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Nd and Sr isotopes from diamondiferous eclogites, Udachnaya Kimberlite Pipe, Yakutia, Siberia: Evidence of differentiation in the early Earth?

Gregory A. Snyder [a], Eric A. Jerde [a], Lawrence A. Taylor [a], Alex N. Halliday [b], Vladimir N. Sobolev [c] and Nikolai V. Sobolev [c]

[a] *Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996, USA*
[b] *Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109, USA*
[c] *Institute of Mineralogy and Petrography, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia*

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ABSTRACT

Nd and Sr isotopic data from diamond-bearing eclogites found in the Udachnaya kimberlite, Yakutia, Siberia, are interpreted as indicating an early ($\geqslant$ 4 Ga) differentiation event, whereby the mantle split into complementary depleted and enriched reservoirs. Reconstructed whole-rock $^{87}Sr/^{86}Sr$ ratios (present-day) range from 0.70151 to 0.70315 and are consistent with a mantle origin for these rocks. The Nd isotopic evolution lines of four samples (U-5, U-37, U-41 and U-79) converge at 2.2–2.7 Ga. Sample U-5 is unique in exhibiting the most enriched signature of any of the samples yet analyzed (present-day ϵ_{Nd} of -20), and this sample points unequivocally to an old, enriched component. A complementary depleted mantle component is suggested by two of the eclogite samples, U-86 and U-25, which yield ϵ_{Nd} values (at 2.2 Ga) of $+13$ and $+7$, respectively. The two mantle reservoirs possibly formed prior to 4 Ga and evolved separately until 2.2–2.7 Ga. At that time, the reservoirs were melted forming eclogites both as residues (from the enriched reservoir) and as partial melts of peridotite (from the depleted reservoir), resulting in demonstrably different histories for eclogites from the same locality.

1. Introduction and geologic framework

Ancient, stable, continental cratons possess thick, subcontinental lithosphere mantle 'keels' which favor particularly the emplacement of diamondiferous kimberlites, peridotites and eclogites [e.g., 1–3]. Among the suite of inclusions in kimberlites, eclogites generally comprise only a small portion of the xenoliths present at a given locality, the principal population being ultramafic xenoliths such as garnet peridotites, lherzolites and harzburgites. However, several workers have postulated that such eclogites may be manifestations of the Earth's earliest differentiation event(s). Indeed, Anderson [1,2] has suggested that eclogites may be remnants of the accretion of the Earth. McCulloch [4] claimed that two Yakutian eclogites (from the Obnazhënnaya pipe) were derived from an ultra-depleted mantle, which may have been the result of a terrestrial magma ocean [5]. This is similar to the origin proposed for the lunar high-Ti basalts [6]. Such a terrestrial mantle source would have a present-day ϵ_{Nd} of approximately $+45$ and could have formed prior to 4 Ga ago. Eclogites may be a key with which to unlock the mysteries of mantle evolution during the earliest portions of Earth history.

The kimberlites of Yakutia are located both on the margins and at the center of the Siberian platform and contain a wide variety of xenoliths [e.g., 7]. The Siberian platform occupies a large area in north-central Asia extending northward from Lake Baikal to beyond the Arctic Circle. Diamond-bearing kimberlites are mainly located in the central areas of the ancient Archean–Proterozoic basement. Although Yakutian kimberlites exhibit a wide range in ages from 157 to 443

Ma (U-Pb and zircon [8]), most of the diamondiferous kimberlites, including the Mir, International, Sytykanskaya and Jubilee pipes, have a restricted range of U-Pb zircon ages from 345 to 362 Ma [9]. No zircon is available from the Udachnaya pipe, but its close proximity, as well as similarity in geologic setting, to the Sytykanskaya and Jubilee pipes suggests a similar age. Importantly, there is evidence that metasomatism of the Siberian lithosphere has been considerably less intense and less extensive than for the Kaapvaal craton [10]. The "exceptional freshness" [4] of these Siberian xenoliths should make it considerably easier to elicit their igneous/metamorphic histories.

Diamonds occur not only within the kimberlites from Yakutia but are also hosted by the eclogite xenoliths within the kimberlite. The first find of a diamond-bearing eclogite was recorded at the Mir pipe by Bobrievich et al. [11]. The Siberian mantle samples have included many unique deep-seated xenoliths, such as the grospydites (*gros*sular, *py*roxene and *di*sthene (kyanite) [12]). However, these and other Siberian mantle samples have received little attention in the western world [e.g., 7,10,13,14,15], largely because suitable suites of Yakutian samples have not been readily available.

