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THE COMPOSITION OF IRON METEORITES: A STUDY BY FACTOR ANALYSIS

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A factor analysis has been performed on nickel and trace element data for iron meteorites. The technique shows that the present distribution of these elements is the result of three processes. These can be identified from the elements involved:

(1) Ga, Ge, Sb and Zn (condensation and accretion).

(2) Ni, Pd, Co and Cu (oxidation and sulphuration).

(3) Ir, Au, As, Re, Pt, Os, Ru and Cr (an igneous event).

The distribution of Mo, however, is not readily explicable in terms of these processes. Within the groups IAB and IIAB only one process is required for all elements, but in groups IIIAB and IVA the situation for Ga, Ge and Sb is more complex.

INTRODUCTION

Following suggestions by Shaw (1974) and Shaw and Harmon (1975), I have carried out a factor analysis on published trace element data for iron meteorites. Moore *et al.* (1977) have already considered the application of statistical techniques to the classification of iron meteorites, and here I will concentrate on the identification of geochemical trends and their interpretation. The interpretation of trace element abundance patterns in iron meteorites has been thoroughly investigated over the last decade or so, and some major advances have been made (*e.g.* Scott and Wasson, 1975; Scott, 1972; Kelly and Larimer, 1977; Sears, 1978). Despite this, the factor analysis reported here has proved useful in emphasizing certain processes which have tended to be given only passing attention, and it has simplified the overall picture by identifying which elements have been mainly affected by each process.

Essentially, factor analysis looks at the element correlations which exist within a set of analyses. When a number of elements show good mutual correlations, they are said to have been driven by the same factor. From the geochemistry of the elements, one hopes to identify the physical nature of

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the factor; for example, it might be fractional crystallization or condensation and accretion. The strength of factor analysis is that, by looking at so many elements, it is generally easier to identify the processes which have been operative. The extent to which each element is driven by a given factor is expressed as the "loading" of that factor on the appropriate element. It is also possible to measure the extent to which a given factor affects each meteorite by calculating its "score". Details of the technique appear in textbooks such as that of Davis (1973) and a brief description appears in Shaw (1974). The calculations here were made on the University of Manchester Region Computer Centre's CDC 6300/ICL 1906A joint computer system, using the NAG library program FAC 2. The results shown here include the effect of a varimax rotation. This is a technique which sets the loadings as near to +1, −1 or zero as possible. It is usually a considerable aid to interpretation. Factor analyses were performed with and without taking the logarithms of the elemental abundances. The results were much the same, but the former gave more significant correlations and are shown here.

The data used were those published by Smales *et al.* (1967), Fouché and Smales (1967), Crocket (1972) and Wasson (1974). For the sake of convenience, Wasson's values for Ga, Ge, Ir and Ni were used, but, as he notes, there is no significant difference between his results and those of the other authors. Data were not used from other sources because the increase in the amount of the data did not warrant the introduction of gaps in the data matrix. Three runs were made: 37 meteorites for 16 elements; 45 meteorites for 15 elements; and 66 meteorites for 13 elements. Details of the meteorites and elements appear in Table 1. In addition, I have also performed a factor analysis on each group in turn.

RESULTS

Factor analysis of all meteorites

The results are presented in Figure 1 which shows the loadings taken from the 66-meteorite run. Results from the other runs have been superimposed where it is necessary in order that all elements are represented.

