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PENULTIMATE PROVENANCES OF CRUSTAL ROCKS

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Abstract

Sm-Nd and Rb-Sr isotopic data, together with plausible assumptions regarding the geochemical evolution of crustal materials have been used to ascertain the times at which new segments of continental crust were formed. It was assumed that the continental crust comes from the emplacement of magmatic rocks derived from a "uniform" reservoir in the mantle, and that the differentiation processes which produce the magmatic rocks occur with a marked chemical fractionation of the daughter and parent elements relative to the source region. The average times of formation of new crust have been obtained from a diverse range of rocks, including composites of igneous and metamorphic rocks from different structural provinces of the Canadian Shield and metamorphic and sedimentary rocks from several continents.

Analyses of composites representing the Superior and Slave Structural Provinces indicate that these Provinces were formed within the period 2.5 AE to 2.7 AE, in agreement with previous age determinations. However the time of crustal formation of the Churchill Province was also found to be 2.5 - 2.7 AE which is much greater than the K-Ar ages found in that region. It appears that the igneous activity around the period 2.5 AE to 2.7 AE is unparalleled in geologic history, and that continental growth may be governed by processes which are sharply episodic. A younger 1.0 AE age obtained for the Grenville Province indicates the addition at this time of new crust onto the pre-existing Canadian Shield.

Studies of sedimentary rocks indicate that the Sm-Nd isotopic systematics are apparently not disturbed during sedimentation or diagenesis, which has enabled the mean age of formation of their crustal sources to be

determined. In contrast, Rb-Sr studies show pronounced enrichments of Rb relative to Sr occur and yield ages which are generally more compatible with the time of sedimentation or diagenesis. The Sm-Nd provenance ages have been used to characterize and in particular cases to identify the provenance of the sediment. This has permitted the identification of the old crust which acted as the source for Archean sediments on the Yilgarn Block of Western Australia, the Swaziland System from South Africa and the Birch Creek Schist in Alaska. The mean age of large areas of the North American and Asian Continents has also been ascertained from the provenance ages of loess deposits. The approach described in this study may have general applications in large scale geologic mapping and regional studies.

Introduction

The ability to determine the time of formation of new crustal segments is of fundamental importance in attempting to understand the growth and evolution of continental crust. We consider "new crust" to be the addition to the continents of material that has not previously been present in the crust but which is newly added during periods of continental growth and has its penultimate origin from the mantle as a result of differentiation processes. However, as a consequence of multiple generations of crustal formation, metamorphism, remelting and erosion, the actual time of formation of new continental crust is not always easy to ascertain. For example, it is often difficult to establish whether younger parts of continental crust as defined by relative geologic age or by isotopic age determinations, represent the addition of new material, or are simply the product of metamorphism of older pre-existing provinces or materials. In some cases[(1)] it has been possible to use the initial $^{87}Sr/^{86}Sr$ values in rocks of well established isotopic age to identify remelted crustal rocks.

The purpose of this study is to show that by using Sm-Nd and Rb-Sr isotopic systematics, together with plausible assumptions regarding the geochemical evolution of crustal material from the mantle sources, that the times of formation of new crust can be obtained from both igneous rocks and metamorphic and sedimentary derivatives. In particular, it will be shown that by using Sm-Nd isotopic systematics, the times of formation of new crust can be obtained from a more diverse range of rocks (e.g., sedimentary and metamorphic) than has been contemplated before. This approach should permit further insight into questions relating to the episodic or uniform growth of continental crust through time. In addition, the identification of provenances of sedimentary rocks may be possible by determining the time of formation of new crust, which acted as sources for the sediments.

The general approach which we have used is to assume that the dominant contribution to the continental crust comes from the emplacement of magmatic rocks derived from a "uniform" mantle reservoir, and that the differentiation processes which produce the magmatic rocks occur with a marked chemical fractionation of the daughter and parent elements relative to the source region. It is then the time of this chemical fractionation which is dated. The times of chemical fractionation which are presented will, of course, be model dependent.

The "uniform" mantle reservoir which is taken to be the penultimate source of the new crust is assumed to have evolved through geologic time with the characteristic Sm/Nd and Rb/Sr ratios as identified by DePaolo and Wasserburg (2,3). These workers used the evolution of Nd through geologic time and the correlation of Nd and Sr isotopic variations in geologically young samples to identify the characteristics of the mantle reservoir. Such a simplified model will be subject to revision insofar as the Nd and Sr isotopic correlation is imprecise or not fully understood, and the mantle sources are chemically and isotopically complex regimes. The ultimate planetary source of the material from which the mantle sources come are presumed to be the product of early differentiation within the earth.

<u>Sm-Nd and Rb-Sr Systematics</u>

The $^{143}Nd/^{144}Nd$ measured today for a rock derived T years ago from a source with an initial $^{143}Nd/^{144}Nd$ (I_s) is given by

$$(^{143}Nd/^{144}Nd)_M = I_S + \left(\frac{^{147}Sm}{^{144}Nd}\right)_M \left(e^{\lambda T}-1\right) \qquad (1)$$

where $^{147}Sm/^{144}Nd$ is the ratio measured in the rock today and the decay constant for ^{147}Sm is $\lambda = 6.54 \times 10^{-12}\ yr^{-1}$.

In terrestrial samples, study of the variations in the initial ratio of $^{143}Nd/^{144}Nd$ through geologic time was first undertaken by DePaolo and Wasserburg (2,3). To a reasonable approximation, they showed that the evolution of $^{143}Nd/^{144}Nd$ in the source of continental rocks implies a Sm/Nd essentially equal to that in chondrites. This can be seen from Figure 1, which shows the initial $^{143}Nd/^{144}Nd$ of a variety of igneous rock types as a function of age. Fractional deviations in parts in 10^4 of the initial $^{143}Nd/^{144}Nd$ (I_S) from $^{143}Nd/^{144}Nd$ in a chondritic Sm/Nd reservoir $I_{CHUR}(T)$ are given by

$$\epsilon_{Nd}(T) \equiv \left(\frac{I_S}{I_{CHUR}(T)} - 1\right) \times 10^4. \qquad (2)$$

These deviations are shown in the inset of Figure 1. The maximum deviation is less than 3 parts in 10^4 and is at present only recognized in continental rocks younger than 1 AE. It is thus plausible to assume that the mantle reservoir which is the source of crustal rocks has a Sm/Nd ratio which is very close to a chondritic uniform reservoir (CHUR). The value of $^{143}Nd/^{144}Nd$ in CHUR today is defined as $I_{CHUR}(0)$ and is given by

$$I_{CHUR}(0) = I_{CHUR}(T) + \left(\frac{^{147}Sm}{^{144}Nd}\right)_{CHUR} (e^{\lambda T}-1) \qquad (3)$$

where $I_{CHUR}(T)$ is the $^{143}Nd/^{144}Nd$ in CHUR at any time T in the past and $(^{147}Sm/^{144}Nd)_{CHUR}$ is that in CHUR. A magma derived from the CHUR reservoir T years ago has $I_S = I_{CHUR}(T)$ and an enrichment factor of Sm relative to Nd of $f_{Sm/Nd}$. Then from equations 1 and 3 for a closed system and no subsequent change in Sm/Nd, the time of fractionation and concurrent derivation from the CHUR reservoir is given by

$$T^{Nd}_{CHUR} = \frac{1}{\lambda} \ln \left[1 + \frac{\epsilon_{Nd}(0)\, I_{CHUR}(0)\, 10^{-4}}{f_{Sm/Nd}\, (^{147}Sm/^{144}Nd)_{CHUR}} \right] \qquad (4)$$

where $f_{Sm/Nd} = \left[\frac{(Sm/Nd)_M}{(Sm/Nd)_{CHUR}} - 1\right]$ (5) and $\varepsilon_{Nd}(0) = \left[\frac{(^{143}Nd/^{144}Nd)_M}{I_{CHUR}(0)} - 1\right] \times 10^4$. (6)

It is apparent from equation 4 that T^{Nd}_{CHUR} is indeterminate for $f_{Sm/Nd} = 0$. For precise determination of T^{Nd}_{CHUR} ages, relatively large fractionation of Sm/Nd from chondritic at the time of derivation from CHUR and $\varepsilon_{Nd}(0)$ distinct from zero are required. An example is shown schematically in Figure 2 for a rock with an enrichment factor $f_{Sm/Nd} = -1$ (i.e., $(Sm/Nd)_M = 0$) and with $^{143}Nd/^{144}Nd$ measured today (R_A) unchanged since the derivation from CHUR $T^{Nd}_{CHUR}(A)$ years ago. In this example for a closed system, (i.e., no addition of Sm or Nd) remelting, metamorphic and sedimentary processes do not change $(^{143}Nd/^{144}Nd)_M$ and thus the T^{Nd}_{CHUR} age would be unaffected by these processes. A more general example is shown with $f_{Sm/Nd} < 0$ and the $(^{143}Nd/^{144}Nd)_M$ as measured today (R_B) being somewhat evolved since derivation from CHUR. Again, for a closed system, later metamorphic and sedimentary events shown schematically as T_{MET} and T_{SED}, respectively, do not change the T^{Nd}_{CHUR} age.

