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# Secular Variations of the Upper Crust Composition: Implication of Geochemical Data on the Upper Precambrian Shales from the Southern Urals Western Flank and Uchur–Maya Region

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**Abstract**—In the mid-1980s, it was concluded based on geochemical study that Th, Sc, La concentrations and ratios Th/Sc, La/Sc and Eu/Eu* did not wary significantly in the post-Archean time. It was impossible to judge about compositional variations of upper crust during the Riphean and Vendian, because data of that time characterized a limited number of samples from the post-Archean basins of Australia, New Zealand, and Antarctic. Considered in this work are variations of Eu/Eu*, LREE/HREE, Th/Sc, and La/Sc ratios in Upper Precambrian fine-grained siliciclastic rock of the Southern Urals western flank (Bashkirian meganticlinorium) and Uchur–Maya region (Uchur–Maya plate and Yudoma–Maya belt). As is established, only the Eu anomaly in the studied siliciclastic rocks is practically identical to this parameter of the average post-Archean shale. Three other parameters plot on the Riphean–Vendian variation curves with positive and negative excursions of diverse magnitude, which do not coincide always in time. It is assumed that these excursions likely mark stages of local geodynamic activity, destruction of pre-Riphean cratons, and progressing recycling of sedimentary material during the Riphean.

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*Key words*: Late Precambrian, Bashkirian meganticlinorium, Uchur–Maya plate, Yudoma–Maya belt, isotopic and geochemistry, peculiarities of fine-grained siliciclastic sediments.

## INTRODUCTION

In the mid-1980s, Taylor and McLennan (1985) analyzed distribution of major, trace, and rare elements in fine-grained sedimentary rocks ranging in age from approximately 3.0 Ga to recent time in order to elucidate secular variations in the upper crust composition during the last three billion years of the Earth's history. Unfortunately, the post-Early Proterozoic geological records (younger than 1.7 Ga) were considered with inadequate time resolution, and relevant records have been divided in two intervals only: from 1.7 to 0.6 Ga and from the last value until recent time. As is concluded in that work based on geochemical characteristics of fine-grained siliciclastic rocks, in particular on distribution Th, Sc, and La and on Th/Sc, La/Sc, Eu/Eu*, and LREE/HREE ratios, there is no evidence indicative of a considerable variation of above parameters in the post-Archean shales. This conclusion greatly influenced the later models of the continental crust evolution during the Proterozoic and Phanerozoic, as it meant that juvenile material derived from the lower crust or mantle and added to the upper crust did not change essentially the bulk composition of preexisted crust.

This conclusion was derived however from a limited database, which included only 48 analyses of post-Archean rocks from Australia, New Zealand, and Antarctic. Being reduced to two end points (Fig. 1), this database gives no opportunity to judge confidently about variations in the upper crust composition during the Riphean and Vendian, i.e., during the time span greater than one billion years.

At present, it is possible to clarify the situation using analytical data on fine-grained siliciclastic rocks (shales and argillites)[1] from representative Riphean and Vendian successions of Northern Eurasia. In the western flank of the Southern Urals (Bashkirian meganticlinorium) and southeastern Yakutia (Uchur–Maya plate

[1] Following Logvinenko (1984), we consider argillites as compact cemented rocks of low porosity, which are lacking plasticity and remain hard or soften hardly when soaked in water. In addition to these properties, shales can be easily split into flat fragments up to few mm thick.

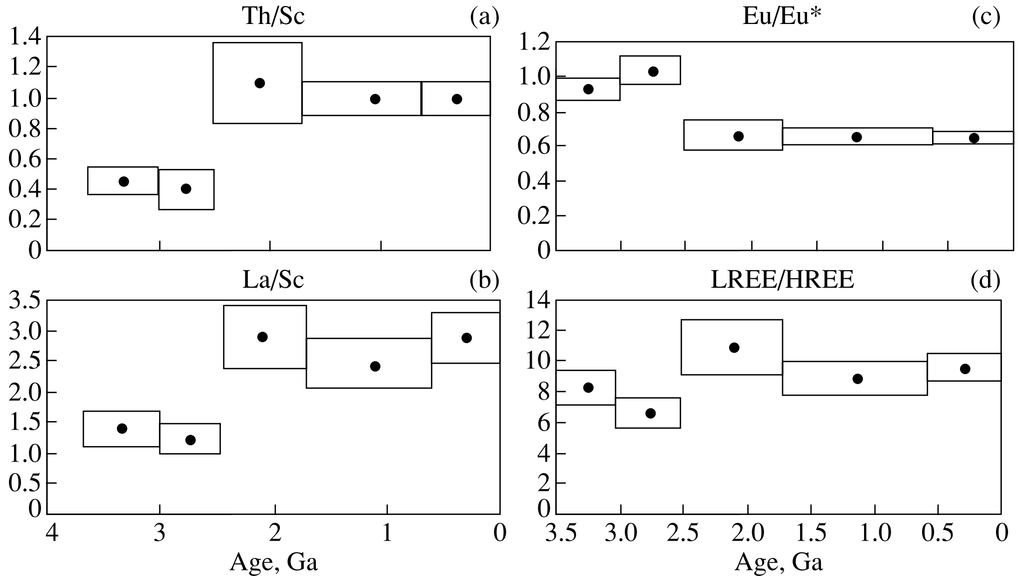


**Fig. 1.** Variations of Th/Sc (a), La/Sc (b), Eu/Eu* (c), and LREE/HREE (d) ratios in Archean and Phanerozoic fine-grained siliciclastic rocks of Australia, New Zealand, and Antarctic (after Taylor and McLennan, 1985).

and Yudoma–Maya belt)[2], the relevant successions are perfectly studied in terms of isotopic geochronology (methodically reliable results of U–Pb, Pb–Pb, Sm–Nd, and Rb–Sr dating) and geochemistry (Maslov et al., 2000, 2001, 2004a; Podkovyrov 2001; Podkovyrov et al., 2002, 2003).

## LATE PRECAMBRIAN SEDIMENTARY SUCCESSIONS OF BASHKIRIAN MEGANTICLINORIUM

The Bashkirian meganticlinorium in the Southern Urals western flank is the Riphean stratotype area, being known simultaneously as the distribution region of sufficiently complete successions of the Lower and Upper Vendian (Shatsky, 1945, 1960; Keller, 1968; Bekker, 1968, 1988; *The Riphean Stratotype…*, 1983; *The Vendian System…*, 1985; Maslov et al., 2001, 2002).

### *Lithostratigraphy of the Riphean and Vendian in the Bashkirian Meganticlinorium*

The Riphean type succession includes the Burzyan, Yurmata, and Karatau groups, while the Vendian is represented by deposits of the Asha Group. All the groups have been well characterized in several publications (*The Riphean Stratotype…*, 1983; *The Lower Riphean…*, 1989; Krupenin, 1999; Maslov et al., 2001, 2002), and here we describe them in brief.

From the base upward, the Burzyan Group includes the Ai, Satka, and Bakal formations. The Ai Formation rests with angular unconformity on the eroded surface of the Taratash Complex of the Archean–Lower Proterozoic. Volcanic rocks present in lower horizons of the formation are 1615 ± 45 Ma old according to results of the U–Pb zircon dating (The Lower Riphean…, 1989). Carbonate rocks of the Satka Formation have been intruded by the Berdyaush rapakivi massif 1348 ± 16 Ma ago (U–Pb zircon date cited from Krasnobaev, 1986). The Pb–Pb age of 1430 ± 30 Ma is established for the early diagenesis of limestones from the Berezovaya Member of the Malyi Bakal Subformation, the Bakal Formation (Kuznetsov et al., 2001, 2003a). The Rb–Sr age of "Main Dike" crosscutting sediments of the Bakal Formation in the Bakal ore field is 1360 ± 35 Ma (El'mis et al., 2000).

The Yurmata Group is divided into the Mashak, Zigal'ga, Zigazy-Komarovo, and Avzyan formations. In basal conglomerates of the Mashak Formation, there are pebbles and boulders of quartzitic sandstone derived from the Yusha Formation of the Lower Riphean (Anfimov et al., 1983; Rotaru, 1983). According to Krasnobaev (1986), volcanogenic rocks of the Mashak Formation are 1330 to 1346 Ma old (U–Pb zircon dates and Rb–Sr age of whole-rock samples). The K–Ar age of glauconite in the Avzyan Formation (whole-rock samples) approximately corresponds to 1220 Ma (Garris et al., 1964; Garris, 1977; *The Riphean Stratotype…*, 1983). In opinion of Gorozhanin (1997), glauconite in Riphean deposits of the Bashkirian meganticlinorium has been considerably recrystallized during epigenetic alteration about 800 Ma ago.

In the western limb and central areas of the meganticlinorium, the Karatau Group is divided into the Zilmerdak, Katav, Inzer, Min'yar, and Uk formations. In the

[2] Further in this work, both structural zones are termed for convenience the Uchur–Maya region like in other publications (Semikhatov and Serebryakov, 1983; Shenfil', 1991; Podkovyrov, 2001; Sergeev, 2003).

eastern limb above the latter, there is distinguished also the Krivaya Luka Formation.

The minimal isotopic age (α-U method) of clastic zircons from the Biryan Subformation of the Zilmerdak Formation is less than 1100 Ma (Krasnobaev, 1986; *The Riphean Stratotype…*, 1983). The K–Ar ages of glauconite from the upper part of the Katav Formation and from the Inzer Formation corresponds to 970–938 and 790–683 Ma respectively (Garris, 1977; *The Riphean Stratotype…*, 1983). The Rb–Sr age of early diagenetic illite from shales of the Inzer Formation ranges from 805 to 835 Ma (Gorokhov et al., 1995; Ovchinnikova et al., 1995). The early diagenesis of limestones from the Podinzer Beds is dated at 836 ± 25 Ma using the Pb–Pb method (Ovchinnikova et al., 1998). Shale interlayers intercalated with dolostones of the Min'yar Formation contain vase-shaped microfossils *Melanocyrillium* (Maslov et al., 1994), which appear in geological record shortly before 800 Ma (Porter and Knoll, 2000; Kuznetsov et al., 2003b). The K–Ar ages of mineralogically unstudied glauconites from the lower part of this formation range from 740 to 710 Ma (Garris, 1977; *The Riphean Stratotype…*, 1983). Ovchinnikova et al. (1998) published the weighted mean Pb–Pb age of 778 ± 80 Ma calculated for dolostones of the Min'yar Formation. Minerals of glauconite group from sandstones of the lower Uk Subformation are dated at 688 ± 10 and 670 ± 10 Ma by the Rb–Sr isochron and K–Ar methods respectively (Gorozhanin, 1990; Gorozhanin and Kutyavin, 1986). The Al-glauconite from the same level yielded the Rb–Sr date of 664 ± 11 Ma (Zaitseva et al., 2000). The Rb–Sr age of about 660 Ma is obtained for gabbro-diabase dikes crosscutting the Krivaya Luka Formation (Gorozhanin, 1995).

In the western limb of the Bashkirian meganticlinorium, the Asha Group is divided into the Bakeevo, Uryuk, Basa, Kuk-Karauk, and Zigan formations. According to results of K–Ar dating, glauconites from the lower part of the Bakeevo Formation range in age from 609 to 605 Ma. The Rb–Sr age of glauconite from the same level is 617 ± 12 Ma (Gorozhanin, 1995). The K–Ar dates from 582 to 569 Ma are known for glauconite from sandstones of the Uryuk Formation (*The Riphean Stratotype…*, 1983). Glauconites from sandstones and siltstones of the Basa Formation are dated by the same method at 600 to 557 Ma (*The Riphean Stratotype…*, 1983).

### *Accumulation Settings of Upper Precambrian Sedimentary Successions of the Bashkirian Meganticlinorium*

Views on accumulation settings of Riphean and Vendian sedimentary successions of the Bashkirian meganticlinorium are controversial. For instance, S.N. Ivanov and his colleagues (see in *Formation of the Earth…*, 1986) denied existence of an ocean during the Riphean and Vendian to the east of the Urals. They also doubted deposition of the Late Precambrian sedimentary complexes along the eastern passive margin of the East European platform.

Milanovskii (1988) suggested that the Urals–Mongolia belt originated in response to destruction of protocontinental crust in the Early–Middle Riphean, which was of a limited intensity and caused development of extension zones comparable in structure with aulacogens.

