Geochimica et Cosmochimica Acta, 1973, Vol. 37, pp. 1985 to 1989. Pergamon Press. Printed in Northern Ireland

NOTE

Foreign inclusions in stony meteorites—I. Carbonaceous chondritic xenoliths in the Kapoeta howardite

LAUREL L. WILKENING
Enrico Fermi Institute and Department of Chemistry,
University of Chicago, Chicago, Illinois 60637, U.S.A.

(*Received* 25 *January* 1973; *accepted in revised form* 5 *March* 1973)

Abstract—Small, 1–3 millimeter-sized, black xenoliths containing chondrules and chondrule fragments embedded in a fine-grained matrix are present in the Kapoeta howardite. Forsteritic olivine, pentlandite and a nickel-rich (0·3–2·8 wt.%) matrix indicate that these xenoliths are carbonaceous chondrite material.

INTRODUCTION

ENRICHMENTS of various trace elements in the so-called dark portions of certain gas-rich achondrites led some investigators to suggest that a carbonaceous chondritic component had been mixed into the parent materials of these meteorites (MÜLLER and ZÄHRINGER, 1966; MAZOR and ANDERS, 1967). More recently, JÉROME and GOLES (1971) suggested that all howardites contain an admixed chondritic component. Although Ramdohr, as reported in MÜLLER and ZÄHRINGER (1966), observed a carbonaceous mineral of the approximate composition, FeCS, in the dark portions of Kapoeta, the subject has not been pursued. Whereas all the previous reports are concerned with indirect observations, it is the purpose of this paper to describe actual millimeter-sized inclusions of carbonaceous chondrite-like fragments in the howardite Kapoeta. Thus, Kapoeta joins Bencubbin (LOVERING, 1962) and several chondrites in which carbonaceous chondritic fragments have been well characterized e.g. Mezö-Madaras (VAN SCHMUS, 1967), Tieschitz (KURAT, 1970), Sharps (FREDRIKSSON *et al.*, 1969) and Plainview (FODOR and KEIL, 1972).

PROCEDURE

Two black xenoliths were removed from a piece of Kapoeta (Fig. 2, WILKENING, 1971) for which rare gas, particle track, and mineral composition data have previously been reported (WILKENING *et al.*, 1971; WILKENING, 1971; MARTI *et al.*, 1972). The xenoliths were embedded in epoxy resin and polished. As the two xenoliths have the same textures, only one was analyzed.

Microprobe analyses were performed with the ARL-EMX electron microprobe in the Department of Geophysical Sciences, University of Chicago. Analyses were made with the minimum beam diameter, 1·0 μm, a beam current of 0·5 μA and an accelerating voltage of 15 kV. The observed intensity ratios were corrected using the EMPADR VII computer program (RUCKLIDGE and GASPARRINI, 1969). Olivine analyses were also run through Steele's (personal communication) PYX-OL-FELD program. The latter program calculates and plots approximate pyroxene and olivine compositions using count rates for Ca, Fe and Mg. In it the correction procedures are those of BENCE and ALBEE (1968) using updated alpha values from BEAMAN and ISASI (1970). Because of the small size and fragile nature of the inclusions, only polished sections were studied. Even so, microprobe analyses were hampered by the small grain-size of the sample and the cracks and voids in the section. Three to five analyses were made on each grain. Olivine analyses that did not conform to stoichiometry: Mg + Fe + Ca = 2·0 atoms and Si = 1·0 atoms, within the limits Mg + Fe + Ca = 1·88–2·10 atoms and Si = 0·95–1·07 atoms, were rejected. In part because of the approximate nature of the calculations and also the difficulties presented by the sample, almost one half of the seventy olivine analyses were rejected on the basis of these rather stringent criteria.

Results and Discussion

The black xenoliths are composed of a very fine-grained matrix in which are embedded chondrules, chondrule fragments, and other irregular fragments, Fig. 1. The fine-grained matrix typically contains 22–27 wt.% Fe and 0·3–2·9 wt.% Ni. These values are similar to the ranges for 8 C2 chondrites (18–26 wt.% Fe and 0·3–2·8 wt.% Ni) reported by Wood (1967a, b). There were three highly reflecting grains large enough to be analyzed in the xenolith studied; two of these grains are visible in Fig. 1. These two grains are pentlandite, $Fe_{\sim 6}Ni_{\sim 3}S_8$. Analyses of the other grain (probably pentlandite also as indicated by high Ni concentration) which is actually a very fine-grained aggregate (grain-size <0·1 μm) were rejected because of low totals. Primary independent pentlandite is a common sulfide mineral in carbonaceous chondrites (Ramdohr, 1963). Because of the higher degree of oxidation of the carbonaceous chondrites, Ni, which alloys with metallic iron in ordinary chondrites, is forced into the sulfide phase forming pentlandite. Pentlandite, sometimes intergrown with troilite, is found in some ordinary chondrite *finds*; in these it is thought to be the product of weathering.

