MINERALOGICAL MAGAZINE, SEPTEMBER 1979, VOL. 43, PP. 415-21

Origin of anomalous iron meteorites

EDWARD R. D. SCOTT

Department of Mineralogy and Petrology, University of Cambridge, Cambridge CB2 3EW

and

Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road NW, Washington, DC 20015, USA[1]

SUMMARY. Anomalous iron meteorites are those which do not have Ni, Ga, and Ge contents appropriate to one of the twelve chemical groups; they account for 14% of all irons. The chemistry of irons in the twelve groups can be largely understood in terms of primary fractionation in the nebula, which established the bulk composition of the groups, and secondary fractionation in the parent bodies (probably fractional crystallization), which produced the chemical trends within groups. Logarithmic element-Ga graphs containing data for groups and anomalous irons reveal that anomalous irons experienced the same primary and secondary fractionations as affected the groups.

The uniformity of chemical trends within groups allows possible genetic relationships between anomalous irons and groups and among anomalous irons to be tested. It is concluded that the sixty-nine anomalous irons are samples from fifty-odd additional groups, which had similar histories to the twelve groups. Less than five of the anomalous irons could be compositional end-members or reprocessed irons from the groups.

Because 'anomalous' means abnormal, some other term for the irons which do not belong to the twelve groups would be a useful reminder that these irons formed in a similar way to irons in the *major* groups. They could be called members of *minor* groups or grouplets.

NEARLY 500 iron meteorites have been classified chiefly on the basis of their bulk concentrations of Ni, Ga, and Ge (Wasson, 1974; Scott and Wasson, 1975, 1976). On plots of Ga and Ge against Ni (fig. 1) there are twelve well-defined clusters each containing 5-160 irons. Ga and Ge are the best elements for classification because within a single group (excluding IB and IIICD) concentrations of Ga and Ge vary by factors of 1.2 to 2.3, whereas for all twelve groups concentrations vary by factors of 10^3 and 10^4 respectively. However, other parameters such as mineral abundances, textures, or other element concentrations may also be used to classify irons (Scott, 1972; Buchwald, 1975).

About 14% of analysed irons are called anomalous because their compositions lie outside the fields of the twelve groups. Although the chemical classification of irons has proved invaluable in investigations of the origins of iron meteorite groups, the origin of the anomalous irons remains uncertain. The aim of this paper is to investigate the origin of these irons in the light of recent studies of the composition and formation of the groups.

Four possible origins for the anomalous irons are considered here. They may be: compositional end-members of the twelve groups, or chemically reprocessed members of these groups; the anomalous irons may have an entirely different formation history from irons in the twelve groups; or they may represent samples from numerous additional groups that experienced chemical processes similar to those which affected the twelve groups. Scott and Wasson (1975) favour the last explanation but present no supporting evidence.

Before considering these explanations it is necessary to discuss the compositions and formation histories of irons in the twelve groups. The chemical fractionations that affected the groups are conveniently discussed in terms of a primary process that fixed the bulk composition of each group and a secondary process that produced the chemical trends within the groups.

Secondary fractionation. An initial survey of secondary fractionations within groups (Scott, 1972) showed that four large groups, IAB, IIAB, IIIAB, and IVA, tended to show similar inter-element correlations, but trends in IAB were milder or absent. Subsequent analyses confirm that except for IIICD (and perhaps IIIE) the remaining groups show inter-element correlations similar to those in group IIIAB (Scott and Wasson, 1976; Scott, 1977, 1978*a*, and unpublished data). The As-Ni plot in fig. 2 illustrates the similarity of chemical trends in large and small groups (excluding IAB and IIICD). Two additional groups, which have lower As contents, IIIF and IVB, also show positive As-Ni

[1] Present address.

