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Isotopic constraints on crustal growth and recycling

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The Sm-Nd isotopic data on clastic and chemical sediments are used with the present-day age distribution of continental crustal rocks to estimate the rates of crustal accretion, growth and recycling throughout earth's history. A new method for interpreting Nd model ages on both chemical and clastic sediments is proposed. A general relationship is derived between the mean crustal residence time of material recycled from the crust to the mantle (i.e., sediments), the mean age of the crust, and the crustal growth and recycling rates. This relationship takes into account the fact that the age distribution of material in the continental crust is generally different from the age distribution of material recycled into the mantle. The episodic nature of the present-day age distribution in crustal rocks results in similar episodicity in the accretion and recycling rates. The results suggest that by about 3.8 Ga ago, ~ 40% of the present continental volume was present. Recycling rates were extremely high 3–4 Ga ago and declined rapidly to an insignificant value of about 0.1 km^3/a during most of the Phanerozoic. The Nd model age pattern on sediments suggests a fairly high rate of growth during the Phanerozoic.

1. Introduction

A variety of isotopic tracers (Pb, Sr, Nd, Hf) has been used to constrain the evolution of the earth's crust through time [1–10]. Crustal rocks have been found with ages ranging from 0 to 3.8 Ga, however, there is an apparent lack of pre-3.8 Ga continental crust. The mean age of the crust has been estimated to be ~ 2 Ga. However, there is still disagreement on the detailed history of the extraction of the earth's crust from the mantle. Most of the uncertainty in deducing the growth curve of the continental crust is associated with the difficulty in constraining the recycling of the crust into the mantle throughout earth's history.

Models based on Pb isotopic data have emphasized the role of recycling of crust into the mantle in crust-mantle models and have been used to support a no-growth model for the crust over the past 4 Ga [9]. Because of the low Pb concentration in the mantle, however, the crust dominates in any mantle-crust interaction which may be the reason for the emphasis placed on crustal recycling in Pb isotope evolution models [10]. However, recently Pb isotopes have also been used to argue for minimal recycling of crustal material into the mantle [11]. Sr isotopic data have also been used to support the view that recycling of the crust has been insignificant since the early Archean and that crustal growth is a quasi-continuous process [12]. More recent Nd and Hf isotopic data have been used to support each of these contrasting views on crustal evolution [6,13–15].

An extensive and reliable data base on Nd isotopes exists for both the crust and depleted mantle. Thus, while Pb, Sr and Hf isotopic data may add some additional constraints, the crustal growth and recycling estimates of this paper will be derived mostly from the Nd isotopic data and various estimates of the present day crustal age distributions.

Many published models for crustal growth involve assumptions about mantle structure and the transport mechanism. The purpose of this paper is to examine what constraints are provided by data obtained on the crust itself. A new framework for interpreting Nd model ages is presented that emphasizes the importance of distinguishing clearly between the mean age of the crust and the mean crustal residence time of material recycled from the crust into the mantle.

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2. Notation

To be consistent with previous usage, the notation of Jacobsen and Wasserburg [2] will be used. The continental crust and the depleted upper mantle are identified as reservoirs 3 and 2 respectively and the bulk Earth is reservoir 1. Bulk earth, as defined here, excludes the core and refers to the silicate portion of the earth only.

The number of atoms of species i in reservoir j is N_{ij} and the total mass of reservoir j is M_j. The concentration of species i in j is $C_{ij} = N_{ij}/M_j$. The species under consideration are: s, a stable nuclide with no radioactive parent; r, a radioactive nuclide with decay constant λ_r; and d, a stable nuclide (of the same chemical species as s) which is the decay product of r.

The time, τ, runs forward from the initial state at the formation of the earth. The time measured backward from today (i.e., the age) is called T, such that $T = T_0 - \tau$ where T_0 is the age of the earth today. Fractional deviations of the isotopic ratios N_{dj}/N_{sj} from the bulk Earth values are:

$$\epsilon_{dj}(\tau) \equiv \left[(N_{dj}/N_{sj})/(N_{d1}/N_{s1}) - 1 \right] \times 10^4 \quad (1)$$

For the Sm-Nd system ($d = {}^{143}$Nd, $s = {}^{144}$Nd) the ϵ-value in reservoir j is normally abbreviated to $\epsilon_{\text{Nd}j}(\tau)$. The chemical fractionation factors between the radioactive parent isotope and the stable reference isotope are:

$$f_j^{r/s} \equiv (N_{rj}/N_{sj})/(N_{r1}/N_{s1}) - 1 \quad (2)$$

For the Sm-Nd system ($r = {}^{147}$Sm), this notation is normally abbreviated to $f_j^{\text{Sm/Nd}}$. In addition, a bulk earth parameter for each decay system is defined by $Q_d = 10^4 \lambda_r\ (N_{r1}/N_{d1})$. For the Sm-Nd system this parameter is abbreviated to Q_{Nd}. The bulk earth parameters used in this paper are provided in Table 1 [16,17]. This ϵ, f and Q notation follows that introduced by DePaolo and Wasserburg [18].

TABLE 1

Present-day bulk earth parameters for Sm–Nd

N_{r1}/N_{s1}	0.1967
N_{d1}/N_{s1}	0.511847
Q_d	25.13 Ga^{-1}
C_{s1}	1.26 ppm
r	^{147}Sm
d	^{143}Nd
s	^{144}Nd
λ_r	0.00654 Ga^{-1}

Sources: DePaolo and Wasserburg [18], Jacobsen and Wasserburg [2,3,16,17].

3. Rates of crustal growth and recycling

Crustal additions occur primarily through accretion of island arcs along young continental margins and andean-type arc magmatism. The erosion products of continental crust are deposited in trenches and onto the ocean floor and may be recycled into the mantle at subduction zones. The crust is assumed to grow from an initial zero mass ($M_3(0) = 0$). At any time subsequent to $\tau = 0$, the mass of the crust, $M_3(\tau)$, is > 0 as a consequence of crustal growth. The growth rate of the crust, $(\mathrm{d}M_3/\mathrm{d}\tau)$, is the net result of processes that both add and subtract mass from the continents. Thus:

$$\frac{\mathrm{d}M_3}{\mathrm{d}\tau} = \dot{M}_{23} - \dot{M}_{32} \quad (3)$$

where $\dot{M}_{23}$ is the total mass flux of crustal additions (crustal accretion rate) from mantle reservoirs and $\dot{M}_{32}$ is the mass flux of continental materials recycling into the mantle (crustal recycling rate). In terms of the fractional accretion rate ($\psi(\tau) \equiv \dot{M}_{23}/M_2$) and the fractional recycling rate ($\phi(\tau) \equiv \dot{M}_{32}/M_3$), this yields:

$$\frac{\mathrm{d}M_3}{\mathrm{d}\tau} = -(\psi + \phi) M_3 + \psi M_2^0 \quad (4)$$

The growth curve of the crust $M_3(\tau)$ can be calculated from (4) if ψ and ϕ are estimated as functions of time for all of earth's history.

Some estimates of the volumetric accretion, growth, and recycling rates are given in Table 2. The Phanerozoic accretion rate was estimated by Reymer and Schubert [19] by using seismic profiles through magmatic arcs. They obtained a volumetric accretion rate of 1.65 km^3/a and estimated the recycling rate at 0.58 km^3/a. (The recycling estimate reflects both sediment subduction (0.40 km^3/a) and decretion (0.18 km^3/a).) The decretion (tectonic erosion in subduction zones) is highly uncertain, so the recycling rate may be only 0.4 km^3/a. Thus, Reymer and Schubert's growth rate of 1.06 km^3/a for the present is lower than the average growth rate of 1.72 km^3/a over the

TABLE 2

Estimates of crustal accretion, growth and recycling rates

Age (Ga)	Accretion rate (km^3/a)	Growth rate (km^3/a)	Recycling rate (km^3/a)	ψ (Ga^{-1}) [a]	ϕ (Ga^{-1}) [b]
0.0–0.2 [c]	1.65	1.06	0.59	0.004	0.076
1.7–1.9 [d]	> 2.3	2.3	?	> 0.006	?
2.6–3.0 [d]	> 4.7	4.7	?	> 0.012	?
Average [e]	> 1.72	1.72	?	> 0.004	?

