

LOW-TEMPERATURE COOLING HISTORIES OF VIGARANO CAIs: CONSTRAINTS FROM COMPOSITIONS OF METAL PARTICLES; I. Casanova^{1,2} and L. Grossman^{2,3}. ¹Department of Geology, Field Museum of Natural History, Chicago, IL 60605-2496. ²Department of the Geophysical Sciences and ³Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637.

Abstract. Study of metal particles in Ca-, Al-rich inclusions not only provides information about condensation of siderophile elements in the solar nebula but also about the low-T cooling history of CAIs through analysis of their kamacite and taenite. We studied metal in four CAIs from Vigarano (two Type B1, Vig-1 and USNM 477-4; and two Type B2, Vig-2 and USNM 1623-8) as part of our work on the characterization of chemical compositions and inferred cooling histories of metal particles in CAIs from the reduced subgroup of CV3 chondrites (Casanova and Grossman, 1993a,b). Results suggest that metal from different inclusions cooled at different rates at subsolidus temperatures in localized zones of the solar nebula with different dust/gas ratios.

477-4 is an oval (5.2x3.7 mm) CAI that consists of a melilite mantle (300-600 μm thick) and a fassaite+anorthite core, all enclosing spinel poikilitically. Spinel grains in the mantle are smaller (<20 μm) than those in the center of the inclusion (20-60 μm). Two large spinel-free islands (SFI) are present, one roughly spherical, 1 mm in diameter, and the other irregularly-shaped, 2x1 mm. The spherical SFI is enclosed in a palisade body (continuous, closed chain of spinel crystals) and consists of roughly equal proportions of melilite and fassaite, with no anorthite. The melilite crystals in this SFI have homogeneous cores but display normal zoning in the outer 10-15 μm , where their compositions vary from Åk_{51} to Åk_{65} outwards. Fassaite is compositionally identical to that in the main inclusion, displaying a constant $\text{TiO}_2^{\text{tot}}$ content of 9.0 wt% ($\text{Ti}^{3+}/\text{Ti}^{\text{tot}} = 0.816 \pm 0.035$). The other SFI consists of a large single crystal of melilite, homogeneous in composition (Åk_{65-68}) with unzoned rims, poikilitically enclosing irregular grains of Al-rich pyroxene. Metal in the CAI is restricted to the fassaite+plagioclase+spinel-rich area, and makes up ~0.5 vol% of the whole inclusion. It occurs as generally well-rounded blebs that contain kamacite+taenite and occasionally have well-developed, continuous rims of Ca-phosphate (typically 1-3 μm thick). Only two of the 27 metal grains analyzed contain troilite, but in very minor amounts (two small inclusions of <1 and 2 μm). Bulk Ni and Co contents of the larger particles (>10 μm) determined by broad-beam analysis range from 24.5 to 27.8 wt% Ni and from 0.6 to 1.1 wt% Co. On the basis of their PGE (Ru, Os, Ir, Pt) concentrations, metal grains in this CAI can be subdivided into two groups: one with 0.2 wt% Ru, 0.2 wt% Pt, and Os and Ir <400 ppm each, and another with 0.2 wt% Ru, 0.5 wt% Pt, 0.1 wt% Os and 0.1 wt% Ir. There is no clear correlation between bulk Ni and PGE contents of the particles. Detailed microprobe traverses across kamacite-taenite lamellae on grains large enough for accurate analysis (typically >15 μm) show that all analyzed taenite grains have flat profiles, with concentrations between 30.3 and 31.2 wt% Ni; we have observed neither M-shaped Ni profiles in taenite grains nor PGE concentrations of a few wt% in the metal, both of which were reported by Caillet et al. (1988a) in their study of Vigarano 477B, another section of the same CAI. Kamacite exsolution is generally well-defined, with some grains displaying sets of 2-4 lamellae reminiscent of a Widmanstätten pattern. In the smaller grains, however, kamacite nucleates at the interface between the metal grain and its silicate host. Only one FeNi grain (1 μm) has been identified in the interior of the larger melilite-rich SFI. EDS analysis reveals that its bulk major element composition is identical to the metal in the rest of the CAI ($\text{Fe}_{72}\text{Ni}_{26}\text{Co}_1$).