Significantly, the main features of the results were the same for all three runs. This indicates considerable stability of the factors. Except possibly for Cu, Mo and Zn, analytical limitations seem to pose no problems. The significant points which all runs have in common are:

(1) Four factors explain at least 90 percent of the variance.
(2) These may be identified with:
    (i) Ga, Ge, Sb – Factor A
    (ii) Ni, Pd – Factor B
    (iii) Ir, Au, As, Re, Pt, Os, Ru, Cr – Factor C
    (iv) Mo – Factor D

Table 1
Details of meteorites and elements used in this study*

Meteorite	Structure**	Class	Meteorite	Structure**	Class
A. Babb's Mill (Troost's)	A	An	Kingston	Om	An
Ballinoo	Opl	IIC	La Caille	Om	An
Bendegó	Og	IC	La Primitiva	An	An
Bennett County	H	IIA	Mount Edith	Om	IIIB
Billings	Om	IIIA	Mount Magnet	Opl	An
Bohumilitz	Og	IA	Nedagolla	An	An
Boogaldi	Of	IVA	Obernkirchen	Of	IVA
Cambria	Of	An	Otchinjau	Of	IVA
Campo del Cielo	Og	IA	Pan de Azucar	Og	IA
Canton	Om	IIA	Puquois	Om	IID
Canyon Diablo 1891	Og	IA	Salt River	Opl	IIC
Caperr	Om	IIIA	Sams Valley	Om	IIIB
Chinautla	Of	IVA-An	San Cristobal	An	IB
Clark County	Om	IIIF	Santa Catherina	An	An
Cumpas	Om	IIIA	Sao Juliao De Morei	Ogg	IIB
Descubridora	Om	IIIA	Tombigbee River	An	An
Gibeon	Of	IVA	Walker County	H	IIA
Gun Creek	An	An	Wichita County	An	IA
			Youndegin	Og	IA
B. Breece	Om	IIIB	Colfax	Om	IB
Campbellsville	Om	IIIB	Glorieta Mountain	Om	Pal-An
Cape York	Om	IIIA	Grand Rapids	Om	An
Carlton	Of	IIIC	Moonbi	Om	IIIF
C. Arispe	Og	IC	Illinois Gulch	D	An
Bacubirito	Off	An	Kopjes Vlei	H	IIA
Barranca Blanca	An	IIE	Murnpeowie	An	IC
Bischtübe	Og	IA	Rhine Villa	Og	IIIE
Coalhuila	H	IIA	San Martin	H	IIA
Cranbourne	Og	IA	Santa Rosa	An	IC
Gladstone (iron)	Og	IA	Seeläsgen	Og	IA
Henbury	Om	IIIA	Smithland	An	IVA
Hoba	D	IVB	Tocopilla	H	IIA
Huizopa	Of	IVA	Uwet	H	IIA
			Weekeroo Station	An	IIE

*Details of each run are as follows: run 1; 37 meteorites (list A), 16 elements (Ni, Ga, Ge and Ir data from Wasson, 1974, Cu, As, Sb, Pd, Mo, Zn and Cr from Smales *et al.*, 1967, Au and Re from Fouché and Smales, 1967, and Ru, Os and Pt from Crocket, 1972). Run 2; 45 meteorites (lists A and B), 15 elements (as run 1, without Pt). Run 3; 65 meteorites (lists A, B and C), 13 elements (as run 1, without Pt, Ru and Os).

**Key to structures: Opl, plessitic octahedrite; Of, fine octahedrite; Off, finest octahedrite; Og, coarse octahedrite; Ogg, coarsest octahedrite; D, ataxite; An, anomalous; H, hexahedrite.

where factors A, B, C and D explain 22, 16, 48 and 7 percent of the variance, respectively.

(3) Antimony has a contribution from factor C and arsenic has a small contribution from factor A.

The results from the three runs differed in two respects. Firstly, Cu belongs with Ni and Pd in the 37 and 45-meteorite runs, but with the Mo-factor in the 66-meteorite run. This change was caused by the introduction of Santa Catherina, San Cristobal and Hoba, which display an inverse correlation between Cu and Mo:

	Cu	*Mo*
Santa Catherina	3168	2.9
San Cristobal	1016	2.2
Hoba	1	24.5

It would seem, therefore, that Cu and Mo are being driven by the same factor, but in the opposite direction, and that this is being obscured in the first two runs by insufficient data or an insufficient spread of data. Secondly, in the 37-meteorite run Zn had a unique distribution and was therefore assigned its own factor. Since about half its determinations are upper limits, this is clearly an affect of poor data and for the other runs only partial correlations were sought (*i.e.* its correlations with other elements only were used to derive its factors, but not theirs). The later runs therefore reflect more accurately its true distribution. These show it to be controlled by factor A.

