Tue, Feb 3, 1998

A petrologic study of the IAB iron meteorites: Constraints on the formation of the IAB-Winonaite parent body

G.K. BENEDIX[1], T.J. MCCOY[2], K. KEIL[1*], AND S.G. LOVE[3]

[1]Hawaii Institute of Geophysics and Planetology, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, HI 96822 USA.

[2]Department of Mineral Sciences, MRC 119, Smithsonian Institution, Washington, DC 20560, USA.

[3]Mail Stop 306-438, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109-8099, USA

* Also associated with the Hawaii Center for Volcanology.

To be submitted to *Geochimica et Cosmochimica Acta*, August, 1997 Version

Abstract -- We have studied IAB iron meteorites and their silicate-bearing inclusions to elucidate the origin of their parent body. We have divided IAB irons into five categories which best describe the inclusions and other properties of the irons. These are: (1) Sulfide-rich irons, such as Mundrabilla, that contain a significant volume fraction of troilite, with or without associated silicates; (2) Irons with non-chondritic silicate inclusions, such as basaltic inclusions in Caddo County; (3) Irons with rounded, troilite and/or graphite inclusions, sometimes containing embedded angular silicate inclusions; (4) Irons with angular silicate inclusions similar to those of the winonaites, where silicates may comprise up to 40 vol.% of the rock, and (5) Irons with phosphate-bearing inclusions, such as the brianite-bearing IAB San Cristobal. Similarities in mineralogy, mineral and oxygen isotopic compositions suggest that IAB irons and winonaites are almost certainly from a common parent body. IIICD irons may also have originated on this parent body, although evidence supporting this suggestion is less convincing. Previous models for the origin of IAB irons propose that they are either products of selective impact melting in the megaregoliths of a chondritic asteroid, or products of partial melting and fractional crystallization during formation of a sulfur-rich core. The former model suffers from the fact that impact is incapable of causing preferential melting of metal and sulfide on a large scale and pooling of these selective melts into sizable bodies. The latter model does not readily explain the occurrence of often fragmentary, angular silicate clasts in a metallic Fe,Ni host. We propose a new model for the origin of IAB irons that incorporates aspects of both previous models. We suggest that a chondritic, possibly heterogeneous, parent body was heated by a non-collisional heat source which caused partial but not complete melting of the body. After peak temperatures were reached and cooling and crystallization had begun, a major impact catastrophically fragmented this body and the debris gravitationally reassembled, "scrambling" the parent body lithologies. We suggest that the impact caused extensive mixing of molten metallic Fe,Ni and solid silicate material, resulting in the formation of IAB irons with silicate inclusions, whereas winonaites represent metamorphosed rocks and partial melt residues of the precursor silicate lithologies. High temperatures of some of the reassembled debris and deep burial resulted in continued fractionation and formation of the

high-Ni IABs, as well as formation in the solid state of the Widmanstatten structure of the irons between ~600-350° C. Ages of 4.43-4.53 Ga of silicate inclusions of IABs and of ≥4.40-4.54 Ga of winonaites imply that this entire process occurred very early in the history of the solar system.

1. INTRODUCTION

Of the thirteen major iron meteorite groups, only the IAB and IIICD groups have broad ranges in Ni and some trace elements (e.g., Ir, Ga, Ge). These ranges are unlike those of the other 11 groups and are difficult to explain by simple fractionation of a metallic core. Another feature which sets these groups apart from other irons is the presence of abundant silicate inclusions in IAB irons and that also occur in a few IIICD irons. These silicate inclusions are roughly chondritic in mineralogy and composition, but have non-chondritic highly reccrystallized. They are linked through oxygen isotopic (Clayton and Mayeda, 1996) and mineral compositions (Bild, 1976) to the stony winonaites and may be related to the IIICD irons. The apparently contradictory features of these meteorites, namely the occurrence of silicate inclusions (i.e., surficial material) in once-molten metallic Fe,Ni (i.e., deep-seated material) have led to a number of models to explain their formation. For example, Choi et al. (1995) suggested that these meteorites formed by large-scale selective melting by impact of metallic Fe,Ni and troilite but not silicates and pooling of these melts into sizeable bodies. Kracher (1982, 1985) suggested that they formed by parent body-wide partial melting and fractional crystallization during formation of a sulfur-rich core.

Benedix et al. (1997) conducted a petrologic and isotopic study of winonaites and suggested that these meteorites formed from compositionally and mineralogically heterogeneous chondritic precursor material by partial melting, brecciation, and metamorphism. Key evidence for this scenario came from a detailed textural study, which had not been conducted by previous workers and provided important clues to the events and timing of the formation of winonaites. A similar situation exists in the IAB irons, where silicate inclusion mineralogy and compositions have been investigated thoroughly (e.g., Bunch et al., 1970; Bild, 1977), whereas textural features have not been studied in detail. Furthermore, newly-recovered and recently-classified IAB irons reveal a wider range of silicate inclusion types. For these reasons, we undertook a study of silicate inclusions in IAB irons, focusing on textural features to elucidate their relationship with winonaites and the history of their common parent body.

2. SAMPLES AND ANALYTICAL TECHNIQUES

We have focused on those IAB irons that contain silicate inclusions (Table 1). Where possible, more than one section was examined to determine the extent of heterogeneity within individual meteorites. Polished sections were examined in reflected and, when possible, transmitted light. Modal analyses of all sections (Table 2) were made in reflected light at either 20x or 40x magnification. Olivine, orthopyroxene and clinopyroxene were not distinguished but were collectively determined as mafic silicates. Mineral compositions were determined with a Cameca SX-50 electron microprobe. For mafic silicates, the microprobe was operated at an accelerating voltage of 15 keV, a current of 20 nA and with a fully-focused beam. The beam was rastered over a 100 μm^2 area for plagioclase analyses. Well-known mineral standards were used, and the data were corrected using the manufacturer-supplied PAP ZAF routine. X-ray image maps were made on the electron microprobe with the same accelerating voltage and current but a 20 μm beam to allow overlap of scan lines. However, a current of 80 nA was used in collecting the X-ray images of Caddo County and Ocotillo to increase X-ray production.

3. RESULTS

We present textural, mineralogical, and compositional data for silicate inclusions in IAB irons (Tables 2-4). We have concentrated on the textures and heterogeneity of the inclusions and also present new mineral and compositional data for four meteorites (Caddo County, Ocotillo, TIL 91725, Zagora; Table 4) and compare these new data to previously published results.