[a] The fractional rate of mass removal from the upper mantle ψ is related to the volumetric rate of addition to the crust by $\dot{V}_{23}$ (in km^3/a) $\approx 400\ \psi$ where ψ is the fractional addition rate to the crust.

[b] The volumetric rate of recycling at time τ is $\dot{V}_{32}$ (in km^3/a) $\approx 8\phi[M_3(\tau)/M_3(T_0)]$ where $M_3(T_0)$ is the present mass of the crust and ϕ is the fractional recycling rate. Average density of the crust is 2750 kg/m^3.

[c] Estimates from Reymer and Schubert [19].

[d] Calculated from data given in Patchett and Arndt [20].

[e] Calculated using the total continental volume $V_3(T_0)$ of 7.76×10^9 km^3 and an age of the earth of 4.5 Ga.

history of the earth given in Table 2. If we accept Reymer and Schubert's value, the crustal growth rate must have been substantially higher in the past. This is in agreement with the current estimates of the crustal growth rate at ≈ 1.8 Ga and ≈ 2.8 Ga ago given in Table 2. Veizer and Jansen [21,22] estimated the recycling rate to be about 0.5 km^3/a for the past 2 Ga based on a steady state model ($dM_3/d\tau = 0$).

4. The mean age vs. time curve

Isotope data can be used to constrain the mean age of the continental crust [2]. A more general definition of the mean age than that given by Jacobsen and Wasserburg [2] is needed if crust is recycled into the mantle. We introduce a function $A_j(\tau, \xi)$ which is the mass added per unit time to reservoir j at time ξ and remaining at time τ. Note that $A_3(\tau, \xi)$ is just the age distribution of the continental crust at time τ, where $\tau - \xi$ is the age. The total amount of continental crust at time τ is:

$$M_3(\tau) = \int_0^{\tau} A_3(\tau, \xi)\, d\xi \qquad (5)$$

The mean age of the mass of the crust can be defined as the average age of the mass subsequent to its addition to the continental crust and is given by [23]:

$$\langle T_{M3} \rangle \equiv \frac{1}{M_3(\tau)} \int_0^{\tau} (\tau - \xi) A_3(\tau, \xi)\, d\xi \qquad (6)$$

The rate of change of A_3 with time τ can be written:

$$\frac{\partial A_3(\tau, \xi)}{\partial \tau} = -\dot{M}_{32}(\tau)\kappa(\tau, \xi)$$

$$\text{with} \int_0^{\tau} \kappa(\tau, \xi)\, d\xi = 1 \text{ and } \tau > \xi \qquad (7)$$

where $\kappa(\tau, \xi)$ is the age distribution of the recycled material.

The mean age of the material being recycled (or leaving the crust) will be called the mean crustal residence time of recycled material, $\langle \tau_{M3} \rangle$. The mean residence time can be calculated as the average of $(-\partial A_3(\tau, \xi)/\partial \tau)$ since the only contribution to this derivative is the removal rate from the reservoir. The total flux out of the crust is:

$$\dot{M}_{32}(\tau) = \int_0^{\tau} (-\partial A_3(\tau, \xi)/\partial \tau)\, d\xi \qquad (8)$$

which is consistent with equation (7). The mean residence time at time τ is thus defined as:

$$\langle \tau_{M3} \rangle \equiv \frac{1}{\dot{M}_{32}} \int_0^{\tau} (\tau - \xi)\left(-\frac{\partial A_3(\tau, \xi)}{\partial \tau}\right) d\xi \qquad (9)$$

In general, $\langle T_{M3} \rangle$ and $\langle \tau_{M3} \rangle$ are obviously different and we define $\gamma \equiv \langle \tau_{M3} \rangle / \langle T_{M3} \rangle$. Differentiating equation (6) we obtain (using equations (5) to (9)) the following relationship between the mean age of the crust and the mean residence time of the material leaving the crust:

$$\frac{d\langle T_{M3} \rangle}{d\tau} = 1 - \left(\frac{d \ln M_3}{d\tau}\right)\langle T_{M3} \rangle - \phi(\tau)\langle \tau_{M3} \rangle \qquad (10)$$

If we assume that each part of the crust has an equal a priori probability of being recycled, then the recycling age distribution is $\kappa(\tau, \xi) = A_3(\tau, \xi)/M_3(\tau)$ and equation (7) reduces to:

$$\frac{\partial A_3(\tau, \xi)}{\partial \tau} = -\dot{M}_{32}\frac{A_3(\tau, \xi)}{M_3(\tau)} = -\phi(\tau)A_3(\tau, \xi)$$

$$\text{and } \tau > \xi \tag{11}$$

From this it follows that the probability of material added at time ξ to survive at time τ is given by $\exp[-\Phi(\tau) + \Phi(\xi)]$ where $\Phi(\tau) \equiv \int_0^\tau \phi(\xi)\,d\xi$. Thus, mass added per unit time to the continents at ξ and remaining at time τ is given by:

$$A_3(\tau, \xi) = \dot{M}_{23} \exp[-\Phi(\tau) + \Phi(\xi)] \tag{12}$$

if the recycling age distribution $\kappa(\tau, \xi) = A_3(\tau, \xi)/M_3(\tau)$.

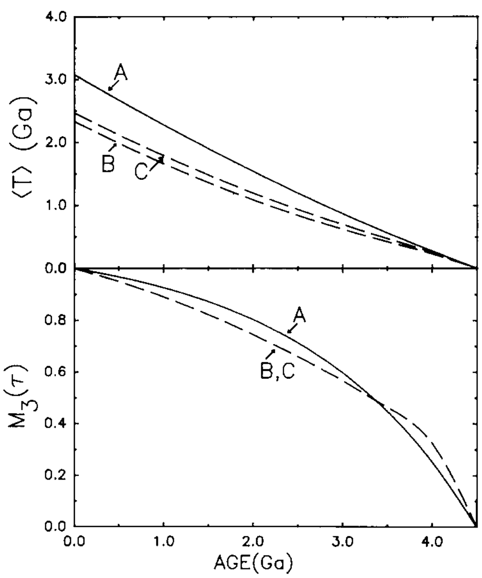

Fig. 1. Cartoon showing the relationship between the mean age of the crust $\langle T_{M3} \rangle$ and the corresponding mass growth curve $M_3(\tau)$ for the crust. Curve A shows $\langle T_{M3} \rangle$ as a function of time for the case of no recycling with a fractional accretion rate (in Ga^{-1}) $\psi = 0.035 \exp[-0.5\tau]$. Curve B shows $\langle T_{M3} \rangle$ for the case with the same ψ as in curve A but with a fractional recycling rate (in Ga^{-1}) of $\phi = 3 \exp[-\tau]$ and $\gamma = \langle \tau_{M3} \rangle / \langle T_{M3} \rangle = 1$ where $\langle \tau_{M3} \rangle$ is the mean crustal residence time of the material being recycled. Finally curve C shows $\langle T_{M3} \rangle$ for the same ψ and ϕ as in A and B but with $\gamma = 0.75$ (i.e., the mean age of the recycled material is less than the mean age of the crust).

The mean age of the crust is in this case given by [3,4]:

$$\langle T_{M3} \rangle = \frac{1}{M_3(\tau)} \times \int_0^\tau M_3(\xi) \exp[-\Phi(\tau) + \Phi(\xi)]\, d\xi \tag{13}$$

In this case, $\langle T_{M3} \rangle = \langle \tau_{M3} \rangle$ $(\gamma = 1)$ and from equation (10) we find that the mean age of the crust satisfies the following differential equation:

$$\frac{d\langle T_{M3} \rangle}{d\tau} = 1 - \left(\frac{d \ln M_3}{d\tau} + \phi\right)\langle T_{M3} \rangle \tag{14}$$

where $(d \ln M_3/d\tau) + \phi = \dot{M}_{23}/M_3 = \psi[(M_2^0/M_3) - 1]$.

