tinue into Archean time; and when did semistable global lithosphere develop? There are yet no clear answers possible for these and many other fundamental questions.

The broad tectonic and magmatic geometry of preserved Archean assemblages may fit a general model of moderately rumpled broad volcanic piles. Granite-and-greenstone terranes may have evolved as new mantle melts entered broad volcanic piles. Early lavas were submarine and were hydrated both during and after initial cooling. Later mafic melts rising into the thickening piles encountered voluminous hydrated rocks and hence generated progressively more evolved secondary and hybrid melts. Deformation within the belts must be due in part to diapiric rise of melts and to related gravitational spreading of magmatic piles. Major shortening obviously affected many Archean assemblages but its cause does not appear to have been in plate collisions analogous to those of Phanerozoic time. Deformation within highly mobile plates of thin lithosphere may have been important, whether bulk mantle convection or asthenospheric uncoupling was involved.

Whatever the tectonic setting of Archean magmatic complexes, they apparently record much more widespread transfer of heat to the surface by magmatism than do modern assemblages. The Archean lithosphere may have been thin and highly mobile; early in the Eon the lithosphere may have consisted primarily of the crust; subduction may not have been possible. Although I doubt that Archean tectonics and magmatism can be accounted for within a framework analogous to that of modern plate tectonics, ambiguities and problems much outnumber the certainties. Was there indeed a magma ocean early in Archean time? If so, any masses of thin lithosphere could have moved very rapidly, and gyroscopically interdependent true polar wander of the outer shell or plates and of the deep interior could have occurred (cf. Anderson, 1984). Even an asthenosphere hotter and shallower than that of subsequent time would permit freer motion of platelets, and perhaps gneiss belts and the elongations of granite-and-greenstone terranes could be explained as due to internal crumpling of hot plates. Did subduction operate in Archean time? If so, it must have differed markedly from that we know in the modern Earth. The abundance of ultramafic lavas would have made the oceanic crust relatively dense and so tended to increase its subductibility in spite of its youth and temperature (Nisbet and Fowler, 1983). Perhaps Archean oceanic crust was delaminated from subducting mantle and rumpled against or underplated beneath overriding plates. Faster plate motions, if they occurred, would require correspondingly rapid subduction of much more Archean oceanic crust per unit time than since; and the geology of the cratons requires that if this indeed took place, then much of it was in a mode of minimal deformation across the weakly coupled interface between converging plates.

Were there continents and oceans, with bimodal elevations and lithologies, in Archean time? The Venusian analogy requires none, although the low rate of heat transfer represented by Phanerozoic Venusian volcanism may invalidate analogy with Archean Earth. If the surviving exposed and subsurface Archean cratons, and the younger orogenic belts that rework Archean crust, do not represent most of the crust that formed within Archean time, what happened to the rest of it? The plate-tectonic explanation is in terms of recycling into the mantle of the crust itself and of sediments derived from it (Armstrong, 1991; Ernst, 1983), but this could have occurred after as well as during Archean time. Another possible factor is that the surviving Archean crust may selectively overrepresent the part to which water was available in sufficient quantity to produce voluminous felsic rocks, and that where such water was not available the voluminous magmatism produced thick crusts of mafic rocks which were subsequently subducted. Indeed, the volumes of continental crust and of the hydrosphere may be decreasing through time (Fyfe, 1978), rather than increasing as commonly visualized.

ORIGIN AND SIGNIFICANCE OF ND ISOTOPIC PROVINCES WITHIN THE PRECAMBRIAN CRUST OF THE CONTERMINOUS UNITED STATES

G. L. Farmer and T. T. Ball

INTRODUCTION

Since the mid-1970s Nd isotopic studies have provided important insights into the origin and evolution of Precambrian crustal terranes in the United States (DePaolo, 1988). From these studies it has been recognized that the Precambrian crust in the United States can be divided into several broad tracts, or provinces, that have distinctly different Nd isotopic characteristics. The Nd isotopic provinces generally coincide with crustal age provinces defined by U-Pb studies, but, at least within the Proterozoic crust, the data reveal that there is a greater variation in the initial Nd isotopic compositions than would be expected based solely on the range of crustal crystallization ages. A more complete understanding of the parameters controlling the Nd isotopic compositions should therefore shed light on aspects of the generation and amalgamation of the ancient crust not accessible from an assessment of the crustal ages alone. The purpose of this paper is to describe the various Nd isotopic provinces, to summarize the interpretations that have been set forth to explain their existence, and to address the implications of the Nd provinces for models of the origin and assembly of the Precambrian crust.

ND-ISOTOPE SYSTEMATICS

Systematic variations in the isotopic composition of Nd in the Earth exist because of the radioactive decay of ^{147}Sm to ^{143}Nd ($t_{1/2}$ = 106 Ga) and the chemical fractionation of Sm from Nd during planetary differentiation processes such as the generation of continental crust by partial melting of the upper mantle (DePaolo, 1988). Although Sm and Nd are both light rare earth elements (LREE), and therefore have similar geochemical characteristics (Henderson, 1984), Nd is preferentially partitioned into the melt during partial melting of the upper mantle and is correspondingly enriched in the crust formed from the melt. There is only a narrow range of $^{147}Sm/^{144}Nd$ in most terrestrial rocks (0.1 to 0.3; DePaolo, 1988), which, combined with the long half life of ^{147}Sm, has allowed only a narrow range (about 1 percent) of $^{143}Nd/^{144}Nd$ to have developed within the Earth. These small variations are typically expressed as ϵ_{Nd} values which represent deviations, in parts in 10^4, from a model chondritic uniform reservoir (CHUR) according to the following expression:

$$\epsilon_{Nd}(T) = \left[\frac{(^{143}Nd/^{144}Nd)_{rock}}{(^{143}Nd/^{144}Nd)_{CHUR}} - 1\right] \times 10^4. \qquad (1)$$