3.1. Classification, Texture, Mineralogy, Modes, and Compositions

The textures of the metal phase of IAB irons have previously been described in detail by several authors (e.g., Buchwald, 1975) and will not be repeated here. Overall, the silicate-bearing IAB irons span the range of structural classifications from hexahedrites (e.g., Kendall County with 5.5% Ni) through fine octahedrites and coarsest octahedrites to ataxites (e.g., San Cristobal with

24.9% Ni). Silicate inclusions contain variable amounts of low-Ca pyroxene, olivine, plagioclase, calcic pyroxene, troilite, graphite, phosphates, and Fe,Ni metal and minor amounts of daubreelite and chromite. Silicate abundances in the inclusions vary dramatically between different irons, as well as between different sections of the same meteorite (Table 2). Plagioclase generally comprises ~10% of the total silicates present, similar to its abundance in ordinary chondrites (Van Schmus and Ribbe, 1968; McSween et al., 1991). Overall, mafic mineral compositions are quite reduced (Table 3), with olivine ranging from $Fa_{1.0}$ (Pine River) to $Fa_{8.0}$ (Udei Station) and low-Ca pyroxene from $Fs_{1.0}$ (Kendall County) to $Fs_{8.7}$ (Udei Station) (Bunch et al., 1970). Plagioclase ranges from $An_{11.0}$ (Persimmon Creek) to $An_{21.5}$ (Pine River) and calcic pyroxene is diopside [$Fs_{2.4}Wo_{44.7}$ (Mundrabilla) to $Fs_{3.9}Wo_{43.9}$ (Persimmon Creek)] (Ramdohr et al., 1975; Bunch et al., 1970).

Despite these gross similarities in inclusion compositions, large differences and are noted in detail in modal abundances of minerals in inclusions between individual meteorites and sometimes between different sections of the same meteorites (e.g., Toluca, Campo del Cielo; Table 2). By and large, these differences are real and not artifacts of poor sampling and suggest considerable heterogeneity in the IAB iron meteorite parent body. Based on mineral occurrences, modal abundances and compositions, and textures and shapes of the inclusions, Bunch et al. (1970) divided IAB irons into two types, the Odessa and Copiapo types. Based on our studies of many more meteorites, we suggest that these irons can loosely be divided into five types, based on both meteorite whole rock as well as inclusion properties, although these types are sometimes transitional and a given iron may have the characteristics of more than one type. These five types are: (1) Sulfide-rich irons; (2) Irons with non-chondritic silicate inclusions; (3) Irons with rounded inclusions (Odessa type of Bunch et al., 1970); (4) Irons with angular silicate inclusions (Copiapo type of Bunch et al., 1970); and (5) Irons with phosphate-bearing inclusions. In many cases, there are too many individual meteorites in a group for all to be described in detail (Table 5). Therefore, we limit discussion to one or two meteorites that illustrate the type characteristics..

3.1.1. Sulfide-rich IAB irons

Several irons have unusually high troilite contents, with the troilite occurring as irregular masses, veins or large grains. It sometimes forms the matrix into which silicates are embedded (e.g., Pitts). The type member Mundrabilla (Fig. 1) plots in the low-Ni cluster (7.47 wt.% Ni in the metallic host) of IAB-IIICD irons on plots of Ni vs. Ir, Ga, and Ge (Choi et al., 1995) and has been variously classified as a IIICD (Choi et al., 1995) or an anomalous IAB iron (e.g., Wasson et al., 1980). Troilite comprises 25-35 vol.% of the meteorite and occurs as mm-sized veins or lenses generally found along parent taenite grain boundaries (Buchwald, 1975). Scott (1982) noted that the weak dendritic texture of the metal grains is a characteristic quench texture of metal-sulfide melts and suggests a cooling rate of ~5°C/yr during solidification.

In addition to abundant troilite and graphite and minor schreibersite, silicates are also present. Mundrabilla contains rare angular silicates that are generally found within troilite nodules. We find that the silicates are scattered throughout the 130 x 60 cm slice (USNM 5730) we examined, not located in a specific area as reported by Robinson and Bild (1977). These silicates are compositionally (Table 3) similar to those of other silicate inclusions in IAB irons (Ramdohr et al., 1975; Bild, 1977; Robinson and Bild, 1977). Texturally, Mundrabilla silicates are similar to those found in Winona (Benedix et al., 1997) and Lueders (McCoy et al., 1996). Modal analysis of a silicate clast from Mundrabilla (Table 2) indicates that plagioclase (15.1 vol.%) is somewhat higher than chondritic values. Mafic silicates comprise ~50 vol.% and FeS is pervasive (~30 vol.%) throughout this silicate clast. Another interesting textural feature of Mundrabilla is the occurrence of graphite, which is widely variable in abundance between different cm-sized areas (Buchwald, 1975). The most spectacular occurrence is as conically-shaped inclusions which radiate from metal and troilite (Buchwald, 1975), similar to those found in Pontlyfni (Benedix et al., 1997).

Other members of this type may include Pitts, Persimmon Creek and Zagora (Table 5). These meteorites contain 9.7-13.8 wt.% Ni in their metallic host and, thus, sample a significant portion of the total range exhibited by silicate-bearing IAB irons. Each section we studied of these meteorites contains abundant troilite (Table 2). However, it is important to remember that the main masses of these meteorites are much smaller than those of Mundrabilla and, in this case, their troilite-rich nature may be partly due to unrepresentative sampling. Troilite occurs as irregular masses in Pitts and Persimmon Creek into which silicates are embedded. In Zagora, troilite occurs as veins which surround silicate inclusions. The silicate inclusions in Pitts, Persimmon Creek and Zagora are angular and this type of inclusions is described in detail in the section on IAB irons with angular silicate clasts. We have also examined Waterville (7.65 wt.% Ni). This anomalous IIICD iron exhibits similar features to Mundrabilla (Buchwald, 1975), but on a finer scale, and does not appear to contain silicates.

3.1.2. IAB irons with non-chondritic silicate inclusions

This type includes Caddo County (basaltic inclusions) and Ocotillo (troctolitic inclusions). Coarse-grained, olivine-rich inclusions in some winonaites [e.g., Winona, Mt. Morris (Wis.)] are similar to this type. We studied Caddo County (9.17 wt.% Ni) in both hand sample and thin section. In hand sample, silicate-bearing inclusions are up to 7 cm in maximum dimension, but are truncated by the edge of the meteorite, and silicates comprise ~35 vol.% of the slice (Fig. 2). Metallic Fe,Ni occurs as the host into which the clasts are embedded, as large grains within the silicate inclusions, and as veins which are clearly produced by post-solidification shock. Hand sample and thin section studies indicate that the silicate grains are highly variable in size. Many inclusions, or parts of inclusions, consist of silicates with roughly chondritic modal proportions, but equigranular, recrystallized textures (Palme et al., 1991, Takeda et al., 1997). These types of inclusions will be discussed in the section on IAB irons with angular silicate clasts. Rare inclusions of basaltic composition are also found in Caddo County. The overall texture of the inclusion of Caddo County we examined (UNM 937) is somewhat recrystallized, and the sub- to anhedral mineral grains are large (0.1-3mm), with abundant 120° triple junctions. It is composed of major calcic pyroxene and plagioclase and minor low-Ca pyroxene, olivine, troilite, and metallic Fe,Ni. Modal analysis indicates that the composition of this inclusion is broadly basaltic (48.2 vol.% plagioclase, 40.1 vol.% mafic silicates; Table 2). Although we did not distinguish the various mafic silicates during modal analysis, the dominance of calcic pyroxene is apparent from X-ray imaging. Our results are in agreement with those of Takeda et al. (1993), who reported abundant plagioclase (55 vol.% on a metal-free basis) in another Caddo County inclusion. Shock effects in the clast in section UNM 937 are very minor (S2), and mafic silicates are relatively reduced (olivine, $Fa_{3.3}$; low-Ca pyroxene, $Fs_{6.5}$; calcic pyroxene, $Fs_{2.5}$). Palme et al. (1991) noted zoning of Ca and Ni at the ppm-level in olivine grains in Caddo County, and we have observed olivine grains with reverse zoning, with cores enriched by up to 1 wt.% FeO relative to the rims.

