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Compositional range in the Canyon Diablo meteoroid

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Abstract—The Ir distribution in the IAB Canyon Diablo meteorites associated with the formation of Meteor Crater, Arizona, ranges from 2.1 to 2.5 μg/g with peaks at 2.17 and 2.34 μg/g. Only Ir, Ni, and Cu show appreciably more variance in the large set of specimens than observed within a single specimen. The Ir peaks may reflect random sampling of the large (40–100 m), fractionated meteoroid or the presence of two distinct metallic regions differing in composition. None of the other elements we determined show strong correlations with Ir; the Au range is strikingly small (1.5–1.6 μg/g). The presence of chondritic silicates and high contents of planetary-type noble gases in IAB indicates that these solidified rapidly following melting, as expected if they originated as pools of impact-generated melt on a chondritic body. The absence of fractional crystallization trends is consistent with such a model. That 14 of 15 Ir contents fall into two "peaks" suggests the possibility that the meteoroid included two "pools." The alternative that the distribution is continuous can be tested by the study of additional specimens; those from the crater rim are particularly important since these are largely shrapnel spalled from the trailing hemisphere of the meteoroid.

Our studies show that the irons named Helt Township, Idaho, Las Vegas, Mamaroneck, Moab, and Pulaski County are probably mislabelled Canyon Diablo specimens; Jenny's Creek and Jenkins are also compositionally indistinguishable. Alexander County, Allan Hills A77283, Ashfork, Fairfield, and Rifle are compositionally distinct, independent falls.

INTRODUCTION

IT IS COMMON TO analyze one or two small (ca. 1 g) samples of an Fe meteorite and assume that the results yield the mean composition of the meteoroid to within the analytical uncertainty. However, the study by ESBENSEN et al. (1982) of different masses of the Cape York IIIAB iron revealed ranges in As, Ir, and Au of factors of approximately 2. The lowest Ir and highest Au and As values were in a 20-ton mass having a modal FeS content nine times higher than normal, an indication of an anomalously high content of trapped liquids. In contrast, a study of 16 samples from the periphery of the 30-t Armanty (or Xinjiang) IIIE iron showed all samples except one to have compositions insignificantly different from the mean, and the most extreme elements in the exceptional sample differed only 10–20% from the mean (WASSON et al., 1988).

The 13 groups of Fe meteorites are divided into 10 magmatic groups that show the compositional trends expected from fractional crystallization and 3 nonmagmatic groups (IAB, IIICD, IIE) that, on log element-log Ni diagrams, show much lower slopes not simply associated with fractional crystallization. Members of the nonmagmatic groups commonly contain planetary-gas-rich (sub-)chondritic silicates and relatively large fractions of FeS or other nonmetallic phases. WASSON et al. (1980) concluded that the gas-rich silicates and the low element-Ni slopes of group IAB were inconsistent with an origin in a large, high-temperature magma, and suggested that a more plausible origin was as individual pools of shock melt having dimensions ranging from several centimeters to tens of meters.

Geometric arguments suggest that fractionation on a scale of meters is more probable for irons originating as impact melts in which pools are comparable in size to the meteoroids than in the magmatic irons that originated in km- to 100-km-size cores. Thus it seemed particularly appropriate to study the largest nonmagmatic iron of them all, the Canyon Diablo (for convenience generally abbreviated to CD) meteoroid whose diameter is estimated to have been 40–100 m based on the energy required to excavate the (Barringer) Meteor Crater (see later discussion).

As emphasized by NININGER (1950), HEYMANN et al. (1966), and MOORE et al. (1967), the Fe meteorites found near Meteor Crater can be divided into the rim specimens, which tend to be smaller and heavily shocked, and the plains specimens, which tend to be larger and lightly or moderately shocked. The rim specimens are believed to be shrapnel mainly from the rear hemisphere of the projectile that made the crater. Some, possibly most, of the plains specimens appear to be fragments that detached from the meteoroid during atmospheric passage and were slowed to terminal velocities (<1 km s^{-1}) before impact. As noted by BUCHWALD (1975), such specimens should show heat-altered zones resulting from atmospheric friction. He states that such zones are observed on the largest CD masses but does not provide documentation. We did not observe this zone on any of our samples, but weathering may have removed it from most exterior surfaces, and our petrographic study was not exhaustive enough to show that it was not present. Included in this study are six large CD meteorites from known plains locations 5–7 km from Meteor Crater; their recovery sites are shown in Fig. 1.

