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Geochemistry (Cosmochemistry)

The early terrestrial crust

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Abstract

Recent geochemical evidence based on the ^{146}Sm–^{142}Nd system and Hadean zircons shows that the Earth's mantle experienced depletion approximately 100 Ma after the formation of the solar system, and possibly even before (earlier than 30 Ma), due to the extraction of a crust enriched in incompatible elements. Depending on the model ^{142}Nd abundance assumed for the Bulk Earth, the early crust may have been stored in the deep mantle, or may have been remixed in the mantle with a timescale of ∼1 Ga. If the Earth is considered to have a ^{142}Nd composition identical to that of ordinary chondrites, then it implies that the early crust (or the enriched reservoir) is now present at the core–mantle boundary and has remained isolated from the rest of the Earth for the past 4.5 Ga. If the primordial crust had a basaltic composition, then it is unlikely that this enriched reservoir remained isolated for more than 4.5 Ga due to entrainment; yet, there is no signature of this reservoir in hotspot lavas that should sample this enriched reservoir. In contrast, if the Bulk Earth has an Nd isotopic composition slightly distinct from that of chondrites, then there is no need to invoke a hidden reservoir and the early crust must have been remixed by mantle convection prior to the formation of the modern continents. ***To cite this article: B. Bourdon, G. Caro, C. R. Geoscience 339 (2007).***

Résumé

La croûte terrestre primitive Des observations géochimiques récentes, basées sur le système ^{146}Sm–^{142}Nd et sur des zircons d'âge Hadéen montrent que le manteau terrestre a subi un appauvrissement environ 100 Ma après le début du système solaire et peut-être même avant (<30 Ma), par extraction d'une croûte enrichie en éléments incompatibles. Suivant le modèle utilisé pour l'abondance du ^{142}Nd dans la Terre totale, on déduit que cette croûte précoce aurait été stockée dans le manteau profond, ou se serait remélangée dans le manteau avec un temps caractéristique de ∼1 Ga. Si l'on considère que l'abondance terrestre en ^{142}Nd est la même que celle des chondrites ordinaires, la croûte précoce (c'est-à-dire un réservoir enrichi) est présente à la limite noyau–manteau et est restée isolée pendant les derniers 4,5 Ga. Si cette croûte primordiale avait une composition basaltique, alors il est peu probable que ce réservoir enrichi ait pu rester isolé pendant plus de 4,5 Ga, à cause du phénomène d'entraînement. Malgré cela, il n'y a pas de trace d'une telle signature dans les laves de points chauds qui devraient échantillonner ce réservoir. Par opposition, si la Terre a une composition isotopique légèrement différente de celle des chondrites, il n'y pas lieu d'invoquer un réservoir caché, et la croûte primordiale a dû être recyclée dans le

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manteau avant la formation des continents présents actuellement. ***Pour citer cet article : B. Bourdon, G. Caro, C. R. Geoscience 339 (2007).***

Keywords: Early crust; Hadean; Neodymium; Chondrites; Zircon

Mots clés : Croûte primitive ; Hadéen ; Néodyme ; Chondrites ; Zircon

1. Introduction

As the Earth is a tectonically active planet, it is very difficult to find direct evidence for its earliest crust. If one considers that the gravitational energy brought by accreting objects was not radiated fast enough, then it is likely that the Earth was molten at least partially at an early stage. Such an event, which has been called a magma ocean, is likely to have taken place during the late stages of the Earth's accretion, when a giant impact such as the one that could have formed the Moon would have deposited rapidly a large amount of gravitational energy [12,47]. Once the Earth was molten, it is likely that it was surrounded by a thick atmosphere (e.g., [28,29]), whose composition was partially controlled by melt-gas equilibria as described, for example, in [22]. The lifetime of this early atmosphere is not well determined, but even if we assume that the entire C present in the Earth's surface reservoirs was in the atmosphere as CO_2, the surface temperature of the Earth would have rapidly dropped below the solidus temperature of silicate rocks at low pressure [25]. Thus, due to inevitable cooling, the surface of the Earth must have been partly frozen, despite a large initial greenhouse effect. The surface of the Earth could have consisted, for example, of hydrated peridotite (serpentinite), as described in [53], or simply as a mafic crust. One should note that the lifetime of serpentine as a chill crust was probably short, because it was not negatively buoyant, and had all reasons to sink back to the mantle. In order to be stable, the early crust must have been significantly buoyant. While this picture of the first stages of Earth history may seem rather speculative, we are starting to find evidence for the later stages that resulted in the formation of a crust.

