American Mineralogist, Volume 64, pages 912–916, 1979

Al–Si disorder of K-feldspar in crustal xenoliths at Kilbourne Hole, New Mexico

EDWARD S. GREW

Department of Earth and Space Sciences, University of California
Los Angeles, California 90024

Abstract

K-feldspar in xenoliths of quartzofeldspathic gneiss at Kilbourne Hole, New Mexico, is sanidine, commonly microperthitic. Cell parameters of a nonperthitic sample ($Or_{69}Ab_{27}An_3Cn_1$) are $a = 8.4713$, $b = 13.0258$, $c = 7.1712A$, $\beta = 116°00'$; $V = 711.22A^3$. These cell dimensions indicate a high degree of Al–Si disorder ($Z = 2[N_{Al(T1)} - N_{Al(T2)}] = 0.064$), one of the highest reported in the literature. The high degree of Al–Si disorder is attributed to the heating of the xenolith when it was incorporated in the basalt, and probably is not a feature of the K-feldspar in the source terrain for the quartzofeldspathic xenoliths.

Introduction

Xenoliths of garnetiferous quartzofeldspathic gneisses, pyroxene granulites, and ultramafic rocks are abundant as cores of bombs of vesicular basalt at Kilbourne Hole, a maar in the Rio Grande rift (Padovani and Carter, 1977a). These bombs are found on bedded tuff overlying an alkaline olivine basalt flow in a unit mapped by Hoffer (1976) as the Quaternary Afton Basalt.

The ultramafic xenoliths are believed to originate in the upper mantle, and the xenoliths of quartzofeldspathic gneisses, pyroxene granulite, and minor charnockite and anorthosite in the lower third of the earth's crust (Padovani and Carter, 1977a). K-feldspar is present in the rocks of crustal origin and is abundant in the garnetiferous quartzofeldspathic gneisses. In the samples examined by Padovani (1977) and by Grew (1977), the K-feldspar is untwinned and has an optic angle of about 10° or less, which is indicative of a high degree of Al–Si disorder. Moreover, K-feldspar in crustal xenoliths at other localities has the optical properties of high sanidine, namely the optic plane parallel to (010) (Lacroix, 1890a,b; Dickey, 1968). Thus a high degree of Al–Si disorder appears to be characteristic of crustal xenoliths from some localities.

However, to my knowledge, detailed X-ray diffraction data have not been reported on xenolithic K-feldspar. I present here X-ray data on K-feldspar from a xenolith of quartzofeldspathic gneiss at Kilbourne Hole, and discuss the evidence relating to the origin of the high degree of Al–Si disorder.

Petrology

The crustal xenoliths from Kilbourne Hole have been described in detail by Padovani (1977) and Padovani and Carter (1977a,b); only a few salient features of the quartzofeldspathic gneisses will be presented here. These gneisses (garnet granulite of Padovani and Carter) are medium-grained, indistinctly layered, friable, light-colored rocks that have a sintered appearance. They contain all or most of the following minerals: quartz, K-feldspar, plagioclase, garnet, sillimanite, rutile, ilmenite, graphite, and zircon. Sillimanite forms prisms that commonly are aligned, and is blue, colorless, or yellow. Rutile is blue, purple, or brown. An orthopyroxene–spinel intergrowth (replacing garnet) and glass are abundant in the gneiss. This glass is in places vesicular and forms microveinlets or nondescript masses, many of which surround garnet and the associated orthopyroxene–spinel intergrowth.

The contacts between the xenoliths and basalt in the rinds are sharp. Xenocrysts of quartz, rutile, and sillimanite are incorporated in the basaltic rind of one sample.

Methods

Samples of K-feldspar for microprobe analyses and X-ray study were selected from about 50 crustal

Table 1. Composition of K-feldspar from Kilbourne Hole, New Mexico, USA (microprobe analyses)