The $^{143}Nd/^{144}Nd_{CHUR}$ refers to the $^{143}Nd/^{144}Nd$ ratio in a model chondritic reservoir at time T (DePaolo, 1988). In general, ancient intermediate to felsic continental crust has negative ϵ_{Nd} values, reflecting the long-term LREE enrichment of the continents relative to the Earth as a whole. The present-day crustal ϵ_{Nd} also generally become more negative with increasing age. In contrast, much of the upper oceanic mantle tapped by ocean island basalts or by mid-ocean ridge basalts has positive ϵ_{Nd} values ranging from about 0 to +10 (DePaolo, 1988). The contrasting isotopic compositions of the oceanic mantle and ancient continental crust is generally attributed to the fact that the LREE-enriched continental crust has been extracted and progressively isolated from the upper mantle through time, although alternative models have been proposed (Hamilton, this volume, and references therein). The reservoir in the mantle complementary to the continental crust has been termed the "depleted mantle", or DM. The isotopic evolution of the DM through time (Fig. 7A) can be loosely constrained by determining the initial isotopic compositions of mafic crustal rocks of various ages (DePaolo, 1988). A commonly used expression that depicts the ϵ_{Nd} values of the depleted mantle through time is (DePaolo, 1981):

$$\epsilon_{Nd}(T) = 0.25T^2 - 3T + 8.5 \qquad (2)$$

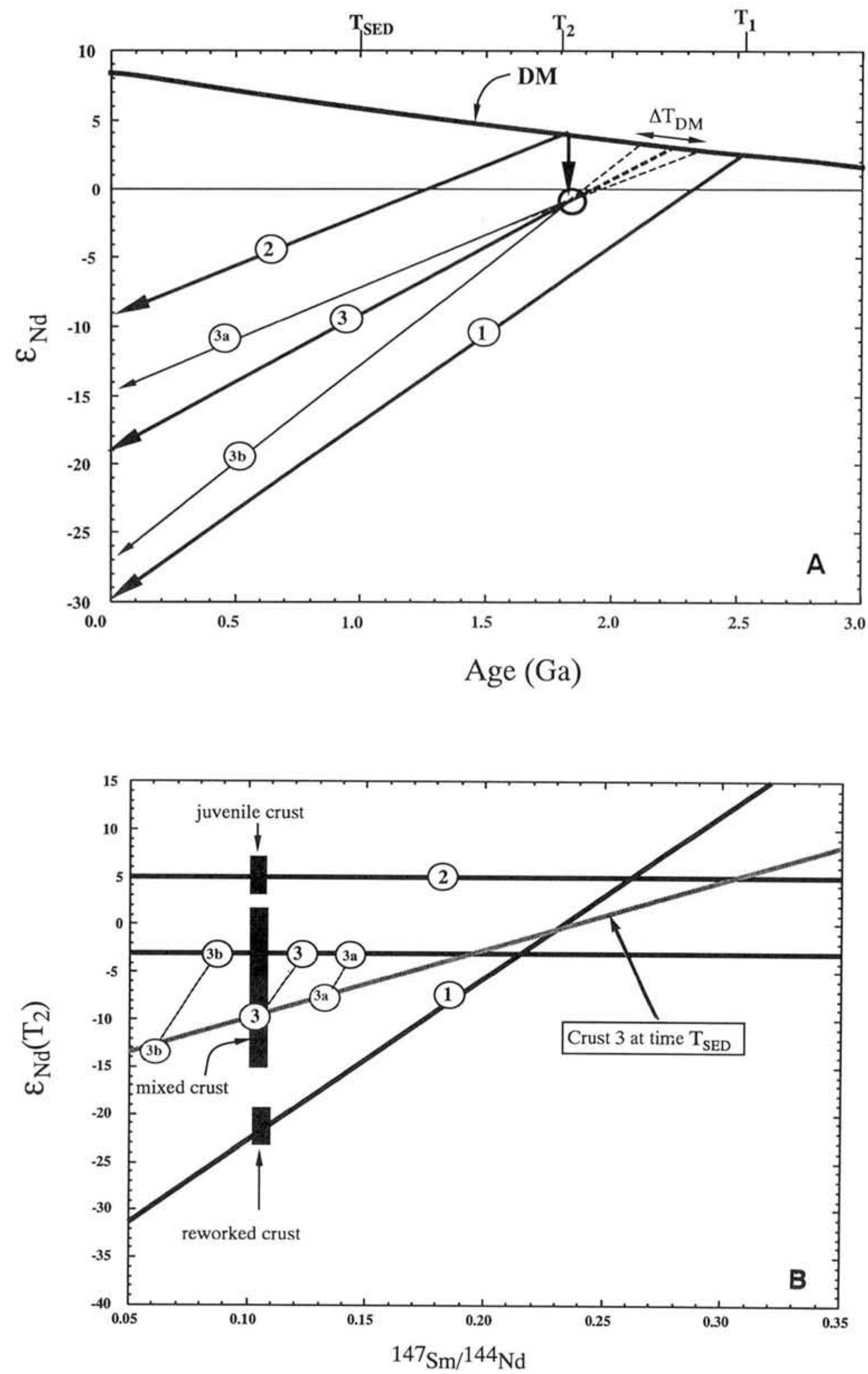
where T refers to time in Ga.

One primary goal of Nd isotopic studies of Precambrian crust has been to establish whether a crustal segment with a given crystallization age was derived directly from the upper mantle (juvenile crust), or whether that crust represents, at least in part, reworking of preexisting continental crust (recycled crust). Determining whether a given crustal segment represents juvenile or recycled crust has important implications for calculations of the rate of crustal growth and for models of the generation and subsequent modification of the continents. Nd isotopic data provide a simple method of characterizing the nature of the crust (Fig. 7A). If the Nd isotopic composition, Nd/Sm ratio, and age of an igneous rock are known, the Nd isotopic composition at the time of crystallization can be calculated. If this composition for a crustal igneous rock plots on the DM isotopic curve, then the rock is considered a segment of juvenile crust. If the crust has lower ϵ_{Nd} values than expected for the upper mantle at the time of its formation, then there may have been involvement of older (low ϵ_{Nd}) crustal material. In the latter case estimates of the isotopic compositions and Nd concentrations of potential mixing end members make it possible to calculate the proportions of each end member in a given crustal segment (DePaolo and others, 1991). In practice, calculated initial values must be critically evaluated in terms of possible postcrystallization changes in Sm/Nd. One must also consider whether the age defined by the internal isotope systematics of the rocks represents the time of their initial extraction from the upper mantle, or reworking of preexisting crust. How these issues have been dealt with in terms of the Precambrian of the United States is discussed below.

