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Remarks on depleted mantle evolution models used for Nd model age calculation

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Abstract

This paper reviews published models on Nd isotopic evolution of the upper mantle, and focusses in particular on the problems of models currently in use for Nd model age (T_{Nd}) calculation and should help to prevent misleading T_{Nd} interpretation. Presently, T_{Nd} calculations are generally based on depleted mantle (DM) evolutionary models (T_{DM}), implying that continental crust is generated from suboceanic, convecting mantle. However, the properties of the secular evolution curve of the DM, are rather controversial. Depending on the models used, differences between calculated T_{DM} ages for a given sample may be as much as a few hundred millions years. In our opinion a linear evolution model beginning at 4.5 Ga and ending with present-day mean mid-ocean-ridge (MORB) Nd isotopic composition is to be preferred as it is the simplest representation consistent with the presently available data. It also fits the generally accepted assumptions that LREE depletion of the upper mantle commenced very early in earth history and that present-day MORB is the best representative for the Nd isotopic composition of today's DM.

Keywords: depleted mantle, continental crust, Nd isotopes, LREE, fractionation, Central Europe.

Introduction

This paper is meant to help in preventing misleading Nd model age interpretations due to the use of inadequate mantle evolution models or overestimation of the accuracy of such ages and as a complement to the publication of ARNDT and GOLDSTEIN (1987) discussing the significance of Nd model ages. Generally, these ages point to the last important fractionation event of the Sm–Nd isotope system, i.e. when mantle material differentiated into crust. After this fractionation each reservoir evolves with a different Sm/Nd ratio and therefore produces distinct $^{143}Nd/^{144}Nd$ ratios as time progresses. Nd isotopic compositions of continental crust tend to develop towards Nd isotopic composition values lower than those observed in the mantle, because continental crust becomes enriched in light rare earth elements (LREE) during fractionation and consequently has lower Sm/Nd ratios than the mantle. Thus, calculating the age when the Nd isotopic composition of a crustal rock was identical to that of its assumed mantle source, i.e. the Nd model age, we theoretically deduce the age of crustal differentiation from the mantle. However, significance and accuracy of such ages are subject to a number of uncertainties. For example, it may just represent the mean age of a mixture of differently old crustal components (ARNDT and GOLDSTEIN, 1987). Another uncertainty is introduced by the basic assumption that after differentiation from the mantle Sm and Nd are no more fractionated during crustal processes as inferred by the narrow range of Sm–Nd ratios in acid crustal rocks (cf. ALLÈGRE and BEN OTHMAN, 1980; GOLDSTEIN et al., 1984; LIEW and HOFMANN, 1988). This is not valid for all samples, e.g. PIMENTEL and CHARNEY (1991) reported a case of intra-crustal Sm–Nd fractionation in late-stage granitic rocks from central Brazil and BERNARD-GRIFFITHS et al. (1991) showed that high-grade metamorphism can also fractionate REE. The fractionation of Sm–Nd in sediments during alteration or diagenesis has been

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discussed in detail by CHAUDHURI et al. (1993). Additionally, questions concerning the accuracy of Nd model ages arise from the uncertainties of any model used to describe the evolution of the mantle source through time. Depending on the samples and models used, the uncertainties may be as much as a few hundred millions years. This paper in particular focusses on the problem of the different models currently in use to describe the Nd isotopic evolution of the depleted mantle.

Nd isotopes and mantle evolution models

JACOBSEN and WASSERBURG (1979) discussed two models of crust and mantle evolution suggesting (1) that continental crust derived from undepleted mantle by melt extraction taking a depleted mantle as the respective residue, or (2) that continental crust formed by repeated extraction from a mantle reservoir which becomes progressively depleted. Because the undepleted mantle is supposed to have bulk earth Nd isotopic composition, Nd model ages corresponding to model (1) can be calculated using he bulk earth isotopic evolution (T_{CHUR}) (Fig. 1). The best approximation for the bulk earth isotopic composition is given by the so called Chondritic Uniform Reservoir (CHUR, DEPAOLO and WASSERBURG, 1976). This approach was used among others by MCCULLOCH and WASSERBURG (1978). However, many published Nd isotope data of various rock

