Permian and Triassic deposits of Siberian and Chukotka passive margins: sedimentation setting and provenances

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ABSTRACT

The numerous current hypotheses on structural evolution of the present day Arctic require validation using data from regional geological studies. We are focusing on terrigenous deposits of Triassic age, which are the key to correlate geological events from the Eastern Arctic and the Verkhoyansk-Kolyma and Anyui-Chukotka fold systems. Triassic deposits of the Verkhoyansk–Kolyma fold system formed along the eastern margin of the Siberian continent. In the Anyui-Chukotka fold system, Triassic deposits accumulated on the southern margin of the Chukotka microcontinent. In present day structure heavily deformed sedimentary complexes of the two passive margins are brought closely together as a result of collision. The Siberian continent collided with the Kolyma – Omolon superterrane to form the Verkhoyansk–Kolyma fold belt. The Anyui-Chukotka fold system was formed as the result of collision between the Siberian continent and the Chukotka microcontinent associated with opening of the Canada Basin within the Amerasia Basin. The main results of our studies are: the directions of sedimentary supply and shelf zone progradation in the present day structure of theVerkhoyansk region and Chukotka differ by almost 180°. Changes in the sandstone mineral composition during the Triassic provide evidence of different source provinces for deposits of the Verkhoyansk and Chukotka passive margins. Changes in the chemical composition imply different evolutionary patterns of the rocks. Compositions of detrital zircon assemblages show dominant spikes of different ages: Verkhoyansk region is dominated by Proterozoic assemblages, and Chukotka by Phanerozoic ones. The level and type of deformation in both cases is represented by folds-and-thrusts of different vergence.

INTRODUCTION

Many paleotectonic reconstructions published in recent years are based on the U-Pb detrital zircon geochronology. This approach has proved to be effective for localizing and estimating the age ranges of provenances and for dating the deformed sedimentary complexes of fold belts (Rohr et al., 2008; Brandon, Vance., 1992; Crowley et al., 2005; and other works). Conclusions of this kind are inferable from age correlation of detrital zircon populations, which presumably coexisted in a provenance of clastic sediments. By analyzing the distribution of averaged geochronological ages of zircon populations, paying particular attention to the most significant peaks in the distribution, plus zircon ages from single samples, the pattern of ages can be extrapolated over vast regions.

One of the reconstructions under consideration is the problem of how and when the Amerasian basin opened. Among the diverse viewpoints on how the basin developed, the most popular is the rotational model suggesting that the Arctic Alaska–Chukotka continental block was detached from the Canadian Arctic margin with subsequent counterclockwise rotation around a pole located in the McKenzie Delta region (Sweeney, J.F., 1985; Grantz et al., 1990, 2011; Embry and Dixon, 1994; Lawver, et al., 2002; 2011).

The rotational hypothesis has been criticized in several recent publications (Miller et al., 2006; Kuzmichev, 2009; Beranek et al., 2010). The comparative geochronological analysis of detrital zircon populations from Triassic sandstones of the circum-Arctic region showed that in Triassic time Chukotka was situated apart from the Canadian Arctic margin on a continuation of the West Siberian rift system eastward of the Polar Urals. This is evident from data, according to which clastic material of Triassic deposits in Chukotka dated at

235–265 Ma was derived from the Siberian traps and associated intrusive and volcaniclastic rocks (Miller et al., 2006).

Hence, the problem of provenances for Triassic deposits of the Chukotka and Verkhoyansk regions is critical for testing the paleotectonic reconstructions. Sedimentological links between the Siberian passive margin and Triassic terrigenous deposits of the Verkhoyansk region are well established (Parfenov, 1984; Zonenshain et al., 1990) and have never been doubted. Sedimentology of these deposits is known in detail (Kossovskaya, 1962; Yapaskurt, 1992). The Triassic terrigenous deposits of Chukotka also accumulated in passive margin settings (Zonenshain et al., 1990; Parfenov et al., 1993; Sokolov, 1992, 2010). On the other hand, relatively old Russian publications (for example Til'man, 1980) showed an overall similarity of Paleozoic-Mesozoic deposits of Chukotka and the Verkhoyansk range but also drew attention to the considerable differences in their structure and stratigraphy

The main objective of this work is to discuss sedimentological differences (sedimentation settings, facies, lithology and geochemistry) and detrital zircon geochronology of Triassic sandstones from the Verkhoyansk region and Chukotka. In both regions, the best studied sections of Permian and Triassic deposits have been chosen for the comparative study. A. Prokopiev (IGABM, Yakutsk) kindly permitted us to use results of his chemical and isotopic studies in this paper. However, we are wholly responsible for our interpretation.

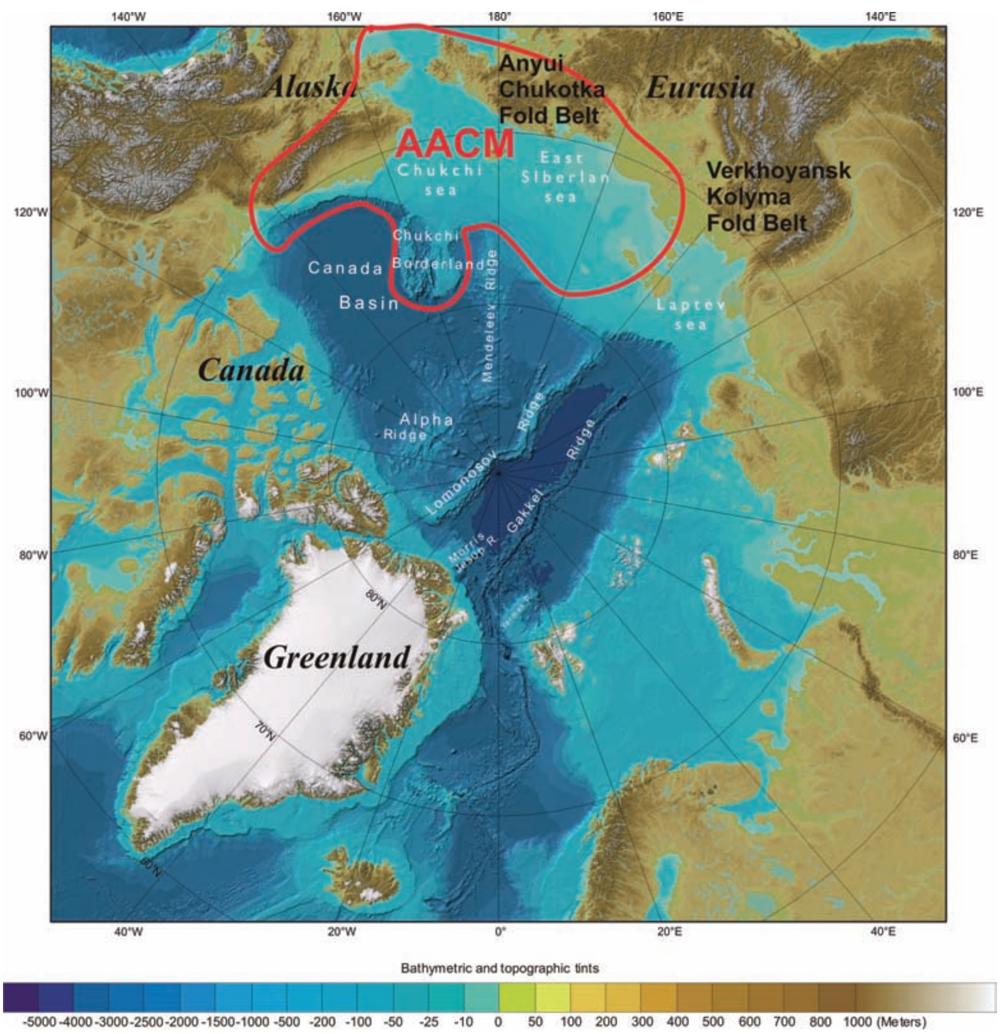


Fig. 1. The assumed outline of the Arctic Alaska –Chukotka microcontinent (AACM), IBCAO_ver2_23_Letter (Jakobsson et al., 2008).

GEOLOGICAL BACKGROUND

The Verkhoyansk-Kolyma and Anyui-Chukotka fold belts (Fig.1) are located to the east of the Siberian craton (North Asian craton in the terminology by Parfenov et al., 1993; Nokleberg et al., 1994). They were formed in the Late Mesozoic as a result of Siberia colliding with the Kolyma-Omolon and Chukotka microcontinents respectively (Zonenshain et al., 1990; Parfenov et al., 1993; Tectonics, geodynamics and metallogeny…, 2001; Geodynamic, Magmatism, and Metallogeny.., 2006; Sokolov, 2010).

The Verkhoyansk terrane between the Siberian craton and Kular–Nera terrane is bounded by thrust faults of western vergence (Parfenov et al., 1993, 1995; Tectonics, geodynamics and metallogeny…, 2001). It is divided into four tectono-stratigraphic units of the Riphean–Vendian carbonate-terrigenous deposits, the Lower–Middle Paleozoic predominantly carbonate rocks, the Upper Paleozoic–Lower Mesozoic terrigenous sediments (Verkhoyansk complex), and Upper Jurassic–Lower Cretaceous foredeep sediments. The Verkhoyansk complex corresponds to the thick (14–16 km) terrigenous sequence of the Carboniferous, Permian, Triassic, and Jurassic rocks. The basal Visean sediments of the sequence characterize a sharp transition from carbonate to terrigenous sedimentation. The uppermost part is of the Bathonian–Callovian in age.

The Chukotka (New Siberian Islands–Chukchi) fold belt stretches from the New Siberian Islands to the Chukchi Peninsula over the continental

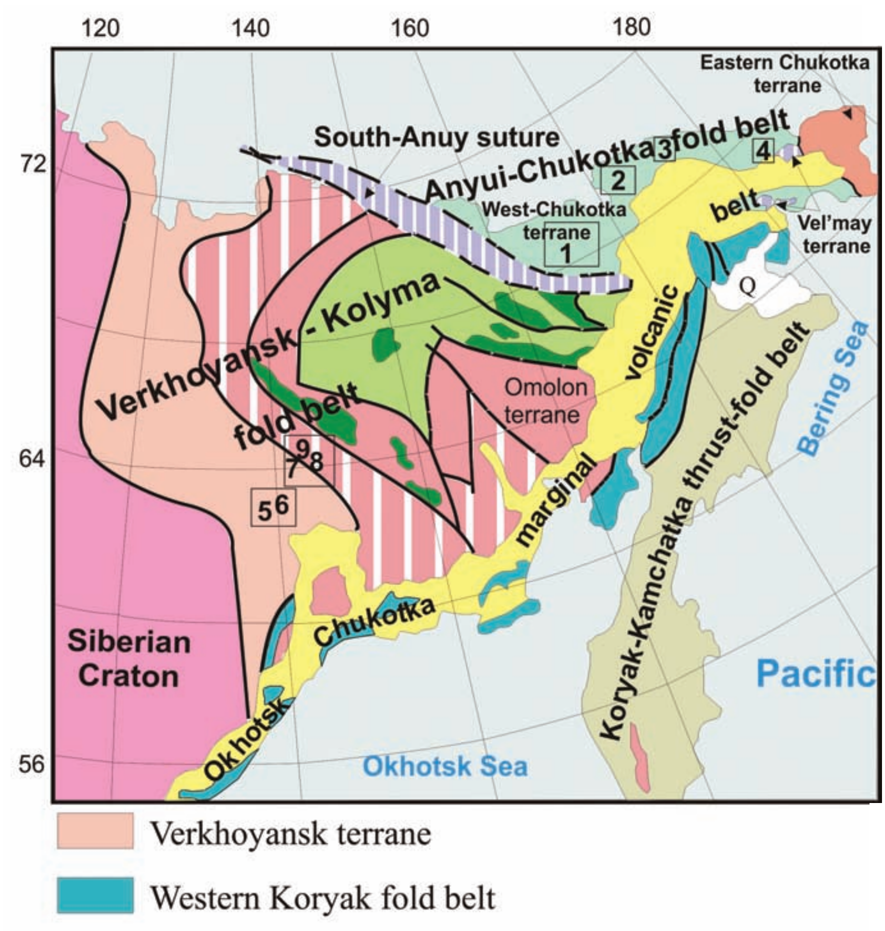


Fig. 2. Tectonic scheme of Northeastern Asia, after (Sokolov et al., 2001), Chukotka fold belt consists of the Anyui-Chukotka fold belt and South-Anyui suture. Number in squares are the main areas referred to in text: 1 – Anyui subterrane, Western Chukotka; 2 – Chaun subterrane, near Pevek, 3 – Chaun terrane, Tanyurer River; 4 – Chaun terrane, Velmay River, 5 – Northern part of the South Verkhoyansk,Kobume River; 6 - Northern part of the South Verkhoyansk, Setarym and Khandyga Rivers; 7 – Distal part of Verkhoyansk margin, Talalakh stream and Bazovsky stream, 8 – Kular-Nera terrane, Malyutka stream, 9 – Kular-Nera terrane, Northwestern flank of Ayan-Yurakh anticlinorium.

