

## Sapphirine, sillimanite, and garnet in granulite xenoliths from Stockdale kimberlite, Kansas

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### Abstract

Xenoliths of granulite are relatively common in the Stockdale kimberlite pipe, Kansas. Two rock types in particular, a pyroxenite and a metagabbro, display mineral reactions which appear to have frozen-in by the incorporation of the xenolith during the rapid ascent of the kimberlite to the surface. Most striking is the replacement of green aluminous spinel by sapphirine,  $(\text{Mg}_{2.95}\text{Fe}_{0.46}\text{Al}_{4.58})^{\text{VI}}(\text{Al}_{4.67}\text{Si}_{1.33})^{\text{IV}}\text{O}_{20}$ . The replacement of plagioclase ( $\text{An}_{53}-\text{An}_{60}$ ) by a symplectic intergrowth of fassaite ( $\text{Di}_{88}\text{Cats}_{17}$ ) and sillimanite appears to be unique. A third reaction includes the formation of garnet ( $\text{Py}_{45}\text{Al}_{33}\text{Gr}_{22}$ ) from earlier fassaite and plagioclase. Pressure and temperature for these reactions have been deduced as being in the range 10–14 kbar and 800–1000°C based on phase chemistry and Fe/Mg partitioning between coexisting garnet and clinopyroxene. These mineral reactions reflect the attempt of basic igneous rocks to reequilibrate under extreme conditions of metamorphism at depths in the region of 30–40 km beneath the continental crust in Kansas.

### Introduction

Several igneous bodies intrude Permian sediments in Riley County, east-central Kansas. Brookins (1970) has described these bodies and has identified them as kimberlite. One intrusion in particular, the Stockdale pipe, (Fig. 1) is characterized by an abundance of xenoliths which include Phanerozoic sedimentary rocks as well as granites, gabbros, metagabbros, pyroxenites, and eclogite (Meyer and Brookins, 1971). Recently, lherzolites have also been recognized. This contribution describes the petrography and mineralogy of some sapphirine-bearing granulite rocks from the Stockdale pipe, because one of the reasons for studying the xenoliths from the kimberlite in Kansas is to obtain an understanding of the mineralogy and petrology of the lower crust–upper mantle region beneath the mid-continental U.S.A. Except for studies of metamorphic xenoliths by McGetchin and Silver (1972) and Lovering and White (1969), most descriptions of xenoliths from kimberlite pipes have been confined to specimens of ultramafic and eclogitic rocks.

A complete geological description of the six kim-

berlite diatremes that occur in Riley County, Kansas has been presented by Brookins (1970). The diatremes are filled with dark to light green brecciated rock consisting of serpentized olivine, pyroxene, partially kelyphitized garnet, and chloritized phlogopite, with minor amounts of ilmenite, magnetite, and much carbonate material. No two diatremes are similar in size, petrography, or mineralogy. All six diatremes contain, in varying proportions, xenoliths of locally derived country rock of possible basement origin; however, only the Stockdale pipe contains xenoliths of gabbro, amphibolite, granulite, eclogite, and lherzolite. The mineralogy of the eclogites from Stockdale has been described by Meyer and Brookins (1971), and sulfide–oxide relationships in the eclogites were described by Meyer and Bector (1975). Pyroxene–ilmenite xenoliths similar to those found in some South African kimberlites have also been described from Stockdale (McCallister *et al.*, 1975).

The granulite xenoliths vary in size, the largest being 7cm in major dimension; they are generally rounded and have some alteration at their outer margins. In some instances this alteration, mostly to ser-

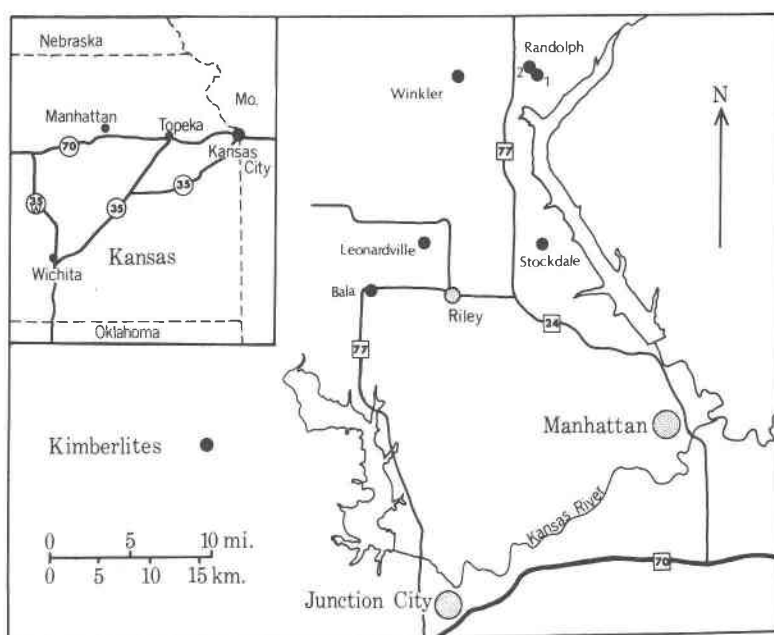


FIG. 1. Sketch map of Riley County region, Kansas, indicating location of Stockdale and other kimberlite diatremes in the area.