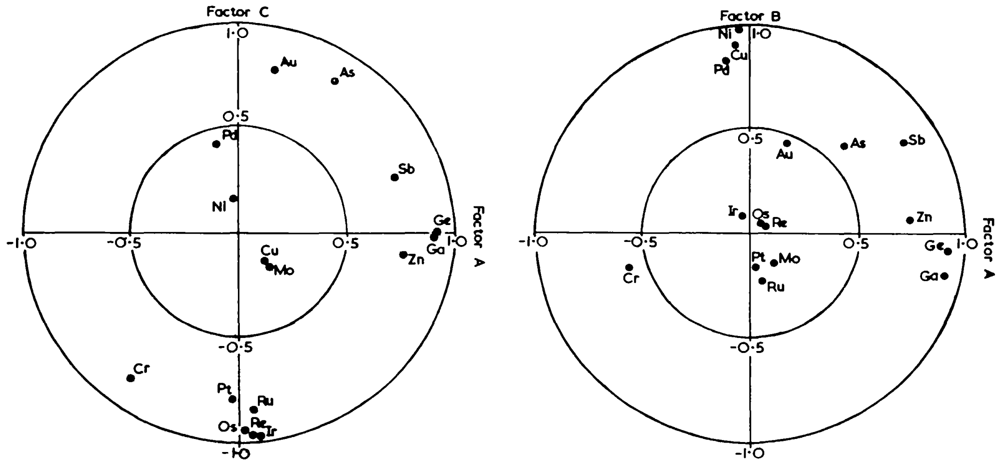


Fig. 1 Plots of factor loadings for 65 meteorites and 16 elements. Ga, Ge, Sb and Zn appear to be driven by factor A; Ni, Pd, Cu, and probably Mo (see text) are driven by factor B; whilst Ir, Au, As, Re, Pt, Os, Ru and Cr are driven by factor C. Antimony, and to a lesser extent As, have contributions from both factors A and C.

Factor scores are also best examined by comparing factors, as in Figure 2. Factor A clearly sorts the meteorites into the groups defined by Goldberg *et al.* (1951), Lovering *et al.* (1957) and by Wasson and co-workers (Wasson, 1974). There are insufficient data to identify the minor groups, but the main groups IA, IIAB, IIIAB, IVA and IVB are readily resolved. Factor B seems only to have separated out group IIAB, which forms a tight cluster with a factor score near minus one. In contrast, the other classes lie symmetrically about a factor score of zero. The meteorites also lie symmetrically about a factor C score of zero. An examination of the factor D scores shows that the Mo distribution cannot be explained by a few anomalous meteorites.

It is already possible to identify some of the well-known trends within the groups from the factor scores. Nickel shows a small variation within the group, in addition to the larger differences between the groups, and the factor C elements show very large ranges in all groups except IAB.