The classic rare earth element (REE) distribution studies by Haskin et al. (4), Taylor (5), Ronov et al. (6), and Shaw et al. (7) have shown that for most crustal rocks the enrichment factor $f_{Sm/Nd} < 0$. This can be seen in Table 1 where estimates of the enrichment factor $f_{Sm/Nd}$ range from -0.26 to -0.46. Regardless of the particular model invoked for the formation of continental crust, the observation that Sm/Nd in a wide variety of crustal rocks is markedly fractionated with respect to their source (CHUR) implies that this is an important characteristic of continental crust. Insofar as the CHUR reservoir is the source of new crustal materials and if the major fractionation of Sm/Nd occurs when rocks are derived from this reservoir, the time of formation of new crustal segments is given by T^{Nd}_{CHUR}. To find T^{Nd}_{CHUR} ages of the sources of metamorphic and sedimentary rocks also requires the assumption that no change in Sm/Nd and $^{143}Nd/^{144}Nd$ occurs during these processes. This can probably only be fully established by the self-consistency of the T_{CHUR}^{Nd} ages, although from REE distribution studies it appears that most metamorphic and sedimentary rocks have relative Sm and Nd abundances characteristic of their source.

The samples that we have studied are composites of igneous and metamorphic rocks from the Canadian Shield, shales, greywackes, loess deposits, a schist and a deep sea sediment. These samples do not represent a single unique source, but are almost certainly a mixture of a variety of sources. The isotopic systematics as outlined were for a single source, but they are also applicable to a mixture of a number of sources. For example, for a mixture of two rocks A and B with different T_{CHUR}^{Nd} ages, $T_{CHUR}^{Nd}(A)$ and $T_{CHUR}^{Nd}(B)$ and enrichment factors $f_{Sm/Nd}(A)$ and $f_{Sm/Nd}(B)$, as in Figure 2, it can be shown that they would give a mean age

$$\langle T_{CHUR}^{Nd}(A+B)\rangle = \frac{T_{CHUR}^{Nd}(A)}{1 + \dfrac{Nd_B\, f_{Sm/Nd}(B)}{Nd_A\, f_{Sm/Nd}(A)}} + \frac{T_{CHUR}^{Nd}(B)}{1 + \dfrac{Nd_A\, f_{Sm/Nd}(A)}{Nd_B\, f_{Sm/Nd}(B)}} \tag{7}$$

where Nd_A is the Nd contribution from rock A and Nd_B is the Nd contribution from rock B. From this equation it can be seen that the mean age $\langle T_{CHUR}^{Nd}(A+B)\rangle$ is simply the average of $T_{CHUR}^{Nd}(A)$ and $T_{CHUR}^{Nd}(B)$ ages, weighted by their Nd concentrations and enrichment factors. So, in general, the average $\langle T_{CHUR}^{Nd}\rangle$ is greater than the minimum T_{CHUR}^{Nd} and less than the maximum T_{CHUR}^{Nd} in any mixture. This equation is also indeterminate for $f_{Sm/Nd} = 0$.

In a manner analogous to Sm-Nd, model ages can also be calculated using Rb-Sr isotopic systematics. For this system

$$T_{UR}^{Sr} = \frac{1}{\lambda} \ln \left[1 + \frac{\epsilon_{Sr}(0) I_{UR}(0)\ 10^{-4}}{f_{Rb/Sr}\ ({}^{87}Rb/{}^{86}Sr)_{UR}} \right] \quad (8)$$

where $I_{UR}(0) = 0.7045$ is the ${}^{87}Sr/{}^{86}Sr$ and $({}^{87}Rb/{}^{86}Sr)_{UR} = 0.084$ in the source of continental rocks today (3). Similarly

$$\epsilon_{Sr}(0) = \left[\frac{({}^{87}Sr/{}^{86}Sr)_M}{I_{UR}(0)} - 1 \right] \times 10^4 \quad (9)$$

and $$f_{Rb/Sr} = \left[\frac{(Rb/Sr)_M}{(Rb/Sr)_{UR}} - 1 \right] \quad (10)$$

The major difference in this system is that for most crustal rocks the enrichment factor $f_{Rb/Sr} \gg 0$. This is also shown in Table 1 where estimates of the crustal $f_{Rb/Sr}$ range from +10.3 to +11.3. In addition, the response of Rb and Sr to metamorphic and sedimentary processes is markedly different from that of Sm and Nd. In metamorphic processes redistribution of Rb and Sr between minerals has been well documented (8). Rb-Sr isochrons have also been obtained from some sedimentary rocks (9), which suggests that large enrichments of Rb relative to Sr, and requilibration of ${}^{87}Sr/{}^{86}Sr$ has occurred, presumably during or subsequent to deposition of these rocks. This is evident in the North American shales composite (Table 1) which has $f_{Rb/Sr}$ approximately a factor of 3 greater than the crustal average, whereas $f_{Sm/Nd}$ is essentially identical to this average. For comparison, T_{UR}^{Sr} ages have also been obtained for many of the samples studied. A relationship analogous to equation 7 for the mean Rb-Sr age of a mixture may also be derived.

Experimental Results

Isotopic data for $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ and the enrichment factors determined by Nd, Sm, Rb and Sr were obtained by isotope dilution techniques. Errors given for these isotopic ratios are $2\sigma_{mean}$ for about 200 ratios for Nd and 100 ratios for Sr. Errors in Sm, Nd, Rb and Sr concentrations include an assessment of errors from gravimetry and measurement of isotopic ratios. The errors in the enrichment factors $f_{Sm/Nd}$ and $f_{Rb/Sr}$ which are calculated from these concentrations are less than 1%. The $2\sigma_{mean}$ errors which are given for the T^{Nd}_{CHUR} and T^{Sr}_{UR} ages only allow for analytical errors and do not include uncertainties in the parameters used for the mantle sources. More detailed descriptions of the experimental procedures are given by Papanastassiou and Wasserburg (10) for Rb and Sr and Papanastassiou, DePaolo and Wasserburg (11) for Sm and Nd. Table 3 summarizes the $\epsilon_{Nd}(0)$, $f_{Sm/Nd}$, $\epsilon_{Sr}(0)$ and $f_{Rb/Sr}$ used to calculate T^{Nd}_{CHUR} and T^{Sr}_{UR} ages. The $f_{Sm/Nd}$ values in this table with only a few exceptions are relatively constant. Hence, variations in the calculated T^{Nd}_{CHUR} age are mainly dependent on $\epsilon_{Nd}(0)$. For this reason, where appropriate, discussion of either $\epsilon_{Nd}(0)$ values or the calculated T^{Nd}_{CHUR} ages will be emphasized.

For the Canadian Shield composites the $T_{geologic}$ ages given in Table 3 are previously determined radiometric ages from samples within the same province. For the sedimentary rocks, the $T_{geologic}$ age is the best estimate of the time at which the sediment was formed, based on the stratigraphic age or from radiometric age determinations.

Canadian Shield Composites

The Canadian Shield is one of the better studied Precambrian areas and the results of these studies have been important in formulating theories of continental growth and evolution. Based on geologic evidence derived primarily from field mapping and integrated with isotopic dating, a number of structural provinces have been recognized in the Canadian Shield. From areas within different provinces, we have measured $\epsilon_{Nd}(0)$, $f_{Sm/Nd}$, $\epsilon_{Sr}(0)$ and $f_{Rb/Sr}$ values and calculated T^{Nd}_{CHUR} and T^{Sr}_{UR} ages. In an attempt to determine the average age of relatively large areas of continental crust without a prohibitive number of analyses, we have analyzed composite samples. These composites, in some cases consisting of several thousand samples, were originally used by Eade and Fahrig (12, 13) and Shaw et al. (7, 14) to estimate the chemical composition of the upper continental crust of the Canadian Shield. The provinces broadly generalized and the areas represented by these composites are shown in Figure 3. From the composites prepared by Shaw et al. (14) we have analyzed the "Quartzofeldspathic" lithologic type (Table 2) which composes approximately 70% of the area sampled. Two different lithologies from the composites of Eade and Fahrig (12) were studied. These are the gneisses and the granite-quartzmonzonites. As described in Table 2, the different lithologies of Eade and Fahrig (12) are comparable to those of Shaw et al. (14) and also constitute a significant portion of the sample area.