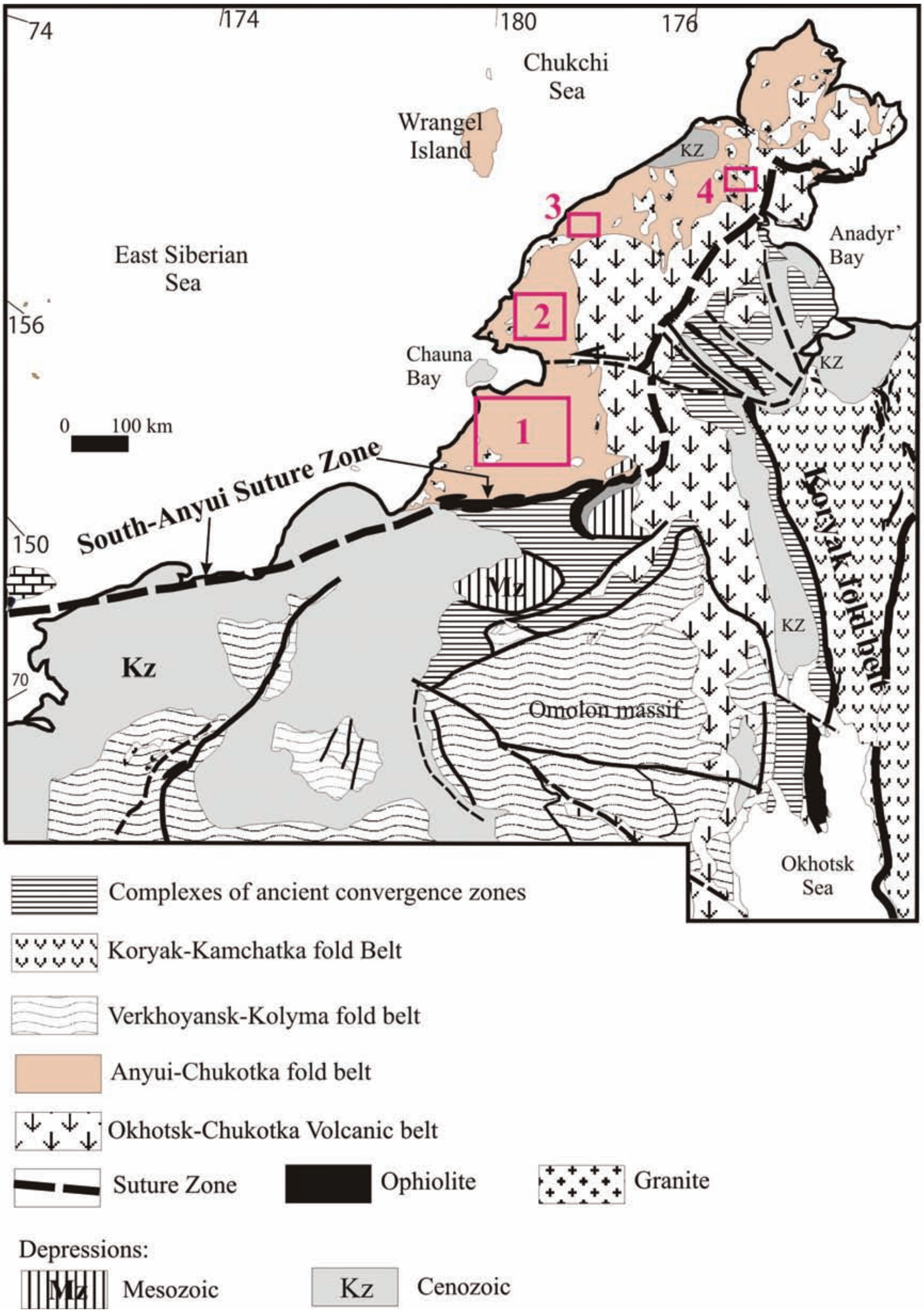


Fig. 3. The main tectonic elements of Anyui-Chukotka fold belt (Sokolov et al., 2011). Numbers in squares are the main areas referred to in text and figure 4: 1 – Western-Chukotka terrane; 2 – Chaun terrane, near Pevek; 3 – Chaun terrane, Tanyurer River; 4 – Chaun terrane, Kolyuchin Bay.

margin and vast Arctic shelf. In the Anyui-Chukchi (AChFB) and South Anyui (SAS) fold belts, crystalline basement is overlain by the Paleozoic–Mesozoic sedimentary cover intensely deformed in the terminal Early Cretaceous. In the paleotectonic aspect, this is a continental block or the Chukchi microcontinent commonly considered as a part of the Arctic Alaska–Chukotka microplate (AACM, Grantz et al., 2011; Lawver et al., 2011) or the Bennett-Borovia one (Natal'in et al., 1999). As is assumed in work by Drachev (2011), the AACM consists of three independent blocks (New Siberian–Chukchi, Arctic Alaska, and Chukchi Borderland), in which tectonic movements and deformations did not depend on the Amerasian basin formation.

The AChFB is divided (Figs. 1 and 2) into the West Chukotka, East Chukotka, and Vel'may terranes (Parfenov et al., 1993; Nokleberg et al., 1994). Crystalline basement and Ordovician–Silurian deposits are exposed in the East Chukotka terrane only. The Paleozoic–Mesozoic platform and shelf deposits of the West Chukotka and East Chukotka terranes are similar in composition. These facies variations in the West Chukotka terrane resulted in identifying the Anyui and Chaun subterranes (Geodynamic, Magmatism, and Metallogeny..., 2006). The Devonian–Lower Carboniferous carbonate deposits with subordinate intercalations of terrigenous rocks are exposed in granite-metamorphic domes and usually show greenschist metamorphic grade, whereas amphibolite grade is less common (Gel'man, 1995). Upper Carboniferous and Permian deposits are missing. The Anyui complex, a terrigenous sequence with abundant turbidite members, is from 1 to 5 km thick in total. In the Rauchua River basin, fossils of the Lower Jurassic have been found in the upper part of the sequence (Til'man, 1980). The Triassic deposits are overlain with angular unconformity by the Upper Jurassic–Lower Cretaceous clastic sediments.

The Vel'may terrane has distinctive lithology which includes ultramafic rocks, gabbroids, plagiogranites, and volcanogenic-cherty deposits

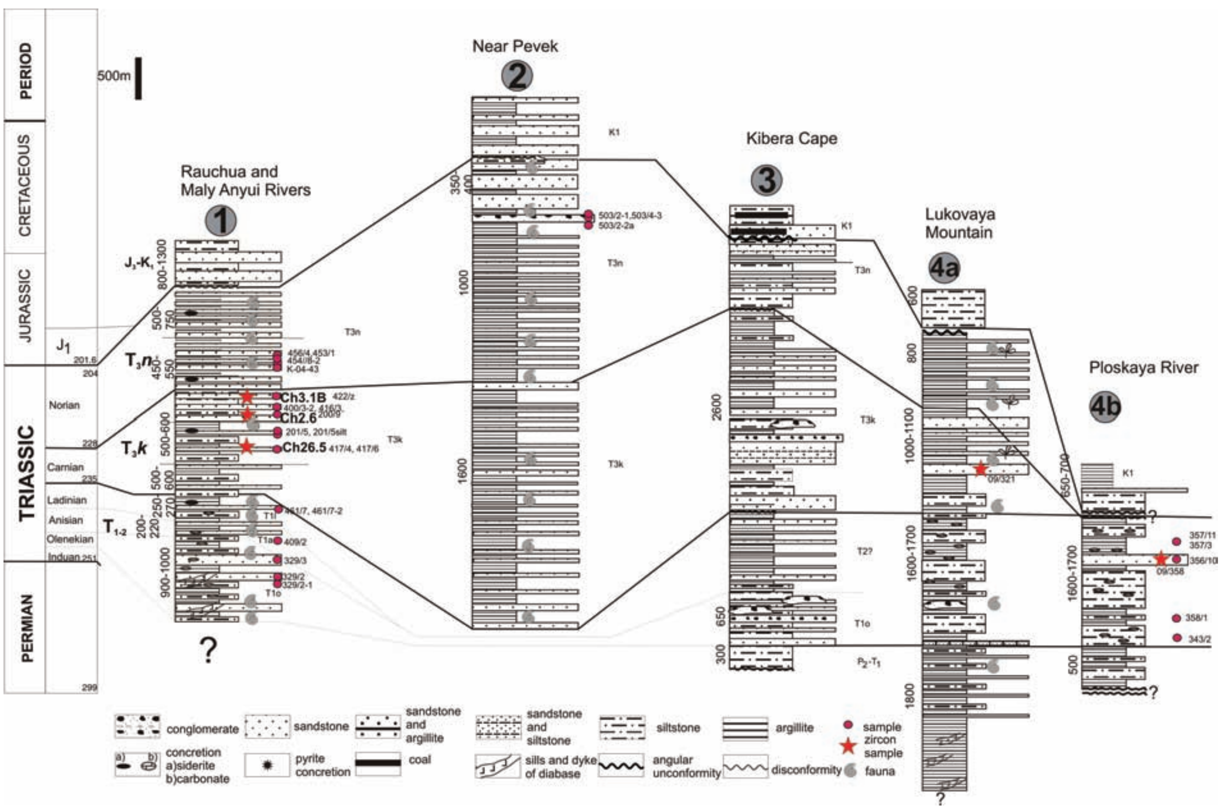


Fig. 4. Correlation chart of the main sections of the Permian and Triassic rock units of Anyui-Chukotka fold belt. Data source for compiled sections are unpublished reports. For numbers of units see figures 2 and 3 and description in text.

widespread in East Chukotka. The age of these rocks is controversial. According to some researchers the whole complex is Late Jurassic–Early Cretaceous in age (Kosygin et al., 1974), while the others argue for Late Triassic age of the rocks (Tynankergav,1987; Bychkov, 1987). The Vel'may terrane is interpreted as a continuation of the South Anyui Suture (SAS).

The SAS is a collisional suture separating structures of Chukotka from the Verkhoyansk–Kolyma fold belt (VKFB). It represents a result of the collision between the Chukotka microcontinent and the Siberian active margin (Parfenov et al., 1993; Sokolov et al., 2002, 2009; Byalobjesky and Goryachev, 2004). At the time of collision, tectono-stratigraphic units of the SAS were thrust northward onto the passive margin of the Chukotka microcontinent. Ultimate stages of that collision were accompanied by development of dextral strike-slip faults (Sokolov et al., 2001; Bondarenko, 2004).

PERMIAN AND TRIASSIC DEPOSITS OF THE AChFB

Anyui subterrane. The Triassic terrigenous deposits unconformably overlie older Paleozoic strata and are represented by three sedimentary complexes of Early–Middle, Carnian and Norian Late Triassic ages. The K-Ar ages of abundant sills and hypabyssal dolerite and gabbro bodies characteristic of the Early Triassic range from 233 to 218 Ma (Geodynamic, Magmatism, and Metallogeny.., 2006). The U-Pb zircon age of hypabyssal gabbro from the Kolyuchinskaya Guba area corresponds to 252 ± 4 Ma (Ledneva et al., 2011) and suggests occurrence of the Upper Permian deposits at the base of the Anyui complex.

The Triassic sequence (locality 1 in Fig. 3) is composed of rhythmically interlayered thin beds of silty mudstones, and sandstones occurring in variable proportions from section to section (Tuchkova et al., 2007, 2009). A characteristic feature of the Lower and Middle Triassic sandstones is their graded and cross bedding (Figs. 4 and 5). Typical for these rock units are slump folds and mud chips. The rocks also contain abundant siderite concretions (Fig. 6). The Carnian sandstone unit contains unconformities at the base. Sandstones are usually massive, sporadically intercalated with graded and cross-bedded sets. The Norian fine rhythmic sequence contains abundant Monotis shells and trace fossils (worm burrows or fucoids).

