Archaean Crust-Mantle Evolution: Constraints from Nb-Th-U Systematics, Arc Trace Element Ratios and Nd-Hf-Pb Isotopes

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The degree to which trace elements are enriched in continental crust follows, in general, the order of incompatibility as found in mid-ocean-ridge basalts (MORBs). There are, however, some important exceptions to this rule (Hofmann, 1988; Brenan et al., 1998): Pb, Li, and Be are over-proportionally concentrated in continental crust and contents of the pentavalent elements Nb, Ta, and Ti are lower than expected. The over-enrichment in Pb, Li, and Be is the result of preferential transfer of these elements to the mantle wedge by fluids originating from subducted slabs. The reason behind this phenomenon is that the slab mineralogy/fluid partition coefficients for Pb, Li, and Be are more than one order of magnitude smaller than those for the similarly compatible (in MORB melting) Nd, Yb, and Nb. Furthermore, Ta is noticeably less depleted in the continents than its geochemical twin Nb, which translates to a subchondritic continental Nb/Ta ratio of ca. 11 (viz. 18). Complexing in aqueous fluids is the most likely process that fractionates geochemical twin elements and Ta is evidently preferentially lost from the slab during dehydration.

It is important that these fingerprints of slab-dehydration not only characterise modern arc lavas but the continental crust as a whole and more to the point, continental crust of all ages. For example, the granitoid Nd/Pb and Nb/Ta ratios have remained virtually constant through time (Condie, 1993). Our additional data for very early Archaean and late Archaean granitoids verify that these ratios have remained unchanged. The important implication is that at least since 3.8 Ga, extraction of continental crust from the mantle has involved dehydration of subducted slabs and melting of supra-subduction zone mantle wedge. With this knowledge Nb-Th-U systematics can be used to determine the growth and erosion histories of continental crust.

Relative to U and Th, both of which are readily lost to the escaping fluids, Nb is preferentially retained in subducted slabs. Over time, the mantle has therefore become more depleted in U and Th than it has in Nb. The Nb/Th and Nb/U ratios of the mantle should thus mirror the amount of continental crust present at any given time. Because Nb, Th and U are similarly incompatible during MORB melting, the temporal Nb-Th-U systematics of the mantle can be reconstructed from uncontaminated, depleted-mantle derived rocks. A useful guide to avoid contaminated samples is the Nb/Ta ratio which is much lower in the contaminant (i.e. continents) than in the mantle. Additional selection criteria include Nd-isotope systematics and REE-patterns. Collerson and Kamber (1999) showed that during the early and mid-Archaean, the Nb/Th ratio of depleted mantle has only slowly increased from the chondritic value of 8 to ca. 9 at 3 Ga. Between 3 Ga and 2 Ga, however, the Nb/Th ratio increased linearly to ca. 15. Since 2.0 Ga increase of the ratio to the present value of ca. 18 has been slow. This information can be converted to a crust volume versus time curve by postulating that a chondritic mantle Nb/Th ratio corresponds to 0% crust and that the present ratio of 18 corresponds to 100% crust. The 3-stage history of such a curve (slowly increasing crustal volume between 3.8 and 3 Ga; rapid increase of crustal volume to 67% at 2 Ga; and slow increase to present volume) is in very good agreement with independent estimates based on Pb-isotopes (Kramers and Tolstikhin, 1997) and those based on geophysical data (Reymer and Schubert, 1984).

The next important observation is that the present-day depleted mantle Th/U ratio of 2.6 is much lower than the time-integrated ratio of 3.75 obtained from the Pb-isotope composition of MORB. In other words, for substantial periods of time, the depleted mantle must have evolved with a Th/U ratio greater than 3.75. This observation, which is termed the second terrestrial Pb paradox, is corroborated by the temporal evolution of the Th/U ratio of the depleted mantle as reconstructed from the same set of samples used for Nb/Th (Collerson and Kamber, 1999). The Th/U ratio decreased from ca. 4.1 (at 3.8 Ga) to only ca. 3.7 at 2.0 Ga. However, after 2.0 Ga its decrease accelerated throughout the Proterozoic and Phanerozoic to yield the present-day ratio of 2.6. Because the Th/U ratio of the mantle had evidently not been changed significantly by extraction of ca. 67% continental crust at 2.0 Ga, the decrease of mantle Th/U ratio must have a separate reason. The most likely explanation is that after 2.0 Ga, U was preferentially recycled from the continents back into the mantle. We postulate that the change in mantle Th/U ratios ultimately reflects establishment of a pandemic oxidising atmosphere and hydrosphere, in which U became soluble and could be recycled back into the mantle.

When the second terrestrial Pb-paradox is considered it becomes clear that the Nb/U ratio of the depleted mantle reflects two processes. First, between 3.8 and 2.0 Ga, mantle Nb/U solely reflects extraction of continental crust and second, from 2.0 Ga to the present-day, it also reflects recycling of continental crust. Indeed, the temporal evolution of mantle Nb/U ratio is comparable with that of Nb/Th ratio between 3.8 Ga and 2.0 Ga, by which time the ratios had increased from the chondrite value of 30, to a maximum of ca. 58. Since 2.0 Ga, however, the Nb/U ratio has decreased to its present value of ca. 47 in spite of further extraction of continental crust. This sharp kink observed at 2.0 Ga thus also dates establishment of a pandemic oxidising atmosphere and hydrosphere.