In Table 1 are listed the range and mode of the compositions of the olivine in Kapoeta along with olivine compositions of carbonaceous chondrites. Analyses of individual olivine grains are shown in a histogram in Fig. 2. Although distribution patterns of the olivine compositions in all the C2's are similar (Wood, 1967b), the Pollen data which are plotted for comparison were picked as one of the better matches to the Kapoeta xenolith data.

In comparing these data with those of the three other classes of carbonaceous chondrites (Table 1), one finds that the data for the C1 chondrite Orgueil are similar, peaking at about 1 mole% fayalite in the olivines Reid *et al.*, 1970). Olivine compositions in C3's cover a wide range of fayalite contents, and the distribution of compositions within the range is generally broad and unpeaked (Van Schmus, 1969), Fig. 2. However, in some cases the fayalite content peaks at a high mole % fayalite e.g. 40 mole% Fa in Warrenton (Van Schmus, 1969) and in still other cases, especially among the Vigarano sub-type such as Allende (Clark *et al.*, 1970), the pattern is similar to that of C2's.

Table 1. Olivine compositions in carbonaceous chondrites and in Kapoeta

Name or type	Range mole% fayalite	Mode mole% faylite	Comments	Reference
Kapoeta xenolith	0·1–33·5	1·0	18 grains	This work
Kapoeta bulk	8·5–37·7	—	5 grains	Fredriksson and Keil, 1963
Orgueil, Cl	0·1–13·0	1 ± 1	15 grains	Reid *et al.*, 1970
C2	0·1–69·0	1·0	10 meteorites	Wood, 1967
C3	0·1–70·0	Variable	Usually an unpeaked distribution	Van Schmus, 1969

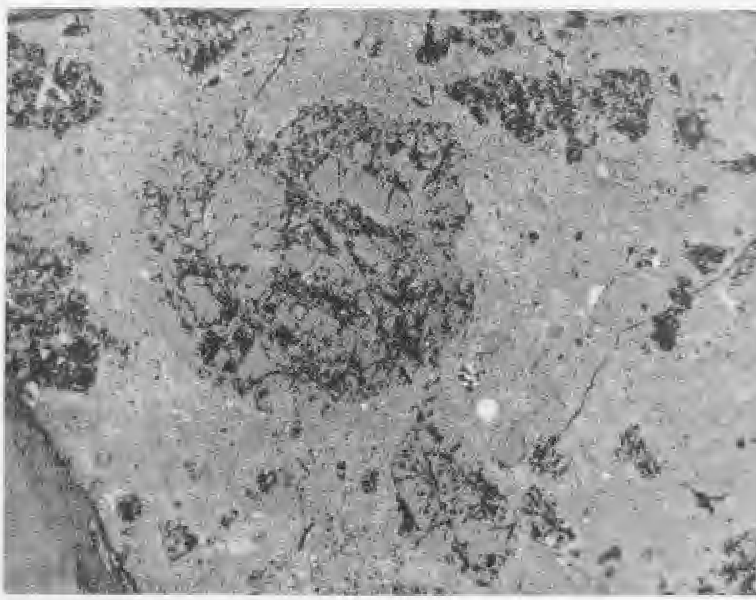

Fig. 1. A portion of a black xenolith from Kapoeta. A chondrule and fragments are set in a fine-grained matrix. The field of view is 0·68 mm × 0·88 mm. Reflected light.

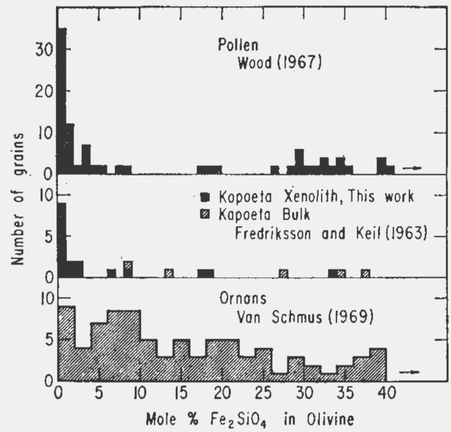

Fig. 2. Histograms of the olivine compositions in Pollen (Wood, 1967b), Kapoeta bulk (Fredriksson and Keil, 1963), Kapoeta xenolith (this work) and Ornans (Van Schmus, 1969). The similarity of the Kapoeta xenolith data to those of the C2 chondrite Pollen is readily apparent.