Ocotillo (7.09 wt.% Ni) also contains non-chondritic silicate clasts, although not all of these are basaltic in composition. Ocotillo is a recent recovery (1990) and its mineral compositions are reported here for the first time (Table 3). We examined a polished thin section (UH 226) which is composed primarily of metallic Fe,Ni (matrix metal to inclusion ratio is listed in Table 2), but also contains a variety of silicate inclusions up to 5 mm in size. These include a single, twinned, low-Ca pyroxene grain 5 mm in size; a fine-grained inclusion similar to the angular silicate inclusions which are discussed later; and two coarse-grained inclusions with major plagioclase, calcic pyroxene or olivine, and minor low-Ca pyroxene, which are of particular interest. Figure 3 illustrates the sizes of three of these clasts as well as their variable grain sizes. The plagioclase-calcic pyroxene-rich inclusion (Fig. 3; clast 2) is broadly basaltic in composition, whereas the plagioclase-olivine-rich inclusion (Fig. 3; clast 1) is best described as a troctolite, although this classification may be biased due to the coarse grain size and small size of the clast which may have resulted in unrepresentative sampling of phases in the plane of the thin section. Finally, shock features of the silicates in this meteorite are minor (S1-S2), and compositions of olivine ($Fa_{3.4}$), low-Ca pyroxene ($Fs_{5.8}$), and calcic pyroxene ($Fs_{2.8}$) are as reduced as are those in other silicate inclusions in IAB irons (Table 3).

3.1.3. IAB irons with rounded inclusions

Several irons have rounded to ovoid inclusions that contain variable amounts of silicates, graphite and troilite, the latter two often being the dominant or sole constituents. These include Odessa, Toluca (and the paired Tacubaya), Canyon Diablo, Jenny's Creek and Youndegin and were previously included into the Odessa-type of Bunch et al. (1970). These meteorites have a relatively narrow range of bulk Ni (6.80-7.86 wt.%) in the host metal and plot in the low-Ni cluster of IAB irons. We have chosen Toluca for detailed studies, because a large number of specimens were available for study, allowing us to investigate inter-inclusion variability.

We note that our classification does not precicely duplicate the earlier assignments of meteorites into Odessa- and Copiapo-types (Bunch et al., 1970). For example, Campo del Cielo and Linwood, which Bunch et al. (1970) included in their Odessa-type, are classified by us as irons with angular inclusions. This stems from the fact that our samples are from the large El Taco mass, which clearly contains very large, angular silicate inclusions, as also noted by Bunch et al. (1970). Inclusions in Linwood are neither rounded nor angular but are transitional in shape. We therefore choose, somewhat arbitrarily, to classify Linwood inclusions as angular. Unlike Bunch et al. (1970), we also include Tacubaya with irons with rounded inclusions, since it is clearly paired with Toluca (Scott and Wasson, 1976). These differences in classification point out the somewhat arbitrary nature of any classification scheme for IAB iron silicate-bearing inclusions, as noted by Scott and Wasson (1975) in discussing Toluca and Tacubaya. Bunch et al. (1970) noted that Mn, Zn and Ti are present at levels of > 0.1 wt.% in troilite in Odessa-types, but are below the detection limits in Copiapo-types. We have measured troilite compositions in meteorites of both types, including Campo del Cielo, Landes, Linwood, Lueders and Odessa and found that these elements are below detection limits in all samples. We can only speculate that the elevated levels of these elements in Odessa-types resulted from beam flaring in the microprobe used by Bunch et al. (1970), causing beam overlap with coexisting sulfides rich in these elements (e.g., sphalerite).

Inclusions in Toluca consist of a core of either silicates or, more often, troilite surrounded by a sequence of swathing minerals such as graphite, schreibersite and cohenite, although these minerals are not always present. Inclusions that contain troilite and silicates are typically ovoid, whereas the graphite-troilite-rich inclusions tend to be rounded. The silicate inclusions, when present, are generally surrounded by cm-sized troilite areas, and silicates appear always to occur with either troilite or graphite-troilite surrounding them. Marshall and Keil (1965) and Buchwald

(1975) reported similar characteristics for inclusions in Odessa and Canyon Diablo. Mafic silicates are reduced (Fa_{3-6}; Table 3) and are similar in composition to those of silicates in other IAB irons.

A feature that seems to be common among IAB irons is the heterogeneous distribution of the inclusions within a single meteorite. As a case in point, we examined a large number of individual hand specimens of Toluca in the collections of the Smithsonian Institution and Texas Christian University and determined by modal analysis that graphite-troilite-silicate inclusions appear to comprise only a few vol.% of the meteorite and are quite heterogeneously distributed. As a result, small specimens, because of their small volume, rarely display inclusions. Inclusions range in shape from nearly round to elongate and amoeboid. Troilite-rich inclusions tend to be more irregular in shape than graphite-rich inclusions. Silicate clasts in many of these inclusions are highly angular (Fig. 4) and it is the rimming graphite and troilite that give the inclusions their round shapes. We have determined the modal compositions of four inclusions from three specimens of the meteorite. They range from a troilite nodule with a schreibersite rim to an elongate inclusion with a silicate clast on one end, troilite predominantly on the other and graphite both intermixed with the silicates and rimming the troilite. Modes of the four plugs (Table 2) are highly variable, with mafic silicates ranging from 0-17.5, plagioclase from 0-3.4, troilite from 6.9-58.3, schreibersite from 9.6-45.2, cohenite from 0-28.8 and graphite from 0-21.1 (all in vol.%).

3.1.4. IAB irons with angular silicate inclusions

This type is characterized by the angular, fragmentary shapes of the inclusions and includes most of the IAB irons that Bunch et al. (1970) referred to as Copiapo-types. Typical examples are Campo del Cielo (Wlotzka and Jarosewich, 1977; Bild, 1977; Fig. 5) and Lueders (McCoy et al., 1996; Fig. 6), and the majority of IAB irons examined in this study fall into this category (Table 5). Pitts, Persimmon Creek and Zagora contain angular silicate inclusions and are also members of this type. Ni contents of the metallic Fe,Ni host into which the inclusions are embedded range widely (6.58-13.78 wt.%), extending beyond the low-Ni cluster of IAB irons. Of all inclusion types found in IAB irons, these angular inclusions most closely resemble the stony winonaites in textures, mineralogies and mineral compositions (Benedix et al., 1997). Silicates occur in three basic morphologies: fine-grained, re-crystallized "chondritic" silicates (usually the more angular types); medium-grained silicates; and coarse-grained monomineralic crystals usually rounded and found individually in the metallic matrix, as first noted by Bunch et al. (1972). Inclusions of this type are the most silicate-rich ones of any of the IAB irons, but their abundance varies considerably. The large El Taco mass of Campo del Cielo, for example, contains a few vol.% of angular silicate inclusions, whereas other IABs such as Lueders, Landes and Woodbine contain up to 40 vol.% silicate inclusions (e.g., McCoy et al., 1996).

