

## ISOTOPIC GEOCHEMISTRY OF THE CONTINENTAL CRUST

Isotope systems have particular value in studies of mantle geochemistry because of the difficulty of obtaining direct, representative samples of mantle. Because isotope ratios are unchanged during the magma generation process, we can use mantle-derived magmas as samples of the isotopic composition of the mantle even though they are unrepresentative of the elemental chemistry of the mantle. The upper crust is largely accessible to direct sampling, so we are less dependent on isotopic composition in geochemical studies of the continental crust. While isotope ratios of crustal melts are sometimes used to make inferences about the composition of the lower crust, the primary value of radiogenic isotope studies of the crust is the time information they contain. Thus the question of the rate of crust evolution will be of primary interest to us in this section of the course. We will nevertheless begin by attempting to assess the average isotopic composition of the crust.

### SEDIMENTS AS SAMPLES OF THE CRUST

The Earth is a big place and obtaining a representative sample of the continental crust is therefore a big job. Just as we let nature do some of the work of sampling the mantle for us (by bringing magmas to the surface), we take advantage of nature's sampling of the crust. Weathering and erosion is constantly removing material from the continents and depositing it in the oceans as sediment. Thus to

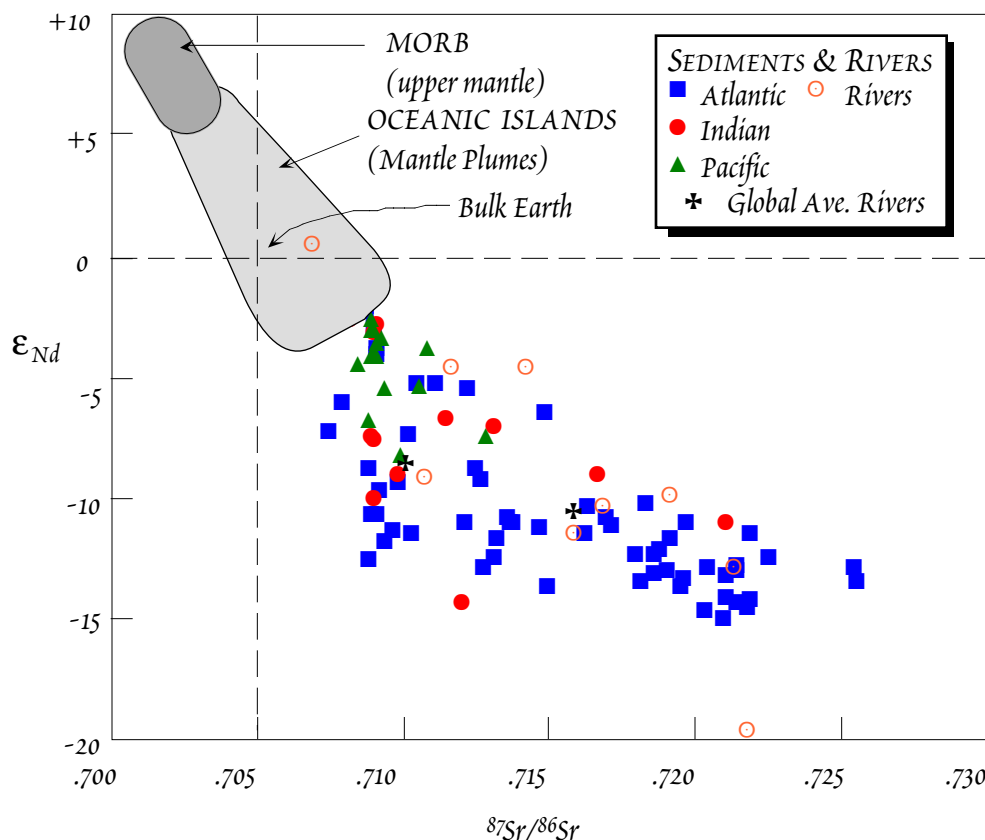


Figure 20.1 Sr and Nd isotope ratios in modern marine sediments (from Ben Othman et al., 1989). Also shown are data on the isotopic composition of suspended loads of rivers (from Goldstein and Jacobsen, 1988), and their estimated global river average of Goldstein and Jacobsen ( $^{87}\text{Sr}/^{86}\text{Sr} = 0.716$ ;  $\epsilon_{\text{Nd}} = -10.4$ ).