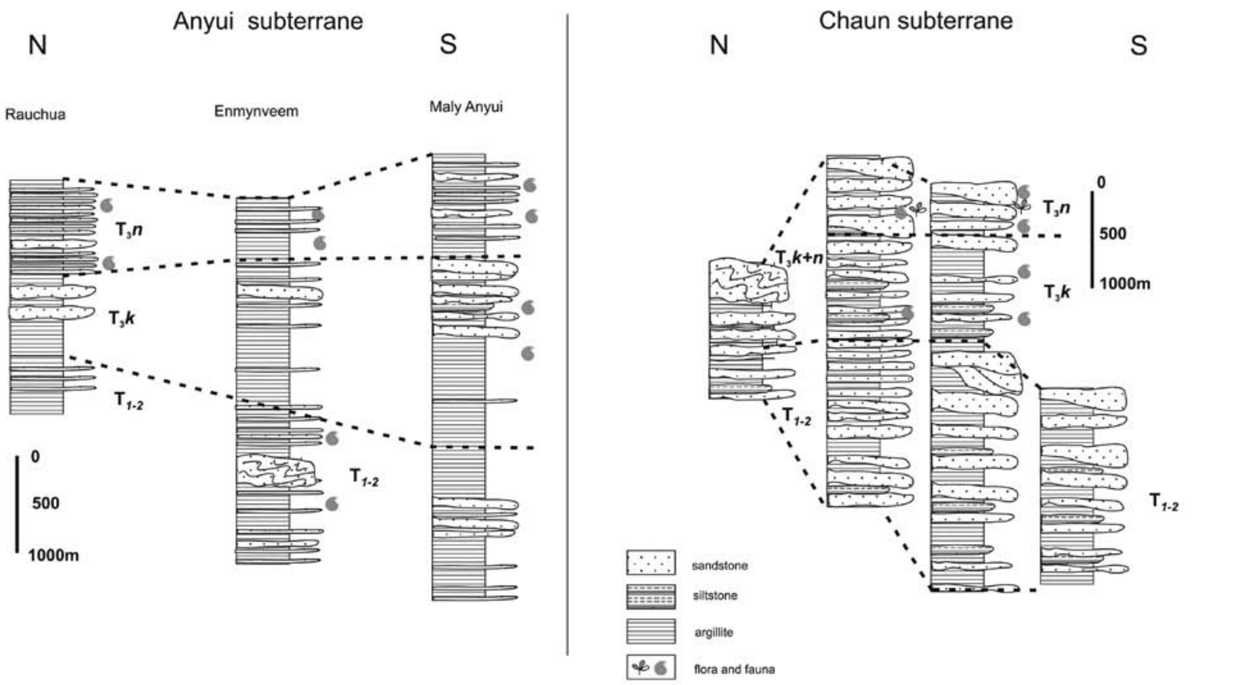


Fig. 5. Correlation of type sections in the northern and southern parts of the Anyui and Chaun subterranes (after Tuchkova et al., 2009, Morgan, 2001).

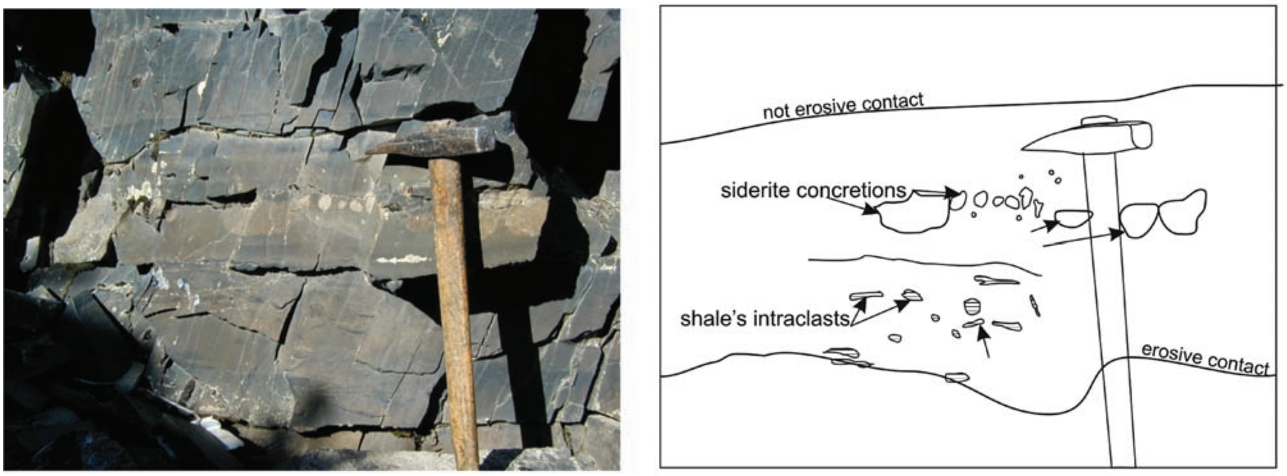


Fig. 6. Fragment of the Aalenian section at the Enmyveem River. The photo shows small clayey intraclasts oriented parallel to the turbidity flow; in the middle part, rounded siderite concretions (light) with the upper surface eroded by the flow. Photo by M.I. Tuchkova.

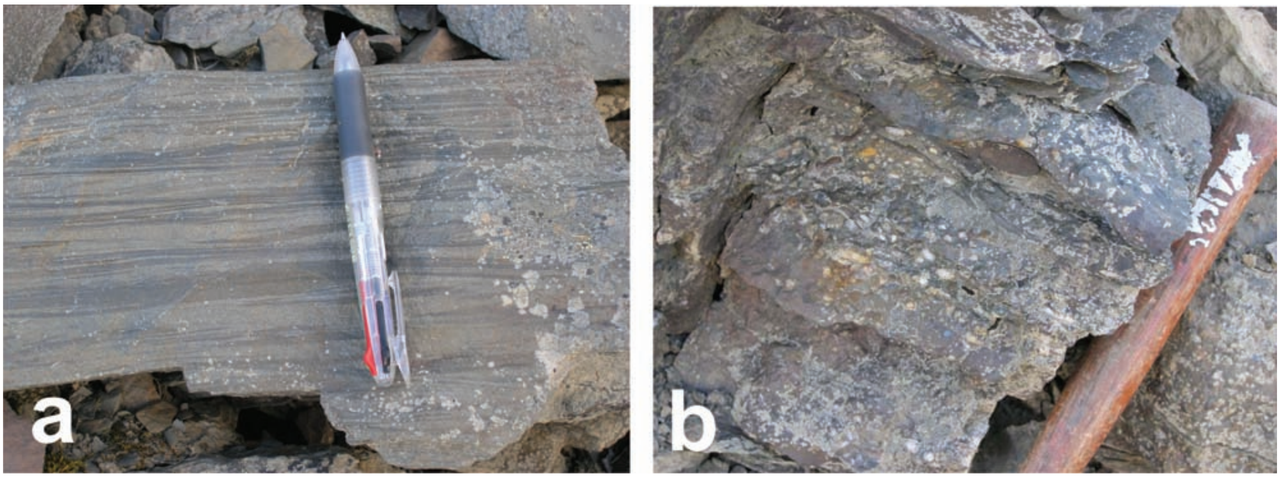


Fig. 7. Fragments of the Upper Triassic section of the Chaun terrane, Outcrop 44, samples 503/4-3 and 503/2-1. (a) different types of bedding (cross and lenticular, alternating with the laminar bedding) in a sandstone bed; (b) lenticular bed of gravelly coarse-grained sandstone with rounded grains of milky quartz.

Sedimentation in the basin was controlled by a large deltaic system. Distribution of sedimentary facies suggests that the basin was deepening southwestward in present-day coordinates with gradual progradation of the shelf into deeper zones of the basin (Tuchkova, 2011; Fig. 5).

Chauna subterrane.

In the Chauna Bay area and southward of Kibera Cape (locality 2 in Fig. 3), Permian and Triassic terrigenous deposits are represented by siltstones and shales with sandstone interlayers that are locally calcareous. Among the Olenekian strata there are rare lenticular intercalations of small-pebbled conglomerate (Fig. 7).

On the east of the Chauna subterrane (locality 3 in Fig. 3), Permian and Triassic deposits are exposed along northern spurs of the Pekulney Range and in the Amguema riverhead area (Morozov, 2001). A sequence of interlayered sandstones, siltstones, and mudstones 250–300 m thick in total is tentatively attributed here to the Permian. The undivided Lower–Middle Triassic, Carnian, and Norian deposits conformably rest on this sequence. The maximum thickness of Triassic rocks is estimated as 3.5–4.5 km (Figs. 4 and 5). The Lower–Middle Triassic deposits of the Amguema riverhead area are represented by interlayered sandstone, siltstone, and silty mudstone

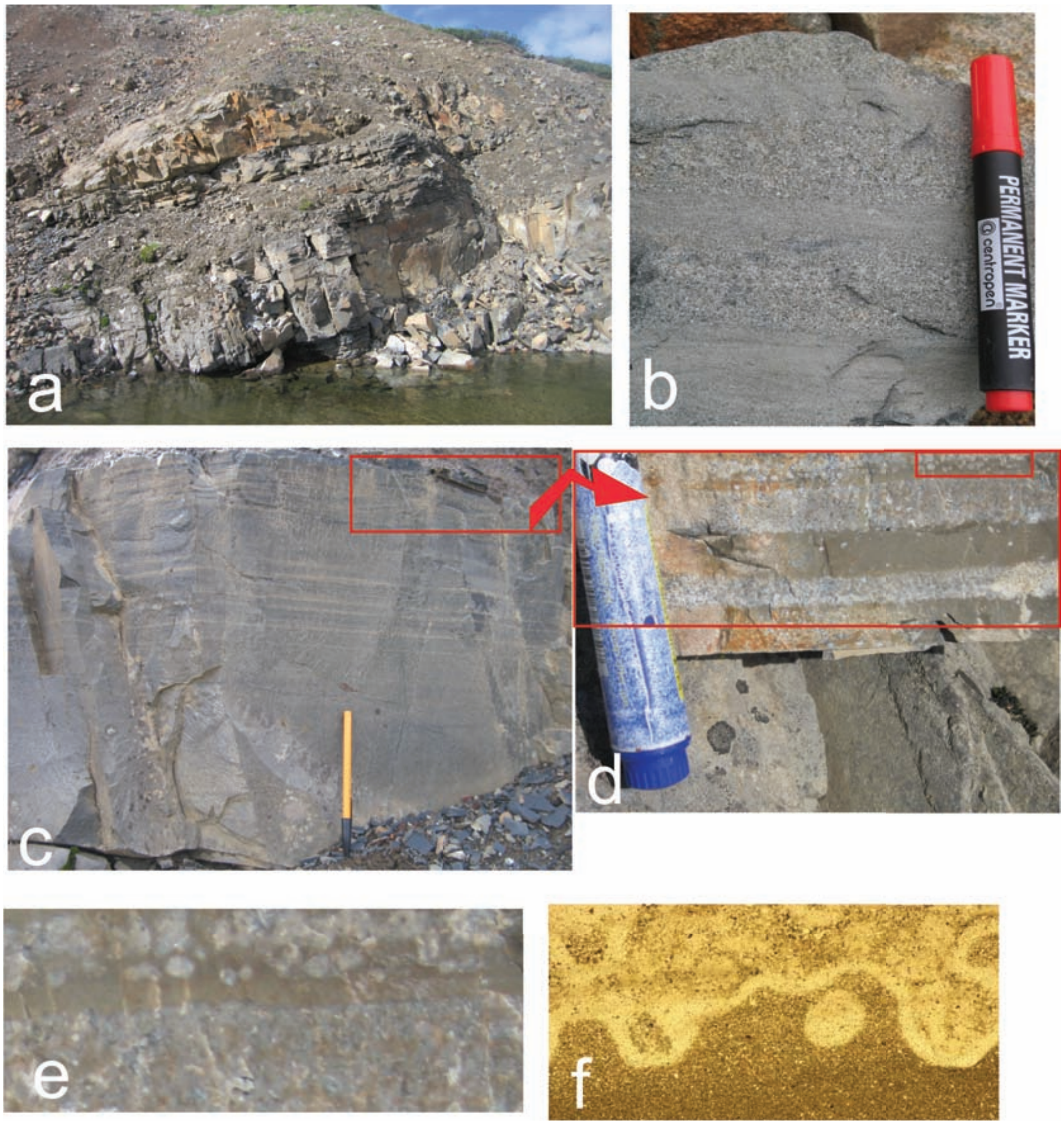


Fig. 8. The Lower–Middle Triassic section along the Ploskaya River. (a) photo by S.D. Sokolov; (b) sediments of density volcaniclastic flows alternating with host silty shales;(c) fragment of the section at the Ploskaya River, host silty shales with laminar bedding, rectangle designates a zone shown in (b); (d) fragment of a bed of brown host silty shales with isolated rounded or slightly flattened structures (hot lava drops); (e) detail of photo (d); (f) microimage of a thin section with rounded volcaniclastic structures intruded into host wet unconsolidated sediments, Sample 357/11.

beds. Gray to greenish gray frequently calcareous sandstones contain siderite concretions.