Combined Nb-Th-U systematics suggest that growth of continental crust as we know it today was fastest between 3 and 2 Ga. This does not necessarily mean that more material was added to the continents than is today (i.e., higher growth rate). Rather, it reflects that destruction rates of continental crust were slower. This suggestion is supported by Nd-isotope systematics of sedimentary rocks that show that, up to 2.0 Ga, the difference between deposition age and Nd mantle extraction age was small, but that the difference rapidly increased thereafter. The reason for the implicit acceleration of erosion after 2.0 Ga is unknown but the temporal coincidence with establishment of a pandemic oxidising atmosphere is remarkable. There is a possibility that the change from a largely anoxic to an oxygenated atmosphere had a drastic effect on climate leading to conditions that facilitated weathering and erosion. Alternatively, the UV-shielding ozone layer of the post 2.0 Ga atmosphere could have allowed colonialisation of the continents by primitive biofilms that accelerated weathering.

Net continental growth rate was influenced by additional factors. It is to be expected that during times of supercontinent assembly, addition of juvenile material was reduced because of the decrease in total subduction length. The virtually constant crustal volume between 2 and 0.6 Ga coincides with extended periods of supercontinent amalgamation (Nena, Rodinia, Gondwana). The other important observation is that crustal growth rate was slow between 3.8 and 3.0 Ga. This is rather surprising in view of the fact that high heat loss almost certainly was accommodated by high production rate of oceanic crust. Two explanations appear plausible. First, much of crust that was produced was not of arc character (and its extraction thus did not affect the mantle Nb/Th and Nb/U ratios) and was later fully recycled into the mantle. Second, oceanic crust may, on average, have been too thick to be subducted in the modern sense. We have estimated, based on isentropic melting models, that the average thickness of oceanic crust may have dropped from ca. 22 km at 3.8 Ga to ca. 17 km at 3.0 Ga. The sharp acceleration of crustal growth post 3.0 Ga may therefore indicate that a threshold in oceanic thickness was reached, beyond which modern style subduction became feasible.

It has been suggested in the past that subduction zone magmatism experienced a change from direct slab melting in the Archaean towards supra-subduction zone melting thereafter. We have further tested this hypothesis by a detailed comparison of Archaean tonalite-trondhjemite-granodiorites (TTGs) with modern adakites. Adakites form where unusually hot (young) lithosphere is being subducted and these rocks are interpreted as direct melting products of the crustal part of the oceanic lithosphere. Trace element geochemistry shows that these rocks indeed lack the typical continental Nb/Ta, Li/Yb, Be/Nb and Nd/Pb ratios. In other words, the enrichment of typical arc rocks in some elements (that are preferentially lost from the slab to the supra-subduction zone mantle wedge) is not seen in adakites. However, Archaean TTGs do not resemble adakites but have typical arc trace element patterns, although they are more depleted in the heavy rare earth elements (REEs). The important point, however, is that Archaean continental crust as a whole was no more depleted in heavy REEs than modern crust (Condie, 1993). The Sm/Nd ratio of continent-derived sedimentary rock has remained constant. The strong heavy REE depletion of Archaean TTGs is thus not a source characteristic but reflects more efficient intracrustal differentiation.

The improving Os-isotope database confirms that continental crust has grown in unison with its subcontinental lithospheric mantle (SCLM). Indeed, a stable SCLM keel is pertinent to preserve continental crust. Direct melting of oceanic crust (to yield a quartz-dioritic to tonalitic composition) would not produce any SCLM, because the depleted refractory residue (i.e., the eclogitic slab) would invariably descend into the deeper mantle. The continental crust that has survived to the present day has largely formed from the supra-subduction zone mantle wedge. This tectonic environment is the only one capable of providing both the slab-dehydration fingerprint and the refractory SCLM on which the continents can survive. It is possible that different types of continental crusts may have formed during the Archaean. Mantle Nd-isotope systematics show, however, that these would have been short-lived and Nb-Th-U systematics show that such crust could not have chemically resembled what we now define as continents.

Arc-magmatism requires the existence of a liquid hydrosphere. Estimates of energy release during the late heavy meteorite bombardment indicate that liquid water was not likely to have existed at that time. Lunar age data constrain the end of the heavy meteorite bombardment to 3.80 to 3.85 Ga. There have been claims for 3.87 Ga waterlain terrestrial sediments but the interpretation of these zircon ages has been questioned. On the present evidence it is more likely that a liquid hydrosphere on Earth was established between 3.80 and 3.85 Ga. We regard this age estimate as the birth of subduction -related tectonics on Earth.

The nature of even older terrestrial mantle-crust differentiation is enigmatic. Very few rocks have been found that are older than 3.8 Ga and their original geochemical fingerprints are difficult to reconstruct. Nevertheless, well-preserved 3.8 Ga Nulliak metakomatiites from Labrador have subchondritic Nb/Th ratios (ca. 6). If pristine, the subchondritic ratio could imply that a mantle-derived melt was contaminated with even older crust (assuming that such crust had subchondritic Nb/Th). However, 4.0 Ga Fra Munro Lunar Highland basalts also have subchondritic Nb/Th of 5.3. On moon, such ratios cannot be interpreted to reflect contamination with pre-existing (arc-produced) crust. Rather, Nb/Th fractionation may indicate a different style of mantle differentiation which may also have caused the apparent strong fractionation of the Sm-Nd and Lu-Hf systems in very early Archaean mantle.

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