Radiogenic isotopic studies of these xenoliths are also sparse. Two eclogite samples from the Obnazhënnaya pipe were studied in detail by McCulloch [4], and one has been studied previously from the Udachnaya pipe [16]. In all, eight eclogite samples (eight garnet separates and eight clinopyroxene separates) have been analyzed to date on the Udachnaya pipe, seven from our group. The samples chosen for this reconnaissance study are all from the Udachnaya pipe and include seven diamond-bearing eclogites and one diamond-free eclogite (U-281). An in-depth study of the mineralogy, petrography and mineral chemistry (including ion probe analyses of individual garnet and clinopyroxene grains) has been presented elsewhere [17].

2. Nd-Sr isotopic data and age information

Ultra-pure mineral separates (and the whole-rock sample, U-86) were leached using a scheme modified from Zindler and Jagoutz [18]. The techniques for chemical separation and mass-spectrometric analysis of the isotopes of Rb, Sr, Sm and Nd and isotope dilution procedures are detailed in Lee et al. [19] and Snyder et al. [20]. All Sr and Nd isotopic analyses are normalized to $^{86}Sr/^{88}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$ respectively. Analyses of SRM 987 Sr and La Jolla Nd standards were performed throughout this study and gave weighted averages (at the 95% confidence limit (external precision)) of $^{87}Sr/^{86}Sr = 0.710250 \pm 0.000011$ and $^{143}Nd/^{144}Nd = 0.511854 \pm 0.000011$ respectively. The data in Table 1 are presented corrected for total procedural blanks as follows: Rb = 11 ± 0.5 pg, Sr = 127 ± 2 pg, Sm = 6 ± 0.1 pg and Nd = 112 ± 3 pg. The blank corrections for Rb and Sr in clinopyroxene and Sm and Nd in both clinopyroxene and garnet were always negligible. Some of the Rb and Sr data for garnet required correction and the uncertainties in these corrections are incorporated in the Rb/Sr and Sr isotopic compositions. Errors in the isochron ages are 2σ [21] of the scatter, as calculated in the ISOPLOT program of Ludwig [22].

Sr isotopes in ultra-pure clinopyroxene separates yield measured $^{87}Sr/^{86}Sr$ in the range 0.70150–0.70311 (Table 1) and exhibit lower Rb/Sr ratios than coexisting garnet (Fig. 1). Garnet separates yield more variable $^{87}Sr/^{86}Sr$ (0.70207–0.71162). The clinopyroxene/garnet partition coefficients for Sr vary over a relatively restricted range of 85–258. In contrast, the clinopyroxene/garnet partion coefficients for Rb range through almost two orders of magnitude, from 0.47 to 38. This is explicable if the higher Rb concentrations in garnet are due to infiltration by Rb-rich melts and fluids. Higher Rb concentrations are found in garnets with the most radiogenic Sr (U-5 and U-281). As such, the temporal significance of the Rb-Sr isotopic data, while equivocal (Fig. 1), probably relates to Rb enrichment prior to entrainment. Measured $^{143}Nd/^{144}Nd$ in clinopyroxene separates varies from 0.51134 to 0.51867 and correlates with $^{147}Sm/^{144}Nd$ (Table 1). The garnets yield $^{147}Sm/^{144}Nd$ ratios of 0.353–0.944 and $^{143}Nd/^{144}Nd$ from 0.51205 to 0.52059. In contrast to mineral separates from eclogites of South Africa [23], these mineral separates always yield positive slopes, allowing interpretation of 'age' information (Fig.

2). Without exception, these rocks yield Phanerozoic ages—in fact, ages which approximately indicate the time of emplacement of the host kimberlite. These Nd mineral ages range from 214 ± 11 Ma to 570 ± 17 Ma, with an average of 390 ± 80 Ma (MSWD = 255). Exclusion of the highest and lowest values yields virtually the same average age of 389 ± 4 Ma (MSWD = 35), but with a much higher precision. This age is similar to a weighted average age of K-Ar correlation diagrams generated by Burgess et al. [24] from clinopyroxene inclusions in Udachnaya diamonds (384 Ma). We interpret the Sm-Nd weighted average age of 389 Ma to represent the crystallization age of the kimberlite. An alternative explanation of the data is that the xenoliths have equilibrated to varying degrees and the youngest age represents a maximum for the time of emplacement.