The Lower–Middle Triassic deposits have of a distinct rhythmic structure. Elements of the rhythms show massive, cross- and laminar bedding. Sole marks and slump structures are typical for the base of the sandstone beds. Upward in the sequence, rhythms become thicker, and sandstone content increases.

In southern and southeastern areas of the subterrane, the Carnian–Norian deposits have the same structure. Concurrent beds of a lesser thickness having lenticular bedding and ripple marks are observed to the north and northeast of the Amguema riverhead area, where abundant faunal remains and fucoids have been found. Large plant fossils are known from the Norian sandstones and siltstones.

Early–Middle Triassic deposition occurred on a continental slope and rise and was controlled by gravity mass flows, and sandstone bodies increased in abundance by the end of the Middle Triassic (Morozov, 2001). Northward and upward in the sequence shelf sediments replace turbidites. This facies zonation indicates southerly shelf progradation.

In the Ploskaya River basin (locality 4 in Fig.

3), the Permian and Triassic sequence of rhythmic structures is up to 600 m thick, composed of silty sandstone and siltstones with rare sandstone interbeds (Blagodatsky and Bychkov, ed., 1978). Cross- and laminar bedding are characteristic of gray to greenish gray sandstones sometimes containing an admixture of carbonate material (Fig. 8). In the background sediments (argillaceous and silty interlayers) original bedding is often disturbed by impacts of small drop-shaped lapilli. These Permian and Triassic deposits accumulated most likely on a shallow shelf presumably in coastal marine settings.

Paleogeographic schemes for the Early–Middle and Late Triassic times are shown in Fig. 9. Deltaic systems that controlled discharge of sedimentary material derived from provenances are established in the Anyui terrane and provisionally in the central part of the Chauna subterrane (Tuchkova et al., 2007, 2009).

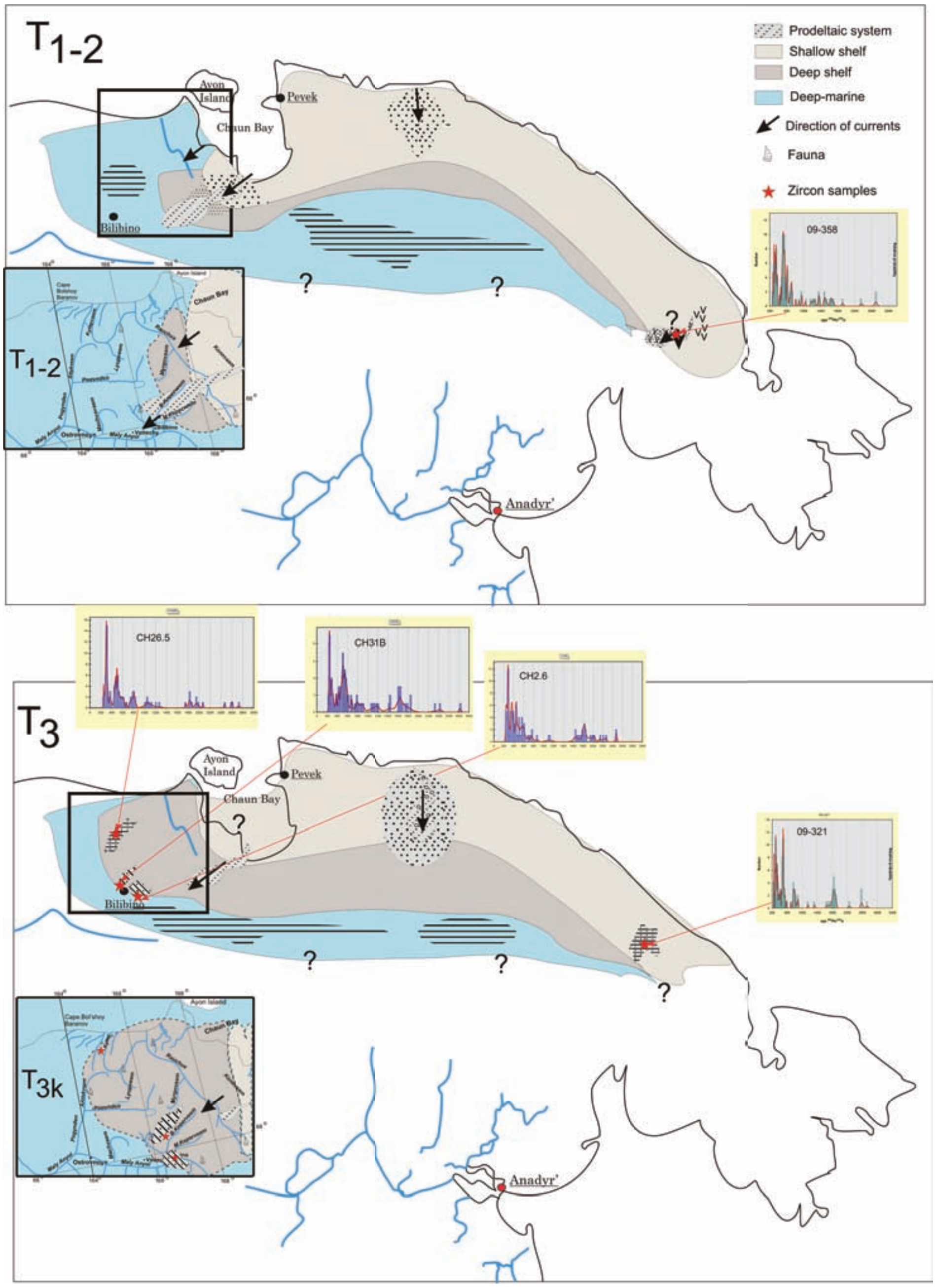


Fig. 9. Paleogeographic reconstruction of the Chukotka basin for the Early-Middle Triassic time (a) and Late Triassic time (b). Black rectangle corresponds to the area shown in the magnified lower part of the figure. Histograms correspond to detrital zircons from sandy rocks; sample positions are shown by arrows.

PERMIAN AND TRIASSIC DEPOSITS OF THE VKFB

Verkhoyansk

On the north of the southern Verkhoyansk region (Figs. 10 and 11), Permian deposits have been studied along the Setorym and Kobyume rivers. These are interlayered beds of poorly sorted sandstones, siltstones, and silty mudstones with rare conglomerate intercalations. The Permian sequence is conformably overlain by Triassic deposits, although some researchers argue for an angular unconformity at this level (Tectonics, geodynamics and metallogeny of the Sakha Republic, 2001).

The Triassic deposits of the Verkhoyansk terrane are widespread on the north of the South Verkhoyansk (localities 5 and 6 in Figs. 4, 10, 11) and comprise all three series of the system. Near the frontal zone, they overlie Permian strata with an erosion surface at the base, whereas in the inner parts a gradual transition between Triassic and Permian deposits was documented (Parfenov, 1984; Tectonics, geodynamics and metallogeny of

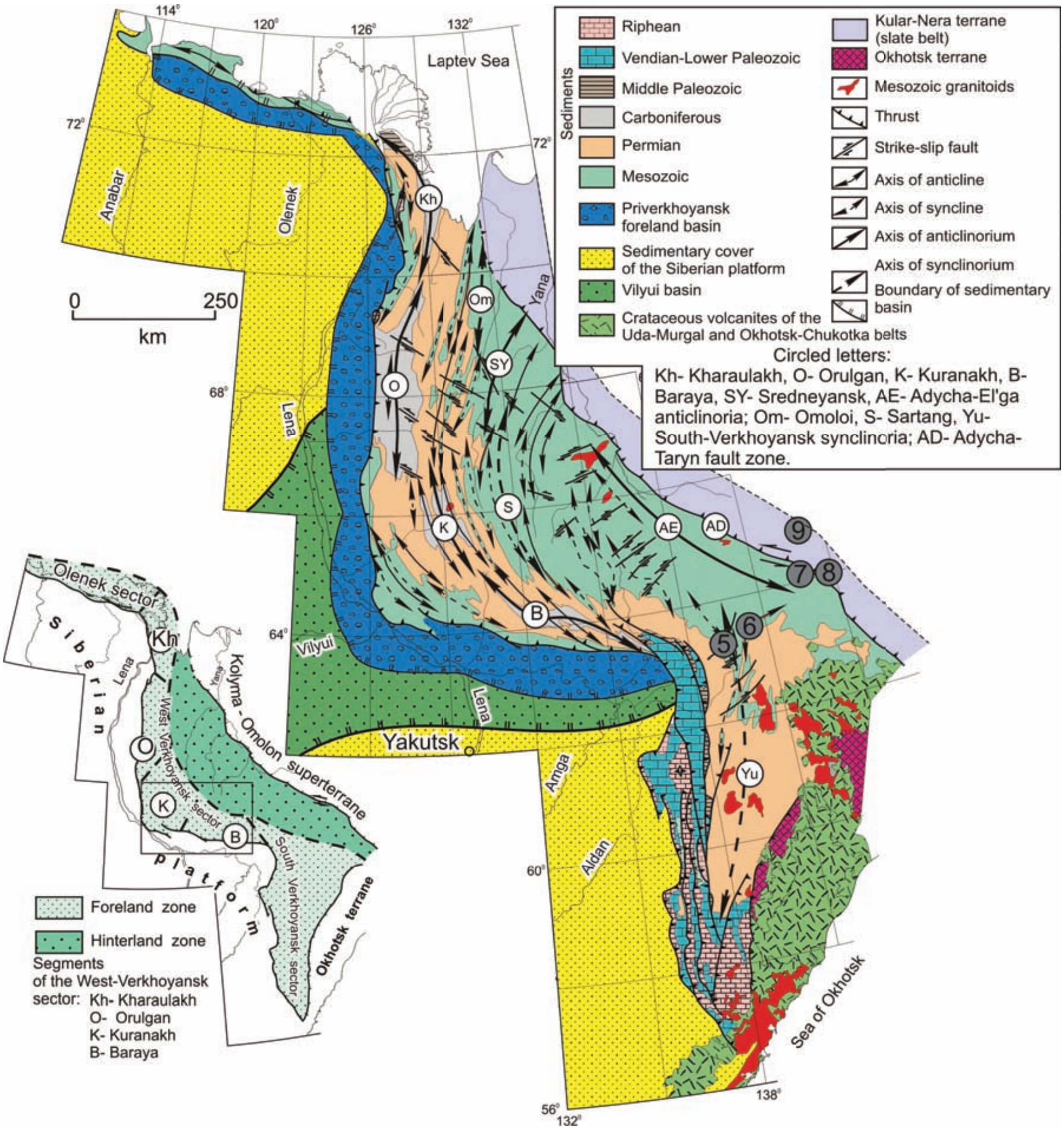


Fig. 10. The main tectonic elements of Verkhoyansk-Kolyma fold belt (Parfenov et al., 1995; Prokopiev et al., 2008). Number in gray circles are the main areas referred to in text and figure 11: 5- Northern part of South Verkhoyansk, Kobyume and Setarym Rivers; 6 – South Verkhoyansk, Allakh-Yun' zone; 7 – Distal part of Verkhoyansk margin; 8, 9 – Kular-Nera terrane (shists belt)

