimeters. Two major types of inclusion are recognized: (i) flamboyant x-ray antiperthite with equant or needlelike "quench" crystals of pyroxene; and corona structures of chromian augite surrounded by bronzite, olivine, chromite, schreibersite, troilite, and nickel-iron, with little or no feldspar glass; and (ii) highly granulated, partially fused chromian diopside grains in a glassy matrix that consists of K-feldspar glass, devitrified albite glass, and potassic maskelynite. Type (ii) also contains whitlockite, chromite, troilite, and schreibersite. Potassium-feldspar glass is light in color and mostly isotropic, with evidence of flow structure.

Potassic maskelynite is clear and isotropic and retains cleavage traces, planes of inclusions, and grain boundaries of preexisting crystalline feldspar; it is slightly higher in relief than the adjoining fused K-feldspar glass; for convenience we use the term potassic maskelynite to distinguish it from fused glass. Tschermak (*4*) originally applied the term maskelynite to unusual plagioclase glass in meteorites. Milton and De Carli (*5*) produced maskelynite in shock-loading experiments and defined it in more precise terms as a shock-formed noncrystalline phase (solid-state transformation) that retains the external features of crystalline feldspar. Electron-microprobe analyses across the growth direction of the flamboyant x-ray antiperthite indicate a reciprocal relation between K and Na; maximum Na_2O of 11.1 percent corresponds to a minimum K_2O content of 0.8 percent, and the maximum K_2O of 4.2 percent corresponds to a minimum Na_2O of 7.6 percent. Potassic maskelynite is compositionally homogeneous, but fused K-feldspar glass is highly variable in composition. Electron-microprobe analyses of major elements, atomic proportions, and molecular end-members of feldspar and feldspar glasses of all three meteorites appear in Table 1 (*6*).

The rounded-to-irregular inclusions in Colomera are much smaller on the average than those in either Kodaikanal or Weekeroo Station; most are a few millimeters or less in greatest dimension, resembling those in Kodaikanal in variability of amounts of glass, phase compositions, and texture; a few consist entirely of a single feldspar crystal,

Table 1. Results of electron-microprobe analyses of feldspar from Weekeroo Station, Kodaikanal, and Colomera (percentages). Numbers of grains analyzed appear in parentheses; n.d., not determined.

Mineral	Weekeroo Station: Subhedral oligoclase (8)	Weekeroo Station: K-feldspar (10)	Kodaikanal: X-ray anti-perthite (8)	Kodaikanal: Albite (fused glass) (5)	Kodaikanal: K-feldspar (maske-lynite) (5)	Colomera K-feldspar (3)
SiO_2	67.9	67.4	66.9	66.6	66.7	65.3
Al_2O_3	19.6	18.9	18.7	20.4	18.2	18.4
FeO	0.27	0.23	0.91	0.84	0.41	0.17
CaO	2.33	1.91	.27	.35	.16	.05
Na_2O	9.5	7.6	9.6	10.6	6.1	1.00
K_2O	0.86	4.9	2.79	0.72	7.30	14.7
Rb_2O	$< .03$	n.d.	0.16	$< .03$	0.15	< 0.03
Totals						
	100.46	100.94	99.33	99.51	99.02	99.62
Number of ions on the basis of 32 oxygens						
Si (*Z*)	11.878	11.931	11.957	11.770	12.079	12.040
Al (*Z*)	4.041	3.974	3.939	4.249	3.884	3.988
Totals (Z)						
	15.919	15.905	15.896	16.019	15.963	16.028
Fe (*X*)	0.040	0.021	0.136	0.124	0.062	0.022
Ca (*X*)	.437	.361	.052	.066	.031	.011
Na (*X*)	3.222	2.592	3.327	3.632	2.142	.354
K (*X*)	0.192	1.104	0.636	0.162	1.686	3.456
Rb (*X*)	n.d.	n.d.	.018	n.d.	0.018	n.d.
Totals (X)						
	3.891	4.078	4.169	3.984	3.939	3.843
Totals (X + Z)						
	19.810	19.983	20.065	20.003	19.902	19.871
Molecular percentages						
Albite	84	64	82	93	55	9
Anorthite	11	9	2	3	1	0
Orthoclase	5	27	16	4	44	91

while others are of glass or devitrified glass. Electron-microprobe step-scanning analyses across several large twinned albite crystals show K-rich areas 2 to 15 μ in length. A few small grains ($< 10\ \mu$) of K-feldspar (Table 1) commonly occur near the inclusion-matrix interface but are too small to be separated for x-ray work. Other identified phases are aluminous diopside, bronzite, chromian augite, whitlockite, tridymite, chromite, rutile, nickel-iron, troilite, schreibersite, feldspathic glass, and an osumilite-type mineral (*7*).

