

# Comments on 'Kaersutite from San Carlos, Arizona, with comments on the paragenesis of this mineral' by Brian Mason

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**SUMMARY.** Electron probe analyses have been made of eight kaersutites from San Carlos, Arizona, and one from Kakanui, New Zealand; also of olivine, clinopyroxene, ilmenite, and spinel from San Carlos. There is not as yet adequate evidence that the kaersutite is an upper mantle phase.

MASON (1968a) suggests that kaersutite, as exemplified by the occurrence at San Carlos, Arizona, as well as from some other localities, may represent the amphibole phase in upper mantle rocks. The possibility of amphibole as an upper mantle phase was most clearly suggested by Oxburgh (1964) since it would help explain the alkali content of basaltic rocks, which otherwise would be derived from alkali-poor ultramafic mantle rocks.

Since we are carrying out a detailed study of the ultramafic inclusions of the San Carlos, Arizona, locality, we would like to clarify some of the petrologic significance of the kaersutite from this area because it leads us to different conclusions from those of Mason. Hopefully, our comments will be of value to others suggesting amphibole as an upper mantle phase.

*San Carlos locality.* The kaersutite described by Mason (1968a) in the San Carlos locality occurs as a granular aggregate of anhedral crystals, with a little inter-granular ilmenite. It occurs more commonly, however, as polymineralic aggregates in a basalt flow or as blocks thrown from a central vent. Texturally, kaersutite often occurs as large poikilitic plates, which most commonly enclose olivine. Often the kaersutite is intergrown with clinopyroxene in textural relationships that resemble lamellar or blebby exsolution textures, but appear to be primary intergrowths. The amphibole is a primary phase and crystallized late in the crystallization sequence, as evidenced by its poikilitic texture.

Kaersutite in xenocrysts and in peridotite inclusions have the same composition (see Mason, 1968a, and table II, this report) and there is little doubt that they are of similar origin. However, the occurrences in peridotite inclusions allow more significant petrologic conclusions, since coexisting minerals may be studied.

Kaersutite-bearing inclusions in this locality coexist with olivine, clinopyroxene, orthopyroxene, plagioclase, spinel, and ilmenite. Orthopyroxene and plagioclase are usually minor constituents or are absent. Modal variations, as shown in table I, are

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large. The wide modal variation is not entirely due to analysis of inadequate surface area of coarse-grained rocks, as thin sections covering different parts of the same inclusion give similar modes. Thus each mode represents a large area and approaches the composition of the entire inclusion. Large modal variations are also found in other types of inclusions in this area. A discussion of their significance is beyond the scope of this report but may imply considerable differentiation in their past history. Most of the rocks in table I may be called kaersutite wehrlites.

TABLE I. *Modes of kaersutite wehrlites from San Carlos, Arizona*

	PA-42	PA-43	PA-44	PA-47	PA-53A	PA-7	PA-1A	PA-1B	A-6
Olivine	52.9	12.4	21.6	33.5	38.7	47.1	13.8	9.2	83.9
Clinopyroxene	—	66.3	24.8	42.8	16.7	1.0	65.4	74.5	11.4
Orthopyroxene	tr	0.1	—	—	—	10.5	—	—	—
Kaersutite	43.8	11.6	49.4	7.5	41.9	40.3	1.6	1.0	0.9
Kaersutite inter- grown with clinopyroxene	—	4.8	1.5	5.8	—	—	—	—	—
Plagioclase	—	1.1	—	—	—	—	—	—	—
Spinel	1.1	0.8	0.8	2.0	1.6	0.2	18.7	2.5	0.9
Ilmenite	2.2	2.9	1.9	8.4	1.1	0.9	0.5	12.8	2.9

Table II contains electron microprobe determinations of 8 kaersutites from different samples (most of which are in table I) of kaersutite wehrlites in this locality. Structural formulae are calculated on the anhydrous basis of 23 oxygen since H<sub>2</sub>O cannot be determined with the probe. Analyses were performed on an ARL-EMX instrument with accelerating potential 20 keV, sample current 0.02  $\mu$ A, 1 to 2  $\mu$  beam size, and 10-second counting time. The major variations are in Fe and Mg, which have an inverse relationship. The Fe-Mg variation in relation to compositions of co-existing phases will be reported later. It is probably related to the differentiation sequence.

