Origin of Iron Meteorite Groups IAB and IIICD [*]

John T. Wasson [***] and John Willis [**]
Institute of Geophysics and Planetary Physics
University of California, Los Angeles, CA 90024 USA

Chien M. Wai
Department of Chemistry, University of Idaho, Moscow, ID 83843 USA

Alfred Kracher
Mineralogische Abteilung, Naturhistorisches Museum, A-1014, Wien, Austria

Z. Naturforsch. **35a**, 781–795 (1980); received June 11, 1980

Several low-Ni iron meteorites previously assigned to group IAB are reclassified IIICD on the basis of lower Ge, Ga, W and Ir concentrations and higher As concentrations; the low-Ni extreme of IIICD is now 62 mg/g, that of IAB is 64 mg/g. The resulting fractionation patterns in the two groups are quite similar. It has long been established that, in contrast to the magmatic iron meteorite groups, IAB and IIICD did not form by fractional crystallization of a metallic magma. Other models have been proposed, but all have serious flaws. A new model is proposed involving the formation of each iron in small pools of impact melt on a parent body consisting of material similar to the chondritic inclusions found in some IAB and IIICD irons, but initially unequilibrated. These impact melts ranged in temperatures from ~ 1190 K to ~ 1350 K. The degree of equilibration between melt and unmelted solids ranged from minimal at the lowest temperature to moderate at the highest temperature. The lowest temperature melts were near the cotectic in the Fe-Ni-S system with Ni contents of ~ 12 atom %. Upon cooling, these precipitated metal having ~ 600 mg/g Ni by equilibrium crystallization. The Ni-rich melt resulted from the melting of Ni-rich sulfides and metal in the unequilibrated chondritic parent. Low-Ni irons formed in high temperature melts near the composition of the FeS-Fe eutectic or somewhat more metal rich. We suggest that the decreasing Ge, Ga and refractory abundances with increasing Ni concentration reflect the trapping of these elements in oxide phases in the unequilibrated chondritic material, and that very little entered the Ni-rich melt parental to the Oktibbeha County iron. The remaining elements tended to have element/Ni ratios in the melts that were more or less independent of temperature. The remarkable correlation between I-Xe age of the chondritic inclusions and Ni content of the host metal is explained by a detailed evolution of (mega)regolith in which these groups originated. The most Ni-rich melts could only be generated from an unequilibrated chondrite parent; as the continuing deposition of impact energy produced increasingly higher grades of metamorphism, the maximum Ni content of the impact melts (and their subsequently precipitated metal) gradually decreased.

Introduction

Eleven of the 13 iron meteorite groups [1, 2] show evidence of having originated by fractional crystallization of a metallic magma, as suggested for group IIIAB by Wasson and Kimberlin [3] and extensively documented for numerous groups by Scott [4]. These 11 groups are commonly designated the "igneous" or "magmatic" groups.

Wasson [5, 6] noted that the absence of pronounced fractionations in group IAB was inconsistent with its having undergone fractional crystallization, and that the presence of unfractionated chondritic [+] silicates observed in many IAB irons was inconsistent with the metal having ever reached temperatures within the melting range of such materials, reported to be 1450 – 1620 K for ordinary chondrites [7]. Formation ages of IAB silicates based on Rb-Sr [8], I-Xe [9, 10] and ^{39}Ar-^{40}Ar [11] techniques are within experimental uncertainties equal to the 4.52 Gyr age (^{87}Rb decay constant of $1.42 \cdot 10^{-11}$ yr^{-1}) of the solar system, thus any high temperature period must have occurred very early in the history of the solar system. Scott and Bild [12] summarized data indicating that the small group IIICD had formed by processes very similar to those that formed IAB.

---

[*] Paper dedicated to Professor H. Hintenberger on the occasion of his retirement.

[**] Also Department of Chemistry.

[***] Also Department of Earth and Space Sciences.

[+] Throughout the remainder of this paper we use chrondritic in a relatively broad sense that allows minor amounts of melts to form in the material and in some cases to migrate.

0340-4811 / 80 / 0800-0781 $ 01.00/0. — Please order a reprint rather than making your own copy.

Most members of group IAB fall in the dense "IA" cluster at the low Ni end of the group; Ni concentrations in IA range from 64 to 89 mg/g. The group was gradually expanded toward higher Ni concentrations as precise analytical data on high-Ni meteorites were obtained. The latest and largest expansion just occurred; Kracher et al. [2] extended the group from 250 out to 585 mg/g Ni with the addition of the unique Oktibbeha County iron. In contrast, IIICD has remained essentially static in its configuration since it was first refined by Wasson and Schaudy [13]. We now report the results of a survey of elemental trends indicating that group IIICD should be extended down to a Ni concentration of 62 mg/g as a result of the addition of 6 irons previously associated with IAB.

The formation of IAB and IIICD has been discussed by Wasson [5, 6, 14], Scott [4, 15], Scott and Bild [12], Bild [16] and Kelly and Larimer [17]. As discussed in more detail below, none of these studies produced a model capable of explaining all the properties of these groups.

Redefinition of Groups IAB and IIICD

Figure 1 shows the relative positions of groups IAB and IIICD on Ge-Ni and Ga-Ni diagrams published by Scott and Bild [12]. Group IIICD plotted below the IB portion of IAB with slightly steeper negative slopes. On an Ir-Ni diagram the relative positions of the IIICD and IAB fields are quite similar. Scott and Bild noted that the IIICD trends could be extrapolated to lower Ni values to include Mundrabilla and Waterville (designated by Xs in Fig. 1) but presented no justification for such an extrapolation, and these irons were later designated IAB-anomalous (IAB-An) by Scott and Wasson [1].

Willis and Wasson [18] surveyed all published analytical data on iron meteorites, including their own unpublished analyses of Co, Cu, As, Sb, W, Re and Au in 125 irons. Elemental data sets were selected on the basis of quality criteria and, if necessary, multiplied by factors to eliminate systematic biases. These procedures resulted in a large quantity of first-quality data. New IAB and IIICD diagrams based on these data showed a number of significant differences between the two groups. At Ni concentrations above 100 mg/g Cu, Ga, Ge, Mo, Ru, Sb, Re and Ir were distinctly lower and Co, As, and Au slightly higher in IIICD than in IAB. The differences between the two groups tend to decrease with decreasing Ni content, suggesting that some low-Ni IIICD members incorrectly designated IAB could now be recognized on the basis of more extensive and precise data. Examination of the compositions of individual meteorites has led us to the redefined

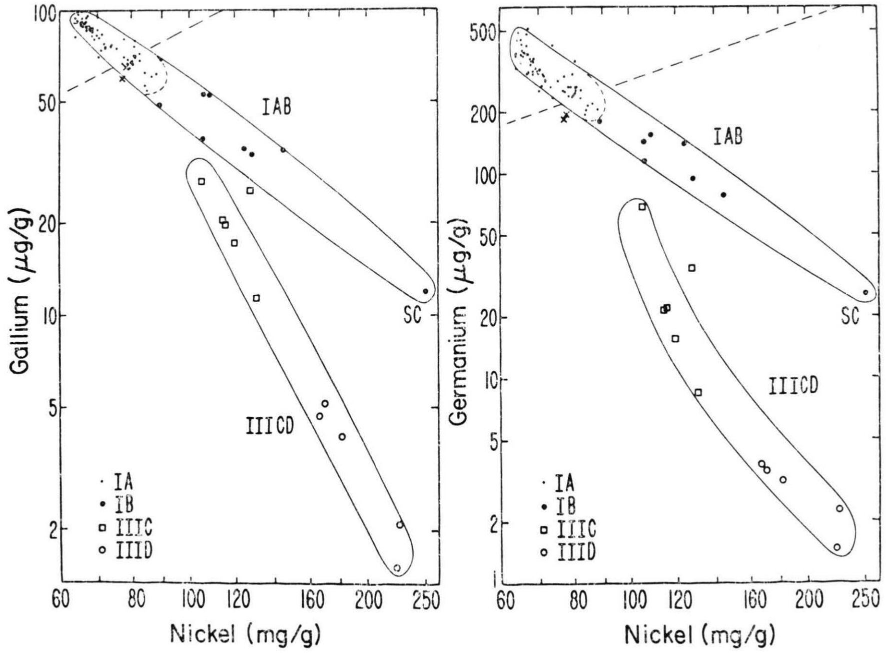

Fig. 1. Logarithmic plots of (a) Ga and (b) Ge against Ni for members of groups IAB and IIICD published by Scott and Bild [12]. Mundrabilla and Waterville (X) were identified as two possible low-Ni IIICD candidates at that time but were later classified as IA-An. In this paper 5 low-Ni irons are added to group IIICD (see Table 1).