An additional reason to define the compositional range

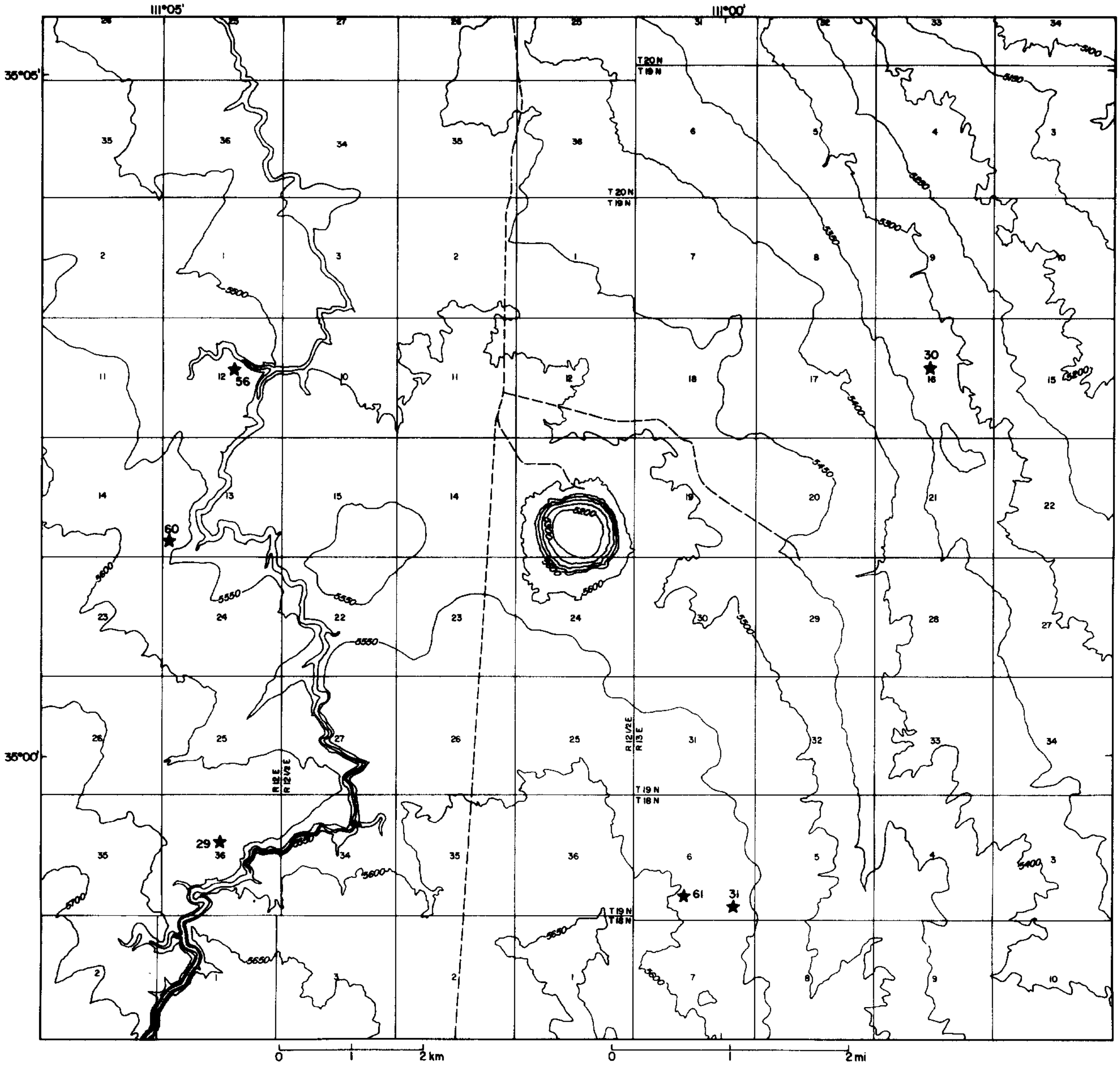

FIG. 1. Recovery locations of six Canyon Diablo meteorites from known sites 5–7 km from Meteor Crater. Contour intervals are 50 ft (~15 m). The last two digits of the specimen numbers are shown.

within the Canyon Diablo meteoroid has to do with its extremely wide distribution among meteorite collections. In addition to >20 fragments having masses >100 kg, perhaps 10^5 fragments having masses between 100 g and 100 kg have found their way into virtually every meteorite collection in the world. As a result of accidental or deliberate mislabelling, tens of these smaller Canyon Diablo specimens have masqueraded as new meteorites until careful structural and compositional studies have provided strong circumstantial evidence that mixups are involved (WASSON, 1968; BUCHWALD, 1975). It is essential to define the compositional range in certified Canyon Diablo specimens in order to provide a basis for recognizing whether or not new IAB irons should be interpreted as transported CD irons. Cases in point are a new iron from Fairfield, Ohio, USA, which has a structure and composition similar to that of Canyon Diablo, and the Allan Hills A77283 iron which is not only compositionally and structurally closely related to Canyon Diablo but is also the only other Fe meteorite known to contain diamonds (CLARKE et al., 1981).

As demonstrated in WASSON et al. (1989), improvements in our neutron activation techniques allow us to achieve unprecedented precision for several elements, particularly Co, As, Au, and Ir. Our recent studies confirm that resolvable compositional differences exist between different specimens of Canyon Diablo. To define the entire range we have analyzed a suite of specimens collected from known locations near the crater and compared them with other Arizona octahedrites that appear to be prehistorically transported CD samples. Additional irons that are more-or-less similar in composition were included to broaden the comparison.

SAMPLES

Our set of CD samples consisted of nine irons collected within 7 km of Meteor Crater, four Arizona IAB irons (Bloody Basin, 5 kg; Camp Verde, 62 kg; Fossil Springs, 5 kg; Houck, 67 kg) that WASSON (1968) identified as transported Canyon Diablo fragments, and irons from Las Vegas, Nevada (>3 kg), and Moab, Utah (20 kg), that BUCHWALD (1975) suggested were transported CD fragments, an inference supported by our new data. Because of their large masses (≥20 kg), we infer that Camp Verde, Houck, and Moab are plains specimens. The nine irons collected near the crater consisted of CD965 (UCLA specimen 965), probably a rim specimen, original mass ca. 500 g; CD2 (Arizona State University specimen 371.2), original mass ca. 100 g, one of 5 specimens (total mass 1.6 kg) designated Canyon Diablo No. 2 by NININGER (1940) and Canyon Diablo (1936) by the British Museum catalog (GRAHAM et al., 1985); CD81 (UCLA 81), probably a plains specimen, mass 19.4 kg; CD1256 (UCLA 1256), a ca. 630 g plains specimen collected in section 12, township (t) 19N, range (r) 12E, about 5.2 km WNW of the center of Meteor Crater; CD1260 (UCLA 1260), a 5.0 kg specimen collected in the SW corner of section 13, t 19N, r 12E, 5.5 km W of the crater center; CD1261 (UCLA 1261), a 1.75 kg specimen collected in the south central part of section 6, t 18N, r 13E, about 5.1 km SSE of the crater center; CD1529 (Smithsonian Institution [SI] specimen 1529), a 20.0 kg plains specimen recovered from section 36, t 19N, r 12E, about 6.5 km SW of the crater center; CD1530 (SI 1530), a 15.5 kg plains specimen recovered from section 16, t 19N, r 13E, about 5.3 km ENE of the crater; and CD1531 (SI 1531), a 30.7 kg plains specimen from the SE quarter of section 6, t 18N, r 13E, about 5.0 km SSE of the crater center. The latter three samples were collected or obtained by H. H. Nininger; CD1256 was recently obtained from Steven Schoner, and CD1260 and CD1261 from Bob Harrison. Locations of the latter six samples are shown on Fig. 1.

We also analyzed a sample of Canyon Diablo No. 3 (called Canyon Diablo (1949) in GRAHAM et al., 1985); as discussed in the Appendix our data are inconsistent with it being part of Canyon Diablo. Among our set of comparison samples we included two other Arizona IAB irons—Seligman and Ashfork. WASSON (1968) showed Seligman to be compositionally distinct, but Ashfork was attributed to Canyon Diablo by WASSON (1968) and BUCHWALD (1975). We also included the IAB iron from Rifle, Colorado, that BUCHWALD (1975) inferred to be transported Canyon Diablo material, and the geographically ill-located Helt Township, Idaho, Mamaroneck, and Pulaski County IAB irons having compositions and structures similar enough to Canyon Diablo to suggest that they are human transported CD material (BUCHWALD, 1975; SCOTT and WASSON, 1976). Because of its importance we carried out new INAA on the diamond-bearing Allan Hills A77283 iron and the compositionally similar Purgatory Peak A77006 iron; we also analyzed the new Fairfield iron mentioned above.

An interesting and related question is whether there are irons originating from locations distant from Meteor Crater whose provenances seem well defined but whose compositions are unresolvable from Canyon Diablo. On the basis of our published Ge and unpublished Ir data we have selected a set of such irons having Ge contents between 300 and 350 μg/g and Ir contents between 2.0 and 2.5 μg/g. The four irons yielded by this screening are from Jenkins, Missouri, USA; Jenny's Creek, West Virginia, USA; Vaalbult, South Africa; and Youndegin, Western Australia, Australia.

ANALYTICAL TECHNIQUES

The instrumental-neutron-activation-analysis (INAA) procedure is that described by WASSON et al. (1989). Samples were cut to 3.2 ± 0.3 mm thickness and to masses of 530 ± 90 mg; surfaces were cleaned with SiC paper and, if necessary, with a stainless steel dental drill. After irradiation for 4 h in the lazy susan of the Triga nuclear reactor at the University of California, Irvine, the samples are cleaned by a light etch and mounted onto cards for counting. Standards include solutions pipetted onto 3.2 mm thick hydrophilic polyethylene, the Filomena IIAB hexahedrite, the Odessa and Canyon Diablo IAB octahedrites, and NBS standard steel 809B. Samples are counted four times over a period of four weeks. Large, well-defined gamma-ray peaks are integrated by algorithms in the SPECTRA program of BAEDECKER and GROSSMAN (1989). Poorly defined peaks are plotted and integrated by the analyst using computer graphics software.

