ISOTOPIC GEOCHEMISTRY OF THE CONTINENTAL CRUST II

ISOTOPIC COMPOSITION OF THE LOWER CRUST

Like the mantle, the lower continental crust is not generally available for sampling. While much can be learned about the lower crust through remote geophysical means (seismic waves, gravity, heat flow, etc.), defining its composition and history depends on being able to obtain samples of it. As with the mantle, three kinds of samples are available: terrains or massifs that have been tectonicly emplaced in the upper crust, xenoliths in igneous rocks, and magmas produced by partial melting of the lower crust. All these kinds of samples have been used and each has advantages and dissadvantages similar to mantle samples. We will concentrate here on xenoliths and terrains.

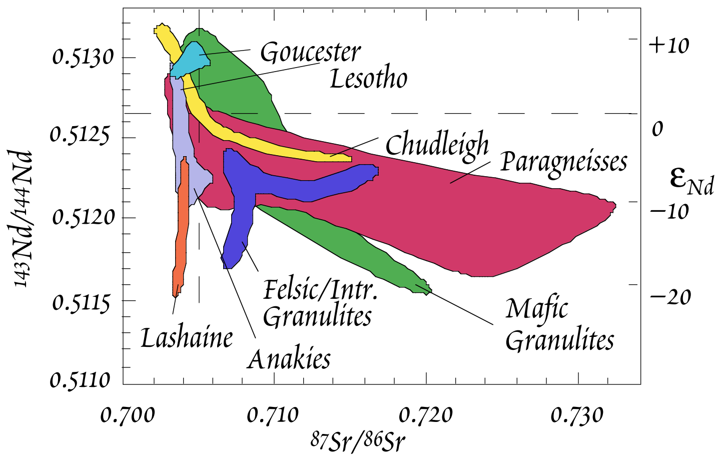

Figure 21.1. Sr and Nd isotopic composition of granulite† and xenoliths in volcanic rocks. Chudleigh, Gloucester, and Anakies are in Australia, Lashaine in is Tanzania, and Lesotho is in south Africa. From Rudnick (1992).

Figure 21.1 summarizes Sr and Nd isotopic compositions of lower crustal xenoliths. The results of initial Sr and Nd isotopic studies of the lower crust indicated it had similar ε_{Nd} to the upper crust, but low $^{87}Sr/^{86}Sr$. It is clear from Figure 21.1 that while this may be partly true, the lower crust is quite heterogeneous in its isotopic composition and is not easily characterized by a single isotopic composition. Some lower crustal xenoliths have very radiogenic Sr.

The Pb isotopic composition of the lower crust is a particularly important question because of the mass balance problem we discussed in the previous lectures. The upper crust, the upper mantle, and mantle plumes all have Pb isotopic compositions lying to the right of the Geochron. Mass balance requires a significant reservoir of unradiogenic Pb, i.e., Pb that plots to the left of the geochron somewhere in the Earth. Some early studies of granulite terrains, such as the Scourian in Scotland, suggested the lower crust might be characterized by unradiogenic Pb. Furthermore, the lower crust is known to have a low heat production, implying low concentrations of U and Th.

Rudnick and Goldstein (1990) found that while most Archean lower crustal terrains did indeed have very unradiogenic Pb, post-Archean ones did not. This is summarized in Figure 21.2. Furthermore, many lower crustal xenoliths also do not have unradiogenic Pb (Figure 21.3). Rudnick and Goldstein concluded that unradiogenic Pb can only develop in regions that have remained stable for long time periods, i.e., only in cratons. In areas where orogenies have occurred subsequent to crust formation, the Pb isotopic composition of the lower crust is rejuvenated trough mixing with radiogenic Pb from upper crust and mantle-derived magmas.

† granulite is a high-grade, largely anhydrous, metamorphic rock. It most commonly contains plagioclase and pyroxene as essential minerals, and may sometimes contain garnet. A paragneiss is a rock derived from a sedimentary precursor.

