Episodic crustal growth and mantle evolution

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Introduction

We propose a new model for global crust-mantle evolution, which connects evidence for variable rates of crustal growth, non-steady or alternating modes of mantle convection, and geochemical evidence for an 'open-system' upper mantle. During periods of penetrative two-layer convection, the upper, depleted mantle is partially replenished by exchange with the lower mantle, and the continental crust grows rapidly, probably through oceanic plateau accretion and underplating. During periods of more restricted two-layer convection the continental crust grows more slowly and only by arc accretion, while the upper mantle is progressively depleted.

Geochemical puzzles

Nearly three decades of isotope and trace element studies have demonstrated beyond reasonable doubt that the enrichment of the continental crust in incompatible trace elements is roughly balanced by a complementary depletion in the upper mantle (e.g. Hofmann, 1988). However, several apparent inconsistencies and puzzles remain which show that the continental crust could not have formed exclusively from the upper mantle: (1) The isotopic composition of lead in the depleted upper mantle (as sampled by MORB) is decoupled in some manner from both the Th/U ratio (Galer and O'Nions, 1985) and the U/Pb ratio (White, 1993). The Th/U-depletion age (as measured by the radiogenic $^{208}Pb^{*}/^{206}Pb^{*}$ ratio) of the upper mantle is much younger than the mean age of the continental crust, and $^{206}Pb/^{204}Pb$ ratios in MORB show little or no correlation with U/Pb ratios. (2) Mass balance considerations using Sr, Nd and Pb isotopes (e.g. Allègre *et al.*, 1983) show that the upper mantle is insufficient to balance the continental crust, and the same result is obtained using trace element ratios (Nb/U and Ce/Pb) that effectively discriminate between crust and residual mantle (Hofmann, 1989). (3) The amount of ^{40}Ar in the atmosphere is derived from about 50 % of the primitive mantle, not just the uppermost 30% (Allègre *et al.*, 1986/87).

Crustal growth and mantle convection

The global geochronological record shows clustering of rock ages, which appear to indicate that crustal growth rates were variable or even intermittent. This interpretation is certainly controversial, and it may be that the 'quiescent' periods merely represent missing continental material, which has been recycled back into the mantle. However, Reymer and Schubert (1984, 1986) have shown that crust formation rates during some geological periods exceeded by far the rate prevailing during Phanerozoic time, when it is only 1 km^3 per year or less. At the very least, their results show that local crust formation rates in some regions, such as the Arabian-Nubian shield or the Superior Province, have been as high as or higher than the present-day global rate of crust formation. On balance, the evidence favoring the hypothesis that crustal growth rates have varied is at least as good as evidence for the hypothesis that the rate has remained steady.

Recent simulation studies of mantle convection have indicated the likelihood of mantle flow patterns that alternate between single layer (or 'whole mantle') and two layer convection (Machetel and Weber, 1991; Tackley *et al.*, 1993). It is likely that mantle convection and crust formation are coupled in some way, so that the convective flow pattern may alternate between modes where continental crust formation rates are high and other modes where these rates are low.

Isotopic evolution of juvenile crust

Published plots of initial ε_{Nd} versus formation age crustal rocks generally show large scatter, roughly filling a triangle between the hypothetical evolution line of depleted upper mantle, estimated to be at $\varepsilon_{Nd} = 10$ at present, and the evolution of primitive mantle (or 'chondritic uniform reservoir'). If we restrict the database to major, areally extensive orogens, including the 2.7 Ga old Superior Province, the 2.1 Ga Birimian (W. Africa), the 1.8 Ga 'North Atlantic Continent', the 1.3 to 1.5 Ga Grenville Province, and the 0.6 to 0.8 Ga Arabian-Nubian Shield and apply minor filtering to eliminate regions obviously hybridized with older crust and rare, N-type MORB ophiolites, the resulting evolution becomes monotonic and essentially linear, growing from $\varepsilon_{Nd} = 2$, 2.7 Ga ago, to $\varepsilon_{Nd} = 6$ today, essentially the composition of PREMA (Wörner *et al.* 1985), which is neither like depleted upper mantle ($\varepsilon_{Nd} = 10$) nor primitive ($\varepsilon_{Nd} = 0$) .