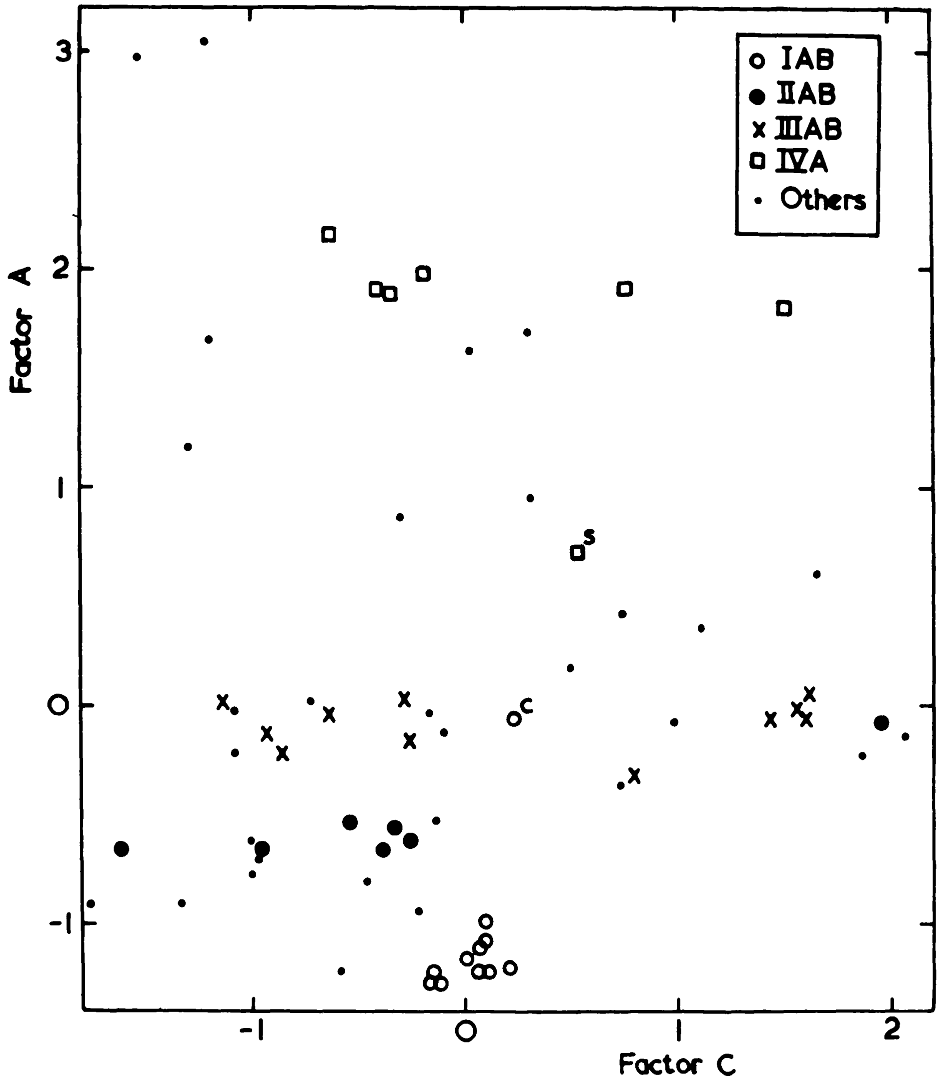
Factor analysis within the groups

The major problem in performing factor analysis on each group separately is the highly restrictive size of the data matrix. The meteorites sampled and the elements involved may be determined by reference to Table 1.

IAB (12 meteorites, 15 elements; in addition, In and Ag from Smales et al.*, 1967)*: One factor dominates Ni, Cu, Sb, As, Pd and In in a positive sense, and Ga, Ge, Ir, Mo and Au in the opposite sense; in other words, whatever process this factor is representing, it affects these two groups of elements in opposite ways – depleting one and enriching the other. Re has its own factor, and the same factor also has some influence on Au but in the opposite sense (this is probably due to Wichita County, IAB, which has low Re and high Au, both by factors of 10). Cr, Zn and Ag are all chalcophile and require three individual factors. This is almost certainly a sampling effect. The chalcophile elements are associated with sulphide nodules which are macroscopic and sparse and consequently difficult to sample adequately. In the absence of Wichita County, and the poorly sampled chalcophiles, only one factor is required.

IIAB (7 IIA and 1 IIB meteorites, 13 elements): A single factor dominates Ni, As, Au, Pd and possibly Sb in one sense, and Ga, Ge, Ir, Cu, Re and Os in the other. The factor separates the only IIB member. A second factor dominates Mo.

