PERIDOTITE MELTING TO 6GPa AND GENESIS OF PRIMARY MANTLE-DERIVED MAGMAS

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The anhydrous melting behaviour of lherzolite has been studied experimentally from 0-6GPa with emphasis on careful determination of the solidus temperature and the compositional changes of liquids and residual phases as functions of pressure, temperature and degree of partial melting. The lherzolite composition studied (MORB Pyrolite) is suitable as a source composition for modern mid-ocean ridge basalts and as such also approximates to a 'primitive' or most typical source composition for voluminous basaltic, picritic or komatiitic volcanism throughout geological time. The study also enables comparison with parallel melting studies on "Hawaiian pyrolite" (source composition for intraplate 'hot-spot' magmas), on refractory Tinaquillo lherzolite (?source composition for back-arc basin tholeiites) and on K-enriched 'sub-continental' lherzolite (?source composition for high K/Na 'continental' basalts). The solidus of 'MORB Pyrolite' lies ~25°C above Hawaiian pyrolite solidus and essentially coincident with Tinaquillo lherzozlite solidus from 0-4GPa. The solidus slope is ~100°C/GPa between 2 and 4 GPa and results in convergence of liquidus and solidus up to 5GPa. This is accompanied by change in melt composition with melts at higher pressures becoming more olivine rich, and at low degrees of melting, more strongly silica undersaturated (fig. 1).

Melting of lherzolite is dominated by cotectic melting of solid solutions and thus the solidus temperature varies smoothly rather than discontinuously as a function of pressure. There is an inflection in the solidus around 1.5GPa, seen in both MORB Pyrolite and Tinaquillo lherzolite compositions. At any pressure the degree of melting increases regularly with increasing temperature. Detailed matching of liquids generated at 0.8 to 2 GPa, ranging from quartz tholeiites to tholeiitic picrites, with the spectrum of natural MORB glasses and aphyric basalts, demonstrates that primary magma production on divergent plate margins on the modern earth requires the existence of tholeiitic picritic (15-35% normative olivine) magmas as well as primary alkali picrites (lower degrees of melting). Primary olivine tholeiites, tholeiites and quartz tholeiites (lower pressures of magma segregation) can also be identified among ocean floor basalt glasses but some of these glasses require more refractory source peridotite compositions than MORB pyrolite and are interpreted as second stage melting of MORB pyrolite. The role of second-stage melting (i.e. a second melting of refractory residue after partial or complete extraction of a first stage melt) is particularly evident near convergent plate margins in the modern earth. In this environment, high magnesia quartz tholeiites or olivine-poor tholeiites (e.g. Tongan fore-arc lavas, Troodos Upper Pillow lavas) are produced from source peridotite resembling Tinaquillo lherzolite composition. Extremely refractory boninite lavas are interpreted as 'third stage melting' of residual harzburgite following access of water-rich fluids in the subduction environments.

In the studies of melting relationships at 5 GPa, the extremely high temperatures of the solidus, permits extensive solid solution between coexisting pyroxenes, and orthopyroxene is eliminated as a residual phase before either garnet or clinopyroxene ('pigeonitic' with 6-7%CaO). Residues from moderate to high degrees of melting at 5 GPa are therefore not harzburgitic but remain lherzolitic in character. On the other hand liquids are rich in both normative olivine and hypersthene components and approach compositions of pyroxenitic komatiites. The melting interval for MORB pyrolite composition at 5 GPa remains >200°C and liquids of pyroxenitic komatiite character (~26% MgO) require high degrees of melting - they are not small melt fractions produced at near-solidus conditions.

Our melting studies confirm the high temperatures and high degrees of melting [assuming a lherzolite source with 3-4% CaO, Al_2O_3 and $Mg^{\#}$=90] required to generate peridotitic komatiite liquids and show that liquids at 1750°C and 1800°C at 5 GPa are not peridotitic komatiite in character but approach pyroxenitic komatiite. The most conservative models for peridotitic komatiite genesis are those requiring the lowest temperatures at depth of magma segregation and thus the coolest model geotherm for

Archaean period. On this basis, the preferred model for Archaean peridotitic komatiite genesis involves multistage or continuous extraction of melt from mantle diapirs ascending at ~1700°C. Dunite xenoliths in kimberlite pipes are possible refractory residues from extraction of such melts. The roles of olivine, chromite and low Ca, low Al orthopyroxene as residual phases imply low pressure [<2 GPa] melt extraction processes for this xenolith type.

