PALLASITES AND THE GROWTH OF PARENT METEORITE PLANETS.

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The rates at which metal-bearing meteorites cooled through the temperature interval 6000° - 4000° C in their parent planets can be estimated from the nature of Ni diffusion gradients preserved in their metal alloys (1). The slower the cooling rate, the lower the temperature (and hence the higher the Ni content of the alloy) when diffusion was immobilized. Characteristic cooling rates for a number of meteorite classes are summarized in Fig. 1. This figure also suggests possible cooling sites for the meteorite types, by displaying cooling rates as a function of depth in planets of asteroidal dimension.

Many writers have concluded that the meteorites came from differentiated, concentrically layered parent bodies, structurally analogous to Earth. Iron meteorites would represent the cores of these bodies. Others (4) have advocated parent planets with "raisin bread" structure, meaning that relatively small zones of metallic Ni,Fe were dispersed at all depths in them.

This paper considers the nature and origin of pallasites, stony-iron meteorites that consist of roughly equal amounts of coarse olivine (~0.5 cm) and metallic Ni,Fe. The olivine crystals are in close-packed array, with metal filling the spaces between them. Clearly the solid olivine crystals accumulated stably in this configuration while the metal was molten (i.e., in the temperature range 1600° - 1400° C). It is difficult to reconcile this mixture of high- and low-density materials with physical conditions in hypothetical molten "raisins," but such an array would form stably at the core-mantle interface of a concentrically zoned internally differentiated planet (Fig. 2). The amount of pallasitic material that can be

Fig. 1. Left, cooling rates of metal-bearing meteorite classes (2). Right, depths at which cooling would have occurred at these rates, in four hypothetical planets of asteroidal dimension (3).
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Fig. 2. Radial columns in an internally melted small planet. A: The case where a solid shell of unmelted rock is supported by its own strength. Olivine crystals, slightly denser than the enclosing mafic silicate liquid, form a cumulate layer at the interface between immiscible silicate and metal/sulfide liquids. The weight of the cumulate layer presses the lowermost olivine crystals down into the dense metal/sulfide liquid. The depth of submersion is such that the upward buoyant forces exerted by olivine crystals in metal/sulfide liquid balances the weight of the cumulate layer above the interface. B: A more realistic system than A, in which mafic liquid is able to erupt to the surface and the weight of all the solid layers of the planet rests on the olivine cumulate layer. This additional weight gives rise to a thicker layer of submerged olivine crystals ($R_1 - R_2$; potentially pallasites). C: The same directed stresses that submerge olivine crystals in liquid metal/sulfide tend to deform the olivine crystals, which are weak at the temperature of molten iron. Crystals would tend to close up together, squeezing metal/sulfide liquid downward and mafic silicate liquid upward and eliminating the pallasitic layer in favor of a zone of dunite.

The volume of pallasitic material produced is independent of the absolute size of the planet. In principle, the volume of pallasitic material that would form in an internally melted planet (relative to pure Ni,Fe metal) is substantial, larger than the ratio of pallasites to irons in museum collections.

Absolute values of the weight exerted downward by cumulate olivine at $R_2$ can be estimated: 4, 16, 63, and 390 bars, in planets of total radius 50, 100, 200, and 500 km respectively, for reasonable compositions and internal configurations. These are small stresses, but olivine is extremely weak at the high temperatures of molten iron, and even small stresses cause it to yield by the mechanism of power-law creep (5). The total amount of deformation olivine would experience before the enclosing metal solidified is found to increase as a very large power of the planetary radius.

It was found that deformation great enough to obliterate the characteristic pallasite geometry would be experienced by olivine crystals at the core-
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Fig. 3. Positions of the $R_2$ and $R_1$ levels (which define the thickness of the pallasite zone), as a function of the total size of the metal + pallasite zone (the core). All values are relative to the overall radius of the planet (R); the relationships are independent of absolute size. Dashed portions of curves correspond to unrealistically large cores, larger than would be produced by total melting and differentiation of ordinary chondrites.

Mantle interfaces of planets larger than ~10 km radius. Olivine deformation in this circumstance would have the effect of squeezing molten metal out the bottom of the pallasitic layer and molten mafic silicate out the top of the overlying layer (Fig. 2C), resulting in a stable layer of virtually pure dunite. Deformation experienced in >100 km planets (such as Fig. 1 appears to require as a cooling site for pallasites) is excessive by such a large factor (>10^8) that even generous allowance for the uncertainties attached to the estimate does not make it possible to reconcile the circumstances of formation with the circumstances of cooling of pallasites.

It appears inescapable that the pallasites formed in small (~10 km) bodies, but these subsequently must have joined larger (>100 km) bodies before final cooling through 500°C occurred. The size and energy requirements and the timing of the first generation of bodies are consistent with the Goldreich-Ward mechanism of planetesimal formation by gravitational instability of a dust disk within the primordial nebula (6) and the 26Al content of early solar system material (7). Presumably the second generation was accumulated by planetesimal encounters over a longer time period, after the dissipation of the nebula.

As a final observation, it appears likely that the (second generation) parent meteorite planets did have "raisin bread" structures, as a consequence of their assembly from smaller differentiated bodies, but there is no reason to expect that the "raisins" in any particular second-generation body were geochemically related.