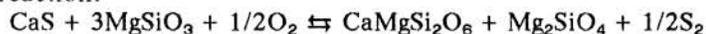


**THE ENSTATITE CHONDRITE-ACHONDRITE LINK.** R. A. Fogel, P. C. Hess and M. J. Rutherford, Brown University, Providence, RI 02912.

The enstatite achondrites are similar to the enstatite chondrites in their degree of reduction and the occurrence of enstatite(En) as the primary phase. Because of these similarities, there has been much speculation as to the possibility of deriving the enstatite achondrites from enstatite chondrite(EC) material(1). Various scenarios have been proposed which have the enstatite achondrites forming from the E-chondrites as either partial-melts or partial-melt residues. Such models must rationalize certain features that distinguish aubrites from E-chondrites: 1) the presence of diopside(Di) and forsterite(Fo), 2) the higher plagioclase albite(Ab) content, 3) the higher Ti content of troilite and 4) the higher troilite/kamacite (Tr:Km) modal ratio(2,4).

The silicate portion of the enstatite chondrites is comprised of nearly pure enstatite, Ab-rich plagioclase ( $EL \approx Ab_{85}$ ,  $EH \approx Ab_{95}$ ) and subordinate silica(Q). Di, and with a few exceptions Fo, are conspicuously absent in E4-E6 chondrites. The melting of the silicate fraction of enstatite chondrites can be approximated by the system forsterite-albite-silica. E-chondrite bulk compositions(BC) usually contain En:Ab:Q modal weight ratios on the order of 100:10:1, although these ratios vary widely. Within the Fo-Ab-Q system, the bulk composition of the enstatite chondrites(BC on Fig. 1) lies close to enstatite and slightly above the enstatite-albite join toward the silica apex. Both the partial-melt and residuum models require an understanding of the melting relationships within this system. Moreover, these models must produce Fo and Di from parental rock that contains neither phase.

*Residuum Model.* Melting of EC material begins at the En-Ab-Q peritectic at 1062°C and follows the path A-H-C-BC (Fig. 1). Formation of forsterite in the residuum is achieved at temperatures greater than or equal to the En-Ab-Fo peritectic (1095°C) where forsterite is formed by the incongruent melting of enstatite. Since Ab is not stable at  $T > 1095^\circ\text{C}$ , the formation of forsterite and its coexistence with Ab (as found in the aubrites) can be achieved if the melt is withdrawn from the peritectic or some melt is left in the residuum. Unfortunately, partial melting of the silicate fraction of E-chondrites cannot produce diopside in the residuum. However, some Di (and even some Fo) could be produced via the reaction:



The observation that the aubrites contain only minute amounts of oldhamite, that oldhamite has only been found in a few of these meteorites and that the E-chondrites contain far greater amounts of this mineral than do the aubrites, tends to support this process. The problem with this mechanism is that most E-chondrites contain only a few tenths of a percent of oldhamite. The source material for the residuum would need to contain considerably more CaS than in most E-chondrites to account for over 8 vol% diopside in aubrites such as Cumberland Falls. This method, however, could easily account for the modal abundances of Di in Aubres (0.2%) and Mayo Belwa (0.6%).

The albite content of aubrite plagioclase ( $Ab_{91}$ - $Ab_{96}$ ) can be rationalized with the residuum model only if the source material for aubrites was the EH chondrites. EH plagioclase contains roughly the same albite content as that of the aubrites but range slightly higher from  $Ab_{93}$  to  $Ab_{99}$ . Partial melting of albite-rich plagioclase will result in residual crystals with lower Ab content. Thus, an aubrite source region of EH composition could produce plagioclase of the required composition, although the extent of An enrichment would be subject to the amount of plagioclase melted.

At  $T > 1062^\circ\text{C}$  where EC silicates begin to melt and for the bulk composition of the E-chondrite metal-sulfide fraction, an Fe-FeS liquid would coexist with residual kamacite. A metal-sulfide melt drawn off at the T of the En-Ab-Fo peritectic would leave kamacite in the residuum and little or no troilite depending on how much melt is left in the residua. Furthermore, aubrite troilite contains Ti contents of 1-4 wt% as opposed to 0.3-0.7 wt% in the E-chondrites; an enrichment that partial melting fails to achieve in the residuum. To retain troilite, melting would have to cease at the Fe-FeS eutectic at 988°C; a condition unacceptable to the residuum model. A process other than partial melting is thus required.