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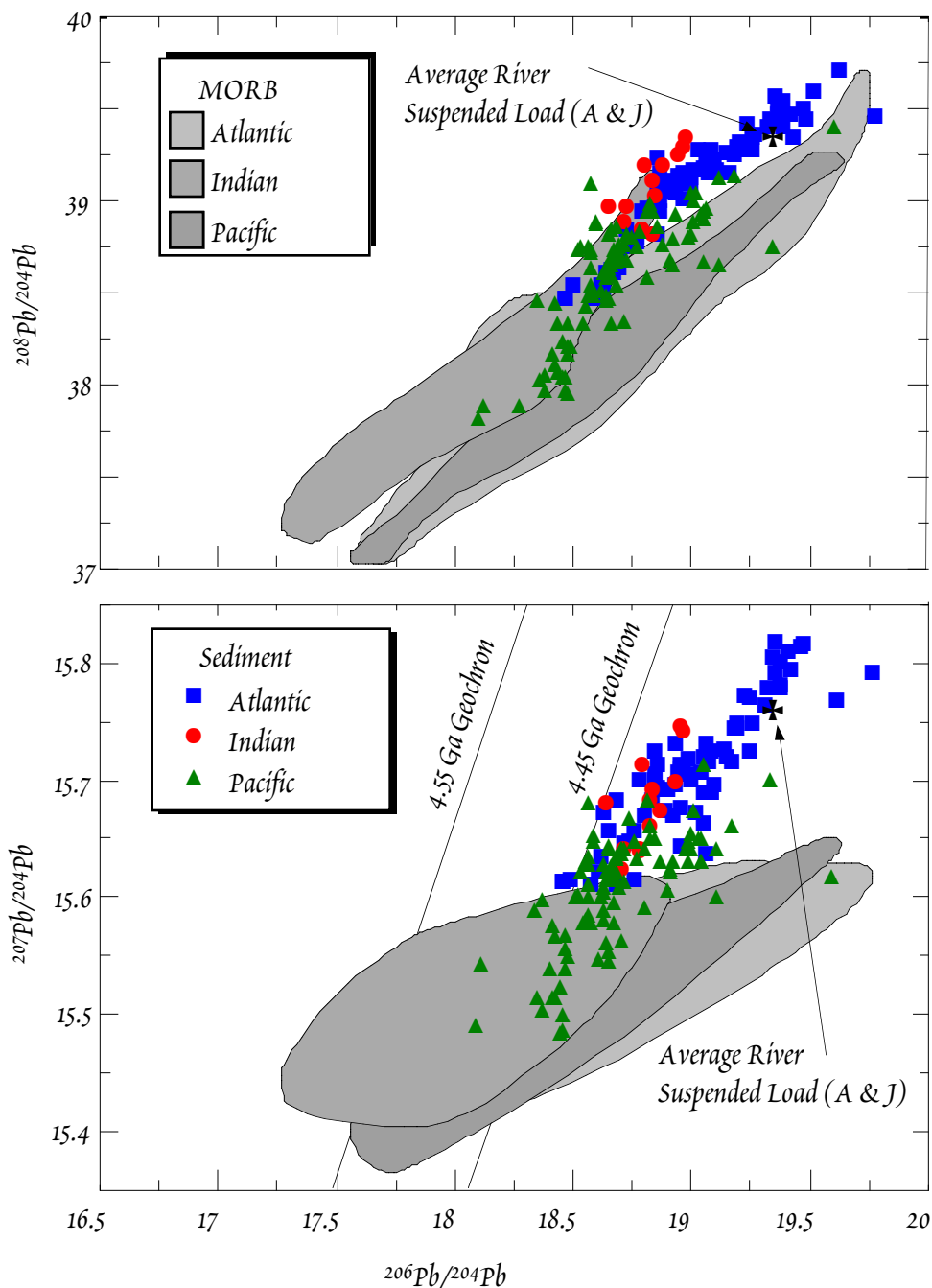


