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STORED MAFIC/ULTRAMAFIC CRUST AND EARLY ARCHEAN MANTLE DEPLETION

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Abstract

Both early and late Archean rocks from greenstone belts and felsic gneiss complexes exhibit positive ϵ_{Nd} values of +1 to +5 by 3.5 Ga, demonstrating that a depleted mantle reservoir existed very early. The amount of preserved pre-3.0 Ga continental crust cannot explain such high ϵ values in the depleted residue unless the volume of residual mantle was very small: a layer less than 70 km thick by 3.0 Ga. Repeated and exclusive sampling of such a thin layer, especially in forming the felsic gneiss complexes, is implausible. Extraction of enough continental crust to deplete the early mantle and its destructive recycling before 3.0 Ga ago requires another implausibility, that the sites of crustal generation and of recycling were substantially distinct. In contrast, formation of mafic or ultramafic crust analogous to present-day oceanic crust was continuous from very early times. Recycled subducted oceanic lithosphere is a likely contributor to present-day hotspot magmas, and forms a reservoir at least comparable in volume to continental crust. Subduction of an early mafic/ultramafic "oceanic" crust and temporary storage rather than immediate mixing back into undifferentiated mantle may be responsible for the depletion and high ϵ_{Nd} values of the Archean upper mantle. Using oceanic crustal production proportional to heat productivity, we show that temporary storage in the mantle of that crust, whether basaltic, formed by 5-20% partial melting, or komatiitic is sufficient to balance an early depleted mantle of significant volume with ϵ_{Nd} at least +3.0.

1. Introduction: Early Archean Depleted Mantle and the CHUR Reference

It is now well established that both early Archean (3.9-3.2 Ga) and late Archean (3.2-2.5 Ga) rocks exhibit positive initial ϵ_{Nd} values. This is true both of greenstone-belt mafic and ultramafic volcanics and felsic gneiss complexes. The available data have been compiled and reviewed by Shirey and Hanson [1], who reference all the data shown in our Figure 1. In contrast to the trend of increasing ϵ^{Nd} known from 1.9 Ga to present (see e.g. [2]), it is very noticeable that the Archean data suggest a rather constant ϵ_{Nd} value of +1 to +5. Within this range, there seems to be random variation, which may have a variety of causes [1].

It seems worthwhile to state at the outset that there is only a vanishingly small probability that the discrepancy between Archean initial Nd isotopic ratios and the CHUR reference curve could be due to an error in the curve itself. Such a reference curve has two components © a supposed initial solar system isotopic ratio of $^{143}Nd/^{144}Nd$, and a bulk planetary $^{147}Sm/^{144}Nd$ ratio. The initial $^{143}Nd/^{144}Nd$ was established from chondritic meteorites, and none of the chondrites analyzed by Jacobsen and Wasserburg [3] are inconsistent with it by more than a fraction of an epsilon unit. An isotopic discrepancy between the Earth and chondrites, such that the Earth acquired a different $^{143}Nd/^{144}Nd$ due to a different mix of nucleosynthetic components, can be ruled out because the anomalies in other isotopic ratios expected in this scenario are not seen. If the Earth accreted ~ 200 Ma later than the chondrites, it would have started life with $^{143}Nd/^{144}Nd$ four epsilon units higher. However, assumption of a 4.55 Ga age for the Earth, coupled with the likelihood that any unaccreted matter between 4.55 and 4.35 Ga would have had chondritic Sm/Nd ratio, means that the CHUR curve [3] would still apply to the Earth. The Sm/Nd ratio of CHUR was chosen as a mean of chondrite analyses, which varied by a few percent [3]. To adjust the Sm/Nd upwards for the Earth, such that $^{143}Nd/^{144}Nd$ could be even only two epsilon units higher at 3.8 Ga, however, would mean that today's CHUR value would lie in the middle of the MORB-source depleted mantle at +12. This would lead to an Earth that could not be balanced chemically, and is clearly impossible.

