

# Experimental definition of mantle melting and implications for mantle dynamics

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## Introduction

The natural sampling of the Earth's Mantle by xenoliths or by magmas gives evidence for the presence of carbon and hydrogen within the upper mantle and extending into the Transition Zone. Models of accretion and studies of subduction respectively provide arguments for degassing of primitive C-H species from the upper mantle and for re-cycling of oxidized C-H species into the upper mantle. Thus the melting behaviour of the Mantle cannot be understood without an appreciation of the melting behaviour of peridotite-C-H-O.

## Melting of peridotite-C-H-O

Experimentally, one may define two melting regimes. The 'major melting' regime occurs at temperatures above the (C+H)-free solidus, where the extent of melting increases rapidly with temperature increase or decompression. Magma types such as MORB, 'Hot-spot' olivine tholeiites, back-arc basin olivine tholeiites and island arc picrites and boninites, have petrographic, major element and phase petrology signatures which are consistent with derivation (magma segregation or initial pooling) in the major melting field.

The 'incipient melting' regime is the large P, T field which lies below the (C+H)-free solidus and above the appropriate peridotite-C-H-O solidus. In this field the amount of melting is primarily determined by the C-H-O volatile content. Since all primitive magma types from MORB to boninites contain evidence for degassing of C-H-O fluids, the presence of an incipient melting regime is the general asthenospheric melting case and is applicable whether porous flow/dynamic melting or diapirism/batch melting models are invoked. The incipient melting regime is dominated by the presence of garnet as a residual phase and the sampling of melts from this region relies on mechanisms to mobilise, pool and extract small melt fractions. One approach to interpreting major, trace element and isotopic abundances of natural magmas may be to consider them as mixing products of small 'incipient melt' incre-

ments and large 'major melting' increments. The nature of incipient melts themselves are illustrated by intraplate magmas particularly those containing mantle xenoliths and which range from olivine-rich basanites to olivine melilitites, and by kimberlites. Sodic, dolomitic carbonatites at 60 km < depth < 100 km or magnesian carbonatites at higher pressures, are also incipient melts at temperatures below the silicate solidus, in 'oxidized' regimes ( $f_{O_2} > IW + 2.5$  log units). These incipient carbonatite melts seldom, if ever, reach the surface but are responsible for mantle metasomatism or are captured and dissolved within silicate melting regimes.

The critical dependence of the peridotite-C-H-O solidi on oxidation state is illustrated in Table 1 where the solidus at two depths (100 km and 70 km) is defined in terms of fluid, melt and crystalline phases present as a function of  $f_{O_2}$  and volatile content. Column 1 is C-H free and  $f_{O_2}$  variation from IW+1 to IW+4 has little or no effect on melting. Column 2 is fluid-excess melting in that approximately 0.4% H<sub>2</sub>O is the maximum water content held in fertile amphibole lherzolite at ~ 20–30kb, 1000°C. The fluid is H<sub>2</sub>O  $\gg$  CO<sub>2</sub>. Column 5 also represents fluid excess melting but at much lower  $f_{O_2}$  so that the fluid is (CH<sub>4</sub> + H<sub>2</sub>O). Columns 3 and 4 are fluid-absent melting at different oxygen activities. The solidus temperature varies over 500°C at 100 km, from the minimum with carbonatite melt at 925°C to the C-H free solidus at 1460°C. Even with a fluid which is methane and water (approximately 1:1 mol. proportions) the solidus is depressed by 220°C. In this case the melt is silica under-saturated and contains dissolved carbon as CO<sub>3</sub><sup>2-</sup> and OH<sup>-</sup>, both acting to flux melting. In relation to melt geochemical characteristics, in the absence of C&H, the melt at the solidus at either 70 or 100 km depth is buffered by olivine, two pyroxenes and spinel and garnet is absent. By contrast in all of the examples with C&H present, garnet is present in the residue for melting at the solidus, and trace element partitioning will reflect this. Within the 'Incipient Melting' region (? asthenosphere), melt migration by porous flow will enrich the upper part (and base of the lithosphere) with

incompatible elements (OIB signatures) and deplete the lower part (N-MORB signature). The time scale for such fractionation within the asthenosphere may be sensitive to intensity of deformation with the asthenosphere due to relative lithosphere/deep mantle motion.