Figure 20.2. Pb isotope ratios in modern marine sediments. Asmeron and Jacobsen's (1993) estimate of the average riverine suspended load is also shown.

the isotope geochemist, sediment is a sort of premixed (homogenized) and prepowdered sample of the continental crust. Figures 20.1 and 20.2 show Sr, Nd and Pb isotopic compositions of marine sediments from the world oceans. The data provide some indication of the composition of the crust. As may be seen,  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios are much higher and  $^{143}\text{Nd}/^{144}\text{Nd}$  isotope ratios much lower than those of the mantle. This is precisely what we expect since we know that Rb and Nd are enriched in the crust relative to Sr and Sm.

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We believe that U, Th and Pb also are enriched in the crust in the order  $\text{Th} > \text{U} > \text{Pb}$ . Somewhat surprisingly, we find that  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios in the crust overlap the MORB range considerably.  $^{207}\text{Pb}/^{204}\text{Pb}$  ratios are, however, systematically higher. For a given value of  $^{206}\text{Pb}/^{204}\text{Pb}$ ,  $^{208}\text{Pb}/^{204}\text{Pb}$  ratios in the crust are also systematically higher than in MORB (which are shown in these figures primarily to represent the isotopic composition of the upper mantle), indicating a higher Th/U ratio in the crust as expected. The  $^{207}\text{Pb}/^{204}\text{Pb}$  ratio is an indicator of U/Pb ratios in the early part of earth's history: the  $^{235}\text{U}$  present in the Earth today is only about 2% of the  $^{235}\text{U}$  the Earth started out with; i.e., 98% of  $^{235}\text{U}$  has already decayed to  $^{207}\text{Pb}$ . Half of the  $^{235}\text{U}$  had already decayed by 3.8 Ga. So the high  $^{207}\text{Pb}/^{204}\text{Pb}$  of the crust relative to  $^{206}\text{Pb}/^{204}\text{Pb}$  tells us that in the early part of Earth's history, crustal rocks, or their precursors, had a higher U/Pb ratio than the mantle. The half-life of  $^{238}\text{U}$  is about the same as the age of the Earth, so  $^{206}\text{Pb}/^{204}\text{Pb}$  has grown almost linearly over Earth's history. The similarity of  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios in crust and upper mantle suggests the average U/Pb ratios of the two have been roughly similar over all of Earth's history.

The Pb data on the crust poses another problem: one of mass balance. We have previously noted that the Pb isotopic composition of the Earth as a whole must lie on the geochron, but both the crust, as sampled by sediments, and the upper mantle lie to the right of the geochron. If the Earth has not lost Pb, mass balance requires the presence of an additional reservoir lying to the left of the geochron. There are three obvious possibilities: the core, the lower mantle, or the lower crust. The core could only plot to the left of the geochron if Pb has been added to it at times substantially after the formation of the Earth. This idea was at one time fairly popular, but recent studies designed to detect depletion of the mantle in siderophile or chalcophile elements have failed to find evidence of loss of these elements from the mantle after the formation of the Earth, so the idea has largely been abandoned. The other possibilities remain. There is some evidence that this reservoir is the lower crust. We will return to the question of the isotopic composition of the lower crust in the next lecture.