Thus, the olivines of the Kapoeta xenolith are closer in composition to the olivines of C1, C2 and Vigarano-sub-type C3's than to any other chondrites or to the rare, large, individual olivines distributed throughout bulk Kapoeta. Furthermore, when the textures are considered, the C1-type which has no chondrules and very rare high temperature minerals (only 15 olivine grains were found in the three thin sections studied by Reid *et al.*, 1970) must be ruled out. In the small areas (0·1 cm^2) of xenoliths examined the chondrules observed were not of the Vigarano C3 sub type (large, 0·5–2 mm, spongy with profuse opaque material). Hence, of the known types of meteorites, the Kapoeta xenolith is most like the C2 type although C3 cannot be entirely ruled out.

It should be noted that not all of the black appearing fragments of 1–5 mm size in Kapoeta are chondritic inclusions. In some cases they are pyroxene crystallites in an opaque matrix. Jérome (1970) has suggested that similar features in the Washougal howardite are the result of incomplete devitrification.

At this point it should be remarked that the Kapoeta 'extra-dark' material analyzed for xenon by Rowe (1970) is not the same material as that described here. I have found the mineralogy of Rowe's fragment to be substantially the same as that of bulk Kapoeta, that is, the major minerals are calcic feldspar and pyroxene. Furthermore, trace element analyses of Kapoeta extra-dark material show that the abundances of Ag, Br, In, Bi, and Zn are similar to Kapoeta 'dark' and quite different from carbonaceous chondrites (R. Ganapathy, personal communication). Despite its ^{129}Xe excess the 'extra-dark' material, which may be a breccia fragment from an earlier brecciation, is certainly not a chondritic xenolith.

The evidence presented here confirms earlier suggestions that a chondritic component has been mechanically admixed to Kapoeta. Furthermore, the admixture has taken place in such a way that some fragments have been preserved.

The presence of foreign fragments is another piece of evidence that howardites such as Kapoeta are low-grade microbreccias formed from a thoroughly reworked regolith on a parent body. To illustrate this point the following evidence may also be cited. Although there exist both igneous and breccia (the so-called light material of the gas-rich howardites) fragments in the howardites, pre-existing breccia fragments are far more abundant than the rare igneous lithic fragments. Secondly, the host material is so finely comminuted that individual mineral grains are the major constituent. And finally, the presence of solar-type rare gases and solar flare cosmic ray tracks in some howardites (ZÄHRINGER and GENTNER, 1960; MAZOR and ANDERS, 1967; LAL and RAJAN, 1969; PELLAS *et al.*, 1969) emphasizes the surficial nature of the parent regolith and the low grade brecciation [Kapoeta seems to correspond to the 0 or 1 class of lunar breccias as defined by WILLIAMS (1972)].

It is in just such a breccia that one should be able to recover fragments of exotic types of meteorites if the velocities of the incoming particles were low enough for the material to survive the impact. Although material of carbonaceous chondrite-like composition appears to be the main constituent of interplanetary matter falling on the Earth and Moon (GANAPATHY *et al.*, 1970) only one intact fragment of a carbonaceous chondrite was found in the examination of more than 2000 particles from the regolith at the sites of Apollos 11 and 12 (WOOD *et al.*, 1971). And that particle shows substantial indications of shock. Thus, I conclude that (1) typical impact velocities in the source region of the Kapoeta howardite were lower than those on the moon and (2) carbonaceous chondrite-like material was a prominent constituent of the interplanetary debris in the source region of the Kapoeta howardite.

Acknowledgment—I thank E. ANDERS, M. W. ROWE and H. E. SUESS for providing the samples of Kapoeta used in this study and I. STEELE for assistance with the microprobe data-reducing computer programs. I am indebted to E. ANDERS for many helpful suggestions. This research was supported in part by NASA Grant NGL 14-001-010.

REFERENCES

BEAMAN D. R. and ISASI J. A. (1970) A critical examination of computer programs used in quantitativo electron microprobe analysis. *Anal. Chem.* **42,** 1540–1568.

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

CLARKE R. S., JR., JAROSEWICH E., MASON B., NELEN J., GÓMEZ M. and HYDE J. R. (1970) The Allende, Mexico, meteorite shower. *Smithson. Contrib. Earth Sci.* **5,** 1–53.

FODOR R. and KEIL K. (1972) Carbonaceous and non-carbonaceous lithic inclusions in the Plainview, Texas, chondrite. Paper presented at the 35th Annual Meeting of the Meteoritical Society, Chicago, Illinois, November 16–18.

FREDRIKSSON K. and KEIL K. (1963) The light–dark structure in the Pantar and Kapoeta stone meteorites. *Geochim. Cosmochim. Acta* **27,** 717–739.