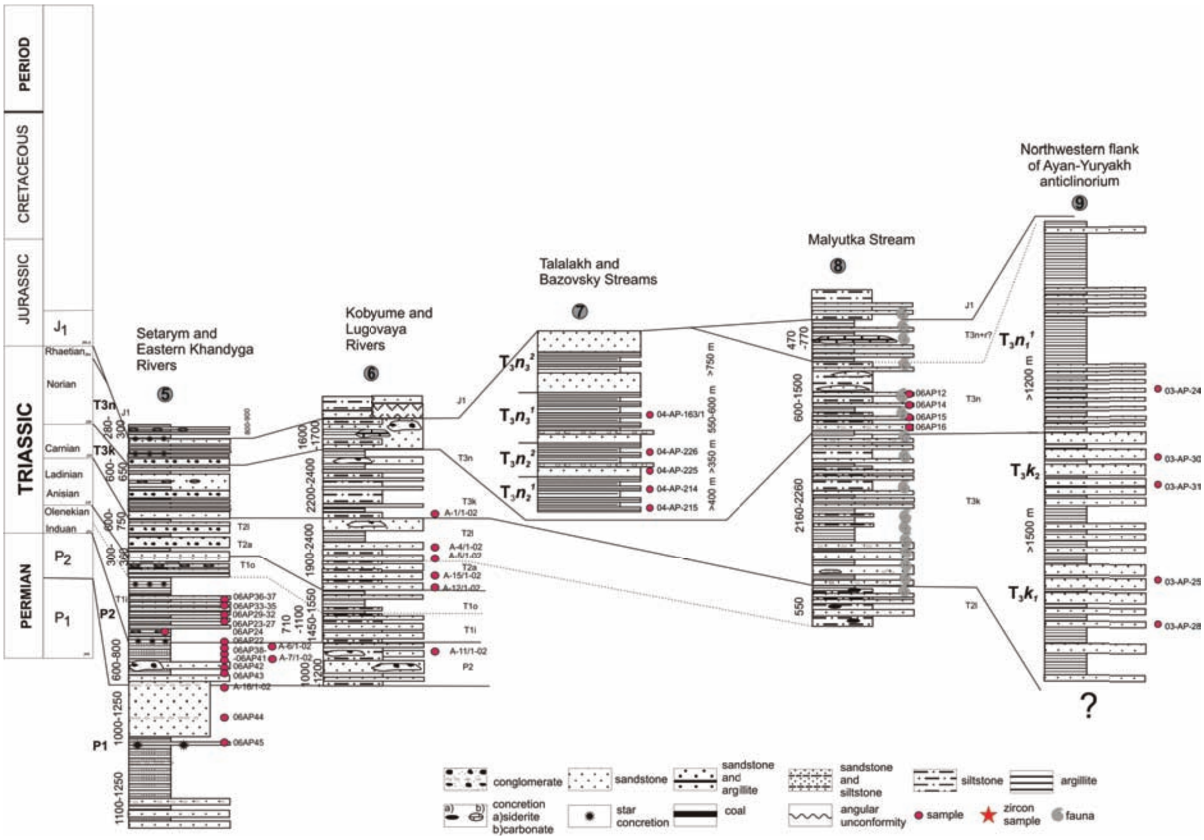


Fig. 11. Correlation chart of the main sections of the Permian and Triassic rock units of Verkhoyansk-Kolyma fold belt. Data source for compiled sections are from Prokopiev et al.,2001; Prokopiev,Ivensen, 2008. Numbers of units are the same that in figure 2 and 10. See description in text.

the Sakha Republic, 2001). This distinction led to recognition of the proximal and distal parts of the Verkhoyansk passive margin.

The Triassic sequence is composed of dark gray to gray and greenish gray sandstones and siltstones, locally intercalated shales and fine-grained calcareous sandstones (Figs 12a, 12b, 12c). Carbonate and clay-carbonate nodules are characteristic of the Lower Triassic strata. Sandstone beds and conglomerate intercalations are more typical for the Carnian–Norian rock units. Total thickness of the sequence is over 7 km.

Characteristic Permian and Triassic rocks of the Allakh-Yun zone (East Khandyga River, locality 6 in Figs. 10, 11) are tuffaceous sandstones and siltstones, as well as mafic to felsic volcanic rocks (Prokopiev and Ivensen, 2008). Submarine fans and associated deep-water deposition occurred here during the Early Permian time, and deltaic systems appeared in the Late Permian (Khudoley and Guriev, 1994). The Induan Stage corresponds to an epoch of predominantly shallow-water terrigenous sedimentation (Korostelev, 1982; Khudoley and Guriev, 1994).

The Upper Triassic sequence of the Kular–Nera terrane (localities 8 and 9 in Figs. 10, 11) and distal part of the Verkhoyansk margin (locality 7 in Figs. 10, 11) is composed of shales, siltstones, and rare sandstone beds. Among these deposits slope apron facies are identified giving place northeastward to more distal medium- to fine-grained turbidites of a submarine fan (Prokopiev and Tronin, 2004). The Carnian–Norian rocks are over 1000 m thick. Turbidites in the distal part of the Verkhoyansk passive margin (Prokopiev and Tronin, 2004) accumulated clastic material transported into this part of the basin (Fig. 13) by the large rivers paleo-Lena and paleo-Aldan (Prokopiev et al., 2008). The largest rivers run through the area of the present-day Vilyui syneclise having sources in the Baikal Mountain system

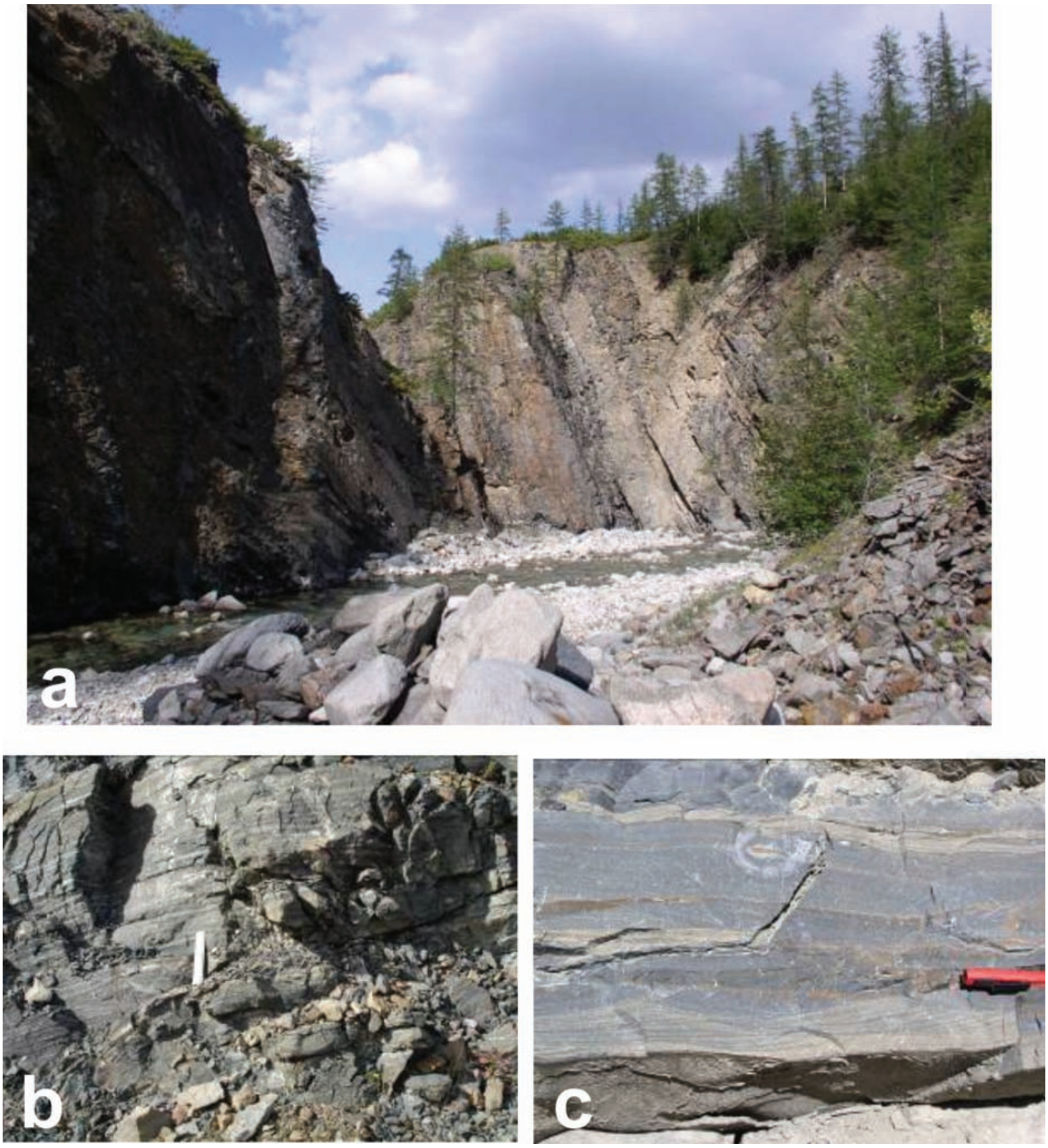


Fig. 12a. Bedded Permian rocks of the southern Verkhoyansk region. Photo by A.V. Prokopiev. **12b**. Alternating sandstones and silty shales in the Triassic section of the southern Verkhoyansk region. **12c.** Fragments of the section with lenticular bedding

(Kossovskaya et al., 1960; Prokopiev et al., 2008, Fig. 13). The other fluvial system was hypothetically situated at the southern margin of Siberian platform (Korostelev, 1982; Prokopiev et al., 2008).

Triassic sedimentation on the Verkhoyansk passive margin inherited trends of the Paleozoic sedimentation regime. Nevertheless, new facies boundaries were displaced eastward relative to those of the Paleozoic that has been interpreted as evidence of the passive margin progradation in an easterly direction (Parfenov, 1984; Tectonics, geodynamics and metallogeny of the Sakha Republic, 2001). It has also been postulated that a gradual transition from continental to marine sedimentation and deepening of sea basin progressed from the southwest to the northeast (Korostelev, 1982).

PROVENANCE STUDY

Data on mineral composition, geochemistry, and isotopic characteristics of Triassic sediments from the Chukotka and Verkhoyansk regions (Tables 1a, b and 2a, b) are discussed below to determine paleogeography and tectonic evolution of the respective sedimentary basins.

Petrographic data

According to the classification of Pettijohn (1981), the Lower–Middle and Upper Triassic sandstones of Chukotka correspond respectively to graywackes with more than 15% of matrix and litharenites with 3–10% of matrix. The mineral composition of sandstones is as follows: quartz 10–65%, feldspars 5–45%, lithoclasts 20–75% (Tuchkova et al., 2009). The association of rock-forming components of sandstones suggests that clastic material of Triassic rocks was derived from a provenance composed of metamorphic rocks and subjected to gradual erosion (Tuchkova et al., 2009). In addition, some components of the Lower Triassic sandstones could be derived from volcanogenic rocks of basaltic andesite composition (Tuchkova et al., 2007). As lithoclasts of the Upper Triassic sandstones are more diverse than in underlying rocks, this can be regarded as an indication of orogenesis and drainage area expansion with time.

Triassic sandstones of the Verkhoyansk region correspond in composition to sublitharenites and lithic arenites (Prokopiev et al., 2008). By the transition from the Lower to Upper Triassic sandstones, increasing quartz content of up to 80–95% of the rock volume is reported. In general, these sandstones consist of quartz (35–65%), feldspars (5–30%), lithoclasts (25–45%), and matrix (5–10%. Rock types identified among lithoclasts are granodiorite, volcanics, and cherts. The amount of lithoclasts decreases upward in the sequence.