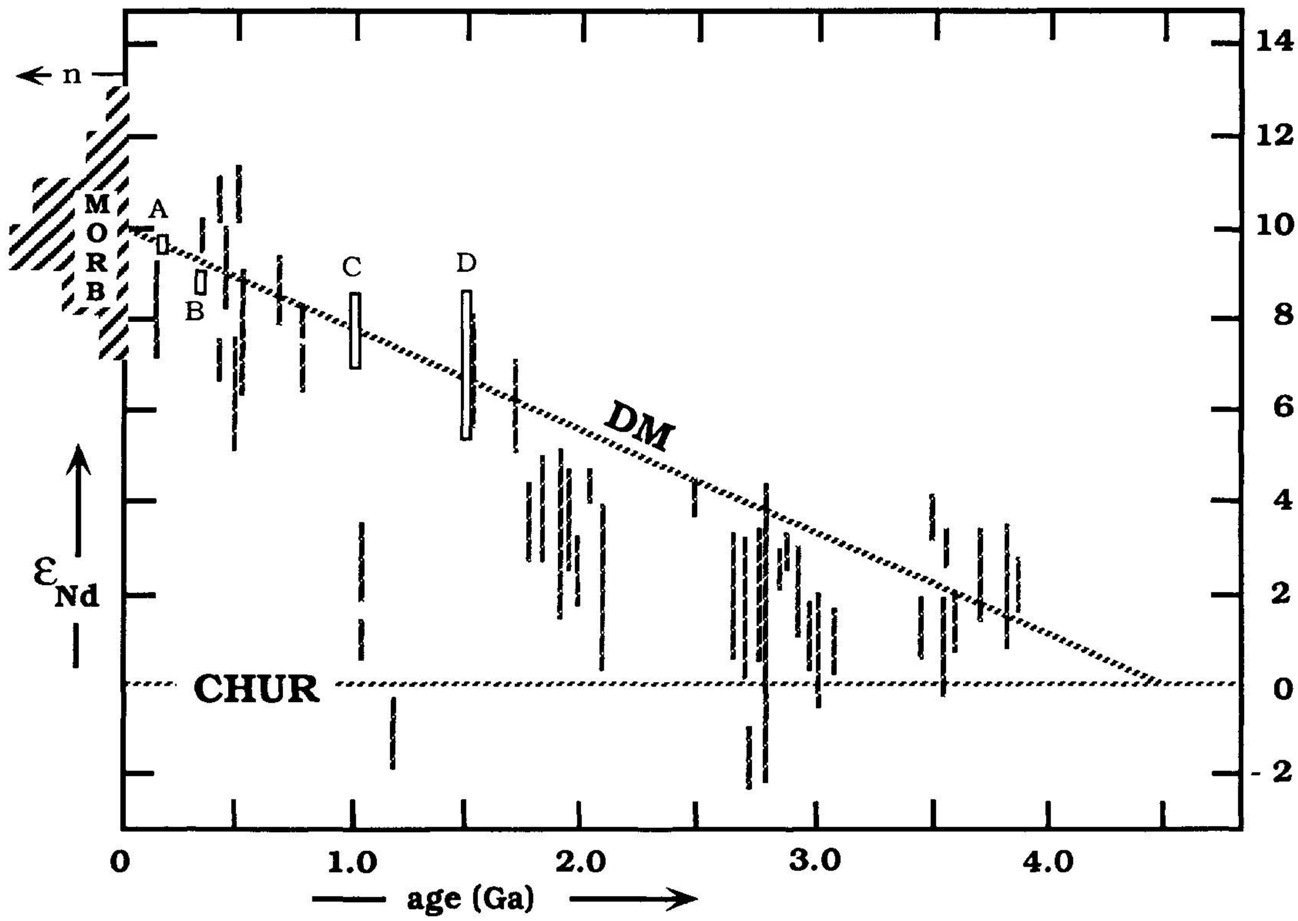

Fig. 1 Initial ε_{Nd} values based on the compilation of GALER, GOLDSTEIN and O'NIONS (1989). The real evolution curve of the depleted mantle is assumed to lie above or towards the upper boundary of these data, as possible additions of older sialic crust would have lowered the initial Nd values. Present-day MORB is shown as a simplified histogram based on MORRIS and HART (1983). Some published data from European samples are added (white bars):
A: Two ophiolite samples (Bündnerschiefer, Alps); $\varepsilon_{Nd[T]}$ = +9.6; +9.8 (STILLE, CLAUER and ABRECHT, 1989)
B: Amphibolites (Poland); $\varepsilon_{Nd[T]}$ = +8.5 ± 0.1 and +8.8 ± 0.1 (PIN, MAJEROWICZ and WOJCIECHOWSKA, 1988)
C: Amphibolites with MORB – like chemical characteristics (Penninic nappe / Alps); $\varepsilon_{Nd[T]}$ = +7.9 ± 0.8 (STILLE AND TATSUMOTO, 1985; STILLE, 1987; SCHENK-WENGER and STILLE, 1989)
D: Initial of Sm–Nd whole rock isochron on sediments (Almaden/Spain); $\varepsilon_{Nd[T]}$ = +7.1 ± 1.6 (NÄGLER, SCHÄFER and GEBAUER, 1992).
They give weight to the model of GOLDSTEIN, O'NIONS and HAMILTON (1984) (shown as DM) which in our opinion should be generally adopted for the interpretation of Nd data from European samples.

Tab. 1 DM evolution models ; n.d. = not defined; n.e. = not existing

Authors	$\varepsilon_{Nd[0]}$	$\varepsilon_{Nd[T]} = 0$ in Ga	$^{147}Sm/^{144}Nd$ constant	$^{147}Sm/^{144}Nd$ at T = O
GOLDSTEIN et al., 1984	10.2	4.5	.214	
NELSON and DEPAOLO, 1984	8.5	n.d.		.197
ALLÈGRE and ROUSSEAU, 1984	8.9	n.e.		.221
DEPAOLO, 1981	8.5	4.6		.220
LIEW and HOFMANN, 1988	10.0	3.5	.219	
MICHARD et al., 1985	9.6	3.0	.222	
DEPAOLO et al., 1981	8.6	4.5	.212	
LIEW and MCCULLOCH, 1984	10.0	2.7	.225	