From Figure 3 it can be seen that the New Quebec and a large portion of the North Quebec composites are in the Superior Province. This province contains some of the oldest rocks in the Canadian Shield where a major granodiorite-forming event has been recognized at $\sim$ 2.5-2.7 AE (15). For

New Quebec $\epsilon_{Nd}(0) = -29.4 \pm 0.4$ with a T^{Nd}_{CHUR} age of 2.66 ± 0.06 AE. The T^{Sr}_{UR} age is 2.73 ± 0.03 AE and is in reasonable agreement. The North Quebec composite which includes a small proportion of younger material from the Grenville Province gives $\epsilon_{Nd}(0) = -28.9 \pm 0.3$ and, a T^{Nd}_{CHUR} age of 2.50 ± 0.05 AE and a T^{Sr}_{UR} age of 2.52 ± 0.03 AE. The good agreement between the T^{Nd}_{CHUR} and the T^{Sr}_{UR} ages for New Quebec and North Quebec composities is also fully consistent with previously determined radiometric ages (15) and confirms that the Superior Province consists predominantly of new crust formed 2.5-2.7 AE ago.

The Fort Enterprise composites are in the Slave Province of northern Canada (Figure 3). This province has some K-Ar dates (2.5-2.7 AE) of the same age as those found in the Superior Province and is generally thought to be of a similar age. For the gneissic composite the T^{Nd}_{CHUR} age is 2.62 $\pm$ 0.05 AE and the T^{Sr}_{UR} age is 2.58 ± 0.03 AE. From the same area, the granite-quartzmonzonite composite gives a T^{Nd}_{CHUR} age of 2.49 ± 0.04 AE and a T^{Sr}_{UR} age of 2.56 ± 0.03 AE. The T^{Nd}_{CHUR} and T^{Sr}_{UR} ages for the two different lithologies are in reasonable agreement, indicating that lithologic type is not important in determining the time of formation of this crustal segment.

Composite samples from Baffin Island and Saskatchewan from different areas of the Churchill Province have been studied. For Baffin Island the T^{Nd}_{CHUR} age is 2.78 ± 0.05 AE and a somewhat lower T^{Sr}_{UR} age of 2.56 ± 0.03 AE years has been obtained. The Saskatchewan composite gives a T^{Nd}_{CHUR} age of 2.68 ± 0.06 AE and a T^{Sr}_{UR} age of 2.43 ± 0.03 AE. These crustal formation ages are quite distinct from the distinctly younger K-Ar ages of ~ 1.8-1.9 AE which are most commonly found in these areas (16).

Adjacent to the eastern margin of the Superior Province is the Grenville Province. Within this Province, the Quebec composite with $\epsilon_{Nd}(0)$ = -7.1 ± 0.3 gives a T^{Nd}_{CHUR} age of 0.80 ± 0.04 AE and a T^{Sr}_{UR} age of 1.01 ± 0.01 AE. The T^{Sr}_{UR} age of 1.01 AE is consistent with previously determined crystallization ages (17) but the T^{Nd}_{CHUR} age is approximately 0.2 AE younger. While substantial evidence (17) shows that some rocks in the Grenville Province are remobilized 2.5 AE rocks, particularly at the weld between the Grenville and Superior Provinces, the present data indicates that the bulk of the area sampled is comprised of much younger crust.

The T^{Nd}_{CHUR} and T^{Sr}_{UR} ages of the Churchill Province are essentially identical to those obtained for the Superior and Slave Provinces. Although this has been hinted at by some age determinations of past workers (18), there now appears to be compelling evidence from the present data that the Superior, Slave and Churchill Provinces were all formed as crustal segments within the same period from 2.5 AE to 2.7 AE. This now poses the problem of how these structural provinces with relatively distinct boundaries and structure patterns but consisting of materials formed at nearly the same time were juxtaposed. The good correlation between the K-Ar ages and the structural provinces (16) suggests that the K-Ar ages represent the time at which the different provinces were metamorphosed and deformed and obtained their structural characteristics. If this is the case, then the structural characteristics of the Superior and Slave Provinces were imposed concurrently with or within 0.2 AE of their formation, while the Churchill Province structural features were obtained approximately 0.8 AE after formation. It is not, however, apparent whether the reworking of the Churchill Province occurred prior to, during or subsequent to the provinces assuming their present relative positions. This will require careful reevaluation of available evidence and further study, particularly in areas adjacent to and including the boundaries of these provinces.

The T_{CHUR}^{Nd} and T_{UR}^{Sr} ages of $\sim$ 0.8-1.0 AE for the Grenville Province composite are markedly younger than the other Canadian Shield composites. This indicates the addition of younger material onto the pre-existing Canadian Shield. However, from the T_{CHUR}^{Nd} and T_{UR}^{Sr} ages of the Superior, Slave and Churchill Province composites it is evident that the Canadian Shield contain only a relatively small amount of material substantially younger than 2.5 AE. Older structural units are manifest on the North American continent. Work by Hurst et al. (19) Catanzaro (20) Silver (21) and Goldich et al. (22) has shown the presence of rocks of $\sim$3.6 AE age in North America. Ancient cratonic components have been found in Greenland (23) and Africa (24). There is a hint in the present data of possible older crust from the Baffin Island composite (T_{CHUR}^{Nd} = 2.78 AE). However, considering the wide variety of materials and the distinctive areas sampled, we must conclude that the period of 2.5-2.7 AE was a major epoch of formation of new continental crust. This has been manifest from the studies of previous workers who observed the relatively high frequency of radiometric ages in this period but it can now clearly be extended to a much broader context. From present knowledge of times of formation of continental crust, it appears that the activity around 2.5-2.7 AE is unparalleled in geologic history. It also appears certain that some truly major periods of continental crustal growth are sharply episodic. This raises the interesting possibility that the dramatic decrease in the volume of continental crustal production subsequent to 2.5 AE may have been due to a change in the mechanism rather than only a change in the rate of crustal formation.

From heat flow data and the chemical composition of exposed lower crustal rocks, it is well known that the upper crustal composition as represented by these composites cannot extend to a depth of more than 10 km. It has been inferred (25, 26, 27) that Rb/Sr in the lower crust is at least a factor of two smaller than in the upper crust. The T_{UR}^{Sr} ages indicate that this enrichment of Rb/Sr in the upper crust occurred during the period 2.5-2.7 AE. Thus the younger events which reset the K-Ar ages in the Churchill Province did not redistribute Rb or Sr over a scale greater than that sampled. Furthermore, the relatively good agreement between the T_{CHUR}^{Nd} and T_{UR}^{Sr} ages (i.e., 2.5-2.7 AE) requires that the fractionation of Sm and Nd was contemporaneous with that of Rb and Sr. From these data, the enrichment of Rb/Sr in the upper crust appears to be a primary feature of continental crust, being associated with the formation of new crust and does not reflect later metasomatic or metamorphic processes.

In the Churchill Province composites, the enrichment factors, $f_{Rb/Sr}$, are approximately a factor of 2 greater than in the Superior and Slave Province composites. This distinction may possibly be attributed to more extensive erosion of the Superior and Slave Provinces, exposing a greater proportion of a lower crust more depleted in Rb. Consistent with this is the relatively widespread occurrence of granulite facies rocks in the Superior Province (28) which are indicative of formation depths greater than ∿10 km. An analogous variation of the enrichment factor $f_{Sm/Nd}$ is not present in the same composites. Thus, although Sm, Nd and Rb, Sr were fractionated at the same time, their relative elemental distribution through the continental crust does not appear to be correlated.

The use of Sm-Nd and Rb-Sr isotopic studies on composite samples to ascertain the average times of formation of large areas of continental crust, with relatively few analyses, can of course be applied to other continental segments. This approach may be particularly useful where there exists little or no other radiometric age information indicative of formation times of new crust or where complex metamorphic processes makes the identification of primary magmatic crystallization ages difficult.