Geochemistry

XRF and ICP-MS analyses of sandstones from both study regions are shown in tables 1a, b and 2 a, b. Classification diagrams based on the chemical composition of the analyzed rocks are shown in Figs. 14a and 14b. Data points characterizing the Lower–Middle Triassic sandstones of Chukotka plot, with considerable dispersion, predominantly in the field of graywackes, whereas data points of the Upper Triassic sandstones are displaced into the

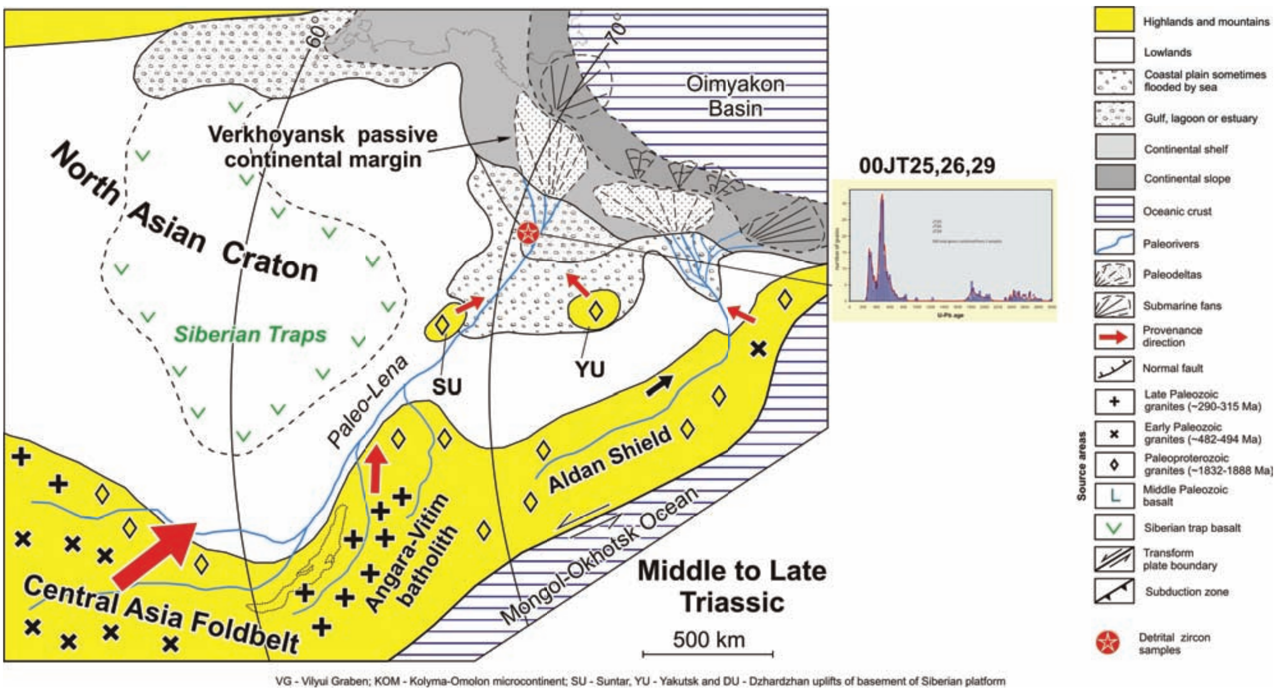


Fig. 13. The schematic paleogeographic map of the Verkhoyansk basin for the Middle–Late Triassic time (from Prokopiev et al., 2009).

Table 1a. Contents of major elements in sandstones of Chukotka region, Triassic unit. Major element were analyzed by XRF method, GIN RAS, Moscow

Map area	sample	Group	Position	SiO2	TiO2	Al2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O	H2O-	H2O+	PPP	P2O5	CO2	Sum
	329/2-1	T1-2	Enmynveem River	56,83	1,2	16	2,34	7,67	0,07	3,71	2,41	0,54	2,04			6,48	0,21	1,71	101,21
	329/2	T1-2	Enmynveem River	55,92	1,25	15,58	3,54	6,89	0,08	3,82	1,97	2,17	2,05			6,12	0,25	1,04	100,68
	329/3	T1-2	Enmynveem River	49,12	1,19	12,03	2,32	5,39	0,11	2,81	11,8	2,32	0,67			11,91	0,18	9,31	109,16
	404/3	T1-2	Yanramkyvaam River	67,55	0,98	13,46	3,19	3,62	0,05	1,76	0,96	0,49	2,51			4,67	0,2	0,24	99,68
	405/4п	T1-2	Yanramkyvaam River	47,81	1,71	16,6	4,1	8,83	0,11	4,49	4,29	2,47	1,24			7,38	0,23	2,08	101,34
1	**406/3**	T1-2	Lyupveem River	67,68	1,27	11,13	1,64	6,4	0,06	3,63	1,07	2,17	0,22			3,95	0,17	0,34	99,73
	407/6	T1-2	Lyupveem River	59,67	0,98	17,92	2,39	3,96	0,07	2,61	1,4	7,67	0,42			2,04	0,18	<0,2	99,31
	409/2п	T1-2	Str. Tundrovy	71,33	0,99	12,07	1,74	4,19	0,04	1,84	0,61	3,55	0,7			2,47	0,15	0,27	99,95
	461/7	T1-2?	Vernitakayveem River	65,81	1,34	12,51	0,71	8,32	0,06	3,30	0,25	2,57	0,28			4,17	0,15	0,20	99,67
	461/7-2	T1-2?	Vernitakayveem River	70,90	1,02	11,78	0,20	6,43	0,04	2,46	0,62	1,28	0,83			4,23	0,14	0,20	100,13
	460/7	T1-2	Vernitakayveem River	50,04	2	13,53	3,47	9,7	0,17	7,23	5,84	1,74	0,07	0,16	3,89	5,4	0,19	0,83	104,26
	201/5silt	T3k	Maly Anyui River	77,18	0,77	9,51	1,9	2,52	0,07	2,58	0,26	1,9	1,06		0,17	2,2	0,14	0,46	100,72
	201/5san	T3k	Maly Anyui River	75,94	0,59	8,68	1,76	2,95	0,1	2,34	1,06	1,42	0,9		0,22	3,49	0,13	1,33	100,91
	422/z	T3k	Maly Anyui River	67,72	0,73	12,68	1,04	3,88	0,07	2,18	1,98	1,05	1,93			6,16	0,13	3,05	102,60
	200/9a	T3k	Bilibino	68,53	0,77	11,9	2,06	6,36	0,13	1,94	1,2	1,52	1,16			3,92	0,17	0,29	99,95
1	**400-3-2**	T3k	Maly Keperveem River	70,85	0,55	9,29	4,12	3,97	0,13	1,69	1,25	1,52	0,77			5,13	0,15	1,76	101,18
	414/3п	T3k	Kytepguytenryveem R.	76,46	0,56	5,23	1,73	4,35	0,06	1,62	1,82	0,27	0,65			6,57	0,11	5,43	104,86
	414/7	T3k	Kytepguytenryveem R.	76,97	0,6	9,67	2,54	2,69	0,04	1,15	0,23	0,97	1,48			2,99	0,14	0,35	99,82
	416/3	T3k	Srt. Gnom	73,27	0,59	8,66	2,2	2,63	0,08	1,64	2,36	1,91	0,75			5,2	0,12	3,41	102,82
	417/4	T3k	Str.Ugol	73,9	0,58	9,43	1,93	2,47	0,03	1,1	1,31	2,1	0,99			5,54	0,15	4,14	103,67
	417/6	T3k	Str.Ugol	68,18	0,68	11,46	2,35	4,25	0,03	1,36	0,82	2,34	1,35			6,73	0,14	4,56	104,25
	454/3	T3n	Machvavaam River	71,82	0,82	10,9	2,63	2,52	0,05	1,21	0,56	1,17	1,51	0,57	2,37	6,3	0,08	2,95	105,46
	K-04-43	T3n	Machvavaam River	67,68	0,82	13,08	1,67	3,9	0,15	1,38	0,56	1,19	1,78	0,8	3,31	7,55	0,11	3,45	107,43
1	**454/8-2**	T3n	Machvavaam River	72,8	0,59	10,44	1,37	4,86	0,17	1,72	0,74	1,54	1,05	0,52	2,58	4,15	0,1	0,92	103,55
	456/4	T3n	Pyrkanay Ridge	75,08	0,4	8,23	2,88	1,72	0,3	1,41	2,41	1,42	0,93	0,39	1,68	5,04	0,11	2,99	104,99
	453/1	T3n	Irguneyveem River	71,3	0,63	10,42	0,63	6,48	0,13	1,56	0,87	1,71	0,97	0,6	2,15	4,51	0,17	1,68	103,81
	358/1	P-T	Ploskaya River	56,84	0,9	14,24	1,48	4,56	0,13	2,71	5,1	1,3	2,05			9,83	0,24	4,81	104,19
4	**357/3**	P-T	Ploskaya River	56,64	1,11	20	2,2	4,85	0,06	3,6	0,5	0,69	3,89			5,48	0,25	0,24	99,51
	343/5	P-T	Lukovaya Mts	64,68	0,83	12,46	1,43	4,53	0,09	2,87	3,52	1,85	1,02			5,69	0,24	2,54	101,75

Table 1b. Contents of major elements in sandstones of the Verkhoyansk region, Permian-Triassic unit. Major element were analyzed by XRF method, VSEGEI, Spetersburg

Map area	sample	Group	Position	SiO2	TiO2	Al2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O	H2O-	H2O+	PPP	P2O5	CO2	Sum
	06AP21	$P_2 im_2$		84,28	0,24	6,78	0	1,52	0,07	0,67	0,77	2,52	0,93	0,18	0,65	0	0,38	0,53	99,47
	06AP25	$T_1 nc_1$		63,88	0,61	10,17	1,94	6,64	0,45	1,96	5,41	0,99	0,99	0,28	3,36	0,14	0,92	2,33	99,93
	06AP29	$T_1 nc_2$		62,21	0,87	12,72	1,34	5,85	0,18	2,77	4,03	1,74	1,7	0,32	3,73	0	0,34	2,38	100
	06AP31	$T_1 nc_2$		76,64	0,4	11,03	0,44	2,39	0,09	1,19	0,98	2,76	1,54	0,22	1,25	0	0,38	0,25	99,35
5	**06AP32**	$T_1 nc_2$	South part of Verkhoyansk	67,66	0,64	15,18	1,1	3,61	0,09	1,6	0,45	2,6	3,77	0,08	2,41	0	0,38	0	99,51
	06AP34	$T_1 nc_2$		73,51	0,63	11,83	0,88	3,04	0,06	1,04	1,07	3,29	2,28	0,02	1,52	0	0,38	0	99,54
	06AP36	$T_1 nc_2$		76,71	0,34	10,12	0,15	1,49	0	0,83	2,35	3,33	1,97	0,1	0,93	0	0,36	1,35	99,94
	06AP37	$T_1 nc_2$		76,94	0,35	11,26	0,26	2,23	0	0,75	0,71	3,55	2,3	0,24	0,88	0,13	0,36	0	99,74
	06AP38	$P_2 im_2$		63,47	0,62	13,33	1,04	1,89	0,22	1,93	5,16	3,65	2,51	0,22	1,97	0	0,36	3,44	99,86
	06AP39	$P_2 im_2$		62,69	0,8	17,3	2,26	2,17	0,04	3,1	0,3	3,6	3,99	0,56	2,21	0	0,42	0	99,88
	04-AP-215	*T3nor*	Str.Bazovsky	81,63	0,33	7,9	2,75	0,47	0,05	0,31	0,71	2,17	1,25			1,53	0,38	0	99,48
	04-AP-225	*T3nor*	Str.Bazovsky	89,43	0,12	3,99	0,86	0,36	0,03	0,72	1,03	1,24	0,4			0,89	0,11	1,05	100,3
	04-AP-226	*T3nor*	Str.Bazovsky	79,35	0,47	8,62	0,95	1,57	0,05	0,91	1,24	2,43	1,17			1,72	0,19	1,62	100,3
	04-AP-163/2	*T3nor*	Str.Talalakh	62,1	0,72	10,76	0,78	3,85	0,31	2,84	6,43	1,47	1,86			2,76	0,48	5,45	99,86
	04-AP-164	*T3nor*	Str.Talalakh	62,92	0,81	11,7	0,75	4,65	0,22	2,9	4,98	1,38	2			2,76	0,45	3,86	99,41
	04-AP-192	*T3nor*	Str.Bazovsky	80,67	0,28	9,39	1,15	1,71	0,03	0,7	0,56	1,8	1,51			1,53	0,19	0	99,58
	04-AP-211	*T3nor*	Str.Bazovsky	76,47	1,28	9,41	3,32	0,89	0,05	0,6	1,5	1,6	1,83			2,13	0,33	0,55	100
7	**04-AP-212**	*T3nor*	Str.Bazovsky	57,84	0,63	11,49	1,01	3,91	0,36	2,31	6,42	2,98	1,94			2,4	0,39	8,28	99,96
	04-AP-214	*T3nor*	Str.Bazovsky	80,09	0,16	9,59	2,5	0,48	0,05	0,51	0,43	2,36	1,63			1,89	0,16	0	99,85
	04-AP-220	*T3nor*	Str.Bazovsky	65,08	0,84	13,57	3,61	2,17	0,09	1,7	0,96	2,07	2,72			3,57	0,48	2,48	99,36
	04-AP-221	*T3nor*	Str.Bazovsky	57,82	0,99	15,55	3,6	3,73	0,04	3,09	0,53	2,33	3,36			4,96	0,48	2,7	99,23
	04-AP-223	*T3nor*	Str.Bazovsky	60,41	1,03	15,11	0,83	4,95	0,05	2,64	0,96	2,17	3,09			4,05	0,58	3,7	99,59
	04-AP-219	*T3nor*	Str.Bazovsky	52,43	1,18	18,98	2,75	3,3	0,05	2,9	0,87	2,39	4,32			7,32	0,45	2,21	99,22
	04-AP-221	*T3nor*	Str.Bazovsky	58,46	1,07	17,1	2,7	2,76	0,03	2,12	0,56	2,57	3,56			5,97	0,45	2,17	99,57
	04-AP-233	*T3nor*	Str.Bazovsky	57,42	1,19	19,4	4,83	3,23	0,04	2,04	0,22	2,26	3,56			4,6	0,48	0	99,34
8	**06AP12**	*T3*	Str.Pyl'	48,28	0,69	11,77	1,19	6,1	0,48	3,51	8,55	1,43	2,12	0,06	3,34	0	0,33	12,08	99,95
	06AP14	*T3*	Str.Malyutka	72,17	0,25	6,02	0,4	3,86	0,11	1,71	4,64	1,5	0,96	0,08	0,73	0	0,53	6,37	99,27
	PROK-1	$T_1 tl$	Western part of Verkhoyansk margin	71,18	0,81	11,27	2,15	3,86	0,07	1,55	1,24	2,67	1	0,26	2,67	0,26	0,39	0,27	99,39
	PROK-2	$T_1 tl$		69,95	0,78	13,28	1,5	2,89	0,06	1,05	1,09	3,62	1,92	0,24	2,14	0	0,37	0,82	99,51
	PROK-3	$P_2 dl$		68	0,36	11,02	0,35	1,4	0,1	0,41	5,69	3,27	1,85	0,16	1,98	0	0,32	4,89	99,65