In the modern and Phanerozoic Earth, maximum temperatures of primary magmas are ~1450°C, consistent with overall cooling of the Earth through time and changes in patterns of convective heat loss. C-H-0 fluids play a key role in modern magma genesis. Deep levels of the Earth's Mantle are at low oxygen fugacities (~IW) and the earth is degassing reduced volatiles dominated by methane + hydrogen. The asthenosphere acts as a fluid-absent zone of partial separating $CH_4 > H_2$ fluids in the deep mantle from H_2O-rich or $H_2O + CO_2$ fluids in the lithosphere. The lithosphere is variable in oxygen fugacity (IW to FMQ) and acts as a lid or seal to melt migration from the asthenosphere, due to stability of pargasitic amphibole ± phlogopite. A process of "redox melting" [fig.2] may occur in the peridotite-C-H-0 system by interaction of reduced CH_4-rich fluids with oxidized lithosphere. This process is advanced as an explanation of the association of diamond (precipitated by oxidation of methane) and extremely refractory garnet harzburgite with Fo_{94} olivine and extremely low-calcium garnets. The fluid-rock interaction produces a kimberlitic or olivine lamproitic melt due to the water-rich character of the fluid on the diamond-fluid saturation surface at P~50-55kb, T~1200°C.

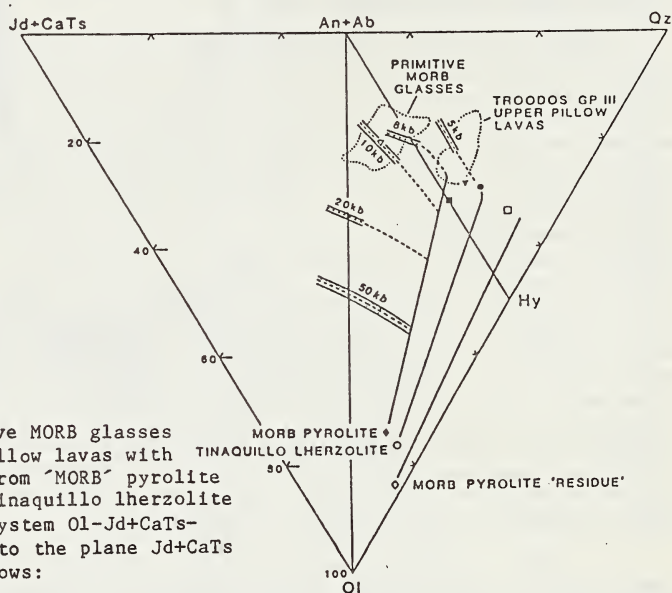

FIG.1 Comparison of primitive MORB glasses and Troodos Gp.III upper pillow lavas with equilibrium partial melts from 'MORB' pyrolite at 8, 10, 20 and 50kb and Tinaquillo lherzolite at 5kbar in the normative system Ol-Jd+CaTs-Qz-Di, projected from Di onto the plane Jd+CaTs-Qz-Ol. Symbols are as follows:

(■) calculated parental composition for the Troodos Gp.III upper pillow lavas.
(▼) Refractory primitive magma composition identified from glass inclusions in magnesian (Fo94) olivine phenocrysts fom Tonga.
(●) Marianas fore-arc lava
(□) Cape Vogel boninite parental magma composition
(∇) Primitive MORB glass DSDP3-18-7-1

    ~~~~~~~   Ol + Opx + Cpx Cotectic

    - - - - -   Ol + Opx   Cotectic

    ─────────   Olivine   only residual phase

A. OXIDIZED (MW) AT DEPTH   B. REDUCED (IW) AT DEPTH   C. DEEP LITHOSPHERIC
   IW⇌MW THROUGH LVZ   IW⇌MW IN LITHOSPHERE   FRACTURES