Each sample is analyzed two or more times in separate irradiations. Canyon Diablo specimens differing in Ir content were analyzed together; thus, it is certain that the distinctive Ir variations are real and not irradiation-specific artefacts.

RESULTS: COMPOSITION OF THE CANYON DIABLO METEOROID

Analytical Precision and Sampling Variations

The reproducibility of our procedure can be judged by the data listed in Table 1 for CD965, which was analyzed 21 times between 1983 and 1990. This sample was a secondary standard in the 21 runs; thus, the standard deviations are artificially low. However, because Filomena and NBS 809B were the primary standards and are more homogeneous, the standard deviations are only a few percent lower than they would have been had CD965 not been a secondary standard. This small effect plays no role in the subsequent discussions in this paper. We list INAA Ge and Sb data only for those irons for which no radiochemical neutron activation data are available; when the more precise radiochemical Ge and Sb data were available, they were given much more weight in the listed means.

The standard deviations listed in Table 1 reflect a combination of sampling variations within a single small specimen and analytical uncertainties. In contrast, the standard deviations listed for 15 CD specimens in Table 2 represent specimen-to-specimen variations that in part reflect real compositional differences. All Table 2 data are means from replicate analyses; thus, we would expect the relative standard deviations to be smaller (by about $\sqrt{2}$) than those in Table 1, if there were no large-scale compositional variations within the meteoroid. For most elements the standard deviations in Table 2 are lower, an indication that interspecimen variations are small compared to analytical and phase-sampling uncertainties. However, for Ir the standard deviation in Table 2 is much larger and for Cu marginally larger than that in Table 1, an indication of resolvable interspecimen differences for these elements.

A Multimodal Ir Distribution?

The Ir concentrations appear to be multimodal. Two histograms are shown in Fig. 2: one for each of the 15 CD spec-

Table 1. Concentrations of 13 elements in Canyon Diablo sample 965. Concentrations in μg/g except Ni and Co (mg/g) and Sb, W and Re (ng/g).

date	Cr	Co	Ni	Cu	Ga	Ge	As	Sb	W	Re	Ir	Pt	Au
1083	13	4.46	68.4	164	86.9	---	15.7*	---	1110	260	2.03*	---	1.70*
0685	20	4.80	68.7	152	87.4	---	13.4	490*	740	280	2.11	---	1.63
0885	30	4.57	67.6	142	80.1	---	11.9	370	860	200	2.05	---	1.59
1285	21	4.61	68.0	146	81.5	---	11.5	270	1160	200	2.15	---	1.48
0186	24	4.75	69.7	147	81.9	---	12.5	290	1520*	200	2.16	---	1.61
0286	17	4.74	67.5	146	86.6	---	13.5	300	1010	220	2.42*	---	1.65
0386	26	4.52	67.8	148	80.8	310	12.7	290	1020	220	2.21	4.1*	1.63
0486	31	4.53	71.4	149	80.2	330	12.2	300	1160	240	2.13	---	1.47
0686	32	4.74	69.6	145	84.5	300	12.2	310	860	240	2.18	6.5	1.48
1086	28	4.52	70.0	146	79.2	220*	11.7	250	1040	190	2.07	4.6	1.49
1286	33	4.43	68.5	160	79.4	360	12.3	250	1070	220	2.07	6.0	1.43
0487	9*	5.02	70.9	147	88.1	320	14.5	390	840	210	2.20	6.5	1.63
0488	18	4.73	68.6	145	82.6	320	12.8	270	950	210	2.17	4.9	1.58
0688	27	4.67	69.4	141	81.3	320	13.0	310	1060	190	2.12	6.6	1.57
0289	18	4.73	71.3	150	86.2	330	13.7	300	1040	250	2.29	7.0	1.65
0489	26	4.83	68.2	138	86.3	330	12.7	290	860	230	2.16	6.3	1.62
0689	16	4.86	71.2	145	82.3	330	12.6	290	790	250	2.18	6.9	1.65
1089	38*	4.56	71.3	154	82.1	310	12.7	250	1230	220	2.19	5.9	1.55
0190	22	4.68	65.6	141	86.9	340	13.0	300	960	210	2.31	6.2	1.60
0390	26	4.79	67.8	149	84.0	280	12.7	250	1010	260	2.22	7.8	1.55
0490	24	4.79	71.5	148	91.1	330	13.3	320	1030	290	2.21	6.2	1.61
mean	24	4.68	69.2	148	83.8	322	12.7	295	990	228	2.17	6.3	1.57
s+	24	3.2	2.4	4.1	4.0	5.9	5.6	13	13	12	3.1	13	6.9

* not included in mean

+ relative standard deviation in %

Table 2. Mean compositions of 15 Canyon Diablo iron meteorite specimens. Concentrations in µg/g except Ni and Co (mg/g) and Sb, W and Re (ng/g).

meteorite	n*	Cr	Co	Ni	Cu	Ga	Ge	As	Sb	W	Re	Ir	Pt	Au
CD965	21	24	4.68	69.2	148	83.8	322	12.7	295	990	228	2.17	6.3	1.57
CD2^	2	26	4.67	75.9	224	84.8	340	12.8	270	1360	280	2.24	5.6	1.56
CD81	2	22	4.66	69.5	148	84.1	340	13.7	300	1220	260	2.34	5.6	1.53
CD1256	2	31	4.52	70.1	160	81.3	310	13.1	280	1160	230	2.36	5.7	1.55
CD1260	2	29	4.63	67.9	160	84.4	310	12.6	350	1060	250	2.30	6.0	1.56
CD1261	2	24	4.64	68.6	140	84.0	320	13.3	330	1010	280	2.53	7.4	1.54
CD1529	2	21	4.66	68.6	150	81.2	330	13.4	250	1070	230	2.21	6.0	1.54
CD1530	2	18	4.66	70.4	170	81.0	320	13.2	300	1010	210	2.14	6.6	1.52
CD1531	2	21	4.66	66.5	144	80.3	320	12.8	250	1010	250	2.39	6.0	1.56
Bloody Basin	2	27	4.60	69.6	150	78.7	330	12.2	290	880	230	2.32	5.4	1.57
Camp Verde	3	24	4.67	69.9	146	81.6	330	13.3	260	980	290	2.34	6.1	1.55
Fossil Springs	2	28	4.54	70.2	151	79.7	300	12.0	240	1010	240	2.32	6.4	1.53
Houck	2	18	4.76	69.1	146	83.1	360	13.4	270	1230	270	2.18	6.6	1.58
Las Vegas	2	26	4.66	68.0	135	79.7	280	12.7	290	1040	210	2.10	5.9	1.53
Moab	2	27	4.62	69.8	145	85.2	330	13.3	320	1100	270	2.24	6.6	1.50
mean	-	24	4.64	69.1	150	82.0	321	13.0	288	1055	246	2.28	6.2	1.54
s+ (%)	-	1.6	1.3	1.6	5.9	2.5	5.9	3.8	11	9.1	11	5.3	8.3	1.4

* n is the number of replicate samples included in the mean
+ relative sample standard deviation
^ Results for Canyon Diablo No. 2 not included in the mean or standard deviation

imen means listed in Table 2, and one for means of successive CD965 analyses (not included are the first two analyses and the 2.42 μg/g value). By plotting the means of two analyses we obtain a precision similar to that applicable to the 15 means in the upper histogram.