Vig-2 is a comma-shaped fragment of a Type B1 inclusion, previously described by Simon and Grossman (1991). The metal is not as abundant as in 477-4 (<0.1 vol%), although texturally and compositionally it is very similar to the latter. The FeNi in this inclusion is also concentrated in the spinel+fassaite+plagioclase core, with only a few small particles in the melilite mantle. Metallic grains are usually well-rounded and display well-defined kamacite+taenite exsolution, although well-developed, Widmanstätten-like sets of kamacite lamellae were not found. Bulk compositions of single metallic grains range from 26.0 to 29.0 wt% Ni, 0.8-2.1 wt% Co, 0.1-0.3 wt% Ru, <400 ppm-0.6 wt% Os, <400 ppm-0.3 wt% Ir, and 0.1-0.5 wt% Pt. Unlike 477-4, however, there are no clearly distinguishable compositional groups among the metal particles in Vig-2. Microprobe traverses across kamacite-taenite grains show flat Ni profiles in the taenite at 32.0-33.1 wt%, and in kamacite at 5.0-6.1 wt% Ni.

The silicate mineralogy and chemistry of **1623-8** was studied by MacPherson and Davis (1993), and Casanova and Grossman (1993b) reported preliminary results on its metallic fraction. We have extended this study to fully characterize 19 metal particles. There are two compositionally distinct populations of metal in 1623-8. One is represented by 15 well-rounded FeNi grains similar in composition to M1, described by Casanova and Grossman (1993b). Their bulk compositions range from 23.1 to 29.0 wt% Ni and from 0.9 to 2.0 wt% Co, depending on the kamacite/taenite ratio. Total PGE contents are 4-5 wt%. Taenite in these metal grains shows flat Ni profiles, with contents in the interior of different crystals varying between 30.3 and 33.1 wt% Ni. The other 4 metal particles are very rich in PGE, with bulk compositions of 10 wt% Ni, 0.4 wt% Co, 0.6 wt% Re, 0.5 wt% Pt, 6.2-7.0 wt% Ru, 4.0-4.3 wt% Os, and 7.5-8.0 wt% Ir, similar to that of M2 (Casanova and Grossman, 1993b). They are irregular in shape and monomineralic.

Vig-1 is a complex Type B2 inclusion that contains palisade bodies that did not equilibrate with the CAI liquid,

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and abundant alteration products (Simon and Grossman, 1991). Unlike 477-4, Vig-2 and 1623-8, the metal particles in Vig-1 contain numerous Ca-phosphate grains, <1-3 μm in size, sprinkled throughout the metal and, rarely, forming rims around it. These phosphate grains are most likely pseudomorphs of phosphide grains that exsolved from the metal and were later oxidized and reacted with Ca-rich minerals from the silicate host. Broad-beam analysis of bulk compositions of metal particles yielded consistently low totals (89-94 wt%), probably due to inclusions (commonly phosphate and occasionally an Fe-rich phase, possibly magnetite) and, consequently, grain boundary effects. Bulk Ni and P contents are 20.5-37.1 and <0.02-0.15 wt%, respectively. The bulk PGE contents range typically from 0.1 to 0.9 wt% Ru, <400 ppm-0.5 wt% of each of Os and Ir, and 0.2-0.6 wt% Pt. Kamacite and taenite are intergrown in submicron-to-micron-sized, plessite-like domains, and do not display clear grain boundaries as in the other CAIs. Nickel contents in taenite and kamacite (determined by point analyses with good analytical totals) are quite variable from grain to grain, showing ranges of 37.2-42.5 and 4.5-6.5 wt%, respectively.