Table 2a. Minor and Rare earth element composition (ppm) of Permian and Triassic sandstones of Chukotka basin

Map area	Sample	Group	Co	Ni	Zn	Sc	V	Cr	Y	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Th	U
1	Б-1-1/1	T1-2	18,8	69,5	129	14,1	143	57,4	21,7	591	30,1	64,2	6,6	24,6	4,9	1,2	4,5	0,66	3,9	0,78	2,4	0,34	2,3	0,32	4,0	0,63	6,0	2,2
	329/3-3	T1-2	10,4	41,4	62,0	9,0	80,5	31,1	15,6	243	18,8	45,6	4,6	17,8	3,5	0,52	3,3	0,47	2,6	0,56	1,7	0,25	1,6	0,23	3,2	0,43	4,9	1,5
	422/z	T3k	19,3	58,5	122	11,8	99,6	62,0	17,8	214	24,6	53,2	5,2	20,1	3,9	0,80	3,8	0,56	3,2	0,64	1,9	0,27	1,9	0,26	3,1	0,59	6,6	1,8
2	503/2-1	T3	9,0	40,4	65,9	13,3	139	109	29,8	518	33,9	68,4	7,8	31,4	6,1	1,2	5,4	0,84	5,2	1,1	3,3	0,47	3,3	0,48	6,4	1,1	13,2	2,7
	503/4-3	T3	10,4	35,8	72,5	9,7	59,5	55,5	6,6	164	16,0	35,4	3,7	14,6	2,7	0,55	1,9	0,23	1,6	0,23	0,7	0,10	0,9	0,13	1,5	0,33	4,9	1,3
4	357/1	P-T	9,7	77,5	84,9	19,0	234	126	14,2	744	24,1	71,6	5,9	23,5	4,9	1,2	4,3	0,60	3,4	0,71	2,2	0,34	2,5	0,40	4,5	1,0	7,2	3,4
	343/5	P-T	9,8	61,4	104	14,2	125	131	12,5	246	19,8	47,2	5,5	22,8	5,0	1,1	4,5	0,64	3,3	0,62	1,7	0,26	1,8	0,26	2,2	0,50	4,9	1,7
	358/1	P-T	12,0	65,3	297	16,1	142	99,1	21,9	354	19,5	49,0	5,9	25,8	5,9	1,6	5,9	0,89	5,0	0,97	2,8	0,40	2,7	0,41	3,3	0,70	6,1	2,6

Table 2b. Minor and Rare earth element composition (ppm) of Permian and Triassic sandstones of Verkoyansk basin

Map area	sample	Group	Co	Ni	Zn	Sc	V	Cr	Y	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Th	U
5	06AP21	P_2im_2	8,16	43,2	28,4	2,87	20,5	326	8,09	118	16,6	33,1	3,51	12,9	2,12	0,52	2,19	0,3	1,58	0,31	0,91	0,13	0,91	0,14	2,81	0,74	3,64	1,05
	06AP25	T_1nc_1	28,2	37,4	71,3	14,3	129	111	39,2	159	38,6	92,8	12,1	54,5	13,9	3,75	15,5	1,98	10,1	1,63	3,77	0,46	2,92	0,43	5,02	1,27	6,08	1,39
	06AP29	T_1nc_2	28,2	41,8	86,9	16,6	151	80	28,3	264	34,4	77,4	8,88	35,1	6,6	1,7	7,43	1	5,7	1,1	3,09	0,46	3,03	0,45	7,02	1,7	8,5	2,1
	06AP31	T_1nc_2	9,94	23,7	41,1	6,78	55,2	145	15,9	290	33,8	68,7	7,78	28,5	4,94	1,14	4,92	0,61	3,23	0,61	1,73	0,28	1,8	0,27	7,24	1,31	7,73	1,64
	06AP32	T_1nc_2	19,5	28,3	87,1	9,2	71,7	71,8	25,3	980	43,2	90,1	10,3	39,1	7,47	1,44	6,84	0,94	5,11	1,01	2,9	0,4	2,74	0,4	8,43	1,92	11,3	2,45
	06AP34	T_1nc_2	16,5	20	64,4	7,23	61	107	20,5	791	44	89,4	10,2	36,6	6,32	1,7	6,2	0,81	4,19	0,74	2,2	0,31	2,07	0,35	10,8	1,72	13,8	2,18
	06AP36	T_1nc_2	8,18	14,5	35,3	5,25	28,1	151	13,3	667	32,5	64,3	6,83	25,1	4,26	1,1	4,12	0,54	2,79	0,49	1,36	0,2	1,23	0,2	4,86	0,94	7,7	1,15
	06AP37	T_1nc_2	10,5	17,4	36,1	4,85	34,7	129	13,4	822	29,8	64	6,91	25,5	4,3	1,12	4,42	0,53	2,86	0,52	1,5	0,22	1,39	0,22	5,56	1,19	7,85	1,34
	06AP38	P_2im_2	13,8	14,7	70,5	8,75	51,1	83,4	23,5	701	30,6	64,3	7,55	28,5	5,44	1,43	5,66	0,81	4,6	0,85	2,4	0,33	2,23	0,36	7,39	1,29	8,72	2,52
	06AP39	P_2im_2	16,6	16,9	50,2	8,62	67,5	61,4	22,2	791	41,5	85,1	9,6	35,4	6,12	1,36	6,25	0,82	4,5	0,9	2,57	0,39	2,76	0,42	8,76	1,69	11	2,96
8	06AP12	T_3	22,5	42,6	92,2	13	87,4	57,7	24,3	278	24,5	50,1	5,88	23,6	5,34	1,57	6,48	0,85	4,86	0,9	2,34	0,33	2,12	0,32	3,92	1,43	6,25	1,81
	06AP14	T_3	8,55	30,1	46,9	6,39	95,5	164	22,4	157	16,5	39,4	4,87	20,9	5,1	1,44	6,14	0,85	4,77	0,89	2,14	0,27	1,65	0,25	2,36	0,75	5,6	1,49
9	A3/5-1	T_3	9,4	37,3	65,9	8,5	87,6	44,4	15,8	561	30,9	64,4	6,5	24,1	4,4	0,89	3,9	0,54	3	0,6	1,8	0,26	1,8	0,25	4,1	0,61	7,1	1,8
	03AП25	T_3	8,7	66,1	120	4,5	46,5	20,2	10,7	60,0	14,4	31,3	3,5	14,4	3,3	0,64	2,9	0,4	1,9	0,36	1,1	0,15	1,1	0,16	2,8	0,32	4,4	1,1

a. **b.**

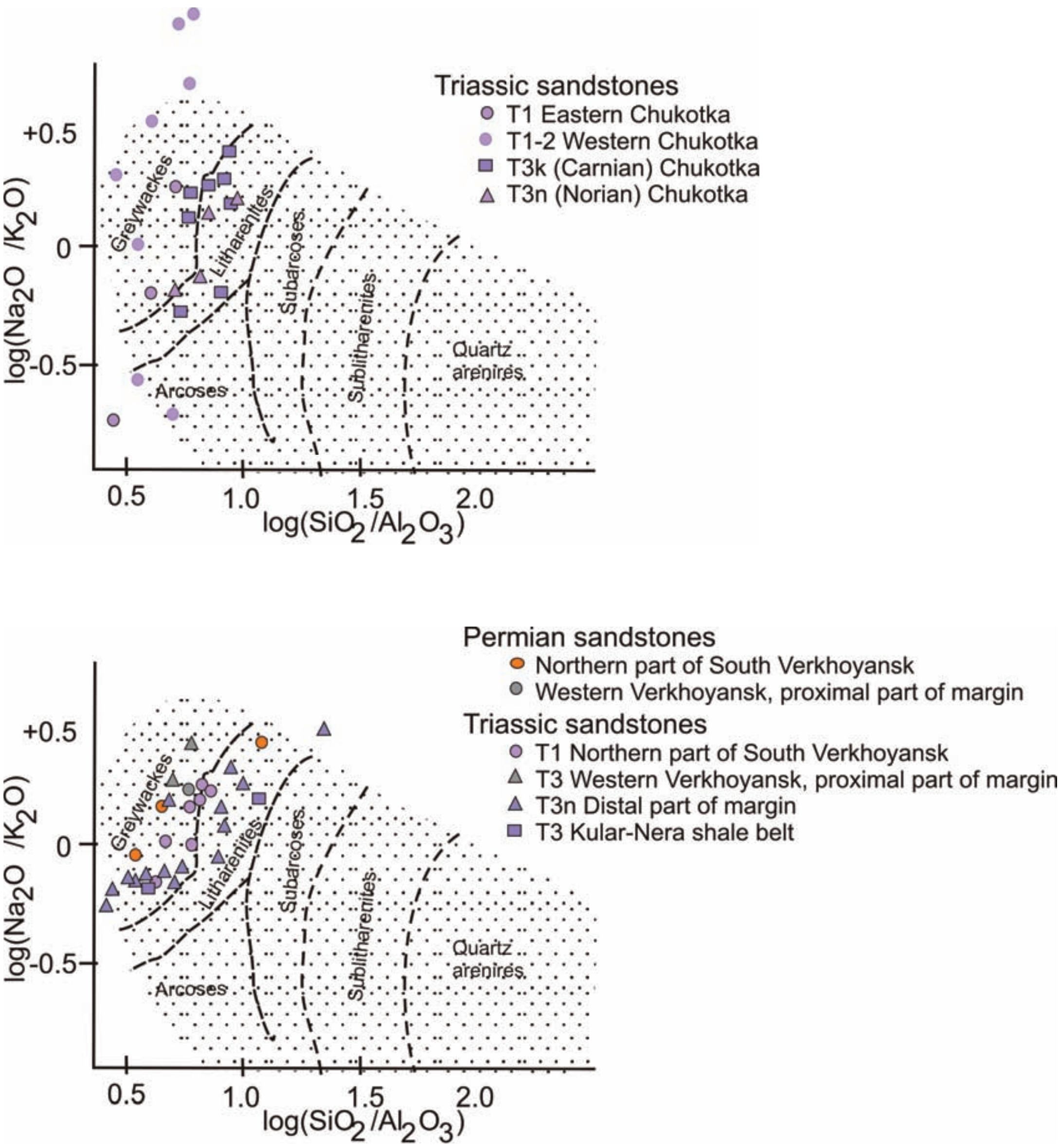
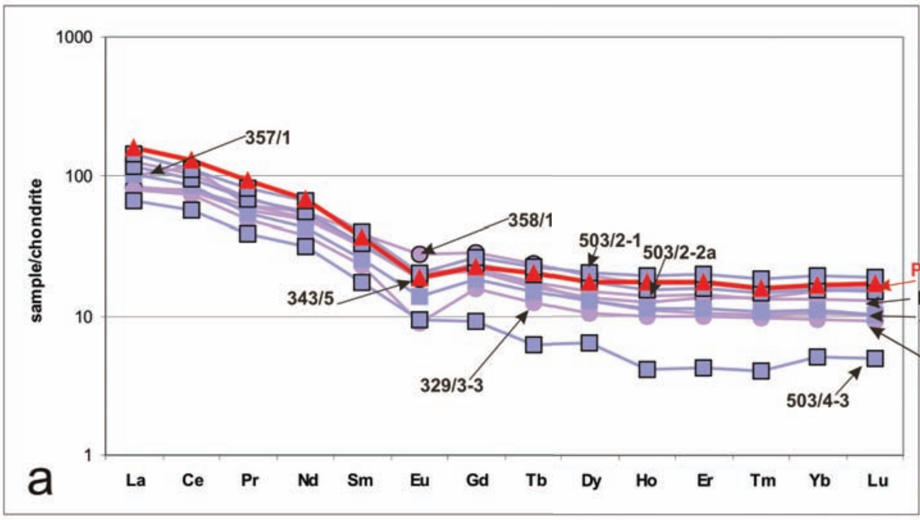