2. Evidence for an early crust on Earth

The earliest record of a crust on the Earth has been found in old cratons in Greenland, Canada, South Africa, and western Australia [6,7,32,35]. The oldest terrestrial materials are detrital zircons discovered in the Jack Hills meta-conglomerates (western Australia), with a few crystals as old as 4.4 Ga, which is practically as old as the Earth [31,51]. The oldest Jack Hills zircons are still 130 Ma younger than the age of the Earth, as inferred from Hf–W systematics (4.53 Ga, [26,52]). Thus, they may not necessarily have recorded events that took place during the earliest part of the Hadean era. A more extensive geological record has been found in the highly metamorphosed Acasta gneiss in northern Canada, whose oldest zircons were dated back to 4.0 Ga [6,7]. However, the quality of the Acasta gneiss as an archive for the Hadean period is questioned by its whole-rock Sm–Nd data, yielding a crystallisation age almost 600 Ma younger than that of the oldest zircons [33]. The Isua supracrustal belt (western Greenland) is better constrained chronologically at 3.7–3.8 Ga by various methods [33,36], and includes complete sediment, volcanic, and magmatic series. These terranes have been the subject of intense scrutiny in the recent years, given the important archive they could provide about the early history of our planet.

3. The record of an early crust from Jack Hills zircons

Much research has focused on the zircons of Jack Hills, as they represent the oldest remnants of continental material from the Hadean era (4.5–4.0 Ga). As the analyses necessary to extract a geochemical message from the zircon require new and technically challenging methods, this area of research has been the subject of recent important findings that are summarized below.

Only very few of the Jack Hills zircons are actually as old as 4.4 Ga. There is in fact a large range of ages and only less than 1% is older than 3.9 Ga. A first point of debate is whether the presence of zircons, which are traditionally thought to be saturated in silica-rich melt [49], really indicates the presence of a differentiated granitic crust around 4.4 Ga. If the zircons crystallized from mafic lava, then their temperature should be above 1000 °C, while if they formed from felsic lava, then they should indicate a lower temperature. A geothermometer based on the Ti content [50] has been argued to indicate relatively cool temperatures (around 700 °C) for zircon crystallization; this would indicate a melt generation in a water-rich environment.

A second important question relates to the nature of the silicate inclusions found in the Jack Hills zircons. The presence of granitic melt composition in itself would indicate the presence of water in the source of the primary melt yielding the granite. Additionally, a report of O isotopes in zircons has yielded $\delta^{18}O$ between 5.3‰ (mantle zircon) and 8‰, a value typical of zircons from S-type granites [16,31,40,51]. Some $\delta^{18}O$ data even reach 15‰, but could be due to alteration [16]. These observations have been taken to indicate the presence of liquid water at the surface of the Earth. At face value, this would indicate that the temperature at the surface of the Earth was sufficiently cold to allow water condensation from the atmosphere [48]. For an atmospheric pressure of 100 bar, the starting condensation temperature could have been 570 K approximately, based on the phase diagram of water.

Another important record given by the Jack Hills zircons is their Lu–Hf systematics. As Hf is a major element in the zircon chemistry, and Lu/Hf ratios are close to zero, it is thought that zircons faithfully record the Hf isotope composition of the parent magma from which they crystallized. Harrison et al. [21] have recently analyzed in situ the Jack Hills zircons by MC–ICPMS, and the data clearly show that the majority of zircons were derived from an enriched reservoir, possibly some pre-existing crust. Furthermore, the ε_{Hf} values increasingly deviate from chondritic to negative ε_{Hf}, as zircons decrease in age from 4.4 to 4 Ga. There is however evidence for some degree of source heterogeneity, as shown by the positive initial ε_{Hf} for less than 25% of the samples. These observations clearly point to the existence of a crust that is at least 4.4–4.5 Ga old and this old crust might have been involved in new crust generation throughout the Hadean era. The complementary trend of increasing $\delta^{18}O$ in zircons for 4.4 to 4 Ga shows that remelting of this primordial crust was accompanied by the incorporation of a significant sedimentary component.