IIICD membership listed in Table 1. Group IIICD now extends down to a Ni concentration of 62 mg/g, slightly lower than the minimum of 64 mg/g Ni in group IAB.

Figure 2 shows 9 log element-log Ni diagrams for the redefined groups IAB and IIICD. Regression lines [19] are shown for those cases where correlation coefficients show high significance levels. The lines appear to be good approximations to the true distributions, but it is possible that the true trends should show some curvature on log-log diagrams such as these. At low Ni concentrations the two trends tend to converge, but even at the lowest Ni concentrations IIICD members plot below the IAB trend on Ga, Ge, W, Re and Ir and above the IAB trend on As element-Ni diagrams. In general, precise concentration data for 4 elements, Ni, Ga or Ge, As and Ir allow definitive assignment to one or the other of the two groups. Caveat: It is possible that in the future more advanced analytical and/or statistical techniques will lead to the redefinition of groups IAB and IIICD at low Ni concentrations; K. Esbensen, S. Wold and J. T. Wasson will soon calculate an optimum multivariate classification based on factor analysis of the current data set.

Although at high Ni concentrations the distinctly higher Cu concentrations in IAB provide good discrimination, the data suggest that the trends merge at low Ni concentrations. The IIICD Au-Ni trend line is higher than that for IAB, but scatter in the data make Au of marginal value as a taxonomic parameter. The same applies for P, for which the IIICD trend is generally higher than IAB by a larger factor than for Au, but the uncertainties associated with the data points are greater by a larger factor still.

The removal of the 6 IIICD meteorites having Ni concentrations <90 mg/g from IAB has significantly reduced the scatter near the low-Ni extreme of the Ga, Ge and Ir element-Ni distributions. The Scott-Wasson (1) classification of IAB and IAB-An irons not listed in Table 1 remains unchanged for the present. We are confident, however, that there are additional IIICD members still designated IAB because of inadequate compositional data.

At similar Ni concentrations the structures of IAB and IIICD irons are very similar. As discussed in some detail by Scott and Bild [12], their mineralogical inventories are essentially the same, and cooling rates inferred from their bandwidths and bulk Ni contents are unresolvable at ~ 2 K/Myr.

All meteorites that contain large ($\gtrsim 5$ mm) fragments of chondritic silicates are IAB or IAB-An.

Table 1. Revised membership of group IIICD listed in order of decreasing Ni concentration. Concentration data are listed for 9 elements.

meteorite	group assignment		Co	Ni	Cu	Ga	Ge	As	W	Ir	Au
	this work	previous [a]	(mg/g)	(mg/g)	(µg/g)	(µg/g)	(µg/g)	(µg/g)	(µg/g)	(µg/g)	(µg/g)
Pittsburg	IIICD	IA	4.90	61.6	—	83.0	359	13.3	1.30	2.0	1.61
Ballinger	IIICD	IA-An	4.70	61.9	—	84.5	326	14.3	1.10	2.1	1.60
Carrizalillo [b]	IIICD	IA	4.80	62.0	—	81.0	337	13.5	1.38	2.04	1.56
Jaralito	IIICD	—	4.77	65.2	146	91.6	376	12.6	1.30	1.54	1.63
Nantan	IIICD	—	4.66	68.0	138	78.0	293	12.8	1.14	1.70	1.64
Zaffra	IIICD-An [c]	—	4.66	71.2	137	73.2	244	14.5	0.67	0.061	1.60
Hassi-Jekna	IIICD	IIIC	5.56	105	—	27.4	69.6	23.4	0.26	0.18	2.49
Magnesia	IIICD	IIIC	5.24	110	191	14.5	22.4	22.6	—	0.18	2.80
Havana	IIICD	IIIC	—	114	—	20.5	21.6	—	—	0.30	—
Mungindi	IIICD	IIIC	5.40	115	—	19.4	22.1	21.3	0.12	0.47	1.78
Anoka	IIICD	IIIC	5.14	120	—	17.2	15.7	18.8	0.085	0.16	1.61
Edmonton, KY	IIICD-An [c]	IIIC	5.36	127	403	25.4	34.6	21.7	0.31	0.55	1.71
Carlton	IIICD	IIIC	5.44	130	252	11.4	8.59	21.1	—	0.076	1.68
Tazewell	IIICD	IIID	5.55	166	396	4.69	3.79	30.0	0.12	0.063	1.87
Dayton	IIICD	IIID	5.75	170	515	5.16	3.52	25.6	0.09	0.028	2.04
Föllinge	IIICD	IIID	6.40	181	430	4.02	3.15	—	—	0.072	—
Wedderburn	IIICD	IIID	6.30	224	—	1.51	1.47	—	—	0.052	—
Freda	IIICD	IIID	6.32	226	—	2.09	2.24	30.0	0.07	0.021	2.11

[a] Scott and Wasson [1]. [b] We accept Buchwald's [3] spelling of Carrizalillo.

[c] Zaffra is designated an anomalous IIICD member because of its very low Ir and W contents, Edmonton because its Ni concentration is about 15 mg/g higher than expected from Ge, Ga and Ir element-Ni trends.

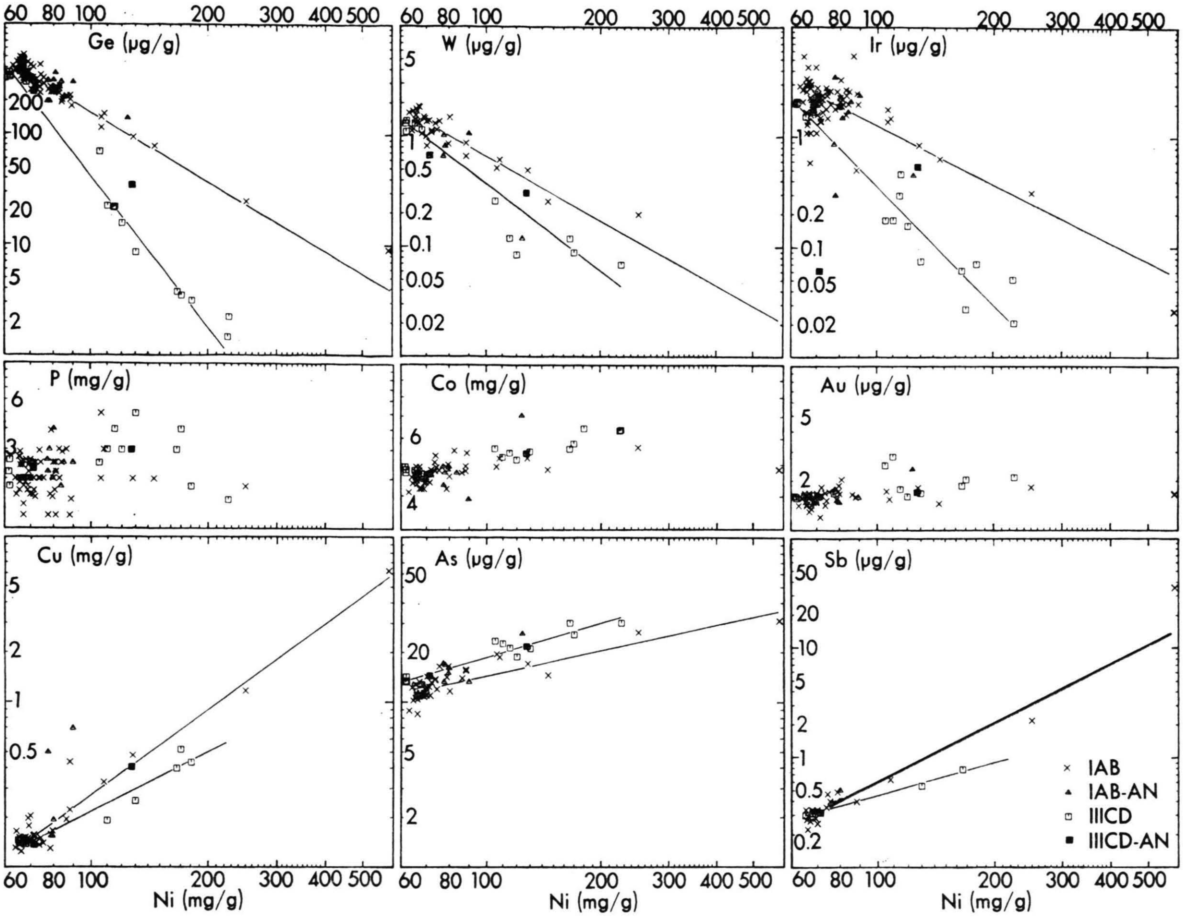

Fig. 2. Log-log plots of Ge, W, Ir, P, Co, Au, Cu, As and Sb vs Ni in groups IAB and IIICD. Linear regression lines were calculated without considering the anomalous groups members.