In opinion of Nikishin et al. (1997), successive pre-Riphean orogenic phases amalgamated a series of terranes into a giant craton, the Baltica. It is assumed also that an oceanic basin opened in the mid-Early Riphean to the east of Baltica. Rifting affected the eastern and western peripheral zones of the craton in the mid-Yurmatinian time. The Tornquist basin, which appeared in the western periphery, closed in the terminal Yurmatinian that resulted in origin of the Dalsland orogen. The orogenic events welded Baltica with Laurentia, Greenland, and Amazonia (presumably) to give birth to the supercontinent Rodinia. The Cis-Timan and Cis-Urals epicontinental marginal seas featured the passive continental margin affected by rifting.

Surkov et al. (1993) argued for existence in the Early Riphean of a mantle plum that caused crustal arching in central Laurasia and origin of a triple-junction system of intracontinental rift basins. They homologate the Riphean complexes of western Urals with sedimentary successions of passive continental margins observable at present. Similar interpretations can be found in some other works (Mossakovskii et al., 1996; Samygin, 2000).

Puchkov (2000, 2004) is of opinion that Riphean and Vendian deposits of the Bashkirian meganticlinorium accumulated under quiet tectonic conditions. As he believes, the Uralian paleoocean emerged in the Ordovician, when a large continental block was detached from the Baltica.

Samygin and Ruzhentsev (2003) suggested than an oceanic basin adjacent to eastern margin of the East European craton existed already in the Riphean–Vendian or Vendian time. The basin development and associated tectonic transformations continued later on.

Comprehensive sedimentological and lithologic-paleogeographic investigations of Precambrian deposits in the Bashkirian meganticlinorium and Volga–Ural region located westward showed that the Early Riphean sedimentary successions are represented by rudaceous continental and coastal-marine complexes, which are intercalated with sediments of moderately deep settings and fill in a vast epiplatform basin (Maslov, 1997a; Maslov and Isherskaya, 1998). Accumulation of the Yurmata Group commenced after reorganization of the regional structural patterns. A relatively narrow rift depression, filled in with volcanogenic-sedimentary deposits up to 3000–3500 m thick, originated on the east of in the Bashkirian meganticlinorium at the early Middle Riphean time. Afterward it was transformed into a broad basin extending above the rifted crustal zone and adjacent areas of the East European craton. Subaerial exposition and erosion of deposits, which accumulated within the area of Bashkirian meganticlinorium, took place presumably 1200 m.y. ago (Maslov, 2001).

The pericratonic trough in the east–northeastern periphery of the East European craton originated in the Late Riphean (Maslov et al., 2001). In the earliest Karatavian, influx of arkosic clastic material transported into this basin from the west and northwest gave rise to accumulation of alluvial, alluvial-deltaic, and coastal-marine facies. In the second half of the Zilmerdak time, there were deposited siliciclastic sediments of shallow-water settings, while clay-carbonate shallow-water strata accumulated in the Katav time. Siliciclastic and carbonate shallow-water sedimentary successions dominate in middle and upper levels of the Karatavian.

Almost throughout the Riphean, the Middle Volga megablock of the East European craton, which is composed of the Archean granitoid, gabbronorite-anorthosite, and volcanogenic-sedimentary complexes and of the Early Proterozoic, predominantly crystalline rocks (K-granitoids, sediments and volcanic rocks subjected to ultrametamorphism), was the main provenance of clastic material (Bogdanova, 1986; *Precambrian Geology…*, 1988; Maslov et al., 2004a). Only conglomerates of the Mashak level are composed likely of material derived by erosion from the Lower Riphean sediments and metasedimentary rocks (Anfimov et al., 1983). Proportions of mafic and ultramafic rocks in the crust affected by erosion were relatively low. Judging from distribution of large lithologic-facies complexes at the Inzer level and from presence of quartz-sandstone interlayers in eastern sections of the Min'yar Formation, it is possible to suggest a limited influx of siliciclastic material from the east (Maslov et al., 1988, 1997b). Sediments of the Riphean accumulated mostly in semiarid environments, while humid and subglacial epochs were considerably lesser in duration (Gareev, 1989; Maslov et al., 2003a).

The Lower Vendian of in the Bashkirian meganticlinorium corresponds to distal sedimentary facies deposited by shelf glaciers and to siliciclastic sediments of interglacial epochs (Chumakov, 1998; *Climate and Epochs…*, 2004; Smith, 2001). According to many features, sedimentation basin of the Middle–Late Vendian time (590–535 Ma) was of the foreland type (Bekker, 1968, 1988; *The Riphean Stratotype…*, 1983).

The Vendian sedimentary successions of in the Bashkirian meganticlinorium accumulated under influence of both the western (Bakeevo–Uryuk ? time) and eastern (Kuk-Karauk–Zigan time) provenances (Bekker, 1968). The Beloretsk Uplift originated during the Cadomian orogeny is the likely candidate for the eastern provenance (Puchkov, 2000).

The studied typomorphism and U–Pb ages of clastic zircons (Willner et al., 2003) show that sandstones of the Avzyan and Zilmerdak formations contain besides the metamict varieties the zircon grains derived from high-grade metamorphic complexes and S-type granites. Zircon populations range in age from 1.8 to 2.3 Ga. Willner et al. (2003) reported that basement of the East European platform was the likely source of zircons that is consistent with our conclusion, based on petrographic analysis, about composition and spatial localization of provenances, which supplied clastic material to the Riphean basins of sedimentation (Maslov, 1988; Maslov et al., 1997). Sandstones of the Kuk-Karauk and Basa formations contain zircons, which are derived from acid magmatic rocks ranging in age from 643 to 512 Ma. We assume that these zircons appeared in sediments during erosion of the Beloretsk terrane, which was exhumed and raised up to the upper crustal horizons after 620 Ma.

### *Secular Variations of Th/Sc, La/Sc, Eu/Eu*, and LREE/HREE in Riphean and Vendian Fine-Grained Siliciclastic Rocks of in the Bashkirian Meganticlinorium*

Database used to consider geochemical characteristics of shales and argillites from the Burzyan, Yurmata, Karatau, and Asha groups includes over 100 determinations of REE, Sc and Th concentrations. The analytical results are obtained at the Institute of Geology and Geochemistry, Uralian Division, Russian Academy of Sciences, under guidance of Ronkin. The sample preparation procedure has been described earlier (Maslov et al., 2004a, 2004b). Data on median concentrations[3] and their standard deviations in shales and argillites from various Upper Precambrian lithostratigraphic subdivisions of the Bashkirian meganticlinorium are presented, along with amounts of analyzed samples and calculated La/Sc, Th/Sc, LREE/HREE and Eu/Eu* ratios, in Table 1.

As is postulated in this work, shales and argillites of the Late Precambrian correspond predominantly to mechanogenic sediments (Frolov, 1992). In opinion of many researchers (Melezhik and Predovskii, 1982; Taylor and McLennan, 1985; Ronov and Migdisov, 1996; Maslov et al., 1999, 2001; Podkovyrov, 2001; Podkovyrov et al., 2002), exactly the mechanogenic clays yield information characterizing petrographic composition and climate of provenances, thus supplementing those inferences, which can be obtained by investigation of sandstones and conglomerates. Of course, postsedimentary (pre-metamorphic) alterations are able to change in some or other way the primary mineral and chemical composition of rocks, their structural and textural characteristics or structures of constituent minerals. However, effect of these changes is not as great in general as alterations during sedimentogenesis (Frolov, 1992; Yapaskurt, 1999).

[3] Median values characterize the general assessment of analytical results with unknown character of statistical distribution (Rock et al., 1987).

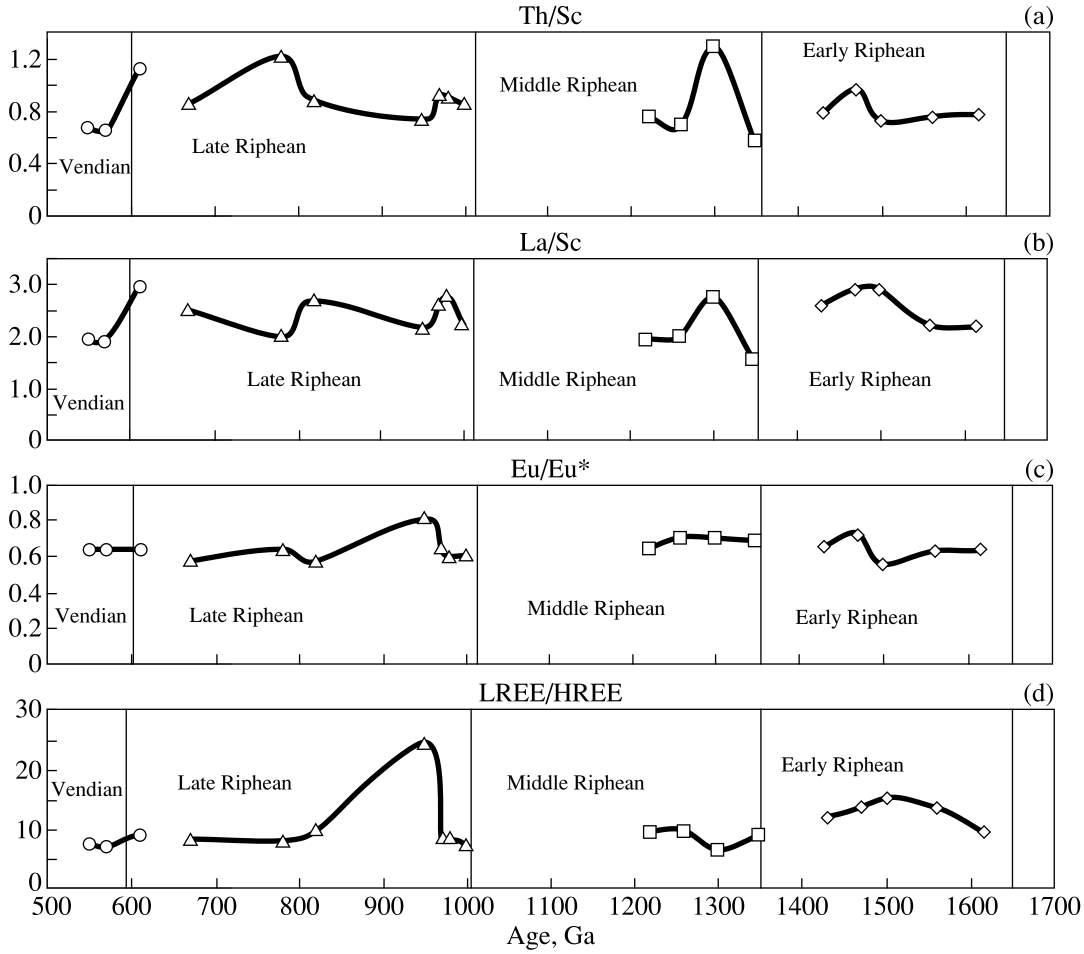


**Fig. 2.** Variations of median Th/Sc (a), La/Sc (b), Eu/Eu* (c), and LREE/HREE (d) ratios in Upper Precambrian shales and argillites of the Bashkirian meganticlinorium.

Composition of Upper Precambrian shales and argillites from the Bashkirian meganticlinorium has been described in detail not long ago (Maslov et al., 1990), and we do not consider it in this work.

In most samples of Riphean and Vendian clay rocks from the Bashkirian meganticlinorium, Th/Sc ratios are within the range of 0.57–1.0 (Fig. 2a). Higher values of 1.30 ± 0.59, 1.21 ± 0.50, and 1.12 ± 0.13 are established only in shales of the Zigal'ga Formation and in argillites of the Min'yar and Suirovo formations, respectively, but these exceptions appear to be not significant in principle owing to the relevant standard deviations. In general, the Th/Sc median ratio in clay rocks of the Bashkirian meganticlinorium is equal to 0.83 ± 0.37 thus being intermediate between the values typical of Archean (0.43 ± 0.07) and post-Archean (1.0 ± 0.1) fine-grained siliciclastic rocks (Taylor and McLennan, 1985). Like the Eu/Eu* ratios (see below), this means that the dominant Early Proterozoic complexes (Maslov et al., 2003b) associated in provenances with subordinate Archean rocks.