With so few specimens it is not possible to determine the modality of CD Ir distribution. However, comparison with the CD965 histogram (Fig. 2) shows that the data are consistent with 14 of the 15 CD samples having originated in two compositionally distinct reservoirs each as uniform as our CD965 standard. Calculated standard deviations for the two peaks are essentially the same as that observed for CD965 (Fig. 2).

Application of the Kolmogorov-Smirnov test shows that it is possible to account for the Ir distribution of the full set of 15 CD means by random sampling of a Gaussian distribution having the calculated mean and standard deviation (2.28 ± 0.11). Application of the χ^2 test shows that the 14 results in the two "peaks" are also consistent with random sampling of a continuous range of Ir concentrations extending from 2.10 to 2.39 μg/g. Until more data are available the question of whether the full set of CD specimens shows zero, one, or multiple modes cannot be resolved. Because the presence of two or three modes has important implications for the nature of the IAB meteoroid and the origin of group IAB, we will assume, for purposes of our later discussion, that there are three populations, one at 2.17 ± 0.05 (CD2 was excluded), one at 2.34 ± 0.03, and an isolated value at 2.53 μg/g.

In Fig. 3 we plot Co, Cu, Ga, As, Sb, and Au vs. Ir for the Canyon Diablo specimens listed in Table 2 and for Canyon Diablo No. 3. With the exception of the high Cu in CD2 (which also has an anomalous Ni content—see discussion in the Appendix), the distributions for elements other than Ir appear to be consistent with random distributions about the mean. As noted above, the ranges and standard deviations for the 15 specimens are approximately the same as those observed in the CD965 specimen. Note that the relative standard deviations for elements other than Cu and Ir are lower in Table 3 by the factor of $\sim\sqrt{2}$ anticipated because each Table 2 value is the mean of two (in two cases, more) analyses. The Ni range is also larger if the CD2 value is included in the set. Particularly striking is the limited range of Au concentrations, which is smaller than anticipated from the CD965 replicates.

Inspection of Table 2 and Figs. 2 and 3 shows that the six irons attributed to Canyon Diablo are indistinguishable from the CD irons. For most elements the inclusion of the six irons in the CD set causes a negligible shift in the mean and only a minor increase in the range. Although we cannot state with certainty that none of these irons is an independent fall, the results are consistent with the conclusion that all are transported CD specimens. The incorrect inclusion of one independent fall in Table 2 would mainly affect Ir; the maximum resulting change in the Ir mean would be about 0.011 μg/g, or a 0.5% relative change.

The specimen called Canyon Diablo (1949) or Canyon Diablo No. 3 falls outside four of the six fields, and also differs in its Ni and W contents; as discussed in the Appendix, it appears to be mislabelled.

Other Irons Possibly Related to Canyon Diablo

In Table 3 we list the compositions of several irons that are probably mislabelled samples of Canyon Diablo, some that have been attributed to Canyon Diablo but are compositionally distinct, and some that are independent falls but compositionally very similar to Canyon Diablo. These are discussed in the Appendix.

POSSIBLE LOCATIONS OF CANYON DIABLO METEORITES ON THE PREATMOSPHERIC METEOROID

Recent estimates of the energy released during formation of Meteor Crater range from $6 \cdot 10^{16}$ J (RODDY et al., 1980) to $25 \cdot 10^{16}$ J (SCHMIDT, 1980); we will use a geometric mean of these values, $1.2 \cdot 10^{17}$ J. E. M. SHOEMAKER (priv. comm., 1990) notes that these energy estimates are for vertical incidence; Eqn. (7.8.1c) of MELOSH (1989) shows that the energy should be increased by a factor of $(\sin\theta)^{-1.19}$ where θ is the incidence angle. SHOEMAKER (1962) showed that, a priori, the most probable incidence angle is 45°; this would increase the estimated energy by a factor of 1.5 to $1.8 \cdot 10^{17}$ J. The orbits of Earth-crossing asteroids lead to a mean impact velocity with the Earth of 20 (SHOEMAKER, 1983) or 18 km s^{-1}

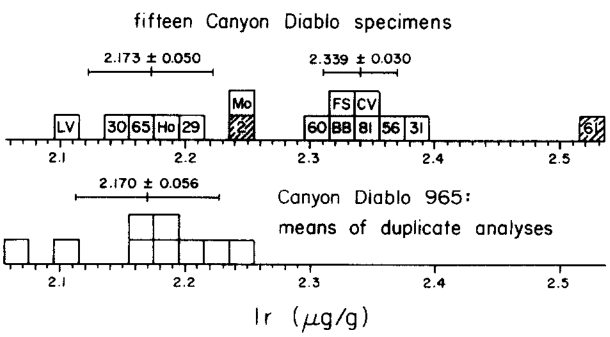

FIG. 2. Iridium shows a bimodal distribution in Canyon Diablo samples. Means and standard deviations of these modes are shown based on the assumption that they are independent populations. The last two digits are shown for Canyon Diablo specimens; initials or initial and first letter are used to designate mislabelled specimens.

