A MODEL FOR CORE SEGREGATION WITHIN THE EARTH


Introduction The earth is believed to have formed by accretion from a swarm of planetesimals consisting of metallic iron and silicates, e.g. (1,2). To progress from the protoearth to the present silicate mantle-metallic core structure, a model for segregation of the dispersed metal component from the silicates must be constructed. A Stokes' Law calculation indicates that gravitational separation in the solid state would require \( \sim 10^{17} \) years for crystals of several cm in diameter to sink to the core and hence is not a plausible mechanism for differentiation of the earth with respect to iron. The core formation mechanism is likely to involve extensive melting of either the silicate or metallic phases, or both. Geochemical evidence such as the homogeneity of major element and compatible minor element distributions throughout the mantle, combined with the lack of evidence for a thick primordial crust, implies a lack of gross chemical fractionation which would be indicative of extensive melting, e.g. (1,2). This indicates that core formation would have required selective melting of the metallic phase. The melting temperature of iron and the melting interval of the mantle are very similar at mantle pressures (2), however, and it is unlikely that the metallic phase could be effectively separated from unmelted silicate phases as molten iron. It is well documented that the melting point of iron can be considerably lowered by alloying with a wide variety of light elements (3), and there is strong geophysical evidence that the core contains substantial amounts of a light alloying element. It seems likely, then, that the light element is primarily responsible for lowering the melting point of iron whereby the metal can be segregated from silicate phases at temperatures below silicate melting points.

Core formation Based on previous work in the system Fe-FeO-MgO (4,5), we believe oxygen is an attractive candidate for the light element because

1) FeO probably exsolves as a dense high-pressure phase (hpp) from the rocksalt phase \((\text{Fe,Mg})\text{O} (\text{Bl})\) at high \(P,T\). FeO chemistry is thus decoupled from MgO chemistry at high pressure.

2) Fe and FeO are probably miscible in the liquid state at high temperature and pressure. Solution of FeO in Fe lowers the melting point of the iron alloy \(~1000\text{K}\) below the melting point of pure Fe.

This suggests the following model for development of the present core-mantle structure of the earth.

1) The earth accretes in the primordial solar nebula as an intimate and homogeneous mixture of metallic iron particles and \((\text{Mg,Fe})\) silicates and oxides. The gravitational energy of infalling planetesimals liberated as heat warms the surface of the accreting earth, but temperatures are low with respect to the relevant silicate and metal melting points.

2) The earth continues to accrete and interior temperatures rise as adiabatic compression becomes significant. Pressure becomes sufficiently high to allow exsolution of FeO (hpp) from the \((\text{Mg,Fe})\text{O}\) component of the primordial mixture. Temperatures remain below all relevant melting points.

3) The phase FeO (hpp) continues to exsolve and remains intimately mixed with the Fe metal-silicate mixture until temperatures, within a zone (A) at depth within the earth, exceed the Fe-FeO eutectic temperature. The metallic melt coalesces to form blobs which sink through the underlying region (B) of unmelted Fe metal-silicate + FeO (hpp) mixture, to begin formation of
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the core.

The residual Fe-depleted silicate in region A coalesces to form large diapirs which rise upwards to the surface to form the mantle. Note the contrast between the physical segregation process involving oxygen and sulphur; the process involving sulphur must necessarily take place near the surface of the earth, e.g. (6), whereas the segregation of Fe-FeO melt proceeds only at great depths (>2000Km).

(4) Accretion continues. The rise of interior temperatures and the displacement of material from zone B into the zone of melting (region A) contribute to the overall reduction and eventual elimination of region B. The overall temperature distribution within the earth approaches an adiabatic gradient due to vigorous convection. Solidification of an inner core from the Fe-FeO melt begins as pressure raises the eutectic temperature above the prevailing temperature at the centre of the core.

(5) Accretion of the earth is almost complete. Melting and segregation continues in region A and the metallic core and silicate mantle continue to grow in size. The thin outer layer of dense material resulting from the final stages of accretion is subducted into the mantle and vigorous convection assists in homogenization of material comprising the silicate mantle.

Constraints on the Model Geochemical and geophysical evidence suggest that the Fe/(Fe+Mg) ratio remains relatively constant throughout the lower mantle, e.g. (2), which must be a constraint on the model. In our model the mantle comprises the silicate material remaining after removal of the metallic melt, and the ratio Fe/(Fe+Mg) is determined primarily by P,T conditions which prevailed at the depth where segregation occurred. To achieve a constant Fe/(Fe+Mg) ratio by balancing the effects of pressure and temperature (the Fe/(Fe+Mg) ratio of the B1 phase decreases as pressure rises and increases as temperature rises), the temperature gradient within the earth would have to exceed at least 5K/km to compete with exsolution of FeO (hpp) (4). Such gradients are very unlikely. We suggest that the fundamental core-forming equilibria (exsolution of FeO (hpp); miscibility of Fe and FeO) occurred in a P,T "window", corresponding to a limited region immediately overlying the growing core during the major phase of accretion of the earth. It is tempting to speculate that the Fe/(Fe+Mg) ratio believed to be characteristic of most of the mantle is a direct consequence of segregation equilibria occurring near the core-mantle boundary, indicating that the major proportion of core segregation occurred in this region. Vigorous convection initiated during the core segregation process and continuing after its completion would also aid in achieving a uniform distribution of FeO throughout the mantle.