Oxide	Sample Number 76-5-12 Lens*	76-5-12 Matrix	76-5-1	76-5
	Weight Percent			
SiO_2	64.50	64.49	63.85	64.91
Al_2O_3	19.50	19.55	19.97	19.63
Fe_2O_3	0.03	n.a.	0.10	0.02
BaO	0.43	0.39	0.85	0.43
CaO	0.58	0.65	0.93	0.63
Na_2O	3.03	3.01	3.21	2.79
K_2O	12.01	12.01	11.40	12.45
Total	100.08	100.10	100.31	100.86
	Mole Percent			
Orthoclase	69.7	69.6	65.8	71.7
Albite	26.7	26.5	28.2	24.4
Anorthite	2.8	3.2	4.5	3.1
Celsian	0.8	0.7	1.5	0.8

n.a. - not analyzed
**Composition from x-ray data: $Or_{69.2}Ab_{30.8}$ (Table 2)*

xenoliths collected by me, and supplemented by sample 76-5 donated by E. R. Padovani. I have also examined in thin section about 15 samples of xenolithic quartzofeldspathic gneisses I collected at Bournac, Haute-Loire, France.

K-feldspars in polished thin sections of quartzofeldspathic gneiss (Table 1) were analyzed with a wavelength dispersive system (nonautomated) on an ARL-EMX electron microprobe in the Department of Earth and Space Sciences, UCLA, and the analytical data were reduced by the Bence–Albee method (Bence and Albee, 1968).

Table 2. X-ray data on a K-feldspar from Kilbourne Hole, New Mexico, USA. Sample 76-5-12

Cell Dimensions (using 24 reflections)	a (Å)	b (Å)	c (Å)	β	V (Å³)
Measured value	8.4713	13.0258	7.1712	116°00'	711.22
Standard error	0.0026	0.0026	0.0011	0.9'	0.21

Composition (from x-ray data, using equations of Hovis, 1977)

From cell edge a:	$Or_{69.2}Ab_{30.8}$
From cell volume:	$Or_{69.2}Ab_{30.8}$

Structural State and Estimated Temperature of Formation (from Hovis, 1974)

Ordering parameter: $Z = 2[N_{Al(T1)} - N_{Al(T2)}] = 0.064$

where $N_{Al(T1)}$ is mole fraction of Al in site T1

Estimated temperature: 1050°C

A nonperthitic K-feldspar for X-ray work was picked by hand from a concordant lens one cm thick in one of the xenolithic quartzofeldspathic gneisses (sample 76-5-12). The unit-cell parameters were determined with graphite-crystal monochromated Cu*Kα* radiation by the powder method. A slurry of the K-feldspar and a silicon standard was dried on a glass slide. The 2*θ* values were scanned three times at 0.25° 2*θ* per minute, twice with decreasing and once with increasing 2*θ*. The 24 reflections used in the cell refinement were indexed using the tables of Wright and Stewart (1968) and Borg and Smith (1969). Cell parameters were calculated using a least-squares computer program. Precision is estimated to be 0.15 to 0.3 percent of the values given (Table 2).

K-feldspar

Both nonperthitic and microperthitic K-feldspars are present in the xenolithic gneisses. Mm-sized cleavage fragments of the nonperthitic K-feldspar in the lens used for X-ray study are colorless, glassy, and limpid.

In thin section, the nonperthitic K-feldspar is recognized by its negative optical sign. In microperthitic K-feldspar, the plagioclase lamellae are generally 0.002 to 0.01 mm wide and up to 0.1 mm long (locally to 0.025 mm wide and 0.5 mm long). This range in size corresponds to the ranges for strings and rods described by Alling (1938) from plutonic rocks. The microperthite resembles the hair perthite described by Eskola (1952) from granulite-facies rocks (see also Smith, 1974b, p. 424–425). The plagioclase lamellae in the xenolithic K-feldspar commonly do not extend to the boundary of the host grain (see also Padovani and Carter, 1977a), a feature that is characteristic of rod and hair perthite (Alling, 1938; Eskola, 1952).

Grains of nonperthitic K-feldspar from Kilbourne Hole range in composition from Or_{65} to Or_{83} (Padovani, 1977) and contain up to 4.5 mole percent anorthite and 1.5 mole percent celsian (Table 1). The Ca/Ba ratios (3 to 4.6) and K/Ba ratios (44 to 100) of the K-feldspars (Table 1) are on the average higher than those reported from metamorphic rocks, but lie within the range of the ratios from plutonic rocks (Smith, 1974b, p. 93–95).

