MINERAL CONDENSATION FROM THE SOLAR NEBULA

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The studies (made at the University of Chicago) were based on two important carbonaceous chondrite meteorites: Allende (type C3) which fell at Chihuhuhua, Mexico on February 8, 1969 (King *et al*, 1969; Clarke *et al*, 1970), and Murchison (type C2) which fell on September 28, 1969, 135 km north of Melbourne, Australia (Lovering *et al*, 1971).

C2 and C3 carbonaceous chondrites contain (in addition to a matrix and chondrules) hard Ca-Al-Ti rich inclusions composed mainly of spinel ($MgAl_2O_4$), perovskite ($CaTiO_3$), hibonite ($CaO.6Al_2O_3 \pm TiO_2$, MgO), diopside ($CaMgSi_2O_6$), fassaite (Al, Ti clinopyroxene - $Ca(Mg,Al,Ti)(Si,Al)_2O_6$), and melilite (melilite series: - gehlenite ($Ca_2Al_2SiO_7$) - akermanite ($Ca_2MgSi_2O_7$). Much of the interest in these types of inclusions stems from the similarities between the mineralogical composition ot the coarse-grained (type A) Ca-Al-Ti rich inclusions in the Allende meteorite (Grossman, 1980), and the phase assemblages predicted from equilibrium thermodynamic calculations (Grossman, 1972). These calculations predicted that the condensation sequence from a gas of solar composition at P_{TOTAL} 10^{-3} atmospheres would be corundum (Al_2O_3)-(1743°K), perovskite (1667°K), melilite (1625°K), spinel (1553°K), diopside (1438°K). The prediction is very similar to the inclusion assemblage mentioned above, except for hibonite and fassaite. Since corundum was not found in these inclusions, it is generally considered that hibonite (closest to corundum in composition) is the first major mineral to condense, and that significant amounts of titanium could also have condensed at high temperatures to form the pyroxene solid solution mineral fassaite.

Grossman (1973,1977) also calculated equilibrium thermodynamic condensation temperatures for many trace elements from a gas of solar composition. The elements Os, Re, Ir, Ru, W, Mo, Zr, Hf, Y, Sc, REE, Pt and Rh in the Allende (type A) coarse-grained Ca-Al-Ti inclusions are enriched 15-20 times relative to C1 carbonaceous chondrite (Grossman, 1975). The major feature of these trace elements is that their calculated condensation temperatures from a gas of solar composition is above or within the range of the condensation temperatures of the main mineral phases in the Ca-Al-Ti rich inclusions. Mg-Fe-silicate mineral phases condense at temperatures below the Ca-Al-Ti mineral phases, and there is a corresponding depletion in volatile trace elements in the Ca-Al-Ti inclusions.

There is a wealth of information on the refractory inclusions in the Allende meteorite (Grossman, 1980), but similar inclusions from the C2 Murchison meteorite have yielded less information because of their small size and relatively low abundance.

During this study, many new inclusions were recovered from the Murchison C2 meteorite using multiple freeze-thaw cycles to dissaggregate the material into fine powder, and separation of the powder into density fractions with heavy liquids (MacPherson *et al*, 1980). The inclusions recovered were split into two parts in a clean environment. One part was made into a polished thin section and studied by optical petrographic and scanning electron (SEM) microscopy; the electron microprobe was used to obtain chemical analyses (MacPherson *et al*, 1980; Bar-Matthews *et al*, 1980 a,b). An additional study was made of the Mg isotopic composition (Tanaka *et al*, 1980; Hutcheon *et al*, 1980; Bar-Matthews *et al*, 1980 b). With the second part, RNNA and INAA measurements were made to study the trace elements and REE compositions (Tanaka *et al*; Bar-Matthews *et al*, 1980 a). This work is still in progress. These new mineralogical and trace element data support the hypothesis that the Ca-Al-Ti inclusions in the Murchison meteorite were formed at higher temperatures than those of Allende (Fuchs *et al*, 1973). In the Murchison meteorite, we found many blue inclusions composed almost entirely of hibonite, spinel, and perovskite, with little or no melilite, diopside, and fassaite (some do not contain any silicate minerals - MacPherson *et al*, 1980). This contrasts with the Allende Ca-Al-Ti (type A) inclusions which are melilite rich and hibonite poor. Trace element studies on some of the refractory inclusions show that they are enriched in some of the most refractory trace elements, 30-60 times relative to C1 carbonaceous meteorite (e.g., Os, Ir, Dy, Ho, Lu) (Boynton *et al*,1980; Tanaka *et al*, 1980). Based on the mineralogical and trace elemnet differences between Allende and Murchison meteorites, we can infer that the Murchison Ca-Al-Ti rich inclusions have been isolated from nebular gas at higher temperatures than those of Allende Ca-Al-Ti (type A) rich inclusions. It is difficult to explain the rarity of melilite, since according to the calculated condenstation sequence, the gas reacts with corundum to form first melilite and then spinel. If the sequence of reaction is unchanged when hibonite is substituted for corundum, it would be possible to produce inclusions composed of hibonite, perovskite, and melilite, with no spinel, by isolation of the condensates from the gas above a certain temperature, but impossible to produce the observed assemblage - hibonite-perovskite-spinel with no melilite, in this way. On the other hand, it may be that the thermodynamic stability of hibonite is sufficiently different from that of corundum, so that when hibonite reacts with the solar nebular gas, spinel forms at higher temperatures than melilite.