Equations (4) and (10) or (14) constitute a system of two coupled ordinary differential equations from which we can calculate $\langle T_{M3} \rangle$ and M_3 as functions of time if ψ and ϕ (and γ) are known. If we know $\langle T_{M3} \rangle$ as a function of time, the mass of the crust today, and ϕ (and γ), we can calculate the mass of the continents through time.

The relationship between $\langle T_{M3} \rangle$ and $M_3(\tau)$ is shown schematically in Fig. 1. In the case where $\langle T_{M3} \rangle$ is different from the residence time of recycled material $\langle \tau_{M3} \rangle$, we need to establish a relationship between these two parameters and use equation (10) instead of equation (14). We note that the maximum slope of $d\langle T_{M3} \rangle/d\tau$ for $dM_3/d\tau \geq 0$ is 1 and corresponds to no growth.

5. Estimating mean ages directly with Nd model ages

A depleted mantle reservoir (DM) has existed in the mantle throughout most of earth's history [16,17]. Therefore, it has become common practice to calculate Nd model ages T_{DM}^{Nd} relative to a depleted mantle reservoir (cf. [24–26]). Although the detailed evolution curve for the depleted mantle is not well known, it is commonly assumed to be linear, beginning with $\epsilon_{Nd} = 0$ at the origin of the earth (4.55 Ga) and evolving to +10 today (i.e., average value observed in present mid-ocean ridge basalts).

The single-stage Nd model age relative to the depleted mantle (DM) is given by:

$$T_{DM}^{Nd} = \frac{1}{\lambda_{Sm}} \ln \left[1 + \frac{\left(^{143}Nd/^{144}Nd\right)_{meas} - \left(^{143}Nd/^{144}Nd\right)_{DM}}{\left(^{147}Sm/^{144}Nd\right)_{meas} - \left(^{147}Sm/^{144}Nd\right)_{DM}} \right] \quad (15)$$

where $\lambda_{Sm} = 6.54 \times 10^{-12}$ a^{-1}, $(^{147}Sm/^{144}Nd)_{DM} = 0.2136$ and $(^{143}Nd/^{144}Nd)_{DM} = 0.512359$. McCulloch and Wasserburg [27] noted that when mantle material is differentiated to form continental crustal material, the Sm/Nd ratio in new crustal material is approximately half of that in the mantle and remains constant afterward. Thus, a single-stage T_{DM}^{Nd} model age for most continental igneous crustal rocks yields a good estimate of the time of separation from the mantle source. The definition of the T_{DM} model age is shown schematically in Fig. 2.

The Sm/Nd ratio is essentially constant in most clastic sedimentary rocks [27] and is similar to the average crustal ratio. Thus, as a general rule, one would expect the weighted mean age of the crustal source rocks of a clastic sediment to be very similar to its T_{DM}^{Nd} value. The global average T_{DM}^{Nd} value (measured today) for clastic sediments deposited at T_{STRAT} (stratigraphic age) is related to the mean crustal residence time of eroded material at T_{STRAT} by:

$$\langle \tau_{M3} \rangle = \left\langle T_{DM}^{Nd}(\text{today}) \right\rangle - T_{STRAT} \quad (16)$$

For marine authigenic minerals, a two-stage model age, T_{2DM}^{Nd}, is appropriate for estimating the mean age of continental sources of Nd [28] since they are commonly fractionated relative to their continental sources at the time of deposition. The sample evolution from the time of deposition (T_{STRAT}) to the present is given by the $f^{Sm/Nd}$ value of the sample (f_{meas}); the sample evolution from the time of differentiation of the crustal source areas from the mantle to the time of deposition ($T_{2DM}^{Nd} - T_{STRAT}$) is given by the typical continental crustal $f^{Sm/Nd}$ value. Thus, the two-stage model age (T_{2DM}^{Nd}) can be obtained from the single-stage T_{DM}^{Nd} model age by the equation:

$$T_{2DM}^{Nd} = T_{DM}^{Nd} - \left(T_{DM}^{Nd} - T_{STRAT}\right)\left(\frac{f_{cc} - f_{meas}}{f_{cc} - f_{DM}}\right) \quad (17)$$

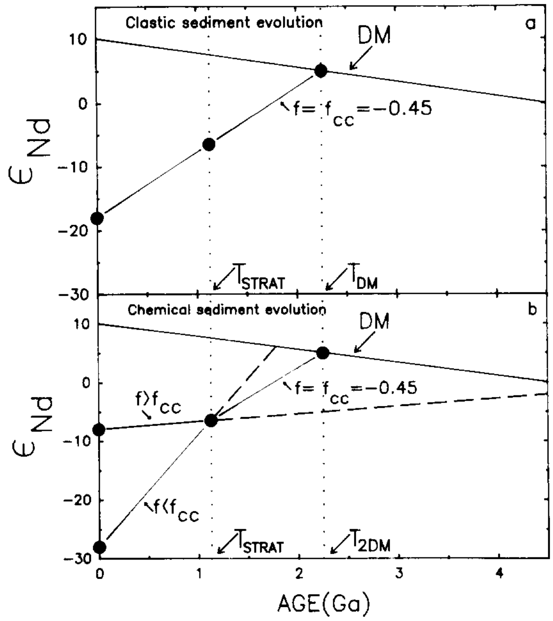

Fig. 2. Cartoon illustrating Nd model ages. For both single-stage and two-stage model ages all continental materials are assumed to be derived from a depleted mantle source (DM) evolving linearly from $\epsilon_{Nd} = 0$ at 4.5 Ga ago to $\epsilon_{Nd} = +10$ today. (a) For a clastic sediment there is no change in the $f^{Sm/Nd}$ value at the time of deposition (T_{STRAT}) of the sediment. Thus, from the measured $\epsilon_{Nd}(0)$ value and the measured $f^{Sm/Nd}$ value (which is normally very similar to the average continental value $f_{cc}^{Sm/Nd} = -0.45$) we can calculate a single-stage model age T_{DM}^{Nd} that represents the intersection of the closed system evolution line for the clastic sediment with the DM evolution line. This model age should approximate the mean age of the crustal sources of the sediment deposited at T_{STRAT}. The mean crustal residence time as defined in the text is the time interval $T_{DM} - T_{STRAT}$. (b) For a chemical sediment the $f^{Sm/Nd}$ value is often different from the average crustal value $f_{cc}^{Sm/Nd}$ of -0.45. Thus, to estimate the mean age of the crustal sources of the chemical sediment, we need to use a two-stage model age T_{2DM}^{Nd} with $f^{Sm/Nd} = f_{cc}^{Sm/Nd}$ in the first stage. As shown in the figure, extrapolation of the closed system evolution for a chemical sediment prior to T_{STRAT} yields an intersection with DM or a T_{DM} model age that is too low if $f^{Sm/Nd} < f_{cc}^{Sm/Nd}$ and too high if $f^{Sm/Nd} > f_{cc}^{Sm/Nd}$.

Here the typical continental crustal $f^{Sm/Nd}$ value of $f_{cc} = -0.45$ is used with $f_{DM} = 0.08592$ which is the $f^{Sm/Nd}$ value of the DM reservoir. The relationship between T_{2DM}^{Nd}, T_{DM}^{Nd} and T_{STRAT} is shown schematically in Fig. 2.

The global average value of T_{2DM}^{Nd} model ages for chemical sediments deposited at T_{STRAT} is related to the mean crustal residence time of the Nd in their eroded source rocks by:

$$\langle \tau_{M3} \rangle = \langle T_{2DM}^{Nd}(\text{today}) \rangle - T_{STRAT} \quad (18)$$

A global average value can be obtained by estimating the size of each of the major oceans through time and obtaining their T_{2DM}^{Nd} values as a function of time [29]. From this approach a global average $\langle \tau_{M3} \rangle$ curve can be obtained as a function of time throughout the Phanerozoic. A similar approach cannot be easily attempted with clastic sediments because it is difficult to estimate the relative sizes of various clastic deposits formed at a single time in the past.

