Lithosphere Thickness Control on the Extent and Pressure of Mantle Melting Beneath Intraplate Ocean Islands

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Summary

We have examined island-averaged geochemical data for 115 volcanic islands [1] with known eruption ages and ages of the underlain lithosphere from the Pacific, Atlantic and Indian oceans [2]. These age data allow calculation of the lithosphere thickness at the time of volcanism [2]. After correcting the basalts (and the alkaline varieties) (< 53% SiO_2) for fractionation effect to $Mg^{\#} = 0.72$ [3,4], we found that the island-averaged Si_{72} and Al_{72} decrease whereas Fe_{72}, Mg_{72}, Ti_{72} and P_{72} increase with increasing lithosphere thickness. The island-averaged $[La/Sm]_{CN}$ and $[Sm/Yb]_{CN}$ ratios also increase with increasing lithosphere thickness [2]. The correlations of these petrologic parameters with lithosphere thickness become outstanding when the data are averaged into each of the ten 10-km lithosphere thickness intervals regardless of ocean basins and geographic locations, i.e., $R_{Si72\text{-}Lithosphere\ Thickness\ (LT)} = -0.825$ (statistically significant at a > 99% confidence level), $R_{Al72\text{-}LT} = -0.879$ (> 99.5%), $R_{Fe72\text{-}LT} = 0.600$ (> 95%), $R_{Mg72\text{-}LT} = 0.751$ (> 99%), $R_{Ti72\text{-}LT} = 0.901$ (> 99.5%), $R_{P72\text{-}LT} = 0.745$ (> 99%), $R_{[La/Sm]CN\text{-}LT} = 0.682$ (> 98%) and $R_{[Sm/Yb]CN\text{-}LT} = 0.819$ (> 99%). These significant trends are most consistent with the interpretation that the extent of melting decreases whereas the pressure of melting increases with increasing lithosphere thickness. This is physically consistent with the active role the lithosphere plays in limiting the final depth of intra-oceanic mantle melting (i.e., the lid effect [5-7]). That is, beneath thin lithosphere, a parcel of mantle rises to a shallow level, and thus melts more by decompression with the aggregated melt having the property of high extent and low pressure of melting. By contrast, a parcel of mantle beneath thick lithosphere has restricted amount of upwelling, and thus melts less by decompression with the aggregated melt having the property of low extent and high pressure of melting. This finding confirms the earlier suggestions [5-7] and demonstrates that oceanic lithosphere thickness variation exerts the primary control on the chemistry of ocean island basalts (OIB). Variation in initial depth of mantle melting as a result of fertile mantle compositional variation and mantle potential temperature variation can influence OIB compositions, but these must have secondary effects because they do not overshadow the effect of lithosphere thickness variation that is prominent on a global scale.

Figure 1. Island groups: 1, Amsterdam-St. Paul (2); 2, Ascension (1); 3, Austral-Cook (12); 4, Azores (10); 5, Balleny (2); 6, Bouvet (1); 7, Cameroon Line (5); 8, Canary Islands (8); 9, Cape Verde (10); 10, Caroline (10); 11, Cocos (1); 12, Comoros (5); 13, Crozet (4); 14, Desertas (3); 15, Desventuradas (3); 16, Easter seamount (1); 17, Fernando de noronha (1); 18, Galapagos (23); 19, Gough chain (1); 20, Guadalupe (1); 21, Hawaiian (12); 22, Heard (1); 23, Iceland (4); 24, Jan Mayen (1); 25, Juan Fernandez (3); 26, Kerguelen (7); 27, Line Island Chain (1); 28, Macquarie (1); 29, Maderia (2); 30, Marion (1); 31, Marquesas (12); 32, Martin Vas (1); 33, Mascarene (1); 34, Mauritius (1); 35, Mcdonald (1); 36, Peter I island (1); 37, Pitcairn, Gambier (6); 38, Prince Edward (1); 39, Reunion (1); 40, Revillagigedo (4); 41, Ross Island (1); 42, Samoan (4); 43, Selvagen (2); 44, Society (10); 45, St Helena (1); 46, Svalbard (1); 47, Trinidade (1); 48, Tristan da Cunha (5); 49, Tuamotu (1). On diagram; island chain marked with red circle and number. Islands chains given in alphabetical order and number of islands associated with that chain in brackets. Map courtesy of http://chuma.cas.usf.edu/~juster/volc1/world%20map.gif