Many workers choose to assess the nature of the crust by reference to Nd model ages, rather than to initial Nd isotopic compositions. Depleted mantle model ages (T_{DM}) are most commonly used and simply represent the time when the crust and the DM had the same isotopic compositions (Fig. 7A; Arndt and Goldstein, 1987). Typically, equation 2 is used to express the isotopic compositions of the DM through time. Juvenile igneous crust, which undergoes no subsequent modification of its isotopic compositions (except by in situ decay of Sm), or in its relative abundances of Sm and Nd, has identical T_{DM} and crystallization ages. Such "single-stage" model ages for juvenile crust have been variously termed "crust formation" ages, or "mantle-separation" ages (DePaolo, 1988; DePaolo and others, 1991). In the case of recycled crust, mixtures between material derived from different crustal segments, or between mantle-derived magmas and preexisting crust, generally will produce Nd model ages intermediate between those of the mixing end members weighted by the amount of Nd derived from each reservoir (Fig. 7A).

Unfortunately, the indiscriminant use of the Nd model ages can lead to erroneous conclusions regarding the timing and nature of a given crust-forming event. For example, open-system modification of crustal Sm/Nd at the time of, or subsequent to, crust formation produces multistage model ages, which are inherently difficult to interpret in terms of the timing of crust formation (Arndt and Goldstein, 1987). It is still possible to estimate the original crustal model age, but only if the timing of any modification in the crustal Sm/Nd is known (DePaolo and others, 1991). In this chapter we minimize the use of Nd model ages and instead emphasize the application of initial Nd isotopic compositions in characterizing the Precambrian crust (Fig. 7A).

The above discussion relates mainly to igneous and metaigneous rocks. However, Nd isotopic data are also available from Precambrian siliciclastic sedimentary rocks. Siliciclastic sediments generally preserve the Sm/Nd isotopic systematics of their source regions (McCulloch and Wasserburg, 1978; Nelson and DePaolo, 1985) and so the sedimentary rocks may provide information regarding Precambrian crustal segments that are no longer preserved. However, interpretation of the Nd isotopic compositions of siliciclastic sediments, particularly the interpretation of Nd model ages, can be complicated by mixing between detritus from isotopically distinct crustal sources, or by mechanical sorting of the detritus during transport and deposition. This is



T_SED
T_2
T_1
DM
ΔT_DM
ε_Nd
Age (Ga)
1
2
3
3a
3b
A
juvenile crust
mixed crust
reworked crust
Crust 3 at time T_SED
ε_Nd(T_2)
147Sm/144Nd
B

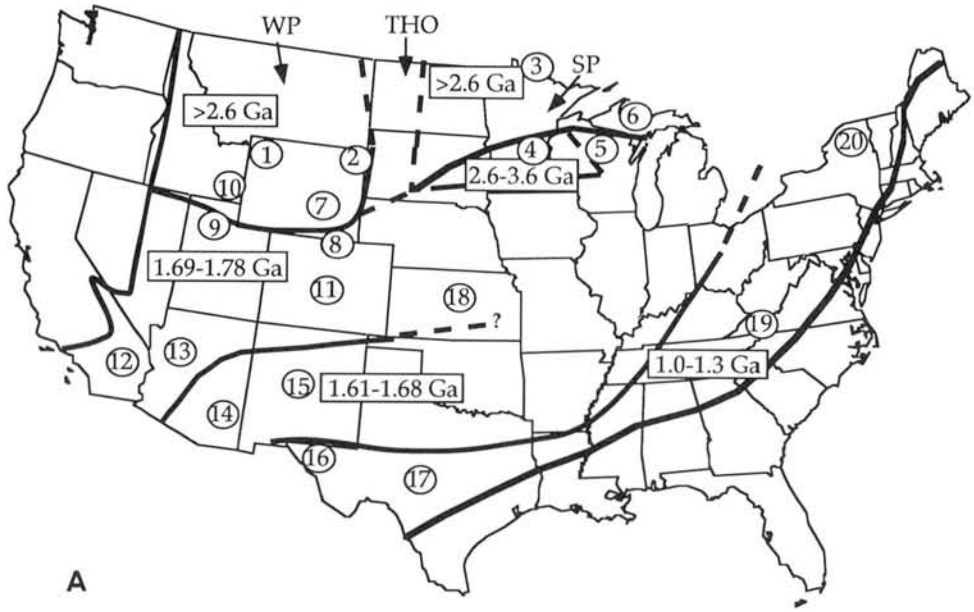
a particular problem for detritus derived from recycled crust. The problem arises from the fact that minerals comprising a given rock need not all have the Sm/Nd ratio, or the same ϵ_{Nd} value. Therefore, sorting of detrital minerals during sediment transport and deposition can produce sedimentary deposits that have Sm/Nd and Nd isotopic compositions different from the average whole rock from which the minerals were derived. Nevertheless, sediments derived from source rocks whose initial values plot on the DM curve retain the Nd model age of their source. In contrast, detrital minerals derived from recycled crust (crust 3, Fig. 7A) will not necessarily have Nd model ages equivalent to their source regions. Instead, a spread of model ages (Δ T_{DM}) can be produced for different sediments derived from the same source (dashed lines, Fig. 7A) and erroneous conclusions regarding the source of such sediments could be reached if only the model ages were considered.