The global mean crustal residence time of materials eroded from the continents for the past 800 Ma has been estimated by Keto and Jacobsen [29]. The curve is shown in Fig. 3 and was calculated from the average ϵ_{Nd} curve of the Phanerozoic oceans estimated on the basis of mostly phosphatic fossil data. From 800 to ~500 Ma, the trend is roughly consistent with $d\langle \tau_{M3} \rangle / d\tau \approx 1$ or essentially no crustal growth. After this time, the overall trend in $d\langle \tau_{M3} \rangle / d\tau \approx -0.75$ and is consistent with substantial growth over the past 450 Ma.

The available clastic sediment data for the past 800 Ma are compared to the global chemical sediment trend in Fig. 4. Although there is considerable scatter in the data, they roughly follow a trend with zero slope ($d\langle \tau_{M3} \rangle / d\tau \approx 0$) which also suggests substantial growth during this period. We note that at ~400–500 Ma most of the clastic sediment data cluster around values consistent with those obtained for phosphatic fossils of the Iapetus Ocean by Keto and Jacobsen [28]. This is reasonable since most of the plotted samples for this period are from France or Great Britain and probably had similar sources as the chemical sediments of the Iapetus Ocean. However, the Iapetus was a small ocean compared to the Pacific-Panthalassa Ocean at that time and therefore these numerous clastic sediment data from Great Britain and France are unlikely to reflect global values. The clastic sediment data as plotted support substantial growth of the crust during the last 600 Ma. This is in contrast to conclusions drawn by others [31,41] from the same set of clastic sediment data.

The overall $\langle \tau_{M3} \rangle$ trend for clastic sediments over all of earth's history is shown in Fig. 5. Also shown is the global chemical sediment trend for the past 800 Ma when the Nd budget of the oceans was dominated by continental sources [29]. Chemical sediment data from the Proterozoic and especially the Archean should not be used for this type of plot since the oceans during those times had substantial hydrothermal contribution to their Nd budget [43]. Thus, using the chemical sediment trend during the past 800 Ma and clastic sedi-

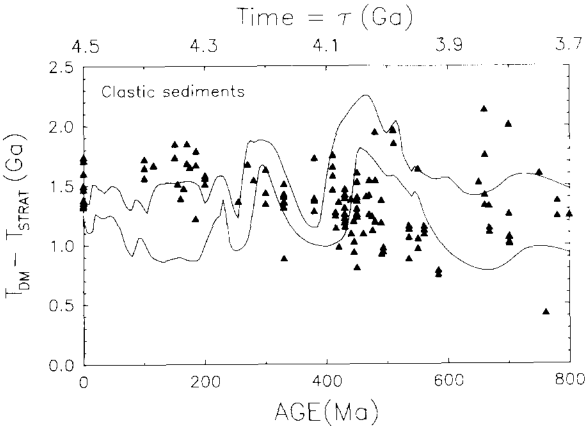

Fig. 4. Crustal residence times of clastic sediments based on Nd model ages ($\langle \tau_{M3} \rangle = T_{DM}^{Nd} - T_{STRAT}$) through the Phanerozoic [27,30–34]. The average seawater curve of Fig. 3 is shown for comparison. Modern oceanic sediment (pelagic clays) data from [35].

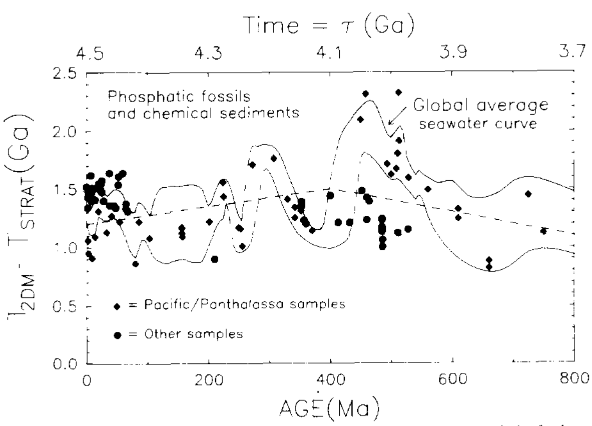

Fig. 3. Global mean crustal residence time of materials being recycled ($\langle \tau_{M3} \rangle = T_{2DM}^{Nd} - T_{STRAT}$) based on Nd model ages of phosphatic fossils and chemical sediments through the Phanerozoic [28,29]. The band shown was calculated from the Phanerozoic global average seawater curve of Keto and Jacobsen [29].

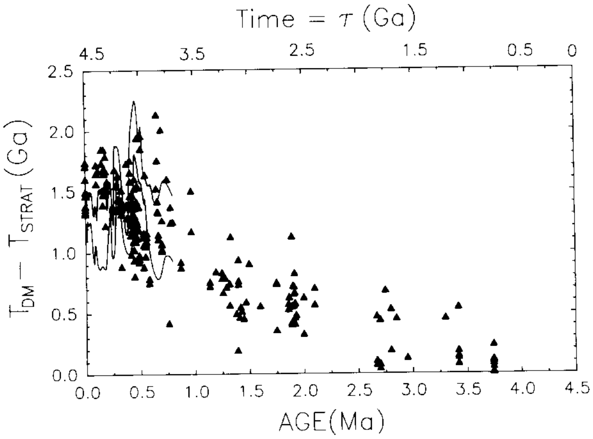

Fig. 5. Crustal residence times of clastic sediments based on Nd model ages for all of earth's history [27,30–34,36–42]. The curve based on seawater is shown for the past 800 Ma (see Fig. 3).

ments prior to this time it should be possible to use equation (10) to invert this data to obtain a crustal growth curve. To do this, we need both estimates of the recycling rate and the relationship between $\langle \tau_{M3} \rangle$ and $\langle T_{M3} \rangle$.

6. Effect of erosion

If the recycling rate is proportional to the area of the continents, we obtain $\phi(\tau) = \beta \dot{e}(\tau)/\rho_c h_c$ where $\dot{e}(\tau)$ is the mass erosion rate per unit area and $\rho_c h_c$ is the average effective mass of a crustal column of unit area. Here β is the fraction of the eroded material that is actually recycled into the mantle.

Young crust generally tends to be at higher elevation than old crust and therefore erodes at a much faster rate than ancient continental regions. An erosion law is therefore needed to properly relate T_{DM}^{Nd} and T_{2DM}^{Nd} model ages of sediments to the mean age of the crust. The erosion rate $\dot{e}(\tau)$ is probably roughly proportional to surface height above sea level, h. Thus:

$$\dot{e}(\tau) = \alpha h(\tau) \tag{19}$$

The amount eroded after time τ is then $E(\tau) = \int_0^\tau \dot{e}(\xi)\, d\xi$. If the change in surface height is governed by isostasy, $h(\tau) = h(0) - \omega E(\tau)$ where $\omega = (1 - (\rho_c/\rho_m))$ and ρ_c and ρ_m are the densities of eroded crustal and mantle material respectively. This yields:

$$E(\tau) = E_\infty(1 - \exp[-\tau/\tau_e]) \tag{20}$$

where $\tau_e = (\alpha\omega)^{-1}$ is the time constant for erosion and $E_\infty = h(0)/\omega$ is the amount eroded at infinite time. The rapid changes (over 35–90 Ma) in Fig. 3 from high ($\approx$ mean age) to low mean crustal residence time and then back to high values more similar to the mean age of the crust imply τ_e in the range from 15 to 30 Ma.