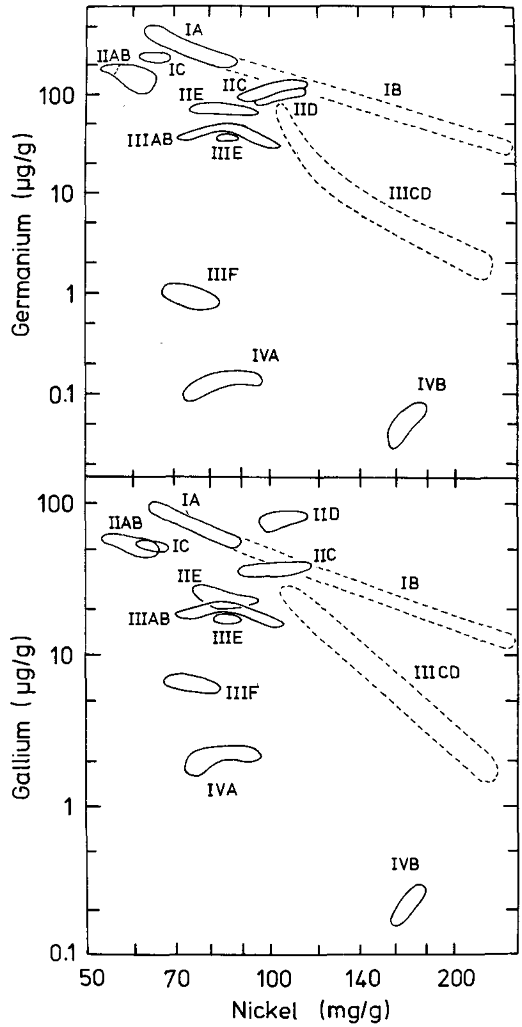

FIG. 1. Logarithmic Ge-Ni and Ga-Ni plots showing the outline of the twelve groups that contain 86% of all iron meteorites. The remaining irons, which lie outside the compositional fields of the groups, are called anomalous. Groups IB and IIICD, which account for only 4% of all irons, have larger and more diffuse fields than the other groups, but chemical and mineralogical evidence suggests that these two groups have a different history. Data from Wasson (1974), Scott and Wasson (1976), and Scott (1978*a*).

correlations like those shown in fig. 2 (Scott, 1978*a*). With few exceptions groups IC, IIAB, IIC, IID, IIE, IIIAB, IIIF, IVA, and IVB all show positive correlations of Au, As, Co, and P with Ni, while Cr, W, and Ir are negatively correlated with Ni. These trends are igneous in origin and probably result from fractional crystallization of molten metal in the parent bodies (Scott, 1972). Trends in group IVA have been attributed to partial melting (Kelly and Larimer, 1977).

Element-Ni diagrams like figs. 1 and 2 show that groups IAB and IIICD have trends that are very different from those in other groups; As-Ni, Au-Ni, P-Ni, Co-Ni, Ir-Ni trends are much less steep or absent entirely. Mineralogical evidence also indicates that these two groups have a different history from the others. Chondritic silicates, for example, are common in IAB and IIICD but absent in other groups (Scott and Bild, 1974; Kracher and Kurat, 1977). The fractionations that caused these trends are not understood. Nebular (Scott and Bild, 1974) and planetary (Kelly and Larimer, 1977) mechanisms have been proposed; both seem inadequate.

Primary fractionation. The process responsible for establishing the bulk compositions of the groups is best studied by averaging data for closely related irons to minimize secondary fractionation effects, and then normalizing element/Ni ratios to the appropriate CI chondrite ratios. In all but the least fractionated groups (IAB, IC, IIAB, IIC) these relative elemental abundances are positively correlated with the equilibrium temperatures calculated for 50% condensation of the elements from a nebula of solar composition (Wasson and Wai, 1976; Wai and Wasson, 1977; Scott, 1978*b*; Wai *et al.*, 1978). Chondrites also have relative elemental abundances that tend to decrease with decreasing condensation temperature (see Larimer and Anders, 1967; Wai and Wasson, 1977). In irons and chondrites refractory elements have mean abundances that are relatively close to CI levels, whereas volatiles show the largest variation. There is little agreement as to which condensation or accretion mechanisms produced the depletion of volatiles in irons and chondrites, although it is generally agreed that some nebular process was responsible.

Ga and Ge show the largest ranges in irons as these are the most volatile siderophile elements (Sears, 1978; Wai *et al.*, 1978). The small ranges within groups are caused by the weak preferences of Ga and Ge for solid or liquid Fe, Ni during fractional crystallization. This combination of factors ensures that Ga and Ge are the most useful elements for classifying irons.