### Mantle dynamics in relation to peridotite-C-H-O

The determination of liquidus temperatures of primitive magmas, including the use of melt inclusions in magnesian olivines, argues for a mantle potential temperature around 1450°C. There is little or no difference in this temperature for 'hot-spot' (? ~50°C cooler) or back-arc spreading locations, suggesting that, apart from within the down-going slab, mantle temperature variations related to convective motions are small or alternatively, that large temperature variations interpreted from geophysical models, are not directly sensed by magma type or magma extrusion temperatures.

The major implications of the peridotite-C-H-O phase diagram include the presence of a fluid absent, partially molten layer in which  $f_{O_2}$  may vary continuously. This lies between a fluid-present ( $CH_4 + H_2O$ ) or diamond +  $H^+$ -bearing silicates regime at  $> \sim 200$  km, and a lithosphere in which amphibole  $\pm$   $CO_2$ -rich fluid is stable. The transport of excess oxygen within the subducted slab into mantle regions has profound effects in stimulating redox-melting and oxidized ( $CO_2 + H_2O$ ) melting within and above the subducted slab. Models of mantle dynamics should include incipient melting along normal intraplate geotherms, with potential large effects on mantle viscosity. The presence of the partially molten layer (petrological 'asthenosphere') results in decoupling between temperature or compositional anomalies in the mantle at depths  $> 200$  kms and lithospheric fractures and plate motions.

TABLE 1. Melting of peridotite-C-H-O, compiled from published studies of a fertile mantle lherzolite (Hawaiian pyrolite)

Log $f_{O_2}$ , relative to Iron-Wustite Chemical Attributes	IW + 1 to + 4 C&H absent	$> IW + 2.5$ $H_2O > 0.4$ wt% C ~ 100-1000ppm	$> IW + 2.5$ $H_2O < 0.4$ wt% C ~ 100-1000ppm	IW + 1.5 to + 2 $H_2O \ll 0.4$ wt% C ~ 100-1000ppm	IW + 1 $H_2O \ll 0.4$ wt% C ~ 100-1000ppm
100 km depth ~3GPa T solidus (°C) C-H species Subsolidus	1460 nil	925 $H_2O$ -rich fluid $\pm$ magnesite	925 Amphibole + magnesite	~1025 $H_2O$ -rich fluid $\pm$ graphite	1240 $CH_4 \pm H_2O$ fluid
Above solidus	nil	Carbonatite $\pm$ $H_2O$ -rich fluid	Carbonatite + amphibole	$H_2O$ -rich, $CO_3^{2-}$ -rich bearing silicate melt	Silicate melt $OH^- > CO_3^{2-}$
Mineralogy at solidus Ol, Opx, Cpx, +	Spinel	Ga + magnesite	Ga + amphibole + magnesite +	Ga $\pm$ phlogopite graphite	Ga $\pm$ graphite
70 km depth ~2.2GPa T solidus (°C) C-H species Subsolidus	1380 nil	930 $H_2O$ -rich fluid + dolomite + amphibole	940 Amphibole + dolomite	1090-1130 Amphibole + graphite	1200 $CH_4 + H_2O$ fluid $\pm$ graphite
Above solidus	nil	Carbonatite + amphibole $\pm H_2O$ -rich fluid	Carbonatite + amphibole	$H_2O$ -rich, $CO_3^{2-}$ - bearing silicate melt	Silicate melt $OH^- > CO_3^{2-}$
Mineralogy at solidus Ol, Opx, Cpx, +	Spinel	Ga + amphibole + dolomite	Ga + amphibole + dolomite	Ga + amphibole + dolomite	Ga $\pm$ graphite