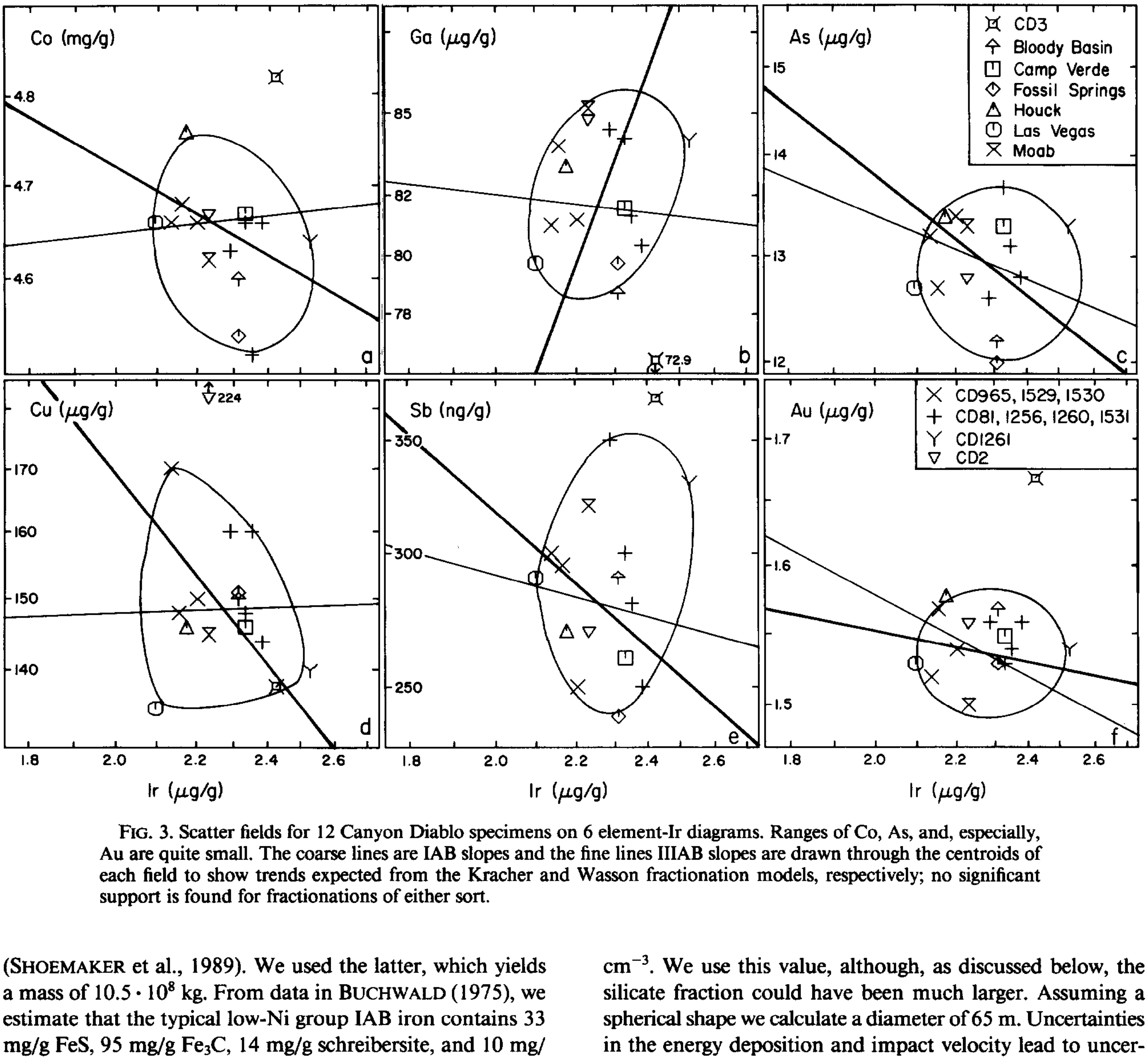

FIG. 3. Scatter fields for 12 Canyon Diablo specimens on 6 element-Ir diagrams. Ranges of Co, As, and, especially, Au are quite small. The coarse lines are IAB slopes and the fine lines IIIAB slopes are drawn through the centroids of each field to show trends expected from the Kracher and Wasson fractionation models, respectively; no significant support is found for fractionations of either sort.

(SHOEMAKER et al., 1989). We used the latter, which yields a mass of $10.5 \cdot 10^8$ kg. From data in BUCHWALD (1975), we estimate that the typical low-Ni group IAB iron contains 33 mg/g FeS, 95 mg/g Fe_3C, 14 mg/g schreibersite, and 10 mg/g chondritic silicates; these lead to a mean density of 7.63 g cm^{-3}. We use this value, although, as discussed below, the silicate fraction could have been much larger. Assuming a spherical shape we calculate a diameter of 65 m. Uncertainties in the energy deposition and impact velocity lead to uncertainties in the diameter approaching a factor of two; the diameter was probably in the range 40–100 m.

Table 3. Concentrations of 13 elements in 11 IAB irons compositionally, structurally or geographically related to Canyon Diablo but now held to be independent; the final line gives the Canyon Diablo mean from Table 2. Concentrations in μg/g except Ni and Co (mg/g) and Sb, W and Re (ng/g).

meteorite	Cr	Co	Ni	Cu	Ga	Ge	As	Sb	W	Re	Ir	Pt	Au
Canyon Diablo	**24**	**4.64**	**69.1**	**150**	**82.0**	**321**	**13.0**	**288**	**1055**	**246**	**2.28**	**6.2**	**1.54**
Speculatively linked to CD and compositionally unresolvable													
Helt Township	27	4.66	68.4	142	83.1	360*	12.4	270	1160	240	2.33	7.8	1.54
Idaho	23	4.66	72.2	157	83.6	320	13.4	290	1060	260	2.49	4.9	1.56
Jenkins	28	4.56	69.1	151	87.1	353	13.1	340	1190	250	2.16	-	1.56
Jenny's Creek	23	4.71	68.0	141	83.4	320*	13.6	350	1140	280	2.37	5.7	1.53
Mamaroneck	29	4.68	67.9	149	82.5	360*	12.8	370	1040	240	2.45	6.2	1.53
Pulaski County	25	4.64	67.1	156	79.4	330	12.1	280	1000	220	2.18	6.8	1.56
Speculatively linked to CD but compositionally distinct													
Alexander Co.	29	4.55	64.6	142	100.	520	11.2	260	1630	330	3.63	11.0	1.44
ALHA77283	26	4.87	70.3	141	78.8	300	14.8	320	1030	220	2.19	7.0	1.71
Ashfork	24	4.62	69.8	140	82.0	330	12.6	260	1020	320	2.69	6.0	1.53
Canyon Di.No.3	22	4.82	78.1	138	72.9	320*	16.2	370	3520	240	2.43	5.3	1.67
Fairfield	19	4.67	69.0	140	78.4	340	12.8	260	1000	160	1.78	5.8	1.54
Rifle	25	4.64	69.9	137	77.7	285	14.4	360	940	210	1.81	5.6	1.61
Seligman	30	4.58	66.9	162	93.0	423	12.1	340	1280	330	3.30	7.2	1.49
Independent but compositionally similar to CD													
PGPA77006	23	4.73	70.9	145	79.0	284	14.7	310	910	230	2.29	5.4	1.57
Vaalbult	32	4.54	68.4	145	83.7	323	14.8	-	1240	280	2.13	-	1.59
Youndegin	26	4.70	69.1	147	85.2	330	12.9	300	1070	220	2.16	5.4	1.52

* INAA Ge value

The two possible mechanisms that led to survival of CD material as meteorites are (1) detachment from the main mass during atmospheric passage and aerodynamic deflection into new trajectories that allowed them to be slowed to terminal velocity and to impact in regions outside the crater, or (2) the spalling-off of material, mainly from the rear hemisphere of the meteoroid, by the shock wave during impact, and entrainment together with crater ejecta. Materials removed by the first mechanism would probably have originated along the "equatorial band" of the meteoroid whose axis is defined to be the diameter parallel to its motion through the atmosphere. Given equal probabilities of detachment along the equator, these fragments would be separated by up to the full diametric distance of ~65 m, and the mean separation distance would be about 0.60 of the diameter, or ~40 m. Materials removed by spalling during the impact would mainly be detached from the trailing hemisphere of the meteoroid with the yield probably increasing with latitude. We suggest that mean separation distances of sharpnel were two to three times smaller than those of fragments detached during flight.

FRACTIONATION WITHIN THE CANYON DIABLO METEOROID

Solid-State Differentiation

The irons belonging to groups IAB (and IIICD) contain large amounts of troilite (often intermixed with graphite), cohenite, and schreibersite. WASSON (1967) suggested that the moderately large Ni variations in CD specimens might reflect local differences in the relative abundance of taenite and kamacite related to the formation of these phases. Cohenite abundances vary on a scale of tens of cm; patches 10–20 cm across with cohenite in the centers of most kamacite lamellae are adjacent to similar-size patches with no visible cohenite. Because it is sited in the centers of kamacite lamellae, it appears that cohenite nucleated together with the earliest kamacite that formed after the material cooled across the $\gamma/(\alpha + \gamma)$ boundary. Carbon diffused into these regions from the nearby metal. Simultaneously, diffusion increased the Ni contents in the low-C regions and further delayed kamacite nucleation. When kamacite in these high-Ni, low-C regions precipitated (thus fixing the bulk Ni), their higher Ni contents would have resulted in higher taenite/kamacite ratios, lower Co concentrations (Co partitions into kamacite), and higher concentrations of the other siderophiles (that preferentially partition into taenite) relative to those in the cohenite-rich regions.