It seems inescapable that the positive ϵ_{Nd} values for 3.9-2.5 Ga rock units are real [1], and represent the effects of chemical differentiation in the early Earth. Because the isotopic effects in Nd are in the direction produced by Sm/Nd higher than CHUR, it is necessary that the Archean rock units sample regions of the mantle that had already been depleted by extraction of some more enriched, lower-Sm/Nd material. Because it takes time to produce isotopic deviations, it is further necessary that the extracted fraction had a long residence time before being mixed back into the mantle from which it was extracted; a residence time of at least 300-400 Ma is needed. For this reason, terrestrial crust cannot produce mantle ϵ_{Nd} change if it is mixed back into the same mantle on a short time scale.

2. Models and Model Parameters

The models we have calculated are based on a one-way, one-pass differentiation of primitive mantle into a residual depleted mantle and either oceanic or continental crust. Because of the increasing probability of recycling and remixing as the differentiated reservoirs grow in size, this kind of model should not be valid for more than about the first 2 Ga of Earth history. The governing equations are taken from Jacobsen and Wasserburg [4], Model I, and are solved numerically by a fourth-order Runge-Kutta technique with adaptive step-size control. The Nd and Sm distribution coefficients, degrees of melting, residual mineral compositions, and assumed present mantle composition are shown in Table 1. The distribution coefficients are taken from the compilation by Jacobsen and Wasserburg ([4], Table 4), except for the values for garnet [5]. As can be seen in the comparison of distribution coefficients given by Frey et al [6], the garnet Nd and Sm coefficients from Shimuzu and Kushiro [7] used by Jacobsen and Wasserburg [4] have approximately the same ratio as pyroxene distribution coefficients, minimizing the effect of garnet in the residue. To be conservative, we have used coefficients with a higher ratio of Sm values to Nd values so that extraction of continental crust, which involves residual garnet, will have maximum impact. The Shimuzu and Kushiro coefficients would lower our calculated mantle depletion approximately by a factor of two. None of the oceanic crust models has garnet as a residual phase.

3. Constraints on Abundance of 3.8-2.5-Ga Continental Crust

Conventionally, mantle depletion in Sm and Nd, and hence increase in residual Sm/Nd ratio, is held to be the result of extraction of continental crust [3,8-10]. Today it seems from these references that around one-third of the mantle has been depleted to form the continental crust. While it has been suggested [11] that widespread crust may have existed before 3.0 Ga, it is a feature of that model that recycling of continental crust into the mantle was very rapid before 3.0 Ga, whereas long-lived crust is needed to generate isotope evolution of a depleted mantle residue.

Figure 2b shows a consensus curve for the chemical age distribution of present-day continental crust. Prior to 3.0 Ga, we have reproduced the ~ 10% of present mass given by Taylor and McLennan [12], although it seems to us to be an overestimate. At 2.5 Ga the Taylor and McLennan curve has been modified downward to 50% to allow for the data of Nelson and DePaolo [13], Patchett and Arndt [14] and McCulloch [15].

The pre-3.0 Ga continental crust preserved today is inadequate to explain $\epsilon_{Nd} = +4$ in depleted mantle 3.8-3.0 Ga ago if it was extracted from the whole upper third of the mantle. One way out of this difficulty is to assume that only very limited parts of the mantle were depleted. Then, if 10% of crust was present 3.0 Ga ago, only 10% of the upper third of the mantle had been depleted, and it is then possible to generate $\epsilon_{Nd} = +2$ in that mantle by 3.0 Ga ago. This is curve (A) of Figure 3, which assumes 4.5 Ga as the starting time for continental generation. This limited mantle volume could have been disposed as a uniform layer ~ 65 km thick around the Earth, or in deeper patches. The problem with this scenario is that this small-volume depleted mantle would have to have been repeatedly and preferentially sampled in 3.8-2.5 Ga differentiation events, as attested to by the $\epsilon_{Nd} = 0$ to +4 values for many Archean rocks. Felsic gneiss complexes could not have acquired positive ϵ_{Nd} unless this depleted mantle was the main mantle involved in their genesis, because any recycling of older crust into them would have reduced the average ϵ_{Nd} value that they obtained. We believe it absurd to repeatedly sample a < 100 km-thick and/or patchily distributed depleted mantle in preference to more easily melted peridotites.

If we limit ourself to stabilization of a significant volume of continental crust starting no earlier than presently observed crustal ages (curve B of Figure 3), then a depleted mantle reservoir could not achieve ϵ_{Nd} values of +4 by 3.5 Ga, and its volume would be even more insignificant.

