KOMATIITES AND THE ARCHEAN MANTLE, P. C. Hess, Dept. Geological Sciences, Brown University, Providence, RI 02912

Recent experimental phase equilibria studies have demonstrated that high MgO komatiites (25-30% MgO) may originate at relatively low pressures ($P \leq 40$ kb) by large degrees of melting leaving olivine as a residue or by smaller degrees of melting at much higher pressures leaving a multiphase assemblage (1,2). Since our knowledge of the thermal structure of the Archean mantle is strongly influenced by the existence of komatiites only at this time, it is important to identify appropriate constraints to discriminate between the two modes of melting.

The following parameters must be considered in the origin of komatiites: (A) The 1 bar liquidus of olivine saturated melts are approximated by the relation $T(\circ C) = 1000 + 20$ MgO, where MgO is the concentration of MgO (in weight percent) in the liquid. A komatiite with 30% MgO, for example, has a 1 bar liquidus at 1600$\circ$C (3). (B) The high pressure komatiite liquidus increase rapidly with pressure and approximately parallel the peridotite liquidus, as indeed do most olivine-liquid equilibria. The liquidus for komatiite with 30% MgO is approximately 1825$\circ$C at 30 kb and probably flattens at high pressure, mimicking the behavior of the peridotite liquidus. (C) The mean adiabatic temperature gradient of peridotite in the upper 400 km of the Earth’s mantle is approximately 1.5$\circ$C/kb (4). (D) The mean adiabatic temperature gradient of liquid komatiite is about 4.5$\circ$C/kb given that the $\alpha$/$C_p$ ratio ($\alpha$, coefficient of thermal expansion; $C_p$, specific heat capacity) is about 3 times greater than peridotite under comparable conditions (5, 6). (E) The latent heats of fusion for the magnesian end members of mantle minerals at their melting points are approximately $Mg_2SiO_4 = 210$ cal/gm, $MgSiO_3 = 175$, $CaMgSi_2O_8 = 150$ cal/gm, $Mg_3Al_2Si_3O_12 = 145$ cal/gm (6, 7). The latent heats of fusion of peridotite can be estimated from these parameters if they are corrected for FeO contents, temperatures different from the melting points, high pressures, the proportion of minerals being melted and the heat of mixing of the liquid ($\Delta H_{mix}$). The heat of fusion needed to produce komatiite at high $P$ and $T$ is about 180 cal/gm assuming that the effects of FeO contents and $\Delta H_{mix}$ (which lower latent heats) roughly cancel the P-T effects (which raise them). (F) The extra hotness ($\Delta T$) of the adiabatic mantle needed to provide the latent heat of fusion is $\Delta T = \frac{\Delta H_{f}}{C_p} \cdot X$, where $\Delta H_{f}$ is the latent heat of fusion (180 cal/gm), $C_p$ is the specific heat of peridotite (0.30 cal/gm $\circ$C) and $X$ is the weight fraction of melt. For every 10% increment of melt, the temperature of the adiabatic mantle must decrease about $\frac{180}{60}$ $\circ$C ($\Delta T = 0.30 \cdot 0.1$).

The high MgO content, the near chondritic interelement ratios of certain elements of high MgO “undepleted” komatiites, and mass balance considerations indicate that komatiites can be produced by about 50% melting of fertile peridotite, leaving only olivine in the residue. Approximately 90 cals/gm of latent heat are absorbed, and the temperature of the adiabatic mantle must decline by 300$\circ$C. A solid adiabat fixed at 1600$\circ$C, 1 bar (the liquidus for 30% MgO) intersects the mantle solidus at about 1675$\circ$C, 50 kb. To provide for the latent heat of melting, the temperature of melting must be 300$\circ$C above the adiabat at some depth. Temperatures must be close to 2000$\circ$C at pressures greater than 50 kb. Such temperatures are close to or above the peridotite liquidus within the upper 400 km of the mantle. These are minimum temperature estimates, since the adiabat must be influenced by the thermal expansion of the liquid and heat must also be lost to the thermal boundary layer at the Earth’s surface. It is concluded that if komatiite (25-30% MgO) represents a liquid derived by about 50% melting of peridotite, then a magma ocean or localized regions of near total melting existed in the Archean (8).

It has been argued, however, that komatiites may be generated by relatively small degrees of melting near the solidus at high pressures. The liquidus of komatiite (30%
MgO) approaches the solidus of peridotite at about 100 kb and 1900°C. Suppose komatiite is generated at this depth through adiabatic decompression of upwelling mantle. Suppose further that the melt escapes the region, collects into a sizable body and is somehow isolated from the mantle. It will then rise along a liquid adiabat and cool at a rate of 4.5°C/kb. Not only would this path pass below the komatiite liquidus at all pressures, but it would approach the solidus of peridotite over a large depth range. The liquid would not be a komatiite with MgO = 30% by the time it attained the Earth's surface. A komatiite with no more than about 20% MgO is possible, however.

As an alternative, assume that komatiite liquid escapes the enclosing mantle by a porous flow mechanism. If the proportion of liquid to peridotite is small, the liquid will follow a solid adiabat to the surface and cool at a rate of 1.5°C/kb. This path passes close to the komatiite liquidus and would emerge at 1750°C near the Earth's surface. The liquid might then preserve its komatiite signature.

On closer inspection, this latter model has serious defects. Adiabatically upwelling mantle begins to melt at 100kb and would continue to produce increments of melts until the surface thermal boundary layer is attained. At a given instance, a column of mantle with entrained melt extends all the way to the Earth’s surface. The temperature of the mantle at a given depth is determined by the adiabatic gradient and by the latent heats absorbed during melting. A packet of komatiite liquid produced at depth must pass through this “cooled” mantle and must crystallize to adjust to lower temperatures. It could not preserve its primitive komatiite composition. An additional complication is that the primitive komatiite liquid must be mixed and diluted by less MgO-rich liquid, generated in the mantle at shallow depths.

It is not obvious how komatiite liquid can be generated by small degrees of melting and yet be extruded onto the earth's surface in pristine condition. The favored model is that komatitites were produced in an Archean magma ocean or within very hot diapirs rising from deep within the mantle. In either case, large degrees of melting are implied.

REF:

1) Arndt, NT (1977) Cont Min Pet, 64: 205-221;