Stein and Hofmann (1992) have suggested that plume heads, at least by the time they are sampled by basaltic volcanism, may be comparatively homogenized and also have the isotopic composition of PREMA. New data have confirmed this for the Ontong Java Plateau, which shows a surprisingly small range of $\varepsilon_{Nd} = 5$ to 6 (Mahoney *et al.*, 1993). A widely accepted interpretation of its origin is that it represents the head of a very large plume derived from the base of the mantle (Richards *et al.*, 1989; Griffiths and Campbell, 1990). We suggest that the PREMA composition may represent a (possibly biased) vertical average of the mantle column traversed by major plumes rising from the core-mantle boundary.

The model

The mantle normally convects in a two-layer mode exchanging little material between upper and lower layers. Periodically, the two layers do exchange material, probably by the ascent of major plumes and the descent of subducted lithosphere. Accretion of plume head-generated oceanic plateaus (with PREMA-type isotopic composition) cause rapid growth of juvenile continental crust (Ben-Avraham *et al.*, 1981; Reymer and Schubert, 1984), and the depleted upper mantle is partly replenished in incompatible trace elements by input from the lower mantle. During the normal, two-layer convective mode, plate tectonics operates in a 'conventional' manner with the Wilson cycle of opening and closing of oceans, continental drift and collisions. Continental crust formation rates are low, and the upper mantle is progressively depleted in highly incompatible elements. The sink for these elements is partially the continental crust but also the oceanic crust, which is subducted and partly stored at the base of the upper mantle. A Wilsonian period of 500 Ma suffices to process and differentiate nearly all of the upper mantle through generation and subduction of oceanic lithosphere. Consequently, the chemical composition of the more depleted portion, which currently generates the so-called N-type (= 'normal') MORB, is biased in favor of the basalt-depleted mantle residue. Small plumes and diapirs originating from the base of the upper mantle generate most oceanic island and seamount basalts. Large plumes originating from the lower mantle are comparatively rare.

Mass balance considerations

If the PREMA value of $\varepsilon_{Nd} = 6$ represents an unbiased vertical average of mantle material entrained in major plume heads, the mass balance with the continental crust and the mantle will probably require an additional significant reservoir for Nd. This might exist in enriched parts of the subcontinental lithosphere and in the boundary layers of the upper and lower mantle. Alternatively, the entrainment and mixing process might bias the final composition of the plume head toward high values of ε_{Nd} predominating in the upper mantle. These aspects will need further exploration.

References

Allègre, C.J., Hart, S.R. and Minster, J.-F. (1983) *Earth Planet. Sci. Lett.*, **66**, 191–213.

Allègre, C.J., Staudacher, T. and Sarda, P. (1986/87) *Earth Planet. Sci. Lett.*, **81**, 127–50.

Ben-Avraham, Z., Nur, A., Jones, D. and Cox, A. (1981) *Science*, **213**, 47–54.

Galer, S.J.G. and O'Nions, R.K. (1985) *Nature*, **316**, 778–82.

Griffiths, R.W. and Campbell, I.H. (1990) *Earth Planet. Sci. Lett.*, **99**, 66–78.

Hofmann, A.W. (1988) *Earth Planet. Sci.*, **90**, 297–314.

Hofmann, A.W. (1989) *Phil. Trans. R. Soc. Lond.* A, **328**, 425–39.

Machetel, P. and Weber, P. (1991) *Nature*, **350**, 55–7.

Mahoney, J.J., Storey, M., Duncan, R.A., Spencer, K.J. and Pringle, M. (1993) *Amer. Geophys. Union. Geophysical Monogr.*, **77**, 233–61.

Reymer, A. and Schubert, G. (1984) *Tectonics*, **3**, 63–77.

Reymer, A. and Schubert, G. (1986) *Geology*, **14**, 299–302.

Richards, M.A., Duncan, R.A. and Courtillot, V. (1989) *Science*, **246**, 103–7.

Stein, M. and Hofmann, A.W. (1992) *Earth Planet. Sci. Lett.*, **114**, 193–209.

Tackley, P.J., Stevenson, D.J., Glatzmaier, G.A. and Schubert, G. (1993) *Nature*, **361**, 699-704.

White, W.M. (1993) *Earth Planet. Sci. Lett.*, **115**, 211-226.