4. The ^{142}Nd record of mantle-crust differentiation

An alternative method to investigate early crust formation on Earth is based on the extinct radioactivity of ^{146}Sm (half life = 103 Ma). This p-process nuclide was produced prior to the beginning of the solar system and has been detected in meteorites (e.g., [27,42,43]). Although the abundance of ^{146}Sm is low (the initial $^{146}Sm/^{144}Sm$ in the solar system was $\sim 8 \times 10^{-3}$, [27]), it is perfectly detectable and any Sm/Nd fractionation occurring prior to 4.2 Ga will result in an anomaly in the abundance of the daughter nuclide of ^{146}Sm, ^{142}Nd. After 4.2 Ga, the abundance of ^{146}Sm is too low to generate any anomalies, except if the Sm/Nd fractionation is extreme. Initial attempts to investigate the $^{146}Sm–^{142}Nd$ terrestrial record were spectacular with the first evidence for ^{142}Nd anomalies as large as 30 ppm in an Isua sediment [20], but they were further met with skepticism, as a comprehensive assessment of the reproducibility of the instrument showed that the precision of Harper and Jacobsen's data was perhaps overestimated [46]. Data from several other groups [19,30,45] also contradicted the first report by Harper and Jacobsen [20].

With the better precision attainable with a new generation of instruments [14,15], clear evidence for ^{142}Nd anomalies in the Isua rocks became available (Fig. 1). The magnitude of the anomalies does not exceed 15 ppm approximately, which is significantly smaller than the 30-ppm anomalies claimed by Harper

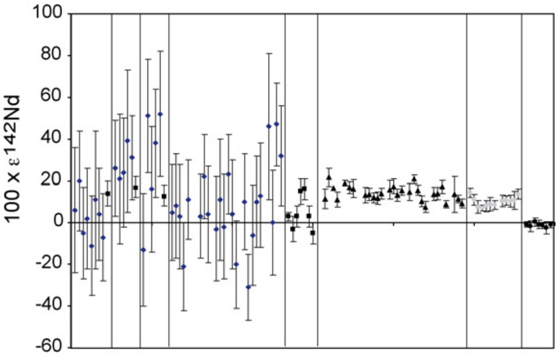

Fig. 1. Compilation of published ^{142}Nd data for Early Archean rocks, including uncertainties of the measurements. Solid diamonds, Boyet et al. [10] ; solid squares, Boyet et al. [8] ; solid triangles, Caro et al. [14] ; grey circles, Caro et al. [15]. Other data by Caro et al. [15] are reported for reference (solid circles). The Early Archean data of Caro et al. [14,15] and Boyet et al. [8] show clearly resolved anomalies thanks to the better uncertainties obtained by thermal ionization mass spectrometry. It must be noted that the data by Boyet et al. [8] did not yield resolvable ^{142}Nd anomalies in all samples.

Fig. 1. Compilation des données de ^{142}Nd publiées sur des roches archéennes montrant les incertitudes de mesures. Losanges, Boyet et al. [10], carrés, Boyet et al. [8] ; triangles, Caro et al. [14] ; ronds gris, Caro et al. [15]. Les autres données de roches archéennes de Caro et al. [15] sont montrées pour référence (ronds pleins). Les données sur l'Archéen de Caro et al. [14,15] et de Boyet et al. [8] montrent des anomalies de ^{142}Nd bien résolues, grâce aux incertitudes obtenues par spectrométrie de masse à thermo-ionisation. On doit noter, cependant, que les échantillons de Boyet et al. [8] n'ont pas tous montré d'anomalies résolvables.

and Jacobsen [20] and the anomalies reported later by Boyet et al. [10] using an MC–ICPMS. A report by Papanastassiou et al. [39] on the same sample as Harper and Jacobsen [20] could not confirm a 30-ppm anomaly. This indicates that the level of ^{142}Nd anomalies claimed by Harper and Jacobsen [20] and Boyet et al. [10] has not been confirmed, as shown by studies by Caro et al. [14,15], Boyet and Carlson [9] and Bennett et al. [4]. The most recent data set presented by Bennett et al. [4] is remarkably consistent with the data of Caro et al. [15].