Kaersutite from Kakanui, New Zealand, has also been analysed with the electron microprobe, with the following results: SiO<sub>2</sub> 40.4 %, TiO<sub>2</sub> 4.6 %, Al<sub>2</sub>O<sub>3</sub> 14.4 %, FeO 13.7 %, MnO 0.19 %, CaO 9.9 %, MgO 11.6 %, Na<sub>2</sub>O 2.8 %, and K<sub>2</sub>O 1.52 %. This analysis is similar to analyses of kaersutite from this locality by Mason (1968a) and Dickey (1968). However, Kakanui kaersutites have higher Fe/Mg ratios than most kaersutites from San Carlos even though Kakanui rocks are a pyrope-bearing assemblage (Mason, 1968b). Again this indicates that understanding of relationships between coexisting minerals in different assemblages from an area are necessary before petrologic significance can be deduced.

The minerals coexisting with kaersutite in peridotites from San Carlos have compositions similar to those that White (1966) found in alkali basalts, and which Kuno (in press) calls the wehrlite series. These authors conclude that the wehrlite series are deep crustal and could not form in the upper mantle, as compared to the lherzolite series, which might be upper mantle rocks. These conclusions have also been reported

for similar rocks by Aoki and Kushiro (1968) for Dreiser Weiher, Binns (1969) for megacrysts in lavas near Armidale, New South Wales, and Aoki (1968) for ultramafic and mafic inclusions in alkali basalts of Iki Island, Japan.

TABLE II. *Kaersutites from kaersutite wehrlites, San Carlos, Arizona*

Spec. no.	PA-32	PA-42	PA-43	PA-44	PA-47	PA-53A	PA-7	A-6
SiO <sub>2</sub>	40.0	40.0	40.5	40.0	40.2	40.2	40.2	43.2
TiO <sub>2</sub>	4.7	5.0	4.2	5.6	5.5	4.5	5.2	4.9
Al <sub>2</sub> O <sub>3</sub>	15.3	14.6	15.3	14.5	14.4	15.0	14.5	13.2
FeO*	9.7	11.7	9.9	11.2	11.8	11.0	8.4	7.9
MnO	0.10	0.16	0.13	0.13	0.17	0.13	0.10	0.08
CaO	11.1	10.6	10.9	11.0	10.5	10.9	11.2	11.3
MgO	13.9	13.0	14.2	13.0	13.0	13.2	15.1	15.8
Na <sub>2</sub> O	3.0	2.8	3.0	3.1	2.8	3.0	2.9	3.1
K <sub>2</sub> O	0.85	1.19	1.09	0.85	1.18	0.79	1.07	0.84
Total†	98.65	99.05	99.22	99.38	99.55	98.72	98.67	100.32
<i>Structural formulae</i>								
Si	5.812	5.808	5.849	5.818	5.840	5.845	5.892	6.096
Al	2.188	2.192	2.151	2.182	2.160	2.155	2.108	1.905
Z	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Al	0.427	0.342	0.454	0.310	0.316	0.428	0.329	0.294
Ti	0.511	0.553	0.453	0.607	0.596	0.498	0.562	0.521
Mg	3.001	2.839	3.068	2.807	2.808	2.864	3.212	3.325
Fe	1.777	1.438	1.194	1.357	1.437	1.345	1.004	0.928
Mn	0.123	0.020	0.016	0.016	0.021	0.016	0.012	0.010
Y	5.24	5.19	5.19	5.10	5.18	5.15	5.12	5.08
Ca	1.726	1.665	1.688	1.720	1.640	1.711	1.707	1.702
Na	0.858	0.809	0.844	0.866	0.798	0.861	0.809	0.857
K	0.158	0.223	0.201	0.158	0.219	0.147	0.195	0.151
X	2.74	2.70	2.73	2.74	2.66	2.72	2.71	2.71

\* Total iron determined as FeO.

† H<sub>2</sub>O not determined.

The mineral compositions of kaersutite-bearing and other inclusions from the San Carlos locality will be reported at a later time, but for purposes of this report some typical compositions of the major phases in kaersutite peridotites are presented in table III. These mineral compositions are distinctly different from lherzolites (see Ross, Foster, and Myers, 1954, and White, 1966) and are very similar to those of the wehrlite series. Lherzolites have more Cr-rich compositions, especially for spinel. Olivines in lherzolites are Mg-rich, usually Fo<sub>89-91</sub>, whereas olivine here is Fo<sub>73</sub>, and a wide range of compositions in other samples is found (unpublished data). Clinopyroxene in lherzolites is richer in Mg and Cr, and has less Ti, Na, Fe, and Al than in clinopyroxene reported here. Clinopyroxenes from wehrlitic rocks in Dreiser Weiher (Aoki and Kushiro, 1968) are very similar to those in the kaersutite wehrlites of San Carlos. The presence of minor amounts of plagioclase (not from the basaltic host) shows that some rocks crystallized at pressures near the boundary of the spinel peridotite and feldspathic peridotite fields (Kushiro and Yoder, 1966), and clearly indicates lower pressures than for lherzolitic inclusions.