It is appropriate at this point to consider just how representative the isotopic composition of marine sediments is of the continents. Sediments are only representative of those parts of the crust undergoing erosion. This excludes entirely the lower crust. So it is therefore proper to consider sediments as representative of only the upper crust. Furthermore, it is likely to be a biased sample of the upper crust. Elevated regions erode faster and therefore generate more sediment than low plains. Tectonically active areas are typically elevated relative to stable areas. By and large, new additions to crust occur exclusively in tectonically active areas. In essence, this means sediments will be biased toward younger crust, and will have lower Sr and higher Nd isotope ratios. This biased sampling is to some degree apparent when the data are considered ocean by ocean. The Pacific Ocean is surrounded by tectonically active continental margins, and as we might expect, Sr, Nd, and Pb isotope ratios are lower in Pacific sediments than in those from the Atlantic and Pacific. Finally, we need to assure ourselves that when a rock weathers and erodes, the erosion products carried to the sea have isotopic compositions of the rock as a whole. This is probably the case for Nd because it ends up primarily in the clay fraction. A larger fraction of Sr may be carried to the sea as dissolved load, but this eventually precipitates in carbonates, and is probably representative of the eroding rock. However, for the Lu-Hf system, it is possible that the Hf carried to the deep ocean is not representative of the composition of the eroding rock. This is because much of the Hf in crustal rocks is contained in zircon, which is extremely resistant to weathering. As a result, it is not readily transported great distances from its source. It will typically be retained on the continents as sandstone. That which does reach the sea will sediment out on the continental shelf. The Lu/Hf ratio of zircon is lower than that of the bulk rock, so that Hf that does reach the sea may have higher  $^{177}\text{Hf}/^{176}\text{Hf}$  ratios than the eroding rock. Similarly, while much of the  $^{204}\text{Pb}$  is probably in phases such as feldspars that break down readily to form clays, the radiogenic isotopes will, to some degree, be retained in zircon. Thus Pb isotope ratios of sediment may underestimate  $^{206}\text{Pb}/^{204}\text{Pb}$ ,  $^{207}\text{Pb}/^{204}\text{Pb}$ , and  $^{208}\text{Pb}/^{204}\text{Pb}$  (less so the latter) ratios of the eroding rock. Finally, some of the Sr and Pb in marine sediments are derived from the oceanic crust through hydrothermal activity. In summary, sediments do provide a sample of the continental crust, but it is a biased one. They can nevertheless provide useful information on the composition of the

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crust today, but, as we shall see in the next lecture, a perspective on the evolution of the crust through time.

A slightly different, but closely related way of estimating crustal composition is to measure the isotopic composition of dissolved or suspended loads in rivers. Rivers carry most of the weathering products from the continents to the oceans (other material is carried by winds and glaciers), hence this strategy is similar to that of sampling oceanic samples. By using the river samples, we avoid the problem of hydrothermal contributions to sediment. Furthermore, we can calculate weighed averaged, based either on the flux of the rivers or the area they drain, to come up with a more accurate estimate of crustal composition than using marine sediments. An attempt to measure the riverine Sr and Nd isotopic fluxes have been made by Goldstein and Jacobsen (1988), who measured isotopic compositions of *suspended load* in a subset of rivers (mainly North American) and attempted to extrapolate their results to obtain a global average (shown in Figure 20.1). They estimated the  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\epsilon_{\text{Nd}}$  of the continental crust exposed to weathering as 0.716 and -10.6 respectively. However, they had no data on a number of major rivers, notably the Brahmaputra, Ganges, and Yangtze. In a related study Goldstein and Jacobsen (1987) also attempted to estimate the global average Sr and Nd isotopic composition of the *dissolved load* of rivers and estimated these as  $^{87}\text{Sr}/^{86}\text{Sr} = 0.7101$  and  $\epsilon_{\text{Nd}} = -8.4$  respectively. Palmer and Edmond (1989) did a more thorough job of measuring the Sr isotopic compositions of the dissolved load of rivers and obtained an average  $^{87}\text{Sr}/^{86}\text{Sr}$  of 0.7119, but did not measure the Nd isotopic composition. Given the more thorough sampling done by Palmer and Edmond, their estimate is probably more accurate. Since Goldstein and Jacobsen's estimate of average and suspended loads are based on the same rivers sampled at the same locations, it possible, and perhaps likely, that their estimate of the isotopic composition of the suspended load is also low. It is nevertheless the best estimate available.

As we noted above, a small but significant fraction of the Sr in rivers is in dissolved form, whereas the amount of dissolved Nd is insignificant compared to the that in the suspended load. Goldstein and Jacobsen (1988) also calculated the bulk load (dissolved plus suspended) carried by rivers. Their estimate of the  $^{87}\text{Sr}/^{86}\text{Sr}$  of the bulk load was 0.7133. The lower  $^{87}\text{Sr}/^{86}\text{Sr}$  in the dissolved fraction reflects the influence of dissolving carbonates, which have lower  $^{87}\text{Sr}/^{86}\text{Sr}$  than silicate rocks because their Rb/Sr is low and seawater, from which they precipitate, is influenced by hydrothermal activity at mid-ocean ridges.