X-ray data

Precision X-ray data on a nonperthitic K-feldspar from Kilbourne Hole show that this feldspar is a high sanidine in which there is little ordering among the T_1 and T_2 sites (Table 2). The Al occupancies of the T_1 and T_2 sites are 0.266 and 0.234, respectively (Hovis, 1974, eq. 4a and 4b). This K-feldspar is therefore one of the most disordered reported in the literature (Stewart and Wright, 1974; Hovis, 1977). Moreover, it is an "anomalous" or "strained" feldspar according to Stewart's and Wright's (1974, p. 362) index of strain $\Delta a = a_{obs} - a_{est}$, where a_{est} is obtained from these authors' *b–c* plot (Fig. 1). For sample 76-5-12, $\Delta a = -0.08$; but unlike other "strained" feldspars, the Kilbourne Hole sample has a negative index. However, there is good agreement among the probe data, composition estimated from cell volume, and composition estimated from the *a* dimension, using Hovis' (1977) equations for his highly disordered alkali feldspar series. Thus the "anomalous" character of the feldspar may be due to its unusually high Al–Si disorder, and not to a cryptoperthitic structure, which is generally believed to be the cause of the anomalous cell dimensions (see Smith, 1974a, p. 276).

Preservation of a highly disordered feldspar indicates that the xenoliths have been rapidly quenched after the thermal event during which the high degree of Al–Si disorder was attained. Other evidence for quenching is glass in all the quartzofeldspathic xenoliths (Padovani and Carter, 1977a,b) and an apparently homogeneous ferrian ilmenite of composition $Il_{66}Hem_{34}$ in one xenolith (Grew, 1977).

Conditions of formation

The extent of Al–Si disorder in the sample studied by X-ray diffraction indicates a temperature of formation of about 1000°C, assuming a pressure of formation between 0 and 15 kbar (Hovis, 1974; Stewart and Wright, 1974). The low $2V$ and absence of twinning in the xenolithic K-feldspars examined by Padovani (1977) and by me imply that the high degree of Al–Si disorder in sample 76-5-12 may be characteristic for the K-feldspars at Kilbourne Hole, but more X-ray work, particularly of the perthitic K-feldspar, would be needed to demonstrate this.

Origin of the Al–Si disorder

The presence of high sanidine in crustal xenoliths at Kilbourne Hole raises the question of whether a high degree of Al–Si disorder is characteristic of alkali feldspars in the earth's lower crust. K-feldspar having optical properties of high sanidine, such as a low optic angle or optic axial plane parallel to (010), is common in crustal xenoliths at some localities. Examples are quartzofeldspathic gneisses containing sillimanite and garnet at Bournac and other localities in the Massif Central of France (Lacroix, 1890a,b; Grew, 1977), and a garnet granulite in New Zealand. The high sanidine in the New Zealand xenolith is microperthitic (Dickey, 1968). These xenolithic gneisses are believed to be samples of the lower crust that have been brought to the earth's surface by the volcanic rock in which they are found (Padovani and Carter, 1977a; Leyreloup *et al.*, 1977).

However, the xenoliths have been heated during their incorporation in the volcanic host rock. Another possible origin of the Al–Si disorder is this heating event.

Padovani and Carter (1977a, p. 50) conclude "that the mineral assemblages [in the xenoliths] reflect the ambient geothermal gradient in the deep crust as estimated from heat flow measurements." However, Davis and Grew (1978) obtained a $^{207}Pb–^{206}Pb$ age of 1375 m.y. on zircon separated from a xenolith collected at Kilbourne Hole. They conclude that this age is a minimum value for the age of the metamorphism of the source terrain of the xenoliths, and that no later event was severe enough to completely reset the zircon U–Pb age. In this case, it appears unlikely that the mineral assemblages in the xenoliths could reflect the ambient geothermal gradient, and consequently they are not suitable indicators of the present-day depth of the source terrain of the xenoliths. Thus we have no unambiguous petrologic evidence that the crustal xenoliths at Kilbourne Hole originated in the lower crust. As there are no known exposures of granulite-facies terrains in the vicinity of Kilbourne Hole and none are reported from wells drilled in this area (Padovani and Carter, 1977a), granulite-facies rocks probably do not immediately underlie the Phanerozoic sedimentary fill of the Rio Grande rift at Kilbourne Hole. However, we have no other direct information on the possible depth of the granulite-facies source terrain, so that a deep crustal origin of the high Al–Si disorder in the xenoliths at Kilbourne Hole remains a moot question.