For the Kodaikanal specimens the two phases of an x-ray antiperthite were detected by the $(\bar{2}01)$ method; the composition of each was estimated on the basis of reported data (*8*) and the estimated solvus of Barth (*9*). These estimates (percentages by weight) follow: orthoclase (solid solution), orthoclase 60–albite 40; albite (solid solution), orthoclase 20–albite 80; bulk composition, approximately 85 percent albite (solid solution) and 15 percent orthoclase (solid solution). Estimated separation temperature is 600° to 700°C. The sodium-rich phase appears to be in its disordered form on the basis of the measurement of separation of $(131)-(1\bar{3}1)$ $[2\theta(131)-2\theta(1\bar{3}1)$, approximately 1.80 deg] (*10*). It must be understood that the compositional values are only very rough estimates. Earlier reported optical data (*1*) for K-feldspar in Kodaikanal are incorrect, representing the optics of the more abundant Na-feldspar (*11*).

Only very poorly crystallized plagioclase patterns were obtained for Weekeroo Station specimens; they exhibited the consistent peculiarity that $d(20\bar{1})$ reflection was always the strongest in the patterns, and that $d(002)$, normally the most intense in sodic feldspar patterns, was always much weaker. We cannot explain this intensity reversal. X-ray patterns (24 hours) of glassy inclusions from Colomera gave the same results as obtained for Weekeroo Station except that reflections were much less intense. The estimated content of potassium-rich portions of feldspars in both Weekeroo Station and Colomera is less than 5 percent by volume, a quantity too small to be recorded in an x-ray powder pattern. Repeated attempts to x-ray the lath-like grains, analyzed as K-feldspar by the microprobe, were unsuccessful. Existence of K-feldspar in both Weekeroo Station and Colomera is thus unconfirmed by x-ray diffraction methods.

The sequence of crystallization of Kodaikanal feldspars can best be reconstructed by assuming that the original feldspars occurred as large homogeneous crystals of K-feldspar and albite. A shock event, either in the parent body or after its breakup, produced many of the present features, including formation of maskelynite and fused feldspar glasses, and mechanical deformation and partial recrystallization of the metal matrix, together with partial fusion and granulation of pyroxenes. Inclusions that contain x-ray antiperthite and little or no glass suggest thorough mixing of the two feldspars during the high-temperature stage of shock, followed by subsequent recrystallization into x-ray antiperthite during fairly rapid cooling. Other inclusions that contain rather homogeneous glasses were quenched after the high-temperature stage and have remained metastable, except for most albite glass, which has devitrified into a mass of cryptocrystalline feldspar and crystallites. However, many intermediate examples of the two contrasted types of inclusions exist, and our interpretation is overly simplified. Lack of original unshocked inclusions makes it difficult to reconstruct accurately the sequence.

Weekeroo Station feldspar (oligoclase), except for grains near the inclusion–iron matrix interface, has also been fused, presumably by shock, and has cooled rapidly into a complex spherulitic mixture of oligoclase and tridymite, with localized separation of K-rich feldspar. None of the three phases in this mixture can be adequately identified with either microscope or electron microprobe, and the x-ray results indicate only oligoclase and tridymite—not K-feldspar.

Potassium feldspar is rare in meteorites; only one other occurrence has been reported (*12*). Bulk analyses of chondritic meteorites indicate that K is present in amounts similar to or somewhat lower than cosmic proportions (*13*). Similarly, Earth is depleted in K relative to cosmic proportions but is highly enriched in the continental crust by chemical differentiation. Alkali metals are present in only small amounts in early formed igneous rocks, but reach major proportions after considerable crystal fractionation and differentiation.

Bulk analysis of Kodaikanal silicate inclusions (*14*) gives 2.57 percent K_2O, a value close to that for the continental crust (*15*). The calculated Rb content (600 parts per million) and Na:K ratio (1.01) of Kodaikanal inclusions and the K:Rb ratio of the K-feldspar (49) are similar to those of terrestrial granites (*16*). Unfortunately, bulk analyses are not available for Weekeroo Station and Colomera silicate inclusions. Clearly the high K_2O content in Kodaikanal suggests strong chemical differentiation. In addition to the enrichment of K and Rb in Kodaikanal, and presumably of K in Weekeroo Station and Colomera, other elements, notably Si, Al, and Na, appear to be enriched in these meteorites. This observation is based on electron-microprobe analyses of all phases, and on the fact that the inclusions in all three meteorites contain more than 50 percent of alkali feldspars. No other known meteorites have such abundances of these elements.

It appears unlikely that the inclusions and metal matrix condensed directly from the solar nebula; nor does it seem likely that the inclusions crystallized as primary segregations in a nickel-iron magma. Rather it seems that the silicates and metal combined after extreme chemical differentiation of the silicate portion from more-basic material. The discordant $^{87}Rb:^{87}Sr$ "ages" of these three meteorites (*17*) appear to indicate different periods of chemical and physical differentiation, and possibly different parent bodies, unless the Rb:Sr ratios were greatly disturbed by shock or other metamorphic events.