In fine-grained siliciclastic rocks from most Riphean and Vendian levels, the La/Sc ratios range from 1.90 ± 0.27 to 2.75 ± 0.48 (Fig. 2b). Within this range, there are higher values defining two maximums: one is confined to the interval from the mid-Satka to mid-Bakal time of the Early Riphean (from about 1500 to 1470 Ma; 2.87 ± 0.71 and 2.87 ± 0.05), and the other one to the early Early Vendian (~610–620 Ma; 2.96 ± 0.55). Besides, there are distinguishable two mesocycles of the Late Riphean (Katav–Inzer and Min'yar–Uk or Min'yar–Suirovo ?), which are about 150 to 180 m.y. long. Within each mesocycle, the initially gradual increase of La/Sc ratio terminates with a rather quick decline. For instance, in argillites of the Katav Formation, which characterize the basal part of first mesocycle, the La/Sc ratio is 2.14 ± 0.08, while in argillites of the Inzer Formation terminating this mesocycle it is 2.66 ± 0.41. The second mesocycle begins from argillites of the Min'yar level (La/Sc = 1.97 ± 0.65), which grade upward into fine-grained siliciclastic rocks of the lower Uk Subformation (La/Sc = 2.50 ± 0.49) and Suirovo Formation (La/Sc = 2.96 ± 0.55). In argillites

**Table 1.** Median Th, Sc, La concentrations (ppm) and some geochemical parameters of Upper Precambrian shales and argillites from the Southern Urals western flank

| Erathem, System | Group | Age, Ma | Formation/Subformation | | Amount of samples | Th | Sc | La | La/Sc | Th/Sc | LREE/HREE | Eu/Eu* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Vendian | Asha | *550* | Zigan | | 7 | 13.55 ± 1.81 | 17.91 ± 2.45 | 37.93 ± 12.18 | 1.96 ± 0.78 | 0.68 ± 0.15 | 7.63 ± 1.91 | 0.64 ± 0.04 |
| | | *570* | Basa | | 2 | 14.10 ± 0.40 | 21.47 ± 0.98 | 40.59 ± 3.90 | 1.90 ± 0.27 | 0.66 ± 0.01 | 7.27 ± 0.12 | 0.64 ± 0.002 |
| | | 609–617 | Suirovo | | 3 | 6.50 ± 5.12 | 5.86 ± 3.72 | 17.36 ± 16.01 | 2.96 ± 0.55 | 1.12 ± 0.13 | 9.27 ± 0.81 | 0.64 ± 0.03 |
| Late Riphean | Karatau | from 688 ± 10 to 664 ± 11 | Lower Uk Subformation | | 3 | 9.53 ± 5.77 | 11.20 ± 3.57 | 27.98 ± 13.28 | 2.50 ± 0.49 | 0.85 ± 0.27 | 8.33 ± 0.64 | 0.57 ± 0.06 |
| | | 740–710*<br>778 ± 80 | Min’yar | | 8 | 13.86 ± 5.30 | 9.20 ± 6.90 | 19.41 ± 8.58 | 1.97 ± 0.65 | 1.21 ± 0.50 | 7.96 ± 1.32 | 0.63 ± 0.07 |
| | | 805–835<br>836 ± 25 | Inzer | Upper part<br>Lower part | 9 | 15.70 ± 2.78 | 16.73 ± 4.40 | 44.64 ± 8.31 | 2.66 ± 0.41 | 0.88 ± 0.12 | 9.83 ± 0.93 | 0.57 ± 0.03 |
| | | 938–970* | Katav | | 2 | 13.93 ± 0.43 | 19.13 ± 2.34 | 40.84 ± 3.56 | 2.14 ± 0.08 | 0.73 ± 0.07 | 24.33 ± 0.91 | 0.80 ± 0.25 |
| | | *970* | Zilmer-dak | Bederysh Subformation | 7 | 13.37 ± 2.41 | 16.05 ± 5.06 | 43.98 ± 9.20 | 2.59 ± 0.45 | 0.91 ± 0.15 | 8.30 ± 1.24 | 0.64 ± 0.04 |
| | | *980* | | Nugush Subformation | 5 | 12.51 ± 5.67 | 12.05 ± 5.27 | 38.12 ± 16.03 | 2.75 ± 0.48 | 0.90 ± 0.13 | 8.42 ± 1.23 | 0.59 ± 0.03 |
| | | 1000** | | Biryan Subformation | 9 | 17.91 ± 7.20 | 16.56 ± 8.02 | 33.97 ± 26.15 | 2.21 ± 0.96 | 0.85 ± 0.81 | 7.20 ± 2.17 | 0.60 ± 0.07 |
| Middle Riphean | Yurmata | 1220* | Avzyan | | 9 | 12.30 ± 4.65 | 16.61 ± 6.67 | 31.63 ± 12.27 | 1.92 ± 0.82 | 0.75 ± 0.32 | 9.44 ± 7.01 | 0.64 ± 0.08 |
| | | *1260* | Zigazy-Komarovo | | 9 | 9.69 ± 4.72 | 12.85 ± 6.45 | 27.00 ± 12.22 | 2.01 ± 0.60 | 0.70 ± 0.11 | 9.50 ± 1.31 | 0.69 ± 0.11 |
| | | *1300* | Zigal’ga | | 4 | 7.02 ± 4.34 | 6.57 ± 2.41 | 16.02 ± 9.03 | 2.74 ± 1.90 | 1.30 ± 0.59 | 6.43 ± 1.45 | 0.69 ± 0.19 |
| | | 1348 ± 30 | Mashak | | 9 | 12.32 ± 3.76 | 22.61 ± 7.01 | 42.2 ± 23.29 | 1.55 ± 1.89 | 0.57 ± 0.16 | 8.96 ± 1.89 | 0.68 ± 0.07 |
| Early Riphean | Burzyan | 1430 ± 30 | Bakal | Malyi Bakal Sub-formation | 4 | 15.16 ± 0.72 | 18.87 ± 0.53 | 48.13 ± 4.56 | 2.59 ± 0.26 | 0.79 ± 0.05 | 11.86 ± 0.99 | 0.65 ± 0.02 |
| | | *1470* | | Makarovo Subformation | 3 | 17.65 ± 0.95 | 16.80 ± 1.69 | 48.63 ± 3.98 | 2.87 ± 0.05 | 0.96 ± 0.09 | 13.61 ± 1.10 | 0.71 ± 0.04 |
| | | *1500* | Satka | Polovinka Subformation | 3 | 14.35 ± 2.38 | 19.66 ± 6.80 | 55.50 ± 5.07 | 2.87 ± 0.71 | 0.73 ± 0.27 | 14.92 ± 4.05 | 0.55 ± 0.08 |
| | | *1560* | | Nizhnyaya Kusa Subformation | 4 | 13.87 ± 0.85 | 18.17 ± 0.43 | 40.27 ± 4.67 | 2.21 ± 0.22 | 0.76 ± 0.06 | 13.54 ± 1.91 | 0.62 ± 0.09 |
| | | 1615 ± 45 | Ai Formation, lower subdivision (Navysh, Lipovo, Chuda subformations) | | 4 | 14.09 ± 0.86 | 18.34 ± 0.81 | 40.10 ± 1.85 | 2.19 ± 0.05 | 0.78 ± 0.07 | 9.61 ± 1.02 | 0.63 ± 0.05 |

Note: In distinction from confident dates, conventional age values used to plot Figs. 2–4 are italicized; K-Ar ages of glauconite (whole-rock method) are marked by single asterisks, and doubled asterisks denote minimal ages of clastic zircons (α-Ub method).

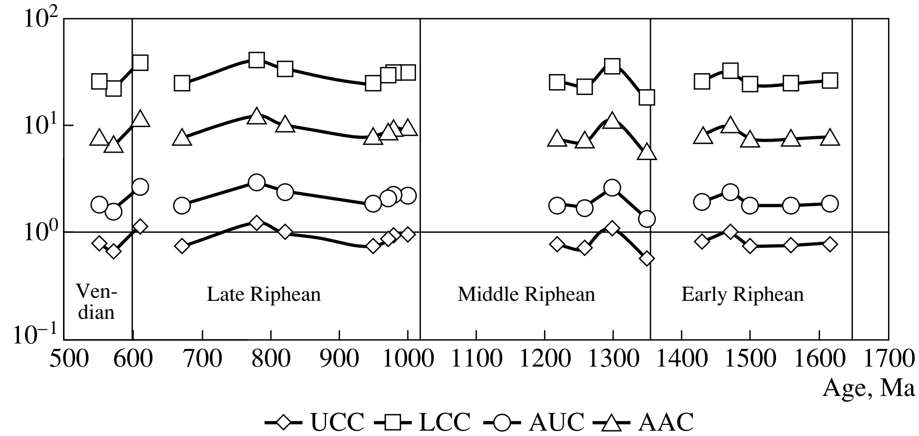


**Fig. 3.** Variations of median Th/Sc ratios in Riphean and Vendian fine-grained siliciclastic rocks of the Bashkirian meganticlinorium when normalized to standard crustal values: (UCC) upper continental crust; (LCC) lower continental crust; (AUC) Archean upper crust; (AAC) average andesitic crust.

of the Vendian Basa Formation, the La/Sc ratio is approximately equal to this parameter in rocks of the Min'yar Formation (1.90 ± 0.27). The La/Sc median ratio in Upper Precambrian shales and argillites of the Bashkirian meganticlinorium corresponds to 2.23 ± 0.87.

Almost throughout the Early and during the Middle Riphean, Eu/Eu* ratios varied from 0.62 ± 0.09 to 0.71 ± 0.04, being reduced down to 0.55 ± 0.08 in the mid-Satka time (~1500 Ma ago) only (Fig. 2c). Similarly low values of this parameter are recorded twice afterward: in the Nugush (>980 Ma; 0.59 ± 0.03) and Min'yar times (~820 Ma; 0.57 ± 0.03). Taking into consideration that this parameter used to be transferred without modifications from provenances into basins of sedimentation, we believe in a growing degree of REE recycling in sedimentogenesis from the initial to terminal Riphean time, because the negative Eu-anomalies are indicative of the crustal recycling and contamination. On the other hand, shales of the Katav Formation (~950 Ma) recorded a considerable increase of Eu/Eu* ratio (0.80 ± 0.25). This could be a result of appearance in provenances of Archean rocks exposed to erosion in the second half of the Late Riphean, because the Eu-anomaly is either insignificant in these rocks, or untypical of them (Taylor and McLennan, 1985). In view of a rather high standard deviation, this conclusion is of preliminary character only.

The Eu/Eu* median ratio in Upper Precambrian clay rocks of the Bashkirian meganticlinorium is 0.64. With due account for standard deviation (±0.08), this parameter is practically identical to value of 0.66 characterizing the post-Archean average shale (PAAS) of Australia (Nance and Taylor, 1976) and comparable with Eu/Eu* = 0.70 calculated for the North American shale composite (NASC) of the Paleozoic (Haskin et al., 1968).

The other reliable indicator of the upper crust composition is the LREE/HREE ratio (McLennan and Taylor, 1991; Taylor and McLennan, 1995; Condie, 1997; and other works). In clay rocks of the Burzyan and Yurmata groups, i.e., during a considerable time span from about 1635 to 1000 Ma, this ratio ranged from 6.43 ± 1.45 (Zigal'ga level) to 14.92 ± 4.05 (Polovinka Subformation of the Satka Formation) that points to a considerable changes in petrographic composition of provenances. A narrower interval of this parameter (from 7.20 ± 2.17 to 9.83 ± 0.93) is characteristic in general of the Late Riphean–Vendian succession of the Bashkirian meganticlinorium, although in the Katav time (~980–940 Ma) the LREE/HREE ratio (24.33 ± 0.91) was extraordinary high (Fig. 2d). In our opinion, this is indicative of a high proportion of Archean substratum exposed to erosion in provenances during the respective time span, because high LREE/HREE ratios (>15) but very low Eu/Eu* values are typical in general of the Archean crust (Taylor and McLennan, 1985). The LREE/HREE median ratio characterizing the entire Riphean–Vendian succession of the Bashkirian meganticlinorium corresponds to 9.06 ± 3.71, while the same parameter of fine-grained siliciclastic rocks 1.7 to 0.6 Ga old is 8.9 ± 0.9 (Taylor and McLennan, 1985).

The Th/Sc median ratios of fine-grained siliciclastic rocks from different Riphean and Vendian lithostratigraphic subdivisions of the Bashkirian meganticlinorium have been normalized to this parameters in upper and lower continental crust (UCC and LCC) and to the Archean upper crust (AUC) or average andesite composition (AAC). The comparison showed that composition of crust subjected to erosion during the entire accumulation period of the rocks under consideration was most close to the UCC standard composition (Fig. 3). Crustal composition transitional between the UCC and AUC can be suggested for provenances of the earliest Middle Riphean time (level of the Mashak Formation).