During this study, a corundum-hibonite-perovskite inclusion was found in the Murchison meteorite. This is the first reported occurence of corundum as a major inclusion phase (Bar-Matthews *et al*, 1980 b; Grossman *et al*, 1980). The texture shows that corundum formed first, then partially reacted with the gas to form hibonite. This is in accord with the thermodynamic model that corundum is the first phase to condense from the solar nebula. The rarity of corundum in refractory inclusions, and the low abundance of hibonite in the Allende meteorite, could be due to equilibration of the inclusions below the temperature at which corundum reacts to form hibonite, with Allende inclusions equilibrating to lower temperatures than those of Murchison.

Supporting evidence for the idea that the spinel-hibonite and the corundum-hibonite inclusions in Murchison are different from the Allende inclusions, comes from the Mg isotope data (Tanaka *et al*, 1980; Hutcheon *et al*, 1980; Bar-Matthews *et al*, 1980 b). The Mg isotope data, in fact, raise new thoughts that the condensation of corundum did not occur in a gas of solar composition, but in a reservoir of a different composition.

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References

Bar-Matthews, M., MacPherson, G.J., Grossman, L. and Tanaka, T., 1980 a. Spinel-pyroxene aggregates in Murchison. *Meteor. Soc., 43'rd Ann. Meet., La Jolla, California, Abstr.*, p. 33.

Bar-Matthews, M., Hutcheon, I.D., MacPherson G.J. and Grossman, L., 1980 b. A corundum-rich inclusion in the Murchison carbonaceous chondrite. *Geochim. Cosmochim. Acta* (submitted).

Boynton, W.V., Frazier, R.M. and Macdougal, J.O., Trace element abundances in ultra-refractory condensates from the Murchison meteorite. *Meteor. Soc., 43'rd Ann. Meet., La Jolla, California, Abstr.*, p. 32.

Clarke, R.S. Jr., Jarosewich, E., Mason, B., Nelon, J., Gomez, M. and Hyde, J., 1970. The Allende Mexico meteorite shower. *Smithson. Contrib. Earth Sci.*, vol. 5, pp. 1-53.

Fuchs, H.L., Olsen, E. and Kenneth, J.J., 1973. Mineralogy, mineral-chemistry and composition of the Murchison (C2) meteorite. *Smithson. Contrib. Earth Sci.*, vol. 10, 39 p.

Grossman, L., 1972. Condensation in the primitive solar nebula. *Geochim. Cosmochim. Acta*, vol. 36, pp. 597-619.

Grossman, L., 1973. Refractory trace elements in Ca-Al rich inclusions in the Allende meteorite. *Geochim. Cosmochim. Acta*, vol. 37, pp. 1119-1140.

Grossman, L., 1975. Petrography and mineral chemistry of Ca-Al - rich inclusions in the Allende meteorite. *Geochim. Cosmochim. Acta*, vol.39, pp. 433-454.

Grossman, L., 1977. High-temperature condensates in carbonaceous chondrite. *Comets, Asteroids, Meteorites - Interrelations, Evolution and Origin.*, A.H. Delsemme (ed.), Toledo, Ohio, Univ. Toledo, pp. 507-516.

Grossman, L., 1980. Refractory inclusions in the Allende meteorite. *Ann. Rev. Earth Planet. Sci.*, vol. 8, pp. 559-608.

Grossman, L., Bar-Matthews, M., Hutcheon, I.D., MacPherson, G.J., Tanaka, T. and Kawabe, I., 1980. A corundum rich inclusion in Murchison. *Meteor. Soc., 43'rd Ann. Meet., La Jolla, California, Abstr.*, p. 21.

Hutcheon, I.D., Bar-Matthews, M., Tanaka, T., MacPherson, G.J., Grossman, L. and Olsen, E., 1980. A Mg isotope study of hibonite-bearing Murchison inclusions. *Meteor. Soc., 43'rd Ann. Meet., La Jolla, California, Abstr.*, p. 20.

King., E.A. Jr., Schonfeld, E., Richardson, K.A. and Eldridge, J.S., 1969. Meteorite fall at Pueblito de Allende, Chihuahua, Mexico: Preliminary information. *Science*, vol. 163, pp. 928-929.

Lovering, J.F., LeMaitre, R.W. and Chapell, B.W., 1971. Murchison C2 carbonaceous chondrite and its inorganic composition. *Nature*, vol. 230, pp. 18-20.

Tanaka, T., Davis, A.M., Hutcheon, I.D., Bar-Matthews, M., Olsen, E., MacPherson, G.J. and Grossman, L., 1980. Refractory inclusions in Murchison: Chemistry and Mg isotopic composition. *Lunar and Planet. Sci.*, vol. 11, pp. 1122-1124.