Caro et al. [4] used a combined ^{143}Nd–^{142}Nd data set to infer an age of mantle differentiation. Their approach is based on the present-day measured ^{142}Nd anomaly as well as calculated $\varepsilon_{143_{\mathrm{Nd}}}$ at the time the Isua rocks formed. The initial $\varepsilon_{143_{\mathrm{Nd}}}$ was inferred from a whole-rock isochron that yielded an age consistent with the zircon age of adjacent terrranes [33]. The calculated differentiation age for the silicate Earth ranges between 4.35 and 4.52 Ga. Since this differentiation must have involved the extraction of a melt from the mantle (leaving a residue with a higher than average Sm/Nd), it was inferred that this event was related to crustal extraction. It could be argued that using a two-stage model to infer an age is unreliable, as the ^{146}Sm–^{142}Nd method would only be sensitive to a Sm/Nd fractionation taking place no later than 4.2 Ga, while the ^{147}Sm–^{143}Nd method is sensitive to fractionation from 4.5 Ga until 3.8 Ga (i.e. the age of Isua). This question can be investigated, for example, by comparing the outputs of a two-stage model, where differentiation takes place at a discrete time with a model with continuous differentiation. It turns out that there is no significant difference, as illustrated in Fig. 2, between the two calculated ages. This indicates that the history post-dating 4.2 Ga does not greatly affect ^{147}Sm–^{143}Nd systematics over the considered time scale. Thus, one may consider that these age estimates of mantle–crust differentiation are reliable. It must be mentioned here that the bulk Earth ^{142}Nd/^{144}Nd composition used for these calculations is equal to the mean composition measured in oceanic basalts and all other mantle-derived rocks, except for Isua [9,14,15]. Since all the terrestrial rocks except for some Early Archean ones have identical ^{142}Nd isotope compositions, Caro et al. [15] further inferred that mantle convection and stirring had erased the signature of the early differentiation.

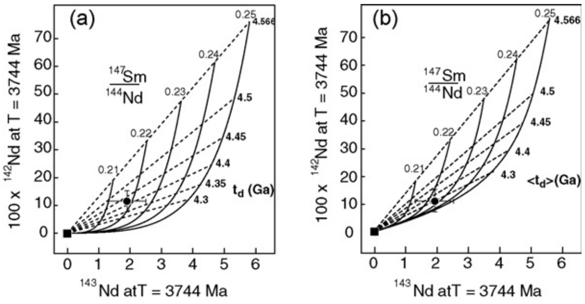

Fig. 2. ^{142}Nd–^{143}Nd model age calculations for Isua and West Greenland rocks using (a) a two-stage model and (b) a continuous growth model. The two-stage model involves instantaneous differentiation of the mantle–crust system at time t_{d} and subsequent closed-system evolution of the two reservoirs. The continuous growth model (equation from Jacobsen and Wasserburg [23], Model 1) involves the formation of crust and depleted mantle according to an exponentially decreasing growth rate. $<t_{\mathrm{d}}>$ is the mean age of the crustal reservoir at the time of formation of Isua ($t \sim 3.75$ Gyr). The results of this model yield a mean age of differentiation slightly younger than that obtained using a two-stage model, but the difference remains small compared with other sources of uncertainties. The absence of a large difference between continuous and instantaneous growth models indicates that differentiation of the early crust must have proceeded almost instantly after the end of terrestrial accretion.

Fig. 2. Âges modèles par la méthode ^{142}Nd–^{143}Nd pour les roches d'Isua et de l'Ouest du Groenland, basés sur (a) un modèle à deux stades et (b) et un modèle continu de croissance crustale. Le modèle à deux stades comprend une différenciation en croûte + manteau au temps t_{d}, suivi d'une évolution en système fermé des deux réservoirs formés. Le modèle continu de croissance crustale (équation donnée dans Jacobsen and Wasserburg [23], Modèle 1) est basé sur la formation d'une croûte et d'un manteau appauvri, avec un taux de croissance suivant une loi exponentielle décroissante. $<t_{\mathrm{d}}>$ est l'âge moyen du réservoir crustal à l'âge où les roches d'Isua se forment ($t \sim 3{,}75$ Gyr). Les résultats de ce deuxième modèle donnent un âge de différenciation légèrement plus jeune que celui donné par le modèle à deux stades, mais la différence entre ces deux âges est faible par rapport aux autres sources d'incertitude. Cette absence de différence significative entre les deux modèles implique que la différenciation de la croûte primitive a dû se faire très tôt après l'accrétion de la Terre.