Even these difficulties might be evaded by proposing that there was quite long-lived continental crust present 4.0-3.0 Ga ago, but that it was later destroyed by recycling into the mantle. While this would probably satisfy the positive ϵ_{Nd} requirement, it encounters overwhelmingly negative plausibility arguments. Because the globally widespread 3.0-2.6 Ga crust is mostly newly differentiated from the mantle (see Shirey and Hanson [1], and our Figure 1), it can only contain rather trivial components of pre-3.0 Ga crust. Something like ten times the present-day observed abundance of pre-3.0 Ga gneiss terrane would be needed to generate ϵ_{Nd} = +4 in the whole upper mantle. Remembering that we are using a conservatively large estimate (10%) of pre-3.0 Ga terrane as a basis, this would require that a crust of the present-day volume existed by 3.0 Ga. From what is known of 3.0-2.6 Ga terranes, we can fairly confidently state that ten times the abundance of known pre-3.0 Ga crust is not hidden in them. This leads to the necessity of destroying the pre-3.0 Ga terrane without its being available for recycling into 3.0-2.6 Ga crust. At the present day, sites of crust creation, island arcs and Andean margins, are also the sites where any possible crust-to-mantle recycling must occur. Where large amounts of crustal sediments are available, a major contamination of the arc volcanics, and hence of potential new crust, occurs [16]. The destruction of widespread pre-3.0 Ga components in late Archean 3.0-2.6-Ga terranes would seem to require that the pre-3.0 Ga crust was subducted into the mantle at quite separate sites from where the 3.0-2.6 Ga crust was generated. At the arc type of site, H_2O-dominated partial melting leading to continental crust production occurred in the absence of more ancient crustal components, while at the other, massive amounts of crust were subducted without giving rise to vulcanism and continental crust capable of surviving. Subduction of cold rocks, H_2O-dominated melting and continental crust generation are closely linked today, and seem to have been closely linked for most or all of Earth history [17]. Consequently, this model is geologically highly implausible. It does not seem to be possible to construct any reasonable scenario whereby the $\epsilon_{Nd} = +1$ to +5 in the mantle was produced by the aging of continental crust, as noted already by Shirey and Hanson [1].

4. Archean Mafic/Ultramafic Crust

None of the objections to formation of a depleted mantle by extraction of continental crust apply to depletion by extraction and temporary storage of an early analog to oceanic crust. Such a crust must almost certainly have been formed and convectively overturned from very early in Earth history; initially storage of a significant portion of such subducted crust in mantle circulation is likely, and even today evidence exists for survival of a reservoir of recycled oceanic crust; its depleted residue would evolve rapidly enough isotopically to match the observations of Figure 1; and the volume of depleted residual mantle formed would be much larger than for an early continental crust because of the much greater crustal creation rate.

There is little doubt that the early mantle convected even more vigorously than at present. Radioactive heat production was more than twice as high as at present: we have used the heat productivity model of Dickinson and Luth [18], with updated decay constants, to represent the variation of radiogenic heat. Scaling relationships of simple convective systems suggest that average spreading rate should vary with the square of heat productivity [19]. The volume of mafic/ultramafic crust produced by partial melting at spreading centers should vary approximately with the spreading rate, and far too much would have been produced not to have rapidly subducted most of it back into the mantle [20]. To be conservative, we have chosen to model a rate of oceanic crust generation and storage directly proportional to the radiogenic heat productivity rather than to its square (Figure 2a), and scaled by the present-day value of ~ 24 km^3/a [21].

After subduction, early mafic crust would eventually be subject to convective stirring and recycling into zones of magma extraction, but the rate of remixing could not become equal to the rate of subduction until a sizable mass of subducted crust had accumulated in the mantle. This is analogous to the way intermediate products in U and Th decay chains approach steady-state abundances after a chemical disturbance. The total mass of subducted mafic/ultramafic crust stored in the mantle should rise, then level off.