Figure 7. A. Schematic diagram of Nd isotopic evolution of ancient crustal segments. DM is the depleted mantle evolution curve. Heavy lines labeled 1, 2, 3 represent the isotopic evolution of average whole-rock crustal material for three different crustal segments. The intersection between these evolution lines and the DM curve defines the model age (T_{DM}) for each segment. Crust 1 and 2 represent segments of juvenile crust derived from the depleted mantle at T_1 and T_2, respectively, and their model ages are equivalent to their crystallization age. T_{SED} corresponds to the time of siliciclastic sedimentation referred to in Figure 7B. Crust 3 represents crust formed by mixing, at T_2, of juvenile and preexisting "recycled" crustal materials and is assumed to have had a uniform Nd isotopic composition when it formed. The model age for crust 3 lies between T_1 and T_2 and does not correspond to the timing of a specific crust-forming event. Nevertheless, the Nd model ages are unique for each crustal segment and can be used to distinguish one crustal segment from another, but we prefer the use of the initial isotopic compositions of igneous rocks for this purpose (see text). An example of the application of the initial isotopic composition is as follows. If the age determined for a crustal igneous or metaigneous rock is T_2, and the initial ϵ_{Nd} value (the ϵ_{Nd} value at T_2) plots on the DM curve, then this rock can be grouped with juvenile crust 2. If the initial value plots in the vicinity of the open circle, then this may be a segment of crust 3. Even lower initial ϵ_{Nd} values would suggest that the rock represents reworking, at time T_2, of the oldest crustal segment (crust 1). A similar approach can be used for any rock, of any crystallization or metamorphic age (an age which represents the time of the last internal isotopic equilibration in the rock), as long as the range of possible isotopic compositions for mantle and crustal rocks at the time of rock formation are known and there have been no unaccounted for shifts in the rock Sm/Nd. The ΔT_{DM} refers to the range of model ages produced by sorting of clastic sediments derived from erosion of crust 3 (see text). B. Hypothetical isochron plot (ϵ_{Nd} versus $^{147}Sm/^{144}Nd$) for crustal terranes in Figure 7A at time T_2. The diagram illustrates that for crustal terranes with uniform initial isotopic compositions the range of possible Nd isotopic compositions for each terrane is restricted to an "isochron," whose position on the diagram depends on the crustal age (at the time for which the diagram is drawn) and the initial isotopic composition. Such diagrams provide a simple manner of assessing whether crustal igneous rocks represent juvenile crust, reworking of older crust, or mixtures of juvenile and preexisting crust. In the example given, a rock with an age of T_2 and a $^{147}Sm/^{144}Nd$ of about 0.10 (a typical value for felsic to intermediate composition rocks) would be considered juvenile crust if it has Nd isotopic compositions plotting on the isochron for crust 2 (a horizontal line at T_2), reworked crust if it plots on the crust 1 isochron, and a mixture of juvenile and preexisting crust if it plots between the two isochrons. Also shown is the isochron for "mixed" crust 3 at times T_2 and T_{SED}. Minerals with different Sm/Nd values in crust 3 develop different Nd isotopic compositions through time, but as long as the minerals had the same initial isotopic compositions they will remain on the crust 3 isochron. Siliciclastic sediments derived from crust 3 without fractionation of Sm from Nd, but in which some of these minerals have been removed during sediment transport or deposition, will still plot on the crust 3 isochron and so it remains possible to identify sediments derived from this crustal segment, unlike the case for the Nd model ages.

The Nd-isochron plot is an alternative method of interpreting the Nd isotopic compositions of siliciclastic sedimentary rocks that circumvents some of the problems of Nd model ages. The method provides a convenient way of comparing the isotopic compositions of sedimentary rocks and potential crustal sources, regardless of their relative ages, and so can provide an assessment of the sediment provenance. The advantages of this approach are discussed in Figure 7B. Isochron plots are used below in depicting the Nd isotopic characteristics of sedimentary rocks derived from Precambrian crust in the United States.

ND ISOTOPIC PROVINCES

The fundamental conclusion drawn from Nd-isotope studies of Precambrian crust in the United States is that it can be divided into a set of provinces with distinctly different Nd-isotope characteristics. The first-order distinction between provinces corresponds to the distinction between Archean and Proterozoic crust. Archean crust generally has single-stage Nd model ages >2.6 Ga, and the Proterozoic crust generally has ages between 1.0 and 2.4 Ga. The distributions of these provinces are shown in Figure 8. Nd crustal provinces with Archean model ages correspond to the Wyoming and Superior geologic provinces (Plate 1), both of which are dominated by plutons of Late Archean age (Fig. 8). Throughout much of the Wyoming province these plutons have lower initial ϵ_{Nd} values (0 to –3) than expected for juvenile 2.7- to 2.9-Ga crust and model ages older than crystallization ages (Leeman and others, 1985; Nelson and DePaolo, 1985; Bennett and DePaolo, 1987; Frost and Frost, 1988; Peterman and Futa, 1988; Wooden and Muller, 1988; Sims and others, 1991). In contrast, Late Archean crystalline rocks in the Superior province, from the eastern Dakotas to northern Wisconsin have initial ϵ_{Nd} values of 0 to +4 (Fig. 9) and Late Archean model ages (McCulloch and Wasserburg, 1980; Shirey and Hanson, 1984b; Nelson and DePaolo, 1985; Peterman and Futa, 1988; Barovich and others, 1989; Sims and others, 1991). The Nd isotopic compositions of Precambrian siliciclastic metasedimentary rocks deposited on and at the margins of both Archean cratons show that the sediments were largely derived from the cratons themselves (Fig. 10). Overall, the isotopic data suggest that the Superior and Wyoming provinces are not entirely equivalent. Much of the Wyoming province represents recycled Early to Middle Archean crust, while the Superior province is largely juvenile Late Archean crust (Peterman and Futa, 1988; Sims and others, 1991).