An alternative view can be considered if one makes the assumption that terrestrial reservoirs were initially strictly chondritic; then it follows that all terrestrial rocks are anomalous in ^{142}Nd relative to the bulk Earth composition [8]. From this observation, Boyet and Carlson [8] concluded that the Earth would then have differentiated earlier than 30 Ma after the beginning of the solar system. It would imply that the signature of mantle depletion recorded by mid-ocean ridge basalts is entirely accounted for by very early differentiation processes, in contrast with the widely accepted model of depletion by continental crust at a much later stage of the Earth's history. The effect of a later differentiation must have been limited in this model, as it would have produced a mantle reservoir more depleted than the MORB-source mantle, which is not observed. This model requires that the depleted reservoir carrying an enriched ^{142}Nd/^{144}Nd (and ^{143}Nd/^{144}Nd) signature has been completely isolated from convective entrainment and mixing for 4.5 Ga.

5. Bulk Earth composition and consequence on inference of crust-mantle differentiation

A standard paradigm for studying the bulk composition of the Earth is that the bulk silicate earth Sm and Nd isotope composition is identical to the mean composition of chondrites. This assumption is based on the fact that Sm and Nd are both refractory elements that should not fractionate during planet formation. Second, as these elements are also lithophile, all of their budget should be in the silicate portion of the planet. Nevertheless, it is worth pointing out that this assumption now needs to be carefully assessed.

The precise measurements of chondrites suggest that their ^{142}Nd/^{144}Nd ratios [2,8] is actually lower by 20 to 40 ppm compared with all terrestrial samples (except for Isua samples, for which the difference is even greater). Interestingly, there is a clear difference in ^{142}Nd between ordinary chondrites, and carbonaceous chondrites [2]. Thus, while Sm and Nd are expected to be distinct among these various types of chondrites, the difference between these groups is at least as large as the difference between Earth material and ordinary chondrites. Furthermore, many other indicators (including oxygen and possibly chromium isotopes) suggest that the Earth-forming material is not necessarily identical to meteorites, which are collected from radial distance ranging between 2 and 3.4 AU. Numerical simulations of the provenance of the Earth-forming material [34] show that the material forming the Earth could be distinct from that in the asteroid belt, where meteorites are presumably being sampled. A less often mentioned hypothesis is to consider that the Earth is not made of material represented in our meteorite collections.

The origin of a distinction in the ^{142}Nd abundance between the Earth and meteorites could be: (1) a difference in Sm/Nd ratio between the Earth and meteorites, (2) a difference in the relative abundance of r- and s-process nuclides in meteorites and the Earth, which would lead to variable ^{142}Nd abundances, or (3) a heterogeneous distribution of ^{146}Sm abundance in the solar system, which would imply a heterogeneous level of relatively long lived p-process nuclides. This would ultimately result in heterogeneities in the abundance of ^{142}Nd.

There are indications that a small Sm–Nd cosmochemical fractionation could take place. For example, during high-temperature processes in the nebula, Sm and Nd do not behave perfectly similarly (e.g., [11,38]). Large anomalies in Sm abundances can be produced during fractional condensation in a very reducing nebular environment. REE fractionation during condensation in more oxidizing conditions (CI as opposed to solar composition) has also been demonstrated in refractory inclusions in chondrites [18]. Although these large effects are not observed in bulk meteorites, their occurrence in primordial meteorite components demonstrate that REE fractionation processes did take place during the initial condensation of the nebula. Incomplete condensation may have therefore resulted in a zonation in the abundance of REE in the disk, and it is possible that the Sm/Nd ratio in the Earth is not exactly identical to that of chondrites, at least at a very fine scale. In order to explain the 20-ppm difference in $\varepsilon_{142_{\mathrm{Nd}}}$ between the Earth and chondrites assuming an initially homogeneous ^{142}Nd/^{144}Nd in the solar nebula, the Sm/Nd ratio would need to be equal to 0.205–0.210. This might be prohibitively high, as argued by Boyet and Carlson [8], but no independent constraint on the Sm/Nd ratio of the bulk Earth can be used to test this hypothesis.

