ANATOMY OF ALLENDE INCLUSIONS: MINERALOGY AND MG ISOTOPES IN TWO CA-AL-RICH INCLUSIONS. I.M. Steele[1] and I.D. Hutcheon[2], [1]Dept. of Geophysical Sciences, [2]Enrico Fermi Institute, University of Chicago, Chicago, IL 60637.

Grossman (1) recognized three types (A,B,I) of coarse-grained, Ca-Al-rich Allende inclusions based mostly on mineralogy. We continued an extensive study of these inclusions utilizing ion and electron microprobes, SEM, and cathodo-luminescence techniques by analysing the detailed mineralogy of one Type B (Al 15 or TS 23) and Mg isotopes in an unusual Type A (Al 3529-45). In (2) we described Na and Mg zoning of coarse-grained, interior anorthite as contrasted with Na- and Mg-poor anorthite at the edge of Al 15. We report major and minor element zoning in Ti-Al-pyroxene (Tpx) and melilite (Mel) as a function of position within the inclusion and contrast this with near-constant spinel (Sp) compositions. These data are discussed in combination with O and Mg isotopic data (2,3) with regard to its formation.

Al 15 is a typical subround (1cm dia.) Type B with a central cavity. Cathodo-luminescence shows five distinct zones schematically shown in Fig. 2: (1) a very thin (50μm) outer rim with complex mineralogy (e.g. (4)); (2) thin (0.75mm) Mel-Sp zone with rare Tpx and minor Sp; (3) narrow Mel zone with distinct optical zoning over ~100μm; (4) Tpx zone with occasional zoned Mel grains and plagioclase, all with included clustered spinel; (5) an inner Tpx-Mel-Pl-Sp zone gradational (over several mm) with zone 4 in which Tpx/(Mel+Pl) decreases toward the center (Pl=plagioclase).

Tpx has variable $Ti_2O_3$ content (2-8 wt.%); no very high Ti was found as reported in (1). Ti is calculated as $Ti^{+3}$(vs. $Ti^{+4}$) giving a slight excess (~1.02/6 Ox) of M1 octahedral cations suggesting a high $Ti^{+3}/Ti^{+4}$ ratio. Ti in Tpx in zone 2 is always high, slightly lower in zone 4, and shows the complete range in zone 5. Based on one conclusion in (5) that the higher Ti content of Tpx represents a higher temp. of formation, some zone 5 and 2 Tpx formed at near equal temperature, while other Tpx in zone 5 formed at progressively lower temperatures.

Spinel is nominal $MgAl_2O_4$ with detectable Ti,V,Cr and Fe; minor elements show no correlation with the position of spinel within the inclusion. Abundances (wt.%): $TiO_2$ 0.13-0.60 (highest values in Tpx, probably affected by secondary fluorescence); $V_2O_3$ 0.17-0.35; $Cr_2O_3$ 0.18-0.33; and FeO 0.06-1.0. Cathodoluminescence revealed three spinel colors: common orange, occasional blue, and a bright yellow observed for the first time in this inclusion. Orange and yellow spinels have similar minor element contents while blue contains high Fe. Spinels in zone 2 often have high Fe especially in proximity to the outer rim, possibly reflecting secondary alteration. The constancy of minor element content independent of position is not unexpected from O-isotopic results (3) showing that spinel has not equilibrated with its host phase. High FeO contents are difficult to reconcile with direct condensation and may indicate partial melting of secondary alteration. Determination of the O-isotopic composition of high-Fe spinels could clarify their origin.

Mel shows the most complex zoning of major phases and is potentially the most useful for deriving petrologic history such as changes due to melting events suggested by O-isotope data (3) subsequent to condensation. Mg,Fe and Na all vary and show clear trends with position within the inclusion (Fig. 1). Ti and V are detectable but at very low levels. Zone 2 Mel is low in Mg,Na and Fe with a slight increase in Mg toward zone 3. In zone 3, Mel is strongly zoned toward åkermanite with correlated increases in Na and Fe. In zones 4 and 5 individual Mel grains show parallel Mg zoning from high-Mg edges rapidly decreasing to Mg-poor cores. Na shows a strong correlation

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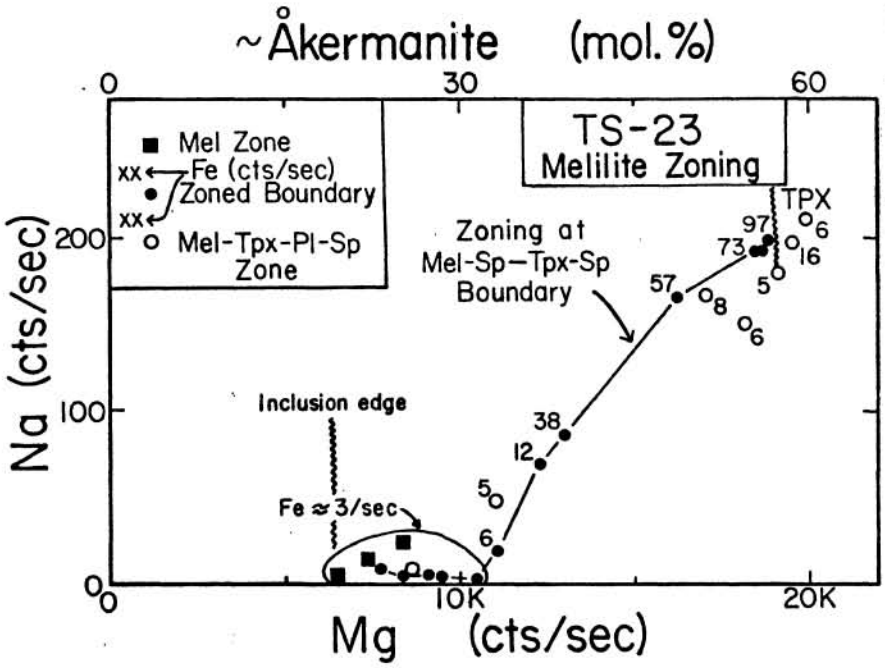


Fig. 1. Compositional variation in TS-23 melilite. Solid line shows zoning in zone 3 melilite; numbers indicate relative Fe content as cts/sec; solid squares are from zone 3 while open circles are from zone 5.

