

**PETROGRAPHY AND TRACE ELEMENT CHEMISTRY OF COLOMERA (IIE)
SILICATE INCLUSIONS: RHYOLITIC PLUMS IN THE PUDDING;**
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The IIE Iron meteorites are exceptional in being one of two groups to contain cm-sized multiphase silicate inclusions. These inclusions have been extensively studied, both isotopically to provide radiometric ages and petrographically to provide hints regarding the genetic relationships between iron and stony meteorites [e.g., 1-9]. Despite these investigations, the petrogenetic history of the IIE's is complicated and remains poorly understood. The IIE meteorites show two distinctive ages [3,4]: $4.54-4.61 \times 10^9$ years for Colomera and Weekeroo Station, about 3.8×10^9 years for Kodaikanal and Netschaevo. Wasserburg et al. [2] proposed that the silicates (plums) formed from strongly differentiated silicate melts trapped in the cooling metal (pudding) after a shock event. Olsen and Jarosevich [8] suggested that the composition of the silicates was similar to that produced by separation from a chondritic melt. Scott and Wasson [9] proposed that Netschaevo represents the parent material of the IIE silicates (contradicted by its young age) and that the IIE's were formed by mixing shock-liquified FeNi metal with the low temperature melting fraction of a parent silicate. Niemeyer [4] proposed that the IIE silicates were formed on two different parent bodies and mixed with IIE metal in a shock event.

In order to test the various models for the origin of the IIE silicate inclusions, we have begun a series of systematic petrographic and trace element studies of the phases in selected individual inclusions. No REE or other trace element compositions have been previously reported for silicate or oxide phases in the IIE's. We have begun with a study of Colomera, one of the IIE's that gives old ages. Selected globular inclusions from the interior of the meteorite [2] were chosen for study with the electron and ion microprobes and the analytical SEM. Analytical procedures employed in the ion microprobe trace element analyses are given in [10]. The inclusions are composed mainly of alkali-silica-rich glass, similar in composition to alkali-rich-rhyolite, that contains included subhedral orthopyroxene as an abundant phase, and included euhedral rutile, chromite-spinel, Cl-apatite, and whitlockite as minor phases (e.g., Fig. 1). The orthopyroxene contains in its cores varying quantities of anhedral-to-euhedral crystals of clinopyroxene. Euhedral rutiles are found throughout the glass and appears to be an exsolution product from the glass, but chromites and phosphates are found almost exclusively at the contact between glass and surrounding metal and appear to be subsequent reaction products between the two phases.

The trace element distributions provide significant constraints regarding the formation history. The REE abundances normalized to C1 are shown in Figure 1. The REE patterns appear to be dominated by three factors: (1) the REE abundances in glass and pyroxene are significantly depleted relative to chondritic abundances and relative to other incompatible elements such as K and Ba. (K is enriched in the glass by about a factor of 10 over chondritic. The concentrations of Ba, Ti and Hf are at about chondritic levels, relative to K, while in the glass La is depleted relative to K by a factor of ~130 for the LREE and by a factor of ~8 for the HREE.) The REE abundances of the phosphate are not large enough to provide a bulk composition anywhere near chondritic abundances, nor were any other carrier phases for REE found in the inclusions. (2) The REE patterns are quite fractionated, with considerable heavy REE enrichments (or light REE depletions) and a large negative Yb anomaly in all phases. (3) The glass and pyroxene exhibit complementary positive and negative Eu anomalies. The REE pattern of the Colomera glass is similar to that for silicate inclusions in other iron meteorites [11-12], with low LREE abundances that decrease slightly from La to Sm, a positive Eu anomaly, smoothly increasing HREE abundances and a negative Yb anomaly (Fig. 2). Low Ca-pyroxene within the inclusion has a LREE depleted pattern and negative Eu and Yb anomalies; calculated cpx/glass partition coefficients (K_d) are typical of literature values [13] suggesting the low Ca-pyroxene crystallized from the melt. The apatite REE pattern is, with the exception of Eu, similar to the glass, but enriched by ~150x for the LREE and by ~30x for the HREE. Apatite does not appear to be in equilibrium with the glass since calculated apatite/glass LREE K_d 's are significantly (2-7x) larger than literature values [4] for apatite with similar HREE K_d 's. A mixture of low Ca-pyroxene and feldspar [11] would produce the REE pattern of the bulk inclusion. The existence of a large negative Yb anomaly must result from evaporation/condensation processes since it could not be produced by igneous processes [15].