Primary fractionation curves. Another way of investigating primary fractionation in irons, which allows insights into the origins of the anomalous irons, is to plot the concentration data on element-Ga graphs. Fig. 3 shows an As-Ga plot with all available iron meteorite analyses plotted and data for groups and clusters of related anomalous irons averaged. For both groups and anomalous irons there is a tendency for As to decrease with decreasing Ga. The line in fig. 3 shows a possible

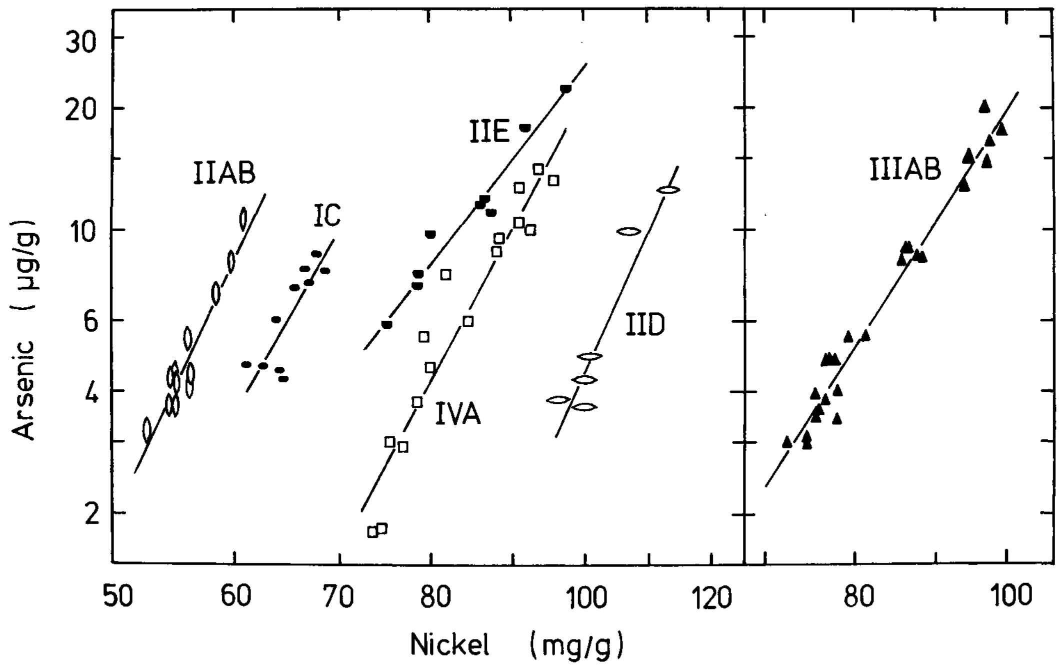

FIG. 2. A logarithmic As–Ni plot showing analyses for irons belonging to six groups. Recent As analyses (Scott, 1977, 1978*a*; unpublished data) confirm earlier indications (Smales *et al.*, 1967; Scott, 1972) that all groups except IAB, IIICD, and possibly IIIE have similar positive As–Ni correlations. The uniformity of these chemical trends for As and several other elements allows possible genetic relationships between anomalous irons and groups and among anomalous irons to be investigated.

primary fractionation curve drawn through all the data.

In order to compare different elements it is useful to plot abundances normalized to CI chondrites as

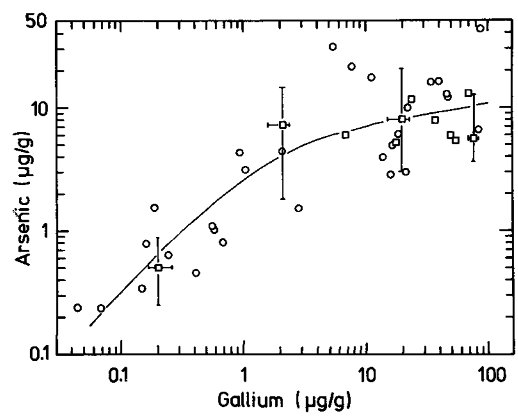

FIG. 3. A logarithmic As–Ga plot showing mean compositions of the groups (□), and data for anomalous irons (○) with analyses for closely related irons averaged. There is a tendency amongst both anomalous irons and groups for As to decrease with decreasing Ga. The curve shown is a possible primary fractionation curve drawn through all the data. Bars mark the concentration ranges in four groups: IVB, IVA, IIIAB, and IID.

described above. Fig. 4 shows a composite plot of six primary fractionation curves. Comparison of figs. 3 and 4 shows that normalization to CI data does not change the shape of the As–Ga curve significantly. As might be expected from the above discussion, the average gradients of the curves in fig. 4 are related to nebular condensation temperatures; the most volatile, Ge, showing the steepest curve. Refractory elements like W tend to define flat curves, close to that for Co. Graphs showing the data used to derive the curves drawn in fig. 4 are given by Scott (1978*b*).