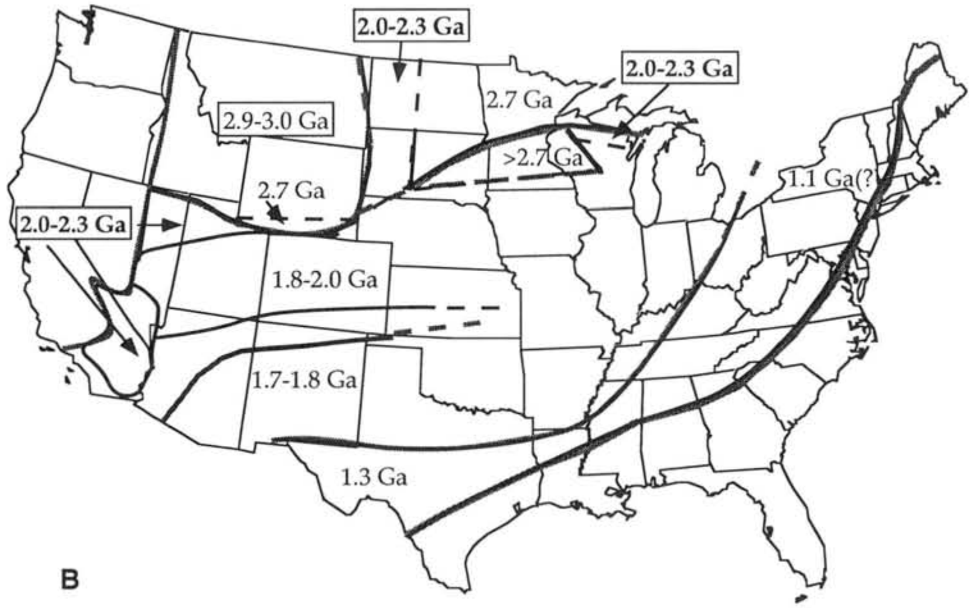


Figure 8. A. Crustal age provinces (after Bickford, 1988; Sims, 1990; Sims and others, 1991) and general locations of Nd isotopic studies of Precambrian crustal rocks (circled numbers). Boxed numbers are approximate crust crystallization ages. THO, Trans-Hudson orogen; SP, Superior province; WP, Wyoming province. Specific studies at each location are: 1, Mueller and Wooden (1988), Wooden and Mueller (1988), Meen and Eggler (1989); 2, Walker and others (1986); 3, Shirey and Hanson (1984a, b); 4, Horan and others (1987); 5, Barovich and others (1989); 6, McCulloch and Wasserburg (1980); 7, Koesterer and others (1987), Peterman and Futa (1987), Frost and Frost (1988), Peterman and Futa (1988), Geist and others (1989); 8, Ball and Farmer (1991); 9, Bryant (1988); 10, Leeman and others (1985); 11, DePaolo (1981), Nelson and DePaolo (1984); 12 to 14, Bennett and DePaolo (1987); 15, Nelson and DePaolo (1984); 16, Patchett and Ruiz (1989), Norman and others (1987); 17, Patchett and Ruiz (1989); 18, Nelson and DePaolo (1985), Van Schmus and others (1989); 19, Pettingill and others (1984); 20, Daly and McLelland (1991). B. Crustal model age provinces (bold lines) versus crystallization age provinces (faded lines). Ages are from references listed in Figure 8A. Ages shown are depleted mantle Nd model ages (T_{DM}). Provinces 1 to 3 defined for Proterozoic crust in the western United States by Bennett and DePaolo (1987). Segments of province 1 crust (T_{DM} = 2.0 to 2.3 Ga) are likely to represent Proterozoic crust with intermixed Archean crust.

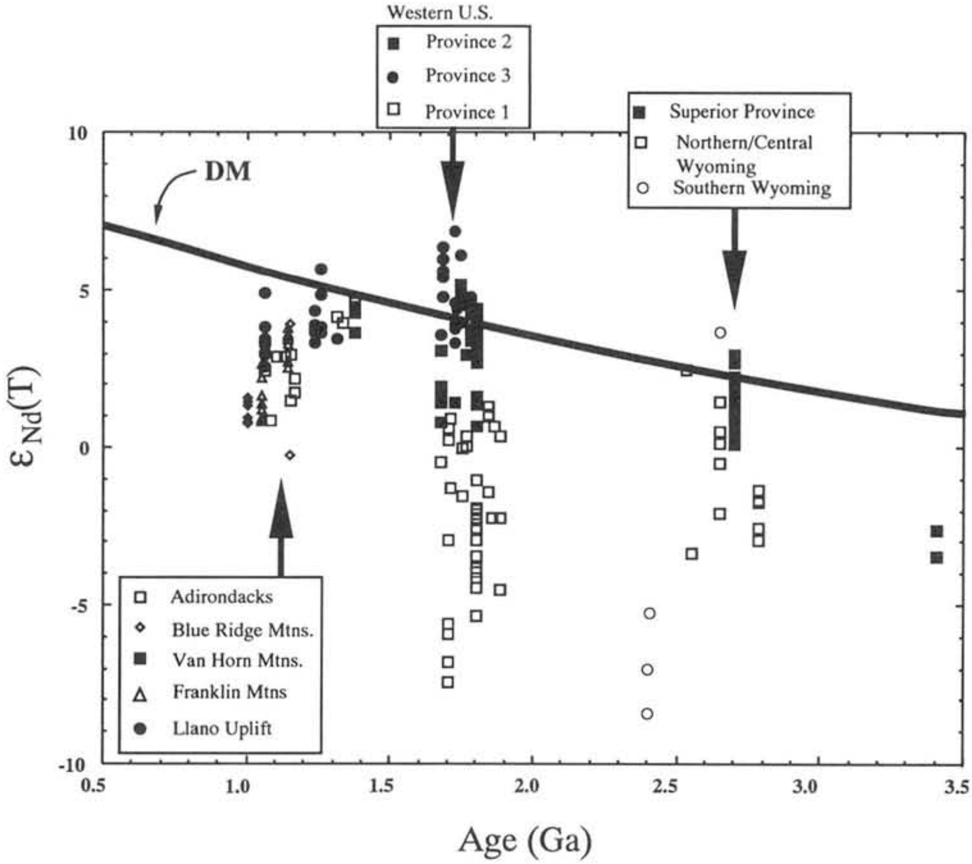


Figure 9. Initial ϵ_{Nd} versus age (Ga) for crystalline crustal rocks in the conterminous United States. Data from references given in Figure 8A.

There is also significant variation in the crustal model ages of Early Proterozoic crust in the western United States, despite the narrow range of measured crystallization ages (see references in Bennett and DePaolo, 1987). Bennett and DePaolo (1987) have divided the Early Proterozoic crust in the western United States into three provinces on the basis of their single-stage Nd model ages.