Discussion. The solidus temperature of the silicate assemblages that host the metal is $\sim 1200^\circ\text{C}$ (Beckett, 1986). This precludes the possibility that the subsolidus cooling history of the metal is relict since kamacite and taenite intergrowths would have dissolved in one another in a few minutes at CAI solidus temperatures. For instance, given a diffusivity for Ni in $\alpha\text{-FeNi}$ at 1200°C of $10^{-6} \text{ cm}^2\text{sec}^{-1}$ (Dean and Goldstein, 1986), a 10 μm kamacite grain would completely dissolve in approximately 8 minutes. Since the volume fraction of metal (<1%) is small, cooling of the FeNi particles was controlled by that of their host inclusions. Thus, the thermal history of the metal reflects the cooling history of the CAI at $T < 600^\circ\text{C}$. The well-developed kamacite+taenite lamellae and the flat Ni profiles of the taenite grains in 477-4, Vig-2 and 1623-8 indicate equilibrium crystallization at temperatures between ~ 600 and 500°C (corresponding to Ni contents in the bulk particles and in the taenite of 23-28 and 30-36 wt%, respectively). Attainment of equilibrium requires slow cooling at metal subsolidus temperatures. Although the influence of minor elements in Fe-Ni interdiffusion is not known, we assume that the amounts of PGEs in the metal particles of 477-4 and Vig-2 (total PGEs <1 wt% in all cases) have no significant effect on cooling rates calculated on the basis of Fe-Ni interdiffusion alone. The observed flat Ni profiles in taenite may be achieved through either (1) slow cooling at a rate of at most 50-100 deg/Myr (based on cooling rate curves by Saikumar and Goldstein, 1988) at temperatures ~ 600 - 500°C and subsequent fast cooling (to prevent further enrichment of Ni in taenite) or, (2) fast cooling to low temperatures followed by reheating (to $\sim 500^\circ\text{C}$) and subsequent quenching of the alloy. In either case, a long (maybe multi-stage) subsolidus cooling history for 477-4, Vig-2 (and perhaps 1623-8) is necessary (on the order of 10^4 - 10^6 yr, as estimated by Caillet et al. 1988b).

On the other hand, the observed variability of Ni contents in taenite among metal particles in Vig-1 suggests non-equilibrium cooling at subsolidus temperatures. The taenite crystals in a single particle are homogeneous, but vary in composition from particle to particle. Since all of the particles consist of kamacite + taenite, the composition of taenite formed by equilibrium cooling would be controlled by the final closure temperature, and all of the taenite grains would have similar Ni contents. The metal particles in the other CAIs discussed above all underwent equilibrium cooling at $T \sim 500^\circ\text{C}$ and the taenite in each exhibits only a small range of Ni contents (0.9 wt% in 477-4, 1.1 wt% in Vig-2 and 2.8 wt% in 1623-8). The taenite grains in Vig-1, however, show a 5.3 wt% range in Ni content. If the taenite grains in Vig-1 cooled at equilibrium, then different equilibration temperatures (between 400 and $\sim 250^\circ\text{C}$) would be required for different particles in the same CAI. This is not plausible and implies that the compositional variability in Vig-1 taenite is due to non-equilibrium crystallization of kamacite and taenite. The cooling history of metal in Vig-1 is, consequently, very different from that of the other CAIs.

To reconcile the different cooling histories indicated by metal in the CAIs studied here, two different scenarios may be proposed: (1) the inclusions cooled at different depths in the Vigarano parent body (Vig-1 near the surface and the others at ~ 20 km in a 100-200 km radius parent body), or (2) cooling of the CAIs occurred in different nebular environments at different rates. The first hypothesis would imply breakup and reassembly of the Vigarano parent body (or breakup of another one, fragments of which accreted later onto Vigarano), in order to mix materials cooled at different depths. It is difficult to envision, however, how the highly unequilibrated nature of the Vigarano silicates and volatile content of its matrix could be maintained at $\sim 500^\circ\text{C}$ for at least several thousand years, the conditions required for the slowly cooled metal grains. Instead, we favor nebular cooling, as such conditions may be possible if high dust/gas ratios existed in localized regions of the solar nebula. The materials that accreted to form Vigarano probably came from a variety of nebular environments with different thermal histories, perhaps regions with different opacities due to different gas/dust ratios.

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