Plumbing the depths: Pb isotope constraints on the origin of the 3.65 Ga Amîtsoq gneiss

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Archaean crust largely consists of tonalite-trondhjemite-granodiorite (TTG) gneiss provinces with associated greenstone belts. Understanding their genesis is a fundamental task in deciphering crustal evolution through time. The oldest well-exposed major TTG-greenstone belt terrain is the Itsaq gneiss complex of southern West Greenland. This complex consists of the TTG-type Amîtsoq gneiss with its highly metamorphosed metasedimentary and mafic inclusions (the Akilia association), and the Isua greenstone belt. The isotope-geochemical signatures of these units, and the conclusions drawn from them, are highly debated issues with far-reaching implications for crustal and mantle evolution. The main controversy centres around the significance of ion-probe U-Pb zircon dates. Zircons from these rocks typically show a wide range (*c.* 3.60 to 3.87 Ga) of near-concordant U-Pb dates. Initial Nd isotope signatures of individual samples, when corrected for ^{147}Sm decay by assuming that the oldest U-Pb zircon dates represent the age of rock formation, span a wide range between +5 and -5 epsilon units (Bennett *et al.*, 1993). These Nd isotope data have been interpreted to reflect both extreme mantle isotope heterogeneity and extreme *LREE*-depletion of early Archaean mantle, implying the existence and persistence of a voluminous crust during early Archaean times (McCulloch and Bennett *et al.*, 1994). Such an interpretation of the Nd isotope data of the Itsaq gneiss complex would require a substantial (irreversible?) change in processes of crustal evolution between mid- and early Archaean times. Here we challenge the above scenario based on new, previously unpublished and published Pb isotope data for the Amîtsoq gneiss.

The ancient Amîtsoq gneiss is characterised by extremely low μ (= ^{238}U/^{204}Pb) values and contains the earth's least radiogenic silicate Pb. In addition to previously published and unpublished whole-rock and feldspar Pb isotope data of Amîtsoq gneiss samples, we have specifically included samples in this study which contain zircons with some ion-probe U-Pb dates extending back to >3.8 Ga. Plotting all 84 samples (whole rocks, feldspars, leachates) in a common Pb diagram reveals two major features. Firstly, in spite of the wide area over which the samples were collected, a tight regression line (MSWD = 17.6) corresponding to an age of 3654 ± 73 Ma is obtained. The second, far more important, feature is that independent of the exact slope of the regression, a very well-defined intercept with plausible terrestrial Pb-isotope evolution curves is obtained. Thus, relative to the depleted mantle evolution curve of Kramers and Tolstikhin (1997), intercept ages of a family of regression lines calculated with sub-sets of the data range only between 3.64 and 3.68 Ga. The scatter around the Pb/Pb regression line is most probably the result of minor initial Pb-isotopic heterogeneity and/or some post-formational metamorphic disturbance. Whilst the slope of the Pb/Pb regression line could, in theory, be spurious if not all samples were genetically related, the really important intercept constraint from the least radiogenic Pb data cannot be discounted by arguing that unrelated rocks have been studied. The only straightforward interpretation of the Amîtsoq Pb isotope data is that the magmatic precursors of the Amîtsoq gneisses were formed over a short period of time (< 100 Ma), most likely *c.* 3650 Ma ago.

The Pb-isotopic constraints are, and have always been, in obvious conflict with the extended (3.87 to 3.6 Ga) crustal growth history proposed by Nutman *et al.* (1996) and with the Nd isotope interpretation of Bennett *et al.* (1993). These authors summarily dismissed the Pb-isotope evidence by stating that these might reflect post-igneous disturbance. However, the only scenario under which the original Pb isotope ratios of 3.87 to 3.6 Ga old rocks could evolve into the observed Pb-isotope array would involve three stages. Firstly, a geological event must be proposed at 3.65 Ga capable of completely resetting the Pb isotopic systematics in every Amîtsoq gneiss sample so far measured. Secondly, the > 3.65 Ga precursors must have evolved with a restricted, mantle-like range of μ values (*c.* 6 to 10). Thirdly, the proposed 3.65 Ga resetting event was further accompanied by a massive loss of U (up to 95%) in order to lower the original μ values to 0.5–1.5. Although such a scenario is theoretically possible, the important issue is how likely it might be compared to the likelihood of interpreting the > 3.70 Ga zircons as inherited.