Using the Nd isotopic data and measured Sm/Nd ratios, the isotopic evolution of the individual minerals can be projected back in time. This is shown for each sample in Fig. 3. Clinopyroxene Nd isotopic evolution lines are always less depleted than coexisting garnet, exhibiting either shallow negative slopes or shallow positive slopes. Garnet evolution lines always yield negative slopes—often steeply negative (U-79 and U-41, Fig. 3). For rocks U-79 and U-41, the garnet evolution lines yield minimum model ages for the rocks of about 1.7 and 1.0 Ga, respectively. The clinopyroxene in rock U-5 yields a minimum age of about 2.0 Ga. Other rocks give demonstrably lower clinopyroxene and garnet model ages. However, the significance of these model ages is dubious. Notice that at no time in the past would the clinopyroxene from rocks U-79 and U-41 have intersected either the mantle CHUR (bulk Earth), or the depleted mantle (just above the CHUR line, but not shown for the sake of simplicity) evolution arrays (Fig. 3). This observation is in contrast to the findings of McCulloch [4], who used clinopyroxene from the Obnazhënnaya pipe eclogites to track their whole-rock evolution paths

TABLE 1

Isotopic composition of mineral separates and a selected whole-rock

Sample	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Sm(ppm)	Nd(ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$
CLINOPYROXENE								
U-5	0.309	667	0.00134	0.702796 ± 11	1.15	7.38	0.0941	0.511340 ± 17
U-25	0.181	181	0.00289	0.703110 ± 11	2.32	9.87	0.142	0.512754 ± 13
U-37	0.123	146	0.00244	0.701839 ± 12	0.458	1.68	0.165	0.512975 ± 12
U-41	0.463	80	0.0167	0.702677 ± 13	0.661	1.87	0.213	0.515429 ± 40
U-79	1.10	33.6	0.0947	0.703003 ± 15	0.542	1.28	0.257	0.518666 ± 45
U-86	0.483	188	0.00743	0.701501 ± 13	0.574	3.47	0.0999	0.512816 ± 14
U-281	0.155	155	0.00289	0.702963 ± 11	1.99	8.47	0.142	0.512778 ± 26
GARNET								
U-5	0.00726	5.09	0.00413	0.702917 ± 13	4.15	6.65	0.377	0.512053 ± 11
U-25	0.390	0.913	1.236	0.71162 ± 22	1.13	1.10	0.621	0.513898 ± 17
U-37	0.0601	1.71	0.102	-------------	1.12	1.71	0.394	0.513296 ± 11
U-41	0.0169	0.598	0.0818	0.703414 ± 56	1.40	0.897	0.948	0.517426 ± 17
U-79	0.0411	0.322	0.369	0.704824 ± 36	1.20	0.771	0.944	0.520593 ± 38
U-86	0.0260	1.07	0.0703	0.702070 ± 42	0.448	0.769	0.353	0.513759 ± 25
U-281	0.327	0.544	1.739	0.70570 ± 20	1.29	1.36	0.577	0.513785 ± 09
U-604	0.0046	1.87	0.00712	0.70304 ± 13	2.24	2.96	0.457	0.515106 ± 13
WHOLE-ROCK								
U-86	1.98	66.2	0.0859	0.702480 ± 11	0.707	3.19	0.134	0.512841 ± 12

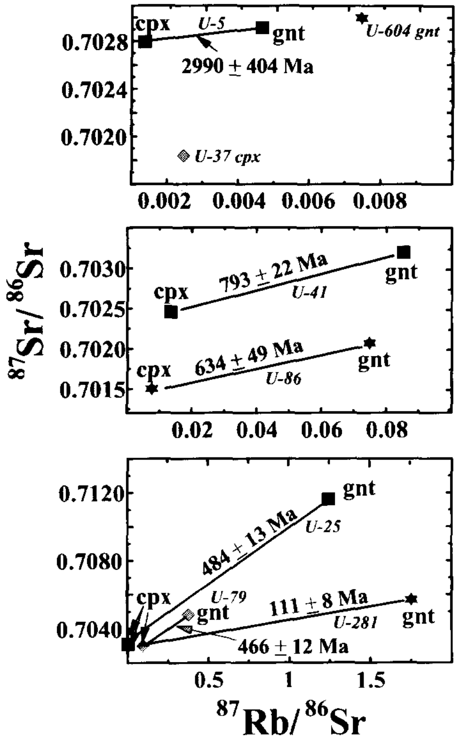

Fig. 1. $^{87}Sr/^{86}Rb$ vs. $^{87}Sr/^{86}Sr$ for garnet–clinopyroxene pairs. Note the different scales on the x-axes of all three figures. Regression ages are given adjacent to the lines connecting the minerals. *cpx* = clinopyroxene; *gnt* = garnet.