types of different ages yield positive ε_{Nd} initial values i.e. they derived from sources with $^{143}Nd/^{144}Nd$ ratios higher than CHUR (Fig. 1, compilation in GALER et al., 1989 and DEPAOLO, 1988, p. 66; ε_{Nd} = deviation of $^{143}Nd/^{144}Nd$ from CHUR in tenth of permille) and consequently GALER et al. (1989) assumed the depleted upper mantle to be the direct source of continental crust. Likewise, DEPAOLO (1988, p. 67) concluded that continental crust clearly has been derived from mantle sources similar to those of modern oceanic basalts. Therefore, model age calculations are presently generally based on depleted mantle (DM) evolutionary models, implying that crust is generated from the suboceanic, convecting and depleted mantle. It is noteworthy that some continental mafic rocks are supposed to be generated from subcontinental lithospheric mantle reservoirs (DEPAOLO, 1988, p. 148). These reservoirs are not subject of our discussion. The properties of the applied DM evolution model, i.e. its $^{143}Nd/^{144}Nd$ of today, the start of its particular evolution (age of intersection with CHUR), the shape of its evolution path (linear with constant $^{147}Sm/^{144}Nd$ ratio or curved with increasing or decreasing $^{147}Sm/^{144}Nd$ ratio) are rather controversial (Fig. 2, Tab. 1).

DEPAOLO (1981a) observed on several metavolcanic rocks and granulite xenoliths, which were geographically remote from each other (a few hundred kilometers), a Sm–Nd isochron of 1800 ± 90 Ma. He therefore concluded that the mantle source of these rocks must have been isotopically homogeneous over large distances. DEPAOLO (1981 a, b) assumed an intra oceanic island arc basalt (OIAB) source, remote from continental crust, to fit best this requirement. Thus, DEPAOLO (1981 a, b) and NELSON and DEPAOLO (1984) proposed a present-day ε_{Nd} value of +8.5 for the mantle source, which is a good approximation for today's mean of OIAB.

In the model of NELSON and DEPAOLO (1984), the evolutionary path (Fig. 2, curve 2) of the depleted mantle for the time-span from 3.5 to 0.8 Ga is very similar to that deduced by GOLDSTEIN et al. (1984) (Fig. 2, line 1) which, however, yields a present-day ε_{Nd} of +10, in agreement with ε_{Nd} values of present-day mid-ocean ridge basalts, the representatives of the convecting, depleted upper mantle.

