THE FORMATION OF THE IIE IRON METEORITES.

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Introduction: The IIEs are unique among iron meteorites due to the diverse range of silicate inclusions that over half the members of the group contain. These inclusions range from chondrule-bearing to highly differentiated [1]. This present study sets out to examine these inclusions in order to determine both the group's formation history and the nature of its precursor material. Work undertaken as part of this project has included oxygen isotopic measurements, as well as petrographic and geochemical analyses [1]. Previous formation theories [2, 3 and 4] for the IIE irons have tended to focus on one, or a few, specific meteorites. By studying and considering a larger range of IIE specimens we seek to develop a more comprehensive understanding of IIE formation.

Analysis methods: Oxygen isotope measurements on 11 silicate-bearing IIE irons were performed by infrared laser-assisted fluorination following the methods of [5]. Textural and quantitative mineral analyses were performed using a Cameca SX-100 Electron Microprobe and a FEI Quanta 200 FIB-ASEM.

IIE characteristics: The IIE silicates display an almost identical range of δ^{18}O and Δ^{17}O as high precision oxygen isotope data for the H chondrites [1] and so are in agreement with previous findings based on less-precise conventional oxygen isotope techniques [6]. The implication of these results is that the IIE silicates and H chondrites likely originate from a common parent body, or at least very similar bodies. The presence of chondrule-bearing IIE silicates highlights the chondritic nature of the IIE precursors.

Two pyroxene thermometry [7] of the inclusions demonstrates that with increasing fractionation, as indicated by bulk and mineral compositions, temperatures decreased, indicating a slower cooling rate for samples that have experienced increased fractionation (Fig. 1).

Petrographic analysis of the differentiated IIE silicates show that they fractionated from a chondritic melt, providing further evidence for a chondritic parent body [1].

On account of textural and mineralogical diversity documented for silicate inclusions in IIE iron meteorites, any formation mechanism must account for the occurrence of primitive chondrule-bearing through to highly differentiated silicate inclusions within a localized area reconciling variations in energy input and cooling rates [1].

The chondrule-bearing IIEs have Δ^{17}O values slightly lower than the other IIE silicates. Interestingly, high precision oxygen isotope data of H chondrites reveal that the H3 chondrites have similar Δ^{17}O values to that of the chondrule-bearing IIEs. This observation indicates that there is a structural or thermal relationship between the IIEs and H chondrites. There continues to be good evidence for the H chondrites originating from a thermally stratified onion-skin type, parent body [e.g. 8]. Co-variation of thermal processing in the IIEs and H chondrites suggests that this structure existed at the time of IIE formation.

One question of interest concerning the IIE iron meteorites is the origin of the metal. A large volume of metal would have been required to form the IIE iron meteorites and therefore would likely require an external source. Siderphile elements analyses of the metal in the IIE iron meteorites show that the metal crystallized from a reduced molten H chondrite precursor [9]. Similarly the composition of the metal of the IIEs and H chondrites are distinctive, with the IIE metal being more reduced than that in the H chondrites [10].

The Ge isotopic composition and the Ni concentration of the IIEs have a significantly different relationship compared to other iron meteorites and show fractionation of lighter Ge isotopes indicative of evaporation. This suggests that the IIE iron material experienced extensive melting during an impact [11]. In order to account for the high metal to silicate ratio in the IIEs it may have been that the impactor was largely a stripped core [12] of an H chondrite-like parent body, although some differentiation/segregation could have occurred following the impact event.

There are 6 IIE iron meteorites which were not studied as part of this project as they do not contain any silicate inclusions. Therefore the formation model for the whole IIE iron meteorite suite must also account for the origin of this metal dominated region in addition to the zone in which mixing between the silicate and metallic material producing the silicate bearing IIEs.

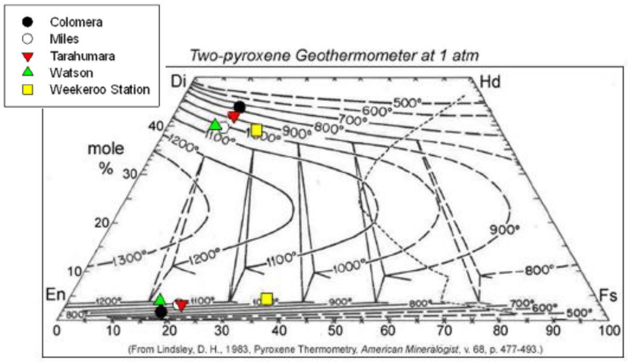
IIE formation mechanism: The most likely process involved in the origin of IIE iron meteorites is an impact of a metallic projectile into an H chondrite-like parent body, resulting in the development of a localized impact pools on the surface of the body. This impact event would have required sufficient energy to partially melt both the projectile and the impacted area of the target body to allow metal and silicate to become mixed. The range in petrographic types observed in the IIE inclusions would then be the result of variations in the cooling rate of different areas of the melt pool. Regions close to the surface and at the edge of the impact pool would cool more quickly than regions located in the centre of the impacted region. The more slowly cooled areas would allow the melt to fractionate and develop textures such as exsolution in pyroxenes and the formation of antiperthitic structures in feldspar, both of which are observed in the differentiated IIEs [1]. The faster cooling surface regions of the melt pool would experience sufficient energy to melt and lose chondritic textures, but rapid cooling would prevent fractionation of the material and therefore the inclusions produced would retain a chondritic composition with a loss of the chondritic textures, such as chondrules. Chondrule-bearing silicate inclusions would have experienced the lowest energy input from the impact and have the most rapid cooling rates, and therefore would most likely form at the edges of the impacted region where melted projectile could mix with chondritic material without extensively altering it (Fig 2). Where cooling rates were slowest it is possible that temperatures remained high enough to allow metal/silicate segregation to occur within this localized setting, forming inclusions with low volume of internal metal.