Asmeron and Jacobsen (1993) estimated the Pb isotopic composition of the crust by measuring Pb isotope ratios in the suspended load of sediments, and then estimating the global average from the correlation between Pb isotope ratios and  $\epsilon_{\text{Nd}}$  in suspended loads. Their estimated composition of the upper crust exposed to weathering is  $^{206}\text{Pb}/^{204}\text{Pb} = 19.32$ ,  $^{207}\text{Pb}/^{204}\text{Pb} = 15.76$ , and  $^{208}\text{Pb}/^{204}\text{Pb} = 39.33$ . This mean value is shown in Figure 20.2.

Esser and Turekian (1993) measured the Os isotopic composition of river sediments and from this estimated the average  $^{187}\text{Os}/^{186}\text{Os}$  of the continental crust exposed to weathering at 10.5 ( $\gamma_{\text{Os}} = 895$ ). Pegg et al. (1994) measured the isotopic composition of leachable Os of river sediments. The isotopic composition of the leachable fraction presumably reflects isotopic composition of dissolved Os (which is in too low a concentration to measure directly).  $^{187}\text{Os}/^{186}\text{Os}$  ranged from 10.1 to 21.5.

Using riverine suspended load eliminates the influence of hydrothermal activity on marine sediments, but the other problems with using sediments to estimate continental material remain: at best we can only estimate the composition of the crust exposed to weathering.

## EVOLUTION AND GROWTH OF THE CONTINENTAL CRUST: AN EARLY PERSPECTIVE

We now want to consider how the continental crust has evolved through time. Perhaps the first quantitative attempt to determine continental evolution rate was by Hurley and others (1962). They compiled radiometric ages (mainly Rb-Sr) of rocks in the North American continent to produce a map that looked similar to that shown in Figure 20.3. Hurley et al. recognized that age provinces in Figure 20.3 could be produced either by tectonic reworking (melting, metamorphism, etc.), of preexisting crust or by new additions to crust. They also recognized they could distinguish reworked crust from

new crust by initial Sr isotope ratios. They argued that because the crust has a higher Rb/Sr ratio than the mantle, new additions to crust should have lower initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios than material produced by reworking old crust. From consideration of both age and initial isotopic composition, they argued that the crust had grown at a more or less steady rate through geological time. Their results seemed to rule out the possibility that the crust had formed at about the same time as the Earth itself: clearly new crust is created out of the mantle.

An alternative hypothesis was formulated by Armstrong in 1968. He argued that although there had been continuing additions to continental crust through geologic time, these additions were balanced by destruction and recycling of continental crust into the mantle so that there had been no net growth of the crust since very early in Earth's history. To this day, it has not been possible to distinguish unequivocally between these alternatives. The most likely answer, however, lies somewhere between the two extremes.

In either hypothesis, new crust has been created throughout geologic time from the mantle. To a first approximation, the crust can be considered a partial melt of the mantle. In detail, there are problems with the apparent composition of the crust, though there is universal agreement the crust has been created by magmatism. We can identify a number of possible mechanisms that would result in the creation of new continental crust. Most of these mechanisms suffer from the problem that they result in a more mafic crust than that observed.

- **Accretion of oceanic crust and oceanic plateaus.** The oceanic crust is generally subducted and returned to the mantle. It might in unusual situations be thrust upon or under continental crust. Subsequent melting of the basalt could produce granite. Thick oceanic plateaus produced by mantle plumes such as Iceland would be subducted less readily than normal oceanic crust. Its isotopic composition would be less depleted.

- **Underplating.** Because of the low density of the continental crust, magmas may sometimes have difficulty rising through it and may become trapped at the crust mantle boundary. This produces new basaltic lower crust, which upon melting would produce a granitic upper crust.

- **Continental volcanism.** For example, flood basalts have occasionally been erupted in tremendous volumes. Volcanism and underplating may occur simultaneously.

- **Subduction-related volcanism.** Volcanism is usually present along active continental margins. Most of the magma is of mantle derivation. Accretion of intra-oceanic island arcs to continents is a closely related mechanism.