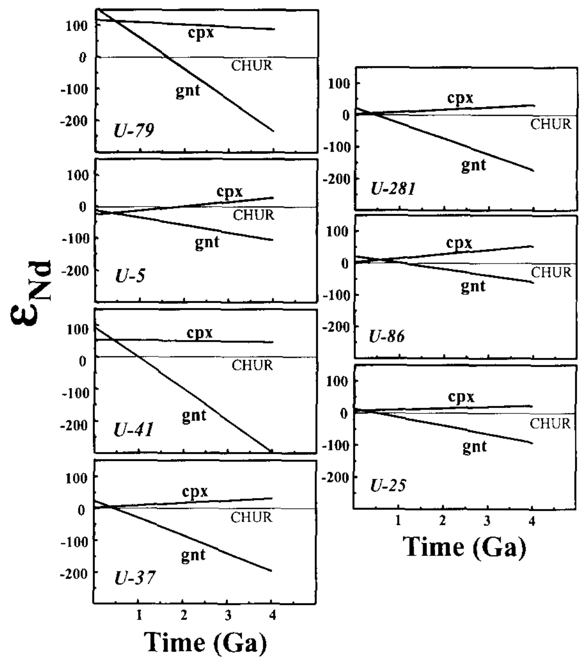

Fig. 3. Nd isotopic evolution diagrams for garnet–clinopyroxene pairs. The CHUR (*ch*ondritic *u*niform *r*eservoir, or undifferentiated mantle) reservoir is designated with a horizontal line. The depleted mantle array would be just above the CHUR line, just outside the resolution of the CHUR line, but for simplicity is not indicated.

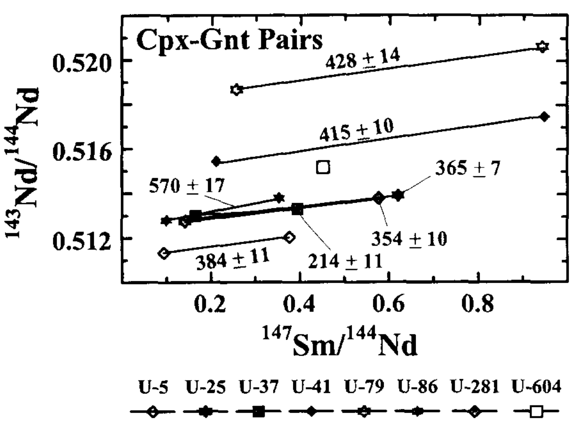

Fig. 2. $^{147}Sm/^{144}Nd$ vs. $^{143}Nd/^{144}Nd$ for garnet–clinopyroxene pairs. Within each sample, garnet plots to the right of clinopyroxene at higher $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$. Regression ages are given adjacent to the lines connecting the minerals.

to a depleted mantle protolith. Also in contrast to the data of McCulloch [4], coexisting clinopyroxene and garnet in the Udachnaya eclogites often have similar abundances of Nd. For these two reasons, clinopyroxene alone cannot be used as an accurate indicator of the evolution of the precursor protolith.

One true whole-rock sample, U-86, has also been analyzed for its isotopic composition (Table 1). This sample has the highest abundance of Rb of any separate analyzed, yet has Sr, Sm and Nd abundances that are well within the range of the garnets and clinopyroxenes. If the whole-rock is truly a mixture of only garnet and clinopyroxene, it should lie between these two minerals and fall along the line which connects these two minerals in Rb-Sr and Sm-Nd isotopic space. However, in both the Rb-Sr and Sm-Nd isotopic systems, the whole-rock data point lies off of the line connecting the garnet and clinopyroxene. This feature of the whole-rock systematics of eclogite is well known [23,25] and is attributed to infiltration of metasomatic fluids and/or kimberlitic material into the eclogite xenolith, as is evident from alteration products such as chlorite and phlogopite. However, due to extensive leaching of the whole-rock sample and possibly to the low degree of metasomatic infiltration, these effects are not as pronounced isotopically as those found in eclogites from other localities (e.g., South Africa [23]). The whole-rock sample of U-5 has a higher $^{87}Sr/^{86}Sr$ ratio than either the clinopyroxene or the garnet, but still yields a very unradiogenic ratio of 0.702480 ± 11. The 'high' Rb content of the whole-rock (1.98 ppm) suggests that some LILE-enriched material has infiltrated the sample, but the low $^{87}Sr/^{86}Sr$ ratio suggests that the amount of material was minor. Furthermore, enrichment in Nd, which would be expected to be greatly elevated in the host kimberlite, is also not evident in the whole-rock sample.

3. Reconstructed whole-rock isotopic evolution

As mentioned above, the actual eclogite whole-rocks contain various alteration minerals which may elevate the LILEs (such as Rb and the LREE). Furthermore, due to the reasons discussed above, clinopyroxene alone [cf. 4] cannot be used as an indicator of the isotopic evolution of the whole-rock. Therefore, reconstructed whole-rock compositions were used in determining model ages. It is accepted that re-equilibration of garnet and clinpyroxene occurred at 389 Ma during kimberlitic magmatism. However, it is assumed that redistribution of Rb, Sr, Sm and Nd occurred only between garnet and clinopyroxene and that there was no addition or subtraction of these elements during this magmatic event. This assumption is supported by isotopic and elemental analyses of the actual whole-rock (U-86), as presented above. Therefore, only the whole-rock reconstructions are considered valid and may be projected back in time beyond the 389 Ma re-equilibration event.