From the work of Allègre and Rousseau [30], we can consider erosion products as a mixture of two components; one contributed from young orogenic areas of mass fraction x and age = T_{young}, and one contributed from older crustal segments of mean age $\langle T_{old} \rangle$. Assuming constant concentrations of Sm and Nd in crustal materials:

$$T_{sed} = \langle \tau_{M3} \rangle = xT_{young} + (1 - x)\langle T_{old} \rangle \tag{21}$$

where T_{sed} is the Nd model age of a sediment. Similarly, the entire continent can be considered a two-component mixture:

$$\langle T_{M3} \rangle = yT_{young} + (1 - y)\langle T_{old} \rangle \tag{22}$$

The erosion coefficient K is the key parameter that relates $\langle \tau_{M3} \rangle$ to $\langle T_{M3} \rangle$ in this model and is given by:

$$K = \frac{x/(1 - x)}{y/(1 - y)} \tag{23}$$

Goldstein and Jacobsen [44] obtained a present-day value of $K = 2.3$ for North America. Allègre and Rousseau [30] modeled the evolution of the crust from shale Sm-Nd data using $K = 2$, 4, and 6. For $K = 2$, they obtained a mean age for the Gondwana continent of 1.93 Ga. This is within error of the mean age of total crust of ≈ 2.0 Ga calculated from Sm-Nd data on the depleted mantle [2–8], and suggests that a value of $K = 2$–3 may have been applicable through much of earth's history.

The case discussed by Allègre and Rousseau [30] corresponds to a recycling age distribution:

$$\kappa(\tau, \xi) = x\kappa_{young}(\tau, \xi) + (1 - x)\kappa_{old}(\tau, \xi) \tag{24}$$

where κ_{young} is the age distribution in young (< 0.2 Ga) mountain belts and κ_{old} is the age distribution in old flat lying crust. From the data of Goldstein and Jacobsen [44], it is apparent that $\gamma = \langle \tau_{M3} \rangle / \langle T_{M3} \rangle \approx 0.76$ today and thus the recycling age distribution is significantly biased toward younger rocks. The present mean crustal residence time indicated by the seawater curve

(Fig. 3) is ≈ 1.35 Ga. Thus using the present value of $\gamma = 0.76$ we obtain a present value for the mean age of the crust of ≈ 1.8 Ga.

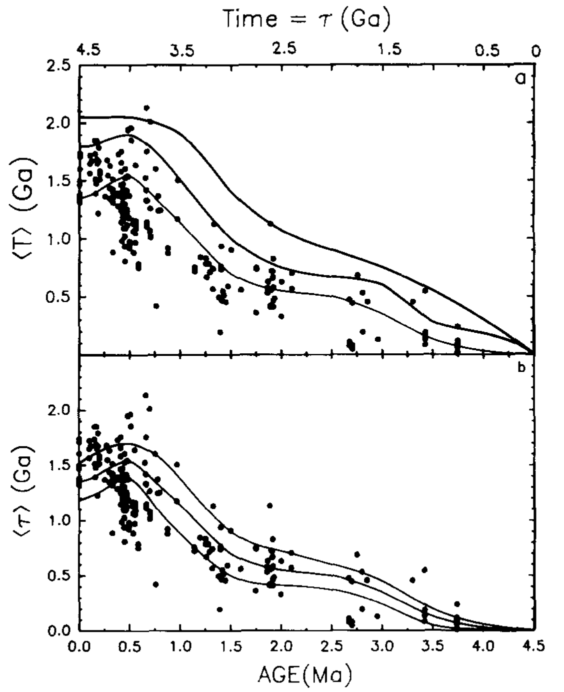

Fig. 6. Variations in the mean age of the crust, $\langle T_{M3} \rangle$, and the mean crustal residence time of material being recycled, $\langle \tau_{M3} \rangle$, as inferred from clastic sediment data, and the chemical sediment data in Fig. 3. The data points shown are the clastic sediment data of Fig. 5. (a) From the present mean residence time indicated by the chemical sediment trend in Fig. 3 (≈ 1.35 Ga) and the present value obtained for $\gamma = \langle \tau_{M3} \rangle / \langle T_{M3} \rangle \approx 0.76$ (see text) we obtain a present average value for the mean age of ≈ 1.8 Ga. The indication from Fig. 3 is that the mean age decreased during the Phanerozoic. The curve we take here as a rough average curve shows a mean age of 1.9 Ga at 0.5 Ga ago and then changes rapidly to a slope $\mathrm{d}\langle T_{M3} \rangle / \mathrm{d}\tau \approx 1$ indicating very little crustal growth from ≈ 0.7 to 1.5 Ga ago, but relatively high growth prior to this time. The upper limit to the mean age used here is a curve drawn through the highest values measured at any time in clastic sediments (assuming these may reflect no erosional bias). The lower limit is taken to be the average trend in the mean crustal residence time shown in (b). (b) The band shown for the mean crustal residence time is drawn through the bulk of the data except for the Phanerozoic where $\langle \tau_{M3} \rangle$ is taken to follow the chemical sediment trend. The large cluster of data below this curve at ≈ 0.5 Ga is mostly from a small area (Great Britain and France) and does not appear to reflect the global average value (see text). Rapid fluctuations around this average value like those shown in Fig. 3 for the Phanerozoic are likely to have occurred throughout earth history.

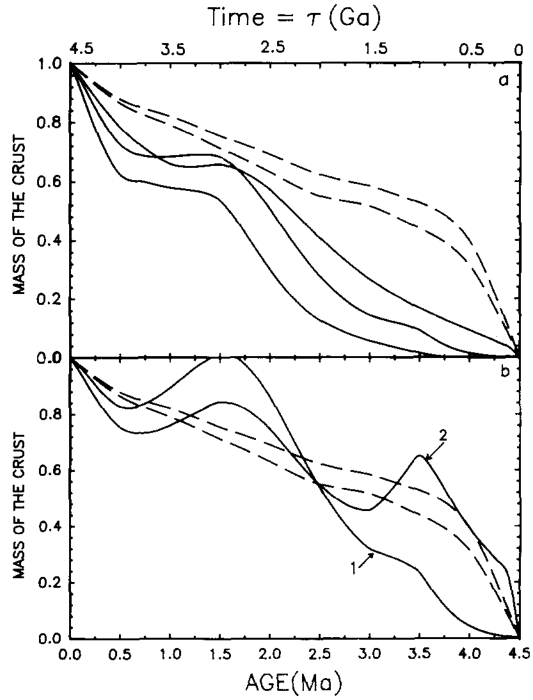

Fig. 7. Mass growth curves of the crust estimated from the mean age curves of Fig. 6. The crustal mass is normalized to its present value. The dashed curves indicate the crustal growth curve obtained by Jacobsen [46] by total inversion of the Sm–Nd isotopic evolution assuming a constant mass for the depleted mantle. (a) Crustal growth curves calculated using the mean age curves in Fig. 6a using equation (1) and assuming no recycling ($\phi(\tau) = 0$). (b) Crustal growth curve *1* was calculated from the average (middle) mean age curve in Fig. 6a with a constant recycling rate $\phi = 0.35$ as suggested by DePaolo [6] for the present value and using equation (10) with $\gamma = 0.76$.

Using this relationship, we estimate $\langle T_{M3} \rangle$ and $\langle \tau_{M3} \rangle$ curves with approximate error bands in Fig. 6 from the clastic and chemical sediment data. The resulting mean age curve is drawn such that $\mathrm{d}\langle T \rangle / \mathrm{d}\tau$ never exceeds its maximum possible value of $+1$. This mean age curve may be used to reconstruct the mass growth curve of the crust for several values of ϕ using equation (10). For simplicity, we assume γ is a constant and ≈ 0.76. The resulting mass growth curves are shown in Fig. 7. They are compared to a crustal mass growth curve obtained by total inversion [45] of the Sm-Nd mass balance throughout earth history assuming a constant mass of the depleted mantle [46]. Fig. 7a shows the result of inverting the mean age curve in Fig. 6a assuming no recycling. It is clear that there is a large discrepancy between the two mass growth curves prior to 2.5 Ga ago. The only way of bringing these into agreement is to have a very high recycling rate prior to this time. Two examples with recycling are shown in Fig. 7b. Curve *1* was calculated using a constant recycling rate of $\phi = 0.35$ Ga^{-1} [6] and $\gamma = 0.76$ and as shown there is still a substantial discrepancy prior to 3.0 Ga. Curve *2* was calculated using an exponentially declining recycling rate that at the present yields a recycling rate of $\phi = 0.08$ Ga^{-1} (Table 2). This growth curve is fairly similar to the curve obtained by total inversion of the Sm-Nd data prior to 2.5 Ga ago. The very high growth rate early in earth's history indicated by the dashed curve is thus only compatible with the Nd model age pattern in sediments if the recycling rate was very high during the first ≈ 2 Ga of earth history.