Nd province 1 is characterized by model ages of 2.0 to 2.3 Ga and initial ϵ_{Nd} near 0. Proterozoic crust of this type occurs in the Penokean orogen (Nelson and DePaolo, 1985; Barovich and others, 1989), the Trans-Hudson orogen (Walker and others, 1986; Peterman and Futa, 1987), and the Mojave Province (Anderson and others, Chapter 4, this volume). On the basis of initial isotopic compositions of crustally derived Late Cretaceous and Early Tertiary peraluminous granites, Farmer and DePaolo (1983) inferred that similar crust underlies Late Proterozoic and Paleozoic miogeoclinal sedimentary rocks in the northeastern Great Basin (Fig. 8B). Recent studies clearly indicate that the northern margin of province 1 crust in the northeastern Great Basin abuts Archean crust (Wright and Wooden, 1991), a conclusion consistent with the isotopic characteristics of xenoliths in Cenozoic basalts (Leeman and others, 1985). Ball and Farmer (1991) have shown that metasedimentary rocks in the Cheyenne belt in southernmost Wyoming have Nd characteristics of province 1 crust (Figs. 9 and 10).

Nd provinces 2 and 3 comprise the accretionary terranes of the Transcontinental Proterozoic provinces: they are exposed primarily in Colorado, Arizona, and New Mexico (Fig. 8B). Nd model ages decrease southward across these two provinces from ~2.0 to ~1.7 Ga and initial ϵ_{Nd} values increase from +2 to +7. The Nd model age and crystallization ages of province 3 rocks in southern Arizona are approximately coincident (Fig. 9). 1.6-Ga rhyolites and granites from the subsurface of Missouri have Nd isotopic compositions similar to the older Proterozoic crust at the time of their crystallization (Nelson and DePaolo, 1985; Bennett and DePaolo, 1987; Van Schmus and others, 1989). 1.4-Ga granitic rocks are widespread in the Transcontinental Proterozoic Provinces (Bickford and Anderson, Chapter 4, this volume), but the available data suggest that these granites were largely derived from anatexis of the preexisting Proterozoic crust (Nelson and DePaolo, 1985; Bennett and DePaolo, 1987). For clarity, the data from the 1.4-Ga rocks have been omitted from the data compilation diagrams (Figs. 9 and 10).

Nd data from Grenville (1.0 to 1.4 Ga) igneous and meta-

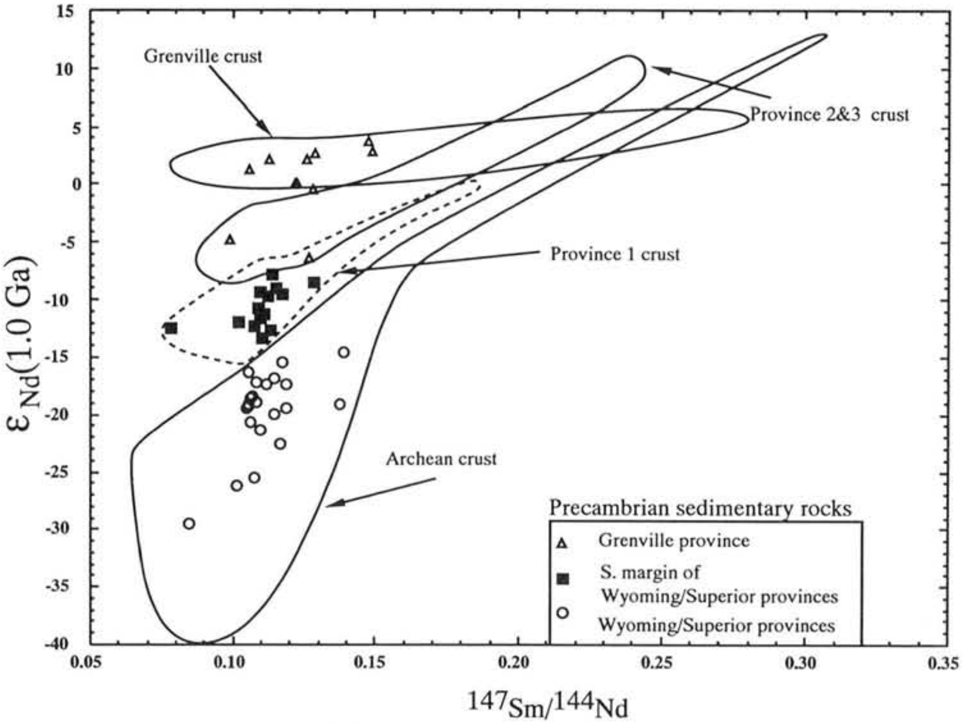


Figure 10. ϵ_{Nd} (at 1.0 Ga) versus $^{147}Sm/^{144}Nd$ for Precambrian metasedimentary rocks in conterminous United States. Outlined areas represent range of data for Precambrian crystalline rocks from various Nd isotopic provinces. Data are from references given in Figure 8A. Sedimentary rocks deposited on Grenville-age, or Archean, crust were largely derived from these crustal terranes. Some of the sedimentary rocks deposited at the margins of the Wyoming and Superior cratons have isotopic compositions intermediate between the values expected for Archean and Proterozoic crust and likely represent mixtures of material derived from both crustal types.

sedimentary rocks are available from the Franklin Mountains and Llano uplift in Texas (Norman and others, 1987; Patchett and Ruiz, 1989), the Blue Ridge Province in Virginia (Pettingill and others, 1984), and the Adirondacks uplift in New York (Daly and McLelland, 1991). The initial ϵ_{Nd} values of these rocks range from about 0 to +6 (Fig. 9).

ORIGIN AND SIGNIFICANCE OF ISOTOPIC PROVINCES

The Nd isotopic provinces outlined above for the Precambrian crystalline rocks in the United States can be divided into two groups based on their initial isotopic compositions. The first group consists of the Superior province and Nd province 3 of the Early Proterozoic provinces, both of which have positive initial ϵ_{Nd} close to expected isotopic compositions of the upper mantle at the time of their crystallization (Fig. 9). The second group includes much of the Archean Wyoming province, Nd provinces 1 and 2 of the Transcontinental Proterozoic provinces, and many Grenville rocks. Rocks from these provinces generally have initial ϵ_{Nd} values less than the DM values at the time of crystallization, although the magnitude of the displacement ranges widely both within and between terranes (Fig. 9).