Sediments

In many respects sedimentary rocks are similar to the Canadian Shield composites. They are originally derived from igneous and metamorphic rocks and often consist of materials from diverse sources. However, although sedimentary rocks cover approximately 80% of the continents surface (29) attempts to characterize and identify their provenances using isotopic tracers have not widely been pursued (30). This is mainly due to the disturbance of these systems by chemical processes during or after sedimentation. In particular, many trace elements are fractionated as a result of preferential weathering of specific mineral phases and from the formation of authigenic minerals such as clays. However, the geochemical coherence and short residence times of REE in seawater may be expected to make the Sm-Nd isotopic system less susceptible to disturbance during sedimentation and diagenesis. This is apparent from Table 3 where the enrichment factor $f_{Sm/Nd}$ for the sediments are all approximately the same and also similar to those estimated for the upper crust (Table 1). This suggests that the Sm-Nd isotopic system may remain closed during sedimentation and diagenesis, in which case the T^{Nd}_{CHUR} age would represent the average time of formation of crust from which the sediments were derived. These sediments could be derived from this crust either directly, or indirectly from recycled materials.

In contrast, the enrichment factor $f_{Rb/Sr}$ is variable and greater by up to a factor of 30 compared to the upper crustal estimates in Table 1. The enrichment of Rb relative to Sr in the sediments is probably due to the formation of clay minerals such as illite and montmorillonite within which Rb is strongly fixed relative to Sr (31). Depending on the relative increase in $f_{Rb/Sr}$ and the initial $^{87}Sr/^{86}Sr$ of the sediment, it would be expected that the T^{Sr}_{UR} age will be more compatible with the time of deposition or diagenesis of the sediment, rather than the time of formation of new crust.

As a preliminary test of this approach, we chose an example of a sediment derived from a relatively young crustal source. A shale from the Rosario Formation, Punta San Jose, western Baja California, Mexico, was analysed (Baja Shale) which contains marine fossils of Maestrichtian age (~ 0.065 AE) and is isolated from older mainland material. Its source was most probably Jurassic or Cretaceous eugeosynclinal rocks which are predominant in this region. No Precambrian terranes appear to be available as possible source regions. Although a small negative T^{Nd}_{CHUR} age of -0.12 ± 0.07 AE was obtained, its $\varepsilon_{Nd}(0)$ value of $+0.7 \pm 0.4$ is clearly characteristic of a very young source and markedly different from the large negative $\epsilon_{Nd}(0)$ for older sources. The T_{UR}^{Sr} age of 0.030 ± 0.001 AE although being more reasonable than the T_{CHUR}^{Nd} age is somewhat younger than the time of deposition. These results reflect the sensitivity of rocks with young sources to the detailed assumptions of their evolutionary history. However, both of these results clearly are compatible with the very young age of the crustal sources which constituted the provenance for this shale.

As an example of a young detrital sediment, derived from old source material, we analyzed sand (San Gabriel Sand) which was collected from the mouth of Santa Anita Canyon in the San Gabriel Mountains of Southern California. The rocks in this area are predominantly granitic rocks of Mesozoic age (32) although at the mouth of the canyon a wedge of Precambrian (33) gneisses is present. This sample has $\epsilon_{Nd}(0) = 9.9 \pm 0.4$ giving a T_{CHUR}^{Nd} age of 1.77 ± 0.09 AE. This suggests that most of the sample was derived from the older Precambrian gneisses. The enrichment factor $f_{Rb/Sr} = 5.16$ is similar to that found in many granodioritic rocks indicating that little or no enrichment of Rb relative to Sr has occurred during the metamorphism or weathering of this material. Thus the low value of $\epsilon_{Sr}(0) = 59.5 \pm 0.8$ probably predominantly reflects the $\epsilon_{Sr}(0)$ in the source. As a result of this low $\epsilon_{Sr}(0)$, the calculated T_{UR}^{Sr} age of 0.69 ± 0.0 AE is highly dependent on the assumed Sr growth curve.

To ascertain the self consistency of this approach, sediments representing a range of depositional ages were studied. These sediments are from the Australian continent, and their locations are shown in Figure 4. They were part of a REE distribution study by Nance and Taylor (34).

The Australian sediment with the youngest depositional age is the Silurian State Circle shale (SC-5). It has a measured $\epsilon_{Nd}(0) = -14.5 \pm 0.4$ with a resulting T^{Nd}_{CHUR} age of 1.32 ± 0.05 AE. However, the nearest Precambrian rocks which could have acted as sources for this sediment are now approximately 450 miles to the west. This suggests that either SC-5 was not locally derived, or derived from recycled older sedimentary material which had in turn been derived from Precambrian sources.

An exceedingly large enrichment of Rb relative to Sr is present in this sediment with $f_{Rb/Sr}$ = 293, which together with the measured $\varepsilon_{Sr}(0)$, gives a T^{Sr}_{UR} age of 0.509 ± 0.005 AE. This age is only slightly greater than the 0.440 ± 0.009 AE age obtained from a Rb-Sr "isochron" by Bofinger et al. (35). A shale (AO-7) from the Pertakaka Formation in the Amadeus basin, Central Australia, has a depositional age of 0.8 AE (36) and $\varepsilon_{Nd}(0) = -16.8 \pm 0.4$ giving a T^{Nd}_{CHUR} age of 1.56 ± 0.05 AE. The Musgrave-Mann and Arunta complexes which surround the Amadeus basin have Rb-Sr and K-Ar ages ranging from 1.1 AE to 1.8 AE (36). These ages are compatible with the T^{Nd}_{CHUR} age which suggests that these complexes could have acted as the source for this sediment. For AO-7, $f_{Rb/Sr}$ = 71.6 which together with the measured $\varepsilon_{Sr}(0)$, gives a T^{Sr}_{UR} age of 0.95 ± 0.01 AE, compared with an age of 0.79 AE obtained previously from Rb-Sr studies (36). A shale (MI-1) from the Mt. Isa Geosyncline, Mt. Isa, Queensland, has $f_{Rb/Sr}$ = 264 and a T^{Sr}_{UR} age of 1.55 ± 0.02 AE. This age is in good agreement with the estimated depositional age of approximately 1.5 AE (37) indicating that the massive enrichment of Rb relative to Sr occurred at this time. From the measured $\varepsilon_{Nd}(0) = -23.5 \pm 0.3$ a T^{Nd}_{CHUR} age of 2.07 ± 0.05 AE is calculated for MI-1. Zircon and Rb/Sr total rock ages of 1.86 AE and 1.84 AE respectively have been determined (38) from the oldest unit in the Mt. Isa basement sequence, the Leichhardt metamorphics.

These ages, in conjunction with the T_{CHUR}^{Nd} age, suggest that the shale could have been derived mainly from this source but with an additional component of substantially older age.

The application of Sm-Nd isotopic systematics to calculate the T_{CHUR}^{Nd} provenance age may also be particularly useful for older sediments, whose sources may no longer be preserved or recognizable. An example is the greywacke KH44 from Coolgardie, Western Australia, which has a depositional age of approximately 2.6 - 3.0 AE and is part of the Archean granite-greenstone terrain prevalent in this area. The greywacke KH44 has $\epsilon_{Nd}(0) = -28.3 \pm 0.5$ giving a T_{CHUR}^{Nd} age of 3.06 ± 0.08 AE. This is consistent with a younger age limit of 2.76 AE that has been determined by Oversby (39) from granitic intrusives in the neighboring areas but indicates a significant contribution of substantially older crust which has not yet been found, although there are other (39) hints of it. The T_{UR}^{Sr} age of 3.01 ± 0.03 AE for KH44 is identical within errors to the T_{CHUR}^{Nd} age. This agreement may be explained by the fact that the enrichment factor $f_{Rb/Sr} = 18.24$ is relatively low compared to those of other sediments.

Another example of a sediment from an Archean granite-greenstone terrain is the Figtree shale from the Swaziland sequence in South Africa. The Figtree group conformably overlies the relatively well preserved Onverwacht group whose ages as summarized by Jahn and Shih (24) range from 3.2 - 3.5 AE. From the measured $\epsilon_{Nd}(0) = -28.0 \pm 0.4$ a T_{CHUR}^{Nd} age of 3.53 ± 0.06 AE is calculated for the Figtree shale. This is consistent with its derivation from the underlying Onverwacht group, although at the upper limit of the proposed age range (24). Allsopp et al. (40) obtained a Rb-Sr "isochron" of 2.98 ± 0.02 AE from the Figtree shale. Interpreted as a minimum age of the shale, the isochron clearly demonstrates that redistribution of Rb and Sr has occurred during sedimentation or diagenesis. The T_{UR}^{Sr} age of 2.94 ± 0.03 AE that we have obtained on a radiogenic sample with $f_{Rb/Sr} = 90.6$, where the assumptions regarding the initial $^{87}Sr/^{86}Sr$ are relatively unimportant, is consistent with the age of Allsopp et al. (40). Thus the T_{CHUR}^{Nd} age indicates that the Figtree shale was derived from a source with a mean age of crustal formation of 3.53 AE, and the T_{UR}^{Sr} age in conjunction with the large $f_{Rb/Sr}$ value suggests that the sediment was probably deposited at ~2.94 AE.