This model is not supported by element-cohenite trends (Table 4). Examination of polished sections adjacent to the analyzed sample showed that lamellar cohenite was abundant in five CD irons and not recognizable in eight; cohenite was abundant in one of the three small examined pieces of Houck. We simplified the elemental data by dividing them into high, intermediate, and low ranges. The intermediate ranges are defined as follows: $2.25 < \text{Ir} < 2.31$ µg/g, $68.5 < \text{Ni} < 69.8$ mg/g, and $4.62 < \text{Co} < 4.68$ mg/g. The tabulated data show no correlation between cohenite and composition.

The interrelationships between Co, Ni, and Ir in the irons listed in Table 2 can be examined on Figs. 4 and 2a. The Co-Ni diagram (Fig. 4a) shows no significant correlations with ($r = +0.11$) or without ($r = -0.14$) inclusion of CD2. The lack of a pronounced correlation is not unexpected, since the metal is dominantly (>95%) high-Co kamacite in both types of regions, and relative differences in Co resulting from this mechanism should be <2%. The Ni-Ir data (Fig. 4b) show no correlation ($r = -0.10$; -0.13 without CD2). The Co-Ir data (Fig. 2a) show a significant negative trend ($r = -0.39$, $2\alpha = 0.16$) that is enhanced if the high Ir sample CD1261 is omitted ($r = -0.49$, $2\alpha = 0.08$). This correlation and the relatively high negative slope between -0.2 and -0.3 are surprising, and inconsistent with the minor Co differences that should result from small differences in taenite/kamacite ratios. Considered together with the absence of a Ni-Ir correlation, they seem more consistent with the sample set originating in two or more chemically distinct regions. Considered together this evidence suggests that interspecimen differences in the kamacite/taenite ratio on a ca. 10-cm scale played only a minor role in generating the observed interspecimen compositional variations.

Table 4. Relationsip between Ir, Co and Ni concentrations and the cohenite content of Canyon Diablo specimens. See text for details.

	Ir	Ni	Co
High cohenite			
Fossil Springs	H	H	L
CD81	H	I	I
CD965	L	I	I
CD1256	H	H	L
CD1260	H	L	I
Intermediate cohenite			
Houck	L	I	H
Low cohenite			
Bloody Basin	H	I	L
Camp Verde	H	I	I
Las Vegas	L	L	I
Moab	L	I	I
CD2	L	H	I
CD1261	H	I	I
CD1529	L	I	I
CD1530	L	H	I
CD1531	H	L	I

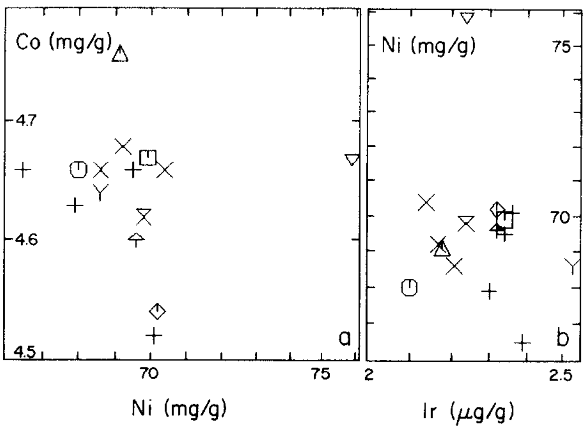

FIG. 4. The 11 Canyon Diablo specimens yield only weak or negligible correlations between Ni and Ir and between Co and Ni. Only a minor portion of the observed fractionations can be attributed to variable kamacite/taenite ratios.

Solid-liquid Differentiation

Slopes on log-log element-Ni diagrams are very different in IAB than in typical magmatic groups such as IIIAB. With a few exceptions (particularly interesting are Ga and Ge) the absolute slopes in IAB are appreciably lower than those in IIIAB.

Two models have been offered to explain the IAB trends. WASSON et al. (1980) proposed that IAB irons represent pools of shock melt produced by impacts in a chondritic body similar in bulk composition to the (compositionally) "chondritic" silicate inclusions present in many IAB irons (e.g., WLOTZKA and JAROSWICH, 1977); the greater the density of released impact energy, the greater the degree of melting, the lower the Ni content, and the higher the content of most other elements. In support of this impact-melting model are the common presence in IAB of silicates (an indication of rapid solidification after the melting event), the presence of planetary-type rare gases and radiogenic ^{129}Xe (an indication that the meteorites formed early in solar system history from an I-rich precursor and that the high-temperature event was of brief duration), and an observed decrease in meteoroid size with increasing Ni content (an indication that the amounts of heat deposition decreased with increasing Ni content of the resulting melt). KRACHER (1985) proposed that, like the magmatic groups, IAB irons formed by fractional crystallization of a core. He attributed the large differences in the observed element-Ni slopes to a S content of the IAB melt much higher than those in the magmatic groups and suggested that IAB crystallized along the metal-FeS cotectic. The observation that low-temperature cooling rates are the same in all IAB irons supports this core-type model.

The two models offer differing predictions regarding the igneous fractionation trends within a single large meteoroid. According to Kracher's model the trends within a meteoroid should be (1) weak-to-nonexistent if the core were large (>1 km) or (2) similar to those in group IAB as a whole if the core dimensions were ≤ 10 times that of the meteoroid. According to the WASSON et al. (1980) model the trends should (1) be weak-to-nonexistent if the melt pool underwent rapid solidification, or (2) moderately strong and similar to those in the magmatic groups if cooling were slow enough to permit appreciable fractional crystallization. As examples of the Kracher trend, I have drawn IAB slopes (the heavy lines) through the centroids of the CD-iron fields on Fig. 3, and, as an example of the Wasson fractionation trend, I have drawn IIIAB slopes (the thin lines) through the centroids.

The greatest differences between the IAB and IIICD element-Ir slopes are for Co, Cu, and Ga; on each diagram the IAB slope is much greater, an inverse reflection of the huge Ir fractionation in IIIAB. Only on the Co-Ir diagram is there a moderate correlation and an apparent slope closer to the IAB than to the IIIAB reference slope. The IAB slopes on the Cu and Ga diagrams should be high and negative and high and positive, respectively. The Ga data show a smaller range than predicted from the IAB trend and no hint of a positive slope. The Cu data also show no trend and, with the exception of three outliers, a much smaller range than expected. On the whole the six diagrams are best interpreted as providing negligible evidence for fractional crystallization and are, thus, most consistent with formation of IAB irons in large cores or as impact melt pools that rapidly solidified.

Two or More Melt Pools?

According to the WASSON et al. (1980) model, the sizes of the metallic portions of the impact melt pools that gave birth to the high-Ni (Ni > 200 mg/g) irons was several centimeters, comparable to those of the recovered meteorites. In contrast, the much larger sizes of the low-Ni (Ni < 80 mg/g) pools cannot be defined. Several IAB meteoroids (Monturaqui, Odessa, Kaalijarv) were large enough to form craters (Meteor Crater is the largest), but in the absence of additional information we cannot infer whether these meteoroids consisted of single pools or a fragment of a single pool or several pools with intervening silicates. The multimodal Ir distribution among CD irons (Fig. 2) suggests either that the CD meteoroid included two compositionally distinct melt pools or that a single pool underwent minor fractionation and was nonuniformly sampled.