The terranes in the first group probably represent juvenile crust derived from the upper mantle without incorporation of preexisting crustal material. This interpretation is consistent with the close correspondence in initial Nd isotopic compositions and isotopic compositions expected for the DM, a correspondence also manifested in the similarity between the Nd model ages and the crustal crystallization ages. Interpretation of these terranes as juvenile crustal segments does not preclude the likely possibility that the rocks now preserved are products of reworking of slightly older mafic(?) crust originally derived from the upper mantle. The isotopic data simply require that this internal differentiation have occurred in each case at or near the time of the original crust production.

The origins of the crustal segments in group 2 are more equivocal. The Nd data show that these rocks are not segments of juvenile crust and must have incorporated significantly older crustal material. Even with this constraint these crustal segments could represent either:

1. complete reworking of older crust with no new crustal additions; or

2. mixtures between juvenile, mantle-derived material and preexisting crust, with mixing occurring at or near the time defined by the crustal crystallization ages.

The first model could explain much of the isotopic variability in 1.0- to 1.1-Ga Grenville rocks. There is evidence for the involvement of ~1.3-Ga crust in these rocks, and the range of Nd isotopic compositions for the 1.0-Ga rocks is within that expected for typical crustal lithologies ~300 Ma earlier (Patchett and Ruiz, 1989; and references therein). Those 1.3-Ga rocks that have been analyzed have high initial Nd isotopic compositions and could be segments of juvenile crust produced at that time (Fig. 9).

On the other hand, the origin of the Nd province 1 rocks is more equivocal. They have been interpreted as crustal material derived directly from the upper mantle at 2.0 to 2.3 Ga, the age defined by their T_{DM} (Bowring and Podesek, 1989), despite the fact that only a few zircons have crystallization ages in that range (see summary in Bennett and DePaolo, 1987). Province 1 rocks that have been analyzed are predominantly plutonic igneous rocks with 1.7- to 1.9-Ga crystallization ages (Bennett and DePaolo, 1987). If province 1 rocks do represent material differentiated from the mantle at 2.0 to 2.3 Ga, this crust must have been so completely reworked that original ages are almost totally obscured. The uniform initial ϵ_{Nd} values in certain large tracts of province 1, such as in the Mojave province (Fig. 8A) and in the Wopmay orogen in northwestern Canada, might be consistent with such an efficient reworking process (Farmer and DePaolo, 1983; Bowring and Podesek, 1989).

However, the fact that province 1 rocks directly abut the Archean craton favors a mixing origin. Early Proterozoic terranes south of province 1 have progressively higher initial ϵ_{Nd} values with increasing distance from province 1 (Bennett and DePaolo, 1987), as if the younger terranes contained less older, low ϵ_{Nd}, material, perhaps because they were shielded from interaction with Archean crust. A progressive south to north increase in the amount of Archean crustal material the Proterozoic crust in the western United States would also be consistent with variations in crustal Pb isotopic characteristics reported by Stacey and Hedlund (1983). In the Penokean orogen, Early Proterozoic granites also have increasing initial ϵ_{Nd} with increasing distance south of the Niagara fault zone, the inferred suture between Archean basement to the north and accreted Proterozoic island arcs to the south (Barovich and others, 1989). Many workers have argued on this basis that province 1 rocks represent mixtures of 1.7- to 1.9-Ga juvenile material with preexisting Archean crust (Patchett and Arndt, 1986; Bennett and DePaolo, 1987; Condie, 1990; DePaolo and others, 1991). Similarly, Grenville rocks near the boundary with older terranes in southeastern Canada show clear evidence for the involvement of older Proterozoic and Archean crust in their generation (Dickin and McNutt, 1989; Dickin and others, 1990).

Assuming a mixed origin for at least some of the crustal segments included in group 2, then the relative proportions of juvenile and recycled crustal materials can be calculated if isotopic compositions and Nd concentrations of both end members are known or can be estimated. DePaolo and others (1991), for example, calculated that the amount of new material added to the crust in the western United States during the Early Proterozoic ranges systematically from about 70 percent by mass in province 1 to at least 90 percent in province 3.

Such calculations are independent of the mechanism of mixing, which is poorly known. Bennett and DePaolo (1987) suggested that mixing in province 1 in the western United States occurred as subduction-related magmas rose through, and interacted with, existing Archean continental crust or sedimentary detritus derived from it. Barovich and others (1989) suggested that the mixing involved in production of province 1 crust in the Penokean orogen occurred in the subduction zone itself, as Archean continental crust or sedimentary detritus was subducted and became involved in arc-related magmatism. Similarly, it has been suggested that the northern Wyoming province was a site of Late Archean subduction and that subducted Early to Middle Archean sedimentary rocks were incorporated into the Late Archean igneous rocks (Mueller and Wooden, 1988; Wooden and Mueller, 1988). In contrast, a detailed study of the Cheyenne belt in southern Wyoming (Ball and Farmer, 1991) showed that Proterozoic crustal material with province 1 isotopic characteristics is limited to paragneisses exposed within the suture zone itself. These gneisses probably represent mechanical mixtures of sedimentary detritus derived from the Archean craton to the north and detritus derived from approaching Early Proterozoic island arcs to the south. All of these mixing processes are valid and all may have been important to various degrees in producing any given segment of province 1 crust.