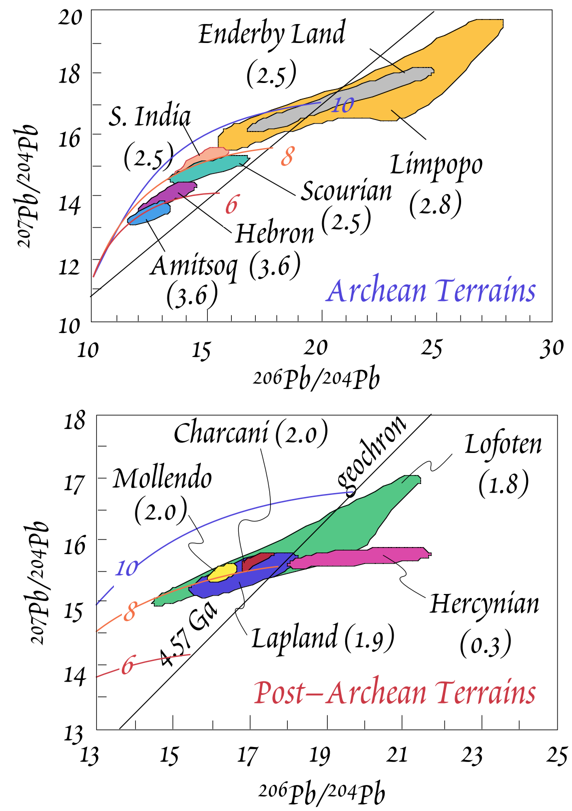

Figure 21.2. Pb isotope ratios in Archean and post-Archean granulite (i.e., lower crustal) terrains. the 4.57 Ga geochron and single stage growth curves for μ = 6, μ = 8, and μ = 10 are also shown. While Archean terrains appear to be characterized by unradiogenic Pb, this is less true of post-Archean terrains. After Rudnick and Goldstein (1990).

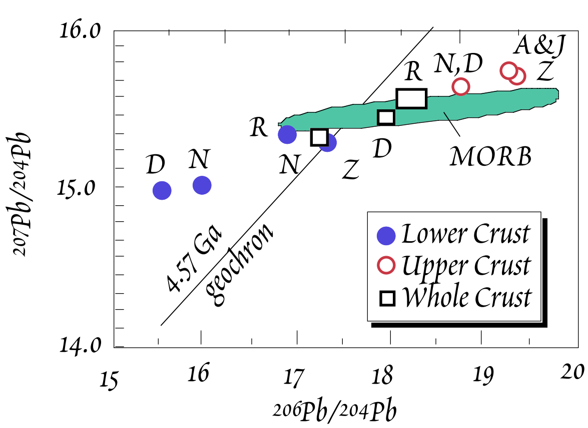

Figure 21.4. Estimates of the Pb isotopic composition of the crust: N: Newsom et al. (1986), D: Davies (1984), Z: Zartman and Doe (1981), R: Rudnick and Goldstein (1990).

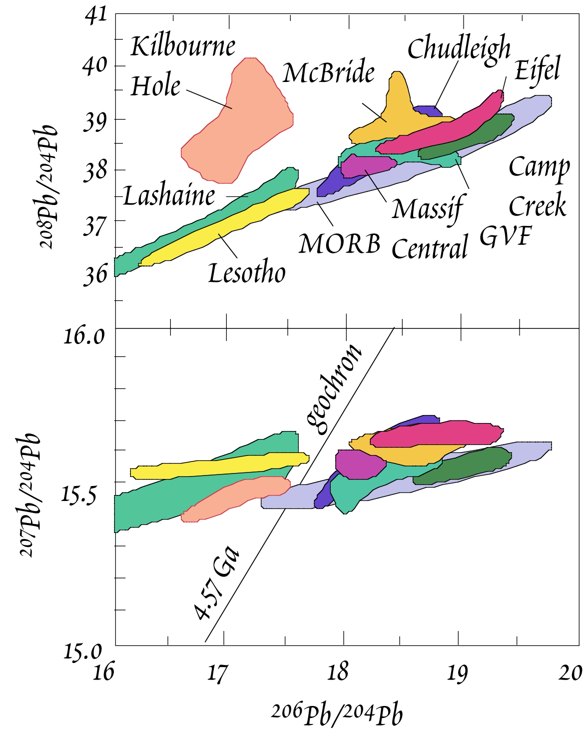

Figure 21.3. Pb isotope ratios in lower crustal xenoliths. Eifel is in Germany; GVF (Geronimo Volcanic Field), Kilbourne Hole and Camp Creek in the southwest US, McBride in Australia; and the Massif Central, in France. From Rudnick and Goldstein (1990).

