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PARENT BODIES OF IRON METEORITES

E. R. D. SCOTT

On the basis of their chemical and mineralogical composition, 420 iron meteorites have been classified into 12 different groups. Each group seems to have come from a separate parent body. The largest group, IIIAB, probably formed an asteroidal core in a body approximately 100 km in radius, which was largely destroyed by collision 630 My ago. Another 67 analyzed irons do not belong to these groups, and may represent samples from another 20 or more bodies.

INTRODUCTION

During the last ten years, there have been numerous chemical and mineralogical studies of about 500 iron meteorites, nearly 85% of the known total. Irrespective of which properties were investigated, it was generally concluded that the irons could not have come from a single source, but that they could be divided into a limited number of groups, each with a different origin. The most useful parameters for classifying irons are the concentrations of Ni, Ga and Ge in the metal. With these Wasson and co-workers divided the irons into 12 groups with between 5 and 150 members in each (Scott and Wasson 1975). About 14% of the irons fell outside these groups and were called anomalous. Figure I shows the outlines of the 12 groups on a logarithmic plot of Ge against Ni. Additional plots of Ga and Ir against Ni were used by Wasson and associates to help define the classification of iron meteorites.

Table I lists the total number of irons, and the number seen to fall, in each of the 12 groups and the 'anomalous' category (data from Scott and Wasson 1975; Wasson 1974). Early studies by Lovering *et al.* (1957) established only four groups, which were labelled I - IV, but it is now thought that IVA, for example, is as unrelated to IVB as it is to IIIF. Some groups have been amalgamated; IIIA and IIIB, for example, are now considered to form a single group called IIIAB. Note also that analyses for Ga, Ge and Ir are not essential for the correct classification of an iron meteorite. Other parameters, such as concentrations of trace elements like Au and As (Scott 1972), or a careful study of the mineralogy (Buchwald 1975) may be used instead. Thus, once an iron is classified into one of the 12 groups by means of accurate measurements of a few parameters, many other properties can be predicted.

There is good evidence in two groups, and some suggestion in most of the others, that the members of each group come from only one parent body. The evidence that each group comes from a separate parent body is more circumstantial. The purpose of this paper is to review this evidence, to estimate the total number of parent bodies necessary to account for all the irons, and to ascertain when these parent bodies existed.

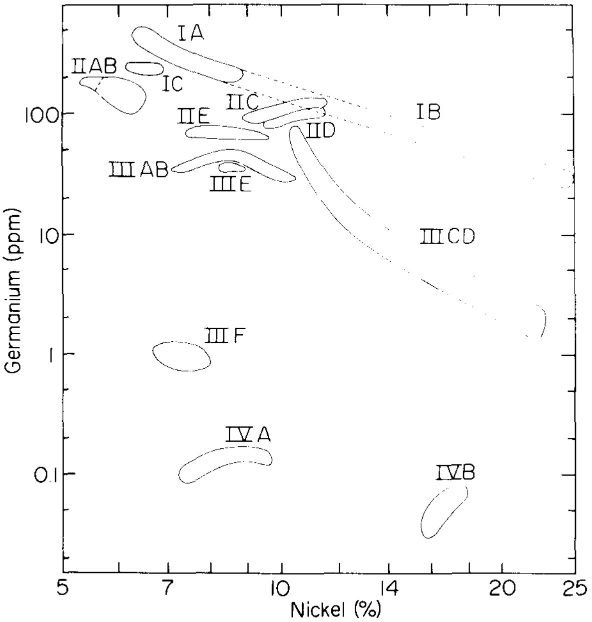

FIGURE 1. On a logarithmic plot of Ge against Ni, iron meteorite analyses cluster into 12 groups, which are shown in outline. About 14% of the 500 analyzed irons fall outside these groups (Table I). Germanium is the most useful element for classifying iron meteorites, but combinations of other chemical or mineralogical parameters can also be used.

TABLE I

IRON METEORITE GROUPS AND THEIR PROPERTIES

Group	Number		Frequency	Cooling Rate	Cosmic Ray
	Falls	Total	(%)	($^{\circ}$ K My^{-1})	Age(My)
IAB	6	90	18.7	1-5	500-900
IC	0	10	2.1	3 - >100	250-900
IIAB	5	52	10.8	0.2 - 2	<100-1000
IIC	0	7	1.4	100-500	-----
IID	2	13	2.7	1-2	-----
IIE	0	12	2.5	0.2 - 400	-----
IIIAB	2	156	32.3	1-10	650
IIICD	1	12	2.4	1-5	100-800
IIIE	0	8	1.7	0.5 - 2	-----
IIIF	0	5	1.0	5-20	-----
IVA	3	40	8.3	5-200	400
IVB	0	11	2.3	5-200	-----
Anom.	4	67	13.9	0.3 - >200	<100-2300
		483			
Unclassified	11	~70			

