Easter Island palm, whatever that may have been.

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Origin of granulites

THE recent 'statistical' study on granulite-facies rocks by Ben Othman *et al.*[1], in which 32 samples of granulites of many different lithologies and from a wide range of geological environments ranging in age from 2,900 to 200 Myr, have been used to make broad generalizations on the evolution of the lower continental crust and to propose a generalized tectonic model of granulite genesis. Using Nd and Sr model ages, they conclude that, in many cases, internal differentiation of continental crust follows primary differentiation of continental crust from the mantle by a "large time interval". I disagree strongly with this shotgun approach to such a major geological problem, particularly in view of the many published geological, petrological, geochemical and isotopic studies on granulite terranes. I maintain that broad generalizations based on so few data from an indiscriminate grouping of petrogenetically different granulites can be misleading. Quite apart from this, the paper contains several geological and geochronological innacuracies. Only a few major criticisms can be mentioned here.

The calculation of geologically-meaningful model ages (especially for Sr) requires assumptions about the isotopic evolution of Nd and Sr in the mantle which are too simplistic to apply in a generalized manner to rock units such as granulites which may have igneous and/or sedimentary protoliths of mixed age and provenance, a wide range of crustal residence ages, a complex polymetamorphic history, and highly variable Sm/Nd and Rb/Sr ratios. Careful and precise Sm-Nd, Rb-Sr, Pb/Pb isochron (and U-Pb zircon) age and initial ratio studies in individual terranes, controlled by detailed geological, petrological and structural studies, are preferable to geochronologically-dubious model ages. Although not many individual terranes have yet been studied by all available isotopic methods (particularly by Sm-Nd), the combined approach has already shown that every high-grade metamorphic terrane must be judged on its own merits. In particular, crustal residence time varies widely both within a single terrane and from one granulite terrane to another, suggesting that no generalized tectonic model, such as that proposed by Ben Othman *et al.*[1], is likely to apply to all granulite terranes.

As an example, Sm-Nd, Rb-Sr, Pb/Pb whole rock, as well as U-Pb zircon, age data on granulites from Finnish Lapland yield concordant ages at ~1,900-2,000 Myr, and show that the time interval between granulite-facies metamorphism and mantle-derived magmatism cannot be resolved[2]. (In this connection, Ben Othman *et al.*[1] refer to a single Lapland granulite whose very discordant model and geological/metamorphic ages bear no resemblence to those given in ref. 2). A similar situation holds in the early Archaean Amitsoq gneisses of West Greenland, where mantle extraction of gneiss protoliths is penecontemporaneous with amphibolite- and granulite-facies metamorphism at ~3,600 Myr, as determined by Sm-Nd, Rb-Sr, Pb/Pb and U-Pb age methods (ref. 3 and N. W. Jones, personal communication). In the Lewisian complex of north-west Scotland, granulite-facies metamorphism and concomitant depletion in incompatible elements may have postdated mantle differentiation by ~200 Myr but almost certainly as part of the same major crustal accretion-differentiation event[4]. (Ben Othman *et al.*[1] wrongly assert that the ~2,700-Myr granulite-facies metamorphism is the age of a major orogenic event associated with granitoid injection. The main period of granitoid injection in the Lewisian complex occurred ~1,000 Myr later[5].)

In many cases, granulite-facies metamorphism is superimposed on very much older igneous, sedimentary or metamorphic rocks during some major tectonic episode quite unrelated to the primary crustal accretion-differentiation event. Such situations can be resolved by detailed age and isotope studies, using the full array of available methods. Of particular interest here is the Pb/Pb whole rock method, which can date episodes of U-depletion (granulite-facies metamorphism) occurring during, or long after, primary rock formation[6,7]. Thus in northern Norway, granulite-facies metamorphism at ~1,800 Myr postdates production of juvenile mantle-derived continental crust by ~800-900 Myr (refs 8, 9). Note that several cases have been reported where the Rb-Sr whole rock system is severely disturbed by later tectonothermal events and geochemical open-system behaviour, which renders the calculation of Sr model ages in complex metamorphic terranes even more questionable. To what extent the Sm-Nd whole-rock system responds to such events is not yet well established, but much work is in progress.

The above criticisms are analogous to those levelled at an earlier paper by Allègre and Ben Othman on granitoid rocks[10-12], which employed a similarly simplistic isotopic approach to a vastly complex, variable, polygenetic family of rocks extending over most of geological history. Just as there are granites and granites, there most certainly are granulites and granulites.

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BEN OTHMAN *ET AL.* REPLY—Moorbath's first criticism involves the study on granulitic facies rocks[1]. However, we do not understand the point that he is trying to make. For example, he criticizes our conclusion on age relationships in granulite facies rocks whereas our claim is that it is impossible to derive any such relationship. He further argues that model ages cannot be used instead of direct radiometric ages. This is, of course, true and we make no mystery about that. In fact, the whole purpose of our paper was to compare the one with the other.

Moorbath's second criticism deserves more attention and raises a fundamental problem of scientific methodology. The question is whether it is more appropriate to tackle a given geochemical problem by a statistical study with many rocks of different origins first or by a series of detailed regional case studies? The answer to this has been the key to the strategy of every geochemistry research group. Moorbath's firm answer is that case studies must take precedence. Let us examine this point before stating our own arguments.

The statistical approach (meant to define the study of many samples picked at random from different regions) has had many significant successes in isotope geochemistry. For example: (1) The first study of lead isotopes in galenas by Nier[2] was performed on 12 galenas from Australia to North America. (2) The age of the Earth was first determined by Patterson[3] with four samples. (3) The first study of lead isotopes in feldspars which lead to the first model of continental growth was made by Patterson and Tatsumoto[4] on six feldspar concentrates. (4) The first study of Sr isotopic variations by Hedge and Walthall[5] was based on data from 10 samples of various origins. (5) The first study of Nd isotopic variations and the first evidence of a correlation between the Nd and Sr isotopic composition of rocks was made using 18 samples