*Discussion.* We do not wish, at this time, to evaluate the evidence in this or other localities for or against the deep crustal or upper mantle (residual or otherwise) origin of kaersutite peridotites or the wehrlite suite in general. These will be presented later with the complete data. But we do stress that the arguments for kaersutite being the

TABLE III. *Compositions of major minerals coexisting with kaersutite wehrlites, San Carlos, Arizona*

	Olivine	Clinopyroxene	Spinel	Ilmenite
SiO <sub>2</sub>	37.9	48.4	—	—
TiO <sub>2</sub>	—	1.19	—	51.7
Al <sub>2</sub> O <sub>3</sub>	—	8.9	61.8	0.18
V <sub>2</sub> O <sub>3</sub>	—	—	—	0.21
Cr <sub>2</sub> O <sub>3</sub>	—	0.15	2.69	0.05
Fe <sub>2</sub> O <sub>3</sub>	—	4.5*	2.78*	6.1†
FeO	24.6	3.18	14.8	33.6
MnO	0.23	0.13	0.22	0.40
MgO	37.0	14.5	17.4	6.9
NiO	—	—	—	0.04
CaO	0.05	19.1	—	—
Na <sub>2</sub> O	—	1.23	—	—
Total	99.78	101.28	99.69	99.18

  

<i>Structural formulae</i>							
	Olivine	Clinopyroxene	Spinel		Ilmenite		
Si	0.998	Si	1.755	Al	15.129	Al	0.011
Fe <sup>3+</sup>	0.544	Al <sup>iv</sup>	0.245	Cr	0.442	Ti	1.883
Mn	0.005	Al <sup>vi</sup>	0.135	Fe <sup>3+</sup>	0.435	V	0.008
Mg	1.453	Ti	0.032	Fe <sup>2+</sup>	2.573	Cr	0.002
Ca	0.001	Cr	0.004	Mn	0.039	Fe <sup>3+</sup>	0.222
		Fe <sup>3+</sup>	0.121	Mg	5.379	Fe <sup>2+</sup>	1.360
Fo	72.8 %	Fe <sup>2+</sup>	0.096			Mn	0.016
Fa	27.2 %	Mn	0.004			Mg	0.496
		Mg	0.783			Ni	0.001
		Ca	0.742				
		Na	0.087				
		Wo	42.6 %				
		En	44.9 %				
		Fs	12.5 %				

\* Fe<sub>2</sub>O<sub>3</sub> calculated to adjust structural formula.

† Fe<sub>2</sub>O<sub>3</sub> calculated using method of Carmichael (1967).

missing upper mantle phase are not based on petrologically sound evidence in the San Carlos area. In this locality the kaersutite peridotites are part of the wehrlite series, which others have interpreted as deep crustal; have minor plagioclase, which indicates low pressures at least for some samples; have mineral compositions that show strong fractionation, or reaction at some later period; and have mineral compositions more Fe-rich and Cr- and Mg-poor than in lherzolites. Thus preliminary

evidence points to considerably lower temperatures and pressures of formation than for lherzolitic rocks.

Little is known as yet of the stability field of kaersutite and the mineral is most commonly found as phenocrysts in alkalic basaltic rocks (Aoki, 1963, and Wilkinson, 1961). Although we do not wish to argue against the possibility of kaersutite being a mantle phase, we reiterate that there is as yet little evidence of this in the San Carlos area.

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*Note added in proof:* We agree with Mason (1968a) that kaersutite may represent the high-pressure solidified equivalent of nepheline-bearing magma. The poikilitic habit of the kaersutite supports the idea of this mineral representing a liquid composition. We also tentatively suggest that the phases coexisting with kaersutite represent high-pressure phases crystallized from this liquid. Spinel lherzolites may be residual material that is the result of extraction of mafic liquids and recrystallization. Preliminary conclusions from modal, mineralogical, and bulk chemical data that we are collecting from San Carlos indicates that chromian phlogopite-spinel lherzolite with mineral compositions intermediate between lherzolite and wehrlite is the primitive material from which lherzolites, wehrlites, and kaersutite wehrlites are derived.

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