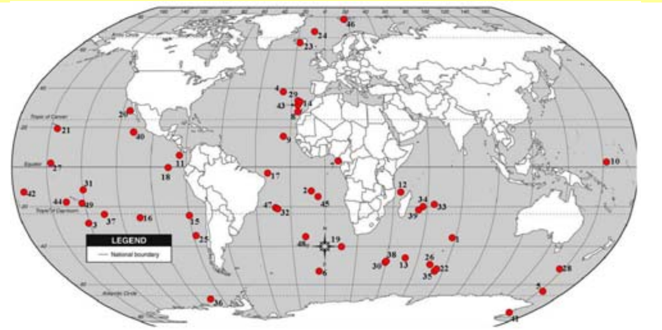
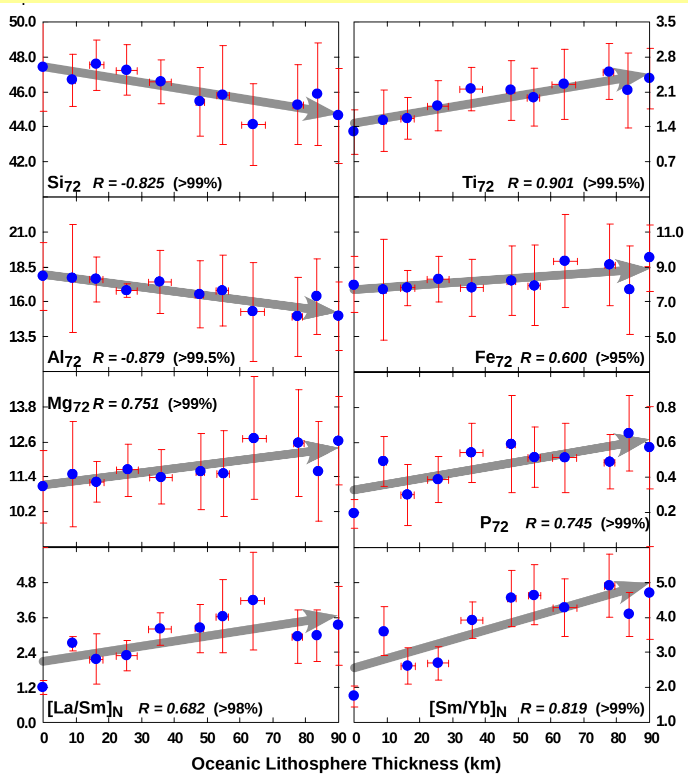


Figure 2. Plots of global OIB petrologic parameters as a function of lithosphere thickness at the time of active OIB volcanism. These parameters include major element oxides (SiO_2, TiO_2, Al_2O_3, FeO, MgO and P_2O_5 in weight percent) corrected for fractionation effect to $Mg^{\#} = 0.72$ (denoted by subscript 72) [3,4] and rare earth element ratios (La/Sm and Sm/Yb) normalized to chondrite values (denoted by subscript N) averaged within 10-km lithosphere thickness intervals regardless of ocean basins and geographic locations.



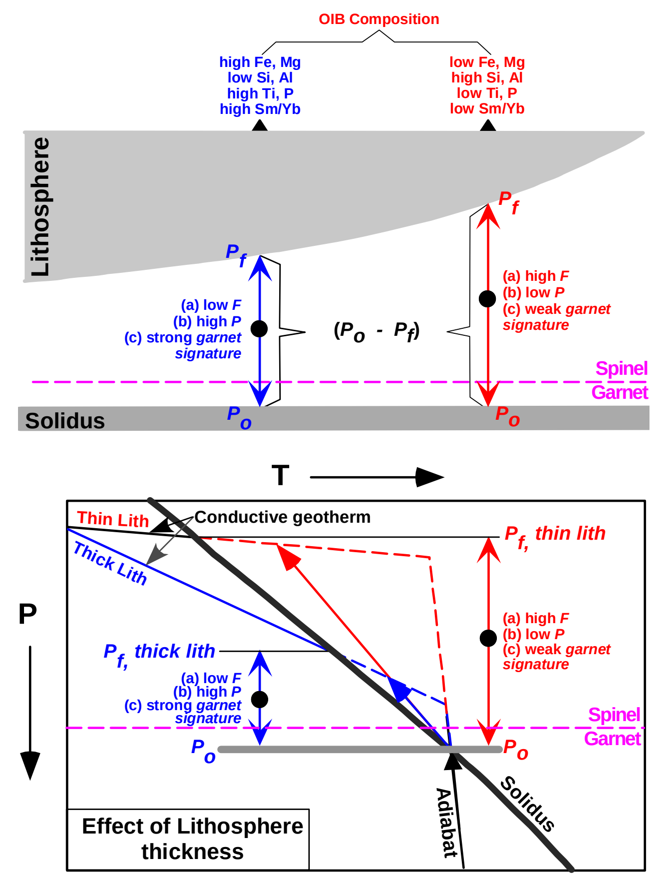


Figure 3. Schematic illustration of the effect of lithosphere thickness control on the extents and pressures of mantle melting beneath intraplate ocean islands. The illustration explains the OIB compositional variation as a function of the lithosphere thickness (Figure 2). **Top**, the deep bound of the lithosphere constrains the final depth of melting (P_f), limiting the vertical range of decompression (P_o-P_f), which is proportional to the extent of melting. The mean pressure of melting recorded in the chemistry of the erupted OIB melts is indicated by the filled circles, hence the inverse correlation between the extent (*F*) and pressure (*P*) of melting. **Bottom**, the above concept is illustrated in pressure-temperature space. The adiabatically upwelling parcel of mantle begins to melt when intersecting the solidus at depth of P_o, continued upwelling leads to continued decompression melting until the upwelling is ceased at P_f constrained by the lithosphere thickness. The significance of all other elements is self-explanatory. Note that the solidus depth is assumed to be the same to illustrate the concept, but it is in fact unconstrained because of unconstrained fertile source composition and mantle potential temperature relevant to individual volcanic islands. Nevertheless, the lithosphere thickness exerts the primary control on first-order OIB compositional variation on a global scale (Figure 2). Also note that the decompression melting is likely initiated in the deep garnet peridotite facies, thus giving the characteristic "garnet signature", i.e., high Sm/Yb ratio in OIB melts, but the intensity of the "garnet signature" is diluted less if the extent of melting is low beneath thick lithosphere (higher Sm/Yb) and diluted more if the extent of melting is high beneath thin lithosphere (lower Sm/Yb) where much of the decompression melting takes place in the shallower spinel peridotite facies.

References

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