The reconstructions used modal abundance information and mineral chemistry. Modal analyses were performed by hand-specimen observation and point-counting of multiple thin sections. Secondary, fine-grained, interstitial, alteration minerals, such as phlogopite and serpentine, always comprise less than 8% of the total rock and were allocated to either garnet or clinopyroxene. Typically, clinopyroxene is subordinate to garnet in the samples analyzed and comprises 15–58% of the total rock. One sample, U-604, contains a small proportion (~ 4%) of kyanite.

Using these estimated whole-rock compositions we can calculate the isotopic composition of the unaltered rock. Using the reconstructed Sm/Nd and Rb/Sr ratios in consort with the $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios, the evolution of these rocks can be projected back in time (Table 2 and Fig. 4). Conventional use of such a diagram hinges on the intersection of these rock-evolution lines with known chemical/petrologic reservoirs such as depleted mantle and CHUR. Depleted-mantle [26] Nd model ages vary widely,

TABLE 2

Reconstructed whole-rock Rb-Sr and Sm-Nd isotopic compositions *

	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Sm(ppm)	Nd(ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	ε_{Nd}
U-5	0.185	389	0.00138	0.70280	2.41	7.07	0.206	0.51162	-20
U-25	0.281	96.4	0.00843	0.70315	1.76	5.75	0.185	0.51286	+4.3
U-37	0.0863	52.2	0.00478	———	0.888	1.70	0.316	0.51319	+11
U-41	0.185	29.9	0.0179	0.70269	1.13	1.26	0.543	0.51633	+72
U-79	0.330	9.33	0.1023	0.70305	1.02	0.908	0.681	0.51986	+141
U-86	0.174	60.9	0.00826	0.70151	0.488	1.63	0.181	0.51312	+9.4
U-281	0.262	60.8	0.0125	0.70298	1.56	4.13	0.228	0.51298	+6.7

* Reconstructed modal proportions: U-5 = 42% garnet + 58% cpx; U-25 = 47% garnet + 53% cpx; U-37 = 65% garnet + 35% cpx; U-41 = 63% garnet + 37% cpx; U-79 = 73% garnet + 27% cpx; U-86 = 68% garnet + 32% cpx; U-281 = 61% garnet + 39% cpx.

and three samples (U-25, U-41 and U-79) can be interpreted as indicating an early to middle Proterozoic depleted mantle protolith. Model ages for an undepleted CHUR reservoir range from 0.8 to 2.3 Ga. Conventional use of the Nd isotope evolution diagram does not yield a unique protolith solution for these samples.

Sample U-5 is unique in that it is the most enriched of all rocks (present-day ϵ_{Nd} of -20) and its projected line of evolution does not intersect either CHUR or depleted mantle. The production of this sample must have involved several stages, including residence in an enriched reservoir. Conversely, this sample could have been enriched just prior to, or consequent with, eruption of the kimberlite (possibly by infiltration of kimberlitic magma or LREE-enriched metasomatic fluids). However, three observations rule out this possiblity. First, the $^{87}Rb/^{86}Sr$ ratio of the reconstructed whole-rock is the lowest of those calculated. Furthermore, the Rb abundance is one of the lowest (0.185 ppm), even though clinopyroxene dominates in this rock. It would be expected that any kimberlitic magma and/or metasomatic fluid added to the rock would have elevated the Rb. Second, the $^{87}Sr/^{86}Sr$ ratio of this reconstructed whole-rock is quite unradiogenic, at 0.70280. Such an unradiogenic isotopic signature is not indicative of kimberlites which typically have $^{87}Sr/^{86}Sr$ ratios above 0.7040 [27,28]. Third, the reconstructed REE pattern of this rock (Fig. 5) is depleted in the LREE and not enriched as would be expected if a LREE-enriched magma or fluid had contaminated the sample.

