Primary magmas at mid-ocean ridges, “hotspots,” and other intraplate settings: Constraints on mantle potential temperature

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ABSTRACT

Intraplate, “hotspot,” and mid-ocean ridge basalts (MORB) are characteristic of the modern Earth, and within the plate tectonics interpretation of the Earth’s behavior become the basis for a petrological model of the lithosphere and asthenosphere. This model is based on experimental studies of various primitive magmas and of peridotite + (C-H-O), including melting and phase relationships under variable oxygen fugacities (fO_2). The deep mantle plume hypothesis requires a large potential temperature difference (DT_p 200–250 °C) between the upwelling plume and normal ambient mantle as sampled by mid-ocean ridge upwelling and by nonplume intraplate basalts. This core tenet of the deep mantle plume hypothesis is testable by comparison of primitive hotspot magmas with intraplate magmas and particularly with primitive MORB.

We have examined picrites and olivine phenocryst compositions from Hawaiian volcanoes and a large new dataset of glass compositions from the Hawaiian Scientific Drilling Project, sampling deep into the main cone-building phase of Mauna Kea volcano. By incremental addition of olivine (reversing the crystallization of magmas saturated only in olivine + Cr-Al spinel) we infer the parental or primitive picrite magma compositions for distinctive compositional suites and individual volcanoes. We then calculate liquidus temperatures (1 atm) and infer conditions of melt separation from residual lherzolite (olivine + orthopyroxene + clinopyroxene 6 spinel) or harzburgite (olivine + orthopyroxene + Cr spinel). The Hawaiian tholeiitic picrites of the main shield-building phase consistently indicate harzburgite residue and pressures of magma segregation around 1.5–2 GPa.

The petrological database of glass compositions from mid-ocean ridge settings contains more than 190 analyses of glass with more than 9.5% MgO. These quenched liquids were saturated in olivine (mole MgO/(MgO + FeO_t) or Mg # = 86–89) and Al-Cr spinel. Olivine addition calculations are used to estimate parental liquid compositions with liquidus olivine Mg # = 90.5–91.5. Further constraint is provided by the requirement that parental liquids lie on ol + opx ± cpx + spinel saturation surfaces for a lherzolitic or harzburgitic residue. We infer primitive or parental MOR magmas to be picrites with 13%–16% MgO, segregating from lherzolite to harzburgite residue for the most part at ~2 GPa but in some cases at pressures as low as 1 GPa. Our analysis of the compositions and liquidus temperatures of parental magmas at a hotspot (Hawaii) and at mid-ocean ridge settings finds that picritic magmas with >13% MgO are characteristic of both settings. Liquidus temperatures have the same range, to a maximum of 1380–1390 °C if volatile-free, but up to 1335 °C (Hawaii) and ~1355 °C (mid-ocean ridges) if volatiles (C-H-O) are included.

The maximum temperatures of primitive magmas and the inferences from the systematics of peridotite partial melting are used to estimate mantle potential temperatures of ~1430 °C at mid-ocean ridges and up to 1400 °C beneath Hawaiian volcanoes. The principal differences between hotspot and MOR primitive magmas are compositional and not thermal. The hotspot source has geochemical signatures that suggest melting, depletion, and refertilization processes in subduction settings, as well as enrichment processes due to migration of incipient melt (carbonatite to olivine nephelinite) in the asthenosphere. The melting and primary differentiation of the Earth's mantle observed at divergent plate boundaries and in intraplate settings, including hotspots, is a consequence of the plate tectonics cycle's acting on the modern Earth with T_p 1430 °C. Plate tectonics introduces chemical inhomogeneity, including redox contrasts, into the Earth's upper mantle, and chemical heterogeneity within the asthenosphere and upper mantle (i.e., below the lithospheric plates) at T_p 1430 °C, together with global degassing of (C-H-O) fluids, is responsible for the diverse intraplate, hotspot, and MOR magmas.