The small ($\lesssim 3$ mm) silicate inclusions found in the IIICD irons Carlton [20] and Dayton [12, 21] are compositionally different than those in IAB silicates [16, 22].

In Dayton and Carlton, enstatite has higher Fs contents (12 and 9, respectively, vs. 4 – 8 in IAB) and plagioclase lower An contents (2 and 4, respectively, vs. 9 – 22 in IAB). Compositions of these minerals in Mundrabilla (IA-An) [23] fall in the IAB range.

Clayton and Mayeda [24] found that the O-isotope compositions of the silicates from several IAB silicates occupied a small field near $\delta^{17}O = 2.1‰$, $\delta^{18}O = 5.0‰$, 0.4‰ in $\delta^{17}O$ below the terrestrial fractionation line. Niemeyer [10] noted that the data scatter near a slope 0.5 fractionation line, and that $\delta^{18}O$ increases with the Ni concentration of the metal. No IIICD data have been published. As discussed later in this paper, small differences in the compositions of the IAB and IIICD parent bodies suggest formation at slightly different distances from the Sun. On this basis we would predict rather small differences in their O-isotopic compositions that may not be resolvable.

Previous Models for the Formation of IAB and IIICD Irons

It seems clear from the similarities of the compositional trends discussed in the previous section that similar processes were responsible for the formation of groups IAB and IIICD. For that reason past and present discussions of IAB origin should apply to group IIICD as well. For historical reasons and for the sake of brevity we will mainly refer to IAB in this and the following sections, but except for slightly different quantitative factors, the statements also apply to IIICD.

Wasson [5, 6, 25] stressed the fact that the silicates embedded in the metal of group IAB are chondritic, and argued that the metal could never have been molten, else the silicates and metal would have separated to the top and bottom, respectively, of the magma chamber. He also argued that shock melting, even for a brief period, would lead to partial melting and fractionation of the chondritic silicates, and concluded that IAB originated "nonigneously" by heterogeneous accretion and segregation of large ($\geqq$ *m*-sized) metallic bodies during the agglomeration of the solar nebula. Wasson [14] mentioned other properties indicating a nonigneous origin for IAB: small ($\leqq$ 50 cm) precursor taenite grains, abundant planetary-type rare gases in the silicates, and the general absence of fractional-crystallization type elemental fractionation patterns. Bild [16] presented a similar model but noted that evidence (he found rare-earth and siderophile fractionations, Wlotzka and Jarosewich [27] found fractionations of major elements) of partial melting indicated that Campo del Cielo silicates had at least reached the melting point of albitic plagioclase, ~1450 K.

The chief problem with these nebular models is their failure to offer an explanation for the observed fractionation trends in IAB metal. If the metal formed in the solar nebula, one would expect the fractionation trends to be understandable in terms of variable mixing ratios among the different types of nebular metal known from experimental investigations of chondrites or inferred to exist based on equilibrium calculations simulating nebular processes. Scott and Bild [12] grappled with this problem, giving particular attention to the decrease in the abundances of refractory elements such as Ir with increasing Ni. They suggested two possibilities. (1) IB metal grains condensed at the same time as IA grains but at a different nebular location where refractory siderophiles were largely trapped in refractory oxide masses such as the white inclusions in the Allende chondrite, and could not enter the Fe-Ni phase when it condensed. (2) Both low-Ni and high-Ni IAB metal formed at the same location; refractory metals were initially trapped in refractory oxide masses, but later equilibration in the nebula or parent body produced a partial equilibration of the refractory material that increased in degree with decreasing Ni concentration. They do not explain how the negative Ir-Ni correlation was produced, nor why Ge and Ir are positively correlated. Scott and Bild suggested that the increase in the Ni/Fe ratio reflected removal of Fe in a separate oxidation event, but they also point out the reason why this explanation is not satisfactory, viz., that there is no increase in the abundance or Fe/(Fe+Mg) ratio of the trapped silicates with increasing Ni content of the metal, as expected from this model.

The Scott-Bild model envisions only one kind of metal at each nebular location, but it seems certain from studies of unequilibrated ordinary chondrites of Rambaldi et al. [27], Afiattalab and Wasson [28] and Rambaldi and Wasson [29] that several different nebular metal components were present at most locations. The following discussion shows that multiple metal component nebular models are also unsatisfactory.

Consider the Ge-Ni and Ir-Ni fractionations; between 64 and 254 mg/g Ni the Ge/Ni and Ir/Ni ratios decrease by a factor of 40; between 64 and 585 mg/g Ni the decrease is by a factor of about 500. Nebular 50% condensation temperatures of Ge, Ni and Ir at a H_2 partial pressure of 10^{-4} atm are 825, 1345 and 1545 K, respectively ([30]; C. M. Wai, unpublished calculations). Germanium is the most volatile siderophile, Ir one of the most refractory; it seems very unlikely that these two would be together in one nebular metallic fraction while Ni is in another, thus three components are the minimum required to explain these three elements. At 10^{-4} atm the nebular condensation temperatures of Ga and Sb are nearly identical, 918 and 912 K, respectively [30], yet the Ga/Ni ratio, like that of Ge and Ir, falls by a factor of 40, whereas the Sb/Ni ratio increases by about a factor of 2 as Ni increases from 64 to 254 mg/g. Although Ga could be assigned to the same low-temperature component as Ge, another low-temperature component seems required for Sb. The complexity of this multicomponent nebular model makes it unattractive.

Kelly and Larimer [17] suggested that the observed Ir-Ni distribution in IAB irons formed by fractional melting of a single kind of metallic starting material. In this model an equilibrium liquid is drained off continuously as it forms and immediately isolated in order to prevent its reequilibration with later liquids or with the residual solid metal. They chose the composition of the starting material to be that of solid metal in equilibrium with a liquid having the composition of San Cristobal metal (254 mg/g Ni, 0.32 µg/g Ir), and showed that the IAB data can be fit reasonably well with solid/liquid (k_x) distribution ratios in the following range: $0.5 \leqq k_{\mathrm{Ni}} \leqq 0.6$, $18 \leqq k_{\mathrm{Ir}} \leqq 22$. These lead to concentrations in the starting materials of 130 – 150 mg/g Ni and 6 – 8 µg/g Ir.

There are many criticisms that can be leveled against this fractional melting model, including: (1) The mean composition of IAB irons should be the same as that of the starting materials, but the arithmetic mean of IAB compositions is about 75 mg/g Ni, 2 µg/g Ir, 2 – 4 X different from the Kelly-Larimer starting compositions. Inclusion of Oktibbeha County in IAB would require starting materials 2.5 X higher in Ni and 4X lower in Ir. (2) Since Ge and Ga show element-Ni fractionations almost identical to that of Ir, they must also have k_x values near 20, but laboratory data and data on the fractionally crystallized iron meteorite groups indicate k_{Ge} values in the range 0.8 – 1.2 [4, 18]. (3) Elements having very low k_x values such as S ($k_{\mathrm{S}} \lesssim 0.1$) should not be present in the later melts, i. e., in IAB irons having Ni contents $\lesssim 130$ mg/g. In fact, S is abundant even in the IAB members having the lowest Ni contents (4). It seems quite implausible both that successive small fractions of melt could equilibrate with the entire parent solid before draining away, and that these melt fractions were not mixed at a later time. Further, the very high temperatures required to produce the later fractional melts ($\gtrsim 1700$ K) would result in total melting and differentiation of associated silicates. Fractional melting is thus also unable to explain the fractionation trends in IAB.

Shock-Melting Origin of IAB and IIICD

We propose that the meteorites of groups IAB and IIICD formed as individual shock melts on a chondritic parent body, and that the range of compositions reflects differences in the temperature of the melt and the metamorphic grade of the chondritic parent. The chondritic inclusions found in these irons to a large extent preserve the composition of the parental material, but the model requires that the original material was relatively unmetamorphosed and unequilibrated. The key element of the model is the hypothesis that *compressible, low-melting materials were selectively melted, isolated from the parent rock, and solidified under equilibrium conditions.* The lowest melting solids in anhydrous chondrites produce sulfide-rich melts having Fe-Ni as the minor component.

We envision a parental material that in many ways resembles the most unequilibrated ordinary chondrites [28, 29, 31]. Some mineral grains were large, and preserved compositions formed at high nebular temperatures. At the other extreme were small grains that had continued to react with nebular gases down to low temperatures.