ALLÈGRE and ROUSSEAU (1984) also accepted MORB as the source for the formation of continental crust. Consequently, in their graph (Fig. 2, curve 3) the DM evolution sets out at $\varepsilon_{Nd[today]}$ = +10. However, using the formula and constants given by these authors, the calculated $\varepsilon_{Nd[today]}$ is +8.9.

ALBARÈDE and BROUXEL (1987) attempted to model the evolution of Nd isotopes in both depleted mantle and continental crust. The data base they used to estimate mantle properties were published data on modern and ancient magmatic rocks or their metamorphic equivalents of which the $^{143}Nd/^{144}Nd$ and the $^{147}Sm/^{144}Nd$ ratios pointed

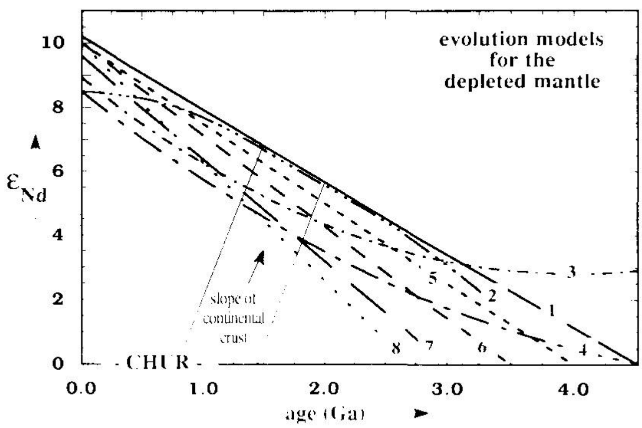

Fig. 2 Evolution models for the depleted mantle
(1) GOLDSTEIN, O'NIONS and HAMILTON (1984)*; (2) NELSON and DEPAOLO (1984); (3) ALLÈGRE and ROUSSEAU (1984)*; (4) DEPAOLO (1981a); (5) ALBARÈDE and BROUXEL (1987); (6) LIEW and HOFMANN (1988); (7) MICHARD et al. (1984)*; (8) LIEW and MCCULLOCH (1985)
*originally not expressed in ε_{Nd} units

to a derivation from a depleted mantle source. After grouping of the samples with respect to their age they deduced an almost linear ε_{Nd} array (Fig. 2, line 5) which intersects the CHUR evolution line at 4.0 ± 0.3 Ga and indicates a $\varepsilon_{Nd[today]}$ of +10. For this investigation the authors excluded island arc samples because of possible incorporation of crustal components on the subducting slab. A similar evolutionary path was presented by DEPAOLO (1988, p. 66) in a figure summarizing published initial $\varepsilon_{Nd[T]}$ values obtained from Sm–Nd isochrons as well as single samples dated by other methods. However, its intersection with CHUR is at 4.5 Ga.

GALER et al. (1989) presented a large compilation of $\varepsilon_{Nd[initial]}$ data from the literature (Fig. 1) and expected that the real evolution curve of the depleted mantle is above or towards the upper boundary of these data, because possible additions of older sialic crust would have lowered the initial ε_{Nd} values. They adopted the linear model of GOLDSTEIN et al. (1984) from $\varepsilon_{Nd[4.5\,Ga]} = \pm\ 0$ to $\varepsilon_{Nd[today]} = +10$ as it represents the simplest one consistent with the data available to them. It is interesting to note that new data on European samples of up to 1.5 Ga in age are in line with this model (Fig. 1).

Even though the mean $\varepsilon_{Nd[today]}$ of MORB is supposed to represent the $\varepsilon_{Nd[today]}$ of the depleted mantle, the same assumption cannot be made for the $^{147}Sm/^{144}Nd$ ratio. This is due to the fact that partial melting of the mantle source produces magmas with similar ε_{Nd} values but $^{147}Sm/^{144}Nd$ ratios lower than those of the source. Indeed $^{147}Sm/^{144}Nd$ ratios observed in MORB samples are variable and scatter down to values below the $^{147}Sm/^{144}Nd$ ratio of CHUR, despite of their ε_{Nd}[today] values averaging +10.