Rudnick and Goldstein (1990) attempted to estimated the average Pb isotopic composition of the lower crust based on this orogenic age—Pb isotopic composition relationship. Their estimate is compared with other estimates for the Pb isotopic composition of the upper and lower crust in Figure 23.4. Rudnick and Goldstein concluded that while the Pb of the lower crust does lie to the left of the geochron, it is not sufficiently unradiogenic to balance the unradiogenic Pb of the upper crust and upper mantle. Thus the mystery of the unradiogenic Pb reservoir in the Earth remains.

Other Approaches to Crustal Composition and Evolution

As we have seen, samples of particulate material in rivers can be used to obtain estimates of upper crustal composition. However, because the Sm/Nd ratio changes little during production of sediment, these sediment samples also contain infromation on the age of the rocks they are derived from through Nd model ages (or crustal residence time). Sm/Nd and $^{143}Nd/^{144}Nd$ ratios in major rivers draining about 25% of the exposed continental crust (excluding Antarctica and Australia) as well as samples of loess and aeolian dusts were analyzed by Goldstein and O'Nions (a different Steve Goldstein than the Steve Goldstein of the Goldstein and Jacobsen papers) are shown in Figure 21.5. The Nd isotope ratios are fairly homogeneous. Sm/Nd ratios are quite uniform, illustrating a point which was already well known, namely that rare earth patterns of continental crustal material show relatively little variation. A further illustration of this point is shown in Figure 21.6. Virtually all crustal rocks have $^{147}Sm/^{144}Nd$ ratios at the extreme end of the range observed in mantle-derived rocks, and the range of $^{147}Sm/^{144}Nd$ ratios in crustal material is small compared to the range observed in mantle-derived rocks. Figure 21.6 suggests there is a major fractionation of the Sm/Nd when crust is formed from the mantle, but thereafter processes within the crust tend to have only second order effects on the Sm/Nd ratio. This is the main reason why crustal residence time calculated from $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ is such a robust parameter.

By studying sediments of various ages, we should be able to draw some inferences about the rates of continental growth. Goldstein and O'Nions (1984) found that the mean crustal residence time (τ_{DM} calculated from $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$) of the river particulates they studied was 1.7 Ga, which they interpreted as the mean age of the crust being eroded. However, they estimated the mean crustal residence time of the entire sedimentary mass to be about 1.9 Ga. Figure 21.7 compares the stratigraphic age* of sediments with their crustal residence ages. Note that in general we expect the crustal residence age will be somewhat older than the stratigraphic age. Only when a rock is eroded into the sedimentary mass immediately after its derivation from the mantle will its

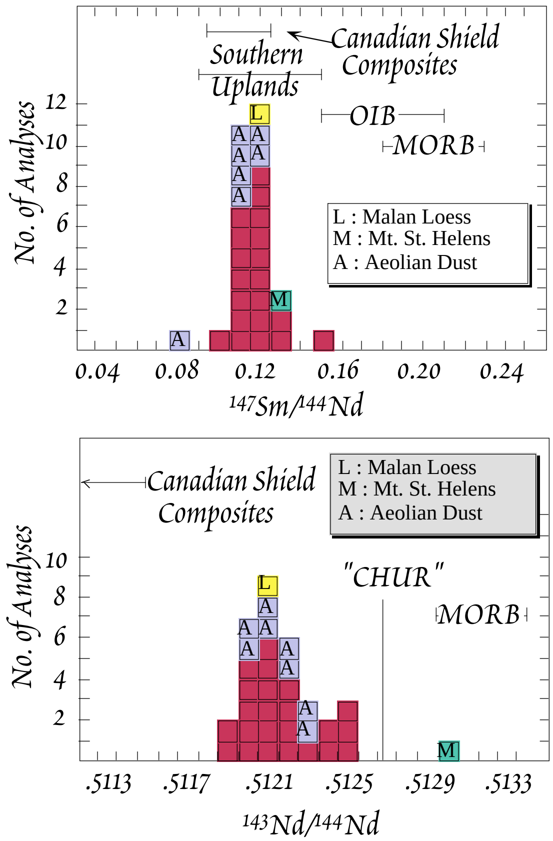

Figure 21.5 $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios in major rivers, aeolian dusts, and loess (from Goldstein and O'Nions, 1984).