pentine and chlorite, has completely replaced the original minerals. Fortunately, the interiors of most xenoliths are unaltered, especially in the case of the sapphirine-bearing granulites. Although several examples of sapphirine-bearing granulites have been observed, it will be sufficient to describe only two samples in detail—a pyroxenite (1128d) and a metabasalt (1128p). These two rocks display the pertinent and important features of these specific granulites. The pyroxenite is the larger of the two samples, and sufficient material was available to obtain a bulk chemical analysis using both wet-chemical and spectrographic techniques. The CIPW norm shows the rock to be silica-deficient, and when compared with the basalt classification of Yoder and Tilley (1962), the composition is equivalent to olivine-tholeiite (normative olivine plus hypersthene).

### Petrography

Rock 1128d is dark grey, holocrystalline, medium-grained, allotriomorphic granular, consisting of clinopyroxene (61%), orthopyroxene (20%), plagioclase (12%) spinel (5%), sapphirine (1%), sillimanite (1%), and garnet (<1%). Clinopyroxene ( $Di_{52}$ ) is the major constituent and followed in abundance by pale pinkish, pleochroic orthopyroxene ( $En_{72}$ ). Both these minerals form anhedral crystals up to 3 mm in dimension, although the average size is in the region of 1.5

mm. The pyroxenes form a granular aggregate with many triple junctions of  $120^\circ$ . The clinopyroxenes exhibit exsolution lamellae of orthopyroxene and also display undulose extinction.

Colorless plagioclase ( $An_{60}$ ) is a primary mineral in the rock. Crystals up to 1mm in size occur, but in general they occur as aggregates forming regions (3 mm) within the major pyroxene mass. Albite and pericline twinning is common; carlsbad rare. Undulose extinction occurs. At the contacts between plagioclase and clinopyroxene, symplectites of diopside and sillimanite project radially into the plagioclase (Fig. 2a). The sillimanite is acicular ( $0.005 \times 0.1$  mm). Regions of the sillimanite-diopside within, or closer to, the original clinopyroxene surrounding the plagioclase have a more micrographic texture. It is believed the plagioclase is being replaced by diopside<sub>88</sub> + sillimanite.

Spinel crystals, dark green in color, anhedral, and up to 0.5mm size, occur randomly throughout the rock. Associated with the margins of the spinel is pale blue to colorless pleochroic sapphirine (Fig. 2b). The sapphirine accounts for less than 1 percent of rock and is forming at the expense of the spinel. Rare garnet also occurs in the rock and is replacing feldspar and original clinopyroxene.

Rock 1128p is medium-grained, grey, holocrystalline, allotriomorphic granular, consisting of cli-