Some irons show clear evidence that the process of mixing solid silicate clasts into molten metallic Fe,Ni was a rather violent one. In some meteorites such as Lueders (Fig. 6), adjacent silicate inclusions may have complementary borders but are separated by metal. This suggests that these objects were once single clasts but that in the mixing process, the clasts were broken and areas between them were invaded by metal without destroying the matching outlines completely and without separating the fragments significantly. Although we suggest that mixing of solid silicate clasts with molten metal involved fragmentation of the parent body by catastrophic impact and gravitational reaccretion of the debris (see discussion), the silicates show only weak shock damage. In fact, undulatory extinction and rare planar fractures in olivine indicate that the silicates are very weakly to weakly shocked (shock stages S2-3 of Stöffler at al., 1991). This is perhaps not surprising, since even in major impacts, only a small portion of the debris shows shock damage (e.g., Stöffler, 1977; Stöffler and Ostertag, 1983; v. Engelhardt, 1990). Alternatively, shock features may have been annealed out as the silicate clasts were mixed with molten metal, and the observed S2-3-level shock features may have been produced by later shock events after mixing and solidification.

Modal proportions of plagioclase relative to total silicates are quite variable: Most inclusions have plagioclase contents in chondritic proportions (~10 vol.%; Van Schmus and Ribbe, 1968; McSween et al., 1991), but some have higher (e.g., Campo del Cielo, Four Corners) or lower abundances (e.g., Udei Station). Although some of these variabilities may be an artifact of unrepresentative sampling resulting from the small inclusion sizes and the sometimes large grain sizes of the silicates, some are clearly real and represent true rock heterogeneities. For example, the low plagioclase contents of inclusions in Udei Station are quite striking, with areas up to 5 mm across that are virtually devoid of plagioclase. We suggest that these inclusions may represent parts of the precursor rock from which partial melts of basaltic (plagioclase-pyroxene) composition have been removed. In contrast, some inclusions in Campo del Cielo exhibit evidence for migration of melts in the form of veins of coarse-grained plagioclase and pyroxene with accompanying graphite, as first noted by Wlotzka and Jarosewich (1977). Examination of a large slice of the El Taco mass (USNM 5614; Fig. 5) suggests that graphite is concentrated near the edges of the inclusions and one inclusion contains 32 vol.% of the phase, with much of it occurring in veins. These clasts generally contain negligible Fe,Ni metal.

Inclusions of this type are also noteworthy because they contain silicate minerals with the most and least reduced compositions. For example, Pine River has olivine of $Fa_{1.0}$ and Kendall County has pyroxene of $Fs_{1.0}Wo_{0.8}$, whereas Udei Station has olivine of $Fa_{8.0}$ and pyroxene of $Fs_{8.7}Wo_{1.7}$. Figure 9 is a plot of Fa vs Fs for silicate inclusions in all IAB irons studied in this work, as well as winonaites studied by Benedix et al. (1997). Silicate inclusions in IAB irons generally have higher Fa and Fs values than the winonaites. However, as in the winonaites, Fa contents of olivines from inclusions in IAB irons are typically lower than Fs contents of pyroxenes, indicating that reduction may have occurred. Supporting evidence for reduction comes from reverse zoning in olivines from Campo del Cielo (Wlotzka and Jarosewich, 1977).

Due to high silicate abundances, most of the existing bulk major and trace element analyses of silicate-bearing inclusions in IAB irons are for inclusions of this type. Major element analyses suggest that silicate inclusions are similar to chondrites (Kracher, 1974; Bild, 1977). This is indicated, for example, by roughly similar Si/Mg ratios for Landes (Kracher, 1974), Woodbine (Jarosewich, 1967), and Campo del Cielo (Wlotzka and Jarosewich, 1977). Bulk trace element analyses of silicate inclusions have been performed for Copiapo, Landes, Woodbine, Campo del Cielo (Bild, 1977) and Udei Station (Kallemeyn and Wasson, 1985). Measured REE pattern shapes and REE abundances for Copiapo and Landes are essentially chondritic. In contrast, Woodbine, Campo del Cielo and Udei Station exhibit fractionated patterns that roughly can be grouped into two types. REE patterns for Campo del Cielo and Udei Station (Bild, 1977; Kallemeyn and Wasson, 1985) are negatively-bowed (V-shaped) with positive Eu anomalies. In contrast, Woodbine (Bild, 1977) exhibits a positively-bowed pattern with a negative Eu anomaly. Interestingly, the same two fractionated patterns are commonly observed for winonaites (Benedix et al., 1997, and references therein). Kallemeyn and Wasson (1985) attribute these patterns to unrepresentative sampling of phosphates which exhibit patterns similar to that for Woodbine. While unrepresentative sampling may be important, Bild (1977) notes that this range of patterns is consistent with heterogeneous distribution of plagioclase, diopside and phosphates, all of which occur in a low temperature melts and for which there is ample petrologic evidence of melt migration (Wlotzka and Jarosewich, 1977; this work).

3.1.5. IAB irons with phosphate-bearing inclusions

Phosphates occur in many of the IAB irons as part of the rim sequence at the boundary between silicate inclusions and metal. However, a small number of IAB and IIICD irons contain more abundant phosphates scattered throughout the silicate inclusions and are included in this type. In addition, these phosphates are often evolved Mg-Na-bearing phosphates (brianite, panethite, chladniite), rather than the more common Ca-bearing phosphates (whitlockite, apatite). San Cristobal (24.97 wt.% Ni; Choi et al., 1995), first described by Scott and Bild (1974), is the only IAB member of this type. We also discuss here the IIICD irons Carlton (13.28 wt.% Ni) and Dayton (17.03 wt.% Ni), which contain abundant phosphates (McCoy et al., 1993, 1994), because of the possible relationship between IAB and IIICD irons (Kracher, 1982; Choi et. al., 1995). These irons are all very high in Ni. Interestingly, Fuchs (1969) reported brianite in the low-Ni IAB Youndegin (6.80 wt.% Ni), although neither compositional data nor the source of the section in which this mineral occurred was given.

Silicate inclusions in San Cristobal examined by us are subangular in shape and incompletely rimmed by schreibersite. Veins of troilite and Fe,Ni metal cross-cut the inclusions. The silicates are equigranular and appear to be recrystallized, and plagioclase comprises ~12% of the total silicates. A trace amount of graphite rims the inclusion and cohenite is observed within the metallic host. Brianite, first identified in San Cristobal by Scott and Bild (1974), comprises 3.7 vol.% of the silicate inclusion (Fig. 7) and is scattered throughout the silicates, but tends to be in contact with metal, either as veins within the silicates or at the edges of the inclusion.