There have already been several investigations of the second hypothesis. For example, Ranen and Jacobsen [44] have reported a distinct barium isotope composition of the Earth compared with chondrites, with a positive anomaly on ^{138}Ba, although these results are apparently in conflict with a recent report [3] that has only observed anomalies in ^{135}Ba and ^{137}Ba. Both Nd and Ba isotope compositions could indicate slight differences in the abundance of r- and s-process nuclides. It is generally assumed that the solar nebula was well mixed to start with, but there could be some remaining chemical and isotope heterogeneities as high as 10% of the starting heterogeneity [13]. In the case of ^{142}Nd isotope, the starting heterogeneity could have been in terms of $\varepsilon_{142_{\mathrm{Nd}}}$ as high as 10 ε [5], such that a residual dispersion of 0.20 ε units is well in agreement with observations. Thus, it is not unconceivable that the material forming the Earth was slightly different from ordinary and carbonaceous chondrites in terms of its REE isotope composition. Yet, the study of Andreasen and Sharma [2] based on Sm isotopes also shows heterogeneities in p-process nuclides between carbonaceous chondrites, on the one hand, and eucrites, ordinary chondrites, the Earth and the Moon, on the other hand. In this case, the bulk Earth Nd isotope composition could be identical to that of ordinary chondrites, which differs from the conclusion of Ranen and Jacobsen [44]. An even more recent study by Carlson et al. [13] shows no ^{138}Ba anomaly in chondrites, and evidences that, once corrected for deficiency in s-process nuclides, the ^{142}Nd isotope abundances in carbonaceous and ordinary chondrites are consistent with each other. The published results in Ba, Nd and Sm nucleosynthetic anomalies are obviously not all consistent and this means that further work is required to clarify this question. Interestingly, it appears that the ordinary chondrites would have Nd and Sm isotope compositions that could match that of the Earth; yet major and trace element data for the Earth do not generally fall on the trends defined by this family of meteorites [1]. Rather, the Earth falls on trends defined by carbonaceous chondrites, so it is certainly premature to conclude that the Earth is made of ordinary chondrites.

While this question is still open at this stage, the preliminary interpretation of Boyet and Carlson [8] suggesting the existence of a hidden reservoir is currently undergoing serious reconsideration [2,3,44]. If there is such an initial heterogeneity in ^{142}Nd isotopes or in Sm/Nd between the Earth and chondrites, then there is no requirement for a hidden reservoir. The implications for the later history of the Earth differentiation are rather dramatic, as discussed in what follows.

6. The fate of the early terrestrial crust

There are competing hypotheses about the fate of the early terrestrial crust (or an early enriched reservoir). In the model proposed by Caro et al. [15], since all the terrestrial rocks show homogeneous ^{142}Nd/^{144}Nd ratios, an obvious interpretation is that all the traces of early differentiation have been erased by convection and mixing, except for those found in the oldest continental crust that were isolated from mantle convection when the Isua crust formed.

The alternative hypothesis proposed by Boyet and Carlson [8] is that the enriched reservoir that would explain the difference between the 'observable Earth' and chondrites has been completely isolated from convective mixing by being stored above the core-mantle boundary. In order to test this hypothesis, we have first estimated the ^{142}Nd/^{144}Nd ratio for the enriched reservoir (not given in [8]) and then estimated the maximum fraction of material that could be entrained without causing noticeable deviation in hotspot lavas (<-2 ppm). This mixing calculation shows that no more than 1% can be entrained before an anomaly is detected in magma erupted in hotspots. Yet, no hotspot lava has shown clear evidence of a negative $\varepsilon_{^{142}\mathrm{Nd}}$ [8,9].

In what follows, we discuss physical constraints on (1) the level of isolation of a dense reservoir stored at the bottom of the mantle and (2) the expected level of heterogeneity of a mantle where there is a low but constant input of enriched material.