Even today there is evidence in the ancient isotopic signatures of ocean island basalts [22,23] of long-term storage of subducted oceanic crust and its eventual return to the surface. From the mean residence time (isotopic age) of ocean island Pb of 1 to 2 Ga [24,25] and an estimated rate of ocean island magmatism of 1 km^3/a [21], we can constrain the present-day volume of the reservoir of subducted, unassimilated oceanic crust. Using a specific mean residence time of 1.4 Ga (estimated from [22], allowing dilution by depleted mantle sources from 0 to 75%, and varying the degree of partial melting to form hotspot magmas between 1% and 5%, the net volume today of the stored ocean crust reservoir is 7 to 140 x 10^9 km^3, between 1 and 20 times the volume of the continental crust. Even this may be an underestimate because of the likelihood of losses from the reservoir of stored ocean crust by other means in addition to ocean island magmatism.

The early oceanic crust was almost certainly generated in greater volumes than at present, but its composition is in some question. The abundance of komatiites in Archean terrains and the problem of buoyancy of Archean oceanic lithosphere has led to the suggestion that early ocean crust might have been ultramafic in composition [26,27]. For a dry mantle, Sleep and

Windley [20] estimate that only about 10% of the early ocean crust would have been komatiite, while Allègre [28] suggests that wet mantle could yield komatiitic magmas when hydrated by subducting slabs, making komatiites the early equivalent of island arc volcanics. To cover the range of possible compositions, we have calculated models for generation and storage of komatiitic crust formed by 50% melting and tholeiitic crust formed by 20% and by 5% partial melting (Figure 3). Compositions of the residua and distribution coefficients are listed in Table 1. Intermediate degrees of partial melting, such as 35% for komatiitic crust, can be approximated by mixing together the effects of our calculated examples.

These models clearly demonstrate that any of these oceanic crust compositions, with generation rates given by Figure 2a, are sufficient to explain the early formation of a depleted mantle reservoir as shown by the Nd isotopes. After 3.5 Ga, all three mafic/ultramafic crust curves pass well above the observed ϵ_{Nd}. This implies, in our model, that the volume of stored ocean crust was beginning to level off as more and more of it became involved in recycling and mixing back into the main mantle reservoirs.

The volume of depleted mantle formed by 3.0 Ga for each of the mafic/ultramafic crust models is much greater than the meager 65 km thick layer formed by extraction of observed amounts of ancient continental crust. The komatiite model with 50% melting forms a 145 km thick residual layer at 3.0 Ga, and the basalt model with 20% melting has a 645 km thick residuum: almost the entire upper mantle. To have formed by 5% partial melting as much basalt as is shown in Figure 2a for 3.0 Ga requires that the entire mantle be processed 1.5 times, and would also require that almost all of the subducted oceanic crust had been mixed back into the mantle. Either the komatiite model or the basalt model with 20% partial melting would in any case be more consistent with higher heat production and hotter mantle in the Archean, and is therefore to be preferred to the 5% partial melting model. If the production of ocean crust were proportional to the square of heat productivity rather than the direct proportionality used here, then remixing of subducted material would have to have been very rapid indeed, to avoid forming a very voluminous and very depleted early upper mantle.

5. Conclusions

For a number of reasons, extraction of the early continental crust is an implausible cause for geochemical depletion of the early upper mantle. Storage of early oceanic crust formed at spreading centers is an actualistic and sufficient explanation of observed initial ϵ_{Nd} ratios of +4 in both mafic and felsic Archean rocks as old as 3.5 Ga.

Acknowledgements

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TABLE 1: PARAMETERS FOR MODELING

Degree of partial melting (F), partition coefficients (D), Nd and Sm concentrations, and residual mineral compositions for the models in Figure 3.

	F	D_{Nd}	D_{Sm}	Nd ppm	Sm ppm
Olivine[1]		0.007	0.010		
Orthopyroxene[1]		0.013	0.022		
Clinopyroxene[1]		0.17	0.26		
Garnet[1]		0.039	0.205		
Residue of tholeiite ($Ol_{60}Opx_{25}Cpx_{15}$)	0.05	0.033	0.051		
Residue of tholeiite ($Ol_{75}Opx_{20}Cpx_{5}$)	0.20	0.016	0.025		
Residue of komatiite (Ol_{100})	0.50	0.007	0.010		
Residue of continental crust ($Ol_{50}Opx_{25}Cpx_{15}Gt_{10}$)	0.015	0.036	0.070		
Continental crust[2]				20	4.1
Present bulk mantle[3]				1.040	0.338