The measured major element compositions of the various phases in these inclusions are similar to those previously reported [e.g., 5]. However, the higher precision nature of the new measurements provide additional constraints regarding formation. (1) The phase compositions and modal abundances of different inclusions are similar, but are not consistent with devitrification of a homogeneous starting material. The bulk compositions of the individual blebs are different. The similarities in composition would be consistent with

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flash melting a relatively homogeneous, fine-grained material of roughly rhyolitic composition into fine droplets that mixed quickly with molten metal before homogenizing. (2) The glass analyses (which were performed under special conditions that minimized alkali element migration that provided problems for previous analyses) show that the Al content, in all points analyzed, is within 2% relative (i.e., within analytical error) of the atomic concentration required for all of the Na, K and Ca to have been a feldspar. The glass compositions are consistent with formation from melting feldspar and 20% quartz for L1 and 25% quartz for L2. The composition of the glass is inconsistent with a shock heating of a feldspar precursor resulting in volatile loss of Na and K as proposed by some investigators. (3) The compositions of the coexisting pyroxenes are not totally consistent with low temperature equilibration using conventional pyroxene geothermometers [see 5]. The Ca/(Ca+Mg) contents of the clinopyroxenes from both L1 and L2 are similar (0.47 ± 0.01) and consistent with an equilibration at about 900° C [5], the K_d for Fe/Mg between opx and cpx is also consistent with an equilibration temperature of about 900°C for L1, where the cpx occurs as rounded blebs in the opx, but the K_d for L2, where the cpx occurs as euhedral laths in the opx, requires an unreasonable temperature of above 1400°C, if the geothermometer is valid.

Conclusions: The major and trace element chemistry suggests that the precursor of the silicate inclusions in the Colomera meteorite was a mixture of alkali feldspar, quartz, and pyroxene that was shock heated and mixed with molten metal that quenched early in the parent body's history. The precursor phases must have been differentiated from a source that originally had a group III type rare earth pattern [15] from some condensation/evaporation process. The differentiation must have resulted in loss of most of the REE without destruction of its group III pattern (perhaps by separation of preexisting phosphates). This process of differentiation, however, did not result in loss of other incompatible elements such as K and Ba. The partial crystallization of the molten silicates and subsequent metamorphic history were slow enough to enable normal partitioning of the REE between glass and pyroxene and at least partial equilibration of the pyroxenes. The process by which such a siliceous component as the starting material for these inclusions could have fractionated on the parent body so early in its history remains an intriguing problem.

Refs.: (1) T.E. Bunch and E. Olsen, *Science* **160**, 1223-1225 (1968); (2) G.J. Wasserburg et al., *Science* **161**, 684-686 (1968); (3) H.G. Sanz et al., *GCA* **34**, 1227-1239 (1970); (4) S. Niemeyer, *GCA* **44**, 33-44 (1980); (5) T.E. Bunch et al., *Contr. Min. Pet.* **25**, 297-340 (1970); (6) A.E. Bence and D.S. Burnett, *GCA* **33**, 387-407 (1969); (7) R.W. Bild and J.T. Wasson, *Science* **197**, 58-62 (1977); (8) E. Olsen and E. Jarosevich, *EPSL* **8**, 261-266 (1970); (9) E.R.D. Scott and J.T. Wasson, *GCA* **34**, 1227-1239 (1970) & prev. papers cited therein; (10) A.K. Kennedy et al., *Meteor.* **23**, 279 (1988); (11) R.W. Bild, *GCA* **41**, 1439-1456 (1977); (12) T. Fukuoka et al., *Lun. Sci. IX*, 356-361 (1978); (13) H. Fujimaki et al., *LPSC* **14**, B662-B672 (1984); (14) H. Fujimaki, *Contr. Min. Pet.* **94**, 42-45 (1986); (15) W.V. Boynton, in *Rare Earth Elel. Geochem.*, P. Henderson, Ed., Elsvier, Amsterdam, 63-114 (1983).

Fig. 1. Colomera Inclusion L1



Fig. 2. REE patterns for L1 phases.