Of particular relevance here is the third requirement. There are two independent lines of evidence against a metamorphic origin for the low μ characteristics of the Amîtsoq gneisses. Firstly, the proponents of such a metamorphic U-loss have always envisaged a high-grade metamorphic event as the main reason for U-depletion. However, the only well-documented high-grade metamorphic event in the area has been dated at 2.7 Ga, and had no obvious effect on the early Archaean Pb isotope signature and the U/Pb ratios of the Amîtsoq gneisses. Why should the proposed (but not documented) high-grade metamorphic event have led to Pb-isotope homogenistation and massive U-loss ? Secondly, the U-content of zircon is a function of that of the melt from which it crystallises. Although the distribution coefficients have not been determined experimentally, the generally remarkably low U-contents of the Amîtsoq gneiss zircons (*c.* 80 ppm, but also as low as 24 ppm!) is direct evidence for a low U-content of the original melt. In brief, we conclude that the low F of the Amîtsoq samples is an original feature, that the Pb isotopes reflect crystallisation of the Amîtsoq gneisses over a period of less than 100 Ma, and that the most likely intrusion age is given both by the intercept with terrestrial Pb evolution curves and the slope of the regression at 3.65 ± 0.05 Ga. The implication is that older zircons were inherited from a pre-existing source and that such zircon dates must not be used to correct for initial isotope ratios.

The Amîtsoq gneisses yield concordant Pb/Pb (3654 ± 73 Ma), Sm-Nd (3640 ± 120 Ma), and Rb-Sr (3660 ± 67 Ma) whole rock ($\pm$ mineral) regression ages and we regard their weighted mean of 3655 ± 45 Ma as the most reliable estimate for the emplacement age of the magmatic precursors of the Amîtsoq gneisses (note that at least some similar ages are also reported for all Amîtsoq samples studied so far by the ion-probe U-Pb zircon method). The initial isotope ratios obtained from these regression lines place limiting constraints on the melt source of the magmatic precursor. The intercept of the Pb/Pb regression line with the depleted mantle curve of Kramers and Tolstikhin (1997) yields a model age of 3650 ± 50 Ma, identical to the individual Pb/Pb, Sm-Nd and Rb-Sr regression ages. A depleted mantle origin is further compatible with the initial $^{87}Sr/^{86}Sr$ ratio of 0.7006 ± 9, obtained from the Rb-Sr regression. The initial epsilon Nd value of $+0.9 \pm 1.4$ obtained from a whole-rock Sm-Nd regression by Moorbath *et al.* (1997) indicates derivation from a mantle reservoir with *LREE* depletion compared to CHUR. A similar degree of *LREE* depletion has recently been found in Lu-Hf isotopic studies (e.g. Vervoort *et al.*, 1996). We conclude, based on the remarkable consistency of the above results, that the magmatic precursors of the Amîtsoq gneisses were derived at *c.* 3.65 Ga from a depleted mantle source with no significant contribution of pre-existing evolved crust but with some inheritance of older zircons (as in several well-known published examples, e.g. the Mt. Narryer metasediments).

Our analysis of the isotopic signatures of the Amîtsoq gneiss thus shows that the principal feature of the earth's oldest well-exposed TTG complex is neither a complex, prolonged magmatic history, nor a fingerprint of mantle which was strongly *LREE*-depleted for *c.* 400 Ma, as advocated by Nutman *et al.* (1996) and Bennett *et al.* (1993) respectively. Thus the outstanding features of the Amîtsoq gneiss are its extremely low F values, its variable (in some cases extreme) *HREE* depletion (O'Nions and Pankhurst, 1974) and the almost negligible contribution of pre-existing evolved crustal material in its source. It is difficult to reconcile these geochemical characteristics as having been inherited from the ultimate melt-source (i.e. the mantle). In any case, U- and *LREE*-depletion of such a mantle domain could not have been a long-standing feature (i.e. *c.* 400 Ma as estimated by Bennett *et al.*, 1993) but could, at most, have taken place *c.* 100 Ma before extraction of the Amîtsoq melts. An equally plausible alternative is that these geochemical features were acquired during crystallisation processes and might thus prove to be the most important clues for the genesis of this oldest accessible example of a TTG complex.

References

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