McCoy et al. (1993) described inclusions in the Carlton and Dayton IIICD irons. These inclusions have high phosphates contents, in some cases comprising up to 70 vol.% of the inclusion and forming the host into which the silicates are embedded. Chlorapatite is the dominant phosphate in Carlton, whereas Dayton contains abundant whitlockite, brianite and panethite. Silicates in these IIICD inclusions extend to more FeO-rich compositions than in IAB irons ($Fs_{11.6}$ in Dayton) and pyroxene compositions correlate with Ni concentrations of the metallic host. In addition, plagioclase compositions are consistently more albitic in IIICD silicate-bearing inclusions ($An_{1.1\text{-}4.9}$) than in IAB inclusions ($An_{9.2\text{-}21.5}$).

3.2. Equilibration Temperatures

Two-pyroxene equilibration temperatures were calculated for the silicate inclusions from the compositions of co-existing low- and high-Ca pyroxenes. We find temperatures that range from 840° (Odessa) to 1230°C (Udei Station) (Table 3), using the transfer equations of Kretz (1982). These temperatures are consistent with the highly metamorphosed to partial melt textures seen in silicate inclusions in IAB irons, although uncertainties due to pyroxene compositional variabilities may be significant. Kretz (1982) cites an uncertainty of ±60°C resulting from precision and accuracy errors. Thus, total errors may exceed 100°C. In spite of these uncertainties, it is interesting to note that Udei Station, which is depleted in plagioclase (Table 2) and may be the residue of partial melting accompanied with removal of a basaltic partial melt, has the highest two-pyroxene equilibration temperature (1230°C).

3.3. Cooling Rates

Cooling rates can constrain the physical setting of IAB irons during their solidification and subsolidus cooling. Scott (1982) argued that, in some cases, the cooling rate at the time of solidification of an iron can be determined. If the parent taenite crystals have a dendritic texture, the distance between the dendrite limbs is proportional to the cooling rate at the time of solidification. The only IAB iron to which this method can be readily applied is Mundrabilla, which exhibits a weak dendritic pattern of the parent taenite crystals within the Fe,Ni-FeS intergrowth. Scott (1982) derived a cooling rate of ~5°C/yr (10^{-7}°C/s) for this meteorite, implying relatively rapid cooling at temperatures near the liquidus of Mundrabilla [1390°C, using the Fe-S binary phase diagram from Ehlers (1972) and a S concentration of ~8 wt.% given by Buchwald (1975)].

The conventional method of determining metallographic cooling rates in the temperature range of ~600-350° C involves measuring the central Ni contents and widths of taenite grains and match those to calculated cooling rate curves (Wood, 1964; Goldstein and Ogilivie, 1965). Using this method, several authors (e.g., Herpfer et al., 1994; Meibom, pers. comm., 1997) determined cooling rates of tens of °C/Myr for a number of IAB irons. These observations suggest that at least some IAB irons may have cooled rapidly at near liquidus temperatures and much slower by the time they had reached lower temperatures. It is interesting to note that the range in Fa of olivine from silicate inclusions significantly exceeds the range of coexisting Fs in low-Ca pyroxene (Fig. 8). This is broadly consistent with resulting from reduction, since diffusion and, thus, reduction, occurs more readily in olivine than in low-Ca pyroxene. Whether this reduction took place during the early heating event prior to fragmentation and reassembly, or after reassembly during annealing in the rubble pile parent body, is difficult to say; it may have resulted during both episodes.

3.4. Ages

Most ages determined for IAB irons are those of silicates from inclusions, since the silicates can readily be dated by a number of techniques (e.g., I-Xe, K-^{40}Ar, ^{39}Ar-^{40}Ar, ^{147}Sm-^{143}Nd). More recently, isotopic systems for direct dating of the metallic host have been developed (e.g., Re-Os), although the interpretation of internal isochrons (e.g., metal-schreibersite pairs; Shen et al., 1996) is not straightforward and may reflect a lengthy period of slow cooling. Absolute ages for the silicate inclusions range from 4.43 - 4.53 Ga, with the oldest age being that of Caddo County measured by the ^{147}Sm-^{143}Nd chronometer that closes at a relatively high temperatures (Stewart et al., 1996). Supporting evidence for early formation of IAB irons comes from I-Xe closure intervals relative to Bjurböle of -3.38 to +2.61 Ma (Niemeyer, 1979a). Ages of 4.43 to 4.52 Ga were derived from the K-^{40}Ar and ^{39}Ar-^{40}Ar systems (Bogard et al., 1968, corrected for a new decay constant by Herpfer et al., 1994; Niemeyer, 1979b, corrected for monitor age by Herpfer et al., 1994), which close at lower temperatures. The ages of silicate inclusions are consistent with those of winonaites (≥4.40 Ga for Mt. Morris (Wis.) to 4.54 Ga for Pontlyfni; Benedix et al., 1997), reflecting their related histories on a common parent body.

4. DISCUSSION

The data presented here, as well as those of others, constrain the geologic history of the IAB iron meteorite parent body. Here, we first explore whether IAB and IIICD irons and the stony winonaites originated on a common parent body. We then briefly review previous models for the origin of these meteorites and, finally, present our model for the origin of these enigmatic rocks and their parent body.

4.1. A Common Parent Body for IAB Irons, IIICD Irons and Winonaites?

It seems almost certain that the stony winonaites are from the same parent body as the IAB irons. Essentially identical oxygen isotopic compositions (Clayton and Mayeda, 1996) imply a common oxygen isotopic reservoir and are consistent with an origin on a common parent body. Mineralogies and mineral compositions of silicates overlap between winonaites and silicate inclusions in IAB irons (particularly for the angular silicate inclusions) (Bild, 1977; Benedix et al., 1997; this work). In addition, textures are nearly identical between the two groups. Cosmic ray exposure ages, which are commonly used to indicate sampling of meteorites by a common cratering event on a single parent body, are of little use due to considerable scatter for winonaites (Benedix et al., 1997) and IAB irons (Voshage, 1967).

It is less certain whether IAB and IIICD irons are from a common parent body, although models for such an origin have previously been proposed (Kracher, 1982; Choi et al., 1995). Some properties of these rocks are clearly consistent with such an origin. For example, oxygen isotopic compositions of silicates from inclusions in IAB and IIICD irons and of winonaites are essentially indistinguishable (Clayton and Mayeda, 1996). In addition, inclusions broadly similar in mineralogy to those in IIICD irons are found among the IAB irons (McCoy et al., 1993; this work). However, important differences do exist. Most prominent among these are the differing trends on log-log plots of Ni vs. Ga, Ge and Ir, particularly at high Ni contents. Kracher (1982) suggested that these different trends could represent complementary fractional crystallization/partial melting trends on a common parent body. Furthermore, Choi et al (1995) suggested that no compositional hiatus exists between IAB and IIICD irons and, thus, they should be treated as a single group originating from a common parent body. While no hiatus exists at low Ni (<7.2 wt.% Ni; Choi et al., 1995), at high Ni the groups are clearly distinguished, a surprising result if these indeed sample a common fractional crystallization sequence. Differences exist within the silicate inclusions as well. Pyroxene compositions of silicate inclusions in IIICD irons are correlated with Ni content in the host metal, a trend not observed in IAB irons, and extend to higher Fs contents than do IAB irons (McCoy et al., 1993). In addition, plagioclase compositions are consistently more albitic than those in IAB irons (McCoy et al., 1993). Thus, it is possible that IAB and IIICD irons are from the same parent body, but the evidence is less convincing than for IABs and winonaites, but additional recoveries of silicate-bearing IIICD irons may help resolve this issue. It is also clear that if IIICDs did not come from the same parent body as the IABs and winonaites, then the IIICD parent body must have had a similar history as the parent body of the IAB irons and winonaites.