The $^{87}Sr/^{86}Sr$ ratio in seawater (SW) is largely controlled by river water (RW) and hydrothermal water (HW) inputs. Goldstein and Jacobsen [47] have shown that:

$$\tau_{Sr}\left(\frac{d\epsilon_{Sr}^{SW}}{d\tau}\right) \approx P_{HW}\left[\epsilon_{Sr}^{HW}(\tau) - \epsilon_{Sr}^{SW}(\tau)\right] + \left[\epsilon_{Sr}^{RW}(\tau) - \epsilon_{Sr}^{SW}(\tau)\right] \quad (25)$$

where $P_{HW} = J_{Sr}^{HW}/J_{Sr}^{RW}$ is the ratio of the hydrothermal Sr flux to the river water Sr flux and $\tau_{Sr} \approx 4$ Ma is the residence time of Sr in seawater. The ϵ_{Sr}^{SW} curve is known for the whole Phanerozoic [48]; $\epsilon_{Sr}^{HW} \sim -10$ to -15 and the ϵ_{Sr}^{RW}-value can be estimated from the ϵ_{Nd}^{SW} curve [29] since $\epsilon_{Sr}^{RW} = -6.44\epsilon_{Nd}^{RW} + 31.2$ [47] and because seawater directly reflects the continental runoff throughout the Phanerozoic (i.e., $\epsilon_{Nd}^{SW} \approx \epsilon_{Nd}^{RW}$). From these relationships, a graph of $P_{HW}^{-1}(\tau)/P_{HW}^{-1}(T_0)$ was calculated (Fig. 8). Three distinct peaks corresponding to times of well known orogenic events are evident at ~ 0 Ma, 400 Ma, and 600 Ma ago. Since the variation in this ratio is a factor of 4–5, it cannot be explained as a consequence of changes in the rate of seafloor production, but must be caused by an increased river water Sr flux at those times. The dissolved Sr flux in rivers (J_{Sr}^{RW}) is roughly correlated with the total dissolved solid and suspended matter (i.e., the erosion rate) (Goldstein and Jacobsen, in preparation). Therefore, the global value of J_{Sr}^{RW} should reflect global changes in the erosion rate. Thus $P_{HW}^{-1}(\tau)/P_{HW}^{-1}(T_0)$ is a measure of relative variation in

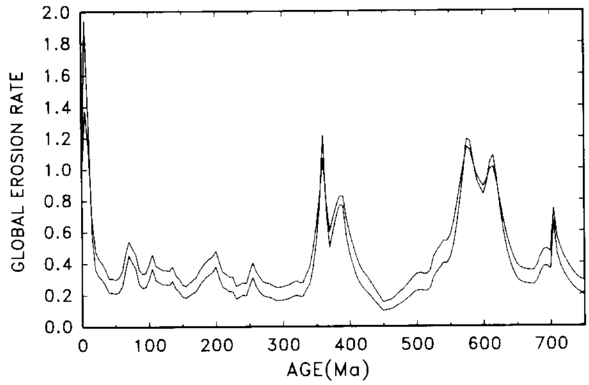

Fig. 8. Changes in Phanerozoic erosion rates normalized to the modern value ($\approx P_{HW}^{-1}(\tau)/P_{RW}^{-1}(T_0)$). The variations were inferred from Sr and Nd isotope mass balance that may be used to estimate the Sr flux to the oceans (which is roughly proportional to the erosion rate) as a function of time (see text).

global erosion rates. As shown in Fig. 8, the erosion rate is a factor of 4–5 lower than the present rate for most of the last 0.8 Ga. Thus the recycling rate given in Table 2 is probably too high for most of the past 0.8 Ga and should be reduced to a value of about 0.1 km^3/a.

7. Age distribution of crustal rocks

The present-day age distribution of crustal rocks (equation (12)) can be written in the following form (for $\kappa = A_3/M_3$):

$$\frac{A_3(T_0, \xi)}{M_3(T_0)} = \psi(\xi)\left(\frac{M_2(\xi)}{M_3(T_0)}\right) \times \exp[-\Phi(T_0) + \Phi(\xi)] \quad (26)$$

where $0 < \xi < T_0$.

The cumulative age distribution today is given by:

$$\Gamma(T_0, \tau) \equiv \int_0^\tau \frac{A_3(T_0, \xi)}{M_3(T_0)} d\xi = \left(\frac{M_3(\tau)}{M_3(T_0)}\right)\exp[-\Phi(T_0) + \Phi(\tau)] \quad (27)$$

and thus $\Gamma(T_0, T_0) = 1$.

Ages of continental rocks tend to cluster around certain values like 1.1, 1.8, 2.7, and 3.6 Ga (cf. [12,49]). Such peaks in age distributions were initially inferred from K-Ar and Rb-Sr mineral data and could be due to the pattern of metamorphism rather than reflecting times of crustal formation. However, an increasing data base on Rb-Sr whole rock isochrons (cf. [12,49]) and Sm-Nd model ages appears to confirm this pattern of distinct episodes of rapid crustal growth [20,25,27]. As discussed above, T_{DM}^{Nd} model ages on basement rocks date the time of extraction of new crust from the mantle. We are now able to quantify these periods of rapid crustal growth by studying Nd model ages of all the continents. Currently, the data base is mostly from North America, Greenland and Europe. The data show two major episodes of

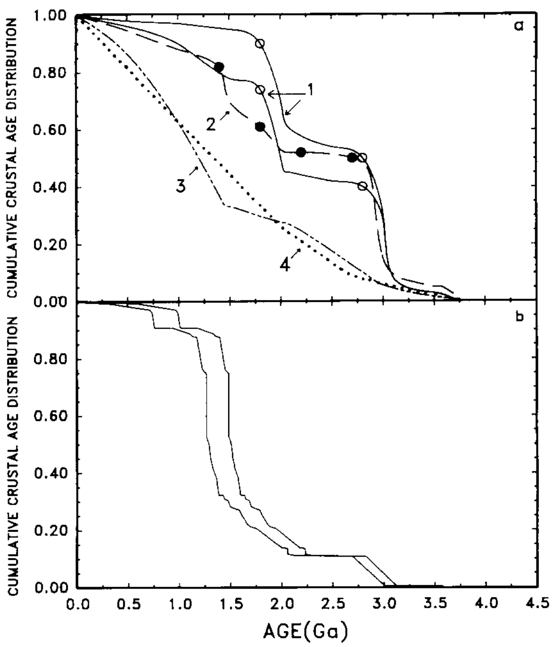

Fig. 9. Comparison of cumulative age distribution curves: (a) The curves labeled *1* are upper and lower limits for North American basement rock age distribution based on T_{DM}^{Nd} model ages after Patchett and Arndt [20]. The lower limit yields a mean age of 2.18 Ga and the upper limit yields a mean age of 2.46 Ga. The curve labeled *2* is the Nelson and DePaolo [25] estimate of the North American basement [25] also based on T_{DM}^{Nd} model ages yielding a mean age of 2.21 Ga. The global Hurley and Rand [50] and Tugarinov and Bibikova [51] curves were based on Rb-Sr and K-Ar data (labeled *3* and *4* respectively) both yield mean ages of ≈ 1.4 Ga. (b) Cumulative global crustal age curves based on river water T_{DM}^{Nd} model ages [26,44,47,52,53] weighted by drainage area. The upper curve (mean age = 1.69 Ga) was based on Nd model ages calculated relative to a DM curve with $\epsilon_{Nd} = +10$ at the present. The lower curve (mean age = 1.48 Ga) was based on Nd model ages calculated relative to a DM curve with $\epsilon_{Nd} = +6$ at the present.