[1]Partition coefficients as used by Jacobsen and Wasserburg [4], except garnet, which is from Schilling [5]

[2]Crust concentrations from Taylor and McLennan [13]

[3]Nd bulk mantle value = 2.25 X Cl of Anders and Ebihara [29], with Sm readjusted to give $^{147}Sm/^{144}Nd$ (CHUR) = 0.1966

Figure Captions

Fig. 1 ϵ_{Nd} values for Archean rocks, compiled by Shirey and Hanson [1]. Total range of compiled values given by open bars for felsic rocks and closed bars for mafic/ultramafic rocks. Note consistently positive maximum ϵ_{Nd} values of +1 to +5 from 3.8 to 2.5 Ga.

Fig. 2 Crustal growth curves. (a) Cumulative mass of "oceanic" mafic/ultramafic crust created, based on growth rate proportional to heat productivity [18]. (b) Cumulative mass of stabilized continental crust, based on Taylor and McLennan [12] and Patchett and Arndt [14]. The dashed line corresponds to continental crustal accumulation starting at 4.5 Ga, and the solid line at 3.9 Ga. Note the much smaller mass of continental crust at all ages.

Fig. 3 Modelled ϵ_{Nd} changes in depleted mantle 4.5 to 2.5 Ga. Data ranges from Figure 1 shown by open bars. Curves for mantle depleted by extraction of continental crust are A: (dashed, corresponds to dashed line, Figure 2b) extraction starts at 4.5 Ga; B: (lower solid line, corresponds to solid line, Figure 2b) extraction starts at 3.9 Ga. Depletion caused by 100% storage of tholeiitic oceanic crust formed by 5% or 20% partial melting or by komatiitic crust formed by 50% partial melting shown by upper, labelled curves, all for growth curve as given in Fig. 2a. Table 1 lists the distribution coefficients and residual compositions for the five models shown.