CHEMICAL COMPOSITION OF GROUPS

It has been suggested, but not fully proved, that the bulk composition of the metal in each group was established during the condensation of the solar nebula (Kelly and Larimer 1976; Wasson and Wai 1976). It is probable that a second fractionation process was responsible for the compositional variations within each group. The variation of Ge (Fig. 1) within groups (excluding IAB and IIICD) is very small in comparison to the total range shown by all the groups, but for other elements like Au (Fig. 2), the variation within groups is more appreciable. Furthermore, the chemical composition varies smoothly within each group so that significant interelement correlations are usually observed.

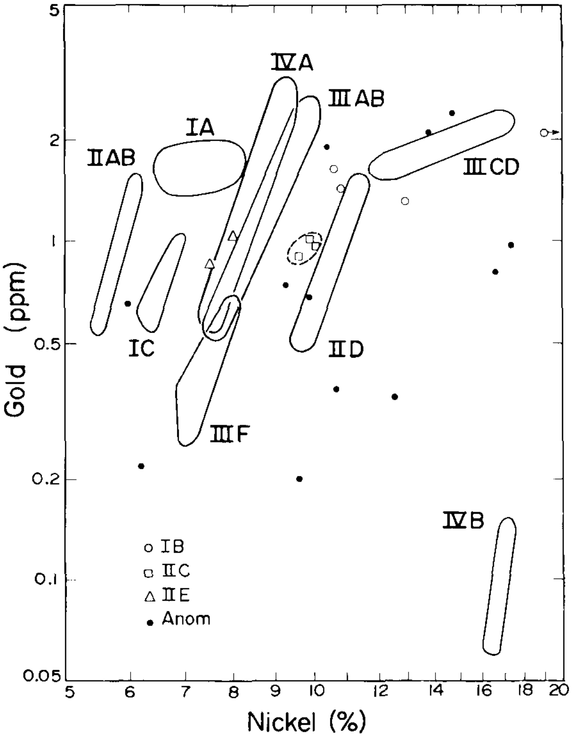

FIGURE 2. A logarithmic plot of Au against Ni for about 200 iron meteorite analyses shows chemical variations within groups that are much more appreciable than in Fig. 1. Most groups are shown only in outline and, except for IAB and IIICD, show positive Au-Ni correlations, which are believed to have been produced during solidification of molten metal pools or cores. (After Scott and Wasson 1975).

Scott (1972) proposed that the chemical trends within groups (excluding IAB and IIICD) were produced during fractional crystallization of molten metal, so that elements which concentrated preferentially in the liquid (like Au and Ni) would be depleted in the first-formed solid and enriched in the late-formed solid. If this model is correct, then all the members of group IIIAB, for example, must have once formed a single molten pool of metal. The difficulty of maintaining in a single body many different liquid pools with Ge concentrations differing by factors of up to 10^4 (Fig. 1) tends to suggest that each group formed in a separate parent body.

Because the irons are believed to have formed in relatively small bodies about 10-200 km in size, the melting of iron probably occurred 10-100 My after the formation of the solar system, irrespective of which of the postulated heat sources was responsible. Thus the parent bodies which supplied the iron meteorite groups must have formed at this time, for the igneous trends within groups to have been preserved.

Some elements show variations within large groups which are almost as large as the total composition range of all the groups and anomalous irons (*e.g.*, Ir in IIAB and IIIAB). This suggests that we have samples from close to the ends of the compositional spectra in each of the parent bodies of the large groups.

COOLING RATES

The width of the kamacite bands which form Widmanstätten patterns in iron meteorites is essentially governed by the bulk Ni content and the cooling rate in the temperature range 1000-800° K, during which diffusion controls kamacite growth (see Goldstein and Axon 1973). Using the phase diagram and diffusion coefficients for the Fe-Ni system, Goldstein and Short (1967) were able to estimate the cooling rates for many iron meteorites. Most cooling rates fell in the range 1-5° K My^{-1}, but the total range in the 12 groups was 0.2 to below 500° K My^{-1} (Table I). Typical cooling rates of a few degrees per million years could be provided by a chondritic insulating layer of thickness about 100 km (Fricker *et al.* 1970). This is much larger than the minimum parent body size which is necessary to account for the observed capture rate by the earth. For group IIIAB, the minimum radius would be 0.3 km (Wasson 1972).