The distribution of province 1 crust also may have implications for tectonic models for suturing of Proterozoic crust to the Archean cratons. In the Penokean orogen, extensive sedimentary rocks occur north of the Niagara fault zone. Some of them, with T_{DM} = 2.0 to 2.4 Ga, are interpreted as foredeep sediments deposited on the southern margin of the Superior craton as Proterozoic island arcs impinged from the south (Barovich and others, 1989). On the other hand, Early Proterozoic metasedimentary rocks now exposed at the southern margin of the Wyoming craton were derived exclusively from Archean crust (Fig. 10; Ball and Farmer, 1991). Early Proterozoic granites immediately south of the suture between the Archean and Proterozoic crust in Wyoming show no evidence of interaction with Archean crust (DePaolo, 1981; Bennett and DePaolo, 1987; Ball and Farmer, 1991), unlike those in the Penokean orogen. Only the small strip of paragneiss within the suture itself has province 1 isotopic characteristics and it has been interpreted as a remnant of foredeep sedimentary rocks trapped between the Archean continental margin and overthrust Proterozoic island arcs (Ball and Farmer, 1991). More extensive foredeep deposits with province 1 isotopic compositions may have been deposited on the margin of the Wyoming craton; if so, they were largely removed by erosion during the postaccretion rebound of the continental margin (Dubendorfer and Houston, 1987). Preliminary Nd isotopic data suggest that at least some of the detritus derived from erosion of these deposits was transported to the southwest and incorporated in the Uinta Mountain Group in northern Utah (Ball and Farmer, unpublished data, 1991).

CONCLUSIONS

Regular variations in Nd isotopic compositions of the Precambrian crust in the United States are best interpreted as reflecting a combination of juvenile crustal age and proportion of older crust incorporated in a given crustal segment. A convincing case can be made that the amount of interaction of Early Proterozoic crust with Archean crust diminished with increasing distance from the older crust, presumably because the Proterozoic crust initially accreted to the margins of the Archean cratons acted as a barrier between the Archean and the subsequently Proterozoic terranes. The subsequently accreted terranes may have cannibalized Proterozoic crust, but isotopic similarity among Proterozoic terranes prevents recognition of such interaction. Only interaction between crustal terranes of substantially different ages can produce large differences in isotopic compositions of the resulting mixtures. The large deviations in the isotopic compositions of the province 1 crust from the values expected for juvenile 1.7- to 1.9-Ga crust implies that significant tracts of province 1 crust such as the Penokean orogen and Mojave province accreted directly against the Archean craton, not against earlier Proterozoic (2.0 to 2.5 Ga) terranes. The apparent absence of Proterozoic crust older than 2.0 Ga suggests that such crust did not accrete to the Archean continental nucleii present in the conterminous United States. Although continental crust may have been produced continuously on a global scale during the Precambrian (Condie, 1990), crustal growth during this interval was clearly periodic in the conterminous U.S.

DEVELOPMENT OF THE SOUTHERN REACHES OF LAURENTIA: A VIEW FROM THE CONTERMINOUS UNITED STATES

J. C. Reed, Jr.

INTRODUCTION

The area of exposure of Precambrian rocks in the conterminous United States is only a small fraction of that in the Canadian Shield, but the area underlain by Precambrian crust (Plate 1) is nearly half of the area of Precambrian crust in the continent. However, the Precambrian rocks exposed in the conterminous United States constitute a biased sample. Archean rocks, which crop out extensively in Canada, are under represented in the United States, and Early Proterozoic rocks are over represented. Outcrops of the Middle Proterozoic Grenville orogen are far more extensive in Canada than in the United States, but rocks of the coeval Midcontinent rift system are exposed chiefly in the United States. In spite of limited outcrop and under representation of some important tectonic elements, the Precambrian record in the United States affords special insights into some significant aspects of the history of the North American craton. Hoffman (1988, 1989a) has provided masterful syntheses of the assembly and Precambrian tectonic history of the entire craton. In this section, we focus on those aspects of its history that are recorded primarily in the rocks of the conterminous United States (Plate 7; Fig. 11).

In this discussion I refer to earliest Paleozoic North America as Laurentia, and include within it the Precambrian shield of Greenland and parts of northwestern Scotland that were detached from it during the Mesozoic (Goodwin, 1991). Following Hoffman (1982), I refer the aggregation of Precambrian blocks that formed the Early Proterozoic ancestor of North America as proto-Laurentia.

EARLY AND MIDDLE ARCHEAN GNEISS TERRANES

The Morton Gneiss, exposed along the Minnesota River in the Gneiss terrane of southwestern Minnesota (Bauer and Himmelberg, Chapter 2, this volume), is the oldest rock so far dated in the United States. The rock is a migmatitic gneiss consisting of a compositionally layered granodioritic to tonalitic protolith that contains lenses of amphibolite and is cut by veins and irregular masses of fine-grained biotite granite. The Morton Gneiss and similar felsic gneisses are interleaved with metagabbro, hornblende-pyroxene gneiss, and metagraywacke. The paleosome of the Morton Gneiss has an Rb-Sr age of 3.680 ± 0.070 Ga (Goldich and others, 1980) and a U-Pb zircon age of 3.580 ± 0.030 Ga by ion-microprobe methods (Williams and others, 1984), making it the oldest rock dated so far in the Superior province of the Canadian Shield. The biotite granite that forms the neosome has several phases, the oldest of which has a Rb-Sr age of 3.045 ± 0.032 Ga (Goldich and others, 1980), but no U-Pb zircon age has been reported. Isotopic data indicate that the Morton Gneiss and associated rocks were subjected to granulite-facies metamorphism twice, once at about 3.05 Ga and once at 2.6 Ga.

Rocks with ages comparable to the paleosome of the Morton Gneiss have not been identified in the Wyoming province, but U-Pb ages using ion-probe techniques (Aleinikoff and others, 1989) have shown that granulite gneiss from west-central part of the Wind River Range (Worl and Houston, Chapter 3, this volume) contain zircons with cores as old as 3.65 Ga and some possibly 3.8 Ga. Granulite-facies metamorphism and migmatitization affected the rocks at about 3.2 Ga. Ion-microprobe U-Pb dates on detrital zircon from quartzite in the Beartooth Mountains, Montana (Mueller and others, 1992), suggest a major episode of crust formation at $\sim$3.3 Ga. Groupings of ages at 3.73 and 3.96 Ga may indicate crust formation at those times. Taken together, the ion-microprobe zircon data hint that sialic crust may have been widespread in the Early Archean in the Wyoming craton or nearby.

Both the rocks of the Minnesota River valley and the older gneisses of the Wyoming province are typical of the "gray gneiss complexes" described in Archean cratons throughout the world,