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Priscoan (4.00–4.03 Ga) orthogneisses from northwestern Canada – by Samuel A. Bowring and Ian S. Williams: discussion

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Bowring and Williams (1999) report zircon U-Pb dates in the range 4.00–4.03 Ga for the Acasta gneisses of northwestern Canada, following earlier reports of 3.96 Ga ages (Bowring et al. 1989). They claim that these zircons most likely date the time of magmatic crystallisation of the tonalitic to granodioritic gneiss precursor. Thus, the Acasta gneisses may be the oldest terrestrial rocks discovered so far. Such ancient samples of continental crust potentially carry isotopic and trace-element information which can provide constraints on the very early evolution of the Earth.

On the basis of ca. 4 Ga zircon dates, Bowring and Housh (1995) had previously claimed that whole-rock Nd-isotope ratios of individual Acasta gneiss samples, corrected back to the oldest zircon ages, indicate extreme geochemical heterogeneity of very early Archean mantle (a conclusion reiterated by Bowring and Williams 1999), which would in turn indicate that a chemically differentiated continental crust, comparable to its present-day mass, existed since a few hundred million years after Earth accretion. In a re-interpretation of this earlier work on the Acasta gneisses, Moorbath et al. (1997) noted a striking colinearity of Sm-Nd data, with an apparent regression age of 3,371 ± 59 Ma (mswd 9.2) and an initial ϵ_{Nd} of -5.6 ± 0.7 for 34 samples of Acasta gneiss. They argued that Nd isotope systematics had been reset (or set) in the mid Archean, and therefore could not be used to draw conclusions on the isotope geochemistry of the Earth's mantle at 4 Ga (and therefore the amount of continental crust present at that time). Bowring and Williams (1999) have not found any 3.4 Ga zircon ages in the samples they studied, arguing therefore that the colinearity of Sm-Nd data noted by Moorbath et al. (1997) has no age significance. Implicitly, the proposal of Bowring and Housh (1995), for a vast amount of continental crust since almost the time of origin of the Earth, could be valid.

Here, we comment on the use of whole-rock Nd isotopes to study the isotopic evolution of the Earth's early mantle. We emphasise that this comment is not intended as criticism of the geochronological data presented by Bowring and Williams (1999), or the interpretation that their analysed zircons preserve evidence for crystallisation from a magmatic precursor at ca. 4.0 Ga. Instead, our discussion focuses on two key issues in this debate which remain unresolved, namely (1) whether the new data of Bowring and Williams (1999) can exclude an age significance of the 3.4 Ga Sm-Nd regression line (Moorbath et al. 1997), and (2) what the consequences are if this Sm-Nd regression line has no age significance, i.e. is there then positive evidence of gross Nd isotope heterogeneity in the Earth's mantle at 4 Ga?

Age significance of the 3.4 Ga Sm-Nd regression line

The three samples studied in detail by Bowring and Williams (1999) clearly preserve evidence for magmatic zircon crystallisation at 4.0 Ga and, as documented, they have also been affected by later (3.75–3.61 Ga) metamorphic events of sufficiently high grade and,

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presumably, regional extent to involve partial melting. The fact that no metamorphic event at 3.37 Ga is recorded in the zircon populations from the samples studied by Bowring and Williams (1999) need not necessarily exclude such an event. Other rocks in the Acasta region have yielded assorted mineral U-Pb ages corresponding to periods of intrusion, deformation and metamorphism at 3.4–3.6 Ga (Bowring et al. 1990), as well as ca. 3.4 Ga granitic sheeting and leucosome formation (Bowring, unpublished data, quoted in Bowring and Williams 1999). Stern and Bleeker (1998) report overgrowths on ca. 4.0 Ga zircons which yield 3,356 ± 14 Ma dates, which they regard as "...the age of a period of high-grade metamorphism coincident with injection of leucosome". If leucosome injection is indeed contemporaneous with the "... dominant period of high-grade metamorphism..." (Stern and Bleeker 1998) within the Acasta gneiss, this might provide the "... framework for possible REE redistribution" (Moorbath et al. 1997) at this time. In addition, Yamashita et al. (2000) have documented 3.38 Ga basement tonalites from the Hanikahimajuk Lake area, ca. 200 km northeast of the Acasta River area which, given the similarity of ca. 3.4 Ga ages, they consider to be part of a "...large crustal block..." together with the gneisses which have yielded the 4.0 Ga zircons. These ages are indistinguishable from the 3.37 Ga Sm-Nd whole-rock regression age reported by Moorbath et al. (1997).