It is clear that at present, and almost certainly throughout the Phanerozoic, the last mechanism has produced the greatest additions to continental crust. It is tempting to assume this has been the case throughout geologic time, but this has not been demonstrated. Because subduction zones appear to play such a key role in the evolution of the crust and

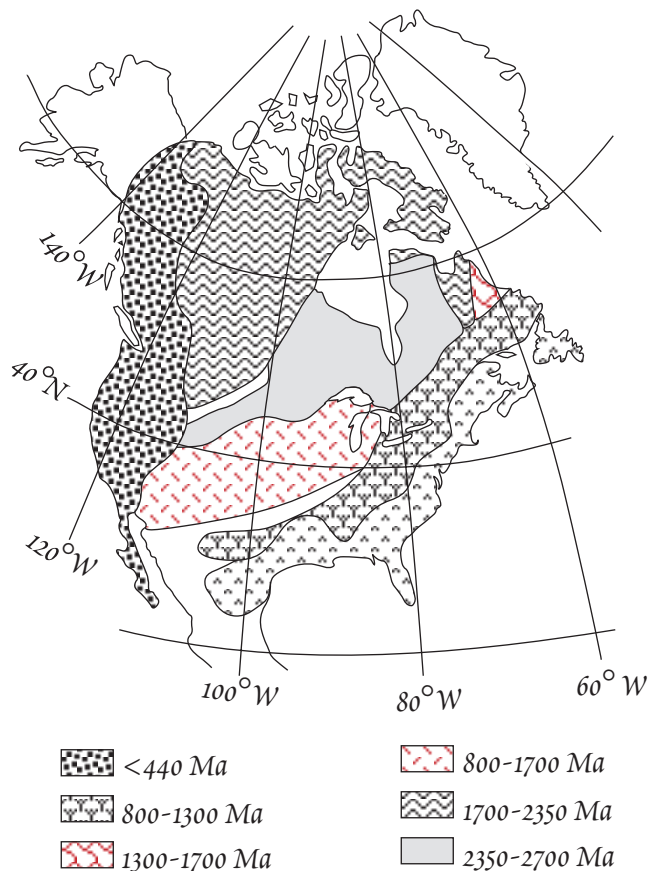


Figure 20.3. Age provinces of the North American continent (after Hurley and Rand, 1969).

mantle, we will discuss them in more detail in a subsequent lecture.

### ND ISOTOPIC STUDIES OF CRUSTAL EVOLUTION

Nd isotope systematics have provided a wonderful tool for examining the evolution of the continental crust. We have already discussed the concept of the Nd model ages, or crustal residence times. This tool will be used extensively in the subsequent discussion. We begin by examining the Western US, a region that has been studied extensively by DePaolo and coworkers.

Figure 20.4 is a map of the Western U.S. showing contours of crustal residence times ( $T_{DM}$ ). The data define 3 distinct provinces and suggest the existence of several others. There is a general similarity to Hurley's map, but the Nd work shows greater detail, and the ages are often older. Figure 20.5 shows the initial  $\epsilon_{Nd}$  values of the granites from the three number provinces plotted as a function of crystallization age. Only in province 3 do we find rocks, tholeiitic and calc-alkaline greenstones, whose crustal residence time is equal to their crystallization ages. In the other regions, the oldest rocks have initial  $\epsilon_{Nd}$  values which plot below the depleted mantle evolution curve. This suggests they contain significant amounts of pre-existing crust. We should emphasize at this point that the crustal residence time gives the average crustal residence time of Nd in the material. Thus if a continental rock formed at 1.0 Ga contained Nd derived in equal proportions from the mantle and 2.0 Ga crust, its crustal residence time would be 1.5 Ga. In each province there have been subsequent episodes of magmatism, but in those subsequent episodes there have been no new additions of crust (they plot along the same evolutionary array as the older material in the province).