The Nd model age calculated for shales and argillites of the Riphean stratotype ranges from 2.5 to

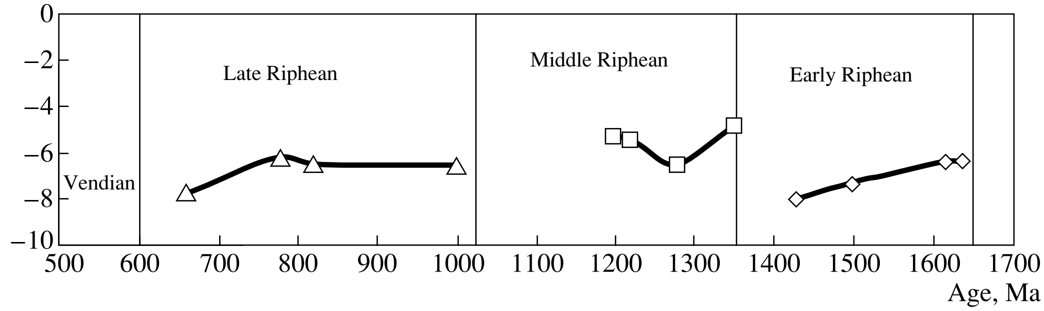


**Fig. 4.** Variations of $\varepsilon_{Nd}$(T) values characterizing shales and argillites of the Riphean stratotype section.

1.7 Ma (Maslov et al., 2003b) and indicates therefore the erosion of the Early Proterozoic basement in eastern segment of the East European platform throughout the Riphean period. Shales of the Lower Riphean Bakal Formation with $\varepsilon_{Nd}$(T) = –8 represent the only level, where this parameter is shifted toward the value, which is lower than in other fine-grained siliciclastic rocks of the stratotype, while in shales of the Middle Riphean Mashak Formation its value is highest, equal to –4.9 (Fig. 4). According to the aforesaid, it is possible to assume that juvenile mantle material appeared in upper crustal horizons of provenance in the terminal Burzyan time and caused some increase of $\varepsilon_{Nd}$(T) values in fine-grained siliciclastic sediments of the Mashak Formation. We failed, however, to estimate the relative proportion of this juvenile material. An alternative explanation to the observable phenomenon is a direct volcanic influx of juvenile mantle components in the pre-Mashak time, because this formation is lacking synsedimentary hiatuses and basaltic sills or lava flows (Parnachev et al., 1986; Maslov et al., 2001).

Comparing Eu/Eu*, LREE/HREE, Th/Sc and La/Sc average ratios in Archean and post-Archean shales, on the one hand, with the same parameters characterizing Riphean and Vendian clay rocks of the Bashkirian meganticlinorium, on the other (Table 2), one can see that the first ratio only is practically identical in the studied rocks and reference standards. In particular, this ratio in the rocks of the Bashkirian anticlinorium is almost equal to the value suggested by Taylor and McLennan (1985) for the post-Archean rocks, the Late Proterozoic fine siliciclastic material included. Three other ratios range between the values typical of the Archean and post-Archean shales. Accordingly, we may assume that the upper crust of the Middle Volga megablock of the Russian platform, which was the main source of siliciclastic material buried in Late Precambrian sedimentary successions occurring in western flank of the Southern Urals, was less mature than the standard UCC consolidated by the end of the Early Proterozoic (Taylor and McLennan, 1985, 1995).

Thus, secular variations of Th/Sc, La/Sc, Eu/Eu* and LREE/HREE ratios in Upper Precambrian fine-grained siliciclastic rocks of the Bashkirian meganticlinorium depict a series of negative and positive excursions relative to the standard values suggested by Taylor and McLennan (1985) for shales, which accumulated 1700 to 600 Ma ago. These excursions are characteristic mainly of the Upper Riphean and Vendian sediments. They do not coincide in time with each other or are of different intensity, and events they are related to have been likely of different character. In the Bashkirian meganticlinorium, there was a series of magmatic events within the time span from 1650 to about 550 Ma (*The Riphean Stratotype…*, 1983; *Formation of the Earth…*, 1983; Alekseev, 1984; Maslov et al., 2001), which could influence composition of fine siliciclastic material deposited in the junction zone between the East European platform and Southern Urals. As is shown below, however, some positive or

**Table 2.** Characteristic geochemical ratios in three shale standards (Taylor and McLennan, 1985) and in Upper Precambrian fine-grained siliciclastic rocks of the South Urals western flank and Uchur-Maya region

| Ratio | Data after Taylor and McLennan (1985) | | | South Urals, western flank | Uchur-Maya region |
|---|---|---|---|---|---|
| | Archean rocks | Post-Archean rocks | rocks deposited 1.7–0.6 Ga ago | rocks deposited 1.65–0.54 Ga ago | |
| Eu/Eu* | 0.99 ± 0.05 | 0.65 ± 0.02 | 0.65 ± 0.03 | 0.65 ± 0.06 | 0.62 ± 0.13 |
| LREE/HREE | 7.4 ± 0.8 | 10 ± 1 | 8.9 ± 0.9 | 8.59 ± 3.65 | |
| Th/Sc | 0.43 ± 0.07 | 1.0 ± 0.1 | 1.0 ± 0.1 | 0.77 ± 0.17 | 0.75 ± 0.24 |
| La/Sc | 1.3 ± 0.2 | 2.7 ± 0.3 | 2.4 ± 0.6 | 2.23 ± 0.40 | 2.4 ± 0.75 |

negative LRRE/HREE, Eu/Eu*, Th/Sc, and La/Sc excursions have no obvious connections with events, which are known at present.

After the "diffuse" rifting of the early Ai time (~1.615 Ga) and associated eruptions of alkaline basic volcanics of the Navysh Complex, the gradually increasing LREE/HREE and La/Sc ratios are distinguishable in the Burzyan Group shales up to the time mark of about 1.5 Ga. The Th/Sc ratio declined simultaneously by several percents and Eu/Eu* ratio decreased from 0,62–0,63 to 0.55. Relative to the Polovinka Subformation of Satka Formation, shales of the lower Bakal level (~1.47 Ga) show in contrast the distinct symbate growth of Eu/Eu* and Th/Sc ratios.

Throughout the Riphean type section, LREE/HREE ratios in clay rocks show the limited interval of variations from 6 to 12–15, and only argillites of the Katav level in the Karatau Group have abnormally high median value (>24) of this parameter. At the same time, it is remarkable that any magmatic or metamorphic events were likely untypical of provenances and had not been manifested in the basin of sedimentation during the respective time span.

A complicated rifting of the Mashak time[4] marking the Early–Middle Riphean boundary in the type section influenced considerably the composition of fine siliciclastic material. The relevant clay sediments accumulated in the Bashkirian meganticlinorium in the terminal Burzyanian and during the first half of the Yurmatinian, i.e., during the time span from about 1430 Ma (the accumulation time of carbonate sediments of the Berezovaya member, the Malyi Bakal Subformation of the Bakal Formation) to 1360–1348 Ma. The decreased LREE/HREE, Th/Sc, and La/Sc ratios in these sediments certainly imply influence on sedimentation of mafic and (?) ultramafic rocks.

The almost concurrent appearance of juvenile mantle material in provenances is also inferable from the fact that parameter $\varepsilon_{Nd}(T)$ in shales of the Mashak Formation is lower than in fine-grained siliciclastic rocks of the Bakal Formation (Maslov et al., 2003b). This event is likely correlative with declined LREE/HREE ratios in shales ranging in age approximately from 1350 to 1300 Ma. However, these ratios increased again by the end of the Avzyan time, and this suggests a considerable (?) proportion of acid magmatic rocks in provenances and influx of arkosic material into sedimentation areas in response to weathering of insignificant intensity. The $K_2O/Al_2O_3$ ratios increasing in the mid-Middle Riphean shales (Avzyan level at 1220–1200 Ma), which show elevated REE concentrations and $La_N/Yb_N$ ratios, are most likely indicative of the same event (Maslov et al., 2004a).

Secular variations of Th/Sc and La/Sc are of the other character. In the Zigal'ga time[5] approximately 50 m.y. after culmination of the Mashak rifting event, shales and fine-grained clayey siltstones recorded excursions of Th/Sc and La/Sc ratios, which suggest crustal erosion in provenances predominantly composed of granitoids. About 30 to 40 m.y. later (again estimated values), both ratios decrease in shales of the Zigazy-Komarovo Formation to the level typical of many other siliciclastic deposits in the stratotype.

In the Karatau Group, basal shales (Biryan Subformation) of the Zilmerdak Formation, which accumulated from nearly 1000 to 980 Ma (both calculated values are after Maslov, 2001), have somewhat lower LREE/HREE and Eu/Eu* ratios than shales of the Avzyan level in the Yurmata Group (~1220–1200 Ma). In argillites of the Biryan and Nugush subformations of the Zilmerdak Formation, the Eu/Eu* ratios are lower in general than in the standard PAAS and correspond approximately to this parameter of the UCC dominated by granitoids (Taylor and McLennan, 1985; Cullers, 1995). On the other hand, Th/Sc and La/Sc ratios in this interval are a bit higher than at the level of Avzyan shales.

In argillites of the Nugush and Bederysh subformations, Th/Sc and La/Sc ratios increase approximately by 12–15%, while the parallel growth of Eu/Eu* ratio remains below the PAAS level. An extreme increase of LREE/HREE and Eu/Eu* values (by 290 and 120%, respectively) is recorded in the Karatau Group at the level of about 950 Ma (Katav Formation), where Th/Sc and La/Sc ratios in argillites are decreased by 18–20%. Later on up to the accumulation time of Zigan Formation (~550 Ma), fluctuations of LREE/HREE ratio are of a lower intensity, ranging between 7.27 and 9.83 with lower values confined to argillites in the Asha Group upper part. As for Eu/Eu* variations, they are in general within the interval of 0.57 to 0.64, and minimal ratios are established at the Inzer (about 820 Ma) and lower Uk (670 Ma) levels.

It is remarkable that throughout the Suirovo–Zigan interval (from 610 to 550 Ma approximately), the Eu/Eu* ratio in argillites remains stable, corresponding to 0.64. Between ~950 and 820 Ma, Th/Sc and La/Sc are growing, but afterward, up to the Zigan level (~550 Ma), they fluctuate.

Secular decline of Th/Sc and La/Sc ratios in the Suirovo–Zigan interval is about 40% that is comparable with changes of both parameters during the Mashak

[4] In the Bashkirian meganticlinorium, intrusive rocks of that time are represented by rapakivi granitoids of the Berdyaush multiphase massif (1348 ± 16 Ma, *The Lower Riphean…*, 1989), by granites of the Ryabinovaya massif (1350 Ma, Tugarinov et al., 1970), by the Kusa–Kopanka differentiated intrusion of gabbroids (1300 Ma, Gorozhanin, 1998), by basic volcanics and sills of the Mashak Formation (1348 ± 30 Ma, *The Lower Riphean…*, 1989), and by Main Dike probably comagmatic to the latter, which intruded 1360 ± 35 Ma ago the siliciclastic-carbonate succession of the upper Bakal Subformation in the synonymous ore field (El'mis et al., 2000).

[5] The time is estimated based on the accumulation period of Zigal'ga Formation with due account for sedimentation rates and thickness ranges of different facies of the Middle Riphean Yurmata Group (see details in Maslov, 2001).

rifting event. In both cases, this is not accompanied by significant changes in Eu/Eu* parameter, while LREE/HREE ratio decreases insignificantly. It is reasonable to assume therefore that the above changes of Th/Sc and La/Sc ratios indicative of higher proportions of mafic and ultramafic rocks in provenances have not been connected with simultaneous erosion of Archean crust. As is shown below, the same is typical of the Uchur–Maya region.

In recent works (Puchkov, 2000, 2004; Willner et al., 2003), the Beloretsk metamorphic complex (terrane) has been considered as main provenance of clastic material during accumulation of Upper Vendian sedimentary successions in the Bashkirian meganticlinorium, and it would be reasonable to suggest therefore that exactly erosion of that complex was responsible for the above decrease of Th/Sc and La/Sc ratios. However, the complex is of sialic composition in general, and eclogites and amphibolites, i.e., metamorphic equivalents of basic sills, represent not more than 10% of its composition (Alekseev et al., 2002; Galieva, 2004). Consequently, erosion of the Beloretsk complex was unable to decrease Th/Sc and La/Sc in argillites of the late Late Vendian.