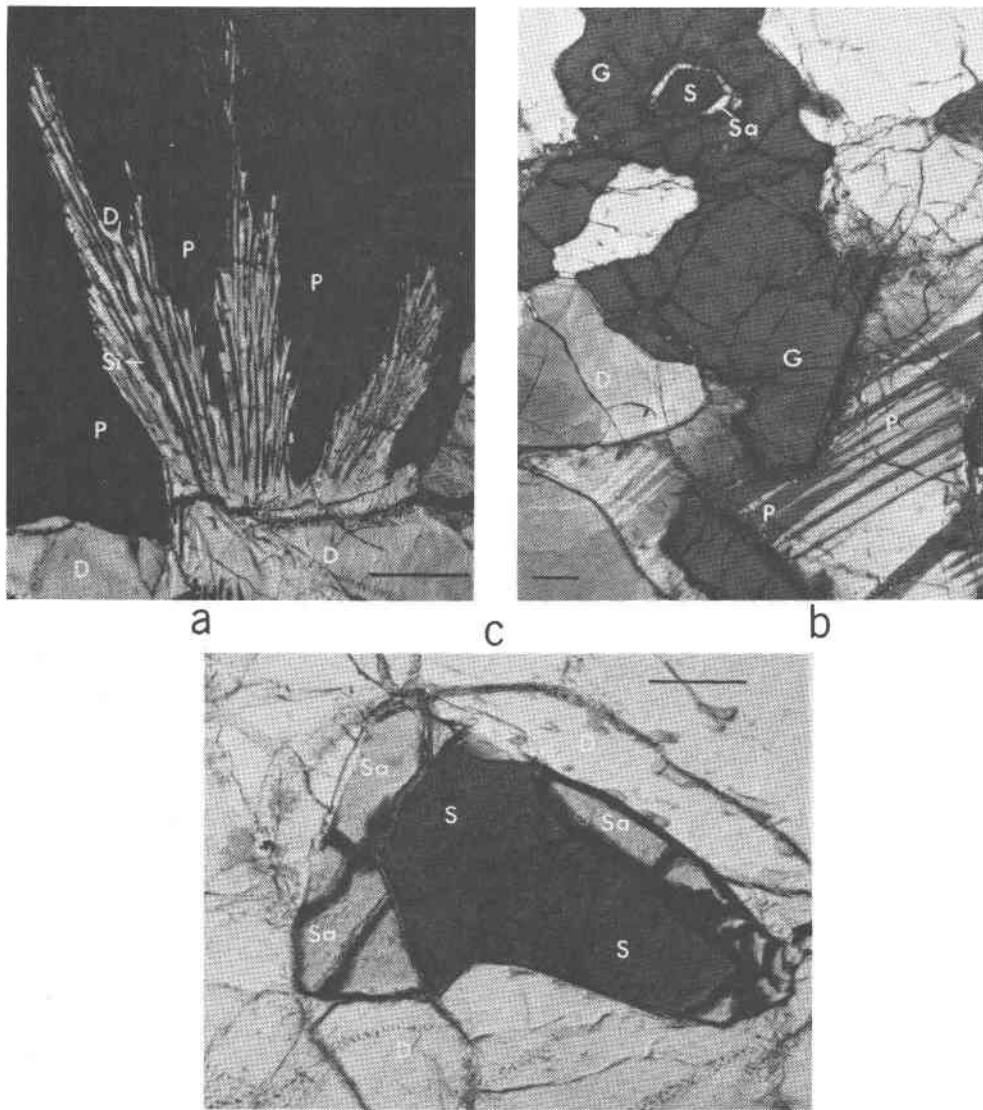


FIG. 2. (a) Sillimanite (Si)—fassaitic diopside (D) symplectite projecting into and replacing plagioclase (P). The plagioclase is at extinction, and the sillimanite is the dark grey thin lamella in the light colored diopside. Original diopside (D) is present in the lower part of the photograph. (b) Garnet (G) replacing fassaitic diopside (D) and plagioclase (P). The garnet has well-developed crystal terminations where it projects into the plagioclase. A small crystal of spinel (S) is mantled by sapphirine (Sa). (c) Spinel (S) showing replacement by sapphirine (Sa). Both spinel and sapphirine are surrounded by fassaite (D). (Plane polarized light) (Length of scale bar on all photographs is 0.1 mm)

nopyroxene (42%), plagioclase (16%), and garnet (39%). Accessory spinel (3%) and sapphirine (<2%) are present together with sillimanite (<1%). The clinopyroxene ( $Di_{69}$ ) is colorless, and individual grains vary in size from 2mm to 0.2 mm. Corroded edges against garnet are common. Undulose extinction occurs, but exsolution lamellae are absent. Anhedral plagioclase ( $An_{43}$ ) grains are usually less than 1mm in size. Albite and pericline twinning are present, and

undulose extinction in some grains. The plagioclase is subordinate in amount to both clinopyroxene and garnet. Garnet ( $Py_{46}Al_{32}Gr_{22}$ ), although a major constituent, is believed to be replacing both clinopyroxene and plagioclase in this rock. It is anhedral for the most part, with rounded or lobate margins projecting into clinopyroxene; whereas when projecting into plagioclase, the margins have well-developed crystal forms (Fig. 2b). Garnet regions extend over

several mms but may be no more than 0.5 to 1 mm in width.

Accessory green spinel is always enclosed by garnet. The spinel is anhedral and rarely greater than 1 mm in size. Pale blue pleochroic sapphirine replaces the edges of the spinel. Surrounding the spinel-sapphirine assemblage and separating it from the enclosing garnet is often a thin border of sillimanite <15 microns wide.

### Mineralogy

Mineral analyses were performed on doubly-polished thin sections of rock, using a MAC-500 electron microprobe. The standards used were predominantly glasses obtained through courtesy of F. R. Boyd. The analyses were corrected for drift, deadtime, background, absorption, fluorescence, and atomic num-

ber effects. It is considered that major elements are accurate to within 1 to 2 percent of the amount present. Minor elements are less accurate but are reproducible to within 0.01 weight percent.