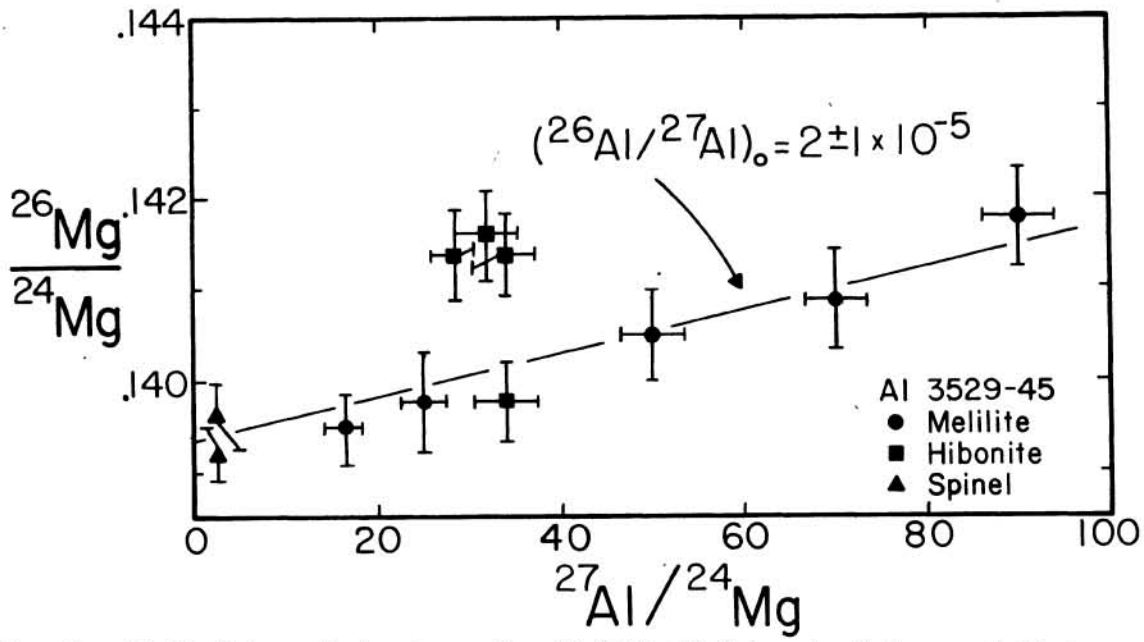


Fig. 3. Al-Mg internal isochron for Al 3529-45 determined in coexisting spinel, melilite, and hibonite by ion microprobe. Errors are ±2σ mean.

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with Mg as in zone 2 but Fe shows consistently low values. Chemical and mineralogical variations are summarized in Fig. 2.

Both major and minor elements are strongly zoned in Mel; these patterns may be a signature of condensation, in which case they survived the exchange of oxygen in Mel, or they may be produced by the event which exchanged oxygen. Presently the distinction remains unclear.

Mg isotope anomalies have been observed in ~12 Allende inclusions (2,6,7). In most Type B inclusions $^{26}Mg$ excesses found in anorthite correlate with Al/Mg and define a single Al-Mg isochron with slope ~$5x10^{-5}$. Mg isotopes from several hibonite-bearing inclusions (7,8) deviate from this simple model and question the chronological interpretation of $^{26}Mg$ excesses. We measured the Mg isotopic composition of a small fragment (~3mm dia) of a Type A inclusion consisting largely (~80%) of coarse-grained melilite containing small (~10μm) euhedral spinels and occasional hibonite. Experimental details are given in (2) except a weaker primary beam was used to analyze individual 10μm areas. Data are shown on the Al-Mg isochron plot in Fig. 3.

Isotopic measurements from 5 melilite crystals with Al/Mg ranging from 17 to 90 and two spinels define an isochron with slope $(^{26}Al/^{27}Al)_o=2\pm1x10^{-5}$. This slope is about half that is found in most Allende inclusions and suggests that either melilite post-dated Type B anorthite by ~$7x10^5$y or lost $^{26}Mg$ in subsequent events. A similar slope was also found in one Type B anorthite(2). Four hibonite crystals all with Al/Mg ~30 were analyzed; data from three do not fit the melilite isochron. The three hibonites, all texturally similar and in the same location, have $^{26}Mg/^{24}Mg$ >4σ above the melilite isochron and >2σ above the normal Allende isochron. The fourth hibonite, found in an interior clast of intergrown melilite and hibonite, has little excess $^{26}Mg$ and lies ~2σ below the Mel isochron.

The clear evidence of isotopic heterogeneity in this inclusion suggests several interpretations of $^{26}Mg$ excesses. (1) Hibonite may have formed first (although not as early as in (7)), then mixed with later generation melilite. The small $^{26}Mg$ excess in clast hibonite may reflect loss of Mg in clast formation. (2) The inclusion preserves isotopic variations in Al originally present in the solar nebula similar to those found in stable isotopes. Two of the three Allende inclusions in which we made detailed measurements are not isotopically equilibrated, possibly reducing the value of $^{26}Al$ as a chronometer and strengthening the concept of a heterogeneous solar nebula.

Fig. 2. General Mineralogical features of TS-23 Type B inclusion.