## UPPER PRECAMBRIAN SEDIMENTARY SUCCESSIONS OF THE UCHUR–MAYA REGION

The Siberian hypostratotype of the Riphean includes the Uchur, Aimchan, Kerpyl, Lakhanda, Ui, and Yudoma groups. The Uchur Group corresponds to the Lower Riphean, while the Middle and Upper Riphean are divided in two groups each, i.e., into the Aimchan and Kerpyl groups in the first case and the Lakhanda and Ui groups in the second one (Semikhatov and Serebryakov, 1983; Sergeev, 2003). The Yudoma Group is of the Late Vendian age (Ovchinnikova et al., 2003; Semikhatov et al., 2003). Composition, structure, and lithostratigraphy of all the groups have been repeatedly described earlier, and below they are described in a very general manner only.

### *Riphean and Vendian Lithostratigraphy of the Uchur–Maya Region*

The Uchur Group of synonymous plate consists of the Gonam, Omakhta, and Enna formations, while in the Yudoma–Maya belt it is divided into the Pionerka, Trekhgorka, Dim, and Belorechensk formations (Semikhatov and Serebryakov, 1983; Shenfil', 1991, Sergeev, 2003). Sediments of the Riphean hypostratotype accumulated since 1600(?)–1520 Ma (Khudolei et al., 2001). In the Uchur plate, K–Ar ages of glauconite from sandstones of the Gonam and Omakhta formations correspond to 1450–1520 and 1360 Ma respectively (Shenfil', 1991). The Early Riphean provenances of clastic material have been situated to the west and northwest of the Uchur basin (Semikhatov and Serebryakov, 1983; Podkovyrov et al., 2002).

The Aimchan Group includes the Talyn and Svetlyi formations. Mineralogically unstudied glauconites from sandstones of the Talyn Formation are as old (K–Ar method) as 1210–1230 Ma (Kazakov and Knorre, 1973; Semikhatov et al., 1973; Shenfil', 1991).

The Kerpyl Group comprises the Totta, Malgina, and Tsypanda formations. The maximum K–Ar age of glauconite from sandstones of the Totta Formation, which is probably indicative of the accumulation time, is close to 1170–1070 Ma (Shenfil', 1991; Sergeev, 2003). The youngest generation of clastic zircons from this formation is 1300 ± 50 Ma old (Khudolei et al., 1999, 2001). According to Pb–Pb age determinations, limestones of the Malgina Formations are 1043 ± 14 Ma old (Ovchinnikova et al., 2001). Chemostratigraphic data (Bartley et al., 2001) also imply that this formation is younger than 1250 Ma.

In the Kerpyl time, clastic material has been transported into the Middle Riphean basin from western provenances of crystalline rocks corresponding to the Siberian platform basement. Local uplifts of the basement presumably existed inside the basin as well (Semikhatov and Serebryakov, 1983; Khudolei et al., 2001; Podkovyrov et al., 2002).

The Lakhanda Group is represented by sediments of the Neryuen and Ignikan formations. Carbonate rocks in the group lower part are 1025 ± 40 Ma old according to results of Pb–Pb dating method (Semikhatov et al., 2000). Carbonates of the Sukhaya Tunguska Formation clamped between stratigraphic equivalents of the Malgina and Neryuen formations yielded the Pb–Pb age of 1035 ± 60 Ma (Bartley et al., 2001).

Siliciclastic sediments of the Lakhanda Group are composed of material that has been transported from westerly inner areas of the Siberian platform and also from the Batom Uplift of basement situated to the west–southwest of the Late Riphean basin of sedimentation (Podkovyrov et al., 2002).

The Upper Riphean succession of the Yudoma–Maya belt is crowned by the Ui Group consisting of the Kandyk and Ust-Kirba formations. Basic magmatic rocks concurrent to deposition of sediments belonging to the Ui Group lower part contain baddeleyite that is 1000–975 Ma old according to results of the U–Pb dating (Khudolei et al., 2001). The U–Pb age of youngest generation of clastic zircons from the Ui Group is 1057 ± 28 Ma (Rainbird et al., 1998).

Fine- to coarse-grained siliciclastic material was transported to basin of the Ui time from crystalline basement uplifts located westward in the Siberian craton. One of the local uplifts probably corresponded to the Okhotsk massif situated eastward (Khudolei et al., 2001; Podkovyrov et al., 2002).

The Yudoma Group of the Yudoma and Maya river basins includes sediments of the Aim and Ust-Yudoma formations. The early diagenesis of carbonates in the Ust-Yudoma Formation took place 553 ± 23 Ma ago according to determination by the U–Pb method (Ovchinnikova et al., 2003).

*Deposition Environments of Upper Precambrian Sedimentary Successions in the Uchur–Maya Region*

Intracratonic basins of sedimentation, which existed in the Uchur-Maya region during the Early–Middle Riphean, received clastic material derived by erosion from magmatic–metamorphic rock complexes close in composition to the UCC and from the Proterozoic granodiorite massifs (Khudolei et al., 2003). High Zr/Sc ratios in sandstones of the Uchur and Kerpyl groups suggest a considerable recycling of siliciclastic material. Clastic zircons ranging in age from 2.06 to 1.82 Ga appeared in studied sediments from provenances of the Siberian platform located westward of the region under consideration. There was also a hypothetical easterly provenance of clastic material, because the rocks contain the other generation of zircons ranging in age from 1.55 to 1.32 Ga, which are unknown in the basement rock complexes of the Siberian platform (Rozen, 2001; Kotov, 2003).

Locally occurring in the Upper–Middle Riphean sedimentary successions and in the Anabar and Aldan shields are magmatic rock complexes of basic composition (alkaline to tholeiitic basalts), which are relatively enriched in B, K, and Pb, being simultaneously depleted in Th, Nb, Sr, and some other elements. These complexes with $\varepsilon_{Nd}(T)$ close to –0.1 are indicative of rifting pulses, which took place 1.50, 1.38, and 1.32 Ga ago (Podkovyrov et al., 2001a).

Magmatic and metamorphic rock complexes of western provenances, which have been subjected to erosion during the accumulation time of the Ui Group lower part (~0.95–1.00 Ga ago), are similar in geochemical characteristics to Proterozoic granitoids of the Aldan Shield. The crust somewhat less mature and dominated by granodiorites has been under erosion at the deposition time of sediments confined to the upper part of the Ui group. In the last period, siliciclastic material was derived from either the inner uplifts of sedimentation basin, or an easterly (?) land mass. Siliciclastic sedimentation of the Ui time was associated with intrusions of thick diabase sills and eruption of basaltic lava flows (Rainbird et al., 1998; Khudolei et al., 2003).

Rifting of the earliest Early Riphean time isolated the Uchur–Maya region from the eastern provenance of siliciclastic material. This event resulted most likely in formation of a large rift system southeastward of the present-day South Verkhoyansk region. Afterward, almost throughout the Late Riphean, continental crust of the study region was under destruction. Rock complexes, which evidence most clearly the Rodinia breakup and the global tectonic transformation of Siberian continent are tholeiitic and bimodal volcanics (Baikal–Muya zone, areas near Sayan Mountains), ophiolites and island-arc volcanics from about 650 to 510 Ma old in southern periphery of the Siberian craton (Podkovyrov et al., 2001a; Semikhatov et al., 2002).

During the Vendian, Paleozoic, and Mesozoic, the eastern periphery of the craton represented rifted continental margin (Khudolei, 2003; Vernikovskii and Metelkin, 2004). The U–Pb and U–Th–Pb (SHRIMP) dating of clastic zircons (Khudolei et al., 2001) imply that the Early Proterozoic basement complexes of the Siberian platform represented main source rocks of siliciclastic material in the Early Yudomian time.

Throughout the Late Precambrian, the study region corresponded to the passive margin of the North Asian craton (Sukhorukov, 2003). The Elsonian orogeny that affected the region in the terminal Early Riphean coincided in time with development of granitoid magmatism in inner areas of the Verkhoyansk belt, where blocks of mafic and ultramafic rocks had been risen up to the day surface. Grains of chromite and Cr-spinel derived from ultramafic rocks occur in basal sandstones of the Talyn Formation, the Aimchan Group. The Grenvillian tectonic phase of the terminal Late Riphean triggered formation of foreland basin in the study region, which is filled in with an orogenic complex. The event was followed by emplacement of dolerite sill-like intrusions and by eruption of tholeiitic to moderately alkaline basalts indicative of significant rifting events. In opinion of Sukhorukov, the Riphean stage of the region evolution terminated with folding of the latest Riphean time. One more event of continental rifting in the initial Vendian time caused deposition of diverse graben facies and emplacement of alkaline ultramafic and carbonatite massifs. In addition Serkina et al. (2004) reported that they failed to detect indications of the oceanic crust erosion at any level of the Riphean–Middle Paleozoic siliciclastic succession in the southeastern margin of Siberian craton.

*Secular Variations of Th/Sc, La/Sc and Eu/Eu* Ratios in Riphean and Vendian Shales of the Uchur–Maya Region*[6]

To consider variations of geochemical characteristics in Riphean–Vendian sedimentary successions of the Uchur–Maya region, we used database that consists of 30 analyses. Trace element and REE concentrations are determined using the INAA method at the Kansas University of the United States, and procedure of samples preparation has been described earlier (Kotov et al., 1995; Podkovyrov et al., 2002). As this database is much less informative than that characterizing shales and argillites of the Bashkirian meganticlinorium, median values of element ratios in Riphean and Vendian subdi-

[6] LREE/HREE ratios are omitted from consideration, because REE concentrations have not been determined in a series of argillite samples from the Uchur–Maya region.

**Table 3.** Th, Sc, La concentrations (ppm) and some geochemical parameters of Upper Precambrian argillites from the Uchur-Maya region

| Erathem, System | Group | Formation | | Age, Ma | Th | Sc | La | La/Sc | Th/Sc | Eu/Eu* |
|---|---|---|---|---|---|---|---|---|---|---|
| Vendian | Yudoma | Ust-Yudoma | | 553 | Predominantly carbonate rocks | | | | | |
| | | Aim | | *570* | 0.48 | 29.2 | 24.6 | 0.8 | 0.3 | 0.68 |
| Upper Riphean | Ui | Ust-Kirba | Upper part | 940 | 1.17 | 20.2 | 42.5 | 2.1 | 0.75 | 0.50 |
| | | | Lower part | *980* | 1.36 | 19.3 | 33.6 | 1.7 | 0.72 | 0.59 |
| | | Kandyk | | *1000* | 0.79 | 15.1 | 39.5 | 2.6 | 0.94 | 0.59 |
| | Lakhanda | Ignikan | | *1015* | 0.96 | 16.8 | 56.9 | 3.4 | 1.0 | 0.49 |
| | | Neryuen | | 1025 | 1.42 | 21.8 | 58.6 | 2.7 | 0.94 | 0.52 |
| Middle Riphean | Kerpyl | Totta | Upper part | *1150* (1170–1070**) | 0.72 | 21.1 | 49.6 | 2.4 | 0.84 | 0.70 |
| | | | Lower part | *1200* (1300*) | 1.2 | 16 | 50 | 3.1 | 0.88 | 0.54 |
| | Aimchan | Svetlyi | | *1280* | 0.89 | 17.5 | 42.4 | 2.4 | 0.74 | 0.71 |
| | | Talyn | | *1350* (1230–1210**) | 0.85 | 31.9 | 28.3 | 0.9 | 0.24 | 0.99 |
| Lower Riphean | Uchur | Dim | | *1400* | 0.38 | 13.1 | 33.3 | 2.5 | 0.76 | 0.74 |
| | | Trekhgorka | Upper part | *1550* | 0.38 | 10.3 | 25 | 2.4 | 0.7 | 0.62 |
| | | | Lower part | 1600–1520* | 0.51 | 11.7 | 26.9 | 2.3 | 0.48 | 0.68 |

Note: In distinction from confident dates, conventional age values used to plot Figs. 5 and 6 are italicized; U–Pb ages of clastic zircons are marked by single asterisks, and doubled asterisks denote K-Ar ages of glauconite (whole-rock method).

visions of the Uchur–Maya region and their standard deviations are not included in Table 3.

