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New mineralogical and chemical data on the Machinga (L6) chondrite, Malawi

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Abstract—The Machinga, southern Malawi, Africa, L6 chondrite (observed fall, 22 January 1981) contains accessory phases of metal, troilite, chromite, and native Cu (which is associated with limonite and found in zones of aqueous alteration). Rare accessory phases are apatite and pentlandite, which are uncommon in L6 chondrites. Major mineral constituents (olivine, orthopyroxene, and plagioclase) indicate shock effects at a level of about 15–20 GPa shock pressure. The meteorite is thus classified to be of L6d type. Melt pockets of widely variable composition are abundant.

INTRODUCTION

THE MACHINGA STONY METEORITE fell on 22 January 1981 in Malawi, Africa. It has a total weight of 93.2 kg and was classified as an ordinary chondrite of L6 type (Graham *et al.*, 1984, 1985). We report here mineralogical, petrological, and chemical data on new samples obtained from the Geological Survey of Malawi, including shock classification, trace-mineral identification, and trace element chemistry.

ANALYTICAL METHODS

Mineralogical studies have been made on a thin section by optical microscopy, and wavelength-dispersive electron microprobe analyses reported here were made on a fully automated JEOL 733 Superprobe. Analyses of olivine, clinopyroxene, orthopyroxene, and chromite were made at an accelerating potential of 20 kV; all other phases were measured at an accelerating potential of 15 kV.

The bulk chemical composition was determined by instrumental neutron activation analysis at the University of Vienna, using standard procedures (*e.g.*, Koeberl *et al.*, 1987; Koeberl, 1988), including replicate counting cycles of up to 200 000 s duration. The concentrations of 42 major and trace elements were measured in a powdered bulk sample of 127.06 mg.

PETROGRAPHY

Textural Observations

There is no visual evidence for terrestrial alteration (*e.g.*, cracks with evaporites, or obvious rust). Chondrules are not very abundant, and we estimate their modal percentage at <3 vol.%. In contrast to observations by Graham *et al.* (1984) our specimen contained a number of well-defined chondrules of up to 2.5 mm in diameter. They are generally spherulitic chondrules with radiating olivine-orthopyroxene intergrowth. However, one well-defined barred olivine chondrule was found as well. Some ill-defined chondrules (of the barred olivine type) display strong intragranular fracturing and, locally at a 10–20 μm scale, even brecciation.

In the matrix, which consists mainly of euhedral to subhedral (but frequently strongly fractured) olivine grains ranging from 50–800 μm in size, melt pockets (<70 μm in diameter) are often observed at contacts between silicate and metal or sulfide phases (Figs. 1a,b) but occasionally are enclosed in silicates only (Fig. 1c). These melt areas contain clasts of partially absorbed silicates or opaque minerals as well as droplets of either troilite, Fe-Ni metal, "pseudoeutectic" intergrowths of both phases (Fig. 1b), or silicates. The modal proportion of recrystallized and molten areas (combined) was estimated at around 40 vol.%.

Accessory phases in the matrix are chromite, troilite, Ni-rich and Ni-poor metal droplets, phosphates, native Cu, and pentlandite. In contrast to observations by Graham *et al.* (1984), our study revealed the presence of apatite (Fig. 2a), which was identified by electron microprobe analysis (composition (wt.%): CaO 51.8–54.0; P_2O_5 39.6–43.8; Cl 3.6–5.6; F < 0.7) and confirmed by its optical characteristics.

Fe-Ni metal occurs generally in two phases, kamacite and taenite and occasionally also as kamacite-plessite paragenesis. Taenite is less abundant than plessite, which has often been altered locally to a phase having the optical characteristics of a hydrated iron oxide. Three occurrences of native Cu grains were observed (*e.g.*, Fig. 2b), twice associated with limonite, and in the third case the Cu grain is contained in a metal grain (~3 μm intergrowths of kamacite and taenite) surrounded by an alteration zone. We cannot exclude the possibility that the alteration to a limonitic phase has occurred during storage of the meteorite after the fall.

Pentlandite was observed at seven locations in the thin section in the form of very small grains (<10 μm). At one locality pentlandite was observed in contact with mackinawite, possibly indicating exsolution of this mineral from the pentlandite. Pentlandite is rare in normal stony meteorites that contain free metal (Ramdohr, 1973).

Shock Metamorphism

All major minerals display deformation effects consistent with a moderate level of shock metamorphism. Some plagioclase and orthopyroxene grains show undulatory extinction, but no mechanical twinning, a shock-diagnostic effect in the shock pressure range from about 5–25 GPa (Stöffler, 1972), has been detected in pyroxene. Larger olivine grains often display shock mosaicism or, at least, undulatory extinction, and, occasionally, single sets of <30 μm long planar fractures. The occurrence of planar elements mentioned by Graham *et al.* (1984) from olivine, however, cannot be confirmed.