4.2. Previous Models for the Formation of IAB Irons and Winonaites

While few hypotheses have been postulated for the formation of the winonaites, several have been suggested for the IAB (and IIICD) irons. Wasson (1972) once argued that elemental trends in the IAB irons were due to condensation of the metal directly from the nebula, giving rise to the term “non-magmatic”. However, this hypothesis was later rejected by Wasson et al. (1980) because, if the variations in elemental abundances are due to nebular processes, comparable ranges in the metal compositions should be found in chondritic material as well, which is not the case.

Another problem with this hypothesis is the difficulty of forming, by condensation, parent taenite crystals tens of cms in size (Wasson et al., 1980).

Wasson et al. (1980) and Choi et al. (1995) suggested that the IAB irons formed in numerous localized impact melt pools in the chondritic megaregolith of their parent asteroid. They argue that impacts would selectively melt low temperature fractions (Fe,Ni-FeS), which would migrate to form pools. Impacts are thought to have occurred over a range of time and temperatures, producing the correlated variations between Ni and Ga, Ge and Ir. In an extreme view, each IAB iron represents an individual melt pool. While the pools would cool relatively quickly, trapping the unmelted, angular silicate inclusions, Choi et al. (1995) argued that both limited fractional crystallization and magma mixing would occur, producing both the high-Ni IAB irons and the scatter in Ga, Ge and Ir observed at high-Ni concentrations. While impact does provide a ready mechanism for mixing silicates and metal, the main problem with this hypothesis is that impacts are incapable of producing copious quantities of Fe,Ni-FeS-rich melts formed by selective melting of these phases. Keil et al. (1997) argue, based on theoretical, experimental and observational evidence, that selective melting by impact occurs only locally and produces an extremely low percentage of melt. Any melt produced quenches rapidly, thus inhibiting migration of selective melts into larger pools, as is required for the formation of the huge IAB irons.

Several authors have proposed that IAB and IIICD irons formed as a result of partial melting and core formation of a differerntiated asteroid. Kelly and Larimer (1977) argued that the composition of the metal is consistent with fractional melting of a single composition which was isolated from later melted material so that it would not reequilibrate. Wasson et al. (1980) marshaled several arguments against this model, the most compelling of which are the apparent contradiction between predicted and measured siderophile element partition coefficients and the unreasonably high temperatures required to form the last fractional melts. Kracher (1982, 1985) suggested that as a result of partial melting, migration of the Fe,Ni-FeS eutectic melt could form a S-rich core at low temperatures. Thus, crystallization of both metal and sulfide determined the siderophile element trends observed. Choi et al. (1995) argued that crystallization of such a magma cannot produce the observed distribution of Ni concentrations. In fact, the system is probably far more complicated than envisioned by Kracher (1982, 1985), who ignored the possibly appreciable contents of carbon and phosphorus in the melt: Both McCoy et al. (1993) and Choi et al. (1995) pointed out that the partition coefficients of siderophile elements in such a complicated system remain essentially unknown. Finally, McCoy et al. (1993) argued that correlated trends between the properties of IIICD silicate-bearing inclusions (e.g., mineral compositions, modal mineralogies) and the Ni concentrations of the metallic host are best explained by reaction between these two during a prolonged period of fractional crystallization of a common metallic magma.

A serious flaw of any of the partial melting models is the inability to readily account for the mixing of unmelted silicate clasts within a liquid metallic Fe,Ni core. This is particularly problematic in an asteroidal core, which probably crystallized from the outside, thus armoring the inner core (Choi et al., 1995). Kracher (1982, 1985) argued that silicates may have been spalled into the core from the core-mantle boundary by impact-generated tectonic activity, but no supporting evidence or modeling has been suggested as to how that mechanism actually worked.

4.3. A New Model for the Formation of IAB Irons and Winonaites

We propose the following scenario for the origin of the IAB irons and winonaites: (1) A chondritic parent body was heated by a non-collisional heat source and began to differentiate. (2) This body experienced extensive partial melting and fractionation, but did not melt and differentiate completely. (3) After heating had reached its maximum extent and some cooling and crystallization had begun, a catastrophic impact occurred that caused fragmentation of the parent body, followed by gravitational reassembly of the debris. (4) During reassembly, extensive mixing of solid and partially melted silicates with molten metallic Fe,Ni took place, accounting for the IAB irons containing variable amounts and types of silicate inclusions. Winonaites represent metamorphosed precursor material or partial melt residues thereof. (5) After reassembly, metal that reassembled very hot began to fractionate and crystallize (creating the high-Ni IAB irons), and metamorphism and cooling continued. Ages of 4.43-4.53 Ga for silicate inclusions in IABs and of ≥4.40-4.54

Ga for winonaites imply that this entire process occurred very early in the history of the solar system.

4.3.1. Precursor material

The bulk compositions and mineralogy of silicate inclusions in IAB irons (e.g., Jarosewich, 1967; Kracher, 1974) resemble those of chondritic meteorites and are consistent with a chondritic precursor material for these rocks. This conclusion is strongly supported by the compositions and textures of winonaites which we and others suggest to have formed on the same parent body. Winonaites are "primitive" achondrites of roughly chondritic composition, and some (e.g., Pontlyfni) even contain what appear to be highly recrystallized relict chondrules (Benedix et al., 1997). However, oxygen isotopic compositions of the silicate inclusions in IAB irons and of the winonaites are unlike those of any known unadulterated chondrite (Clayton and Mayeda, 1996), suggesting that the pristine chondritic precursor material of the IABs and winonaites has apparently not survived the complex melting and impact history of the parent body and, thus, is not represented in the world's meteorite collections.

4.3.2. Heating and partial melting

Our studies of IAB irons (and winonaites; Benedix et al., 1997) suggest that their parent body experienced heating and partial but not complete melting. As argued above, due to the implausibility of impact as a heat source (Keil et al., 1997), it seems likely that the heat source must have been electromagnetic heating or decay of short-lived radioactive isotopes (e.g, ^{26}Al, ^{60}Fe). In case of the winonaites, the presence of relict chondrules and the recrystallized textures of these metamorphic rocks are indicative of peak metamorphic temperatures at least as high as those experienced by petrologic type 6 ordinary chondrites (~750-950°C; Dodd, 1981). Two-pyroxene geothermometry suggests even higher temperatures (730-1200°C), and petrologic observations indicate that some winonaites are highly metamorphosed rocks, whereas others experienced partial melting and are residues of that process. Veins of Fe,Ni metal and troilite in winonaites almost certainly represent eutectic melts which we suggest formed by partial melting rather than by shock. Coarse-grained olivine-rich portions in some winonaites were interpreted as residues formed by up to ~45% silicate partial melting, and irregular calcic pyroxene-plagioclase-rich portions in Pontlyfni may represent basaltic partial melts (Benedix et al., 1997).

