TRACE ELEMENTS IN PHASES OF THE SIKHOTE-ALIN IRON METEORITE

Helmut H. WEINKE[1,2], Wolfgang KIESL[1], Friedrich KLUGER[1†], Christian KOEBERL[1] and Piet VAN ESPEN[2]

[1]*Institute of Geochemistry, University of Vienna, P.O. Box 73, A-1094 Vienna, Austria*
[2]*Department of Chemistry, University of Antwerp, D-2610 Wilrijk, Belgium*

Abstract: A sample of the IIAB iron meteorite Sikhote-Alin has been studied for trace elements in the metal and troilite phases using electron microprobe analysis, radiochemical neutron activation analysis, and secondary ion mass spectrometry. Comparison with other members of the IIAB iron group shows that this is a typical IIAB meteorite, and fits quite well in the group, which shows a wide variations of the content of some trace elements. The variation and also the distribution coefficients of some trace elements between metal and sulphide is not consistent with a simple fractional crystallization model.

1. Introduction

The Sikhote-Alin iron meteorite fell in a shower on February 12, 1947. Some descriptions of the fall and the recovery of the samples can be found *e.g.* in FESENKOV (1947) and KRINOV (1956). Subsequently more than 8500 specimens, ranging from 1 g to 1745 kg and totalling more than 23 t have been collected (BUCHWALD, 1975). The total mass (including dust) was estimated to be near 70 t. Recent field work is described by KRINOV (1970).

Sikhote-Alin is a coarsest octahedrite, showing large kamacite lamellae and granular kamacite (which developed around large troilite and schreibersite inclusions and seems to be related to swathing kamacite). Taenite and plessite are rare. Kamacite is very often rimmed with phosphides. Troilite is rare and by far outweighed by skeletal schreibersite crystals and rhabdite lamellae. Chromite crystals are accessory, and also minor amounts of olivine inclusions have been described (BUCHWALD, 1975).

2. Experimental

2.1. Sample description

The sample available for this study weighed 125 g and constituted the end-piece of a larger specimen of about 300 g. It incorporated a large troilite, which was accompanied by graphite and schreibersite at the phase boundary. The original sample was covered by a fusion crust (containing oxidized materials such as hematite, wüstite,

† Deceased January 27, 1986.

and magnetite). Below the fusion crust there is a 1–2 mm thick α_2-zone with a measured hardness of 190±10.

2.2. Neutron activation analysis

For activation studies, the troilite and the metal phases were carefully separated. About 300–500 mg of each phase were irradiated for four days in the ASTRA reactor of the Österreichisches Forschungszentrum Seibersdorf, at a neutron flux of about 7×10^{13} n cm^{-2} s^{-1}. The samples were processed after cooling for three days. The radiochemical separation scheme described in more detail in our companion paper (KOEBERL *et al.*, 1986, this volume).

2.3. Ion probe measurements

Trace element investigations on the phases of the Sikhote-Alin meteorite were carried out using a CAMECA IMS 300 ion microprobe by one of us (HHW) at the University of Antwerp (Wilrijk, Belgium). Samples were bombarded with $^{16}O^+$ beam under an angle of 45°. The positive secondary ions were separated magnetically and electrostatically and were detected using an electron multiplier. Due to different peak overlaps (which could not be separated completely because of the limitations in mass resolution of this instrument) the maximum mass number which could be measured reliably was 71. The secondary ion currents were recorded in blocks and sent to the memory. The quantitative evaluation was made following the methods of WEINKE *et al.* (1979) and WEINKE (1980).

3. Results

RNAA (Radiochemical Neutron Activation Analysis) studies have been made on the metal phase and on the troilite of the sample. The results are given in Table 1. The distribution behaviour of some trace elements is clearly visible from the numbers presented here. Zn gives rather interesting results. In most meteorites Zn behaves

Table 1. Trace element data for Sikhote-Alin metal and troilite, obtained by instrumental and radiochemical neutron activation analysis. All data in ppm.

	Metal	Troilite
V		70
Cr		15800
Co		120
Ni		9100
Cu		800
Zn	0.3	0.41
As	8.4	0.0012
Se	0.004	99.6
Mo	9.5	3.3
Ru	4.4	0.01
Re	0.0022	0.0004
Os	0.019	0.005
Ir	0.027	0.0007
Au	0.85	0.0012

Table 2. Trace element distribution in Sikhote-Alin kamacite, troilite and schreibersite, as obtained by SIMS analysis. All data in ppm, except as noted.

	Kamacite	Troilite	Schreibersite
Na	<0.07	<3	<8
Mg	<0.3	1	15
Al	2.5	3	5
Si	30	21	128
P	980	<110	11.2%
K	<0.2	<2	<3
Ca	<0.1	1	7
Sc	<0.2	0.3	<0.2
Ti	<0.3	1	3
V	4	40	3
Cr	7	900	16
Mn	170	550	94
Co	0.7%	40	0.09%
Ni		350	
Cu	170	300	190
Zn	<190		120
Ga	70	260	2

Table 3. Reference data for Sikhote-Alin metal, taken from the literature.