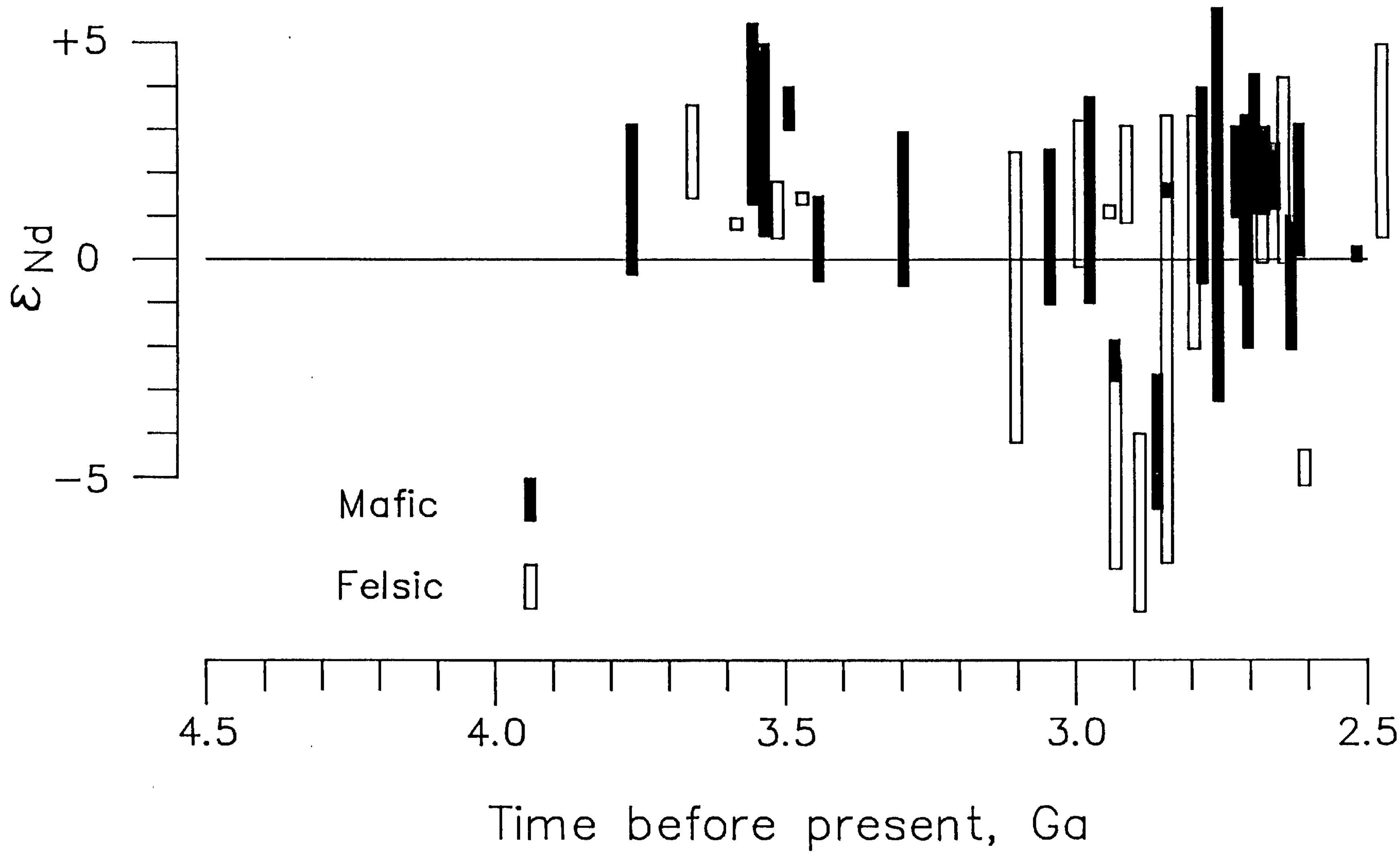

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Figure 1

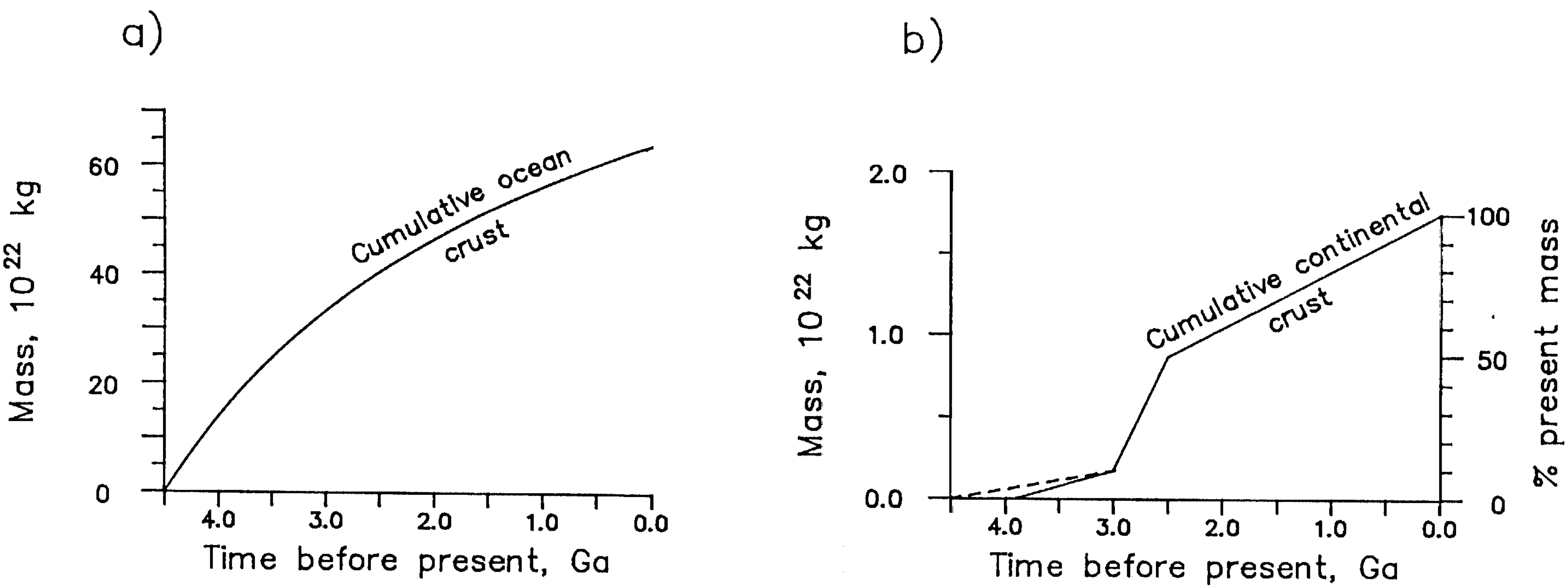