A critical parameter controlling the growth of metamorphic zircon during regional metamorphism is the supply of Zr from the breakdown of minerals such as hornblende (Fraser et al. 1997). In the case of polyphase terranes, the first metamorphic event to affect a rock will transfer Zr liberated by the breakdown of such phases into stable zircon. During subsequent events, there then may be insufficient Zr available to support a second generation of metamorphic zircon growth. A recently documented example of this is the heterogeneous development of ca. 980 Ma Sveconorwegian metamorphic zircon in southwestern Sweden (Söderlund et al. 2000). In this region, ca. 1.7 Ga orthogneisses display metamorphic overgrowths which are primarily related to a 1.46–1.42 Ga event, with little evidence for the regional ca. 980 Ma event which is commonly recorded by metamorphic zircon growth in post-1.42 Ga intrusive rocks.

With specific reference to Acasta, it is interesting to note that Stern and Bleeker (1998) report ca. 3.4 Ga overgrowths on ca. 4.0 Ga zircons which show no evidence for an earlier 3.75–3.61 Ga event, and the data reported by Sano et al. (1999) show no clear evidence for either of these early Archean metamorphic events. Combined with the study of Bowring and Williams (1999), these results show that zircon U-Pb geochronology alone is not necessarily a complete indicator of metamorphic history of a given terrane.

Nd isotope homogenisation on a regional scale in granulite facies metamorphism has been documented by Whitehouse (1988), and complete mineral equilibration in amphibolite facies by Gruau et al. (1996). A metamorphic episode at 3.4 Ga affecting the Acasta gneisses would have been preceded by events at 3.75–3.61 Ga (Bowring and Williams 1999) and, therefore, the fact that no 3.4 Ga date was found in the zircons analysed by Bowring and Williams (1999) does not, a priori, exclude a significant event, capable of resetting Sm-Nd systematics, occurring at this time.

Sm-Nd mixing lines and their implications

In spite of the evidence cited above for the geological significance of the 3.4 Ga Sm-Nd array reported by Moorbath et al. (1997), it is important to consider mixing as an alternative mechanism for producing the array. In this context, Bowring and Housh (1995) stated that "... the Acasta gneisses are compositionally and temporally heterogeneous and thus were not all derived from a single, homogeneous reservoir at the same time...", and "... therefore any linear array on an isochron diagram for these samples is a mixing line, and calculated ages and initial isotopic ratios have no geological significance." The implications of this statement merit more detailed consideration. If mixing occurred after 4.0 Ga, then the Sm-Nd systematics of the gneisses clearly have not remained intact since that time, and calculated initial Nd-isotope ratios assuming this age cannot be valid, whether or not the subsequently developed array has any age significance. In contrast, if mixing occurred at (or before) 4.0 Ga, the mixing line must have had a strongly negative slope in order to generate the younger age, i.e. the mixing component(s) with the lowest ^{143}Nd/^{144}Nd must have had the highest Sm/Nd, and vice versa. A number of Sm-Nd arrays have been interpreted as mixing lines (a prime example being that of Kambalda; Chauvel et al. 1985) but these always yield ages which are too old rather than too young because they result from the mixing of components with correlated ^{143}Nd/^{144}Nd and Sm/Nd ratios. The large spread in apparent initial ϵ_{Nd} values for some Archean gneisses of the North Atlantic Craton has been noted with surprise, even by those who accept them as valid (Bennett et al. 1993). Once the anticorrelation is taken into account, the spread becomes impossible, i.e. there exists no geochemically plausible mechanism to produce both the Sm-Nd anticorrelation and the ϵ_{Nd} spread in 500 Ma from a single chondritic reservoir. It must thus be concluded that the Acasta gneisses cannot have remained chemically intact since 4.0 Ga, regardless of whether the disturbance was mixing or resetting.

Uncertainties of this nature are the reason why the wide range of initial ϵ_{Nd} values claimed for early Archean rocks by some workers (e.g., Bennett et al. 1993; Bowring and Housh 1995) has not been used in recent modelling of secular Nd isotopic evolution of the upper mantle (Nägler and Kramers 1998). Until early Archean rock samples are found which demonstrably escaped subsequent isotope disturbance, geochemical studies have to focus on the dated material (i.e. zircons) itself. Recently, Amelin et al. (1999) reported results of a combined Hf-isotope and U-Pb geochronological study on single 4.2–3.4 Ga zircons from the Mount Narryer quartzite of Western Australia, as well as on 3.6 Ga zircons from the Acasta gneisses. These zircons contain no Hf-isotope evidence for strongly depleted early Archean mantle. One class of zircons shows near-chondritic initial Hf-isotope ratios, whereas the other class (mainly grains which are younger than the maximum age recorded in the area) is characterised by sub-chondritic Hf-isotope ratios (negative ϵ_{Hf} values).

In conclusion, we find that the new zircon U-Pb data of Bowring and Williams (1999) from the 4 Ga Acasta gneisses, although numerous and of high quality, still provide no sound basis upon which to base application of whole-rock Sm-Nd data from these same gneisses to constrain the geochemical evolution of the Earth in its first 500 million years.

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