### Clinopyroxene

The clinopyroxenes from both rocks are aluminum-rich (Table 1), and from the definition of Clark and Papike (1968) are fassaite ( $Al/(Al+Si) > 0.2$ ). The pyroxene from the pyroxenite contains more aluminum and iron than its equivalent in the metagabbro; but in contrast, the metagabbro clinopyroxenes contain more magnesium and sodium. Titanium and chromium are minor in both samples.

Fassaite appears to be confined generally to aluminum-rich rocks. Tilley (1938) observed that fassaite occurs in parageneses in which quartz is absent, and

TABLE 1. Representative analyses of pyroxene, plagioclase, and garnet from spinel-pyroxenite (1128d) and metagabbro (1128p) xenoliths in Stockdale kimberlite, Kansas

	Bronzite		Fassaite		Plagioclase		Garnet	
	1128d	1128p	1128d	1128p	1128d	1128p	1128d	1128p
SiO <sub>2</sub>	50.6	48.1	51.3	52.1	54.2	40.4	40.7	
TiO <sub>2</sub>	0.08	0.43	0.28	<0.03	<0.08	<0.01	<0.04	
Al <sub>2</sub> O <sub>3</sub>	8.46	10.1	7.60	29.3	28.3	23.6	21.8	
Cr <sub>2</sub> O <sub>3</sub>	0.07	0.10	0.07	-	<0.01	<0.01	0.05	
FeO	16.7	5.93	3.92	0.03	<0.02	16.5	15.1	
MgO	24.4	11.8	13.5	<0.03	<0.04	12.1	13.5	
CaO	0.30	21.6	21.4	12.7	11.5	7.96	8.38	
MnO	0.27	0.13	0.03	-	<0.01	0.37	0.33	
Na <sub>2</sub> O	<0.01	1.38	2.17	4.33	5.15	0.02	-	
K <sub>2</sub> O	<0.01	<0.01	<0.02	0.28	0.31	<0.01	-	
	100.8	100.1	100.3	98.8	99.5	100.9	99.9	

Number atoms on basis of X oxygen (x1000)

X =	6	6	6	8	8	12	12
Si	832	1774	1850	2396	2466	2971	3028
Ti	2	11	9	0	0	0	0
Al	358	463	386	1586	1515	2041	1900
Cr	2	3	2	-	0	0	3
Fe <sup>2+</sup>	502	190	118	1	0	1014	934
Mg	1303	633	694	0	0	1324	1494
Ca	12	852	809	626	560	625	665
Mn	9	5	1	-	0	23	21
Na	-	98	158	386	454	0	-
K	-	-	0	17	18	0	-

En: 71.8	Jd: 10.3	12.0	An: 59.5	52.6	Spess: 1	1
	En: 32.1	35.2	Ab: 38.8	45.6	Gross: 21	22
	Fs: 9.4	6.0	Or: 1.7	1.8	Alm: 34	32
	Cts: 12.2	11.6			Pyr: 44	45
	Wo: 36.0	35.2				
	Di: 84	86				
	Cts: 16	14				

believed for this reason that fassaite is unstable in the presence of free silica. Pertinent to this is the comment by Kushiro (1965) that in silica-saturated conditions there is no complete solid solution between  $\text{CaMgSi}_2\text{O}_6$  and  $\text{CaAl}_2\text{SiO}_6$ . In undersaturated conditions the reverse is true. No quartz has been observed in the Kansas granulites. Fassaite has been recognized (Lovering and White, 1969) in xenoliths from basic pipes at Delegate, Australia. The fassaite in these xenoliths is more aluminous than the Kansas specimens and occurs in association with garnet (fassaite eclogites).

#### *Orthopyroxene*

Orthopyroxene (bronzite,  $\text{En}_{72}$ ) is observed only in the pyroxenite (Table 1). Of particular interest is the high  $\text{Al}_2\text{O}_3$  content—up to 8.5 weight percent. Such high values are not uncommon in aluminous rocks of the granulite facies (Deer *et al.*, 1962, p. 35; Eskola, 1952). However, the pyroxene is usually hypersthene, *i.e.* more Fe-rich than recorded here. Orthopyroxenes in two-pyroxene granulites from Delegate (Lovering and White, 1969) have considerably lower  $\text{Al}_2\text{O}_3$  contents (2–4 weight percent), whereas in a spinel websterite from Moses Rock kimberlite (McGetchin and Silver, 1970) the orthopyroxene ( $\text{En}_{87}$ ) contains up to 7 weight percent  $\text{Al}_2\text{O}_3$ .

