9

UNUSUAL PRIMITIVE METEORITES: CHONDRITIC INCLUSIONS FROM GROUP IAB IRON METEORITES

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Several meteorite types, distinct from the large chondrite groups (H, L, LL, E and carbonaceous), are known to also have chondritic compositions. These meteorites preserve information on conditions at additional formation locations in the early solar nebula. Silicate inclusions from group IAB iron meteorites are one such type. Evidence for their chondritic nature is given and their formation discussed.

The study of conditions in the primitive solar nebula is conducted chiefly through the study of primitive types of meteorites. Most attention has been directed at the major chondrite types - CI, CM, CV, and CO carbonaceous chondrites; the H, L and LL ordinary chondrites and the enstatite (E) chondrites. These groups show a wide variety of properties and the simplest models that have been proposed would have each group coming from a different parent body. The properties of the groups suggest very different conditions at the place and time of formation of each parent body. Table I lists some properties useful for classifying chondritic meteorites. The ordinary chondrite groups can be distinguished from each by % total Fe, % metallic Fe and the varying degree of oxidation as measured by the Fe/(Fe + Mg) ratio of the olivine or pyroxene. The mole % fayalite (Fe_2SiO_4) in the olivine [$(Fe,Mg)_2SiO_4$] is shown in the Fa column of Table I. The H, L, and LL groups show some scatter around the average Fa values in the table, but there are distinct hiati between the three groups. The symbols for the groups refer to High total Fe, Low total Fe and Low total Fe-Low metal.

The ordinary chondrites are distinguished from the other large chondrite groups (enstatite and carbonaceous) by these same parameters, by fractionations of refractory elements (Mg/Si and Ca/Mg columns in Table I) and by fractionation of Fe relative to Si. Carbonaceous chondrites, represented by CI chondrites in Table I, are richer in refractories than ordinary chondrites while E chondrites are refractory poor.

Recent work of Clayton and co-workers has resolved several groups of meteorite types based on O isotopes. Meteorites from different O isotope groups could not have been derived from each other by chemical or physical means but must have formed from different original isotopic mixes, presumably at different locations in the solar nebula. The major chondrite groups fall in at least 4 different O isotope groups.

https://doi.org/10.1017/S0252921100070342 Published online by Cambridge University Press

Table I. Chemical properties of some meteorites with chondritic composition. Oxygen isotope groups are identified by a major type of material belonging to that group. (Terr= terrestrial; Diff= most differentiated achondrite groups; H, L, LL= ordinary chondrite types)

Meteorite or type	Tot Fe (%)	Fa (mole %)	Mg/Si (atom)	Ca/Mg (atom %)	Fe/Si (atom %)	O-isotope group	Ref.
CI chondrite	18.4		1.073	6.73	0.89±.08	CI=H Other C's= other groups	e,k,m
LL chondrite	20.0	29	0.940	4.96	0.53±.03	L-LL	e,g,k,m
L chondrite	21.8	23	0.936	5.11	0.59±.05	L-LL	e,g,k,m
Bencubbin "L" inclusion	21.8	19	0.930	5.35	0.608	L-LL	e,j
H chondrite	27.6	18	0.960	5.08	0.83±.08	H	e,g,k,m
Netschaëvo inclusions	34.0	14	0.905	5.99	1.13		b,l
IAB inclusions							
Woodbine	18.7	6	0.904	8.08		Diff	a,b,e,h
Copiapo	16.0	5		6.46			a,b
Landes	23.2	4		6.51		Diff	a,c,e
Campo del Cielo (5 inclusions)	3.4-12.8	3.9-4.2	0.92-1.13	2.0-5.6	0.10-0.22	Diff	a,e,f
Cumberland Falls Black Chondrite	19.0	1.0	0.931	6.09	0.489		d,f
E chondrite	22-35	0.25-1.0	0.758	4.43	0.83±.32	Terr	e,i,k,m

a=Bild (1976)
b=Bunch *et al* (1970)
c=Bunch *et al* (1972)
d=Binns (1969)
e=Clayton (1977)
f=Wlotzka, Jarosewich (1976)
g=Wasson (1974)
h=Jarosewich (1967)
i=Keil (1968)
j=McCall (1968)
k=Mason (1971)
l=Olsen, Jarosewich (1971)
m=Van Schmus, Wood (1967)

are currently in orbits that allow material to be frequently captured by the earth. It is reasonable to expect that there are other chondrite groups which formed in other parts of the solar nebula and are presently in orbits which rarely place fragments in earth crossing orbits. These meteorites would contain information on conditions at additional locations in the early solar system. Some possible additional chondrite types are shown in Table I.

The Bencubbin inclusion has a bulk composition in the range of L chondrites, but the silicates are slightly more reduced (Fa 19) (McCall 1968). The host for the inclusion is very much more reduced (Fa 3.6) (Wasson and Wai 1970).