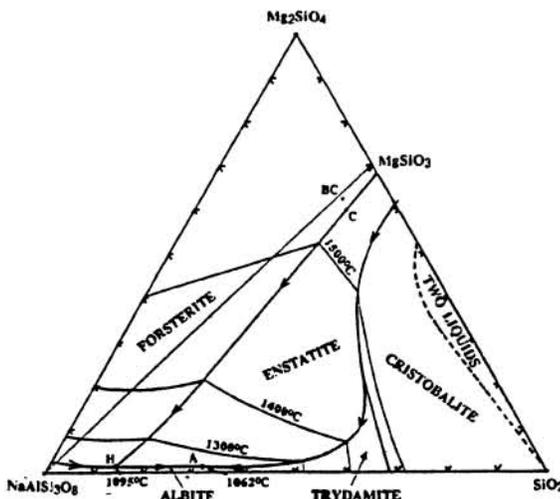
The melting point of TiS is 1927°C and that of FeS is 1195°C. This suggests that the first melts in the FeS-TiS system would be poorer in TiS and the residuum richer in TiS, than the bulk composition. If during melting and while troilite is still present, the melt is fractionated from the system, further melting would result in TiS contents in the liquid that are higher than the initial BC. This would initially lower the systems normative Tr:Km ratio. However, if this is followed at high temperature by kamacite fractionation from the residuum, the necessary Tr:Km ratio could be achieved. Whether density fractionation could accomplish this kamacite fractionation is unknown.

**Partial-Melt Model.** A melt drawn off anywhere along the melting path from the En–Ab–Q peritectic to the exhaustion of enstatite along the En–Fo peritectic line (point C), would generally not crystallize forsterite. Crystallization of a partial-melt would require melting to continue into the Fo field toward the BC in order for forsterite to be present in the crystallized product. Furthermore,  $T > 1500^\circ\text{C}$  and partial melting of  $> 80\%$  would be required. A possible scenario to circumvent this problem is to have the melting occur at depth where the En–Fo peritectic line is displaced away from  $\text{SiO}_2$  relative to the 1 atm peritectic line. If the partial-melt is withdrawn and brought to the surface causing a pressure drop, the En–Fo peritectic line shifts back toward the silica apex and expands the forsterite field placing a melt composition lying anywhere along the En–Fo peritectic line into the Fo field. Upon cooling, forsterite could be fractionally crystallized and preserved within cores of enstatite. The melt composition would then cross the En field, intersect the En–Ab cotectic and end at the En–Ab–Q eutectic where these three minerals form simultaneously.

There are several problems with this scenario. First, a trapped liquid would produce small quantities of cristobalite at the eutectic whereas no silica phase is found in aubrites. This requires that the intercumulous phases (Di, Ab) do not represent trapped liquids; i.e., the more silica-rich liquids were lost. This is fully consistent with the REE contents of the aubrites which usually are less than 1  $\times$  chondrites(3). Secondly, large amounts of albite should be formed relative to the other phases. However, plagioclase makes up no more than 16 vol % of the aubrites. The model calls for plagioclase flotation to leave the mafic cumulates relatively poor in albite. This hypothesis is supported by the negative Eu anomalies reported for the aubrites(3) suggesting plagioclase fractionation. The plagioclase Ab content would be less than the parent rock if the BC is chosen to be the EH chondrites. This would result in Ab contents of aubrite composition.

As in the residuum model, diopside can be formed by the oxidation of oldhamite. For the partial-melt model, this has the added benefit of reducing the silica activity as the reaction goes to the right. Reduction of the silica activity pushes the bulk composition more deeply into the forsterite field enhancing the prospects for forsterite saturation. Moreover, fractional crystallization of olivine, enstatite and albite would progressively raise the diopside activity of the melt. To analyze whether the diopside saturation surface would be reached, the core of the Fo–Ab–Q–Di system needs to be known. Within the Fo–Di–Q system the Di saturation curve lies near the Di apex. Fractional crystallization of EC compositions would intersect the En–Q cotectic before it ever reached the Di–Px cotectic. However, in the quaternary system the Di field expands toward the Fo–Ab–Q base resulting in a fractional crystallization path that intersects the Di–En cotectic.

The high Tr:Km ratio and TiS content of troilite can be explained as follows. The low Tr:Km ratio of the E-chondrites would reach the Fe–FeS liquidus only at very high temperatures ( $> 1350^\circ\text{C}$ ). Thus, melting of parental rock at more moderate igneous temperatures, would produce coectic liquids enriched in FeS. Partial melt withdrawal would leave kamacite in the residuum and produce the required Tr:Km. However, high temperatures would consume all Tr in the parental rock and leave the daughter product with the same TiS content as the parent. Continuous fractionation of metal–sulfide melt would produce cumulates enriched in TiS and poor in Tr+Km modal sum and adequately explain aubrite metal–sulfide properties.



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Fig. 1. The Fo–Ab–Q system (in weight percent). After Schairer & Yoder 1961. Carnegie Inst. Wash. 60, 69–70.