On these element–Ga graphs the anomalous irons define primary fractionation curves that are very similar to those drawn through the groups. In fig. 3 and on plots of Au and Cu against Ga, the existence of a correlation among the group means is entirely dependent on group IVB, which has the lowest Ga concentration. The best plots for demonstrating a correlation among the groups are those of Ge, P, and Co against Ga. On these diagrams both groups and anomalous irons independently show strong correlations and define similar primary fractionation curves. The similarity of the curves for groups and anomalous irons suggests that the anomalous irons experienced the same primary fractionation as affected the groups.

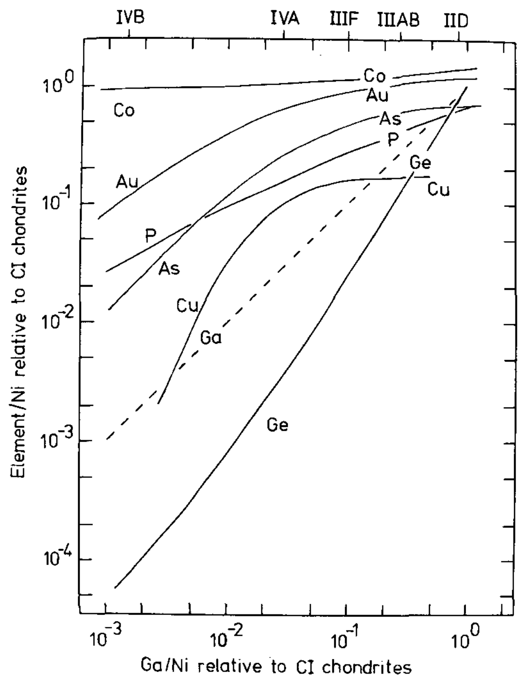

FIG. 4. A composite diagram showing primary fractionation curves obtained from six separate element-Ga plots using data from all iron meteorites. For Ge, P, and Co, anomalous irons and groups independently show element-Ga correlations and fractionation curves close to those plotted. For As (fig. 3), Au, and Cu, primary trends are similar for groups and anomalous irons, although group trends rely heavily on IVB data. This suggests that anomalous irons experienced the same primary fractionation (during nebula condensation) as established the bulk composition of the groups. Data for graphs are given by Scott (1978*b*).

It is argued below that the anomalous irons also experienced the same *secondary* fractionation process as produced the trends within groups.

If analyses for individual members of the groups (excluding IAB and IIICD) were plotted in fig. 3, they would spread out along nearly vertical lines. Arsenic and Au, for example, are positively correlated with Ni within groups (fig. 2), whereas Ir is negatively correlated with Ni. On As-Ga and Au-Ga diagrams, therefore, irons in a single group that plot above the primary fractionation curve will have lower Ir concentrations than those members lying below. For all group members, Ir concentrations are not correlated with those of As (or Au) and Ga, but they are correlated inversely with the vertical displacement above the As-Ga (or Au-Ga) primary fractionation curve.

Fig. 5 shows that the anomalous irons, which also have uncorrelated Ir and As concentrations, have an inverse correlation between Ir concentration and vertical displacement above the curve on the As-Ga diagram (fig. 3) like that shown by all the group members. I thank A. M. Davis for first demonstrating this relationship. Normalizing the concentration data to Ni, which removes any effects due to removal of Fe into sulphide or oxide phases, improves the inverse correlation. Fig. 12 of Scott (1978*b*) is such a normalized plot of Ir against the displacement on a Au-Ga plot. Iridium, Au, As, and P are the best elements for showing correlations among the anomalous irons after allowance for primary fractionation as these elements have the largest secondary fractionations in the groups. These correlations suggest that the anomalous irons experienced the same secondary fractionations as affected the groups.