Recent discussions of the nebular alteration of Fe-Ni with falling temperatures are given by Sears [32] and Afiattalab and Wasson [28]. Below ~ 700 K metal grains corrode both as a result of the reaction of Fe with $\mathrm{H_2S}$ to form FeS and with $\mathrm{H_2O}$ to form FeO. Such corrosion shells are relatively thin on the largest (mm-sized) metal grains, whereas the smallest grains may have been transformed either into corrosion products plus Ni-rich metal or entirely into oxides and sulfides, possibly including some Ni-rich sulfides such as pentlandite $(\mathrm{Fe, Ni})_9\mathrm{S}_8$ or heazlewoodite $\mathrm{Ni_3S_2}$ (although Renazzo and Al Rais are the only chondrites known to have >6% metal and Ni-rich sulfides).

Studies of the Fe-Ni-S system by Kullerud et al. [33] show that a sulfide-metal eutectic trough extends from the familiar FeS-Fe eutectic having an Fe/S atom ratio ~ 1.1 at 1261 K down to a Ni-rich liquid having an Ni/S atom ratio of ~ 2 at ~ 920 K. Figure 3 shows a portion of the ~ 1190 K section through the Fe-Ni-S system, converted from weight

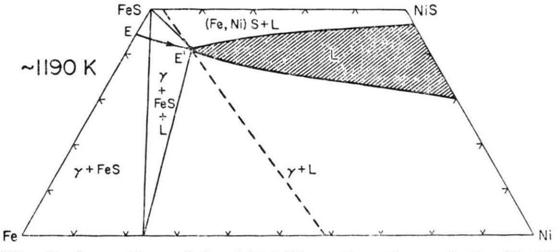

Fig. 3. A portion of the 1190 K section through the Fe-Ni-S phase diagram given by Kullerud et. al. [33]. The section was constructed by interpolating between the published 1173 K and 1273 K sections. The monosulfide solid solution (mss) field (not shown) lies near the edge joining the FeS and NiS corners. The dashed line extending from FeS with a small Ni content to taenite (γ) containing ~ 585 mg/g Ni demonstrates that Oktibbeha County could have formed by equilibrium crystallization of a melt having the E′ composition.

to atomic ratios and interpolated between the 1173 and 1273 K sections given by Kullerud et al. [33]. If a liquid having a composition at point E′ were isolated and crystallized under equilibrium conditions it would yield FeS containing a minor amount of Ni and Oktibbeha Country-like γ-iron containing ~585 mg/g.

How could such a melt have been produced? As shown by Fig. 3, one possibility is by partially melting FeS and γ-iron containing an Ni/(Fe+Ni) ratio of ~24. However, equilibrium partial melting requires an extended period at high temperatures, and this conflicts with our following interpretation of Ga and Ge trends. For this reason we suggest that the composition resulted from rapid melting during impact heating of FeS and Ni-rich sulfides and/or Ni-rich metal. Such a melt seems a plausible low-temperature melt because of arguments given above regarding the formation of Ni-rich sulfides and metal in highly unequilibrated chondrites, and because it seems probable that fine-grained, low-temperature sulfides and/or metals were more porous and thus more susceptible to shock heating than were coarse-grained metal or FeS formed at higher temperatures.

The low-Ni extreme of IAB was produced by more intense shock events that yielded higher-temperature melts. These meteorites contain large sulfide-graphite nodules, and *maximum* estimates of melt temperatures are those that would lead to total melting of the meteorites as constituted. The presence of 10 – 20 mg/g S [34] and smaller amounts of P and C would lower the Fe-Ni melting temperature by 50 – 100 K, perhaps down to 1700 K. However, we think this estimate is grossly high. It seems more likely that the parental melt contained much larger quantities of these 3 minor elements (especially S) and that the amount now present in the IA irons resulted from the accidental trapping of liquid during solidification of the metal. A more realistic maximum temperature is the value of 1450 K inferred by Bild [16] to be that needed to cause the incipient melting of the silicates observed in Campo del Cielo, which contains 66 mg/g Ni in the metal. The Fe-S binary diagram given in Vaughan and Craig ([35], p. 278) shows a temperature of 1450 K when the S concentration is about 180 mg/g, or 28 atom%. Allowance for the presence of Ni, C and P would lower the amount of required S. The Campo del Cielo silicates might have experienced higher shock temperatures than the metal. The minimum temperature at which the melt parental to the IAB metal could have formed is ~1250 K, the temperature of a melt that on cooling would precipitate metal with a Ni/(Fe+Ni) ratio of 0.06. We will use a temperature of 1350 ± 100 K as the temperature of the melt that precipitated the lowest-Ni IAB irons. On the basis of these arguments we suggest that the total range of melt temperatures for IAB irons was about 200 ± 100 K, ranging from ~1190 K to ~1350 K.

The Ni-normalized abundances of both volatile and nonvolatile siderophiles approach CI values near the low-Ni extreme of IAB. Our view is that this reflects the fact that appreciable melting occurred and that temperatures were high enough long enough to allow abundances in the melt to approach those in the chondritic parent. Thus the chief challenge to our model is to explain the variation in element/Ni ratios with increasing Ni content. The second and related problem is to understand why Ni normalized abundances at the low-Ni extreme of the groups differ by factors of up to 4 from CI values.

Figure 4 is a modified version of Fig. 2 extended down to 50 mg/g Ni and truncated at 300 mg/g Ni (i. e., Oktibbeha County is not shown). To it we have added a point showing the expected composition of metal having CI concentrations of Fe, Ni and all other siderophiles; the dashed line shows the locus of points having CI element/Ni ratios (i. e., differing only in Fe concentration).

According to our model the elements expected to have high abundances in the low-temperature melts that produced the high-Ni irons are those elements that were present as Ni-rich metal or Ni-rich sulfides in the unequilibrated chondrite parental material. *Vice versa,* elements expected to have low abundances are those that could not enter the melt because they were trapped inside coarse, Fe-rich metal or oxide phases that were not melted.

Figures 2 and 4 shows that element/Ni ratios of Ge, W and Ir in Ni-rich irons are several hundred times lower than those at the Ni-poor extreme; Ga, Mo, Ru, and Os, not shown, show similar trends. Element/Ni ratios of all other elements are constant to within about a factor of 5; Cu/Ni in both groups and Sb/Ni in IAB increase slightly, Sb/Ni in IIICD remains essentially constant, and element/Ni ratios of As, P, Co and Au decrease slightly with increasing Ni content.