#### *Plagioclase*

Plagioclase (labradorite) occurs in both rocks, but is more calcic ( $\text{An}_{60}$ ) in the spinel pyroxenite than in the metagabbro ( $\text{An}_{53}$ ). The orthoclase component constitutes less than 2 mole percent in both instances, and this value is within the range recorded for plagioclase from granulites (Sen, 1959). Minor-element contents are not noticeably different from those normally observed in labradorite. Albite and pericline twinning are common whereas Carlsbad is rare. Generally, twinned plagioclase is fairly rare in metamorphic rocks (Turner, 1951; Gorai, 1951), but when present albite and pericline twinning are the normal types. In these granulites the frequency of twinning is suggestive of igneous processes, whereas the types of twinning (*i.e.* albite, pericline, Carlsbad rare) are similar to those found in metamorphic rocks. The rocks were probably originally igneous and were subsequently metamorphosed under granulite facies prior to incorporation in the ascending kimberlite.

In the spinel–pyroxenite the plagioclase shows replacement by both garnet and a clinopyroxene + sillimanite symplectite (Fig. 2a), whereas in the metagabbro only garnet appears to be forming at the

expense of plagioclase and clinopyroxene. No chemical zoning was observed in the plagioclase.

#### *Garnet*

Garnet occurs as a major phase in the metagabbro (1128p) but is rare in the pyroxenite (1128d). It has formed at the expense of both plagioclase and clinopyroxene, and in the metagabbro accounts for approximately 40 percent of the rock (Fig. 2b). The garnet in both rocks (Table 1) is a pyrope–almandine with substantial grossular. In composition it is not unlike the garnet in garnet granulites from Delegate studied by Lovering and White (1969, Table 10), who also suggest that in the Delegate rocks the garnet is a result of plagioclase–pyroxene reaction.

#### *Sillimanite*

Sillimanite was recognized in both the pyroxenite and metagabbro. In the pyroxenite it is present as a symplectite in association with diopside, and both minerals replace the calcic plagioclase (Fig. 2a). In the metagabbro, sillimanite occurs as a selvage surrounding the spinel–sapphirine pair, and generally separates these two minerals from the enclosing garnet. Identification of the polymorph of aluminum silicate was by microprobe and X-ray powder diffraction. The sillimanite in both rocks is similar in major and minor element content (Table 2).

#### *Spinel*

Pale green spinel is present in both the pyroxenite and metagabbro but is more magnesian in the metagabbro (Table 2). In both instances spinel proper ( $\text{MgAl}_2\text{O}_4$ ) and hercynite ( $\text{FeAl}_2\text{O}_4$ ) account for more than 92 percent of the total composition. Minor amounts of Cr and Mn are present. The spinel is being replaced by sapphirine.

#### *Sapphirine*

The sapphirine is always associated with green aluminous spinel and from both petrographic and chemical relationships is replacing this latter mineral (Fig. 2c). Similar relationships have been reported by Herd *et al.* (1969) for enstatite-rich rocks from Fiskenaeset, West Greenland, and from MacRobertson Land, Antarctica (Segnit, 1957). Analyses of the sapphirine from both rocks are presented in Table 2. The sapphirine associated with the more iron-rich spinel in the pyroxenite also contains the most iron. A similar relationship can also be observed for chromium, which is the most abundant minor element, (<0.7 weight percent) Titanium, calcium, and manganese are all less than 0.1 weight percent in the sapphirine.

TABLE 2. Representative analyses of sillimanite, spinel, and sapphire from spinel-pyroxenite (1128d) and metagabbro (1128p) xenoliths in Stockdale kimberlite, Kansas

	Sillimanite		Spinel		Sapphire	
	1128d	1128p	1128d	1128p	1128d	1128p
SiO <sub>2</sub>	37.6	37.8	-	-	13.5	11.2
TiO <sub>2</sub>	<0.06	<0.05	<0.04	<0.04	<0.04	<0.04
Al <sub>2</sub> O <sub>3</sub>	61.1	61.1	58.3	63.2	60.5	66.3
Cr <sub>2</sub> O <sub>3</sub>	<0.05	0.11	2.03	0.96	0.70	0.45
FeO	0.72	0.69	25.2	15.9	8.89	4.60
MgO	0.06	0.11	12.9	18.1	16.3	16.7
CaO	0.16	0.07	<0.02	<0.05	0.03	<0.05
MnO	<0.03	<0.01	0.15	0.04	0.09	0.01
	99.7	99.9	98.6	98.2	100.1	99.3
FeO	-	-	FeO*	24.1	13.8	
Fe <sub>2</sub> O <sub>3</sub>	0.80	0.77	Fe <sub>2</sub> O <sub>3</sub>	4.5	2.9	