Nevertheless, REE studies on MORBs indicate that the $^{147}Sm/^{144}Nd$ ratio of their source, the present-day depleted mantle, must be in the range of 0.25 or even higher (DEPAOLO, 1988, 105). ALBARÈDE and BROUXEL (1987) noted that this value has not varied too much during the last 3.5 Ga: e.g. nine 2.7 Ga old komatiite samples gave a mean $^{147}Sm/^{144}Nd$ of 0.24 (DUPRÉ et al., 1984). However, none of the proposed secular DM evolution models reflects this $^{147}Sm/^{144}Nd$ ratio. In contrast, all show significant lower values of about 0.2 to account for the ε_{Nd} evolution through time. This bias between $^{147}Sm/^{144}Nd$ model values (0.2) and the deduced actual value (0.25) can be explained by recycling of continental crust with low ε_{Nd} values into the depleted mantle (e.g. ARMSTRONG, 1981 a, b; WHITE and HOFMANN, 1982), and/or injection of material from a primitive mantle reservoir ($\varepsilon_{Nd} = 0$) (e.g. ALBARÈDE and BROUXEL, 1987). With a more or less continuous crustal growth through differentiation (e.g. DEPAOLO, 1980 or ALLÈGRE and BEN OTHMAN, 1980), the $^{147}Sm/^{144}Nd$ ratio of the mantle should increase through time and thus should have been lower than 0.25 in the past. Consequently, an $\varepsilon_{Nd(DM)}$ evolutionary curve would describe the mantle evolution better than a straight line. However, if the reincorporation of sediments increased within the last 1.5 Ga as proposed by DEPAOLO (1983) and NELSON and DEPAOLO (1984), the effect of increasing LREE depletion of the mantle may be compensated – suggesting a straight line evolution of ε_{Nd} – or even over-compensated as indicated by NELSON and DEPAOLO (1984). On the other hand, ARMSTRONG (1981a) suggested a decrease of crustal reinjection since the Archean.

LIEW and MCCULLOCH (1985) preferred to let their depleted mantle evolution model depart at 2.7 Ga, pointing out that "...significant volumes of complementary depleted mantle would only have been stabilized after the 2.5–3.0 Ga crust generation episode...". However, as can be seen in figure 1, there is proof for the existence of a depleted mantle – $\varepsilon_{Nd[T]} > 0$ – in the early Archean: For example the 2.7 Ga old Kambalda sequence of komatiites and basalts (western Australia) gave e_{Nd} values of up to +4 (CHAUVEL et al., 1985) or the reported a 3815 ± 121 Ma Sm–Nd isochron from northern Labrador with an initial ε_{Nd} of +3 for meta-peridotites and meta-pyroxenites, which were believed to be ancient residual mantle (COLLERSON et al., 1991).

BOWRING et al. (1989) reported an ε_{Nd} of about –2 for the oldest intact terrestrial rocks (3.96 Ga) from the Slave province in Canada. This is a direct indication for a LREE enriched complement to the depleted mantle. Consequently such a mantle probably was in existence before that age. Indication for a LREE enrichment complement to the depleted mantle is also given by the isotope data of Archean chemical and clastic sediments with $\varepsilon_{Nd[T]}$ values generally ranging between 0 and +4 (compilation by STILLE et al., 1993). From the modeling of AZBEL and TOLSTIKHIN (1988, 1990) it is further inferred that the mass of continental crust attained the contemporary value about 4 Ga ago, provided the REE contents of this crust have been the same as today. Following HARPER and JACOBSEN (1992), fractionation of Sm and Nd took place as early as 4.44–4.54 Ga ago due to extraction of a LREE enriched primordial crust. This conclusion is deduced from a combined ^{147}Sm–^{143}Nd and ^{146}Sm–^{142}Nd study on a 3.8 Ga old rock from the Isua supracrustal sequence.

The only dated material older than 4 Ga are detrital zircons from western Australia, which support the existence of continental crust 4.2 Ga ago (FROUDE et al., 1983; COMPSTON and PIDGEON, 1986; MAAS and MCCULLOCH, 1991). The lack of crustal rocks older than 4 Ga may be due to the heavy planetesimal bombardment before 3.85 Ga producing intense cratering that probably reconstituted virtually all of the continental crust that existed prior to about 3.9 Ga. (TAYLOR, 1989; WARREN, 1989). Furthermore, a higher convection rate of the upper mantle and substantial crustal recycling are assumed for the early days of the earth (e.g. ARMSTRONG, 1981b; AZBEL and TOLSTIKHIN, 1990).

