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Microstructural and paleomagnetic insight into the cooling history of the IAB parent body

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Abstract

The IABs represent one of only two groups of iron meteorites that did not form by fractional crystallization of liquid Fe-Ni in the core of a differentiated planetesimal. Instead, they are believed to originate from a partially differentiated body that was severely disrupted by one or more impacts during its early history. We present a detailed microstructural and paleomagnetic study of the Odessa and Toluca IAB meteorites, with a view to further constraining the complex history of the IAB parent body. X-ray photoemission electron microscopy and energy dispersive spectroscopy were used to generate high-resolution Ni/Fe maps. The crystallographic architecture of Odessa was analysed using electron backscatter diffraction. Paleomagnetic signals and the magnetic properties of several microstructures were also assessed using X-ray magnetic circular dichroism. Odessa exhibits a complex series of microstructures, requiring an unusual evolution during slow cooling. A conventional Widmanstätten microstructure, consisting of multiple generations of kamacite lamellae surrounded by M-shaped diffusion profiles, developed via continuous precipitation to temperatures below ~400 °C. Multiple generations of pearlitic plessite nucleated from kamacite/taenite ($T > 400$ °C) and tetrataenite rim/taenite interfaces ($T < 400$ °C), via a process of discontinuous precipitation. Rounded rafts of Ni-rich taenite, observed within some regions of pearlitic plessite, are shown to have the same crystallographic orientation as the parental taenite, and a non-standard orientation relationship with the enclosing kamacite. Contrary to current theories, these rafts cannot have formed by coarsening of pre-existing pearlitic plessite. A new bowing mechanism is proposed, whereby rafts of Ni-enriched taenite form between advancing lobes of an irregular reaction front during discontinuous precipitation. Subsequent coarsening leads to the growth of the taenite rafts, and the partial or complete removal of pearlite lamellae, resulting in spheroidised plessite with a crystallographic architecture matching the experimental observations. We find no evidence for a strong magnetic field on the IAB parent body, suggesting it did not have an active core dynamo at the time of cloudy zone formation. This supports the prediction that the IAB parent body was unable to form a significant core due to the redistribution of metal during an earlier impact event.

Keywords: IAB iron meteorites; Paleomagnetism; Cloudy zone; X-PEEM; EBSD; Microstructures; Pearlitic plessite; Spheroidised plessite; Thermal evolution

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1. INTRODUCTION

The parent bodies of meteorites are traditionally defined as either fully undifferentiated or fully differentiated (Weisberg et al., 2006). The IABs are an unusual group of iron meteorites that have been proposed to come from a partially differentiated body; they show contrasting chemical compositions to the other iron groups (except the IIEs) and do not appear to have formed by fractional crystallisation of a bulk source melt (Wasson and Kallemeyn, 2002; Goldstein et al., 2009; Benedix et al., 2014). They also contain silicate fragments of chondritic and primitive achondritic composition, including basaltic, troctolitic and peridotitic compositions, suggesting silicates within the parent body did not all experience the same degree of differentiation (Benedix et al., 2000). The IABs form several subgroups, which are both isotopically and chemically distinct. It is still a matter of debate whether these subgroups represent isolated pools of metal in one parent body, or represent several separate parent bodies (Worsham et al., 2016, 2017).