It should be possible to answer these questions with additional studies. A simple interpretation of the bimodal composition is that there were two main detachment events during atmospheric passage, i.e., that most plains specimens are sampling two "equatorial" regions that were well separated on the perimeter of the meteoroid. If there was a continuous Ir gradient across the meteoroid, the regions having intermediate Ir contents might be expected towards the center of the trailing hemisphere and might be prominently represented in rim specimens. Studies of rim specimens are indicated.

If we are mainly sampling two melt pools having different mean Ir contents, then the bimodality should be strengthened by additional analyses (including rim specimens). We would also expect that careful ground searches (focusing especially on "shale balls" since silicate-rich specimens may undergo rapid oxidation) would reveal silicate-rich samples. One sample with large (cm-size) silicate inclusions is already known (S. SCHONER, priv. comm.) and will be included in our follow-up studies.

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APPENDIX: IRONS RELATED AND NOT RELATED TO CANYON DIABLO

Canyon Diablo Nos. 2 and 3

NININGER (1940) reported that five specimens of Canyon Diablo (collected by others at unknown locations) differed from typical Canyon Diablo irons in that they showed narrower kamacite bands, a large concentration of taenite, different light reflecting properties of the kamacite, a different arrangement of the schreibersite, and generally showed deformed structures. In one sample the Ni content was reported to be 84.2 mg/g, far higher than the commonly observed mean of about 70 mg/g. These irons were inferred to be from an independent fall and were designated Canyon Diablo No. 2. WASSON (1967) reported 79 mg/g Ni, 79 μg/g Ga, and 317 mg/g Ge in a specimen of this iron. New data for the same specimen are reported in Table 2. The Ni content (75.9 mg/g) is somewhat lower and the Ga content (84.8 μg/g) somewhat higher than reported by WASSON (1967). With the exception of Ni and a remarkably high Cu content (224 μg/g), element concentrations in Canyon Diablo No. 2 are within the range observed in other Canyon Diablo irons, and it seems likely that CD2 is part of the Canyon Diablo meteoroid despite the fact that Ni is 6 and Cu is 8 standard deviations higher than the mean.

Much less is known about the iron that NININGER and NININGER (1950, p. 129) called Canyon Diablo No. 3. It is a single 846 g specimen reported by the original owner to have been found on the rim of the crater. NININGER and NININGER (1950) described it as having "a strikingly different (etch) pattern"; no other information is provided. WASSON (1967) reported it to contain 82.0 mg/g Ni, 80.1 μg/g Ga, and 332 μg/g Ge. The new INAA results show a slightly lower Ni (78.1 mg/g) content well outside the range observed in other Canyon Diablo specimens; the new Ga (72.9 μg/g) is much lower than the old value and 4.4 standard deviations below the CD mean. Several other elements (Co, As, W, and Au) are >3 standard deviations above the CD mean. In fact, the CD3 data in Table 3 are more similar to Toluca than to Canyon Diablo, suggesting that the CD3 sample was mislabelled. Our unpublished Toluca mean is 20 μg/g Cr, 4.90 mg/g Co, 79.5 mg/g Ni, 170 μg/g Cu, 69 μg/g Ga, 250 μg/g Ge, 17.0 μg/g As, 370 ng/g Sb, 850 ng/g W, 250 ng/g Re, 2.42 μg/g Ir, 5.4 μg/g Pt, and 1.68 μg/g Au. The only significant discrepancies between CD3 and Toluca are for Ge and W. The W may reflect contamination of CD3 by a cutting tool; the scatter of our two values (2490 and 5590 ng/g) implies that the W is in a minor phase, and both are far above the range observed in other IAB irons. The high CD3 Ge in Table 3 is by INAA and has a moderately large error, but the Ge content published by WASSON (1967) is similar. We are rerunning CD3 Ge by RNAA and will only pair CD3 with Toluca if the new value is 220–270 μg/g, within ~10% of the Toluca value.

Six Meteorites that may be Transported CD Irons

In the top part of Table 3 we list six IAB irons that are compositionally unresolvable from Canyon Diablo and may be transported fragments; their compositions are plotted in Fig. 5 together with outlines of the fields occupied by CD specimens in Fig. 2; in every case the six irons plot within these fields. BUCHWALD (1975) inferred that Pulaski County (Georgia, USA) and Helt Township (Indiana, USA) were CD fragments despite the great distance from Arizona to their purported discovery locations; our data support these attributions. Before we studied the documented specimen CD 1261 (Ir = 2.53 μg/g), we interpreted the high Ir contents of Mamaroneck (Ir = 2.45 μg/g) and Idaho (Ir = 2.49 μg/g) to show that these were not CD irons. However, their Ir values are now within the observed CD range as are their concentrations of other elements. It seems likely that they are transported CD fragments.

The composition of Jenkins is also unresolvable from that of Canyon Diablo (Fig. 5). READ (1967) notes that he obtained Jenkins second hand 21 years after its recovery; the only location information consisted of an X marked on an aerial photo. Since Jenkins is moderately large (55 kg) and there seems to have been no significant financial incentive to bring a large CD iron to southwest Missouri and pass it off as a new discovery, Jenkins should be treated as an independent fall until isotopic and terrestrial age studies are carried out.

The history of Jenny's Creek (West Virginia, USA) is intriguing. BUCHWALD (1975) states that the discovery report rings true but noted structural similarities to CD (and to Cranbourne and Odessa). However, the report (KUNZ, 1886) has remarkable features. The two pieces that are preserved and another that was lost were recovered from an unusual location, the channel of Jenny's Creek; the larger (10-kg) mass was found there by a Mr. Christian in the spring of 1883. The last (0.6 kg) piece was found "in a pool of still water only 15–20 ft (4.5–6 m) from where he (Mr. Christian) had found the other." A further curiosity was that "It was all broken except one side which is altered to limonite and has no visible trace of unaltered crust." Buchwald notes that the first mass was apparently heavily oxidized along grain boundaries, and that this facilitated its breakup by the local people. A curious and potentially important (but somewhat opaque) part of Kunz's report is that "a shrewd speculator who had in his possession a lump of the metal, had realized largely by burying it on different lands, digging it up again, and then selling the pieces of property successively as being silver bearing. The rumor was current that the vein was 9 to 16 inches thick." Could it be that Jenny's Creek is CD material brought to West Virginia by this speculator and tossed into the creek bed so that it would look like a placer deposit?

As noted by BUCHWALD (1975), the CD irons were well known to Arizona settlers at least as early as 1860; thus, there was ample time for transport of the 11–13 kg of Jenny's Creek material to the eastern USA before 1883. The issue could probably be settled by careful studies of cosmic-ray–produced rare-gas isotopes and a precise ^{14}C-based terrestrial age. Until such data are available Jenny's Creek should still be listed as an independent fall.