	1	2	3	4
Ni %	5.87	5.68	5.94	
Co ppm			3800	4600
Cu ppm			300	114
Ga ppm	51.8			52.5
Ge ppm	161	133		
Mo ppm		6.9		
Os ppm		<0.02		
Ir ppm	0.029	0.014		<0.4
Au ppm		1.26		

(1) WASSON (1969), (2) HEY (1966) p. 612, (3) DYAKONOVA (1958) cited in BUCHWALD (1975), (4) COBB (1967).

Table 4. Reference data for Sikhote-Alin troilite, taken from the literature. All data in wt%. The data of WEINKE et al. (1983) have been obtained by LAMMA.

	1	2	3	4
S	34.50			
Fe	62.7	62.6		
Ti				0.0020
V		0.007		0.002
Cr	1.07	1.58		1.03
Mn			0.029	0.10
Co		0.012		0.0070
Ni		0.91	0.057	0.13
Cu	0.06	0.08	0.054	0.11
Zn		0.005		

(1) DYAKONOVA (1958) cited in BUCHWALD (1975) and BUCHWALD (1977), (2) NICHIPORUK and CHODOS (1959), (3) HEY (1966) p. 608, (4) WEINKE *et al.* (1983).

as a chalcophile element, but in some irons or mineral inclusions Zn is more siderophile than usual. Examples are Canon Diablo or Odessa (KIESL, 1971) or a chromite in Landes (KRACHER, 1985). In Sikhote-Alin Zn follows, however, the common chalcophile trend.

Most other elements behave as expected, like As (strong siderophile character), or Mo (less siderophile). The same trend can be seen also from the ion probe data, given in Table 2. Clearly this meteorite constitutes nothing very unusual. Agreement of our data when compared to literature data (compiled in Table 3 for metal and in Table 4 for troilite) is in most cases very good.

Microprobe studies (using an ARL-SEMQ fully automated five spectrometer electron microprobe) showed the interesting mineral structure of the meteorite, which has been summarized from other samples by BUCHWALD (1975). Our sample showed only a few Widmanstätten bands but Neumann lines are frequent in the kamacite (and up to 10 μm wide). Most impressive are skeletal schreibersite crystals, which can be found near the phase boundary between iron and troilite, also often incorporating troilite nodules associated with graphite.

Microprobe studies show that schreibersite Ni, Co, and Cu contents are rather different in different grains. Some variation is also present within grains, showing a nucleation tendence with higher concentration of these elements towards troilite, but no extensive studies have yet been made on the exact distribution pattern within schreibersite grains. Also, contents of these elements are much higher in schreibersites which have nucleated near troilite nodules than in schreibersite crystals between kamacite lamellae or between troilite and kamacite.

The distribution coefficients of elements like Mo or Re between the metal and mineral phases differ from those which can be inferred from a fractional crystallization model. We conclude that the parent body of these meteorites has undergone a slightly different history than assumed by the previously and perhaps oversimplified model. More realistic modelling than done in the past has to await more data on distribution coefficients of trace elements between mineral phases.

A comparison of the ion microprobe data with those obtained by neutron activation analysis and other techniques shows generally good agreement. The behaviour of vanadium is interesting in respect to the distribution between metal and troilite phases. Vanadium, a chalcophile element, is enriched in the troilite. Comparison with vanadium distributions in other iron meteorites, *e.g.* that in Cape York, however, yield a different partitioning. In Cape York vanadium is enriched also in the schreibersite, which is not the case in Sikhote-Alin. This is an indication that during crystallization schreibersite did not purge the remaining melt of siderophile elements, as commonly observed in IIIAB irons. Usually, siderophile trace elements tend to follow phosphorous during crystallization. Also, Co and Cu are not enriched in Sikhote-Alin schreibersite, although they do show enrichments in IIIAB irons (for which data are available in the literature, see for example KOEBERL *et al.*, 1986, this volume, and references therein).

Clearly there is a difference in the cooling and crystallization history between IIIAB meteorites and the IIAB meteorite Sikhote-Alin, a conclusion which bears no great surprise because of several fundamental differences in the partitioning behaviour of trace elements in these two meteorite groups. A scheme which is different from the parent body history of IIIAB meteorites has to be investigated for the Sikhote-Alin parent body.

We suggest that the crystallization history of the IIAB body, which possibly includes fractional crystallization, was more complicated than previously supposed. Some nonequilibrium processes have to be included. Perhaps schreibersite crystallized from liquids which were not in equilibrium with the previously crystallized metal. Such a model could explain the distribution of the trace elements. Whatever the correct history of the parent body is, we can be sure of a greater complexity of the process. We have, however, to await more trace element distribution data before we can discuss this more quantitatively.

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