Origins of anomalous irons. Since the anomalous irons experienced primary and secondary fractionations like those that affected the major groups, an origin for the anomalous irons radically different from those of the groups (origin 3) can be rejected.

Arguments that the anomalous irons are not

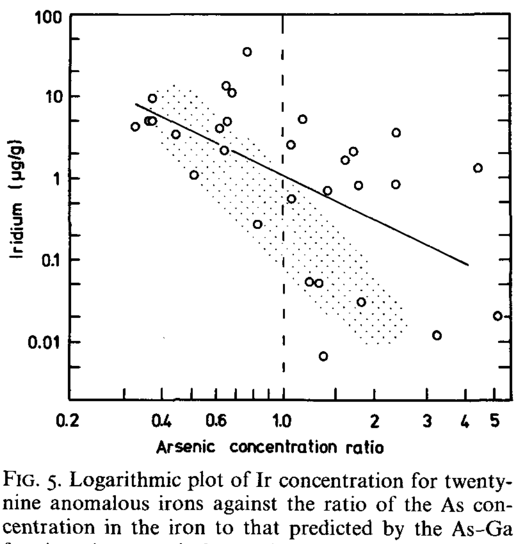

FIG. 5. Logarithmic plot of Ir concentration for twenty-nine anomalous irons against the ratio of the As concentration in the iron to that predicted by the As-Ga fractionation curve in fig. 3. (The As concentration ratio is a measure of the vertical displacement of the datum from the As-Ga curve in fig. 3, as that figure is plotted on logarithmic axes also.) The anomalous irons show a negative correlation (coefficient of correlation is 0.53), which is significant at the 99.9% level, although their actual Ir and As concentrations are not correlated. Group members are also negatively correlated on this plot; the IIIAB irons plot in the stippled area. This similarity between anomalous irons and group members implies that the anomalous irons experienced the same secondary, igneous fractionation as produced the chemical trends within the groups.

reprocessed irons from the twelve major groups (origin 2) are indirect but none the less reasonably strong. First, we have no reason to believe that the primary fractionation was a discontinuous process that produced *only* irons with the Ga and Ge concentrations in the twelve groups, and that anomalous irons were later produced from these groups by subsequent processes. Secondly, the compositions of groups and anomalous irons (with the obvious exception of IB and IIICD) can be understood reasonably well in terms of continuous nebular and igneous fractionations described above. Thirdly, other processes that fractionate elements between silicate, metal, and sulphide appear to be incapable of producing the observed primary fractionations (see Wasson and Wai, 1976), and so are unlikely to have produced anomalous irons from the twelve groups.

Recent analytical data for the groups confirm that anomalous irons are not compositional end-members of the twelve groups (origin 1). The existence of well-defined trends in the minor groups like those in the major groups (excluding IAB) allows Chinga, for example, to be excluded from group IVB. Klamath Falls, however, can be identified as an end-member of group IIIF because its composition fits an extrapolation of the chemical trends in group IIIF (Scott, 1978*a*). For Ventura, analyses for Au, As, Co, etc. are not available and the possibility remains that it is an end-member of group IIIAB and not an anomalous iron.

Although groups IAB and IIICD occupy large fields on the Ga- and Ge-Ni plots (fig. 1), the chemical and mineralogical properties of these two groups are unique. Their existence should not therefore be used as an argument for expanding the compositional ranges of other groups, which show little correlation of field size and population, to accommodate anomalous irons. There are a few anomalous irons, such as Mount Magnet, Santa Catharina, and Dermbach, that show some of the chemical characteristics of group IB and IIICD, including high volatile and low refractory abundances. However, it seems likely that they are not members of these groups. Instead they probably experienced the same fractionation processes as affected groups IB and IIICD. As only 4 % of group members belong to IB and IIICD, it is reasonable that only a few anomalous irons have similar properties (IA irons, which account for 90 % of group IAB, are relatively unfractionated).