On the basis of these findings and a comparison with the experimental shock classification proposed by Reimold and Stöf-

FIG. 1. (a) Melt pocket with troilite droplets and several chromite (medium grey) and feldspar (black) fragments set between troilite (white) and chromite (on the right side of the image). Width of the image: 275 µm, reflected light. (b) Melt with Fe-Ni metal droplets between chromite (upper left corner; medium grey), pyroxene containing small feldspar grains (bottom), and metal (top; white). Arrow (1) identifies a partially melted chromite inclusion. Arrow (2) points to one of several droplets of Fe-Ni metal containing smaller dark sulfide inclusions. Secondary electron image. (c) "Pseudoeutectic" droplets (troilite plus Fe-Ni metal intergrowths) in melt pocket (*cf.* also arrow 2 in Fig. 1(b)). Width of image: 130 µm, reflected light.

fler (1978) and Reimold (1977), the maximum shock degree of Machinga is estimated at 15–20 GPa shock pressure. Considering the amount of locally produced melt, Machinga probably has to be classified into facies d of the Dodd and Jarosewich (1979) classification.

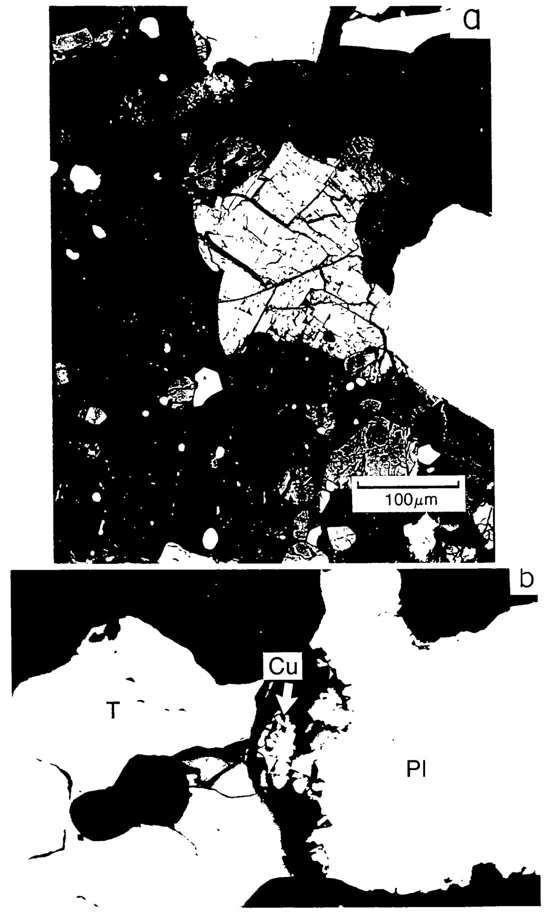

FIG. 2. (a) Apatite (center, fractured) set in granoblastic matrix. Below and left of the apatite grain is orthopyroxene (dark grey) with Fe-Ni metal droplets. Troilite: white; feldspar: black; olivine: light grey. BSE-image. (b) Troilite (T) (left; medium grey) and plessite (P) (right; light grey), separated by alteration zone containing native Cu (arrow). Width of image: 275 µm, reflected light.

Mineral Chemistry

Matrix and chondrule olivine is chemically homogeneous ($Fo_{73.9-78.2}Fa_{21.8-26.1}$, 43 analyses). A uniform composition was also determined for orthopyroxene ($En_{74.7-77.9}Fs_{20.6-25.3}Wo_{0-2.0}$, 49 analyses) from areas of all textural variations. Clinopyroxene is a rare phase and was only analyzed in chondrules as $En_{44.9-46.7}$-$Fs_{7.6-8.3}Wo_{45.2-47.7}$ (14 analyses). The range of composition for 24 feldspar phenocrysts (<50 µm) corresponds to $Ab_{82.2-85.4}An_{9.1-11.5}$-$Or_{4.9-7.3}$. The range of 17 feldspar analyses obtained on tiny crystals in granoblastic zones is slightly wider than the range for the other feldspar crystals.

Forty analyses have been obtained from melt pockets, which contain either droplets of Fe-Ni metal, or droplets of troilite (Table 1). Ranges of compositions are very wide for both types and indicate that the melts were produced from feldspar, olivine (± pyroxene), or as mixtures of all major mineral components, similar to observations made by Dodd and Jarosewich (1979) for L-group chondrites.

Results of the analysis of chromite grains in the matrix (7 grains, 44 analyses) are also given in Table 1. It was not possible

TABLE 1. Electron microprobe analyses of melts from melt pockets, and chromites in the Machinga meteorite. All data in wt.%. The number of analyses is given in parentheses. (–) indicates concentrations below the lower limit of detection; n.d. = not determined.