According to geological data, there was rifting episode of the earliest Riphean time (~1.5 Ga ago) in the Uchur–Maya region, but it did not influence significantly the composition of siliciclastic material accumulated in sedimentary basin. At any rate, Th/Sc and La/Sc ratios in shales of the Trekhgorka and Dim formations tend to increase weakly toward the end of the Early Riphean without distinct fluctuations. This indicates that mature continental crust formed by cratonization of the Siberian platform in the terminal Late Proterozoic (Semikhatov, 1974; *Precambrian Geology…*, 1988) was persistently under erosion during the period under consideration.

The Nd model ages of shales range within the Uchur Group from 2.3 to 2.1 Ga with parallel changes of $\varepsilon_{Nd}(T)$ parameter from –4.0 to –6.9 (Podkovyrov et al., 2002). Granitoid intrusions of the Elsonian orogeny and concurrent exhumation of mafic and ultramafic rocks in inner areas of the Verkhoyansk belt (Sukhorukov, 2003) caused a considerable decline of Th/Sc and La/Sc ratios in shales of the Talyn Formation and parallel decrease of Eu/Eu* values. It is possible as well that crust of relevant provenance included a considerable proportion of Archean rocks (Podkovyrov et al., 2002).

During the accumulation time of the Svetlyi and Totta formation, influence of mafic to ultramafic rift complexes on composition of sediments was less obvious. Fine-grained siliciclastic rocks deposited at that time have Eu/Eu*, Th/Sc, and La/Sc parameters, which prevailed during the Early Riphean. Parameters $T_{Nd}(DM)$ = 1.8 Ga and $\varepsilon_{Nd}(T)$ = +0.3 characterizing argillites of the Totta Formation in the Maya plate suggest, in our opinion, the influx of juvenile mantle material into the area of sedimentation in the early Middle Riphean. It is also possible, however, that source of clastic material corresponded to juvenile continental crust of the Early Proterozoic.[7]

An intense pulse of rifting that is detectable across the Middle–Late Riphean transition in the Uchur–Maya region was responsible for a sudden decline of La/Sc ratio from 3.4 in the Ignikan argillites to 1.7 in lower shales of the Ust-Kirba Formation. The Th/Sc ratio decreases in the same rocks less significantly, by 25–28% only.

The Nd model age calculated for argillites of the Neryuen Formation (Lakhanda Group of the Maya plate) is ~1.6 Ga, while $\varepsilon_{Nd}(T)$ = +0.4 in these rocks is close to the value characterizing siliciclastic sediments

[7] This is assumed by A.B. Kotov in his comments to our manuscript.

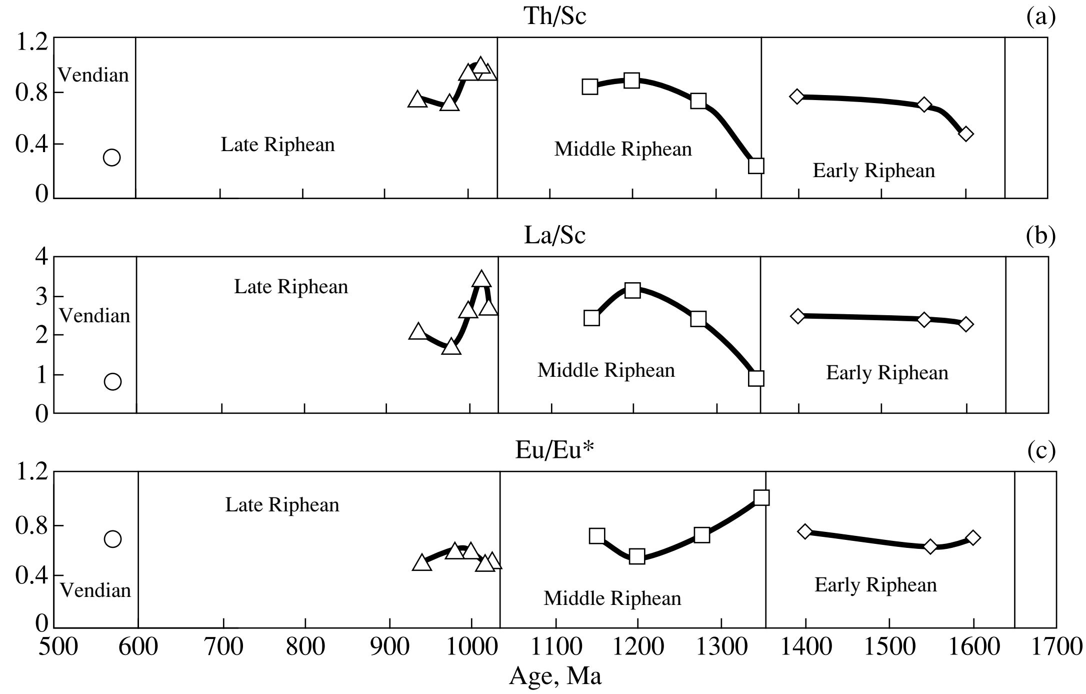


**Fig. 5.** Variations of Th/Sc (a), La/Sc (b), and Eu/Eu* (c) ratios in Upper Precambrian shales and argillites of the Uchur–Maya region.

of the Totta Formation. We believe therefore that the Neryuen time marks one more episode of the mantle material injection into the upper crust. Very low (like at the Talyn level) Th/Sc and La/Sc ratios in argillites of the Aim Formation suggest that the pre-Vendian rifting event also produced an impact on composition of fine siliciclastic material in the Yudoma Group. This is consistent with the Middle Riphean value of Nd model age (1.3 Ga) calculated for the Aim shales having parameter $\varepsilon_{Nd}(T) = -0.3$ (Podkovyrov et al., 2002).

Upward in the Riphean hypostratotype succession, chondrite-normalized REE concentrations approach the standard values characteristic of the NASC and PAAS. This fact and occasionally growing proportion of HREE suggest, as we think, intensification of sediments recycling (Podkovyrov et al., 2002, 2003).

In argillites of the Uchur Group, Th/Sc values are growing upward from 0.48 near the Trekhgorka Formation base to 0.70 near the top of this formation and to 0.76 in the Aim Formation (Fig. 5a). At the base of the Talyn Formation, the Aimchan Group, this parameter is almost three times lower (0.24). Higher in the section, Th/Sc values are increasing, and at the Totta Formation level they are 3 to 3.5 times greater than near the base of the group.

The highest Th/Sc ratios (0.94–1.00) are established in argillites of the Neryuen, Ignikan, and Kandyk formations of the Lakhanda and Ui groups, but they decrease down to 0.72–0.75 in the Ust-Kirba Formation crowning the Ui Group. Argillites of the Aim Formation, basal one in the Yudoma Group, and fine-grained siliciclastic rocks of the Talyn Formation in the Aimchan Group have very low Th/Sc ratios (0.30). Sediments with these extremely low ratios appear to be enriched in Sc thus being comparable with "primitive" (Archean?) substratum composed of crustal and mantle rocks (Podkovyrov, 2001).

In the Uchur–Maya region, Th/Sc ratios most close to this parameter of the PAAS are characteristic of the Middle and Upper Riphean clay sediments. It is reasonable to assume therefore that erosion affected in this period mostly blocks composed of the mature continental crust (Cullers and Podkovyrov, 2002; Podkovyrov et al., 2002). This is consistent with isotopic dates obtained for clastic zircons (Khudolei et al., 2001). In distinction from the other hypostratotype levels, erosion of either the more basic substratum, or the deeper continental crust horizons has been suggested for the accumulation period of the Middle Riphean Talyn Formation (Podkovyrov et al., 2002). Predominance of plagiogranites (probably Archean in age) in provenances of the Talyn time can be suspected based on distribution of data points characterizing argillites of that time in the La–Th–Sc diagram.

Secular variations of La/Sc and Th/Sc ratios in Upper Precambrian rocks of the Uchur–Maya region are nearly of symbate character (Fig. 5b). For instance, La/Sc ratio is weakly growing from the base upward in the Uchur Group of the Lower Riphean. In fine-grained siliciclastic rocks of the Middle Riphean, increase of this ratio is more essential: from 0.9 at the Talyn level to 3.1 near the base of the Totta Formation. Close to the top of the latter, this parameter is equal to 2.4 like in the Svetlyi Formation. Shales of the Neryuen Formation that is basal in the Lakhanda Group have La/Sc = 2.7. Higher in the section, this ratio increases up to 3.4 (Ignikan level) and drops down to 2.6 in fine-grained siliciclastic rocks of the Kandyk Formation and then to 1.7 in lower argillites of the Ust-Kirba Formation. In upper shales of the latter, it is a little higher (2.1).

Of special interest are variations of both ratios across boundaries between principal sedimentary cycles discriminated in the Bashkirian meganticlinorium and Uchur–Maya region. In both regions for instance, there is established an essential decline of Th/Sc and La/Sc ratios across the Early–Middle Riphean boundary, and consequently basic rocks have been more widespread in provenances of the early Middle Riphean than in the terminal Burzyanian time. Much higher Eu/Eu* values in basal shales of the Kerpyl Group imply that Archean rocks became widespread simultaneously in provenances adjacent to the Uchur–Maya region, although similar effects are nor recorded in sedimentary succession of the Bashkirian meganticlinorium. Across the Middle–Upper Riphean boundary, Th/Sc and La/Sc ratios practically do not change, and this can be interpreted as indication of persistent rock composition in provenances throughout the greater interval of the Middle Riphean. The only exception is a sharp increase in abundance of acid rocks for a short (?) period in provenances of the Bashkirian meganticlinorium at the commencement of the Yurmatinian time.

In the Late Riphean, Th/Sc and La/Sc ratios fluctuated less intensively. Minimal values of both parameters and elevated Eu/Eu* ratio in argillites from the lower part of the Karatau Group (Katav level) may indicate that crust of provenances was not as mature in terms of geochemistry as the UCC. In the Upper Riphean argillites of the Uchur–Maya region, Eu/Eu* ratio is essentially lower than in the PAAS and UCC. This may have two explanations: first, a rather mature substratum could be subjected to erosion in provenances of that time; second, geochemical parameters may be indicative of active crustal recycling without addition of new juvenile material.

In argillites of the Uchur Group, Eu/Eu* ratios range from 0.62 to 0.74 (Fig. 5c) depicting a weak tendency to increase by the end of the Early Riphean. In basal argillites of the Middle Riphean Aimchan Group, this parameter increases up to 0.99, whereas higher in the Svetlyi and Totta formation it changes from 0.54 to 0.71 showing the general trend to decline by approaching the time mark of 1200 Ma and to increase a little afterward. Argillites of the Talyn Formation, which are lacking Eu-anomaly, are close to Archean shales in chondrite-normalized REE patterns. Noticeably lower Eu/Eu* ratios are characteristic of argillites of the Lakhanda and Ui groups (0.50 in the upper part of the Ust-Kirba Formation; 0.59 in the lower part of the latter and in the Kandyk Formation). Based on relatively higher HREE concentrations in lower argillites of the Lakhanda Group as compared to other levels, it is possible to assume that acid magmatic rocks dominated in provenances of the early Lakhanda time, and that ancient (recycled) sedimentary material was involved into process of sedimentation (Podkovyrov et al., 2002). A higher Eu/Eu* value (0.68) almost identical to that of the PAAS is characteristic of fine-grained siliciclastic rocks from the Aim Formation of the Vendian Yudoma Group. This value is noticeably greater than in the Upper Riphean siliciclastic sediments of the Uchur–Maya region. It is also remarkable that basal argillites of the Vendian are close to clayey rocks of the Middle Riphean Talyn Formation in chondrite-normalized REE spectra, but they show distinct Eu-anomaly in contrast to the latter.

Comparing La/Sc, Th/Sc, and Eu/Eu* ratios in Upper Precambrian rocks of the Uchur–Maya region (Table 3) with reference values calculated by Taylor and McLennan (1985) for fine-grained siliciclastic sediments deposited 1.7–0.6 Ga ago, one can see that only La/Sc ratios are identical in this case. In contrast, Th/Sc and Eu/Eu* ratios in Riphean and Vendian clayey rocks of the region under consideration are obviously lower than in the standards of Taylor and McLennan (1985). The simplest explanation of this phenomenon is a lesser maturity of upper crust in provenances of fine siliciclastic material during deposition of the Riphean and Vendian sedimentary successions in that region. These provenances could include relatively larges blocks of Archean rocks and experience influx of juvenile mantle material that is evident from variations of $T_{Nd}$(DM) and $\varepsilon_{Nd}$(T) parameters in the studied clayey rocks of the Upper Precambrian.