In the Appendix are listed sixty-nine anomalous irons and their Ni and Ge concentrations as measured by Wasson and co-workers (see Scott and Wasson, 1976), showing those that are closely related. A few irons have been reclassified by Scott (1977, 1978*a*). Some of those listed as unique have Ni, Ge, and Ga concentrations that are within factors of 1.6, 1.7, and 2.3 respectively of other anomalous irons (these ranges are the maximum ones found in the groups excluding IAB and IIICD). Possible pairings can be tested when analyses for additional elements are available by seeing whether they are consistent with chemical trends within groups (Wasson, 1974; Scott and Wasson, 1976). These tests suggested that of the fifteen anomalous irons with < 1 μg/g Ge, for example, no two are as closely related as two groups members (Scott, 1978*a*).

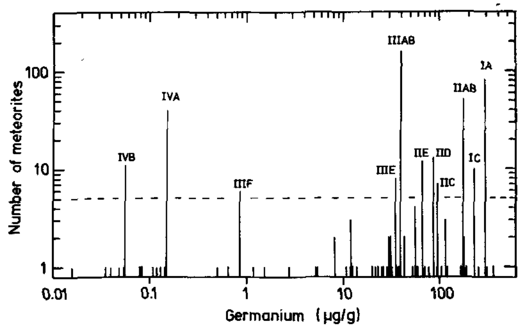

FIG. 6. Histogram showing the population and mean Ge concentration of iron meteorite groups, excluding IB and IIICD, Nedagolla, and Butler. The minimum population for naming a group is arbitrarily set at 5 (Wasson, 1974). The 69 anomalous irons divide into 5 doublets, 2 triplets, and 1 quadruplet; the remainder are unique. Like other elements, Ge shows a similar distribution amongst the named groups and anomalous irons. For example, most anomalous irons and named groups have Ge concentrations in the range 20–400 μg/g. Data from Wasson (1974), Scott and Wasson (1976), and Scott (1978*a*).

Fig. 6 is a histogram showing the population and Ge concentration of the named groups and anomalous irons listed in the Appendix. It provides further indirect evidence for the general similarity between the compositions of irons in groups and anomalous irons. Few anomalous irons have Ge concentrations outside the range shown by the groups (only Butler and N'Goureyma lie outside the plotted range). Eight of the twelve groups and most (57 %) of the anomalous irons have Ge concentrations in the range 20–400 μg/g. Finally, both groups and anomalous irons are scarce in the range 1–10 μg/g Ge, for reasons unknown.

One final piece of evidence that the anomalous irons came from poorly sampled groups that formed in a similar way to the twelve groups (origin 4) is provided by a logarithmic plot of cumulative group frequency against group population (Rajan and Scott, unpublished). Extrapolation of a line through data for the twelve groups predicts 20 unique irons, 7 sets of doublets, 4 sets of triplets, and 3 sets of quadruplets (with *c.* 50% errors). The numbers derived from the Appendix are 49 unique, 5 doublets, 2 triplets, and 1 quadruplet, which are in rough agreement with the predictions. Further pairings, however, can be anticipated.

The conclusion that the anomalous irons experienced a similar history to irons in the twelve groups was not unexpected. Nevertheless, this paper presents the first evidence that the anomalous irons and the group members share a common history.

The word 'anomalous' means abnormal or unusual. Although no author has ever suggested that the anomalous irons had an abnormal formation history, it would be useful to have another term for these meteorites to prevent any possible implication that they formed differently from irons in the twelve groups. Where necessary, the anomalous irons might be referred to as members of *minor* groups or grouplets; the latter term was suggested by J. T. Wasson (oral comm.).

This work suggests that the anomalous irons can be used to help elucidate the primary and secondary fractionations that apparently affected all irons. By plotting the composition of irons on element-Ga diagrams it is possible to make approximate estimates for the bulk composition of a group, even if it is represented by a single iron.

Acknowledgements. I thank A. M. Davis for his insights into the use of element-Ga plots, D. W. Sears for a helpful review, and J. W. Larimer, J. T. Wasson, and S. O. Agrell for valuable discussions. Work at Cambridge was supported by a NERC grant to S. O. Agrell.

Appendix

Anomalous irons are listed in Table I with closely related irons identified. The classification and analyses are largely those listed by Wasson (1974) with some additions and minor modifications from Scott and Wasson (1976) and Scott (1977, 1978*a*). As less than half of these irons have been analysed for Au, As, Co, Cr, etc., it is likely that there are a small number of genetic relationships that have not been identified below.