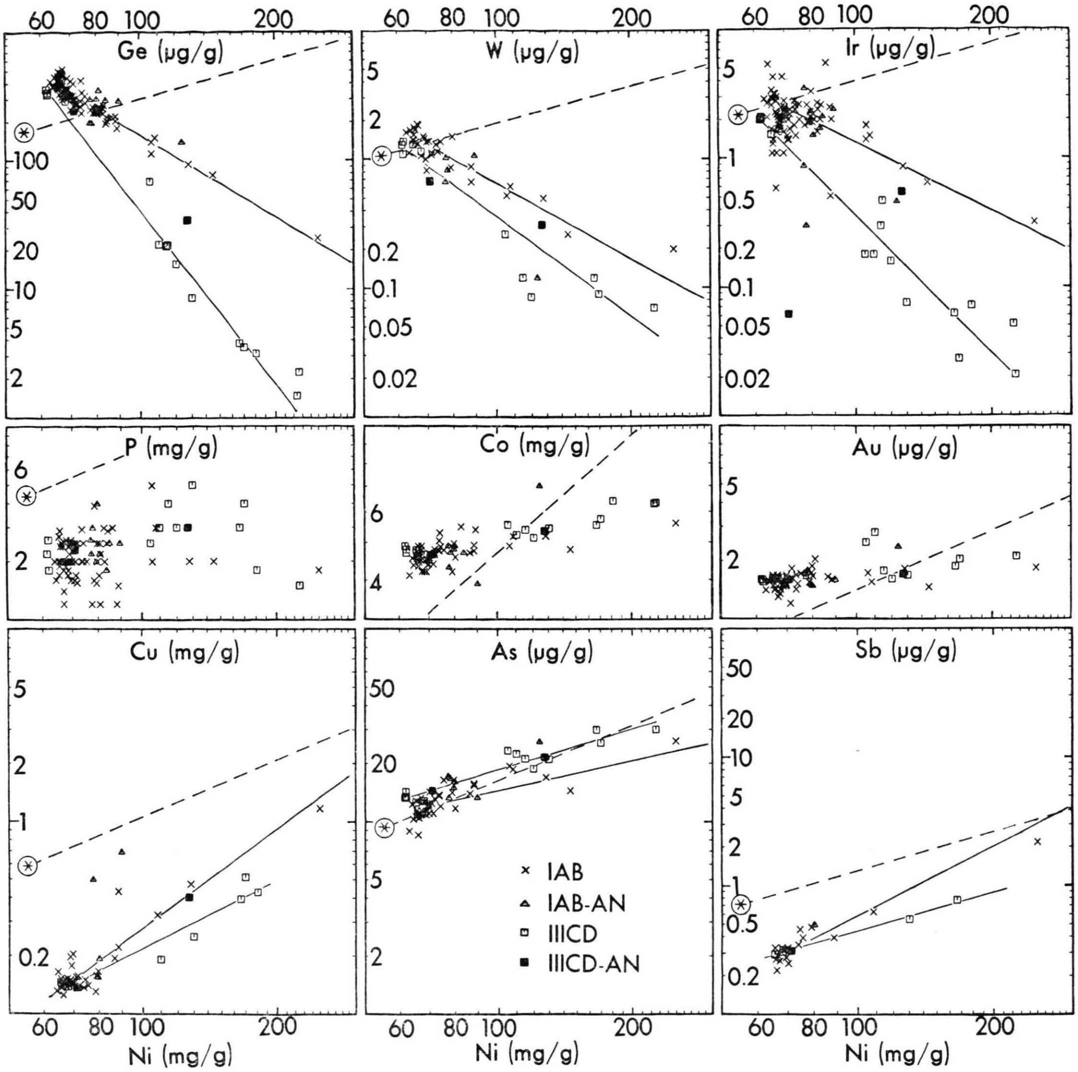

Fig. 4. Log-log plots of Ge, W, Ir, P, Co, Au, Cu, As and Sb vs Ni in groups IAB and IIICD truncated at 300 mg/g Ni (i.e., Oktibbeha County is not shown). The expected composition of metal having CI concentrations of Fe, Ni and all other siderophiles is shown by the star. The dashed line shows the locus of points having CI element/Ni ratios.

The set whose behavior is more difficult to explain are those elements that fractionated from Ni by two orders of magnitude. However, studies of chondrites and models of nebular condensation show that all of them can be present as or in oxides or high-temperature metal.

Gallium and Ge are 2 of the 3 most volatile siderophiles [30]. In contrast to the other volatile, Sb, they form stable oxides at low temperatures. Chou and Cohen [36], Chou et al. [37] and Rambaldi and Cendales [38] carried out magnetic separations on unequilibrated ordinary chondrites and found that Ga is largely in the silicate fraction; they also found that the amount of Ge in the silicate fraction of ordinary chondrites increases with decreasing degree of equilibration, though the bulk of the Ge was associated with the metal fraction in the least equilibrated meteorites studied. Wasson and Wai [39] showed that in a cooling solar nebula Ga and Ge first condense as solutes in Fe-Ni but that their solid oxides become more stable at slightly lower temperatures and that continued equilibration with nebular gases leads to their migration out of the metal and into the silicates. This conclusion remains intact although the condensation reactions of Ga and Ge have been revised in the interim [30, 32].

Wai and Wasson [40] suggest that kinetic (especially diffusional) constraints may limit the amount of a volatile siderophile that can enter Fe-Ni grains, and that the bulk of such elements may condense homogeneously or by adsorption on the surfaces of small grains at temperatures well below their equilibrium condensation temperatures. Such a depression in the condensation temperature would lead to direct condensation of Ga and Ge as oxides, thus eliminating the need for these elements to diffuse out of the metal at low temperatures.

The refractory elements W, Re, Ir and Os condense at high nebular temperatures [41 – 43]. In the Allende CV chondrite a large fraction of these elements are found in refractory inclusions, probably mainly as refractory metal grains that condensed (or remained as a residue, Ref. [44]), before Fe-Ni condensed. It seems clear that in this form these elements would not immediately enter a melt formed at ~1170 K. Although W may have condensed as an oxide instead of metal [43], that portion inside refractory oxides would still have remained trapped during the low-temperature melting event.

An important question is whether the fraction of these volatile and refractory elements that remained trapped during the melting event would have been as high as required by our model. For example, the Ir/Ni ratio in Oktibbeha County is ~700 X lower and the Ge/Ni ratio in Wedderburn is about 500 X lower than the corresponding CI values. Iridium shows large variations among IAB irons having similar Ni contents. We suspect that this reflects some tendency of solids to zone on a scale of tens of cm during precipitation (Ir has a very large solid/liquid ($k_{\mathrm{Ir}} \gtrsim 8$) distribution ratio), thus the actual range in Ir contents in the melts may be smaller. On the other hand, k_{Ge} is near 1, thus the entire Ge variation must be accounted for.

Is it reasonable that only 0.2% of Ge or the other highly fractionated elements would enter the lowest-temperature melts? We agree that such a conclusion is surprising, but we would argue that it is not unreasonable. If the nebular cooling rate at the IAB location was relatively rapid, Ga and Ge could have mainly condensed as oxides. The refractory elements could have largely been locked up in grains of refractory oxides, or, less likely, in large metal grains. A reasonable scenario is that large metal grains formed by heterogeneous nucleation of Fe and Ni on precursor refractory metal nuclei, and that fine metal grains formed at lower temperatures as a result of homogeneous nucleation and contained minimal amounts of refractory metals. Even if an appreciable fraction of the strongly fractionated elements were in the interiors of large metal grains, the following discussion suggests that such materials formed only a small fraction of the lowest-temperature melts.

The first stable sulfide to form is FeS, which formed corrosion shells around metal grains with the underlying metal enriched in Ni. The CI S/Fe ratio is ~0.6, and it is likely that there was insufficient surficial Fe to completely condense nebular H_2S. As result, $H_2S(g)$ would have remained a stable phase as the nebula cooled. After cooling by a few tens of degrees Ni-rich sulfides would also become stable. When collisions resulted in the spalling off of sulfide corrosion shells additional reaction of S with the exposed metal occurred. If the exposed surfaces were Ni-rich, Ni-rich sulfides would dominate, and some Ni-rich sulfides would form even on surfaces that were Fe-rich. Since some Fe but little Ni entered oxide phases, the relative amount of Ni-rich sulfide that formed could have exceeded the ~5% amount produced if metal having an Fe/Ni ratio of 16 – 19 were entirely converted to sulfide. Later in a brief shock melting event on the parent body, the only metal to melt would be that immediately adjacent to the sulfides. If this metal mainly originated as fine grains it could have had very low contents of refractory metals.

At the other extreme of the fractionation spectrum are Cu and Sb, which show small increases in their element/Ni with increasing Ni. This implies that Cu and Sb condensed in phase(s) that were selectively melted during the impact event. The obvious candidates are Ni-rich sulfides or other minor sulfides forming at temperatures well below the 645 K condensation temperatures of FeS. We cannot rule out the possibility that some portion of these elements was dissolved in Fe-Ni near the interface with sulfides.

Another interesting element is Co since, like Ni, it was probably mainly in the metal. The Co/Ni ratio decreases by a factor of 9 between the extremes of IAB. These variations can be understood in terms of our model if the Co/Ni ratio in the materials entering the lowest temperature melt were less than those in the parental materials. In its geochemical behavior Co is intermediate between Fe and Ni. If Co/Ni ratios were higher in Fe-rich sulfides than in Ni-rich sulfides this could explain the trend in the IAB Co/Ni ratio. If the high Ni content of the melt originated in Ni-rich metal rather than Ni-rich sulfides, the decreasing Co/Ni ratio with increasing Ni may reflect that the (Co/Ni in metal)/(Co/Ni in sulfide) ratio decreased with decreasing melt temperature.

The observed decrease in other siderophile/Ni ratios with increasing Ni can be rationalized in similar terms. P, As, and Au may have either been in coarse-grained, Ni-rich metal or, at low nebular temperatures have been incorporated into phases that were less inefficiently dissolved in low temperature impact melts.

Incongruity Between Abundances at the Low-Ni Extreme of IAB and Those in CI Chondrites

If during the precipitation of metal from the melt (a) the amount of fractional crystallization is negligible and (b) the siderophile/Ni ratio in the solid is essentially equal to that in the melt, then the iron-meteorites at the low-Ni extremes of IAB and IIICD should offer good estimates of siderophile abundances in the parental chondritic matter. In Fig. 5 we show abundances read off the regression lines at 64 mg/g for IAB and 62 mg/g for IIICD. For P we have used mean values in irons having ≦ 85 mg/g Ni. The elements are arranged in order of decreasing condensation temperature.

Abundances of three refractory elements W, Re and Ir are within ~30% of CI abundances, thus by our model the fraction entering the highest-temperature melts is approximately the same for these refractories as for Ni. Examination of the Figs. 2 and 4 shows that numerous W and Ir values fall as much as a factor of 2 away from the correlation line. We suspect that this indicates occasional modest degrees of fractionation during crystallization. It would be of interest to search for Ir zoning across a large IA iron, especially one having an extreme Ir concentration.