Methane flushing

CRUST

CRUSTAL FLUID CONVECTION

CARBONATE ALTERATION

$CO_2 + H_2O$

$CO_2 + H_2O$

35km ——— M ——————————————————— M ———

CO_2-rich fluid   LHERZOLITE, HARZBURGITE, DUNITE

± Magnesite   ± Graphite

C-PRECIPITATION GRAPHITE

$CH_4 + H_2O$

$\left.\begin{array}{l} CH_4-H_2O) \\ CO_2-H_2O) \end{array}\right\}$ FLUIDS

90km ——— AMPH IN ———————————————

AMPH OUT fO_2 VARIABLE

H_2O-RICH FLUIDS

± Magnesite   ± Diamond

OXIDATION FRONT

CARBON PRECIPITATION

KIMBERLITE + GARNET HARZBURGITE RESIDUE + DIAMOND

DIAMOND

$CH_4 + H_2O$

$CH_4 + H_2$

150km ——— — — — —

Ga Lherzolite + Kimberlitic Melt with dissolved C-H-O

LVZ

$CH_4 + H_2$

$CH_4 + H_2$ FLUID
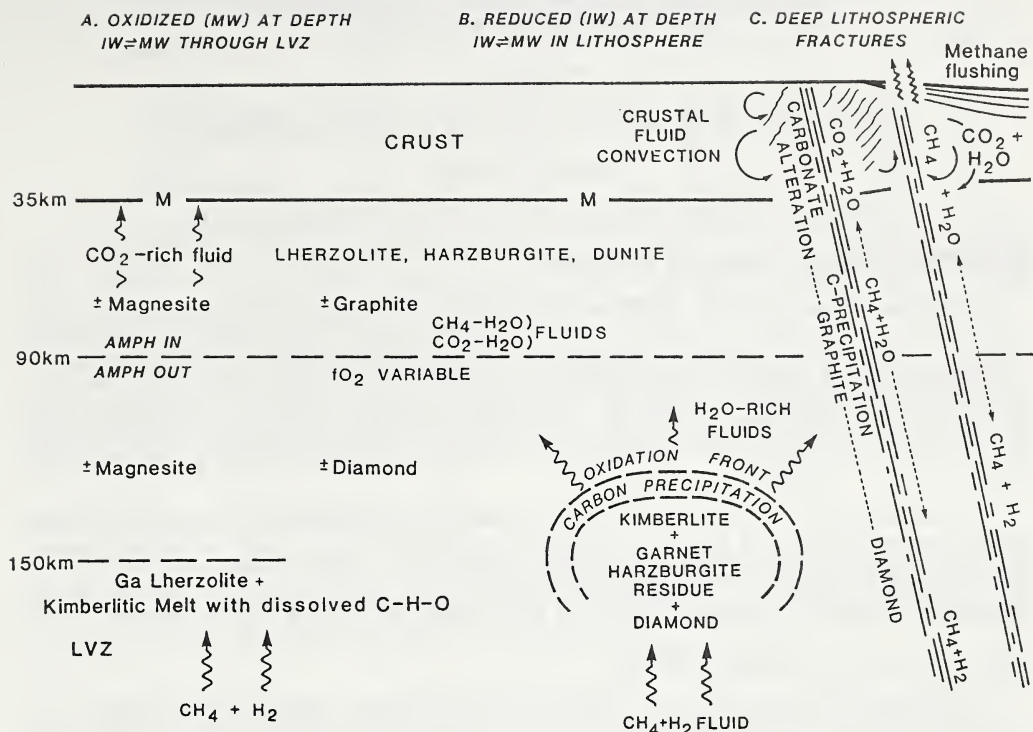
$CH_4 + H_2$

FIG.2 Schematic model for the continental lithosphere beneath Archean/Proterozoic shield regions. The deep mantle is degassing (CH_4 + H_2) fluids but the intrinsic f_{O2} of the lithosphere is very variable from FMQ to IW. Different scenarios (A,B,C) illustrate alternative interactions between reduced fluids and the oxidised lithosphere. ´A´ suggests a deep, thin asthenospheric layer (partial melting) in which the f_{O2} change from mantle to lithosphere is accomodated within the fluid-absent melt. ´B´ suggests a mechanism of ´redox´ melting in which diamond-bearing refractory garnet harzburgite is left as a residue from oxidation of CH_4 + H_2 to H_2O + C with extraction of water-rich kimberlitic melt. ´C´ suggests a role for deep lithosphere fractures in localizing mantle fluid release and interaction of these fluids with oxidised crustal fluids at shallow depths.