The IIE iron meteorites have two distinct age ranges the Old (4.1-4.5Ga) [13] and the Young (~3.7 Ga) [14]. The Young groups contain meteorites with chondrule-bearing to differentiated inclusions and therefore must be the result of a resetting event, most probably a secondary lower energy impact into the IIE region on the H chondrite parent body.

Conclusions: The geochemical characteristics of IIE iron meteorites are complex, and in order to produce all the known characteristics of this group an impact formation, followed by various cooling rates within the melt pool would be required. A further more comprehensive study of IIE cooling rates would establish if this hypothesis is feasible.

The degree of impact generated melting produced by a metallic projectile into a chondritic target can be tested by both impact lab experiments and Hydrocode modelling. Impact experiments have begun using the Light Gas Gun at the University of Kent [15].

References: [1] McDermott, K. H., et al. (2012) LPSC abstracts. Vol. 43. [2] Olsen, E., et al. (1994). Meteoritics, 29(2), 200-213. [3] Casanova, I. et al, (1995). Science, 268 (5210), 540-542. [4] Ruzicka, A., et al. (1999). GCA 63(13), 2123-2143. [5] Miller M. F. et al. (1999). Rapid Commun. Mass Spectrom. 13:1211-1217. [6] Clayton R. N. et al, (1991). GCA 55:2317-2337 [7] Lindsley, D. H. (1983), American Mineralogist 68.5-6 477-493. [8] Trieloff, M., et al (2003) Nature 422.6931 502-506. [9] Teplyakova, S. N., et al (2012). LPSC abstract Vol. 43, p. 1130. [10] Wasson, J. T. and Scott, E. R. D. (2011) LPSC abstract Vol. 42,2 p. 2813 [11] Luais, B. (2007).EPSL, 262(1), 21-36. [12] Asphang, E. et al. (2006), Nature, 439.7073 155-160. [13] Mittlefehldt D. W. et al. (1998). In Rev. Min. 36 (4) 1-195 [14] Bogard D. D. et al, (2000), GCA, 64:2133-2154. [15] McDermott K. H. et al. (this meeting).



(From Lindsley, D. H., 1983, Pyroxene Thermometry. *American Mineralogist*, v. 68, p. 477-493.)

Figure 1: Two pyroxene thermometry diagram showing a general decrease in closure temperature with increasing differentiation observed in the inclusions from Watson 001-Miles/Weekeroo St–Tarahumara – Colomera.

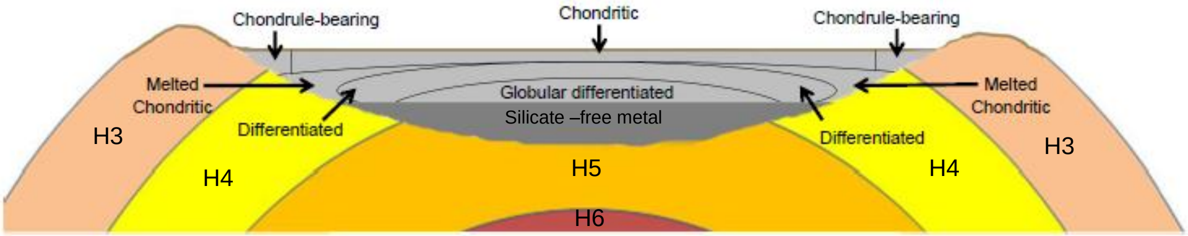


Figure 2: Schematic diagram (not to scale) showing an impact melt pool origin for the IIE iron meteorite suites. After impact melting of the local region and resettling of the ejecta the deepest areas of the body are heated to temperatures that allow metal and silicate material to gravitationally separate, forming a Fe/Ni rich layer at the base of the crater. Above this layer the metal and silicate material are still mixed forming small pods of silicate within the metal. The inclusion groups are separated by the different localised cooling rates.