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Figure 2

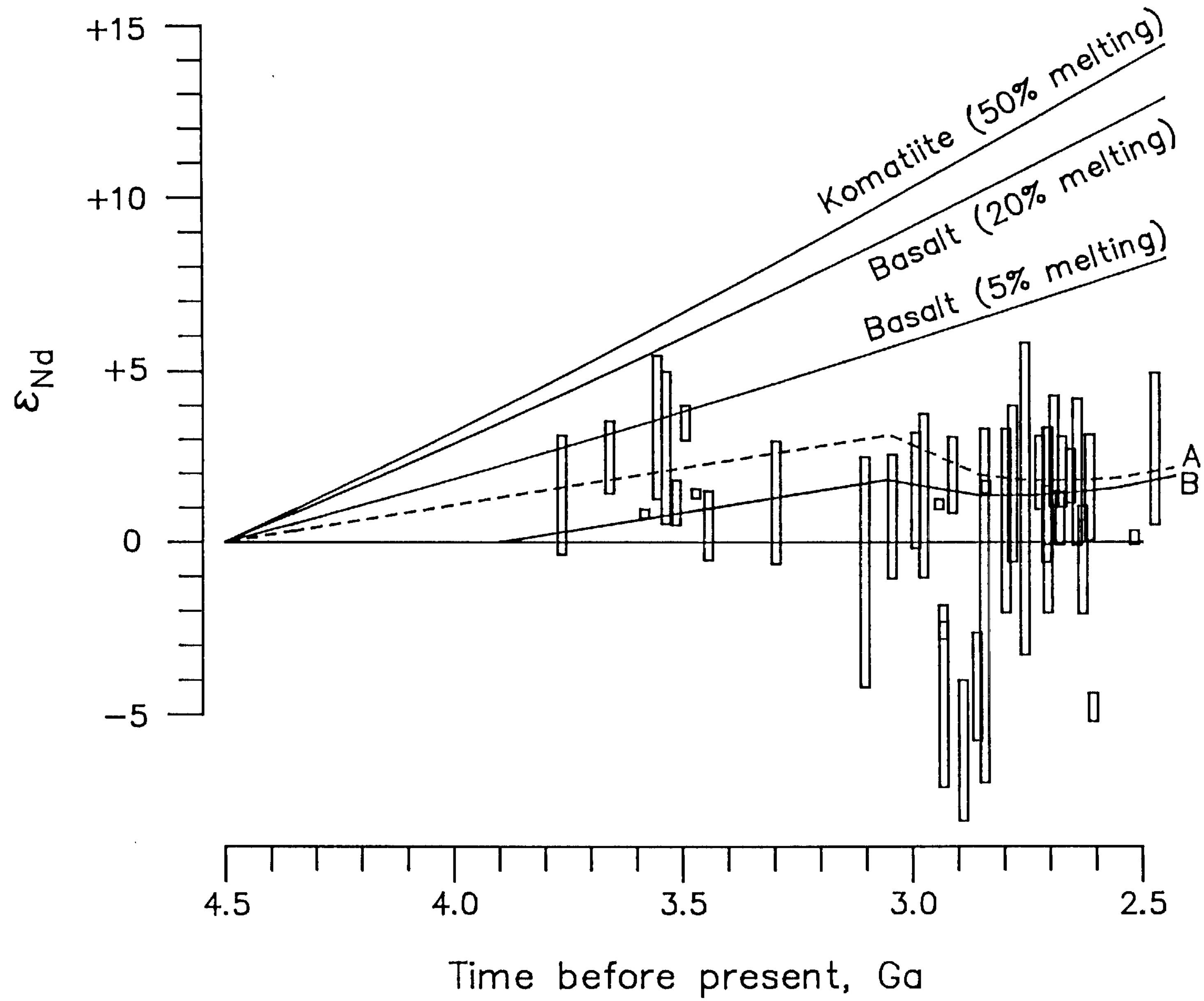

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Figure 3