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European Cretaceous Flints on the Coast of North America

Abstract. *Flint pebbles and nodules from the Upper Cretaceous chalks of Europe occur offshore and at many seaports along the Atlantic coast of North America, where they were brought as ship's ballast. Isolated pieces imported from Europe as gunflints also are present.*

During various geologic investigations of the coastal regions of eastern North America, we independently have encountered flint pebbles and nodules identified as derived from European outcrops of Upper Cretaceous chalks. Some of the specimens were originally believed to have been shaped by early man. Although experts later indicated that probably none of the specimens are artifacts, the circumstances leading to the presence of the pebbles and nodules may be of sufficient interest to warrant this recording; we describe them according to locality from northeast to southwest.

In 1965 Loring and Nota found many flint nodules on the intertidal part of a beach at Prince Edward Island—to the east of Cascumpeque Point, about 3 km south of Alberton (Fig. 1). About 100 kg of nodules 2 to 8 cm in diameter were noted among the local beach materials, which consist of fine to medium sand plus subangular pebbles of the local Triassic red sandstone. Flint is foreign to the region, and these nodules (Fig. 2A) are lithologically similar to many thousands of Upper Cretaceous ones that we had seen along the shores of England and France: gray to dark brown in color; nodule coated with a smooth opaque white crust; brittle; light-brown inclusions; clean conchoidal fractures, with light-brown patina. Thin sections made from two of the nodules showed many small Foraminifera replaced with chalcedony, and abundant sponge spicules replaced with quartz. Identification (*1*) indicated that the planktonic Foraminifera, including *Heterohelix* sp., are Late Cretaceous in age. The following information (*2*) suggests that the nodules may have been left by Jacques Cartier who left Saint-Malo, France, with two ships each of 60-ton burden. Entering the Gulf of St. Lawrence, he discovered Prince Edward Island on 30 June 1534 and explored the northern and northeastern shores. He had difficulty in getting ashore in the Alberton area: "We could find no harbour for the shore is low and skirted with sandbanks where the water is shallow. . . . We went ashore in longboats at a river [Canoe River]" (*3*). The name Canoe River was given by Cartier to what is now Cascumpeque Bay. Because of the shoals he may well have unloaded some of the ballast from Saint-Malo to enable his ships to enter over the sand banks. When this procedure failed, he "lowered sails and lay to," and went ashore in longboats.

At Chatham, New Brunswick (about 25 km above the mouth of the Miramichi River), ships formerly arrived from Europe in ballast. As usual in those days, much of the ballast was dumped in the river, but some of it washed ashore where two men (*4*) independently have found flint nodules. Some of the ballast was used for construction of the town pier that still is in use. Another man (*5*) found a large deposit of flint at Fort Belcher (Fig. 1); he said that flint ballast is present at most of the ports of Nova Scotia.

Flints from several localities in and near Boston, Massachusetts, are of the same lithology as the ones from Prince Edward Island and the English Cretaceous chalks; no similar flint outcrops in Massachusetts. In 1962 Kaye noted large quantities of flint pebbles and nodules on artificially filled land near the shore of Castle Island, South Boston. A thin section of one typical piece revealed abundant Late Cretaceous plankton forms including *Globotrucana* sp.(*1*). Among the fill was one piece (Fig. 2C) that Kaye thought might be a core from which knife blades had been struck by a Paleolithic tool maker, but later examination (*6*) failed to support this interesting belief. It was indicated (*7*) that the flinty fill had been carted to the site from army munitions ships on their return in ballast from England to the Boston Army Base during World War I. Formerly, nodules of flint also were found in the city dump area of Chelsea, just north of Boston; they had been brought by square-rigged sailing ships that berthed nearby during the 18th and 19th centuries. Nodules were collected there (*8*) for a course in flint knapping at Harvard University in 1931 and 1932. Similar flint nodules have been reported 10 km south of Boston, near the Wollaston Golf Course, where marshes adjoining the Neponset River have been filled; and 30 km to the north, at Salem, where they have been picked up (*9*) along the shore near the Beverly Bridge.

Near old wharfs on the west shore of Provincetown, Massachusetts, black flint nodules and pebbles have often been seen (*10*); some were collected about 1935 for experiments in making arrowheads and for striking fire. The flints were considered (*10*) to have come from ballast, and the belief is reasonable in view of the former importance of Provincetown as a cod-fishing center and seaport. In 1967 another flint nodule was found measuring 9 cm in diameter; it was almost black, but covered with the usual white crust that is typical of the European nodules from the Cretaceous chalks. A thin section showed it to contain much organic matter, many sponge spicules, and a few bolivinid Foraminifera—probably Upper Cretaceous (*1*).

About 1945 two huts were excavated, perhaps 150 m apart, in dunes just east of the original Provincetown harbor in Pilgrim Lake. At each site were many clay pipes and handmade nails. The pipes at one hut carried stampings that identified them as having been made between 1700 and 1720; they were stamped "RT" (for Robert Tippit), "Evans" (of Bristol, England), "Parks," or "WR."' Such pipes were introduced into England about 1688 by Dutch soldiers brought by William of Orange (William III) (*11*); two William-III pennies found in the hut confirm this date. At the other hut, where the clay pipes were unstamped but of the same type, were found at least a dozen pieces of flint exactly like the pieces from Prince Edward Island and Boston; the