For many sedimentary rocks the provenance is obscure or a complete enigma. Classic examples are the loess deposits which cover areas extending from north-central Europe to eastern China as well as in the Mississippi Valley and northwest United States. Their origin is still controversial (41) but they are generally believed to be eolian dust of Pleistocene age derived from desert surfaces, from alluvial valleys or from unconsolidated glacial or glaciofluvial deposits. In an attempt to characterize their source regions, we have analyzed loess deposits from Iowa, United States, and Nanking, China. The Iowa loess has $\epsilon_{Nd}(0) = -14.1 \pm 0.5$, and $f_{Sm/Nd} = -0.411$ giving a T_{CHUR}^{Nd} age of 1.38 ± 0.06 AE. From these data, we infer that a major component of material from the older ($\epsilon_{Nd}(0) = -30$, $T_{CHUR}^{Nd} \sim 2.6$ AE) Canadian Shield is prohibited. However, a composite of Paleozoic North American shales (NAS) of Haskin et al. (42) having $\epsilon_{Nd}(0) = -14.5 \pm 0.5$ and $T_{CHUR}^{Nd} = 1.52 \pm 0.07$ AE (2) is almost identical to the Iowa loess. Hence the Paleozoic sediments, or a source similar to the source of Paleozoic sediments, could have provided materials for the Iowa loess. The penultimate source must of course be crustal rocks with a mean age of ~1.52 AE. Rocks of this approximate age are not widely exposed, although radiometric ages have been obtained (43) on the range 1.0 AE to 1.7 AE, from numerous drill core samples of basement from the midcontinent region of the United States. These data suggest that a substantial component of the Paleozoic North American shales composite was probably derived from this Precambrian basement, or from recycled materials derived from this basement. If the Nd isotopic composition ($\varepsilon_{Nd}(0)$) and $f_{Sm/Nd}$ of NAS is representative of the average from the midcontinent region of the United States crust, then the similarity with the Iowa loess suggests that loess deposits may also be good averages of large areas of continental crust. Hence the Nanking loess with $\varepsilon_{Nd}(0) = -10.2 \pm 0.4$ and $f_{Sm/Nd} = -0.410$ giving a T^{Nd}_{CHUR} age of 1.00 ± 0.05 AE may indicate that this part of the Asian continent is an average of approximately 0.40 AE younger than the North American continent. Only relatively moderate enrichments of Rb relative to Sr have occurred during the formation of these loesses, with $f_{Rb/Sr} = 15.3$ for the Iowa loess and $f_{Rb/Sr} = 34.3$ for the Nanking loess. As a consequence the T^{Sr}_{UR} ages of 0.71 ± 0.0 AE for the Iowa loess and 0.350 ± 0.005 AE for the Nanking loess are younger than the time of formation of their provenance as given by the T^{Nd}_{CHUR} age and older than their time of deposition (Pleistocene). The T^{Sr}_{UR} age of 0.76 ± 0.01 AE for NAS is also younger than the T^{Nd}_{CHUR} age and older than the time of deposition (Paleozoic). This is probably also a result of its intermediate enrichment factor of $f_{Rb/Sr} = 30.1$ compared to these of other sediments.

Another example of a rock whose provenance is unknown is the Birch Creek Schist of the Alaska Range which together with the correlated meta-sediments in the Yukon-Tanana Upland composes a pervasive formation in this area. It is predominantly a quartz-sericite and quartz-sericite-calcite schist with its metamorphic grade being established as greenschist facies (44). No original sedimentary structures are preserved, the foliation within the formation being due to alignment of sericite flakes and segregations of quartz and sericite. Rb-Sr and K-Ar age measurements on micas from the polymetamorphosed Birch Creek Schist indicate that it has been locally metamorphosed at 0.12-0.18 AE (45). Total rock Rb-Sr ages of (45) range from 0.664 - 1.17 AE, but do not uniquely indicate a Precambrian age, as they are also compatible with a younger period of metamorphism. A sample of the Birch Creek Schist in the Healy D-4 Quad. of Alaska has $\varepsilon_{Nd} = -27.0 \pm 0.3$ and $f_{Sm/Nd} = -0.464$ giving a T^{Nd}_{CHUR} age of 2.33 ± 0.05 AE. This is definitive evidence that the Birch Creek Schist was derived predominantly from an ancient Precambrian source which was probably the adjacent older portion of the Canadian Shield with a small component of younger crustal materials. The age of formation of the schist has not been established although the T^{Sr}_{UR} age of 0.714 ± 0.008 AE is similar to the total rock Rb-Sr ages of Wasserburg et al. (45) and is suggestive of an early Paleozoic or late Precambrian age for the schist.

"Red" clay is a sedimentary material predominant in the deeper parts of the ocean basins under surface waters of low biological productivity. The source of red clay is still open to dispute, with its formation being attributed to eolian or current transported continental material and to decomposed volcanic ejecta and pyroclastics (46). We have analyzed a sample of "red" clay obtained by the Deep Sea Drilling Project (Leg V, Hole 37, Core 3, Section 2, 22-24 cm, Abyssal hill, N.E. Pacific Ocean). For this sample $\varepsilon_{Nd}(0) = -3.3 \pm 0.4$ and $f_{Sm/Nd} = -0.212$ giving a T^{Nd}_{CHUR} age of 0.63 ± 0.08 AE which is consistent with red clay being composed only of continental material of mean age 0.63 AE. This age is much younger than than the mean age of either the North American or Asian continent as ascertained from the loess and shale results. It may be more reasonable to assume that the red clay consists of a mixture of oceanic basalt with $\varepsilon_{Nd}(0) \approx +10$, $f_{Sm/Nd} \approx 0$ (1), island arc volcanics with $\varepsilon_{Nd}(0) = +7$, $f_{Sm/Nd} \approx -0.28$ (47) and continental material such as the Iowa loess with $\varepsilon_{Nd}(0) = -14.1$ and $f_{Sm/Nd} = -0.411$. For example, the Sm-Nd isotopic characteristics of this red clay could be accounted for by a mixture of approximately equal proportions of oceanic basalt, island arc volcanics and Iowa loess. However, regardless of the proportions, the Sm-Nd results require a significant component of continental material. The Rb-Sr isotopic characteristics of the red clay ($\varepsilon_{Sr}(0) = 53.66$, $f_{Rb/Sr} = 8.41$) can also be accounted for by similar proportions of oceanic basalt ($\varepsilon_{Sr}(0) = 0$, $f_{Rb/Sr} = 0$) (3), island arc volcanics ($\varepsilon_{Sr}(0) \approx -18$, $f_{Rb/Sr} \approx 0.4$) (47), Iowa loess ($\varepsilon_{Sr}(0) = 181.24$, $f_{Rb/Sr} = 15.3$). This agreement may however be fortuitous as the observed $\varepsilon_{Sr}(0)$ value of the red clay may also have been produced by the exchange of Sr with seawater which has $\varepsilon_{Sr}(0) = 65$.

For all the sediments that we have studied, with only one exception (Baja Shale) the T^{Nd}_{CHUR} ages have been greater than the sedimentation age and less than the "age" of the earth (4.47 AE) (49). In addition, where known, the age of crystallization or formation of likely source areas have been consistent with T^{Nd}_{CHUR} ages. This self consistency is also apparent in the $f_{Sm/Nd}$ enrichment factors which are generally within the same range as those estimated for the upper crust (Table 1). This indicates that for the sedimentary rocks studied, the assumptions of no fractionation of Sm/Nd or exchange of Nd since derivation from the CHUR reservoir are plausible. Possible exceptions may be the San Gabriel Sand and the Baja Shale, whose smaller enrichment factors may reflect fractionation of Sm from Nd during the sedimentary process. However from previous REE distribution studies (4, 5, 34, 42) it appears more plausible to assume that these variations in Sm/Nd are simply a result of variations of Sm/Nd in the sediment source. In contrast, massive enrichments of Rb relative to Sr of up to a factor of 30 are often present in the sediments compared to their likely sources. As a consequence the T_{UR}^{Sr} ages are usually more concordant with the time of sedimentation or diagenesis and generally younger than the corresponding T_{CHUR}^{Nd} age. The calculated T_{CHUR}^{Nd} ages are interpreted to be the average age of formation of the crustal sources from which the sediments were derived. These formation ages also appear to be retained in recycled sediments such as SC-5. Thus $\varepsilon_{Nd}(0)$ and $f_{Sm/Nd}$ parameters are characteristic of the sediment provenance and T_{CHUR}^{Nd} is the provenance age.