Analyzing the Nd model ages of Riphean and Vendian argillites from the Uchur–Maya region, one can obtain interesting information about composition, types, and ages of Late Precambrian provenances in East Siberia, which supplied sedimentary basins with fine siliciclastic material (Podkovyrov et al., 2002, 2003). In particular, argillites of the Lower Riphean Uchur Group and of the Middle Riphean Talyn and Totta formations of the Yudoma–Maya belt are characterized by the Early Proterozoic values $T_{Nd}$(DM) = 2.3–2.1 Ga, whereas the model Nd age calculated for of the Totta Formation argillites from the Maya plate is younger ($T_{Nd}$(DM) = 1.8), suggesting appearance of juvenile mantle material in the relevant provenance. Parameters $T_{Nd}$(DM) of argillites from the higher Kerpyl–Lakhanda level range from 1.9 to 1.4 Ga. In contrast, the Nd model age of argillites from the Ust-Kirba Formation of the Ui Group is older in average: from 1.7 (Yudoma–Maya belt) to 2.1 Ga (Maya plate). Finally, the youngest model age (1.3 Ga) is characteristic of the Vendian Yudoma Group and means that relatively young juvenile material (Riphean or even Vendian proper) appeared in provenances. Variations of $\varepsilon_{Nd}$(T) parameters in argillites of the Uchur–Maya

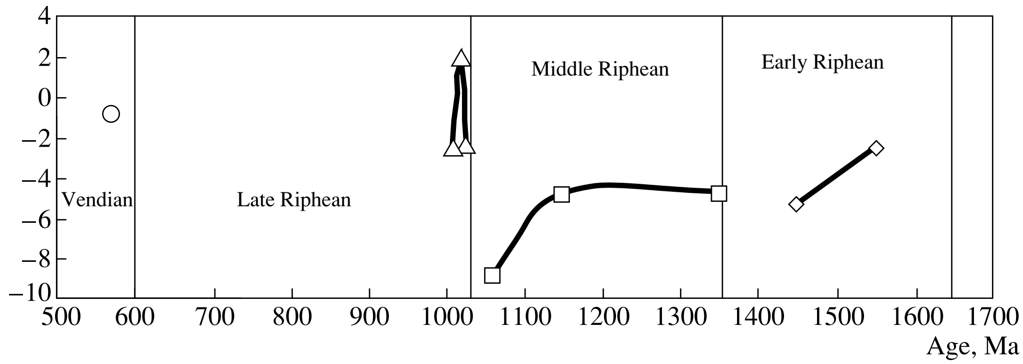


**Fig. 6.** Variations of $\varepsilon_{Nd}(T)$ values characterizing Upper Precambrian argillites of the Uchur–Maya region.

region are also indicative of several innovations in composition of rock complexes eroded in provenances and in general mineral budget of sedimentation.

In sum, data considered above show that juvenile material influenced sedimentation in the Uchur–Maya region two times. The impacts decreased considerably the Nd model ages of argillites from respective levels and sharply increased parameters $\varepsilon_{Nd}(T)$ even up to the positive values.

When calibrating against chronometric scale the aforementioned changes in geochemical characteristics of Upper Precambrian argillites from the Uchur–Maya region, one can see first the sharp excursions of Th/Sc and La/Sc ratios toward low values, which mark an event that took place most likely just after 1400 Ma. This event also caused a sharp decrease of Eu/Eu* ratios in argillites. Afterward, approximately up to 1280 Ma, there are a symbate growth of Th/Sc and La/Sc ratios and parallel decrease of Eu/Eu* ratio. At the very beginning of the Late Riphean, within the time-span 50 m.y. long only (1025–980 Ma), there is recorded a distinct excursion of Th/Sc and La/Sc ratios toward high values (2.7 ⟶ 3.4 ⟶ 2.6 ⟶ 1.7), while Eu-anomaly fluctuates in a quiet manner without sudden decline typical of the initial Yurmatinian time. Consequently, when accumulation of the Late Riphean sedimentary succession commenced in the Uchur–Maya region, fine siliciclastic material was transported into basin of sedimentation most likely from provenances, where the mature continental crust was dominant. The less mature material was subjected to erosion and involved into sedimentogenesis later on, approximately 1005(?)–980(?) Ma ago, and the above ratios noticeably decreased in sediments.

## DISCUSSION

The obtained data on variations of REE, Th, and Sc concentrations in fine-grained siliciclastic rocks of the Late Precambrian (Bashkirian meganticlinorium and Uchur–Maya region) and indicative geochemical ratios show that only Eu/Eu* parameters are practically identical in the standard post-Archean shale (Taylor and McLennan, 1985) and the rocks studied. A relative stability (within limits of data accuracy) of Eu/Eu* in post-Archean fine-grained siliciclastic rocks is commonly out of doubts at present. Some fluctuations of this parameter are caused by local changes in composition of provenances and paleotectonic settings (Taylor and McLennan, 1995).

Values of Th/Sc, La/Sc, and LREE/HREE ratios in Upper Precambrian clayey rocks of the Bashkirian meganticlinorium and Uchur–Maya region deviate (sometimes quite significantly) from the standard crustal values calculated by Taylor and McLennan (1985). In the Riphean stratotype section, this is established for the Burzyanian succession at the level of the Lower–Middle Riphean transition and for the Karatavian interval of the Vendian. In the hypostratotype, excursions are typical of the Lower–Middle and Middle–Upper Riphean boundary beds. The excursions are of different amplitude and not always coincide in time. It seems reasonable to suggest that deviations in question depend primarily on rock composition in provenances, i.e., on local factors. Nevertheless, more or less synchronous excursions in both regions under consideration are likely connected with subglobal stages (Grenvillian, Cadomian or others) of geodynamic activation, when a considerable amount of juvenile mantle material penetrated into the upper continental crust.

**Bashkirian meganticlinorium.** The erosion products of mature continental crust of the East European platform accumulated here practically throughout the Early Riphean (Maslov et al., 2003b, 2004a). Crust of provenances was consolidated in the late Early Proterozoic by culmination of cratonic stage of the Earth magmatic evolution associated with intense, primarily sialic magmatism (Bogdanova, 1986; Bogatikov et al., 1987).

Factors of sharp Eu/Eu* and Th/Sc variations at the level of about 1470 Ma are not very clear so far, although this could be likely a result of compositional variations in provenances. One of possible scenarios is formation of K-granitoids with rather high Eu/Eu* ratios in response to processes of chemical fractionation in the upper continental crust (Taylor and McLennan, 1985).

Perceptible decrease of LREE/HREE, Th/Sc, and La/Sc ratios is detectable approximately from this level upward. In the interval of 1430–1260(?) Ma, Eu/Eu* ratios are almost constant, slightly exceeding the PAAS value, and crust subjected to erosion was therefore more mature a little than the post-Archean crust. The indicated changes were undoubtedly connected with a complex series of rifting-related processes of the Mashak time, which did not resulted however in disruption of continental crust and lasted not long. It is sufficient to say that Th/Sc and La/Sc ratios in shales of the Zigal'ga Formation are already comparable with or even higher than values typical of the Lower Riphean shales.

After about 1200 Ma, there was likely the long-term continental stage in evolution of the region under consideration, when sediments accumulated earlier were partly eroded and dike swarms indicative of a limited crustal extension intruded the crust. It is important however that the mature continental crust was characteristic of provenances almost throughout the Early and in the first half of the Middle Riphean according to LREE/HREE and Eu/Eu* values in shales of the Burzyan and Yurmata groups. Nearly the same crust was exposed to erosion in provenances in the Zilmerdak time of the early Late Riphean, when formation of a vast pericratonic trough commenced along the western flank of the Urals. The structure under formation has been attributed to the passive margin of the Paleo-Asian ocean (Khain, 2001; Dobretsov, 2003), but this interpretation is not universally accepted.

Certain decline of Th/Sc and La/Sc ratios and parallel sharp increase of LREE/HREE and Eu/Eu* values in the Katav time (~950 Ma) points presumably to a short-term erosion of crustal blocks with essential proportion of Archean rocks.

Variations of Eu/Eu*, Th/Sc, and La/Sc parameters within the time-spans of 820–780 and 680–670 Ma have no ultimate explanation so far. As we believe, the only reasonable assumption is possible influence on sedimentation of the Inzer orogenic event (~800 Ma) and basic magmatism of the Arsha epoch (~680 Ma). In the Upper Precambrian succession of the Bashkirian meganticlinorium, there is a distinct decline of Th/Sc and La/Sc ratios recorded in argillites of the Basa and Zigazy formations, although LREE/HREE and Eu/Eu* values in the Suirovo–Zigan interval of a longer duration are approximately constant. It would be reasonable to regard these data as indicative of basic or lower crustal rocks erosion in the Beloretsk terrane, but sialic substratum represents nearly 90% in this structure (Galieva, 2004), which was unable therefore to condition decline by nearly 40% of the aforementioned ratios in the period from 570 to 550 Ma.

**Uchur–Maya region.** Incipient accumulation of Riphean succession was controlled by erosion of mature continental crust in the Siberian craton. This is evident from geological data (Akul'shina et al., 1972; Semikhatov, 1974; Keller et al., 1984; *Precambrian Geology…*, 1988) and inferable from geochemical parameters, because the Lower Riphean shales have Th/Sc and La/Sc ratios close to these parameters of the UCC and Eu/Eu* values almost characteristic of the PAAS. A part of siliciclastic material could be derived from acid magmatic rocks localized to the east of the Uchur–Maya region (Khudolei, 2003). Pulses of rifting, which took place 1.5, 1.38, and 1.32 Ga ago did not resulted in breakup of continental crust. At the Early–Middle Riphean boundary time, emplacement of granitoids and exhumation of crustal blocks composed of mafic to ultramafic rocks caused a sharp decline of Th/Sc and La/Sc ratios in shales of the Talyn Formation (~1.35 Ma), where Eu-anomalies have not been detected. All these geochemical characteristics seem to be a consequence of rifting, but effects of this event are not as impressive as in the Riphean type area affected by rifting of the Mashak time.

Later on from nearly 1280 to 1025 Ma, erosion was in progress in the Siberian craton areas predominantly composed of the Early Proterozoic consolidated crust (Th/Sc ≈ 0.74–0.88; La/Sc ≈ 2.4–3.1), although hypothetical "eastern massif" (Khudolei 2003; Serkina et al., 2004), the source of zircons ranging in age from 1.55 to 1.32 Ga, was likely under erosion as well. The extremely significant rifting event that caused intense destruction of continental crust and quick (in terms of geologic time) accumulation of magmatic, volcanic, and siliciclastic rocks of the Ui Group is recorded in the Uchur–Maya region across the Middle–Late Riphean transition (1005–942 Ma). In geochemistry of argillites, this event is reflected in a sharp decrease of Th/Sc and La/Sc ratios accompanied by a moderate growth of Eu/Eu* values thus resembling the geochemical evolution of shales deposited in the Riphean type area during the terminal Burzyanian–Early Yurmatinian. After accumulation of the Ui Group, there was a long period of continental crust destruction evidenced, in particular, by dike swarms with ages 650, 610, 560, and 510 Ma. The related break in sedimentation was of colossal duration (about 350 to 400 m.y.), accompanied by emplacement of alkaline ultramafic massifs and by development of pre-Vendian deformations of low intensity (Sukhorukov, 2003; and other works). Approximately 650–600 Ma ago, there was one more stage of rifting in the Uchur–Maya region, which coincided in time with the Rodinia breakup (Podkovyrov et al., 2001a, 2003).

It is natural to assume that erosion of mature continental crust, which had been formed prior to 1.9–1.8 Ga, dominated in both regions considered in this work during the Early and Middle Riphean. In the Bashkirian meganticlinorium, significant event of rifting is detectable across the Early–Middle Riphean boundary. Approximately at the same time, crustal blocks immature in geochemical sense (island-arc volcanic and plutonic rocks of the Fedorovo Group 2.1 Ga old; Kotov, 2003) raised up to the erosion level in the Uchur–Maya region. Formation of the Late Riphean–Paleozoic passive margin of the Paleo-Asian ocean (?) commenced in the eastern periphery of the East European platform after 1000 Ma and was interrupted by accretion of the Beloretsk terrane in the Late Vendian (Puchkov, 2000). Break in sedimentation presumably lasted in the Uchur–Maya region almost throughout the Late Riphean, and erosion of the Siberian craton resumed since development of passive margin in the Vendian (Podkovyrov et al., 2002; Khudolei, 2003; Serkina et al., 2004).