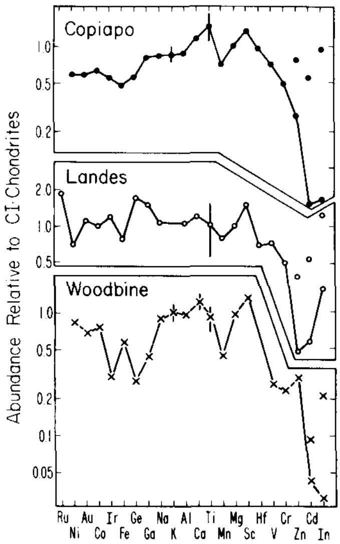
Inclusions in the Netschaëvo iron have been described by Zavaritskii and and Kvasha (1952), Bunch *et al.* (1970) and Olsen and Jarosewich (1971). The latter authors pointed out the similarity to H group chondrites. In fact Netschaëvo inclusions appear to be a new type of ordinary chondrite, extending the trends of total Fe to higher values, Fa to lower values and falling on the ordinary chondrite trends for fractionations of siderophiles.

Another example of unusual chondritic material is the black chondrite inclusions in the Cumberland Falls meteorite. They have total Fe levels similar to LL chondrites but are much more reduced (Binns 1969). The host is an enstatite achondrite (aubrite) which is even more highly reduced (pyroxene Fs

https://doi.org/10.1017/S0252921100070342 Published online by Cambridge University Press

0.046, Wasson and Wai 1970). The Ca/Mg ratio of the inclusions is chondritic rather than aubritic.

The other meteorites shown in Table I are all silicate inclusions from chemical group IAB iron meteorites. (Classification of irons and descriptions of the groups have been reviewed by Scott and Wasson 1975). These inclusions will be discussed in more detail here. Bulk analyses have been reported for inclusions from three IAB irons (Jarosewich 1967; Kracher 1974; Wlotzka and Jarosewich 1976) and these and other authors recognized the chondritic bulk compositions. Microprobe analyses of individual minerals are reported by Bunch *et al.* (1970), Bunch *et al.* (1972), Rambaldi *et al.* (1974), Scott and Bild (1974) and Ramdohr *et al.* (1975). Trace elements in bulk inclusions from 4 IAB irons are given by Bild (1977). In addition to bulk composition, other chondritic features of these inclusions are mineralogy - olivine, pryoxene, albitic plagioclase; contents of planetary-type rare gases (Alexander and Manuel 1968; Hintenberger *et al.* 1969; Bogard *et al.* 1971); I^{129}/Xe^{129} formation intervals (Alexander *et al.* 1969; Podosek 1970) and ages (*e.g.*, Burnett and Wasserburg 1968; Bogard *et al.* 1968; Podosek 1971).



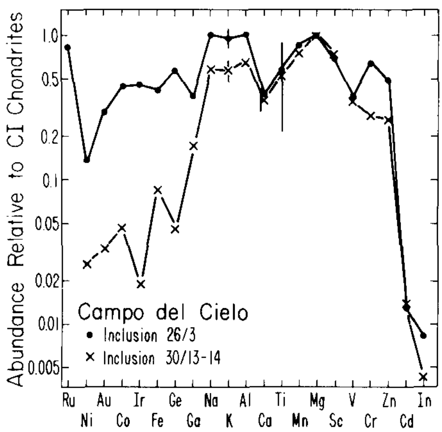
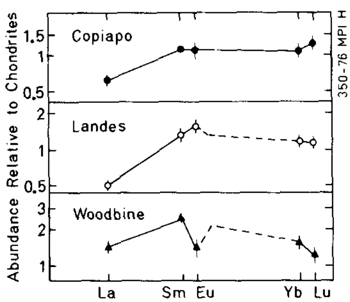


Figure 1. Elemental abundance ratios relative to CI chondrites and normalized to Mg for silicate inclusions from three group IAB iron meteorites. The patterns in all cases are chondritic.

Figure 2. Elemental abundance ratios relative to CI chondrites for two different inclusions from Campo del Cielo (IA) iron meteorite. Lithophiles are basically chondritic. Siderophiles (metals) are depleted relative to lithophiles.

Trace element analysis of bulk inclusions separated from the surrounding matrix metal of the 4 IAB irons listed in Table I also shows the chondritic nature of the inclusions. Figures 1 and 2 show the abundance ratios determined for these inclusions. The ratios are shown relative to CI chondrites because CI chondrites are thought to be the best available estimate of the composition of the early solar nebula for all except the most volatile elements. Mg is used

The groups of chondrites we now see as major are those whose parent bodies as a normalizing element rather than Si because Si was not determined by the neutron activation scheme employed. The data used to make Figs. 1-4 may be found in Bild (1976,1977). On this sort of a plot for chondrites all non-volatile elements occur at about the same level relative to CI chondrites. This indicates they have not experienced igneous fractionations. The Copiapo, Landes and Woodbine inclusions all have lithophiles at about chondritic levels. Na, K, Al, and Ca which are mainly in low melting feldspar occur at about the same level as Mg and Sc which are mainly in pyroxene and olivine. Also notice that even though the normalization is to the lithophile Mg, the siderophilic elements - those that concentrate in the metal phase - are also at about chondritic levels. This same level of siderophiles in two replicates from each of three meteorites is strong evidence that the metal in the inclusions is native to the inclusions and not matrix metal that has been injected into the silicates. The volatile elements (Cd, In and probably Zn) appear to have been contaminated during processing and the abundances shown should be considered upper limits.