Conclusions

Sm-Nd and Rb-Sr isotopic systematics, together with plausible assumptions regarding the geochemical evolution of crustal materials have been used to ascertain the times at which new segments of continental crust were formed. The general approach that has been used is to assume that the dominant contribution to the continental crust comes from the emplacement of magmatic rocks derived from a "uniform" mantle reservoir, and that the differentiation processes which produce the magmatic rocks occur with a marked chemical fractionation of the daughter and parent elements relative to the source region. It is then the time of this chemical fractionation which has been dated. These times of formation of new crust have been obtained from an extremely diverse range of rocks, including metamorphic and sedimentary rocks and composites of igneous and metamorphic rocks from different structural provinces of the Canadian Shield.

Analyses of composites representing the Superior, Slave and Churchill Structural Provinces indicate that these Provinces were all formed within the period 2.5 AE to 2.7 AE. The time of formation of the Superior and Slave Provinces are in agreement with previously determined K-Ar ages, but the time of formation of the Churchill Province is approximately 0.8 AE greater than the K-Ar ages. From present knowledge of the times of formation of continental crust it appears that the activity around the period 2.5-2.7 AE is unparalleled in geologic history and that some truly major periods of continental growth are sharply episodic. A younger 1.0 AE age obtained for the Grenville Province indicates the addition at this time of new crust onto the pre-existing Canadian Shield.

Studies of sedimentary rocks indicate that the Sm-Nd isotopic systematics are not disturbed during sedimentation or diagenesis which has enabled the mean crustal formation age of their provenances to be determined. In contrast, Rb-Sr studies on these sediments have shown that pronounced enrichments of Rb relative to Sr of up to a factor of 30 are present. Depending on the relative enrichment, the Rb-Sr ages from the sediments are generally more compatible with the time of sedimentation or diagenesis. The Sm-Nd provenance ages have been used to characterize and in particular cases to identify the provenance of the sediment. This has enabled old crust which acted as the source for Archean sediments to be identified in the Yilgarn Block of Western Australia in the Swaziland System from South Africa. The mean age of large areas of the North American and Asian Continent has also been ascertained from the provenance ages of loess deposits. As examples of the characterization of sediment provenances using Sm-Nd, we have shown that deep sea "red clay" cannot be produced by only oceanic or island arc volcanism but also requires a significant component of continental material. In addition, a sample of a widespread meta-sediment (Birch Creek Schist) from Alaska has a provenance age indicating derivation from the older portion of the Canadian Shield. Determinations of model crustal formation ages on sediments and on composite samples of well defined lithic units with a broad distribution, may prove to be useful as an aid to geologic mapping and to the better definition of geologic provenances.

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TABLE 1

Estimates of Upper Crustal Sm/Nd and Rb/Sr Enrichment Factors

Composite	$f_{Sm/Nd}$ [a]	$f_{Rb/Sr}$ [b]	
Canadian Shield (CS)	-0.46	+11.3	Shaw et al., (7,14)
Upper Crust (SRT)	-0.45	+10.1	Taylor, (27)
Continental Crust (CCR)	-0.26	--	Ronov et al., (6)
North American Shales Composite (NAS)	-0.46	+30.1	Haskin et al., (42) This work.
Chondrites	0.0	+8.3	Haskin et al., (4), Urey, (49)
Model Mantle Reservoir	0.0	0.0	

a) $f_{Sm/Nd} = \left[\frac{(Sm/Nd)_M}{(Sm/Nd)_{CHUR}} - 1\right]$ b) $f_{Rb/Sr} = \left[\frac{(Rb/Sr)_M}{(Rb/Sr)_{UR}} - 1\right]$

TABLE 2

Lithologies of Canadian Shield Composites

Composite	Lithologic Type
New Quebec[a,b] Fort Enterprise[a]	Banded gneisses, migmatites and granitic gneisses
Fort Enterprise[a]	High level granite, quartz-monzonite
North Quebec[c] Saskatchewan[c] Baffin Island[c] Quebec[c]	Quartzofeldspathic rocks including granite, granitic gneiss, pegmatite rhyolite, arkose, sandstone

a) Eade and Fahrig, (12) ; b) area 12; c) Shaw et al. (14).

TABLE 3

Nd and Sr Provenance Parameters

Sample	$\varepsilon_{Nd}(0)$	$f_{Sm/Nd}$	T^{Nd}_{CHUR} $\times 10^9$ yrs	$\varepsilon_{Sr}(0)$	$f_{Rb/Sr}$	T^{Sr}_{UR} $\times 10^9$ yrs	$T_{geologic}$ $\times 10^9$ yrs
Canadian Shield Composites							
New Quebec	-29.4±0.4[a,e]	-0.444[b]	2.66±0.06[a]	345.3±0.8[a,e]	7.48[b]	2.73 ±0.03[a]	2.5-2.7[c]
North Quebec	-28.9±0.3	-0.464	2.50±0.05	328.9±1.1	7.74	2.52 ±0.03	2.5-2.7
Fort Enterprise Gneiss	-24.3±0.4	-0.372	2.62±0.05	369.2±0.8	8.47	2.58 ±0.03	2.5-2.7
Fort Enterprise Granite	-30.7±0.2	-0.495	2.49±0.04	344.5±0.9	7.99	2.56 ±0.03	2.5-2.7
Baffin Island	-31.7±0.3	-0.457	2.78±0.05	802.8±0.7	18.6	2.56 ±0.03	1.8-1.9
Saskatchewan	-32.5±0.4	-0.486	2.68±0.06	566.1±0.9	13.8	2.43 ±0.03	1.8-1.9
Quebec	- 7.1±0.3	-0.361	0.80±0.04	164.8±0.8	9.81	1.01 ±0.01	0.9-1.2
Sedimentary Rocks							
Baja Shale	+ 0.7±0.4	-0.227	-0.12±0.07	27.0±0.8	55.2	0.030±0.001	0.1[d]
San Gabriel Sand	- 9.9±0.4	-0.225	1.77±0.09	59.5±0.8	5.16	0.69 ±0.02	0.2-1.7
Figtree Shale	-28.0±0.4	-0.317	3.53±0.06	4506.7±1.0	90.6	2.94 ±0.03	2.98
Iowa Loess	-14.1±0.5	-0.411	1.38±0.06	181.1±0.7	15.3	0.710±0.01	0.01
Nanking Loess	-10.2±0.4	-0.410	1.00±0.05	198.7±1.0	34.3	0.350±0.005	0.01
NAS	-14.4±0.5	-0.380	1.52±0.07	380.8±1.1	30.1	0.76 ±0.01	0.5
Birch Creek Schist	-27.0±0.3	-0.464	2.33±0.05	811.8±1.1	68.3	0.714±0.008	0.5-1.8
Deep Sea Red Clay	- 3.3±0.4	-0.212	0.63±0.08	53.7±1.0	8.41	0.38 ±0.01	0.01
Australian Sediments							
SC-5	-14.5±0.4	-0.443	1.32±0.05	2481.6±0.7	293.0	0.509±0.005	0.44
AO-7	-16.8±0.4	-0.433	1.56±0.05	1130.0±0.6	71.6	0.95 ±0.01	0.8
MI-1	-23.5±0.3	-0.455	2.07±0.05	6837.5±0.8	264.0	1.55 ±0.02	1.5
KH44	-28.3±0.5	-0.370	3.06±0.08	928.0±0.8	18.2	3.01 ±0.03	2.7-3.0
CHUR (Sm/Nd)	0.0	0.0					
UR (Rb/Sr)				0.0	0.0		

a) Errors $2\sigma_{mean}$; b) error 1%; c) previously accepted formation age (see text); d) sedimentation age (see text); e) measured $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios can be calculated from equations 6 and 9 respectively and $\varepsilon_{Nd}(0)$ and $\varepsilon_{Sr}(0)$ values listed above.