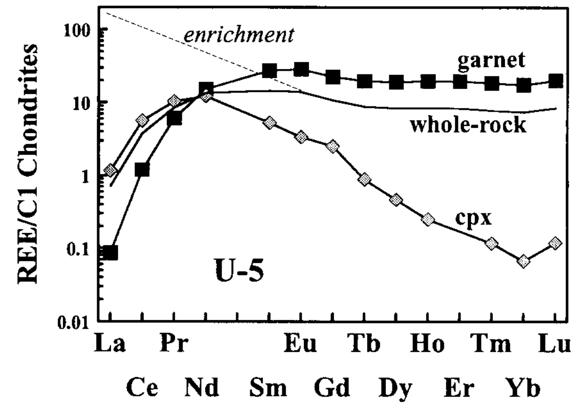

Fig. 5. Clinopyroxene, garnet, and reconstructed whole-rock (58% clinopyroxene + 42% garnet) REE pattern for eclogite U-5 (data in [17]). Note that the Sm/Nd ratio varies from enriched for the clinopyroxene to depleted for the garnet, yet the whole-rock reconstructed pattern remains demonstrably LREE-depleted and indicates MREE enrichment. This MREE enrichment could be an artifact of an early enrichment which is partially masked by a later depletion event.

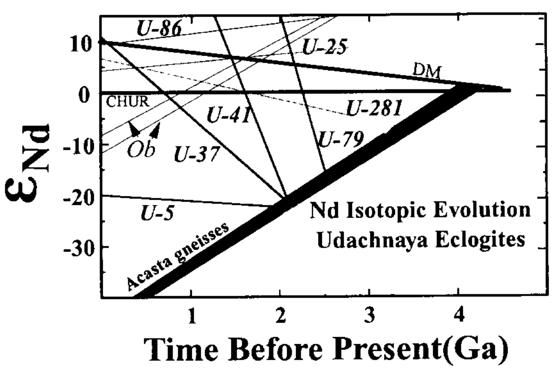

Fig. 4. Nd isotopic evolution diagram for reconstructed whole-rock eclogites. An array for the Acasta Gneisses, Slave Province, Canada (oldest known *enriched* component on the Earth—3.96 Ga [29]) is shown as a reference enriched reservoir. Depleted mantle (DM) and undifferentiated bulk Earth (CHUR) reservoirs are also indicated. The evolution lines for the two Obnazhënnaya (*Ob*) samples reported by McCulloch [4] are also shown.

However, the REE pattern of rock U-5 does exhibit some unusual features, suggesting a two-stage history (Fig. 5). The REE pattern in U-5 seems to indicate *both an early enrichment* (relatively high, flat HREE at 7–10 × chondrites, with a distinct increasing slope from Tb to Eu) *and later depletion* (decrease in the chondrite-normalized abundances from Nd to Ce). With more extensive depletion, the enrichment indicated by the MREE would have been irretrievably destroyed. Regardless of the interpretation, the isotopic composition of rock U-5 must be considered primary. Furthermore, the Nd isotopic evolution line of this sample does not intersect either the CHUR or depleted mantle evolution arrays, even if the proportions of garnet and clinopyroxene in the reconstructed whole-rock are varied drastically. Therefore, this sample unequivocally indicates an *old enriched mantle component*.

4. Speculations on differentiation in the early (> 4 Ga) Earth

Although old enriched *mantle* is difficult to constrain, the evolution of early enriched Archean *crust* has been studied in great detail. An evolutionary array for some of the oldest enriched crust on Earth, the Acasta Gneisses [29], has been plotted for reference in Fig. 4. Note that this enriched material intersects four LREE-depleted eclogite xenoliths (U-5, U-37, U-41 and U-79) between 2.2 and 2.7 Ga. This intersection could be fortuitous, or it may represent the age at which these samples separated from an old, enriched mantle reservoir. The older the enriched component, the lower the Sm/Nd ratio required for the four LREE-depleted eclogites to intersect at 2.2–2.7 Ga. For example, if the enriched component is ~ 4 Ga old, it must have had a $^{147}Sm/^{144}Nd$ ratio similar to the Acasta Gneisses (~ 0.106 [29]). Such extreme differentiation in the Earth's mantle is not likely in the early Archean. However, a less-enriched mantle component akin to lunar KREEP (the K-, REE- and P-rich residuum of crystallization of a lunar magma ocean [30]) generated at 4.4 Ga with $^{147}Sm/^{144}Nd$ of ~ 0.168 is simply not enriched enough. A terrestrial reservoir with Sm/Nd similar to lunar KREEP would not intersect the four converging LREE-depleted samples at 2.2–2.7 Ga (instead, KREEP would have an ϵ_{Nd} value of -6 to -8 at this time). If the postulated enriched reservoir diverged from a bulk earth (CHUR) composition mantle at ~ 4.4 Ga, it would require a $^{147}Sm/^{144}Nd$ of approximately 0.122, intermediate to that of known early Archean crust (Acasta Gneisses) and a mantle equivalent of lunar KREEP. To our knowledge, evidence of such an enriched mafic mantle component has not been indicated in the literature. An old kimberlitic magma could be a likely enriched mantle component. Kimberlites typically exhibit the degree of enrichment required ($^{147}Sm/^{144}Nd = 0.06$–0.10 [e.g., [31–34]). Even though the oldest known kimberlite in the world is no more than 1.2 Ga old [35], the possible existence of kimberlitic (i.e., LREE-enriched) magmas of Archean age has been alluded to previously [36], and Anderson [3] has indicated that kimberlite can be considered the terrestrial equivalent of lunar KREEP. Assuming a lower limit $^{147}Sm/^{144}Nd$ of 0.06 for such a precursor kimberlite, depleted-mantle and CHUR model Nd ages can be calculated for this reservoir which would intersect sample U-5 (and the other convergent samples) at 2.2 Ga. Both the T_{CHUR} and T_{DM} Nd model ages are in excess of 3.5 Ga, still indicating a very old enriched reservoir. More typical, less-enriched kimberlitic precursors would give correspondingly older model mantle separation ages.