IIIAB (6 IIIA and 4 IIIB meteorites, 15 elements): Ni, As, Au, Pd and Mo, are dominated by the same factor as Re, Ir, Cr, Os, Cu and Zn but in the opposite sense. Another factor dominates Ga and Ge and a third Sb.



IVA (7 meteorites, 12 elements – Zn excluded because it was below the detection limit in all specimens): One factor dominates As, Ni, Au, Pd and Cr, Re and Ir in the opposite senses. Ga and Ge are controlled by a separate factor, but there is a contribution from this factor to that which controls As, Ni, Au, Pd and Mo. In all but the latter respect loadings are similar to IIIAB. Sb similarly requires a third factor. Scott (1972) has suggested that the unusual distribution of Sb in group IVA may be an artifact due to experimental error or contamination.

DISCUSSION AND CONCLUSIONS

The present study indicates that the observed compositional properties of iron meteorites are the result of three processes, with possibly a fourth

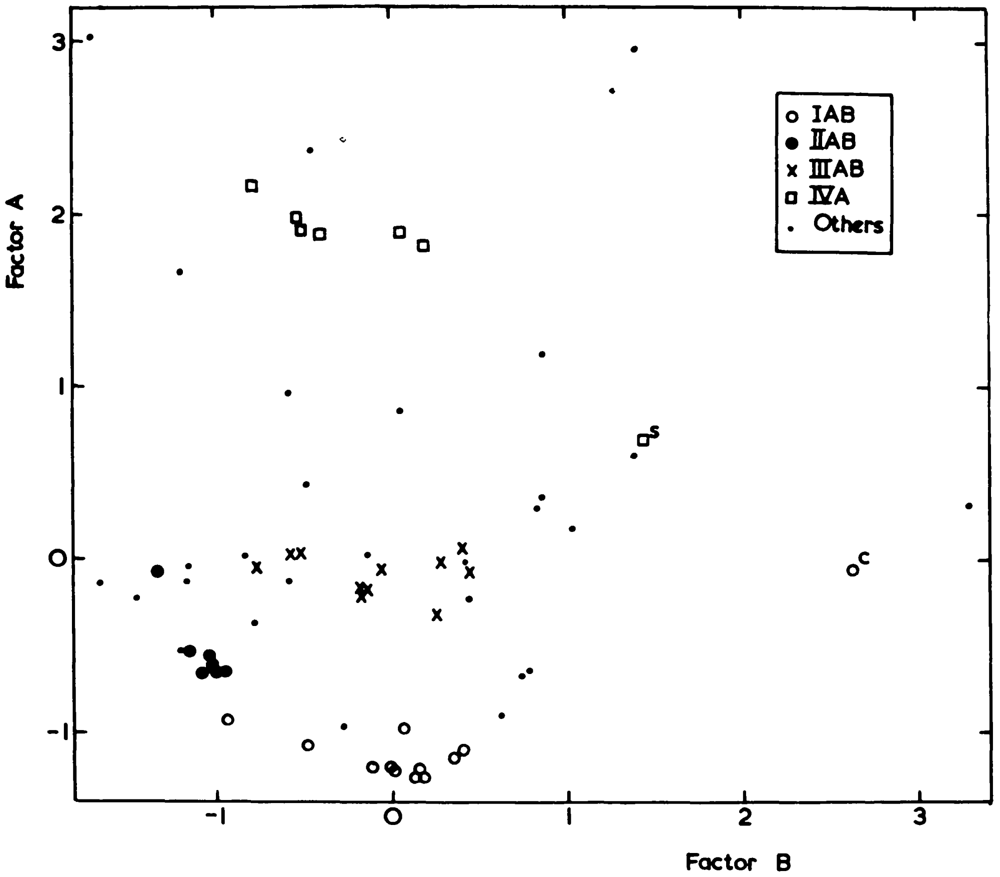


Fig. 2 Plots of factor scores from individual meteorites. C is San Cristobal, the only IB member and S is Smithland, an apparently discordant IVA iron.