Number atoms on basis X oxygen (x1000)

X =	5	5	4	4	20	20
Si	1021	1023	-	-	1622	1332
Ti	0	0	0	0	0	0
Al	1957	1952	1884	1946	8556	9246
Cr	0	2	44	20	66	42
Fe <sup>III</sup>	16	16	94	50	-	-
Fe <sup>II</sup>	-	-	484	296	894	456
Mg	2	4	525	705	2918	2948
Ca	5	2	0	0	4	0
Mn	0	0	3	7	10	2

\*Fe<sub>2</sub>O<sub>3</sub> calculated to satisfy stoichiometry.

The iron content of this sapphire is relatively high (FeO ~ 8.7 weight percent).

Of particular significance is the peraluminous nature of the sapphire in the metagabbro (1128p). Recently, Schreyer and Abraham (1975) have commented on an iron-free peraluminous sapphire occurring in a talc-gedrite-sapphire schist from Afghanistan. If the iron in the Kansas material is assigned to similar crystal sites as Mg in the sapphire structure (Moore, 1969), the specimens from Afghanistan and Kansas are virtually identical (Fig. 3). These compositions are more aluminous than the 7:9:3 formula (7MgO·9Al<sub>2</sub>O<sub>3</sub>·3SiO<sub>2</sub>) proposed by Kuzel (1961) for synthetic sapphire, and are also more aluminous than the 4:4:2 formula found by Taylor (1973) for sapphire in experimental studies of the system MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> at 15 kbar. However,

Bishop and Newton (1975) have synthesized material at 1 atm that is more Al-rich than the 7:9:3 formula. This synthetic material approximates to both the Afghanistan and Kansas sapphire (Fig. 3). It should be noted, however, that if ferric iron is present, this would shift the points in Figure 3 to higher (Al<sub>2</sub>O<sub>3</sub> + Fe<sub>2</sub>O<sub>3</sub>) contents.

From crystal-chemical and petrologic considerations, Schreyer and Abraham (1975) believe that peraluminous sapphire is probably a metastable phase. For the sapphire in the pyroxenite (1128d) from Stockdale, the petrographic data suggest a stable relationship. Moreover, the phases present in the rock as a whole indicate pressure in the region of 12 kbar and 800°C. These observations, together with the high contents of FeO in the sapphire and its obvious genetic association with the spinel phases,