	Melts Ni-rich (20)	Melts w/troilite (20)	Chromites (44)
SiO_2	37.6–70.2	42.1–72.2	n.d.
TiO_2	0.0–0.21	0.05–0.25	2.61–3.68
Al_2O_3	0.0–22.64	0.0–22.45	4.60–5.58
FeO	0.78–25.1	0.41–20.0	30.19–33.62
MnO	0.0–0.50	0.0–0.54	0.61–0.78
MgO	0.0–38.66	0.0–28.14	1.54–2.35
CaO	0.0–3.72	0.51–2.10	n.d.
K_2O	0.0–1.21	0.0–1.30	n.d.
Na_2O	0.0–6.75	0.0–3.51	n.d.
Cr_2O_3	0.0–2.18	0.17–1.70	53.97–58.09
NiO	0.12–1.74	–	0.0–1.60*
V_2O_3	n.d.	n.d.	0.49–0.76
CoO	n.d.	n.d.	<0.02
ZnO	n.d.	n.d.	0.21–0.35

* High Ni in only one grain.

to calculate stoichiometric compositions for any of the analyzed grains, thus they either have lattice defects or contain other elements, besides Fe, in different oxidation states. Two hundred twenty analyses from 24 troilite grains show that Machinga troilite is essentially Cr-free. The data obtained range from <260–700 ppm for Cu, <220–1170 ppm for Ni, and 450–920 ppm for Co. Troilite droplets in melt pockets, however, contain between 2.88 and 4.17 wt.% Cr. Traces of Cu (200–300 ppm) and Co (200–500 ppm) are also present. The composition of the troilite is very homogeneous for major elements (36.8 wt.% S, 63.2 wt.% Fe). Fe-Ni metal was analyzed at 100 spots in 19 grains (Table 2). The results of 13 microprobe analyses in seven pentlandite grains are also given in Table 2.

BULK CHEMISTRY

A bulk sample was analyzed for 42 major and trace elements using instrumental neutron activation analysis (Table 3). XRF-results for some major elements are (in wt.%): SiO_2 45.9, TiO_2 0.14, Al_2O_3 3.7, MgO 24.6, CaO 3.1, and P_2O_5 0.32 (Fe, Na, K from INAA: see Table 3). For most elements, the measured abundances are within the range observed for other L6-chondrites (Mason, 1971; Sears and Weeks, 1986; Kerridge and Matthews, 1988). The siderophile element pattern does not show any prominent indications of differentiation and is flat (with a slight decrease from Ni to Au) at about 0.5–0.6 × Cl. Co and Ni are slightly more depleted in Machinga than in average L6 chondrites.

TABLE 2. Composition of five different Fe-Ni grains in the Machinga meteorite, obtained by electron microprobe analysis, showing the range of compositions encountered in the Fe-Ni metal. In addition, data for 13 analyses of seven pentlandite grains are given. Data in wt.%.

	Fe-Ni metal					Pentlandite
	#1	#2	#3	#4	#5	(range)
Fe	62.7	54.6	95.1	92.9	94.8	35.0–47.0
Ni	37.2	45.1	3.76	5.65	3.55	18.5–29.0
Co	0.19	0.18	0.90	0.89	0.97	0.26–1.82
Cu	0.23	0.27	–	–	–	0.18–0.95
S	–	–	–	–	–	32.9–34.5

TABLE 3. Minor and trace element data for the Machinga L6-chondrite. All data in ppm, except as noted.

	Machinga
Na (wt.%)	0.74
Cl	80.0
K	952.0
Sc	8.34
Cr	3934.0
Mn	2550.0
Fe (wt.%)	20.2
Co	436.0
Ni (wt.%)	0.92
Zn	102.0
Ga	4.8
As	0.61
Se	11.1
Br	1.0
Rb	<5.0
Sr	13.0
Zr	9.5
Ru	0.52
Ag	<0.5
Sb	0.072
Cs	0.043
Ba	<20.0
La	0.35
Ce	0.95
Nd	0.7
Sm	0.22
Eu	0.079
Gd	0.28
Tb	0.054
Dy	0.34
Tm	<0.05
Yb	0.22
Lu	0.032
Hf	0.083
Ta	0.014
W	0.2
Os (ppb)	485.0
Ir (ppb)	518.0
Au (ppb)	110.0
Hg	<0.8
Th	0.036
U	<0.08

The abundance of Au is marginally lower in Machinga as compared to average L6 chondrite abundances (Keays *et al.*, 1971; Sears and Weeks, 1986), which may be indicative of a minimal loss of Au during shock heating. Some volatile element contents (such as Cs, Sb, As) are lower in Machinga than in average L6 chondrites, but others (such as the halogens, or Ga) have normal abundances. Zn seems to be rather high. From the volatile element abundance we can thus conclude that there are some indications of minimal loss (probably due to shock heating). All other elements are consistent with the interpretation of Machinga being an L6 chondrite of rather normal chemistry with some unusual mineralogical features (*e.g.*, the presence of pentlandite). Machinga is a moderately shocked L6 chondrite with normal chemical composition.

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