affecting only Mo. Two of these have been well discussed, although details are still disputed. The distribution of Ga and Ge is commonly thought to be the result of condensation and accretion processes in the solar nebula, so that these nebula processes may be identified with factor A. In this case, the Zn and Sb distributions should similarly be explicable in terms of nebula processes. Wasson and Wai (1976) have proposed that an aerosol rich in these elements was blown away by an early, intense solar wind, and that the extent of the depletion of Ga, Ge (and presumably Sb and Zn) in each group is a reflection of the extent of gas-dust fractionation. Kelly and Larimer (1977) favour accretion at different temperatures to achieve the required abundance patterns, whilst Sears (1978) has suggested that accretion occurred at much the same temperatures for each group, but at very different pressures.

The second process which has been much discussed involves complete or partial melting of the iron meteorites. This factionates elements according to their liquid/solid partition coefficients and we may identify it with factor C. It has had the largest effect on Ir, Re, Os and Ru but all the factor C elements were involved. Scott (1972) proposed that the process was fractional crystallization, but problems with this model – in particular, ten-fold variations in the cooling rates of some groups (Goldstein and Short, 1967), and the presence of sulphur in most of them – led Kelly and Larimer (1977) to suggest that some variant of partial melting could also have been responsible in certain cases. The cooling rates have been disputed by Willis and Wasson (1978).

The third process, which we identify with factor B (Ni, Pd, Cu and the plots of Scott, 1972, suggest we can probably add Co) is oxidation and sulphuration in the meteorite parent bodies or solar nebula (Kelly and Larimer, 1977; Sears, 1978). If the oxidation and sulphuration states were fixed in the solar nebula, then we can place narrow constraints on the accretion temperature; essentially 600-700 K, with IIAB – because of its lower Ni content – some 50 K higher. Nickel and the other factor B elements have partition coefficients near one, so they show only small fractionations within the groups. With the exception of those in group IVB, these elements were fully condensed during accretion, so that they show no condensation effects. The only process that has affected them is the weakest of all.

I am unclear as to the reason for Mo being identified with its own factor. Scott (1972) mentioned that group IVA irons have lower Mo contents than IIIAB, and that within both groups, and over the iron meteorites as a whole, there is a significant Mo-Ni correlation. This suggests that its behaviour is much like the factor B elements discussed above. However, Kelly and Larimer (1977) noted that Mo and Cu "display an unusual pattern within the groups." It is possible that it belongs with the factor B elements, but that the situation has been confused by the melting process.

Another point emphasized by the factor analysis results is that the trends within the groups are not uniform. Only one factor is required in groups IAB and IIAB, but additional factors are required for Ga, Ge and Sb in groups IIIAB and IVA. The sickle-shaped population fields in the Ga or Ge *vs.* Ni plot in these classes is well known (Scott *et al.*, 1973; Schaudy *et al.*, 1972). An explanation offered by Scott (1972) was that the liquid/solid partition coefficients effective during the melting process change from just below 0.9 – the value for Ni – to just above 0.9 during solidification of the groups. In fact, IIAB shows a similar distribution on a Ga or Ge *vs.* Ni plot. However, our data included only one IIB iron, so the factor analysis did not require an additional factor in this case. Only one factor is required for group IAB, and this group does not show a sickle-shaped distribution on a Ga or Ge *vs.* Ni plot. Either it underwent a different kind of igneous event (Kelly and Larimer, 1977) or the elemental abundance patterns in this group are governed by condensation and accretion effects (Scott and Bild, 1974).

To summarise, factor analysis has emphasized that at least three processes have affected the composition of iron meteorites, and that the situation is not the same within all the groups. It has also indicated that the distribution of Mo is not readily understood by these models.

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