Samples U-86 and U-25 indicate *LREE-enriched* whole-rock reconstructions [17,37], although their whole-rock Nd isotope evolution lines do not appear to intersect anywhere in time, and thus do not indicate a unique depleted reservoir. However, due to the inherent imprecision in the whole-rock reconstructions of the rocks, it is possible that sample U-25 contains slightly more clinopyroxene and/or U-86 contains slightly more garnet. Thus, the two whole-rock reconstructions could actually intersect at an ϵ_{Nd} value of $+10$ at approximately 2 Ga. Sample U-281 is one of the few intermediate samples (i.e., the whole-rock may just as likely be LREE-depleted or LREE-enriched, given the uncertainties in the proportions of garnet and clinopyroxene in the original rock). The intermediate Nd isotopic character of this rock is difficult to explain as its Sr isotopic composition is not elevated indicating typical kimberlitic contamination or metasomatic infiltration. The explanation of this rock may lie in the observation that this sample is the only one which is diamond-free. Thus, this sample may be indicating a unique source or process for the other diamond-bearing eclogites. The four samples that converge at an ϵ_{Nd} of -20 at 2.2–2.7 Ga actually show depleted LREE signatures. It is somewhat counter-intuitive, but those samples which could indicate a long-lived enriched mantle protolith are now LREE-depleted, whereas those samples which may indicate an old depleted mantle protolith are LREE-enriched.

Garnets in the three LREE-enriched samples (U-86, U-25 and U-281) also contain the highest abundances of Cr (Fig. 6), which is consistent with a link to depleted mantle peridotites [37]. Garnets in the four samples converging at 2.2–2.7 Ga contain only small amounts of Cr (i.e., < 0.06% Cr_2O_3), consistent with their origin as *partial melts (enriched) of primitive mantle, leaving* *a peridotitic residue*. Furthermore, these four convergent samples exhibit more evolved clinopyroxene compositions (Mg# = 72–87, Fig. 6) than those in the samples which are derived from mantle peridotites (Mg# = 89–91, Fig. 6). This is also consistent with the four convergent samples being derived from a differentiated portion of the mantle. Samples U-25, U-86 and U-281 could have been derived from a residue which was depleted early in Earth's history, whereas the four convergent samples (LREE-depleted) would represent the *residue from remelting of the complementary enriched component* at ~2.5 Ga.

Further evidence of an old ultra-depleted mantle beneath the Siberian platform has been suggested by two independent studies. Zhuravlev [38] analyzed a garnet peridotite xenolith from the Mir pipe which yielded an ϵ_{Nd} value of +23 at 1.7 Ga. McCulloch [4] analyzed a garnet lherzolite from the Mir pipe which gave a similar age of 1540 ± 10 Ma and an initial ϵ_{Nd} of +24.5. He also reported a garnet pyroxenite from the Obnazhënnaya pipe which gave an age of 2600 ± 150 Ma and an initial ϵ_{Nd} value of +20. Two eclogites analyzed from this same pipe were colinear with the 2600 Ma garnet pyroxenite but yielded lower internal isochron ages (1690 ± 50 Ma and 674 ± 40 Ma) and ϵ_{Nd} values (+6.2 and −5.5, respectively; see Fig. 4). McCulloch [4] postulated that all of the Obnazhënnaya xenoliths were derived from an ultra-depleted mantle at 2.6 Ga. This age is similar to the U-5 eclogite Rb-Sr 'isochron' and is well within the 2.2–2.7 Ga range of the four convergent LREE-depleted eclogite samples from Udachnaya and may indicate an important mantle melting event in the region.