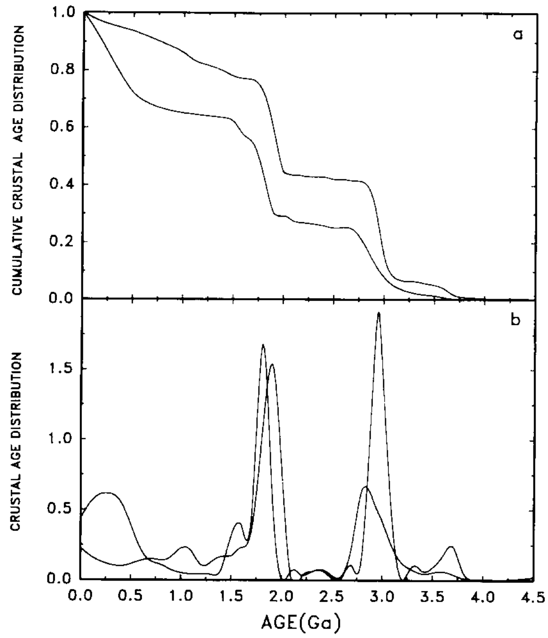

Fig. 10. (a) Selected cumulative age distribution based on mass growth curves in Fig. 7 and cumulative age distributions of Fig. 9. The mean ages for the upper and lower curves are 2.14 and 1.57 Ga respectively. (b) Age distribution function $A_3(T_0, \tau)$ calculated from cumulative curve in Fig. 10a and given as $d\Gamma/d\tau$ in Ga^{-1}.

crustal growth at ~ 1.9 and ~ 2.7 Ga each lasting for ~ 0.2–0.3 Ga [20,25]. These two events provide strong evidence for global episodicity in the rate of crust production.

A comparison of several published cumulative age distribution curves is shown in Fig. 9a and yields a range in the present mean age of the crust from 1.4 to 2.4 Ga. In Fig. 9b, a crustal age distribution curve is constructed on the basis of river water T_{DM}^{Nd} model ages [26,44,47] as these appear to directly reflect the mean age of their continental source areas. The data were weighted by published values [52,53] for the drainage areas of each river. The shape of this curve clearly reflects the scarcity of data for young magmatic arcs and Precambrian shields. However, the mean age implied by this curve of $\langle T_{M3} \rangle = 1.5$ to 1.7 Ga is probably a minimum value. From this and earlier calculations the mean age of the crust appears to be 1.8 ± 0.4 Ga.

Based on the various cumulative age distributions shown in Fig. 9, we selected an error band for the present cumulative crustal age distribution which is shown in Fig. 10a. It is drawn to reflect the times of rapid growth of the Nelson and DePaolo [25] and Patchett and Arndt [20] curves. The high Phanerozoic crustal growth rates indicated by the chemical sediment data were used to obtain a maximum value for the slope $(d\Gamma/d\tau)$ over this period. The lower limit of $d\Gamma/d\tau$ for the Phanerozoic is from the curve of Patchett and Arndt [20]. The upper curve yields a mean age of 2.14 Ga and the lower curve yields 1.57 Ga for the mean age. The age distribution $A_3(T_0, \xi)$ shown in Fig. 10b was obtained from the cumulative curve in Fig. 10a.

8. The freeboard argument

The apparent constancy of freeboard since the Archean has been used as an argument for no crustal growth over the last 2.5 Ga [9,54]. This would suggest that the volumetric addition rate equaled the volumetric recycling rate during this time. However, because the secular decline in heat production of the mantle causes the ocean basins to deepen and the volume of the oceans to increase with time (cf. [55]), growth of the crust is necessary to maintain approximate constant freeboard [19]. Reymer and Schubert [19] derived the following relationship between the area of the continents $a_c(\tau)$ and the mean oceanic surface heat flow $q_s(\tau)$:

$$a_c(\tau) = a_\oplus - a_{oc}(T_0) \times \left[\frac{V_{oa}(T_0)}{V_{oc}(\tau)} + \frac{V_{ob}(T_0)}{V_{oc}(\tau)} \frac{q_s(T_0)}{q_s(\tau)} \right]^{-1} \quad (28)$$

where $a_\oplus$ is the area of the earth, a_{oc} the area of the oceans, V_{oc} is the volume of the oceans, V_{oa} is the volume of the oceans above the ridge crests and V_{ob} is the volume of the oceans below the ridge crests. This follows essentially from using the following relationship between mean oceanic depth below ridge crests d_b and mean oceanic heat flow given by Turcotte and Burke [55]:

$$d_b \propto q_s^{-1} \quad (29)$$

Reymer and Schubert [19], assuming that heat flow followed the decline in radioactive heat generation in the mantle, calculated a crustal growth curve. Perhaps it would be better to use this relationship between continental area and heat flow to constrain the heat loss through ocean basins as a function of time using a crustal growth curve established independently by isotopic data.

9. Inversion of the isotope evolution and the present-day age distribution of crustal rocks

The limits on the cumulative present day age distribution in Fig. 10a can be used with an estimate of the mass growth curve of the crust $(M_3(\tau)/M_3(T_0))$ to obtain recycling as a function of time using equation (27) for the case that $\kappa = A_3/M_3$. The growth curve of the crust was estimated earlier from sediment data alone (Fig. 7), however, assumptions about the recycling rate ϕ were needed to do this. The fraction of continental crust produced by time τ can be estimated by a simple mass balance approach. The mass of the continental crust at time τ is given by:

$$\frac{M_3(\tau)}{M_2(0)} = \frac{f_2^{Sm/Nd}}{f_2^{Sm/Nd} - f_3^{Sm/Nd}} \left(\frac{C_{Nd1}}{C_{Nd3}(\tau)} \right) \quad (30)$$

$$= \frac{\epsilon_{Nd2}(\tau)}{\epsilon_{Nd2}(\tau) - \epsilon_{Nd3}(\tau)} \left(\frac{C_{Nd1}}{C_{Nd3}(\tau)} \right) \quad (31)$$

Using the above equation and the $\epsilon_{Nd}(\tau)$ and $f^{Sm/Nd}(\tau)$ curves obtained by total inversion [45] for the depleted mantle and the crust by Jacobsen

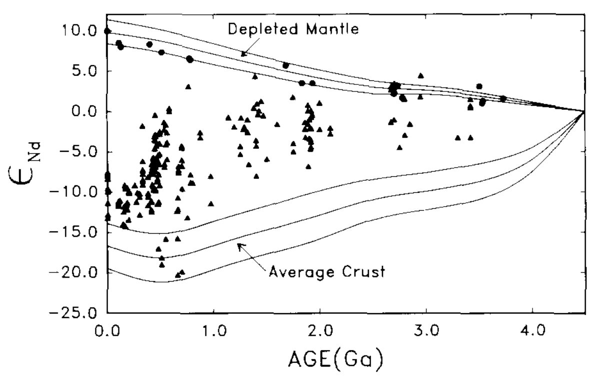

Fig. 11. ϵ_{Nd} curves for the crust and depleted mantle calculated by total inversion of Sm–Nd data for a model with an approximately constant mass of the depleted mantle [46]. ϵ_{Nd} data of mantle-derived mafic igneous rocks (excluding continental gabbros) and clastic sediments are shown for comparison. DM data from [18,56–74] and clastic sediment data from Figs. 4 and 5.

[46] (see Fig. 11), the mass fraction of crust formed by time τ is given by:

$$\frac{M_3(\tau)}{M_3(T_0)} = \frac{\epsilon_{Nd2}(\tau)}{\epsilon_{Nd2}(T_0)}\left[\frac{\epsilon_{Nd2}(T_0) - \epsilon_{Nd3}(T_0)}{\epsilon_{Nd2}(\tau) - \epsilon_{Nd3}(\tau)}\right] \times \left[\frac{C_{Nd3}(T_0)}{C_{Nd3}(\tau)}\right] \quad (32)$$

The results of this are shown as the dashed curve in Fig. 7.