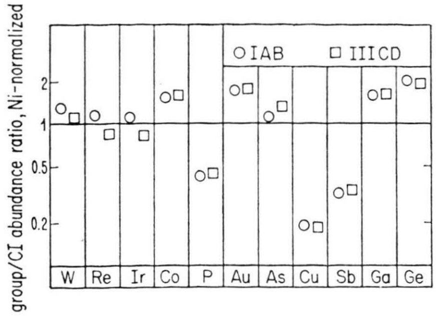

Fig. 5. A plot of the element abundances for groups IAB and IIICD normalized to Ni and CI chondrite abundances. With the exceptions of P, Cu, and Sb, all abundances are similar to or greater than CI values.

The high Co abundances are somewhat mysterious. Cobalt condenses at slightly lower nebular temperatures than Ni, thus the Co/Ni ratio in later fine-grained metal could be higher than that in the coarse-grained metal, melting of selective fine-grained metal would then account for the high Co/Ni ratio. High Co/Ni ratios are not unique to IAB, but are observed in most other groups including IIAB and IIIAB (but not IVA). It may be that the same mechanism is responsible for a portion of the enhanced ratios in IAB and IIICD.

The abundances of P, Cu and Sb are lower than CI values by factors of 2 – 5. As noted by Willis and Wasson [18], this downward biasing relative to elements of similar volatility is found in all iron meteorite groups. Part of the missing portions of these elements are present in minor phases that are generally avoided during sampling, but this is not the whole explanation for P since concentration data are obtained by modal integration of schreibersite.

The abundance of Au is about 1.8 X CI in both groups. In terms of our model this implies that the Au/Ni ratio is higher in the fine-grained or near surface metal or in the FeS that formed the parental melt at the low-Ni extreme. Since Au is significantly more volatile than Ni, it seems reasonable that the

Table 2. Concentrations of 12 elements at the low-Ni extremes of groups IAB and IIICD.

Element	IAB	IIICD
P (mg)	2.1	2.2
Co (mg)	4.62	4.72
Ni (mg)	64.0	62.0
Cu (μg)	130	121
Ga (μg)	95.1	94.7
Ge (μg)	399	363
As (μg)	11.5	13.4
Sb (ng)	270	278
W (μg)	1.57	1.30
Re (ng)	286	202
Ir (μg)	2.84	2.01
Au (μg)	1.56	1.58

interiors of large, high-temperature metal grains would be depleted in Au. Although similar arguments could be made for As, As/Ni is only about 1.3 X CI. In the magmatic iron meteorite groups As is consistently lower than expected by comparison with other elements having similar nebular volatibility. We suggest that like P, Cu and Sb, an appreciable fraction of As is unsampled, although the amount "missing" is much smaller, perhaps 30% of the whole-rock total.

Last, and most volatile, are Ga and Ge, whose element/Ni ratios are about 1.8 X CI values. According to our model, abundances of these elements in parental chondritic matter were similar to CI values, and the high enrichments imply that the host oxide phases (see previous section) equilibrated to a high degree with the sulfide-metal melt parental to the lowest-Ni IAB and IIICD irons. Like Au, the abundance 1.8 X CI can be understood if the melt contained essentially all the Ge but only 55% of the Ni in the parcel of host material that was partially melted during the shock event. In fact, the common enrichment of Ga, Ge and Au by approximately the same factor offers support for any model that explains their enrichments by (a) CI relative abundances and (b) a sequestering of 45% of the Ni.

To summarize this section, we argue that the abundances of siderophiles in the chondritic parents of IAB and IIICD were the same as CI abundances to within a small factor. In all magmatic groups except IIAB abundances tend to decrease with decreasing condensation temperature.

Other Evidence Bearing on the Origin of IAB and IIICD

Stratigraphic Origin and Age of Individual Irons

Figure 6 taken from Niemeyer [10] depicts the observed relationship between ^{129}I-^{129}Xe age and the Ni concentration of several IAB irons and IAB-anomalous Mundrabilla. An excellent negative correlation exists, with the age increasing by 6 Myr between Landes, near the IAB low-Ni extreme, and Woodbine, at 106 mg/g Ni. Such a relationship can be accounted for by the shock melting model.

The impact melt scenario implies that the irons formed in a deep (mega) regolith during an extended period of bombardment. As stated earlier, the initial state of the material is higly unequilibrated, at least as unequilibrated as the most unequilibrated ordinary chondrites. A corollary inference is that, as a result of the accumulation of heat from impacts, the degree of metamorphic recrystallization increased with time, ultimately resulting in the petrographic-type-7 chondritic material now preserved as clasts.

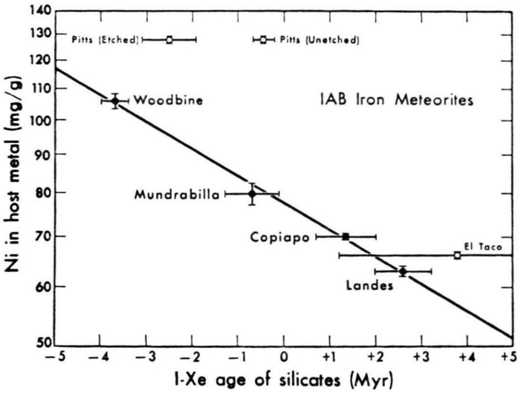

Fig. 6. Plot of Ni content of metal phase vs ^{129}I-^{129}Xe age of silicates (from Ref. [10]). Filled symbols represent samples with well-defined ages. The Pitts samples ages are given by intermediate-temperature lines which do not provide "true" ages. The El Taco sample was irradiated separately accounting for the large error limits.

Consider a snapshot of the situation early in the bombardment history. A spectrum of maximum shock temperatures had been reached at different locations within the megaregolith, with the fraction of material within each temperature interval decreasing with increasing temperature. Since the peritectic temperature decreases with increasing Ni, the number of melt pockets per unit change in Ni content increased with increasing Ni. If evolution had ceased at this point, most IAB and IIICD irons would be Ni-rich.

However, as the metamorphic grade of the chondritic parent increased with time the Ni-rich sulfides were gradually destroyed by recrystallization, and it became impossible to produce impact melts with such high Ni concentrations. Further, some Ni-rich irons would have been remelted and incorporated into melts having lower Ni contents during large impacts. Thus, if the evolution ceased at this intermediate time, the spectrum of Ni concentrations would have a lower mean than that described in the previous paragraph. All the high-Ni irons would be old, whereas both young and old low-Ni irons would be present. The latter would be biased toward younger ages because of the tendency of older ages to be reset, whereas the Ni-rich irons would only be preserved near the bottom of the regolith where the probability of resetting by impact would be the least.

The process continued on (based on the I-Xe age data) for $\geqq$ 6 Myr. At the end of the evolution the irons showed a strong negative correlation of age with Ni content, but the spread of ages for low-Ni irons should be large whereas the spread should decrease with increasing Ni content. Thus, age differences among low-Ni irons such as those observed between Landes and El Taco (Fig. 6) are to be expected. Inclusions in some Ni-poor irons may have ages as young as Woodbine, but they should be very rare because only a small fraction formed early and most of these would have been reset to younger ages.

The relatively constant cooling rates observed in IAB and IIICD irons can also be understood by this model. We suggest that the cooling resulted from a gradual decrease in the bombardment flux with time, and that the rate of cooling was essentially the same for irons stored over a large range of regolith depths.

Abundances of S and Siderophiles in Chondritic Inclusions; are the Inclusions Parental to the Associated Irons?

The mechanical mixing of the chondritic inclusions with the host metal could have occurred during the same shock event that formed the sulfide-rich melt from which the metal precipitated. In this case, we would expect them to be appreciably depleted in S and moderately depleted in Fe and Ni, the degrees of depletion of sulfides and metal depletion both increasing with decreasing Ni content of the metal. An alternative is that the chondritic inclusions were introduced by later shock-induced tectonism, in which case they need not be the immediate parent of the host metal, and also need not be depleted in the easily fusible elements. Examination of the analyses of Woodbine silicates by Jarosewich [45] and Campo del Cielo silicates by Wlotzka and Jarosewich [26] show S/Si and Fe/Si atom ratios factors 1.4 – 3 X lower than Cl-chondrite ratios (0.5 and 0.9, respectively). For Campo del Cielo this result is not unexpected, since there is evidence in some inclusions of depletion of plagioclase which requires still higher temperatures. However, the flat rare earth patterns in Woodbine silicates [16, 46] are not consistent with plagioclase depletion, yet FeS and Fe-Ni are low in these inclusions as well. We conclude that a sulfide-metal melt has been removed in varying proportions from these inclusions.