FREDRIKSSON K., JAROSEWICH E. and NELEN J. (1969) The Sharps chondrite: new evidence on the origin of chondrules and chondrites. In *Meteorite Research,* (editor P. M. Millman), pp. 155–165. Reidel.

GANAPATHY R., KEAYS R. R., LAUL J. C. and ANDERS E. (1970) Trace elements in Apollo 11 lunar rocks: implications for meteorite influx and origin of Moon. *Geochim. Cosmochim. Acta* Suppl. **1,** 1117–1142.

JÉROME D. Y. (1970) Composition and origin of some achondritic meteorites. Thesis, University of Oregon.

JÉROME D. Y. and GOLES G. G. (1971) A re-examination of relationships among pyroxene–plagioclase achondrites. In *Activation Analysis in Geochemistry and Cosmochemistry*, (editors A. O. Brunfelt and E. Steinnes), pp. 261–266. Universitatsforlaget.

KURAT G. (1970) Zur Genese des kohligen Materials im Meteoriten von Tieschitz. *Earth Planet. Sci. Lett.* **7,** 317–324.

LAL D. and RAJAN R. S. (1969) Observations on space irradiation of individual crystals of gas-rich meteorites. *Nature* **223,** 269–271.

LOVERING J. F. (1962) The evolution of the meteorites—evidence for the co-existence of chondritic, achondritic and iron meteorites in a typical parent meteorite body. In *Researches on Meteorites*, (editor C. B. Moore), pp. 179–197. Wiley.

MARTI K., WILKENING L. L. and SUESS H. E. (1972) Solar rare gases and the abundances of the elements. *Astrophys. J.* **173,** 445–450.

MAZOR E. and ANDERS E. (1967) Primordial gases in the Jodzie howardite and the origin of gas-rich meteorites. *Geochim. Cosmochim. Acta* **31,** 1441–1456.

MÜLLER O. and ZÄHRINGER J. (1966) Chemische Unterschiede bei uredelgashaltigen Steinmeteoriten. *Earth Planet. Sci. Lett.* **1,** 25–29.

PELLAS P., POUPEAU G., LORIN J. C., REEVES H. and AUDOUZE J. (1969) Primitive low-energy particle irradiation of meteoritic crystals. *Nature* **223,** 272–274.

RAMDOHR P. (1963) The opaque minerals in stony meteorites. *J. Geophys. Res.* **68,** 2011–36.

REID A. M., BASS M. N., FUJITA H., KERRIDGE J. F. and FREDRIKSSON K. (1970) Olivine and pyroxene in the Orgueil meteorite. *Geochim. Cosmochim. Acta* **34,** 1253–1255.

ROWE M. W. (1970) Evidence for decay of extinct Pu^{244} and I^{129} in the Kapoeta meteorite. *Geochim. Cosmochim. Acta* **34,** 1019–1025.

RUCKLIDGE J. and GASPARRINI E. L. (1969) Electron micro-probe analytical data reduction: EMPADR VII, 37 pp. University of Toronto, Toronto. Unpublished report.

VAN SCHMUS W. R. (1967) Polymict structure of the Mezö-Madaras chondrite. *Geochim. Cosmochim. Acta* **31,** 2027–2042.

VAN SCHMUS W. R. (1969) Mineralogy, petrology and classification of types 3 and 4 carbonaceous chondrites. In *Meteorite Research*, (editor P. M. Millman), pp. 480–491. Reidel.

WILKENING L. L. (1971) Particle track studies and the origin of gas-rich meteorites. Nininger Meteorite Award Paper. Arizona State University, Tempe.

WILKENING L. L., LAL D. and REID A. M. (1971) The evolution of the Kapoeta howardite based on fossil track studies. *Earth Planet. Sci. Lett.* **10,** 334–340.

WILLIAMS R. J. (1972) The lithification and metamorphism of lunar breccias. *Earth Planet. Sci. Lett.* **16,** 250–256.

WOOD J. A. (1967a) Chondrites: their metallic minerals, thermal histories, and parent planets. *Icarus* **6,** 1–49.

WOOD J. A. (1967b) Olivine and pyroxene composition in Type II carbonaceous chondrites. *Geochim. Cosmochim. Acta* **31,** 2095–2108.

WOOD J. A., MARVIN U. B., REID J. B., JR., TAYLOR G. J., BOWER J. F., POWELL B. N. and DICKEY, J. S., JR. (1971) Mineralogy and petrology of the Apollo 12 lunar sample. *Smithson. Astrophys. Observ. Spec. Rep.* **333,**

ZÄHRINGER J. and GENTNER W. (1960) Uredelgase in einigen Steinmeteoriten. *Z. Naturforsch.* **15a,** 600–602.