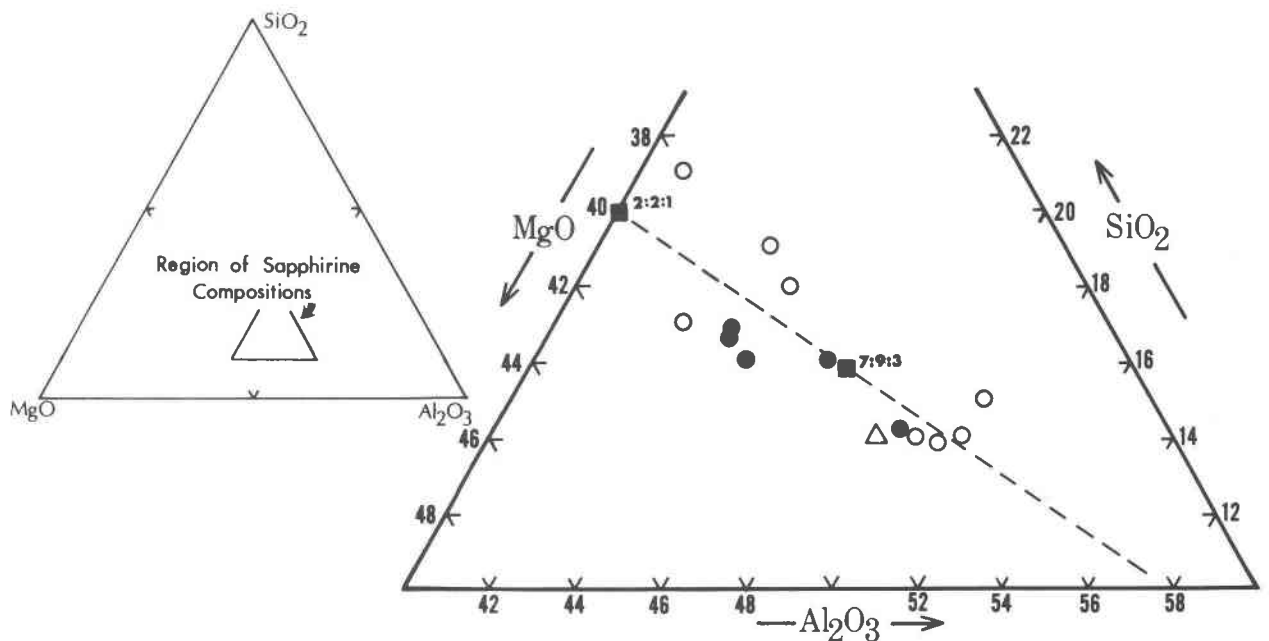


FIG. 3. Part of the system  $\text{MgO-FeO-Al}_2\text{O}_3\text{-SiO}_2$  showing the position of the Stockdale sapphire compositions (solid circles) relative to other selected natural samples (open circles). The two solid squares represent the  $2\text{MgO}:2\text{Al}_2\text{O}_3:1\text{SiO}_2$  and  $7\text{MgO}:9\text{Al}_2\text{O}_3:3\text{SiO}_2$  compositions of sapphire. The open triangle is the composition of synthetic sapphire of Bishop and Newton (1975). Other data from Segnit (1957) Monchoux (1972), and Clifford *et al.* (1975). The analyses on the alumina-rich side of 7:9:3 and shown as open circles are the peraluminous sapphire of Schreyer and Abraham (1975). (MgO includes MgO + FeO).

suggest that more detailed experimental studies of sapphire stability are needed, especially in systems containing FeO.

### Discussion

The occurrence of the few small xenoliths of granulite-facies rocks in the kimberlites of Kansas provides an insight into the petrogenesis and metamorphic history of a lower crustal region about which little is known. These sapphire-bearing granulites provide evidence of metamorphism of basic igneous rocks at significantly great depths ( $\sim 40$  km) within the Earth's crust.

The important reactions observed in these rocks may be stated in a simple non-chemical manner as;

- i. spinel  $\rightarrow$  sapphire
- ii. plagioclase  $\rightarrow$  sillimanite + clinopyroxene
- iii. Plagioclase + clinopyroxene  $\rightarrow$  garnet

All three reactions are represented in the pyroxenite, whereas only reactions i and iii occur in the metagabbro.

The formation of sapphire from spinel requires the addition of silica, *e.g.*  $2\text{MgAl}_2\text{O}_4 + \text{SiO}_2 \rightleftharpoons \text{Mg}_2\text{Al}_4\text{SiO}_{10}$ , but in these rocks the reaction is certainly more complex in view of the presence of Fe and the  $\text{MgO}:\text{Al}_2\text{O}_3$  ratio being other than 1:1. Although

no quartz has been recognized in either rock, Akella and Kennedy (1971) observed that small amounts of quartz are produced in the reaction anorthite +  $\text{Di}_{50}\text{Hd}_{50} \rightarrow$  pyroxene + garnet + quartz. Thus in the metagabbro the similar reaction plagioclase + pyroxene  $\rightarrow$  garnet probably provides the silica to produce the sapphire from the spinel. In the pyroxenite the breakdown of plagioclase to clinopyroxene and sillimanite can be shown to release some silica, which in turn results in the formation of sapphire.

Sapphire is a relatively rare mineral (Seifert, 1974) and appears mostly in Precambrian terrains which have been subject to high-grade regional metamorphism (Dallwitz, 1968; Morse and Talley, 1971; Leong and Moore, 1972; Monchoux, 1972). Occurrences of this mineral are also recorded in association with anorthositic (Herd *et al.*, 1969; Janardhanan and Leake, 1974) and charnockitic rocks (Segnit, 1957). In these and other instances (*e.g.* Clifford *et al.*, 1975), the rocks are generally alumina-rich, although Seifert (1974) indicates that supersaturation with  $\text{Al}_2\text{O}_3$  is not necessary for the formation of sapphire, and Schreyer and Abraham (1975) have found peraluminous sapphire in a relatively alumina-poor schist. In the xenoliths from Kansas all the minerals are highly aluminous (*e.g.* bronzite, 8%  $\text{Al}_2\text{O}_3$ ; diop-

side, 10%  $\text{Al}_2\text{O}_3$ ; plagioclase  $\text{An}_{60}$ ; garnet; and spinel). Furthermore, except for plagioclase all the primary phases have high contents of MgO. This feature is also common in minerals associated with most other occurrences of sapphirine.