The IABs have a complex history, which is, in part, well constrained by isotopic dating and petrologic observations. Hf-W measurements suggest an accretion age ~2 Myr after calcium-aluminum-rich inclusions (CAIs) and metal-silicate segregation ~5 Myr after CAIs (Schulz et al., 2012). Ruzicka (2014) suggests segregation occurred during an initial impact event, which caused partial reheating of the asteroidal parent body, generating small amounts of silicate and metallic melt. An incipient core was then able to segregate, surrounded by a silicate mantle hypothesised to be the source of the Winonaites – a group of primitive achondritic meteorites (Greenwood et al., 2012). The body is assumed to be insulated by a thick chondritic layer from petrological and cooling rate observations (Rasmussen, 1989; Benedix et al., 2000; Takeda et al., 2000; Goldstein et al., 2014). Benedix et al. (2000) used two-pyroxene thermometry to argue that silicates reached a maximum temperature of ~1250 °C during accretion. This is supported by the lack of evidence for extensive melting or fractionation of the IAB silicates. This suggests that a sulphur-enriched core was formed by low degrees of partial melting (Benedix et al., 2014). The metal separates from the silicates when it reaches its eutectic (~85 wt% FeS) at 950 °C for the Fe-Ni-S system (Benedix et al., 2014) or 990 °C for the Fe-FeS system (Qin et al., 2008). Silicate metamorphism and resetting of low-temperature chronometers suggest a large impact event occurred ~8.5–17 Myr after CAIs (Schulz et al., 2012). This is also supported by the highly variable cooling rates and distinct chemical trends of IAB metal, suggesting formation in isolated metal pools throughout the parent body. This early 'scrambling' impact event occurred whilst the metal within the planetesimal was still molten; Re-Os isotope studies suggest metal solidification began 38 ± 21 Myr after CAIs (Horan et al., 1998). The scrambling impact redistributed silicate material, removing the outermost part of the body. The high metal content of the IABs suggests that an incipient metallic core remained, or ductile remobilization allowed the metal to form large pools (Ruzicka, 2014). Once scrambled, metal in the IAB parent body cooled and crystallized. At low temperatures ($\lesssim$780 °C) cooling rates were 63–650 °C Myr^{-1}, dropping to 1–20 °C Myr^{-1} at temperatures below 500–600 °C (Rasmussen, 1989). Cooling rates were determined using the central Ni concentration versus taenite width. This is consistent with estimates from Ni diffusion modelling, suggesting cooling on the order of ~10 °C Myr^{-1} (Yang et al., 2010). A recent Mo, Hf and Os isotope study of the IABs suggests an even more complex formation history, with subgroups forming on up to four parent bodies, each of which experiences a varying degree of internal heating and multiple impact events (Worsham et al., 2017).

There are still several open questions: Do the various IAB subgroups originate from a single parent body or from multiple parent bodies? Did the IAB parent body differentiate enough to form a significant metallic core? Did that core generate a dynamo? How many impact events influenced the evolution of the parent body, and is it possible to distinguish between them? IAB meteorites exhibit the Widmanstätten pattern, commonly observed in polished and etched sections of iron meteorites (Harrison et al., 2017). In addition, atypical microstructures such as spheroidised and pearlitic plessite are commonly observed in IAB meteorites (Buchwald, 1975).

We discuss three microstructures in detail in this paper: the cloudy zone, spheroidised plessite and pearlitic plessite. The cloudy zone (Fig. 1d) forms during slow cooling (<10,000 °C Myr^{-1}) (Yang et al., 2010) of taenite compositions between 25 and 47 Ni wt% (Yang et al., 1996). The taenite cools into a spinodal region below 450 °C at which point it decomposes into islands with composition $Fe_{0.5}Ni_{0.5}$ and a diameter of 10–500 nm, depending on cooling rate, surrounded by an Fe-rich matrix.

Spheroidised plessite consists of taenite spheroids and lamellae in a kamacite host (Fig. 1c). The spheroids are the most Ni-rich component, and are of order 5–10 μm in diameter. Narrow taenite lamellae with a slightly lower Ni content have one consistent orientation and are often interconnected to the spheroids.

Pearlitic plessite is a two-phase lamellar intergrowth of kamacite and taenite (Fig. 1a and b). Lamellae are of order of one micron in thickness and grow at a high angle from the tetrataenite rim. The taenite lamellae typically have a slightly higher Ni content than the surrounding taenite, and the kamacite a slightly lower Ni content.

The origin and significance of these atypical microstructures is poorly understood. We present a detailed high-resolution electron backscatter diffraction (EBSD) and X-ray photoemission electron microscopy (X-PEEM) study of the Odessa Main Group IAB iron, with particular focus on evaluating potential formation mechanisms for spheroidised and pearlitic plessite. EBSD is emerging as a powerful tool to study the formation and history of extraterrestrial materials (Forman et al., 2017). We discuss the composition, textures, crystallographic architecture and magnetic properties of the various Fe-Ni microstructures found, with the aim of further constraining the cooling and impact history of the IAB parent body/bodies during the time between metal solidification and its final breakup.

Paleomagnetic analysis of the cloudy zone was also carried out on both Odessa and Toluca. The cloudy zone has