There is now ample evidence that dense material can be stabilized at the core–mantle boundary as long as there is a density contrast with the overlying material [17]. If the crust consisted of more silica-rich material, then it is likely that it never became negatively buoyant. Thus, one needs to consider the storage of basaltic material and in this case, the predicted density contrast with peridotites for pressures greater than 120 GPa [37] is approximately 1–2%. With such a density contrast, the reservoir will be stable, but there will always be some level of entrainment each time a plume forms. As described by Davaille [17], it is possible to estimate quantitatively the material flux entrained by the plume as well as the lifetime of this reservoir. Obviously, unless the reservoir is unrealistically denser than the

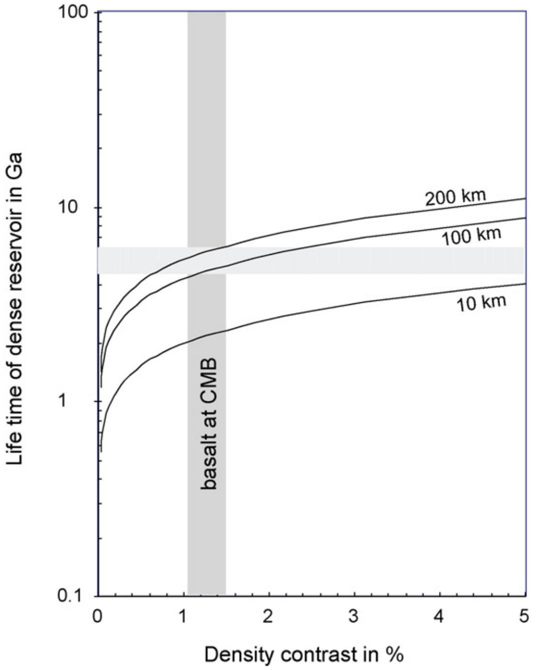

Fig. 3. Lifetime of a dense crustal reservoir at the core–mantle boundary. A typical density contrast for a basaltic crust at the core–mantle boundary would be 1.2%. If the thickness of this reservoir is 100 to 200 km, then the lifetime of this reservoir will be approximately 5 Ga. This calculation was done using the equations given in Davaille [17]. This suggests that a long-lived enriched reservoir could be preserved in the deep Earth.

Fig. 3. Durée de vie d'un réservoir crustal dense à la limite noyau–manteau. Un contraste de densité typique pour une croûte basaltique est de 1,2 %. Si l'épaisseur de ce réservoir est de 100 à 200 km, alors la durée de vie de ce réservoir sera d'environ 5 Ga. Ce calcul a été effectué avec les équations de Davaille [17]. Ceci suggère qu'un réservoir enrichi dense peut être préservé dans les profondeurs du manteau terrestre.

overlying mantle, there is no reason to believe that a reservoir should remain hidden. More importantly, there are good means of estimating the leakage flux. As shown on Fig. 3, for a 200-km layer with a viscosity contrast of 10, the lifetime of the reservoir will be approximately 5 Ga. This indicates that there will be injection of anomalous ^{142}Nd in the convective mantle throughout Earth history. As a consequence, it is not expected that the mantle should be homogeneous with respect to ^{142}Nd (both at present time, as is currently observed, and also in the past). Using the model developed by Caro et al. [15], it is possible to estimate both the mean composition of the mantle reservoir and its heterogeneity as a function of time, assuming that an enriched reservoir advocated by Boyet and Carlson [8] segregated less than 30 Ma after the beginning of the solar system. We make the simplifying assumption that the dense material is being replenished with material with a mantle-like composition, but with an enriched Sm/Nd ratio, such that the present-day ^{142}Nd and ^{143}Nd ratios match the observed mean values. It turns out that the model cannot match the observations properly. If there is a long-lived reservoir at the core–mantle boundary, there will be always lingering isotope heterogeneity in the mantle of up to ±15 ppm. This is in contrast with what has been observed by Caro et al. [15], Boyet and Carlson [9] for mantle-derived rocks. All the mantle-derived rocks (Archean rocks, modern ocean island and mid-ocean ridge basalts) show little deviation in term of ^{142}Nd. This strongly questions the very existence of a hidden reservoir. Of course, it is not impossible that future investigation will show clear evidence for heterogeneity in ^{142}Nd in mantle-derived rocks.