The next question is whether the chondritic materials have undergone diffusional exchange with the surrounding metal during the extensive metamorphic reheating recorded in the silicate textures. Bild [16] analyzed bulk inclusions from Landes, Campo del Cielo, Copiapo and Woodbine; Woodbine has the highest Ni content (106 mg/g) and thus offers the best test. Campo del Cielo showed sampling heterogeneities, probably because of the partial melting experienced by some inclusions. In the remaining 3 meteorites siderophile/Ni ratios were the same in silicate inclusions and metal to within a factor of 1.5, indicating extensive metamorphic interequilibration of the metal phases of the metal and inclusions, the less interesting of the two possibilities. Bild reported curiously high Ge contents of 600 – 1000 μg/g Ge in the kamacite of Campo del Cielo inclusions, 2 – 3 X higher than that in the host kamacite. We are at a loss to explain this apparent lack of equilibration, especially since the Ge/Ni ratios are also 4 – 6 X higher than CI ratios.

Sphalerite FeS Content as an Indicator of Burial Depth

Schwarz et al. [47] and Kissin [48] claim that the FeS concentration of sphalerite in IAB irons correlates with Ge (and thus, with Ni) concentrations. Such a trend might provide useful evidence bearing on our model. However, there is much compositional scatter among the sphalerite grains from individual irons and the reported correlation is mainly based on the low FeS content of Toluca sphalerite.

The mean sphalerite Fe contents are interpreted to imply very high pressures, suggesting that IAB irons were buried at depths of 300 – 400 km. Since such deep burial depths do not fit into our picture involving the generation of impact melt pools near the exterior of the parent body, we have examined the evidence on which the sphalerite barometer is based. The temperature dependence of sphalerite composition at 1-atm pressure is estimated from measurements by Barton and Toulmin [49] in the range 85 – 580 °C. A linear relationship between mole fraction FeS and T was assumed. The Barton-Toulmin data show considerable scatter, and we find that a log mole fraction FeS versus $1/T$

relationship can be fitted to them which yields IAB values at zero pressure and a temperature of ca. 250 °C. Until better low-temperature data are obtained there appears to be no requirement that IAB irons have been formed at burial depths of hundreds of km.

Isotopic Studies of C and O

Deines and Wickman [50, 51] studied the isotopic composition of C in various components of IAB irons. In silicate nodules $\delta^{13}C$ values ranged from -4 to $-13^{0}/_{00}$, but the presumably least altered complex from the interior of large inclusions showed a more restricted range of -4 to $-6^{0}/_{00}$. In contrast $\delta^{13}O$ in graphite is $6.0 \pm 1^{0}/_{00}$ and $20 \pm 2^{0}/_{00}$ in cohenite and taenite. The absence of data for kamacite apparently reflects its very small concentrations (< 0.1 mg/g) compared to taenite ($1-5$ mg/g) [34]. It seems safe to assume that the great bulk of the C in the metal-rich fraction is roughly equally divided between graphite and cohenite, and thus that $\delta^{13}C$ in host metal and associated phases is ~ -12, much lower than the ~ -5 value in the silicates. Without information about the C-bearing phases in the chondritic inclusions we cannot interpret these results. The correct answer may be the relatively trivial interpretation that (a) the C in the inclusions is mainly present as graphite, and (b) extensive exchange of C between inclusions and phases associated with the metal host has occurred.

The $\delta^{17}O - \delta^{18}O$ diagram of Clayton and Mayeda [24] shows that IAB irons roughly follow a slope 0.5 fractionation trend; as noted by Niemeyer [10], $\delta^{18}O$ increases with increasing Ni. Clayton et al. [52] showed that $\delta^{18}O$ is higher in meteorite plagioclase than in mafic minerals. Bild [16] and Wlotzka and Jarosewich [26] found evidence of plagioclase redistribution in Campo del Cielo. If there is a general trend for plagioclase depletion relative to the starting material with decreasing host Ni content (increasing sulfide-metal melt temperature), the $\delta^{18}O$-Ni trend is qualitatively explained.

Relationship between Recovered Mass and Ni Content

The decrease in mean mass with increasing Ni is readily recognizable when the data are compiled. One estimation of the maximum size reached by low-Ni irons is provided by the fact that 5 of them achieved sizes large enough to produce hypervelocity craters [34, 53]. The highest Ni concentration in a crater-producing iron is the 72 mg/g for Odessa, although Buchwald estimates 78 mg/g for the weathered Monturaqui material. In contrast, the largest recovered mass for high-Ni IAB and IIICD irons is 27 kg (Tazewell, IIICD) in the $125-200$ mg/g Ni range and 4 kg (San Cristobal, IB) for irons having Ni > 200 mg/g.

The increase in melt temperatures and increasing melt fraction with decreasing Ni would result in decreasing viscosity of the melt-solid mixture. This would make it easier for larger magma bodies to form. Further, since more shock energy was deposited at the low-Ni melt sites, there was probably a greater degree of shear, a factor which would also lead to move efficient separation of melt solids.

Formation Locations

Although the extrapolated compositions of the parental chondritic material of IAB and IIICD irons are nearly the same, the differences in log element-log Ni slopes of the daughter irons demonstrate that there were detailed differences in the compositions and sizes of phases in the parental material (e. g., more Ni in the sulfides or metal of IAB or more Ge and Ir in the oxides of IIICD). The mean Fe/(Fe + Mg) ratios in the mafic silicates are distinctly different in the two groups. Cosmic-ray ages in IAB clusters near 900 and 500 Myr [54]; those in IIICD cluster near 700 Myr (H. Voshage, private communication). For these reasons we conclude that the two groups could not have originated on the same body. On the other hand, the close similarities in the fractionation patterns of the irons and the Fe/(Fe + Mg) ratios in the silicates suggest formation at similar distances from the Sun.

Wasson [55] inferred an origin in the inner solar system for IAB irons because their O-isotope compositions and degrees of oxidation are similar to those of the Earth. Refractory abundances in IAB silicates scatter [56], but appear to fall in the same general range as the ordinary chondrites, also inferred to have formed in the inner solar system. Since the compositional evidence indicates that IIICD formed near IAB, we infer that it also formed in the inner solar system, i. e., nearer to the Sun than the carbonaceous chondrite groups. Although we would expect the IIICD O-isotope field to be different from the IAB field, we predict that it will be nearer to IAB than to other major meteorite groups such as the EH and EL chondrites.

Summary

We propose that IAB and IIICD meteorites represent individual melt pools formed by impacts on the megaregolithic surfaces of chondritic parent bodies. The observed concentration trends can be understood if the temperature of the melt pools decreased with increasing Ni concentration of the precipitated metal, and if the degree of equilibration between melt and unmelted solids decreased with decreasing temperature. Elements that decrease in concentration with increasing Ni remained largely trapped inside oxide grain aggregates during the formation of low temperature melts. Perhaps the most speculative feature of the model is its requirement that a large fraction of the Ge have been trapped in these hypothetical oxide aggregates.

The low-Ni extremes of IAB and IIICD offer the best estimates of siderophile ratios in the parental chondritic material. Maximum CI-chondrite normalized abundance ratios of volatiles are near 1.8, independent of condensation temperature; nonvolatile abundance ratios are near or below 1. The absence of a relative fractionation among volatiles indicates that the parental chondritic materials included nebular condensates at least as volatile as Ge, the most volatile siderophile. This probably requires efficient collection of fine-grained materials. That some volatile abundances in irons at the low-Ni extreme are higher than those in CI chondrites probably indicates that, relative to Ni and nonvolatile siderophiles, volatiles were preferentially incorporated into the melt pools. The alternative, that the chondritic parent had volatile levels 2 X greater than those in CI chondrites, seems less plausible.

Metallographic cooling rates of the IAB and IIICD iron meteorites are about 2 K/Myr, indicating either a burial depth of ~200 km, or a combination of a heat source and a smaller burial depth. We have proposed that these iron meteorites originated in impact melt pools, and this requires that the projectiles have had impact velocities $\gtrsim$ 3 km/sec. A gradual decrease in the rate of this bombardment could have controlled the cooling history of the IAB or IIICD irons. If this is correct, their burial depths cannot be estimated from cooling rates.

Meteoritic material from the surface of the regolith and from the unmelted interior of the parent body have not been recognized. The simplest explanation of this observation is that such materials would have been essentially chondritic, and thus much less resistant to space attrition. One can estimate from cosmic-ray age distributions that the half-life with respect to attrition of iron meteorites is ~600 Myr, that for reasonably tough chondrites (such as ordinary chondrites) about 50 X shorter.