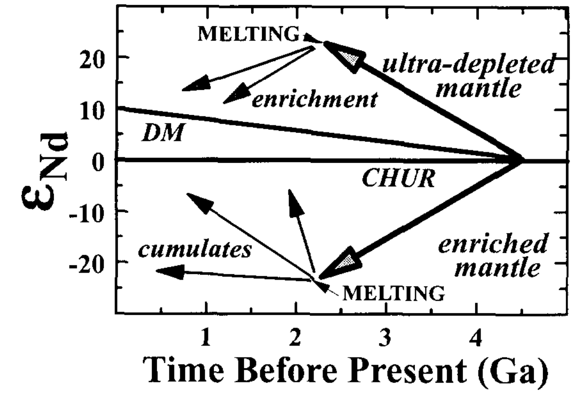

Fig. 7. The current working model for eclogite genesis beneath the Siberian Platform. (1) An early mantle differentiation event, prior to 4 Ga, whereby a chondritic source is melted yielding an enriched basaltic partial melt and a depleted peridotitic residue. (2) These two reservoirs then diverged with time until, at about 2.5 Ga (a) the depleted peridotite source was enriched in some manner (i.e., infiltrating melts or some mantle metasomatic event) giving rise to the *LREE-enriched* eclogites (U-25, U-86 and U-281) and (b) the enriched source was depleted at this time (~2.5 Ga) either by melting (leaving a depleted residue), or by conversion of the basaltic protolith to eclogite, yielding the *LREE-depleted* eclogites (U-5, U-37, U-41 and U-79).

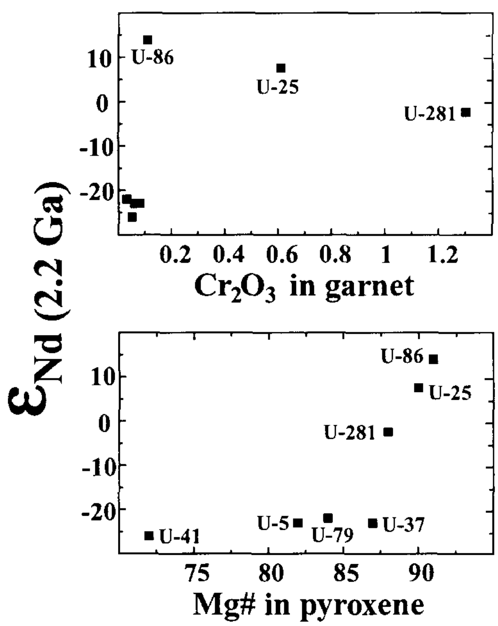

Fig. 6. Combined plots of ϵ_{Nd} values (at 2.2 Ga) for reconstructed whole-rock eclogites vs. Cr_2O_3 in garnet and Mg# in clinopyroxene.

5. Summary

The final working model for genesis of at least some of the eclogites from the Udachnaya kimberlite is as follows (Fig. 7):

(1) An early mantle differentiation event, prior to 4 Ga, whereby a chondritic source is melted, yielding an enriched basaltic partial melt and a depleted peridotitic residue. Evidence of an old ultra-depleted mantle beneath the Siberian platform is also suggested by two eclogite samples

from the Obnazhënnaya pipe [4] and garnet peridotite xenoliths from the Mir pipe which yield ϵ_{Nd} values of +23 at 1.7 Ga and 0.9 Ga [38].

(2) These two reservoirs then diverged with time until about 2.5 Ga when (a) depleted peridotite cumulates, which had been slightly enriched in the LREE, gave rise to the *LREE-enriched* eclogites (U-25, U-86 and U-281), and (b) the enriched source was depleted at this time (2.2–2.7 Ga). Either the basaltic mantle component was finally transformed to eclogite and this led to its depletion, or there was melting initiated at 2.2–2.7 Ga which left a very depleted eclogitic residue and gave rise to the *LREE-depleted* eclogites (U-5, U-37, U-41 and U-79).

Extremely low measured $^{87}Sr/^{86}Sr$ values, as well as reconstructed whole-rock model ages, provide evidence for the antiquity of the Yakutian eclogite protoliths and point to a mantle origin for all samples. To date there is no evidence for the involvement of a crustal component in these eclogites ($\delta^{13}C$ values in diamonds do not indicate a crustal (biogenic) component, and $\delta^{18}O$ values appear to be consistent with a mafic-mantle derived protolith [39]), which is in contrast to eclogites from South Africa which indicate the involvement of oceanic crust. Complex histories for both LREE-enriched and LREE-depleted eclogites indicate that eclogite xenoliths from the same pipe may reflect grossly different histories and further suggest that layering in the mantle occurs on very small scales. Continued studies of eclogites from the Udachnaya pipe and other Yakutian pipes are underway with the hope of obtaining a better understanding of the earliest differentiation of the mantle.

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