Evidence for silicate partial melting also comes from the compositions and textures of silicate inclusions in IAB irons. For example, calculated two-pyroxene temperatures range up to ~1200°C (Table 3). Although these estimates may have uncertainties of ~100°C, they suggest that partial melting of silicates should have occurred. First basaltic (~50% plagioclase and ~50% pyroxene) silicate partial melts form from chondritic precursor materials at ~1050° C. The basaltic inclusions in Caddo County and the coarse-grained, plagioclase-rich areas associated with graphite-rich veins in inclusions in Campo del Cielo provide evidence that this process took place and represent rocks that crystallizd from basaltic partial melts after their removal from the source region. On the other hand, a troctolitic inclusion in Ocotillo and portions in silicate inclusions in Udei Station up to 5 mm in size that are virtually devoid of plagioclase may be residues after removal of a basaltic (plagioclase-rich) melt fraction and may have required temperatures of ~1250° C. Partial melting is also suggested by modal analyses of silicate inclusions in Campo del Cielo (Wlotzka and Jarosewich, 1977; this work) that show variabilities in the abundances of pyroxene and plagioclase, consistent with various degrees of removal of partial melts. Fractionated bulk REE patterns for silicate inclusions in some IAB irons (Bild, 1977; Kallemeyn and Wasson, 1985) are also consistent with melting and mobilization of plagioclase-pyroxene-phosphate-rich melts, although we cannot rule out unrepresentative sampling to explain these patterns.

The most convincing evidence for partial melting in the IAB-winonaite parent body is, of course, the existence of the IAB irons, which clearly must have formed from partial melts. In fact, the first melt produced from a chondritic precursor material is an Fe,Ni-FeS eutectic melt that forms at ~950°C (Kullerud, 1963; Kubaschewski, 1982). However, there is considerable evidence that this temperature was exceeded in portions of the parent body. For example, a temperature of ~1390°C is inferred as the liquidus temperature for the sulfide-rich metallic liquid from which Mundrabilla crystallized. It is difficult, however, to place boundaries on the magnitude of Fe,Ni-FeS partial melting and, particularly, the question whether the parent body developed a single, sulfur-rich core or whether the iron meteorites are samples of smaller, local melt pools scattered throughout the body (the raisin bread model). The existence of several very large IAB irons (e.g., Canyon Diablo), however, requires that melt bodies must have been many tens of meters in diameter. Furthermore, if IIICD irons sample the same parent body, at least two separate melt bodies are required to explain the differences in siderophile element trends in the metallic hosts of IAB and IIICD irons (Kracher, 1982).

The above discussion suggests that the IAB-winonaite parent body must have had temperature gradients of as much as ~400° C. While this temperature range may at first seem extreme, it apparently is not uncommon for asteroidal objects. For example, properties of unequilibrated and equilibrated ordinary chondrites suggest that their parent bodies had temperature gradients of up to ~650°C (Dodd, 1981). However, we have no evidence that would allow us to decide whether the apparent temperature range in the IAB iron-winonaite parent body represents a thermal gradient in an onion shell-type body, or whether the heating was more localized and spatially heterogeneous.

4.3.3. Collisional fragmentation and gravitational reassembly

A major puzzle in explaining the origin of IAB irons is the mechanism that mixed molten metallic Fe,Ni-FeS with solid silicate rock fragments. Based on theoretical studies of the collisional evolution of asteroids (e.g., Davis et al., 1979; Hartmann, 1979) and on evidence from the study of meteorites (e.g., Taylor et al., 1987; Keil et al., 1994), it has been suggested that major impacts can fragment asteroids without causing permanent dispersal of all of the debris. In these scenarios, gravitational reassembly may take place to form bodies that are rubble piles of materials from diverse depths in the original body.

We suggest that the partly melted and differentiated IAB iron-winonaite parent body experienced such a major collision approximately when the heating episode of the body was at its peak. Resulting break-up and fragmentation of the body and gravitational reassembly of some of the debris caused "scrambling" and mixing of relatively deep-seated material such as molten metallic Fe,Ni-FeS with a diverse suite of solid rock fragments, thus explaining the existence of

IAB irons with silicate inclusions. This scenario also readily explains why some IABs contain differentiated silicate inclusions (e.g., Caddo County, Ocotillo) and others do not (Lueders); why some have high amounts of inclusions (e.g., Lueders, Landis), and others do not (e.g., San Cristobal); and why within a given meteorite, abundances of inclusions vary considerably (e.g., Toluca, Campo del Cielo). That the mixing process was a relatively violent one, as one would expect from gravitational reassembly after a major fragmentation event, is indicated by the fragmentary, broken appearance of silicate inclusions in some meteorites (e.g., in Lueders). The winonaites are thought to be residues of the precursor silicate rock of the parent body, modified by metamorphism and partial melting. This scenario also readily explains why the less dense silicate rock fragments did not gravitationally separate from the much denser metallic melt: Mixing of solid silicate rock fragments that presumably were much cooler than the molten Fe,Ni-FeS would cause rapid cooling and solidification of the metal-sulfide melt (Onorato et al., 1978), thus preventing density fractionation. Direct evidence for relatively fast cooling at the time of solidification exists only for Mundrabilla, with a cooling rate of ~5°C/yr (10^{-7}°C/s) (Scott, 1982). IAB irons have Widmanstatten structures whose Fe-Ni concentration gradients across kamacite-taenite interfaces formed by sub-solidus cooling in the temperature range of ~600-350° C at cooling rates of tens of ° C/my. This suggests that the temperature of some of the metal-silicate debris that reassembled must have been >600° C, and that these fragments were buried sufficiently deeply in the reassembled asteroidal body to allow slow sub-solidus cooling and formation of the Widmanstatten structure. In fact, it also seems that some material reassembled at much higher temperatures: It seems likely that high-Ni IABs such as Oktibbeha County with 60 wt.% Ni formed by fractional crystallization in metallic pools that experienced very slow cooling over long time periods (Scott, 1972; Kracher, 1982, 1985; Choi et al., 1995). If the fragmentation/gravitational reassembly model is correct, then age measurements indicate that fragmentation took place very early in the history of the solar system, with insufficient time for fractional crystallization for formation of high-Ni IABs prior to fragmentation.

We suggest that collisional fragmentation and gravitational reassembly occurred approximately at the time that the heating episode of the original IAB-winonaite parent body had reached its maximum and after considerable melting and fractionation had occurred. This is suggested by the existence of the irons themselves, which formed by partial melting of a chondritic precursor material. It is also suggested by the fact that some IABs such as Caddo County and Ocotillo contain fragments of highly evolved and fractionated rocks; that many "chondritic" inclusions in IABs appear to have been depleted in plagioclase (and pyroxene) as a result of partial melting and removal of a basaltic partial melt; and that many winonaites are residues of similar partial melting of chondritic precursors. The relatively old ages of silicate inclusions in IABs of 4.43-4.53 Ga and of winonaites of ≥4.40-4.54 Ga (Benedix et al., 1997) suggest that heating, differentiation, fragmentation and gravitational reassembly occurred very early in the history of the solar system, but that the metamorphic textures of silicate inclusions and perhaps even of some winonaites may have formed during slow cooling after reassembly. The similarities in mineralogical, chemical and isotopic compositions of the silicate inclusions and the winonaites suggest that they are from the same original parent body. Thus, we have been unable to identify any material among the IABs and winonaites that could represent residues of the putative projectile that caused fragmentation of the original parent body.