Cosmic-ray age data of Voshage and Feldmann ([54]; Voshage, private communication) suggest major breakup events on the IAB body at 900 and 500 Myr, and on the IIICD parent body at 700 Myr. If these were the most recent breakup events of these parent bodies, the amount of chondritic material, with mean survival half lives of only ~12 Myr, would have been reduced by a factor of $\sim 2^{-40}$. Thus it is reasonable that the chondritic material from this parent body has not survived. The same general arguments apply to the sulfide-rich materials that should have occupied positions superior to the IAB and IIICD irons. Because FeS is much more easily fractured, collisions with small debris would have sand- and rock-blasted it off the metallic masses.

Much of our model is speculative, and will remain so until a considerably larger body of data has become available. The key evidence that is needed is knowledge about the hypothetical parental material. New IAB-related chondritic meteorites such as Pontlyfni are being discovered on a regular basis. Perhaps one of these will be sufficiently unmetamorphosed to allow us to determine, for example, where the Ga, Ge and refractory siderophiles were sited, and what the bulk volatile abundances were in the parental material. Especially interesting would be the discovery of relatively unmetamorphosed chondritic silicates in a Ni-rich member of one of these groups.

Acknowledgements

We have discussed the problem of IAB origins with Ed Scott on many occasions, and our proposed solution reflects these conversations in many ways; we also thank him for the use of unpublished data. We are indebted to Frank Kyte and Derek Sears for useful criticisms and suggestions, and to H. Voshage for the use of unpublished data. We thank J. Sells, A. Sohn, P. Tu for technical assistance. This research was supported in part by NASA grant NGR 05-007-329.

[1] E. R. D. Scott and J. T. Wasson, Rev. Geophys. Space Phys. **13**, 527 (1975).
[2] A. Kracher, J. Willis, and J. T. Wasson, Geochim. Cosmochim. Acta, in press. (1980).
[3] J. T. Wasson and J. Kimberlin, Geochim. Cosmochim. Acta. **31**, 2065 (1967).
[4] E. R. D. Scott, Geochim. Cosmochim. Acta **36**, 1205 (1972).
[5] J. T. Wasson, Icarus **12**, 407 (1970).
[6] J. T. Wasson, Geochim. Cosmochim. Acta **34**, 957 (1970).
[7] K. N. Alexeyeva, Meteoritika **16**, 67 (1958).
[8] G. J. Wasserburg and D. S. Burnett, In "Meteorite Research" (P. M. Millman, ed.), Reidel 1969, 467.
[9] F. A. Podosek, Geochim. Cosmochim. Acta **34**, 341 (1970).
[10] S. Niemeyer, Geochim. Cosmochim. Acta **43**, 843 (1979).
[11] S. Niemeyer, Geochim. Cosmochim. Acta **43**, 1829 (1979).
[12] E. R. D. Scott and R. W. Bild, Geochim. Cosmochim. Acta **38**, 1379 (1974).
[13] J. T. Wasson and R. Schaudy, Icarus **14**, 59 (1971).
[14] J. T. Wasson, Parent-body models for the formation of iron meteorites. Proc. 24th Int. Geol. Congr. **15**, 161 (1972).
[15] E. R. D. Scott, Origin of iron meteorites. In "Asteroids" (T. Gehrels, ed.) Univ. Ariz. 1979, p. 892.
[16] R. W. Bild, Geochim. Cosmochim. Acta **41**, 1439 (1977).
[17] W. R. Kelly and J. W. Larimer, Geochim. Cosmochim. Acta **41**, 93 (1977).
[18] J. Willis and J. T. Wasson, Elemental abundance patterns in iron meteorites: I planetary fractionations and mean compositions of the groups, in preparation (1980).
[19] D. York, Earth Planet. Sci. Lett. **5**, 320 (1969).
[20] A. Kracher and G. Kurat, Meteoritics **12**, 282 (1977).
[21] L. H. Fuchs, E. Olsen, and E. P. Henderson, Geochim. Cosmochim. Acta **31**, 1711 (1967).
[22] T. E. Bunch, K. Keil, and E. Olsen, Contrib. Mineral. Petrol. **25**, 297 (1970).
[23] P. Ramdohr, M. Prinz, and A. El Goresy, Meteoritics **10**, 477 (1975).
[24] R. N. Clayton, and T. K. Mayeda, Earth Planet. Sci. Lett., **40**, 168 (1978).
[25] J. T. Wasson, Geochim. Cosmochim. Acta **33**, 859 (1969).
[26] F. Wlotzka and E. Jarosewich, Smithsonian Contrib. Earth Sci. **19**, 104 (1977).
[27] E. R. Rambaldi, M. Cendales, and R. Thacker, Earth Planet. Sci. Lett. **40**, 175 (1978).
[28] F. Afiattalab and J. T. Wasson, Geochim. Cosmochim. Acta **44**, 431 (1980).
[29] E. R. Rambaldi and J. T. Wasson, Lunar Planet. Sci. XI, 914 (1980).
[30] C. M. Wai and J. T. Wasson, Nature London **282**, 790 (1979).
[31] R. T. Dodd, W. R. Van Schmus, and D. M. Koffman, Geochim. Cosmochim. Acta **31**, 921 (1967).
[32] D. W. Sears, Earth Planet. Sci. Lett. **41**, 128 (1978).
[33] G. Kullerud, R. A. Yund, and G. H. Moh, Fe-Ni-S systems. In Magmatic Ore Deposits (H. D. B. Wilson, ed.) Econ. Geol. Monographs, Econ, Geol. Pupl. Co., New Haven 1969, pp. 323.
[34] V. F. Buchwald, Handbook of Iron Meteorites. Univ. of Calif. Press, 1975, pp. 1418.
[35] D. J. Vaughan and J. R. Craig, Mineral Chemistry of Metal Sulfides, Cambridge University Press, 1978, pp. 493.
[36] C. L. Chou and A. J. Cohen, Geochim. Cosmochim. Acta **37**, 315 (1973).
[37] C.-L. Chou, P. A. Baedecker, and J. T. Wasson, Geochim. Cosmochim. Acta, **37**, 2159 (1973).
[38] E. R. Rambaldi and M. Cendales, Earth Planet. Sci. Lett. **44**, 397 (1979).
[39] J. T. Wasson and C. M. Wai, Nature London **261**, **114** (1976).
[40] C. M. Wai and J. T. Wasson, Earth Planet. Sci. Lett. **36**, 1 (1977).
[41] L. Grossman and J. W. Larimer, Rev. Geophys. Space Phys. **12**, 71 (1974).
[42] H. Palme and F. Wlotzka, Earth Planet. Sci. Lett., **33**, 45 (1976).
[43] M. Blander, L. H. Fuchs, C. Horowitz, and R. Land, Geochim. Cosmochim. Acta **44**, 217 (1980).
[44] C.-L. Chou, P. A. Baedecker, and J. T. Wasson, Geochim. Cosmochim. Acta **40**, 85 (1977).
[45] E. Jarosewich, Geochim. Cosmochim. Acta **31**, 1103 (1967).
[46] T. Fukuoka and R. A. Schmitt, Lunar Planet. Sci. IX, 359 (1978).
[47] H. P. Schwarcz, S. D. Scott, and S. A. Kissin, Geochim. Cosmochim. Acta **39**, 1457 (1975).
[48] S. A. Kissin, Meteoritics **14**, 444 (1979).
[49] P. B. Barton and P. Toulmin, Econ. Geol. **61**, 815 (1966).
[50] P. Deines and F. E. Wickman, Geochim. Cosmochim. Acta **37**, 1295 (1973).
[51] P. Deines and F. E. Wickman, Geochim. Cosmochim. Acta **39**, 547 (1975).
[52] R. N. Clayton, N. Onuma, and T. K. Mayeda, Earth Planet. Sci. Lett. **30**, 10 (1976).
[53] J. T. Wasson, Meteorites. Springer-Verlag, New York 1974, pp. 316.
[54] H. Voshage and H. Feldmann, Earth Planet. Sci. Lett. **45**, 293 (1979).
[55] J. T. Wasson, Relationship between the composition of solid solar-system matter and distance from the Sun. In "Comets Asteroids Meteorites: Interrelations, evolution and origins" (A. H. Delsemme, ed.), Univ. Toledo, 1977, p. 551.
[56] P. H. Warren and J. T. Wasson, Effects of pressure on the crystallization of a "chondritic" magma ocean and implications for the bulk composition of the moon. Proc. Lunar Planet. Sci. Conf. 10th, Suppl. Geochim. Cosmochim. Acta 1979, p. 2051.