Using this crustal growth curve and the limits on the cumulative age distribution shown in Fig. 10a, we can calculate (using equation (27)) the recycling rate as a function of time. The results of this calculation are presented in Fig. 12 which shows both the fractional recycling rate ϕ and the recycling integral Φ. The figure demonstrates that recycling rates were extremely high from about 3.8 to 2.8 Ga, relatively high at $\approx$ 1.5–2.0 Ga ago, but fairly low during the rest of the earth's history. The recycling rate also shows an episodicity similar to that of the present-day age distribution of the crust. One should note that results for accretion or recycling rates prior to 3.8 Ga are intrinsically non-unique due to the lack of data. All that

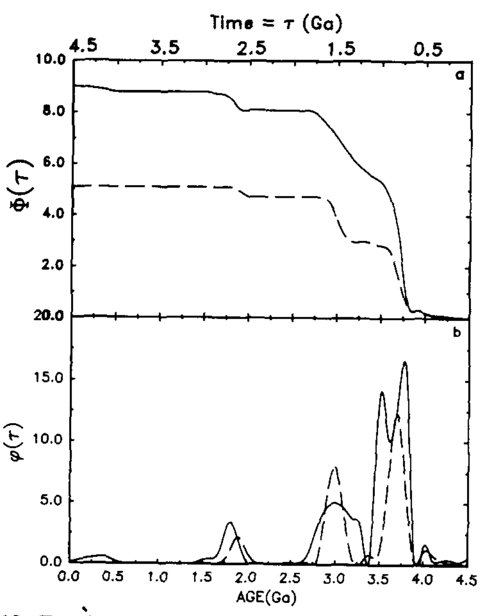

Fig. 12. Fractional recycling rate ϕ (in Ga^{-1}) and the recycling integral Φ (cumulative recycling curve) consistent with the age distribution curves in Fig. 10 and the mass growth curves of the crust estimated from sediment model ages and a mantle-crust evolution model (Fig. 7).

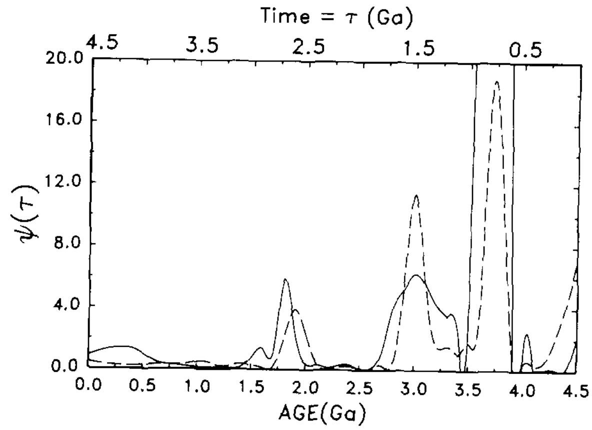

Fig. 13. Fractional crustal accretion rate ψ (in 10^{-11} a^{-1}) calculated from the present age distribution in Fig. 10 and the recycling rate of Fig. 12.

the data seem to show with certainty is a very high growth rate during this time. However, the estimates of accretion versus recycling rates during this period critically depend on the detailed extrapolation of any of our curves from 3.8 Ga back to 4.5 Ga.

The fractional crustal accretion rate can now be calculated easily using equation (26). The results shown in Fig. 13 demonstrate a very high accretion rate early in earth's history (pre-3.5 Ga), subsequent to this period, high accretion rates occurred at $\approx$ 2.8 Ga, 1.8 Ga and during the Phanerozoic.

If the ϵ_{Nd} curves for depleted mantle and continental crust are known, the values of ϕ and ψ as functions of time can be constrained through the differential equations for ϵ_{Nd} evolution for a model with a constant mass of the depleted mantle [46]:

$$\frac{d\epsilon_{Nd2}}{d\tau} = Q_{Nd} f_2^{Sm/Nd} - (\phi/Y_{Nd2})\epsilon_{Nd2} \quad (33)$$

$$\frac{d\epsilon_{Nd3}}{d\tau} = Q_{Nd} f_3^{Sm/Nd} - d_{Nd}(\psi/Y_{Nd3})\epsilon_{Nd3} \quad (34)$$

where d_{Nd} is the enrichment of Nd in new crust relative to the depleted mantle and $Y_{Nd3} = 1 - Y_{Nd2}$. The parameter, Y_{Nd2}, can be evaluated from the following relationship:

$$\frac{\epsilon_{Nd2}}{\epsilon_{Nd3}} = \frac{f_2^{Sm/Nd}}{f_3^{Sm/Nd}} = 1 - \frac{1}{Y_{Nd2}} \quad (35)$$

where $Y_{Nd2} = N_{Nd2}(\tau)/N_{Nd2}(0)$. However, as shown by DePaolo [6] and Jacobsen [46], this yields very high recycling rates during the Phanerozoic. The shape of the mantle ϵ_{Nd} curve may also be explained with a flux from the lower mantle to the upper mantle (cf. [14,75]). The ϵ_{Nd} curves for the mantle and the crust are not very sensitive to episodic versus continuous growth and therefore it is necessary to have a good estimate of the present-day crustal age distribution to obtain the episodic patterns shown in Figs. 12 and 13.

10. Conclusions

It is clear that more data are needed to further quantify both the crustal age distribution and the pattern of crustal residence times of recycled material through time. The method outlined in this paper provides a framework for evaluating crustal accretion and recycling rates utilizing Nd isotopic data. The calculations presented herein assume that continental recycling occurs only by loss of sediment in subduction zones.

(1) The mean age of the continental crust $\langle T_{M3} \rangle$ is related to the mean crustal residence time $\langle \tau_{M3} \rangle$ of continental material being recycled into the mantle, the crustal growth rate, $dM_3/d\tau$, and the fractional recycling rate ϕ:

$$\frac{d\langle T_{M3} \rangle}{d\tau} = 1 - \left(\frac{d \ln M_3}{d\tau} \right) \langle T_{M3} \rangle - \phi(\tau) \langle \tau_{M3} \rangle$$

Insofar as the bulk of recycled material is erosion products of the continents, we can estimate $\langle \tau_{M3} \rangle$ as a function of time using clastic and chemical sediment Nd model ages ($(\langle \tau_{M3} \rangle \approx T_{DM}^{Nd} - T_{STRAT}$ or $\langle \tau_{M3} \rangle \approx T_{2DM}^{Nd} - T_{STRAT}$. The use of chemical sediment data assumes that the Nd isotopic composition of seawater for the past 800 Ma yields a good estimate of the average composition of the detrital load delivered to the oceans.

(2) Because young crust tends to exist at higher elevation than old crust, the mean age of the crust is generally higher than the mean residence time of crustal material that is recycled into the mantle. A typical value appears to be $\langle \tau_{M3} \rangle / \langle T_{M3} \rangle \approx 0.75$; however, this value can fluctuate rapidly. The seawater Nd isotope curve suggests that the time constant for erosion is ~ 15–30 Ma.

(3) A curve for $\langle T_{M3} \rangle$ based on clastic and chemical sediments established a minimum growth curve for the earth's crust. Such a curve has $d\langle T_{M3} \rangle/d\tau \approx 0.3$ from 1.5 to 4.5 Ga ago implying a fairly high growth during this time; $d\langle T_{M3} \rangle/d\tau \approx 1$ from 0.6 to 1.5 Ga ago implying essentially no growth during this time; and $d\langle T_{M3} \rangle/d\tau$ is on average in the range from -0.75 to 0 over the past 0.6 Ga implying very rapid growth during this time. The present mean age of the crust appears to be 1.8 ± 0.4 Ga.

(4) The present age distribution in crustal rocks shows strong episodicity. The calculations performed here using the modern age distribution of crustal rocks imply similar episodicity in crustal accretion rates and in recycling rates.

Acknowledgements

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