On the other hand, there is considerable evidence that the thermal effect of the basalt on the xenoliths was marked. Padovani and Carter (1977a,b) attribute the extensive formation of glass in the xenoliths (a few percent to over 50 percent by volume) to partial melting during incorporation of the xenoliths in the basalt magma followed by rapid cooling after extrusion of the magma. The temperature of the magma may have been as high as 1200°C, the temperature estimated for Hawaiian tholeiitic basalt at the time of eruption (Wright *et al.*, 1968). This temperature is well above 950°C, the temperature of the first appearance of melt at $P = 1$ bar in the system $KAlSi_3O_8$–$NaAlSi_3O_8$–Al_2O_3–SiO_2 under dry conditions (Thompson and Thompson, 1976). Under the dry conditions suggested by Padovani and Carter (1977b) for the partial melting of the xenoliths, extensive formation of melt requires a long period of heat treatment [*e.g.*, 840 hours at 970°C for the formation of glass in the laboratory (Tuttle and Bowen, 1958, p. 82)], or temperatures well above the temperatures needed for the first appearance of melt. In either case, it appears likely that the Al–Si distribution in K-feldspar in the xenoliths would be affected. Orthoclase and microcline have been converted under dry conditions to sanidine in the laboratory at temperatures of 1050–1075°C, *e.g.*, orthoclase in 100 to 300 hours and microcline in 670 to 720 hours (Spencer, 1937, p. 476; Goldsmith and Laves, 1954). Moreover, the time needed to disorder a K-feldspar under dry conditions would probably decrease with increasing temperature (Smith, 1974b, p. 157). Consequently, a thermal event of sufficient intensity to melt a quartzofeldspathic rock under dry conditions is probably also of sufficient intensity to disorder K-feldspar. Natural conversion of orthoclase and microcline to sanidine has been reported in some contact aureoles (Al-Rawi and Carmichael, 1967; Butler, 1961).

In addition, the presence of microperthitic textures similar to those found in K-feldspar in plutonic and regionally metamorphic rocks, but rarely in sanidine, suggests that the xenolithic K-feldspar may be a sanidinized orthoclase or microcline. Perthitic textures are not in all cases destroyed by prolonged heating or sanidinization either in the laboratory or in nature (*e.g.*, Richarz, 1924; Dickey, 1968; Smith, 1974b, p. 490).

In summary, available geologic and petrologic evidence is consistent with the interpretation that the high Al–Si disorder in the K-feldspar is the result of the heating during incorporation of the xenolith in the basaltic rock. Thus the study of xenoliths is not an unambiguous approach to determining the extent of Al–Si disorder in the K-feldspar in the source terrain for the xenoliths at Kilbourne Hole. The heat treatment by the basalt magma probably was sufficiently intense to redistribute Al and Si in the feldspar and destroy whatever Al–Si order existed in the feldspar in the source terrain.

Acknowledgments

The author thanks P. C. Grew for her help in collecting xenoliths at Kilbourne Hole and Bournac and E. R. Padovani for sample 76-5 and for the use of unpublished data in her thesis (Padovani, 1977).

Earlier versions of this paper were read by D. M. Burt, P. C. Grew, R. T. Helz, E. R. Padovani, and D. C. Presnall. The author is grateful to these reviewers for their comments.

The research was supported by NSF grants DPP 75-17390 and DPP 76-80957 to the University of California, Los Angeles. The UCLA electron microprobe was recently upgraded with funds provided through NSF grant DES 74-22672/Ernst.

References

Alling, H. L. (1938) Plutonic perthites. *J. Geol., 46,* 142–165.

Al-Rawi, Y. and I. S. E. Carmichael (1967) A note on the natural fusion of granite. *Am. Mineral., 52,* 1806–1814.

Bence, A. E. and A. L. Albee (1968) Empirical correction factors for the electron microanalysis of silicates and oxides. *J. Geol., 76,* 382–403.

Borg, I. Y. and D. K. Smith (1969) Calculated x-ray powder patterns for silicate minerals. *Geol. Soc. Am. Mem. 122.*

Butler, B. C. M. (1961) Metamorphism and metasomatism of rocks of the Moine Series by a dolerite plug in Glenmore, Ardnamurchan. *Mineral. Mag., 32,* 866–897.

Davis, G. L. and E. S. Grew (1978) Age of zircon from a crustal xenolith, Kilbourne Hole, New Mexico. *Carnegie Inst. Wash. Year Book, 77,* 897–898.