Within groups, the range of cooling rates observed is generally small, and is usually correlated with metal composition. This indicates that the parent bodies of the irons escaped significant fragmentation while the internal temperatures fell from 1700 to 800° K, a period which probably lasted about 10^3 My. There appear to be two possible exceptions; groups IC and IIE both show wide cooling rate variations which are uncorrelated with composition (Scott and Wasson 1976). For these groups, it is possible that the parent body in which the igneous chemical trends were established was destroyed, and the metal fragments reburied in other parent bodies which subsequently cooled through the temperature range 1000-800° K.

COSMIC RAY EXPOSURE AGES

These exposure ages measure the period for which the meteorites existed as m-sized objects in space, and are at least 100 times greater than the terrestrial ages (Wasson 1974). The best exposure ages (Voshage 1967) provide strong evidence that all the members of a group come from a single parent body. These ages (Fig. 3) have relative errors of 100 My; meteorites with ages below 100 My were generally rejected by Voshage.

All but one of 18 IIIAB irons have exposure ages around 650 My, and all but two of 9 IVA irons have ages which cluster about 400 My. If the IIIAB irons had been stored in more than one body, it is highly unlikely that they would show a single age. The spread of ages observed in groups IAB, IIAB and IVB does not necessarily imply that the members of each of these groups were never stored in a single body. It is more likely that their parent bodies were not entirely reduced to sub-m sized pieces by a single collision. Earlier arguments about the completeness of our IIIAB sample, suggest that the IIIAB iron mass was entirely fragmented by single collision 650 My ago.

The typical iron meteorite exposure ages of 10^9 years are in rough agreement

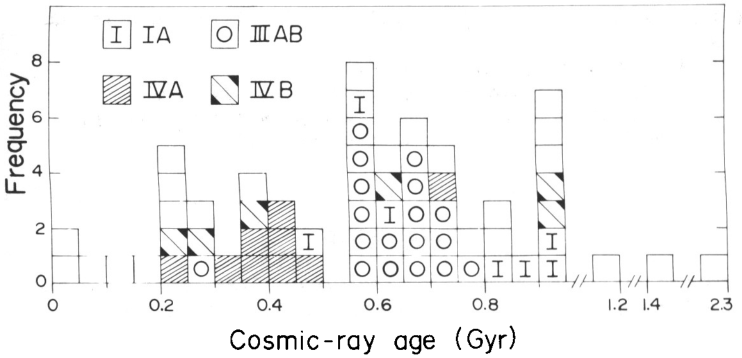

FIGURE 3. A histogram of cosmic ray exposure ages in 62 iron meteorites (Voshage 1967). Two groups show well defined peaks, IIIAB at 650 My and IVA at 400 My. This is good evidence that all the members of each group come from a separate parent body.

with the mean lifetimes estimated for Mars-crossing asteroidal orbits (Arnold 1964).

SUMMARY

Most irons (86%) can be classified on the basis of chemical composition or mineralogy into one of 12 groups each with 5-150 members. The evidence suggests that each of these groups came from a separate parent body. Apart from groups IAB and IIICD, each group probably existed as a single molten metal pool or core in its respective parent body. After solidification these pools or cores (the latter are preferred) lay undisturbed until fragmentation into m-sized pieces about 100-1000 My ago. Two groups may be exceptions in that they both show wide ranges of cooling rates in the temperature range 800-1000^{o} K, which are uncorrelated with the supposedly igneous chemical trends within the groups.

Of the remaining 14% of iron meteorites which do not belong to the groups, 19 cluster into 8 doublets or triplets. The other 48 irons probably come from at least 10-15 additional bodies. Thus the iron meteorites seem to be samples from at least 30 different parent bodies.

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DISCUSSION

GROSSMAN: Do the different members of the Group IIIAB irons have significantly different cooling rates?

SCOTT: As one favoring a core origin for this group, I have suggested that the apparent variation in cooling rates of 1-10° K My^{-1} may not be significant (Scott et al. 1973). Further work is needed to settle this point.

LIPSCHUTZ: It should be pointed out that, as far as I know, 100% of the IIIAB irons have been shocked preterrestrially into the 130-750 kb. range and that ~60% of the IVA group (which is the only other group exhibiting a peak in the cosmic ray exposure age distribution) have been shocked into the same pressure range.

SCOTT: Evidence for heavy shock is not confined to groups IIIA B and IVA. Shock melting of FeS, which requires pressures in excess of 130 kb has occurred in many members of groups IIAB, IID, IIIAB and IVA, and each of the remaining groups contain some occurrences (Buchwald 1976; Scott and Wasson 1975).