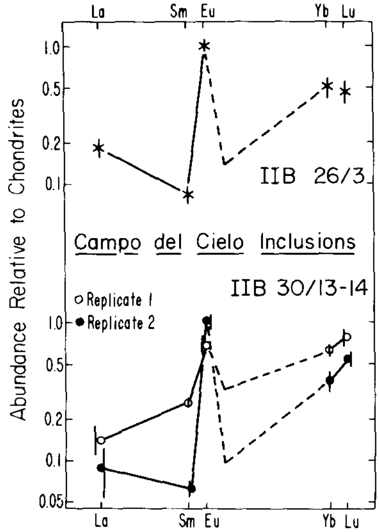


Figure 3. Abundance ratios for 5 rare earth elements from silicate inclusions from three groups IAB iron meteorites. Levels are chondritic.

Figure 4. Abundance ratios for 5 rare earth elements from two inclusions from the Campo del Cielo (IA) iron meteorite. Individual replicates are shown for inclusion IIB 30/13-14. Patterns indicate a fractionation process has occurred.

Two different inclusions from Campo del Cielo were analyzed in duplicate. These also show approximately chondritic levels of lithophiles though inclusion IIB 30/13-14 has only about 1/2 as much feldspar (as measured by Na, K, Al abundances) as inclusion IIB 26/3. Both inclusions are depleted in siderophiles, IIB 30/13-14 by a factor of 20. Wlotzka and Jarosewich (1976) have found evidence for a small amount of partial melting in Campo del Cielo silicates. This is consistent with the neutron activation data and partial melting seems to have affected metal as well as silicate.

The rare earth patterns for Copiapo, Landes and Woodbine (Fig. 3) are consistent with the chondritic interpretation, but the rare earths seen in Campo del Cielo inclusions are further evidence for partial melting (Fig. 4).

Silicate inclusions in IAB irons range in size from rare individual grains in troilite nodules to cm sized angular lumps suggesting formation as a breccia of silicate in a metal matrix. Oxygen isotope data of Clayton (1976) show these silicates are not fragments of ordinary chondrites. They are chondritic material of a unique type. The breccia probably formed on the surface of a parent body where chondritic fragments mixed with metal. Later burial and heating annealed the metal particles to form the continuous metal matrix surrounding the silicates. Inclusions are sometimes rimmed with kamacite and Widmanstätten patterns are not distorted around the inclusions indicating the silicates were in place before the present kamacite started to precipitate and that the temperature was high enough to have all the metal in the taenite field (at least 1040 K at 6% Ni to about 940 K at 12% Ni). This temperature approaches the melting point of the Fe-FeS eutectic (about 1261 K) and reaching the eutectic would allow the mobility of some S-rich fluid. A period of high temperature would also account for the highly recrystallized textures of the silicates. The continuous metal matrix may have helped to prevent the escape of rare gases from the inclusions. A slightly greater degree of heating at the Campo del Cielo location could lead to the mild partial melting inferred for its inclusions.

The coexistence of the immisible metal and silicate phases rules out the possibility of the metal ever being completely molten in the presence of the silicates, and the silicate textures imply the temperature probably never got much above the melting point of plagioclase (1450 K) even in the case of Campo del Cielo.

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DISCUSSION

GROSSMAN: In Copiapo, why do the silicates look like Breccia fragments while the iron doesn't look brecciated?

BILD: The angular silicate fragments contrast with the metal and are easy to see. Boundaries between metal grains are much more difficult to see. Metal grains could anneal to large single grains enclosing silicates at temperatures above about 800^{o} C. Some other silicate containing IAB irons, such as Woodbine, do have a multi-grained metal texture.

BRECHER: Where did these "breccias" form; on a parent body surface? How could molten metal invade the regolith? How come degassing of the silicate inclusions did not occur in the high-T environment provided by the slowly cooling metal envelope?

BILD: The breccias probably formed on the surface of a parent body by mixing the chondritic silicates with metal. There is no need for the metal to ever be molten. Annealing at subsolidus temperatures for the matrix metal could produce the observed texture. The metal structure does not demand temperatures any higher than about 850^{o} C, several hundred degrees lower than the temperatures normally needed to out gas silicates in the laboratory. The slow cooling rates (~2^{o} C/Myr) measured for IAB irons are for the temperature range of about 750-350^{o} C. Rates could have been faster at higher temperatures.