FIGURE CAPTIONS

Figure 1. Evolution of initial $^{143}Nd/^{144}Nd$ versus time in sources of crustal rocks. $I_{CHUR}(T)$ represents the evolution of $^{143}Nd/^{144}Nd$ in a reservoir with chondritic Sm/Nd (CHUR). The inset shows the fractional deviation in parts in 10^4 of initial $^{143}Nd/^{144}Nd$ from evolution in a chondritic Sm/Nd reservoir versus time. After DePaolo and Wasserburg (2,3).

Figure 2. Schematic representation of the evolution of $^{143}Nd/^{144}Nd$ with time on the earth since it condensed at time T_c. The growth rate of $^{143}Nd/^{144}Nd$ is proportional to Sm/Nd. $f_{Sm/Nd}$ is the Sm/Nd enrichment relative to CHUR. Examples are shown of the evolution of $^{143}Nd/^{144}Nd$ with the Sm/Nd fractionated from CHUR at times T(A) and T(B).

Figure 3. Location of the areas sampled by the Canadian Shield composites and the tectonic provinces of the Canadian Shield.

Figure 4. Map of Australia showing the areas sampled (34). Shaded areas are the approximate areas of outcrop of the sampled or related units.

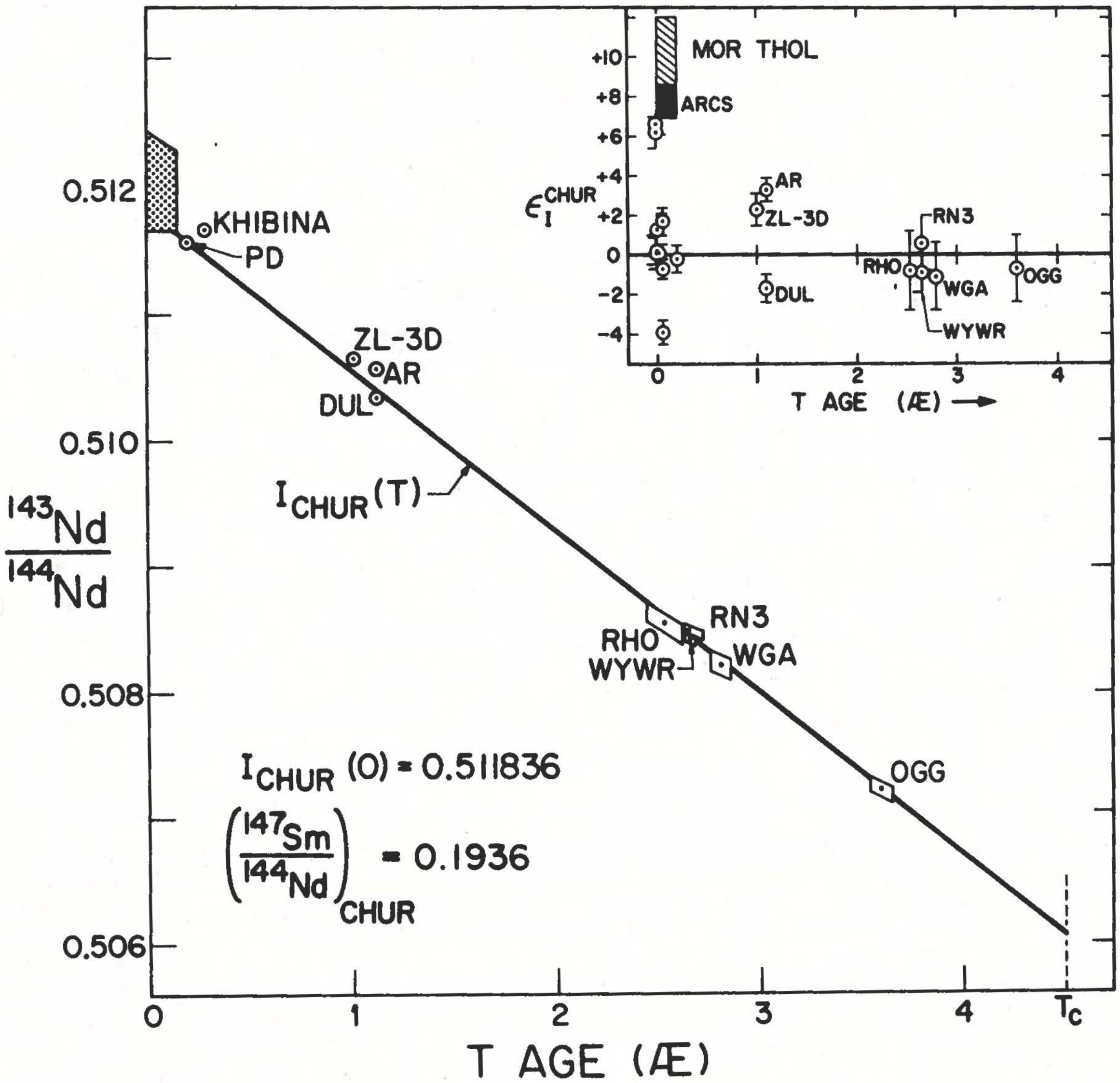

Fig. 1 McCulloch & Wasserburg
Penultimate Provenances of
Crustal Rocks

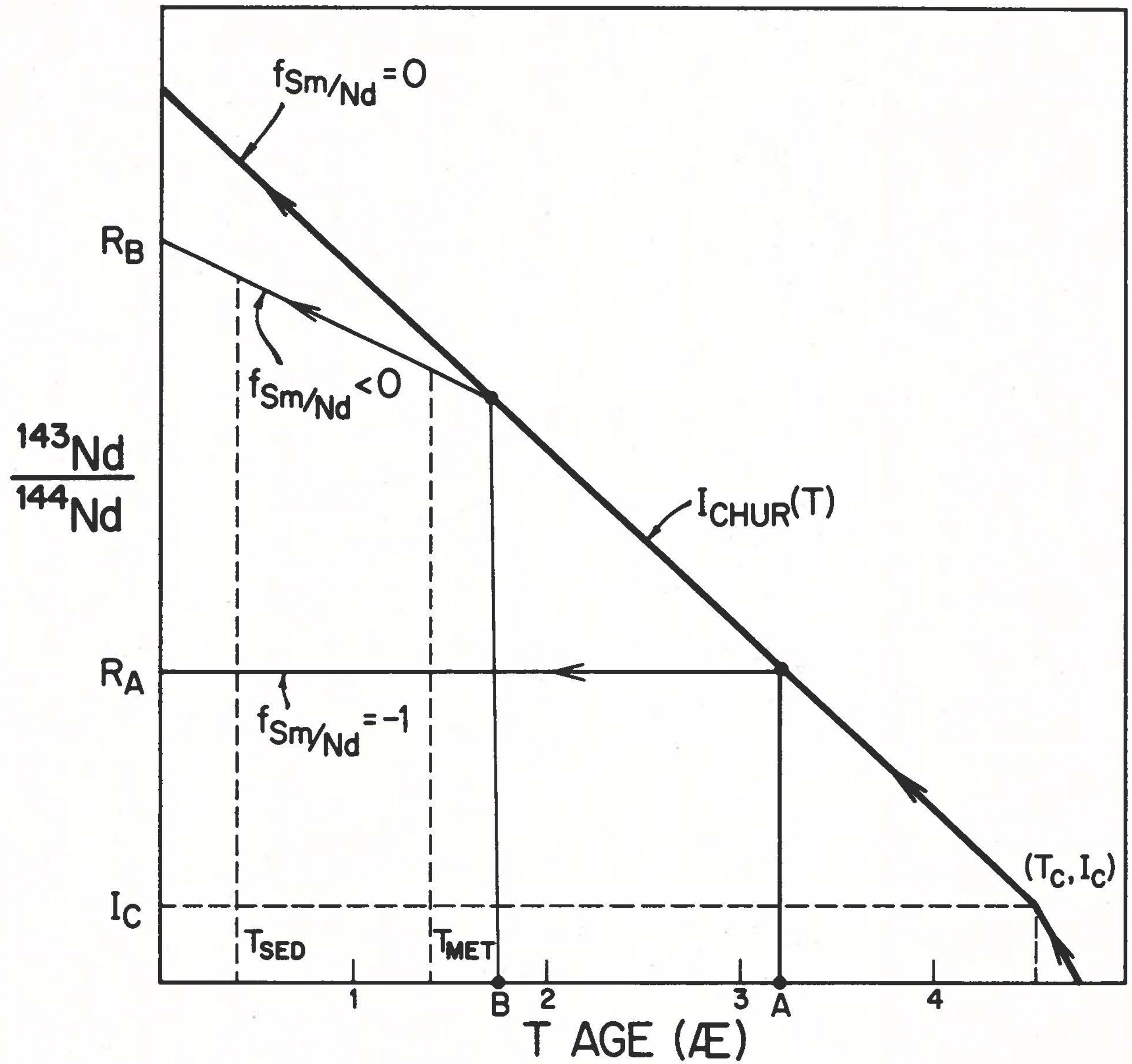

Fig. 2 McCulloch & Wasserburg
Penultimate Provenances of
Crustal Rocks

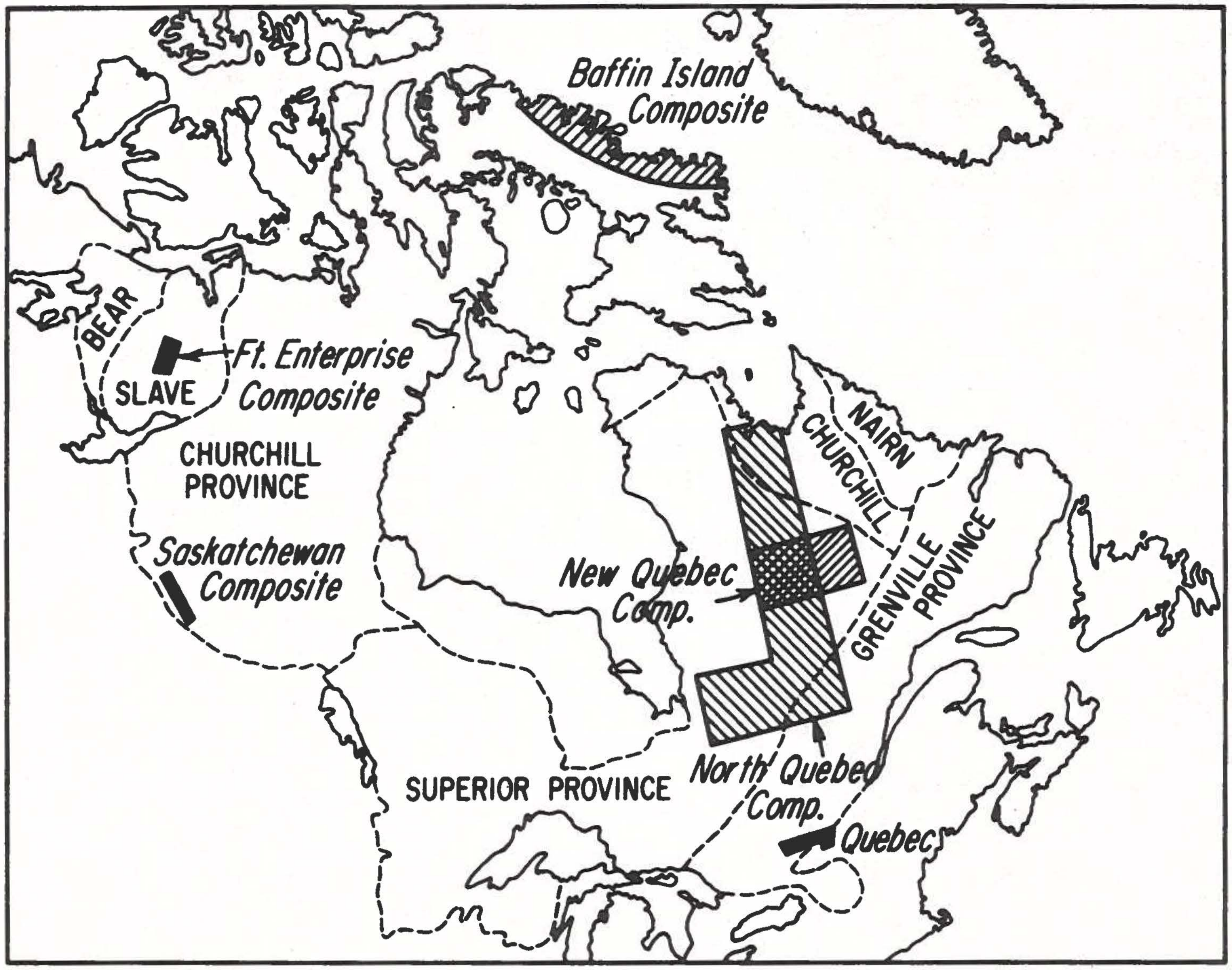

Fig. 3 McCulloch and Wasserburg
Penultimate Provenances of
Crustal Rocks

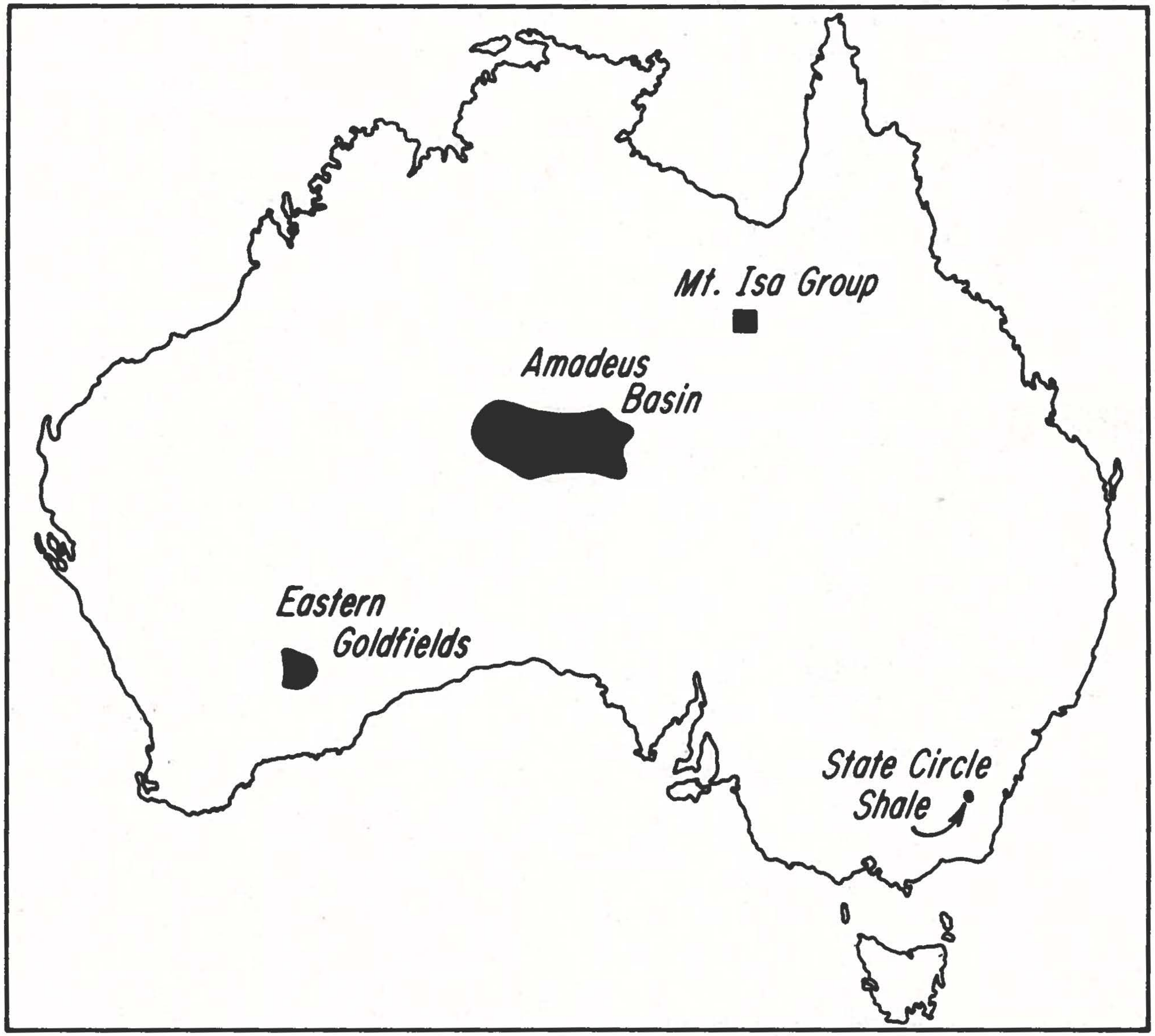

Fig. 4 McCulloch and Wasserburg
Penultimate Provenances of
Crustal Rocks