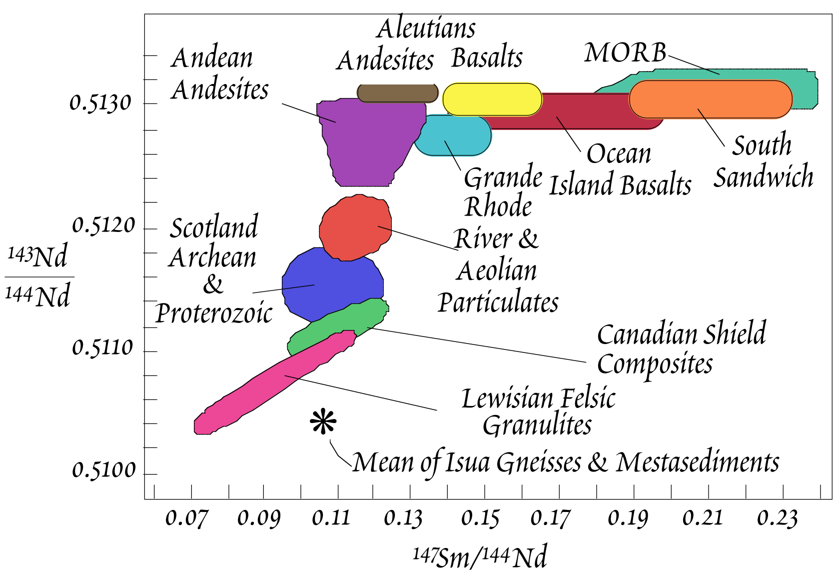

Figure 21.6. $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ in various crustal and mantle-derived rocks (from Goldstein and O'Nions, 1984).

* The stratigraphic age is the age of deposition of the sediment determined by conventional geochronological or geological means.

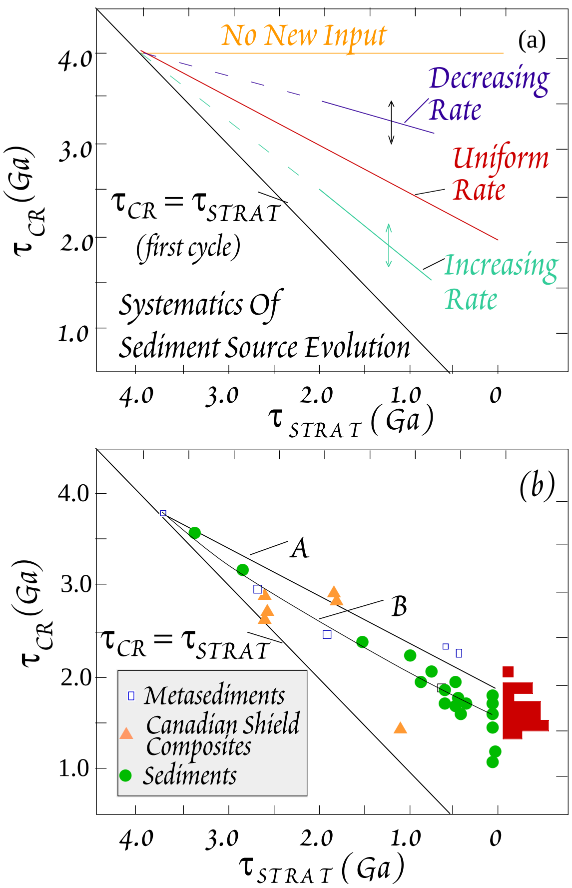

Figure 21.7. Relationship between stratigraphic age of sediments and the crustal residence age of material in sediments. See text for discussion (from Goldstein and O'Nions, 1984).

stratigraphic (τ_{ST}) and crustal residence age (τ_{CR}) be equal.

The top diagram illustrates the relationships between τ_{ST} and τ_{CR} that we would expect to see for various crustal growth scenarios, assuming there is a relationship between the amount of new material added to the continents and the amount of new material added to the sedimentary mass. If the continents had been created 4.0 Ga ago and if there had been no new additions to continental crust since that time, then the crustal residence time of all sediments should be 4.0 Ga regardless of stratigraphic age, which is illustrated by the line labelled 'No New Input'. If, on the other hand, the rate of continent growth through time has been uniform since 4.0 Ga, then τ_{ST} and τ_{CR} of the sedimentary mass should lie along a line with slope of 1/2, which is the line labelled 'Uniform Rate'. The reason for this is as follows. If the sedimentary mass at any given time samples the crust in a representative fashion, then τ_{CR} of the sedimentary mass at the time of its deposition (at τ_{ST}) should be $(4.0\text{-}\tau_{ST})/2^{\dagger}$, i.e., the mean time between the start of crustal growth (which we arbitrarily assume to be 4.0 Ga) and τ_{ST}. A scenario where the rate of crustal growth decreases with time is essentially intermediate between the one-time crust creation at 4.0 and the uniform growth rate case. Therefore, we would expect the decreasing rate scenario to follow a trend intermediate between these two, for example, the line labelled 'Decreasing Rate'. On the other hand, if the rate has increased with time, the τ_{CR} of the sedimentary mass would be younger than in the case of uniform growth rate, but still must be older than τ_{ST}, so this scenario should follow a path between the uniform growth rate case and the line $\tau_{ST} = \tau_{CR}$, for example, the line labelled 'Increasing Rate'.