All three provinces apparently formed between 1.8 and 1.65 Ga, though rocks from province 1 may be slightly older. A scenario suggested by DePaolo that is consistent with the observations is successive accretion or growth of island arcs to the preexisting Archean craton to the north. The earliest formed arcs, or at least those closest to the craton received a substantial component of older crust from the craton. This could have occurred through erosion and subduction, or, if the arc was built directly on the continent, through assimilation of crust. As new Proterozoic crust was built outward from the continent, it screened subsequent arcs from the contribution of material from the Archean crust. A similar effect has been observed in the Proterozoic provinces of Canada.

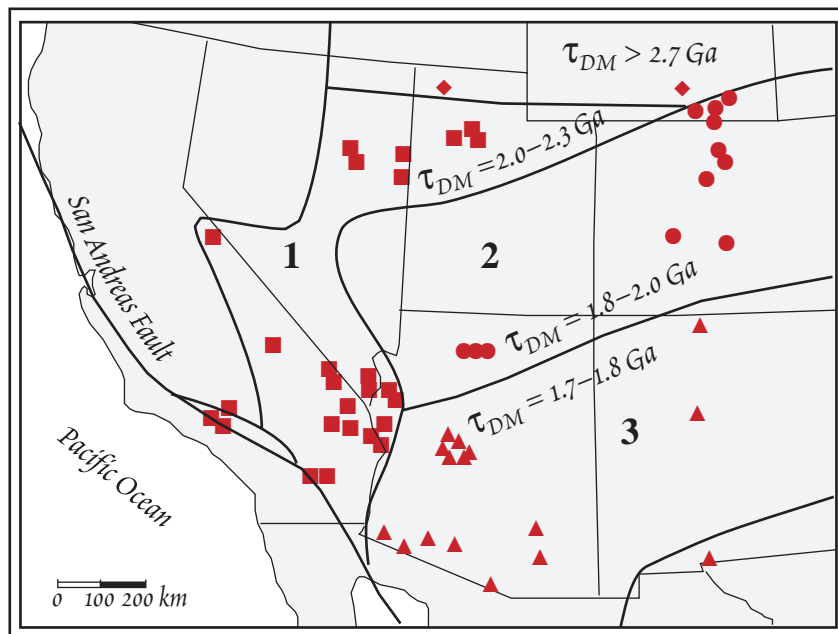


Figure 20.4. Isotopic provinces, based on crustal residence times ( $T_{DM}$ ) of the Western U.S. (Bennett and DePaolo, 1987).

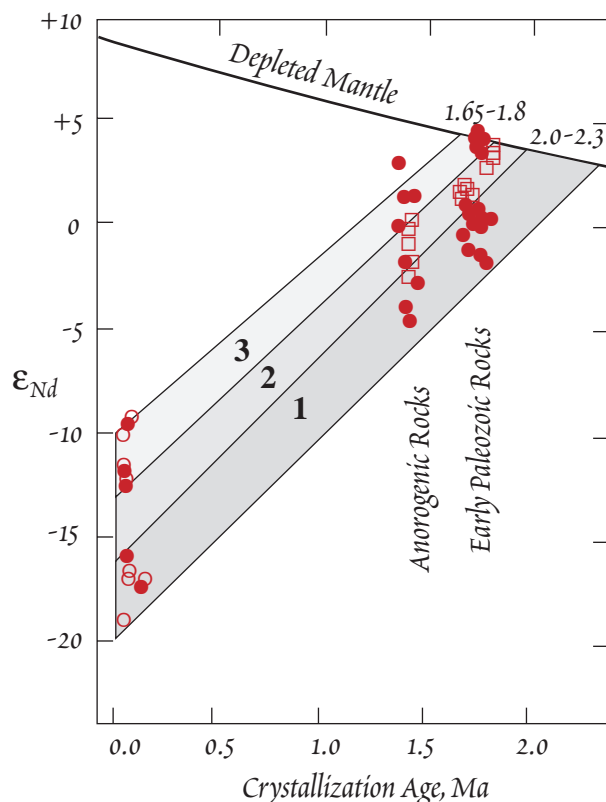


Figure 20.5.  $\epsilon_{Nd}$  (initial) as a function of crystallization age of Western U.S. Groupings 1, 2, and 3 refer to provinces shown in Figure 20.4.

### REFERENCES AND SUGGESTIONS FOR FURTHER READING

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