Thus, main periods of geological development of the Late Precambrian sedimentary basins within the Bashkirian meganticlinorium and Uchur–Maya region were not in phase[8] according to many data, in particular to behavior of Eu/Eu*, LREE/HREE, Th/Sc and La/Sc ratios in Riphean and Vendian shaly rocks. It seems reasonable therefore to suggest that geochemical parameters of fine-grained siliciclastic sediments of the Riphean and Vendian have been controlled in two regions predominantly by local factors.

It is known however that development of continental crust in the Late Precambrian was also controlled by global and subglobal events, such as the amalgamation and breakup of supercontinents (Rodinia, Pannotia, Panterra, etc.), formation of the Grenvillides, and opening of the Paleo-Asian and Protopacific oceans. Did these events influence composition of fine siliciclastic material deposited in most complete successions of North Eurasia, and if did, how significant was the impact?

In a most general manner, the mineral budget history of Late Precambrian sedimentary basins, which were situated in the junction zone of East European craton with the present-day Urals and in the eastern periphery of Siberian craton, can be realized as concurrence of two global runoffs of clastic material. The transported material consisted of erosion products derived from the mature continental crust formed in the course of Svecofennian cratonization 1.9–1.8 Ga ago, on the one hand, and from the crust that originated during the Grenvillian tectonic cycle 1.3–0.9 Ga ago or shortly before, on the other (Taylor and McLennan, 1995; Condie, 1997, 2001; Meert and Powell, 2001; Semikhatov et al., 2002). In the last case, the crust either included a considerable proportion of mantle material, or represented mixture of Paleoproterozoic and Early Riphean crustal and mantle rocks. It is important in principle that crust of this type was mainly localized in the so-called "Grenvillian belts," disposition of which is understood more or less universally by researchers who reconstructed history and outlines of the supercontinent Rodinia (Hoffman, 1991; Weil et al., 1998; Dobretsov et al., 1995; Vernikovskii, 1996; *tectonics Special…*, 1999; Dickin, 2000; Khain, 2001; Meert and Powell, 2001; Powell et al., 2001; Li et al., 2003). In Fig. 7, there are shown these belts in the Rodinia structure reconstructed by Hoffman (1991), which has been reproduced in many works of the last 10–15 years without principal modifications.

As is known, the East European platform was transformed into craton almost entirely by the initial Riphean time, and the originated huge mass of sufficiently mature continental crust (Semikhatov, 1974; Khain and Bozhko, 1988; Nikishin et al., 1997; Khain, 2001) used to be considered in current plate-tectonic reconstructions as the paleocontinent Baltica. A fragment of the Grenvillian belt is known within this continent only in the northwest of Fennoscandia, and its eastern periphery is lacking the Grenvillides, which did not influence therefore composition of the Riphean and Vendian sedimentary successions of the Bashkirian meganticlinorium.

The juvenile mantle material detectable in fine-grained siliciclastic rocks of the Ui and Yudoma groups of the Uchur–Maya region suggests, in opinion of Podkovyrov et al. (2001b, 2003), the active breakup of Rodinia in the Late Riphean and Early Vendian. Ophiolites of the Yenisei Ridge, Baikal–Muya zone, and East Sayan Mountains, which are estimated to be about 1.0 Ga old, mark the initial stage of Rodinia breakup that was accompanied by complete disruption of continental crust in several peripheral areas of the Siberian craton. In the Ui graben of the Yudoma–Maya belt, this stage resulted in formation of mafic dike swarms. In the Bashkirian meganticlinorium events of the relevant time were likely responsible for Eu/Eu*, Th/Sc, and La/Sc variations of opposite signs in shales and argillites. Within the period from 820–800 to ~550 Ma, LREE/HREE were lacking variations here that is indicative of a stable crustal composition in provenances of siliciclastic material.

It is quite safe therefore to suggest that all secular variations of LREE/HREE, Eu/Eu*, Th/Sc, and La/Sc ratios established in clayey rocks of most representative Late Precambrian successions of North Eurasia have been controlled completely or to a considerable degree by local factors.

## CONCLUSION

Secular variations of LREE/HREE, Eu/Eu*, Th/Sc, and La/Sc ratios in fine-grained siliciclastic rocks of most complete Late Precambrian successions in North Eurasia (Bashkirian meganticlinorium and Uchur–

[8] There are antithetic viewpoints on this issue however. For instance, Basharin et al. (2004) argued for the Early Riphean origin and subsequent development of linear troughs in the East European craton and its periphery. In their opinion, the main phase of rifting culminated in the Early Riphean time within the North Asian craton as well. Considering their arguments and data on the North American craton, Basharin et al. (2004, p. 46) formulated the following conclusion: "In three cratons of Laurasia, there are distinguishable two rifting phases, which took place approximately in the same interval of geological history. Their principal characteristics were identical despite some different details."

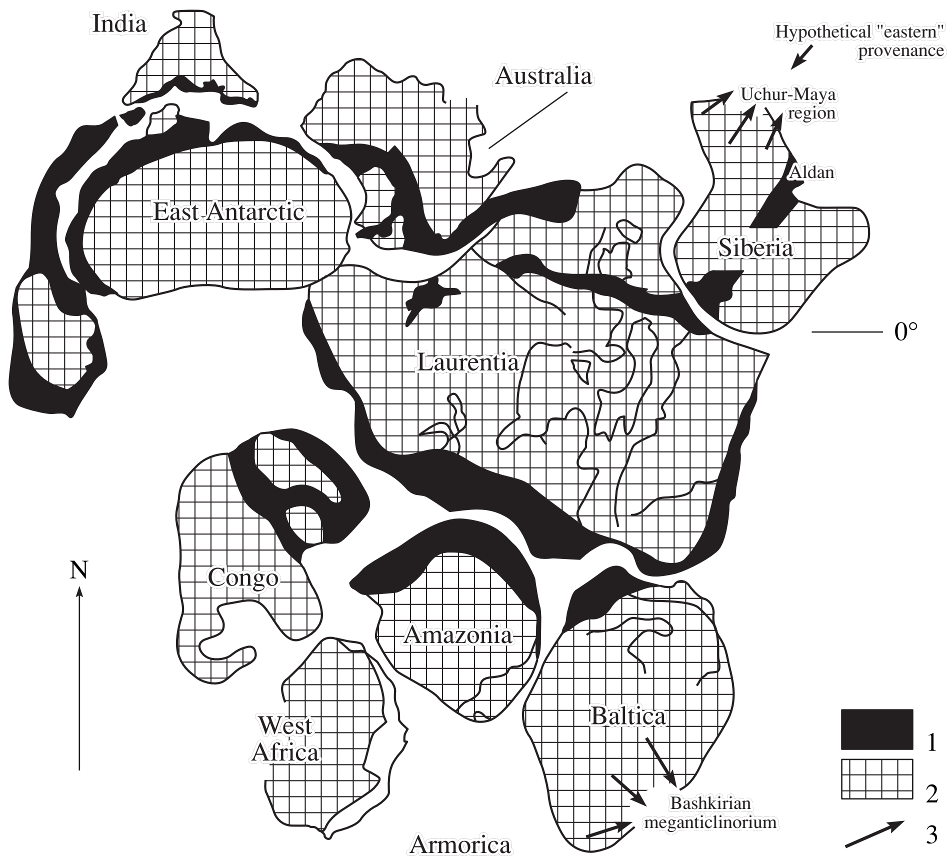


**Fig. 7.** Reconstructed disposition of Grenvillian belts 1.3–0.9 Ga old (out of scale) in the structure of supercontinent Rodinia about 700 Ma ago (After Hoffman, 1991, with additions and modifications after Weil et al., 1998; Powell et al., 2001; Meert and Powell, 2001): (1) Grenvillian belts; (2) pre-Grenvillian cratons; (3) presumable transport directions of siliciclastic material.

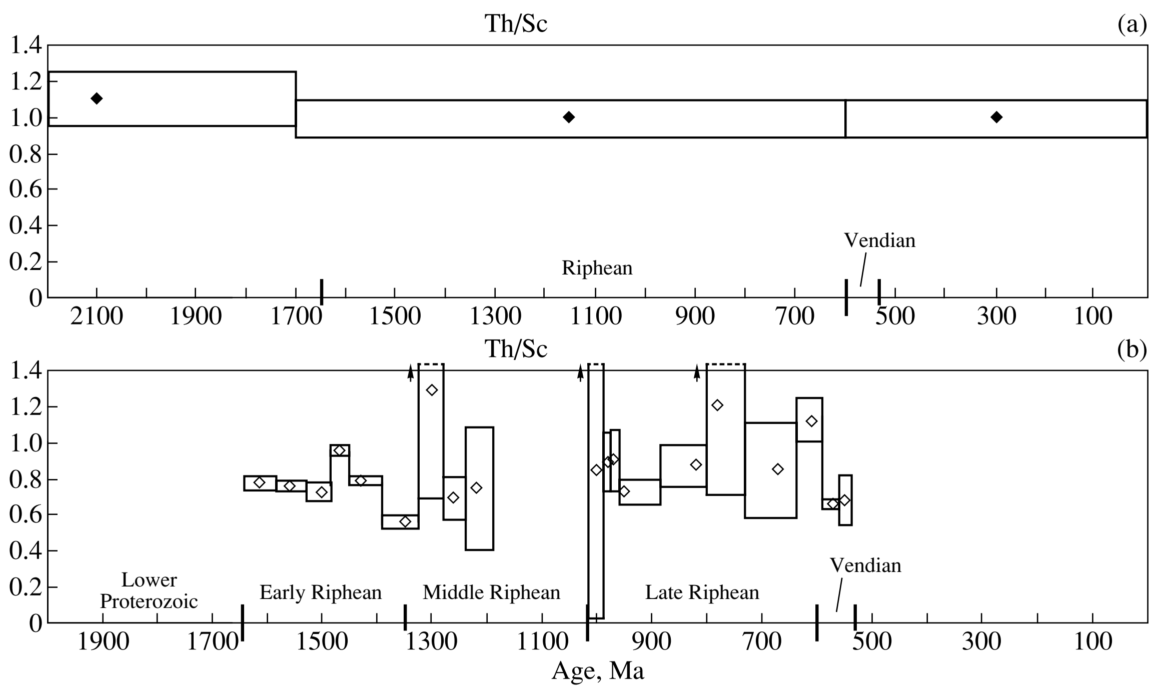


**Fig. 8.** Th/Sc ratios in post-Archean shales (a) after Taylor and McLennan (1985) as compared to variations of this parameter in Riphean and Vendian (1.65–0.54 Ga) fine-grained siliciclastic rocks of the Bashkirian meganticlinorium (b).

Maya region) are established using the representative database of analytical results and isotopic ages determined by confident isotopic methods.

As is established, only Eu/Eu* ratios in fine-grained siliciclastic rocks of both regions are practically identical to this parameter of post-Archean shales of the world. Three other ratios depict excursions of opposite signs relative to the standard values that is most likely a consequence of local changes in composition, sediment transport, paleogeography, paleoclimate, and paleotectonics within provenances of clastic material and basins of sedimentation. The deviations are well seen in Fig. 8, where our data on Th/Sc ratios are compared with standard values calculated by Taylor and McLennan (1985). A noticeable contribution of sedimentary material recycling that progressed during the Late Precambrian is admissible as well.

Data considered in this work suggest that isotopic and geochemical characteristics of fine siliciclastic material have been controlled in two study regions by local factors during the period of geologic time more than 1.1 billion years long. Global and subglobal events of the Late Precambrian responsible for formation of Grenvillian belts, where crustal blocks are combined with juvenile mantle rocks (Semikhatov et al., 2002), did not influence significantly the isotopic and geochemical parameters of clayey rocks in the Bashkirian meganticlinorium and Uchur–Maya region, the well-known type areas of Riphean successions in North Eurasia. Nevertheless, they determined to decisive extent the $^{87}Sr/^{86}Sr$ variations in the Grenvillian and post-Grenvillian seawater (Semikhatov et al., 2002; Kuznetsov et al., 2003b).

The next step of research in this direction is undoubtedly the comparison of considered data with isotopic and geochemical characteristics of Riphean and Vendian shaly rocks from the western periphery of Siberian craton (Yenisei Ridge), where geodynamic settings of sedimentation were likely different in principle (Khabarov, 1994; Nozhkin and Turkina, 2001; Nozhkin et al., 2003).

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Reviewer A.B. Kotov

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