Line A in Figure 21.7b is the uniform growth rate line with a slope of 1/2. Thus the data seem to be compatible with a uniform rate of growth of the continental crust. However, the situation is complicated by various forms of recycling, including sediment-to-sediment and sediment-to-crystalline rock, and crust-to-mantle. Goldstein and O'Nions noted sedimentary mass is cannibalistic: sediments are eroded and redeposited. In general, the sedimentary mass follows an exponential decay function with

† One way to rationalized this equation is to think of newly deposited sediment at τ_{ST} as a 50-50 mixture of material derived from the mantle at 4.0 Ga and τ_{ST}. The equation for the T_{CR} of this mixture would be:

$$\tau_{CR} = \frac{4.0 + \tau_{ST}}{2}\ .$$

At time of deposition, its crustal residence age would have been: $\tau_{CR} = \dfrac{4.0 + \tau_{ST}}{2} - \tau_{ST} = \dfrac{4.0 - \tau_{ST}}{2}\ .$

You could satisfy yourself that a mixture of material having τ_{CR} of all ages between 4.0 Ga and τ_{ST} would have the same τ_{CR} as given by this equation.

a half-mass age of about 500 Ma. This means, for example, that half the sedimentary mass was deposited within the last 500 Ma, the other half of the sedimentary mass has a depositional age of over 500 Ma. Only 25% of sediments would have a depositional ('stratigraphic') age older than 1000 Ma, and only 12.5% would have a stratigraphic age older than 1500 Ma, etc. Line B represents the evolution of the source of sediments for the conditions that the half-mass stratigraphic age is always 500 Ma and this age distribution is the result of erosion and re-deposition of old sediments. The line curves upward because in younger sediments consist partly of redeposited older sediments. In this process, τ_{ST} of this cannibalized sediment changes, but τ_{CR} does not. Goldstein and O'Nions noted their data could also be compatible with models, such as that of Armstrong, which have a near constancy of continental mass since the Archean if there was a fast but constantly decreasing rate of continent-to-mantle recycling.

We should emphasize that the τ_{CR} of sediments is likely to be younger than the mean age of the crust. This is so because sediments preferentially sample material from topographically high areas and topographically high areas tend to be younger than older areas of the crust (e.g. the shields or cratons) because young areas tend to be still relatively hot and therefore high (due to thermal expansion of the lithosphere).

References and Suggestions for Further Reading

Davies, G. F., Geophysical and isotopic constraints on mantle convection: An interim synthesis., *J. Geophys. Res., 89*, 6017-6040, 1984.

Goldstein, S. L., R. K. O,Nions, and P. J. Hamilton, A Sm-Nd study of atmospheric dusts and particulates from major river systems, *Earth. Planet. Sci. Lett.*, 70, 221-236, 1986.

Newsom, H. E., W. M. White, K. P. Jochum, and A. W. Hofmann, Siderophile and chalcophile element abundances in oceanic basalts, Pb isotope evolution and growth of the Earth's core., *Earth Planet. Sci. Lett., 80*, 299-313, 1986.

Rudnick, R. L., and S. L. Goldstein, The Pb isotopic compositions of lower crustal xenoliths and the evolution of lower crustal Pb, *Earth Planet. Sci. Lett., 98*, 192-207, 1990.

Rudnick, R. L., Xenoliths — samples of the lower crust, in *Continental Lower Crust*, vol. edited by D. M. Fountain, R. Arculus, and R. W. Kay, 269-316 pp., Elsevier, Amsterdam, 1992.

Zartman, R. E., and B. R. Doe, Plumbotectonics: The Model, *Tectonophysics, 75*, 135-162, 1981.