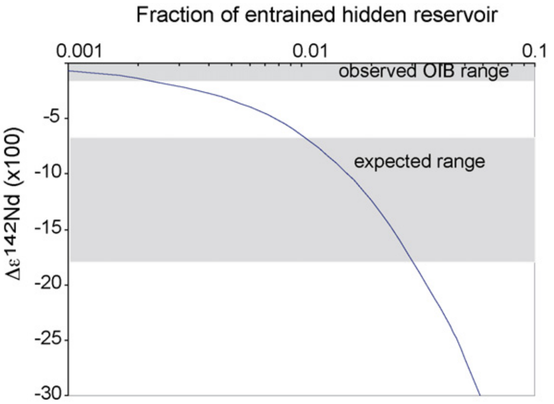

Fig. 4. Detection of an early differentiated crust in the source of ocean island basalts based on ^{142}Nd anomalies. The ^{142}Nd anomalies is reported as a difference from a typical terrestrial value ($\varepsilon_{142_{\mathrm{Nd}}} = 0$). If the fraction of entrained enriched reservoir is more than 1%, then the value of $\Delta\varepsilon_{142_{\mathrm{Nd}}} \times 100$ could easily reach −10 to −15 ppm, which has so far not been observed in terrestrial basalts.

Fig. 4. Détection de la présence de croûte primitive dans la source des basaltes d'îles océaniques, basée sur les anomalies de ^{142}Nd. Les anomalies de ^{142}Nd sont données ici comme une différence par rapport à la valeur terrestre pour laquelle on a $\varepsilon_{142_{\mathrm{Nd}}} = 0$. Si la fraction de réservoir enrichi qui est entraînée est supérieure à 1 %, alors la valeur de $\Delta\varepsilon_{142_{\mathrm{Nd}}} \times 100$ pourrait atteindre −10 to −15 ppm, ce qui n'a pas été observé dans les basaltes terrestres jusqu'à présent.

While the overall heterogeneity of the mantle in ^{142}Nd remains limited, there could also be a local heterogeneity due to either imperfect mixing and/or entrainment of the enriched reservoir during plume formation. The study of Jellinek and Manga [24] shows that tendrils with a radius of 5 to 10 km can be entrained from a dense layer. The radius of the plume when they form could be less than 50 km, such that the mass fraction of entrained material would be more than a few %. As mentioned above, we expect that no more than 0.5% of the enriched reservoir is present in mantle-derived rocks. Given that the enriched reservoir should also be more fertile than a normal peridotite, it is expected that its mass fraction will be even greater once the material starts to melt. Using the solidus and liquidus from Petermann and Hirschmann [41], if the initial mass fraction of enriched material is 2% and it melts by 30%, while the peridotite melts by 10%, the observed ^{142}Nd anomaly should be −12 ppm relative to the terrestrial value, which has never been observed. This is illustrated in Fig. 4, showing the deviation in $\varepsilon_{142_{\mathrm{Nd}}}$ for various entrainment scenarios described above. It is quite clear that there is currently no sign of an enriched reservoir in mantle-derived rocks. Thus, while the hypothesis of a hidden reservoir in the deeper Earth would seem a priori attractive, it needs further testing of its physical plausibility. The simple approach presented here does not lend clear support to this hypothesis.

7. Conclusions

The evidence for an early differentiation of the Earth mantle and the formation of an early crust is becoming quite clear, both on the basis of complementary observations in zircons and in Early Archean rocks. The ^{146}Sm–^{142}Nd systematics requires a crustal extraction prior to ∼4.45 Ga. If the Earth's composition in ^{142}Nd turns out to be identical to chondrites, then this puts additional constraints on the timing of early Earth differentiation and later mantle evolution, by requiring the presence of a hidden reservoir and a differentiation time prior to 4.52 Ga.

However, the presence of a perfectly hidden reservoir is not compatible with modern views of mantle convection, given the density contrast between crustal material and ambient mantle near the core–mantle boundary. To be entirely hidden, a reservoir would have to have a greater density contrast than what has been observed experimentally. These inferences do not disprove the presence of a hidden reservoir, but certainly do not strengthen this hypothesis. Further studies of chemical and isotope heterogeneities in solar system objects will clearly help solving this controversy.

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