The stability of sapphirine in the system  $\text{MgO}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$  has been studied by Seifert (1974) at pressures up to 7 kbar, by Taylor (1973) to 15 kbar, and by Ackermann *et al.* (1975) up to 32 kbar. Chatterjee and Schreyer (1972) reported on the reaction  $\text{enstatite}_{\text{ss}} + \text{sillimanite} = \text{sapphirine}_{\text{ss}} + \text{quartz}$  in the pressure range 12 to 20 kbar. The absence of quartz in these granulite xenoliths is indicative of their undersaturated nature, as too is the presence of fassaite pyroxene (Tilley, 1938). Ackermann *et al.* (1975) have discussed the instability of sapphirine at high pressures, and conclude that sapphirine is a stable phase under all conditions of high-grade metamorphism provided the temperature is high enough and/or water pressure is low. In the Kansas granulites no hydrous phases are present, and it is thus most likely that  $P_{\text{H}_2\text{O}} < P_{\text{Total}}$ . Accordingly, the conditions suggested by Ackermann *et al.* (1975), including the alumina-rich nature of the total rock, are present. This, together with the petrographic data, strongly suggests that the sapphirine in the granulites is a stable phase.

In general, sapphirine in iron-free systems appears to form above about 900°C and 10 kbar. The comment by Seifert (1974) that the presence of FeO in minerals of the system he studied will alter the phase relationships is unfortunately true, and it is thus difficult to predict actual  $P$ - $T$ 's for the sapphirine paragenesis. However, breakdown of anorthite in both rocks provides an indication of minimum pressure-temperature conditions, and the presence of sillimanite also aids in limiting the  $P$ - $T$  field. It is important to note that the present assemblages of phases in each rock are certainly not in equilibrium, since plagioclase and spinel in both rocks are being replaced—the reactions having been “frozen-in” by the rapid ascent of the xenoliths in kimberlite to the Earth's surface.

The assemblage  $\text{diopside}_{\text{ss}} + \text{enstatite}_{\text{ss}} + \text{anorthite} + \text{spinel}$  has been shown experimentally to be stable between 7 kbar/1000°C and 15 kbar/1250°C (Kushiro and Yoder, 1966). At the higher conditions anorthite disappears and is replaced by  $\text{clinopyroxene}_{\text{ss}} + \text{orthopyroxene}_{\text{ss}} + \text{quartz}$ . This reaction is generally equivalent to that occurring in the pyroxenite (reaction ii), except that the aluminous nature of both the initial pyroxenes and plagioclase results in the formation of both fassaite pyroxene and silliman-

ite, with minor silica being released to produce sapphirine from the spinel. The disappearance of plagioclase in this rock probably indicates pressure and temperature in the region of 10–14 kbar and 800–1000°C. This agrees generally with the known stability of sapphirine as well as that of sillimanite (Richardson *et al.*, 1969).

The possible pressure and temperature of crystallization of both rocks can be approximately determined from the studies of Ringwood and Green (1966), Green and Ringwood (1972), Ito and Kennedy (1971) and Kennedy and Ito (1972) on the transition  $\text{gabbro} \rightarrow \text{garnet granulite} \rightarrow \text{eclogite}$ . Garnet granulite ( $\equiv$  metagabbro) equivalent in composition to alkali-poor olivine tholeiite has a region between about 10 kbar and 14 kbar at 1100°C in which plagioclase disappears (Green and Ringwood, 1972). At lower temperatures this region is depressed with respect to pressure, but the pressure-temperature range is still within the stability fields of sapphirine and sillimanite.

The temperature of equilibration for the assemblage garnet-clinopyroxene in both samples can be determined using the method of Råheim and Green (1974) based on the Fe-Mg partitioning between the two coexisting phases. If the pressure is estimated at about 12 kbar, based on the disappearance of plagioclase, a temperature for the garnet-clinopyroxene pairs of 820°C is obtained for the metagabbro and 860°C for the pyroxenite. These values are in good agreement with the conditions suggested previously and based on petrologic phase considerations.

Thus the data from experimental systems suggest both the pyroxenite and metagabbro have reequilibrated under similar conditions of pressure and temperature. However, although in detail the mineral compositions are different, both rocks have generally similar bulk compositions, and also the plagioclases are similar, which is surprising in view of the two different ways in which plagioclase is being replaced. Since  $P$ ,  $T$ , and bulk composition are comparable, the answer to the different plagioclase reactions may lie in the presence of enstatite in the pyroxenite and its absence in the metagabbro.

In spite of this problem the assemblages recorded in these rocks suggest pressures and temperatures equivalent to about 30 to 40 km depth. The similarity of the bulk composition of these samples to normative olivine-tholeiite is interesting in view of the position of the Kansas kimberlites on the southern limb of the mid-continent gravity high which extends from the Lake Superior region of Keweenaw basalts directly across this portion of Kansas. These



basic granulite xenoliths may be representative, albeit regionally metamorphosed, of the material constituting the anomaly in this region.

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