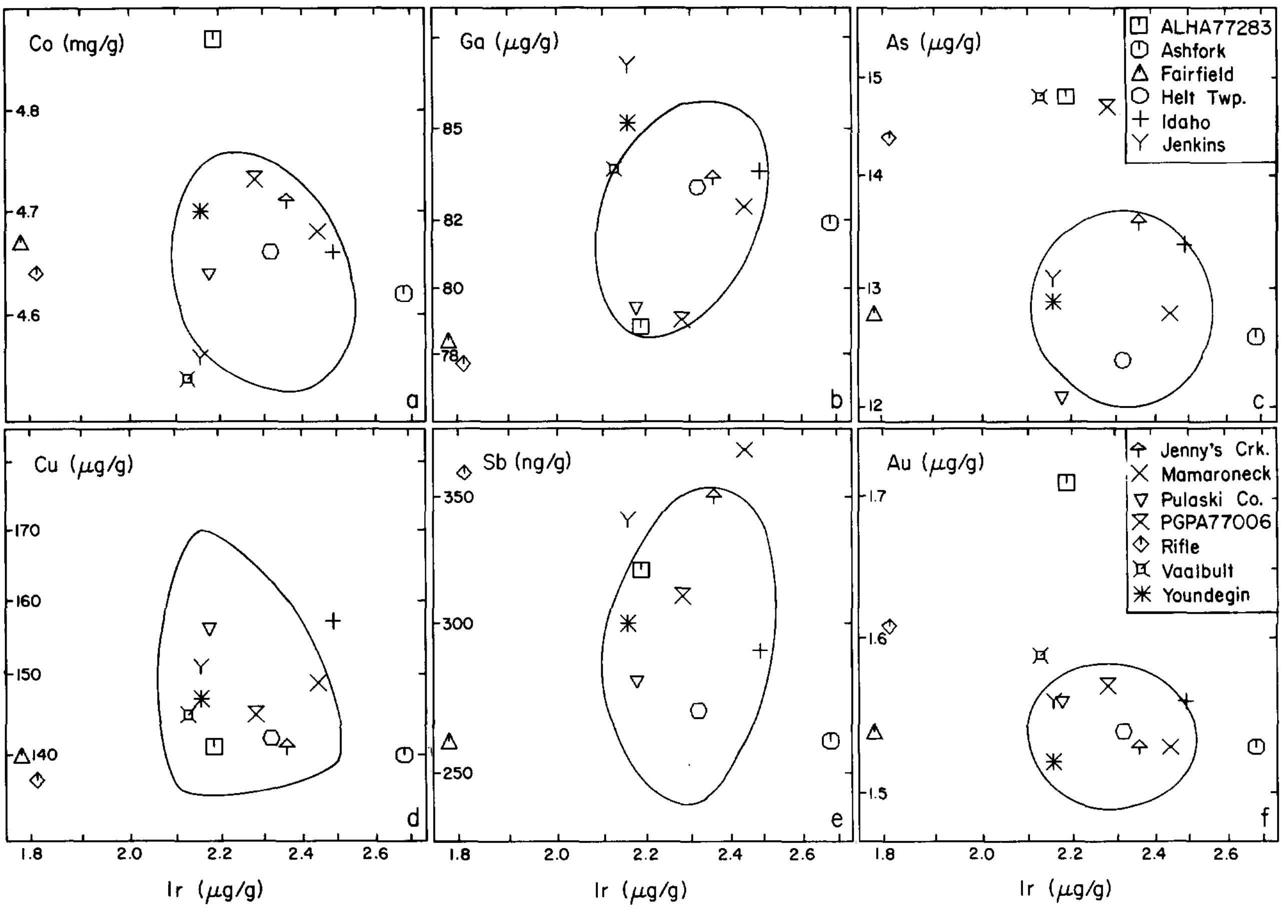

FIG. 5. Scatter fields for ten irons speculatively linked to Canyon Diablo and three others having similar compositions on six element-Ir diagrams. The ovals show the fields occupied by Canyon Diablo specimens on Fig. 2. The Helt Township, Idaho, Jenkins, Jenny's Creek, Mamaroneck, and Pulaski Co. irons are indistinguishable from the Canyon Diablo field; most, possibly all, appear to be mislabelled Canyon Diablo specimens. Though a well-documented independent fall, Youndegin is also unresolvable from Canyon Diablo. All other irons fall outside the CD fields on one or more of the diagrams.

Irons Compositionally Distinct from Canyon Diablo

Previous studies have speculatively linked the seven meteorites in the middle part of Table 2 to Canyon Diablo. Our data are inconsistent with these attributions; the new Ir data alone rule out such an assignment for five of the seven.

As discussed above, our new data indicate that Canyon Diablo No. 3 is not part of the CD fall; it might be a mislabelled Toluca specimen.

Allan Hills (ALH) A77283 is uniquely similar to Canyon Diablo in that it contains shock-produced diamonds and lonsdaleite (CLARKE et al., 1981), and its Ir concentration falls within the range of the low-Ir CD set. MALVIN et al. (1984) suggested the possibility that ALHA77283 might be material accelerated above the atmosphere by the Arizona cratering event. The high Co, As, and Au contents of ALHA77283 (3, 5, and 7 standard deviations above the CD mean; see Fig. 5) show that it is not a CD fragment, consistent with the statement by MELOSH (1989) that the minimum diameter of a crater whose formation is capable of blowing off the overlying atmosphere is 3 km.

Among the remaining irons Rifle has an Ir concentration (1.91 µg/g) nearest the CD range; this is 5 standard deviations below the mean of the low-Ir set, or 3.5 standard deviations below the combined CD set. It is improbable that Rifle is mislabelled CD. Ashfork and Fairfield have Ir contents about 3.5 and 4 standard deviations from the combined CD set, and are almost certainly independent falls. BUCHWALD (1975) suggested a relationship between Alexander County and CD, but the major differences in composition rule out such a possibility; Alexander County is compositionally identical to Magura, and it may be mislabelled. Our new data confirm the conclusion of WASSON (1968) that Seligman is an independent fall.

These new results indicate that entries for Rifle and Ashfork should be restored to the British Museum catalog; GRAHAM et al. (1985) accepted that they were paired with Canyon Diablo following the recommendations of BUCHWALD (1975) and WASSON (1968), respectively, and deleted the information regarding their recoveries.

Independent Irons Compositionally Similar to Canyon Diablo

Vaalbult and Youndegin have compositions similar to those in CD irons ($300 < Ge < 350$ µg/g and $2.00 < Ir < 2.50$ µg/g). We included Purgatory Peak (PGP) A77006 in our set despite its low Ge (284 µg/g) because earlier results showed it to be similar to ALHA77283 in terms of all other elements. Our revised compositions confirm that these two Antarctic irons are quite similar, but As and Au are marginally higher and Ir marginally lower in ALHA77283 than in PGPA77006; the terrestrial ages (110 ± 70 and 90 ± 70 Ka, respectively; NISHIIZUMI et al., 1989) are similar. The recovery areas of the meteorites are ~110 km apart (R. SCORE, priv. comm.). This large distance and the slightly different compositions make it unlikely that they are fragments from a single fall.

Vaalbult (South Africa) is distinguishable from CD only in terms of As, which is 3 standard deviations above the mean. The remote recovery location and the adequate documentation of the recovery (BUCHWALD, 1975) confirm that it is independent.

Many large (>100 kg) masses of Youndegin have been recovered from Australia, and there is no doubt regarding its fall location. This is fortunate, for it is compositionally unresolvable from Canyon Diablo.