Although we are uncertain whether the original IAB-winonaite parent body had a fully developed core (rather than sizable molten metal pockets distributed throughout the body), we have explored the efficiency of impact scrambling of a differentiated body. Specifically, we have applied numerical hydrodynamic simulations of impacts which Love and Ahrens (1996) had carried out for homogeneous, gravity-dominated asteroids, to differentiated asteroids. This procedure employed a 3-dimensional Smoothed Particle Hydrodynamics (SPH) code that models a continuous medium using discrete particles whose physical properties are mathematically "smoothed" out into the neighboring volume. It is good for simulating hypervelocity impacts because it remains accurate even when the collision partners suffer extreme geometrical distortion (*e.g.*, Monaghan, 1992). After the hydrodynamic phase, some of the target asteroid's mass carried enough kinetic energy to climb at least to the surface if launched from the target's center, or to enter orbit around the target if launched from the surface, but did not possess enough energy to escape. This "scrambled" material could reaccrete anywhere on the final rubble pile. Love and Ahrens (1996) found that a significant fraction of the final target can be scrambled, but only in impacts that also permanently eject much of the target's mass. Erosion of about half of the target mass corresponds to ~50% scrambling of the final rubble pile. They also calculated the percentage of the final rubble pile consisting of scrambled particles excavated from the deep interior ("core") of the (homogeneous) rocky target. "Core" material was identified as that initially lying within half the target's initial radius of the target center. Only the largest impacts exhumed significant mass (up to ~ 10 % of the final target's mass) from the "core".

Extending those results to differentiated targets must be done cautiously. The dense Fe,Ni core of a differentiated asteroid is bound to itself more tightly by gravity than a stone core of the same size. This extra binding, working together with the drop in shock velocity that accompanies a transition from a low density to a high density medium, hinders excavation of core material. The "core" scrambling results of Love and Ahrens (1996) using uniform granite targets thus provide only an upper limit on the effectiveness of that process in differentiated targets. With this caveat in mind, we have extended this work to treat asteroids 100 and 300 km in diameter with iron cores occupying the central 9% of their volumes. This fraction represents the amount of metallic Fe,Ni-FeS obtained by complete removal of the metal and troilite fractions of an H chondrite starting composition into a core and, thus, is an extreme case of a fully differentiated parent body. An impact velocity of 5 km/s and impact angle of 45° was used for all trials with differentiated bodies, and Table 6 shows the results for undifferentiated and differentiated targets. As expected, impacts into differentiated or undifferentiated targets have little effect on the amount of target permanently lost from the body (particularly at larger sizes). However, for identical impacts, scrambling of core material is less effective in differentiated targets than in homogeneous ones. This is partly due to the extra gravitational "strength" a differentiated asteroid gains from its dense core, allowing it to endure somewhat larger impacts. These effects combine such that catastrophic impacts (those permanently removing about half the target mass) on large differentiated asteroids yield final rubble piles containing ~5-10 vol.% of material excavated from the core. Thus, mixing of material from the center of the body is less effective for differentiated than for homogeneous asteroids. Nonetheless, these calculations suggest that catastrophic fragmentation and gravitational reassembly is a viable mechanism for mixing metal and silicates in a differentiated asteroid and, thus, producing IAB silicate-bearing irons. Furthermore, it seems likely that in case of partly differentiated asteroids such as the IAB iron-winonaite parent body, the magnitude of scrambling would be greater than in the calculated extreme case of a completely differentiated object.

Acknowledgments - IAB iron meteorite samples were kindly provided by R.S. Clarke, Jr. and G.J. MacPherson (Smithsonian Institution), A.J. Ehlmann (Texas Christian University), J.T. Wasson (Univ. of Ca., Los Angeles), the National Institute of Polar Research, and the Meteorite Working Group. Unpublished data on IAB iron meteorite cooling rates were generously provided by A. Meibom. Helpful discussions were provided by G.J. Taylor, A. Meibom, and J.T. Wasson. Expert technical assistance was provided by T. Servilla and T. Hulsebosch. This study was funded by NASA grants NAGW-3281 and NAG 5-4212 (K. Keil). This is Hawaii Institute of Geophysics and Planetology publication no. **xxx** and School of Ocean and Earth Science and Technology publication no. **yyyy**.

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FIGURE CAPTIONS

Fig. 1 Slab of the Mundrabilla iron meteorite showing metal-troilite intergrowths. White areas are Fe,Ni metal and gray areas are troilite. Scale bar = 20cm. (Photograph courtesy of P. Ramdohr via E.R.D. Scott).

Fig. 2 Slab of Caddo County, showing truncated, silicate-bearing inclusions up to 7 cm. These silicate-bearing inclusions comprise ~35 vol.% of the slab. Maximum dimension of slab = 16 cm. (Photograph courtesy of T.J. McCoy).

Fig. 3 Merged Mg+Al X-ray dot map of Ocotillo illustrating variable types of clasts. Clast 1 is composed primarily of plagioclase and olivine consistent with a troctolite composition and measures ~5mm in maximum dimension. Clast 2 contains a large calcic pyroxene with smaller amounts of plagioclase within the clast. The grain sizes in this clast are less than those of the basaltic composition Caddo County. Clast 3 is a typical, "chondritic" composition clast, similar to the angular inclusions found in many IAB irons. Arrows point to magnesiochromite (medium gray) that is found at the edges of Clasts 1 and 2.

Fig. 4 Photograph of a cut and polished slice of the Toluca IAB meteorite (USNM no. 931) that contains the typical rounded graphite and/or troilite-bearing inclusions which sometimes contain angular silicate clasts (Photograph courtesy of the Smithsonian Institution).

Fig. 5 Photograph of a large (~130 cm) polished slice of the Campo del Cielo IAB iron with common, heterogeneously distributed inclusions. (Photograph courtesy of the Smithsonian Institution)

Fig. 6 Photograph of a polished slice of the Lueders IAB iron with abundant angular silicate inclusions. Maximum dimension = ~10cm.

Fig. 7 Merged Mg+Al X-ray dot map illustrating the distribution of phosphates in a silicate inclusion in San Cristobal. The phosphate brianite [$Na_2CaMg(PO_4)_2$] comprises 3.5 vol.% of the inclusion which is composed mainly of olivine, low-Ca pyroxene, and plagioclase.

Fig. 8 Plot of Fa in olivine vs Fs in low-Ca pyroxene for silicate inclusions in IAB irons and winonaites. The large range in Fa relative to Fs in IAB irons is broadly consistent with reduction of a common precursor composition like Udei Station (US).