TABLE I. *Anomalous irons and their* Ni *and* Ge *concentrations*

Meteorite	Ni (mg/g)	Ge (μg/g)
Algoma	107	38.3
Babb's Mill (Blake's)	114	0.035
Babb's Mill (Troost's)	177	41.0
South Byron	178	45.0
Bacubirito	96.2	31.9
Butler	152	1970
Cambria	101.7	1.52
Chebankol	88.0	52.5
Chinga	162	0.082
Corowa	131	159
Repeev Khutor	143	193
Cowra	129	12.4
Cruz del Aire	90.0	187
Deep Springs	132	0.109
De Hoek	99.5	0.079
Denver City	84.0	0.5
Dermbach	421	0.144
El Qoseir	132	11.7
Elton	69.0	165
Gay Gulch	151	10.7
Garden Head	170	16.6
Kofa	183	8.6
Glenormiston	74.5	77
Grand Rapids	92.6	13.8
Gun Creek	83.8	70
Guffey	99.4	0.082
Hammond	80.7	58.4
Horse Creek	57.5	110
Illinois Gulch	117	2.76
Kendall Co.	54.5	355
Kingston	68.8	58.8
La Caille	91.1	21.5
Laurens Co.	129	23.0
Lime Creek	291	28.5
Livingston (Tenn.)	66.4	250
Mbosi	87.1	26.9
Emsland	94.0	35.0
Monahans	106	127
Del Rio	113	99
Dorofeevka	113	124
Morradal	195	119
Mount Magnet	146	5.26
Murfreesboro	79.1	30.2
Cachiyuyal	78.8	30.3
Nedagolla	60.2	0.005
New Baltimore	63.6	35.9
N'Goureyma	92.6	0.016
Nordheim	116	0.644
Piedade do Bagre	75.1	25.7
Piñon	155	1.16
Rafrüti	93.2	0.055
Redfields	69.1	95
Reed City	73.5	55.5
Santa Catharina	336	8.9
Twin City	301	7.4
Santiago Papasquiero	748	0.040
Shingle Springs	169	0.130
Soper	57.0	10.8
Soroti	129	5.22
Tombigbee River	43.0	62.5
Auburn	45.5	70
Bellsbank	41.3	54.6
La Primitiva	49.0	37.3
Tucson	94.5	0.049
Ventura	101	25.0
Victoria West	118	31.4
Washington Co.	99.6	20.5
Ysleta	76.2	0.120
Zacatecas (1792)	58.8	307

REFERENCES

Buchwald (V. F.), 1975. *Handbook of Iron Meteorites.* University of California Press.
Kelly (W. R.) and Larimer (J. W.), 1977. *Geochim. Cosmochim. Acta,* **41,** 93–111.
Kracher (A.) and Kurat (G.), 1977. *Meteoritics,* **12,** 282–3.
Larimer (J. W.) and Anders (E.), 1967. *Geochim. Cosmochim. Acta,* **31,** 1239–70.
Scott (E. R. D.), 1972. Ibid. **36,** 1205–36.
—— 1977. *Earth Planet. Sci. Lett.* **37,** 273–84.
—— 1978*a*. *Geochim. Cosmochim. Acta,* **42,** 1243–51.
—— 1978*b*. Ibid. 1447–58.
—— and Bild (R. W.), 1974. Ibid. **38,** 1379–91.
—— and Wasson (J. T.), 1975. *Rev. Geophys. Space Phys.* **13,** 527–46.
———— 1976. *Geochim. Cosmochim. Acta,* **40,** 103–15.
Sears (D. W.), 1978. *Earth Planet. Sci. Lett.* **41,** 128–38.
Wai (C. M.) and Wasson (J. T.), 1977. Ibid. **36,** 1–13.
———— Willis (J.), and Kracher (A.), 1978. *Lunar and Planetary Science,* ix. 1193–5. Lunar and Planetary Institute, Houston.
Wasson (J. T.), 1974. *Meteorites—Classification and Properties.* Springer.
—— and Wai (C. M.), 1976. *Nature,* **261,** 114–16.

[*Manuscript received 31 July 1978; revised 31 January 1979*]