Conclusions

a) LREE depletion of the upper mantle began very early in earth history. However, we can not consider all crustal material to be differentiated from such an old DM reservoir.

b) A $\varepsilon_{Nd[today]}$ of ≈ +10 as mean value for present-day MORB is the best representative for the present-day depleted mantle source composition. MORB also shows the largest average displacement from CHUR and thus should represent the least contaminated possible source for crust formation.

c) The apparent $^{147}Sm/^{144}Nd$ ratio of the DM evolution is in the range of 0.197 to 0.225 for all discussed models. If there is no further indication for the evolution of the $^{147}Sm/^{144}Nd$ ratio through time, the simplest model using a linear connection between $\varepsilon_{Nd[today]}$ and $\varepsilon_{Nd[T]} = \pm\, 0$, may serve best.

d) To compare relative mean ages of a crustal region – i.e. to use T_{DM} only as indices – any of these models may be used. Geologically meaningful ages can only be deduced, if either the mantle source of the respective crust or rather its surface equivalents can be investigated or if an error of a few hundred million years reflecting the model uncertainties is attributed to these ages.

e) In our opinion a model involving linear increase of ε_{Nd} from $\varepsilon_{Nd[4.5\,Ga]} = \pm\, 0$ to $\varepsilon_{Nd[today]} = +\, 10$ is to be preferred for Central European samples.

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Appendix

ε_{Nd} notation and Nd model age calculation:
ε_{Nd} values represent the deviation from CHUR of the initial Nd-isotopic composition of a sample in tenth of permille. Its mathematical expression is:

$$\varepsilon_{Nd[T]sample} = \left[\frac{^{143}Nd/^{144}Nd_{[T]sample}}{^{143}Nd/^{144}Nd_{[T]CHUR}} - 1\right] 10^4$$

where T is the age; e.g. $\varepsilon_{Nd[0]}$ reflects the deviation from CHUR today. CHUR parameters according to JACOBSEN and WASSERBURG (1980) are: $^{147}Sm/^{144}Nd_{CHUR(0)} = 0.1967$ and $^{143}Nd/^{144}Nd_{CHUR(0)} = 0.511836$ normalized to $^{146}Nd/^{142}Nd = 0.636151$. If normalized to $^{146}Nd/^{144}Nd = 0.7219$ the respective $^{143}Nd/^{144}Nd_{CHUR(0)}$ value is 0.512638 .

A Nd model age is deduced by calculating the age for which the initial $^{143}Nd/^{144}Nd$ ratio of a sample is identical to that of its source, which can be expressed as:

$$(^{143}Nd/^{144}Nd)_{[T]sample} = (^{143}Nd/^{144}Nd)_{[T]source}$$

$(^{143}Nd/^{144}Nd)_{[T]}$ of a sample or source with a quasi linear evolution is given by:

$$(^{143}Nd/^{144}Nd)_{[T]_i} = (^{143}Nd/^{144}Nd)_{[0]_i} - (^{147}Sm/^{144}Nd)_{[0]_i}\,(e^{\lambda T} - 1)$$

with i = sample or source, respectively and λ = decay constant of ^{147}Sm (= 6.54×10^{-12} a). Thus, from the last two equations model ages for sources with linear evolution can be calculated as:

$$T = \frac{1}{\lambda} \ln\left[1 + \frac{^{143}Nd/^{144}Nd_{[0]sample} - {^{143}Nd/^{144}Nd_{[0]source}}}{^{147}Sm/^{144}Nd_{[0]sample} - {^{147}Sm/^{144}Nd_{[0]source}}}\right]$$

In contrast to the quasi linear models DEPAOLO (1981) defined the evolution curve of the depleted mantle in terms of its deviation from CHUR by a second order polynomial fit:

$$\varepsilon_{Nd[T]}\,DM = 0.25\,T^2 - 3T + 8.5$$

As $\varepsilon_{Nd[T]}$ DM has no unit but the polynomial function has, a mathematically proper deduction of the respective model ages is not given. DEPAOLO (1981) model ages corresponds to T (in Ga) satisfying the condition:

$$\varepsilon_{Nd[T]sample} = 0.25\,T^2 - 3T + 8.5$$