Dickey, J. S., Jr. (1968) Eclogitic and other inclusions in the Mineral Breccia Member of the Deborah Volcanic Formation at Kakanui, New Zealand. *Am. Mineral., 53,* 1304–1319.

Eskola, P. (1952) On the granulites of Lapland. *Am. J. Sci., 250* (Supplement–Bowen Volume), 133–171.

Goldsmith, J. R. and F. Laves (1954) The microcline–sanidine stability relations. *Geochim. Cosmochim. Acta, 5,* 1–19.

Grew, E. S. (1977) Blue sillimanite and the origin of crustal xenoliths at Kilbourne Hole, New Mexico, USA, and Bournac, Haute-Loire, France (abstr.). *Extended Abstracts, 2d International Kimberlite Conference, Sante Fe, New Mexico.*

Hoffer, J. M. (1976) Geology of Potrillo Basalt Field, south-central New Mexico. *New Mexico Bur. Mines and Mineral Resources, Circ. 149.*

Hovis, G. L. (1974) A solution calorimetric and X-ray investigation of Al–Si distribution in monoclinic potassium feldspars. In W. S. MacKenzie and J. Zussman, Eds., *The Feldspars,* p. 114–144. Manchester University Press, Manchester, England.

——— (1977) Unit-cell dimensions and molar volumes for a sanidine–analbite ion-exchange series. *Am. Mineral., 62,* 672–679.

Lacroix, A. (1890a) Sur les enclaves acides des roches volcaniques d'Auvergne. *Bull. Carte Géol. France, 2(11),* 25–56.

——— (1890b) Sur l'existence d'une roche à diaspore dans la Haute-Loire. *Bull. Soc. fr. Minéral., 13,* 7–8.

Leyreloup, A., C. Dupuy and R. Andriambololona (1977) Catazonal xenoliths in French Neogene rocks: constitution of the lower crust. 2. Chemical composition and consequences of the evolution of the French Massif Central Precambrian Crust. *Contrib. Mineral. Petrol., 62,* 283–300.

Padovani, E. R. (1977) *Granulite Facies Xenoliths from Kilbourne Hole Maar, New Mexico, and Their Bearing on Deep Crustal Evolution.* Ph.D. Thesis, University of Texas at Dallas.

——— and J. L. Carter (1977a) Aspects of the deep crustal evolution beneath south central New Mexico. In J. G. Heacock, Ed., *The Earth's Crust,* p. 19–55. Am. Geophys. Union Geophys. Monograph 20.

——— and ——— (1977b) Non-equilibrium partial fusion due to decompression and thermal effects in crustal xenoliths. In H. B. J. Dick, Ed., *Magma Genesis,* p. 43–57. *Oregon Dept. of Geology and Mineral Industries, Bull. 96.*

Richarz, S. (1924) Some inclusions in basalts. *J. Geol., 32,* 685–689.

Smith, J. V. (1974a) *Feldspar Minerals, Vol. 1, Crystal Structure and Physical Properties.* Springer-Verlag, New York.

——— (1974b) *Feldspar Minerals,* Vol. 2, *Chemical and Textural Properties.* Springer-Verlag, New York.

Spencer, E. (1937) The potash–soda–feldspars. I. Thermal stability. *Mineral. Mag., 24,* 453–494.

Stewart, D. B. and T. L. Wright (1974) Al/Si order and symmetry of natural alkali feldspars, and the relationship of strained cell parameters to bulk composition. *Bull. Soc. fr. Minéral. Cristallogr., 97,* 356–377.

Thompson, J. B., Jr. and A. B. Thompson (1976) A model system for mineral facies in pelitic schists. *Contrib. Mineral. Petrol., 58,* 243–277.

Tuttle, O. F. and N. L. Bowen (1958) Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O. *Geol. Soc. Am. Mem. 74.*

Wright, T. L. and D. B. Stewart (1968) X-ray and optical study of alkali feldspar: I. Determination of composition and structural state from refined unit-cell parameters and 2*V*. *Am. Mineral., 53,* 38–87.

———, W. T. Kinoshita and D. L. Peck (1968) March 1965 eruption of Kilauea Volcano and the formation of Makaopuhi Lava Lake. *J. Geophys. Res., 73,* 3181–3205.

Manuscript received, May 18, 1978;
accepted for publication, February 16, 1979.