Earth mantle geochemical evolution: a diachronic fractionation model for U/Pb and Th/U ratios

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MORB and OIB can be considered 'windows to the mantle' since they remain essentially uncontaminated during their ascent and are also unaffected by recent subduction processes. Consequently, they are of utmost importance to the understanding of mantle evolution throughout the Earth's history.

The study of these basalts has led to the development of mantle evolution models on which the depleted upper mantle can be envisaged as an open system periodically replenished by plumes carrying to the uppermost mantle the chemical signatures of ancient recycled oceanic crust, previously incubated at some compensation level (e.g. White, 1993; Hofmann, 1997). This would explain the discrepancy between the present Th/U and U/Pb in depleted mantle and corresponding time-integrated ratios inferred from lead isotope signatures (White, 1993).

The archetype of ancient recycled altered oceanic crust is the HIMU component which is better represented in lavas from Mangaia, Tubuaii and St. Helena islands. Characterized by $^{206}Pb/^{204}Pb > 20$, these rocks clearly plot to the right of the Geochron, implying that they are representative of mantle sources affected by U/Pb increment(s). Additionally, they present $\kappa_{Pb} \approx 3.6$, i.e. clearly lower than the Th/U = 4.2 value assumed for the Bulk Silicate Earth. Therefore, any mantle evolution model should be able to account for the U/Pb increase and Th/U decrease implicit in HIMU basalts lead isotope features.

It is agreed today that sub-seafloor metamorphism and alteration significantly change the chemical composition of ocean floor basalts, which became significantly enriched in uranium. This led some authors to invoke the uranium enrichment of oceanic crust as a likely reason for the U/Pb increase and the Th/U decrease necessary to explain the lead isotope signatures of HIMU basalts (e.g. Weaver, 1991; McCulloch, 1993; Noll *et al.*, 1996). However it has been demonstrated, on the basis of the low Ce/Pb and Nd/Pb values in orogenic basalts and of the constant Nb/U ratios in non-orogenic oceanic basalts, that the high time-integrated U/Pb ratios of HIMU basalts are not stem from U-enrichment, but rather from Pb loss during dehydration of the subducting plate.

Therefore, in our opinion, dehydration processes during subduction are a plausible explanation for the increment of U/Pb, though not for the Th/U decrease. As a consequence, an alternative model is needed to explain the referred variations in U/Pb and Th/U ratios of the mantle.

Martin (1993) and McCulloch (1993) showed that, while dehydration of downgoing slabs has been the most usual situation in the Phanerozoic, partial melting of the subducting slab predominated during the Archaean due to subduction of younger and warmer oceanic crust. In such conditions, the effects of these quite distinct processes on the fractionation of element pairs is necessarily different.

The model that we purpose calls on the diachronic U/Pb and Th/U fractionation which are here considered the reflex of the different processes associated with subduction zones on Archaean and post-Archaean times (Fig. 1).

During Archaean subduction events, when partial melting prevailed, the fractionation of certain element pairs was mainly influenced by the difference on the degree of incompatibility during magmagenesis processes. Thorium being more incompatible than uranium in the presence of residual garnet, Archaean orogenic rocks (TTG) were characterized by very high κ values and, therefore, a residue characterized by low Th/U ratios (and also low Sm/Nd, Rb/Sr, and U/Pb ratios) was repeatedly recycled back to the mantle. As a result of its partial melting, it is likely that Archaean residual slabs will have been fragmented on the upper mantle, where the occurrence of vigorous convective motions would have led to their fast scattering. Accordingly, the existence of a depleted upper mantle, impoverished in the more incompatible elements, would go back to the Archaean, a fact also implied by positive ε_{Nd} values in rocks of that age.

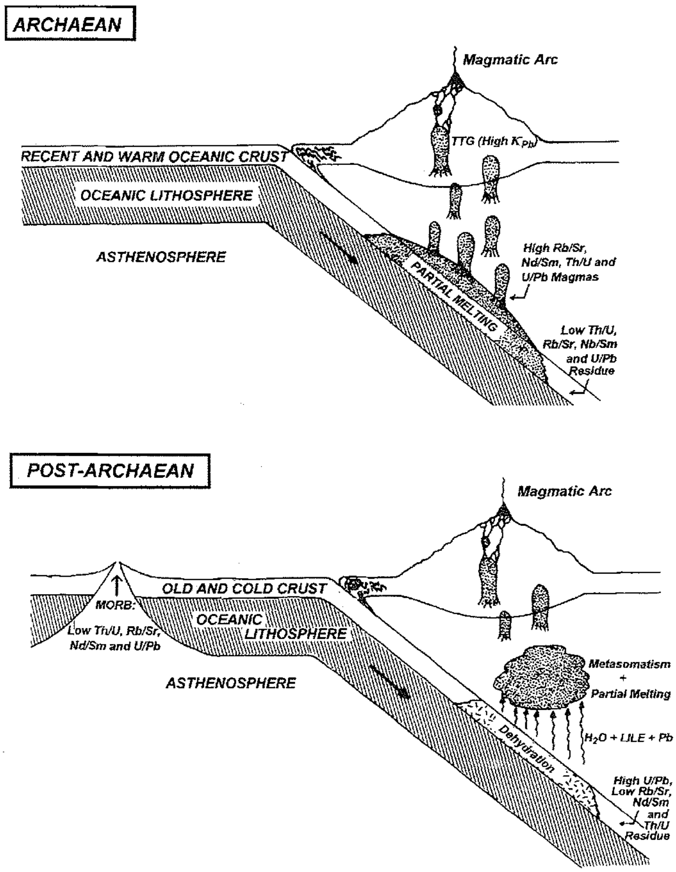

FIG. 1. Schematic representation of the contrasting processes associated to Archaean and post-Archaean subduction events and its influence on mantle evolution.

On post-Archaen times, the inherited low Th/U, Sm/Nd, and Rb/Sr mantle ratios have not changed considerably by dehydration at subduction zones. Nonetheless, this process increases the U/Pb ratios significantly, in spite of the large difference on ionic radius and ionic potential of these two elements, with Pb^{2+}, in opposition to uranium, behaving as a highly soluble element during dehydration.

In conclusion, we propose that the U-Pb and Th-U fractionation required to explain the lead isotope signatures of oceanic basalts was diachronic and caused by different mechanisms. The Th/U decrease occurred through magmatic processes associated with Archaean partial melting of subducting slabs, while the U/Pb increase in the mantle sources is produced by recycling of dehydrated oceanic crust on post-Archaean times.

The suggested difference on age and mechanisms at the origin of Th/U and U/Pb fractionations, also explains why, for MORB and OIB, $^{208*}Pb/^{206*}Pb$ correlates with $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ but not with $^{206}Pb/^{204}Pb$.

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