Fig. 14a. Classification diagram after Pettijohn et al. (1987) showing distribution of major components in the Triassic sandstones of the Anyui-Chukotka fold belt. Triassic sandstones: T1 Eastern Chukotka; T1-2 Western Chukotka; T3k Chukotka; T3n Chukotka. **Fig. 14b**. Classification diagram after Pettijohn et al. (1987) showing distribution of major components in the Permian and Triassic sandstones of the Verkhoyansk-Kolyma fold belt. Permian sandstones: Northern part of the South Verkhoyansk region; Western Verkhoyansk region, proximal part of the Verkhoyansk margin; Triassic sandstones; Northern part of the South Verkhoyansk region, T1; Western Verkhoyansk region, proximal part of the Verkhoyansk margin, T3; Distal part of the Verkhoyansk margin, T3n; Kular–Nera shale belt, T3.

field of litharenites. In general Fig. 14a illustrates growing compositional maturity of clastic material during the Triassic.

Triassic sandstones of the Verkhoyansk–Kolyma belt are divisible in two groups (Fig.14b), of graywackes and litharenites with different log Na2O/K2O values. Graywackes with negative values of this parameter are from the distal part of the Verkhoyansk margin, whereas positive values are characteristic of litharenites from the proximal part of that margin (Fig. 14b). This trend in distribution of data points can be regarded as indicating the previous existence of several provenances of clastic material in the Vekhoyansk region.

The chondrite-normalized rare earth elements (REE) distribution patterns for sandstones from both regions (Figs. 15a and 15b) are sufficiently uniform and typical of terrigenous sediments from



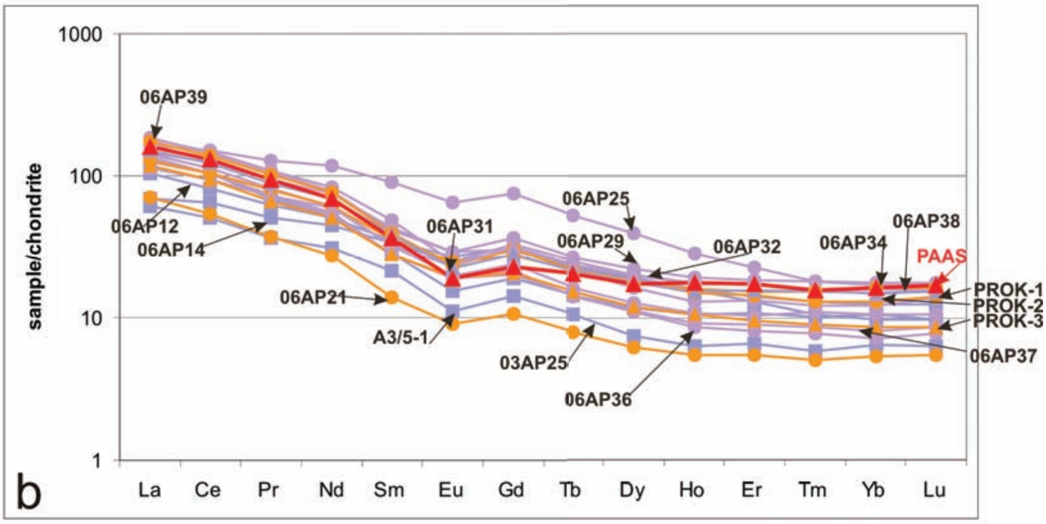


Figure 15. Plots of REE distribution in the Triassic sandy rocks of the Anyui–Chukotka (a) and Triassic sections of the Verkhoyansk–Kolyma (b) fold belts; red line shows the PAAS spectrum.

passive continental margins. As for distinctions between separate groups of rocks, it should be noted that practically all Triassic sandstones from Chukotka are depleted in REE relative to their concentrations in the Post-Arhean Australian Shale (PAAS). On the other hand, the REE concentrations in the Lower Triassic sandstones of the Verkhoyansk region are somewhat higher than in concurrent rocks of Chukotka, whereas the other sandstones of this region are relatively depleted in REE. These geochemical characteristics presumably suggest the polycyclic formation of the Lower Triassic deposits in the north of the southern Verkhoyansk region. The high Th/U ratios (>4, from 3.45 to 6.69, Tables 2 b) in sandstones of this region are also indicative of their polycyclic origin and suggest a considerable influence of the Old Upper Continental Crust (Taylor and McLennan, 1988) on their composition that is clearly seen in the Lower Triassic rocks. In the Lower–Middle Triassic sandstones of Chukotka, the Th/U ratio changes from 2 to 3.5 and rises up to 3.4–5 in the Upper Triassic rocks. This geochemical trend excluding the polycyclic origin of rocks suggests the influence of the Young Undifferentiated Arc source on their composition (Tables 2a and 2b).

To determine the rock types of provenances,

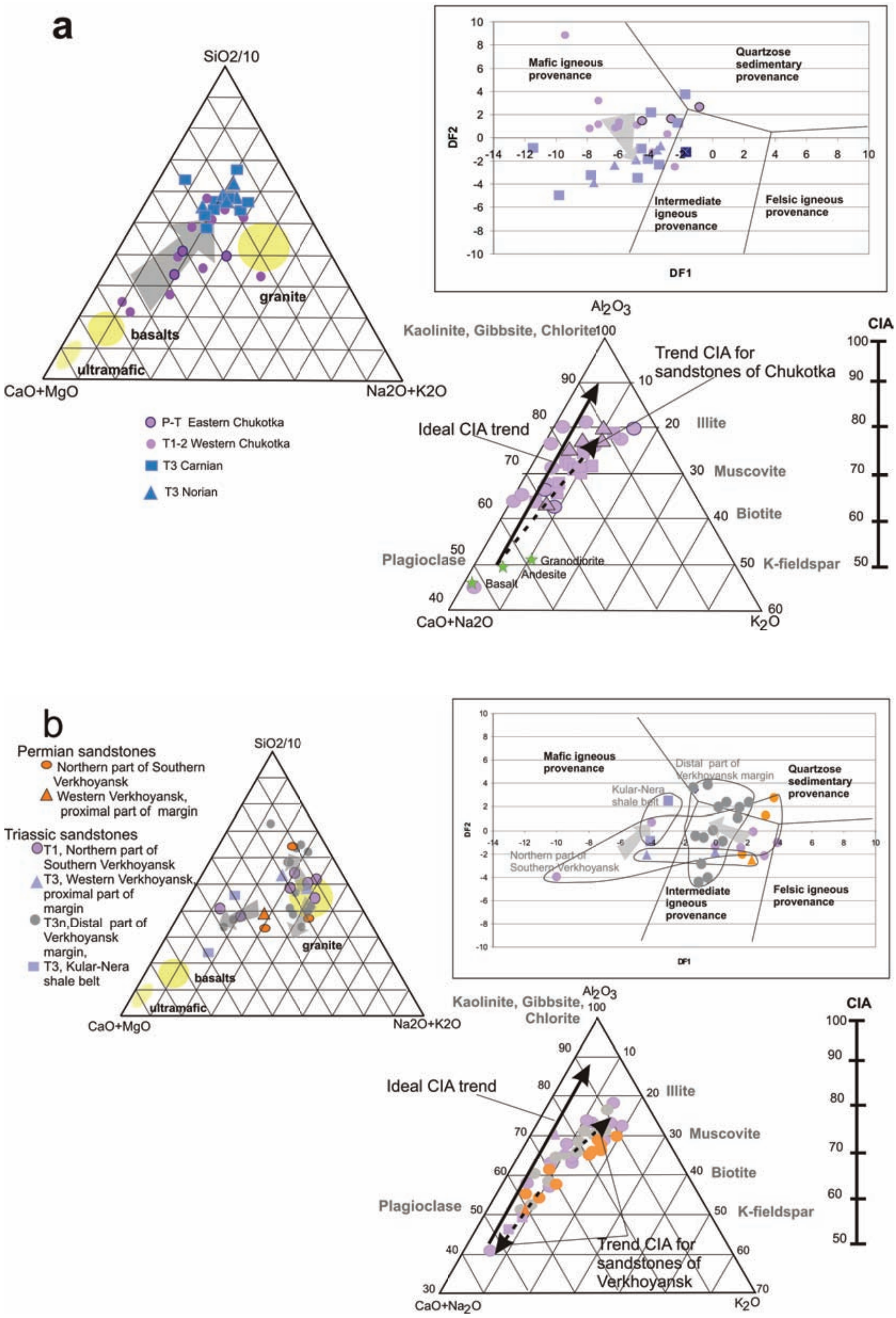


Fig. 16. Discriminant diagrams for compositions of provenances for Triassic sandy rocks of the Anyui–Chukotka (a) and Verkhoyansk–Kolyma (b) fold belts. The arrow shows the evolutionary trend of rock compositions during the Triassic. Left diagram after Taylor and McLennan (1988); Upper right discriminant diagram for major component provenance, after Roser and Korsch (1988). Discriminants and fields are $DF1=30.6038TiO_2/Al_2O_3-12.541Fe_2O_3(total)/Al_2O_3+7.329MgO/Al_2O_3+12.031Na_2O/Al_2O_3+35.42K_2O/Al_2O_3-6.382$. $DF2=56.500TiO_2/Al_2O_3-10.879Fe_2O_3(total)/Al_2O_3+30.875MgO/Al_2O_3-5.404Na_2O/Al_2O_3+11.112K_2O/Al_2O_3-3.89$. Bottom right, Al_2O_3–$CaO+Na_2O$–K_2O diagram (CIA, Nesbitt and Young, 1984) showing compositions for Permian and Triassic sandstone of the Chukotka (a) and Verkhoyansk (b) basins (molar proportions). Average values for basalt, andesite, and granodiorite are from McLennan et al. (2003).

we used diagrams by Taylor and McLennan (1995) and by Roser and Korsch (1988), in which the rocks studied are compared with typical rocks of ultramafic, mafic, and felsic compositions. In the CaO + MgO – Na2O+K2O – SiO2/10 diagram (Taylor and McLennan, 1988, Figs. 16a and 16b), Triassic sandstones from Chukotka suggests mixing of material derived from basaltic and granitoid rocks, its gradual compositional maturation, and increase of felsic components in the rocks by the end of the Late Triassic (Fig. 16a).

In the discriminant function (DF1–DF2) diagram (after Roser and Korsch, 1988), the Triassic sandstones of Chukotka are indicative of mafic provenances (Fig.16a). The Upper Triassic sandstones appear to be slightly displaced toward the field of the intermediate igneous provenance, which implies an elevated content of the silicate component and presumably, higher maturity of clastic material.

The behavior of rock-forming elements provides grounds for estimating the degree of clastic material weathering in the provenance (Chemical Index of Alteration, CIA, after Nesbitt and Yang, 1982, Fig. 16a). Ideally, the CIA trend reflects the degree of rock weathering in the provenance and the loss of K2O and Al2O3; therefore, it is oriented parallel to the left side of the triangle. For the Chukotka sandstones, the CIA trend exhibits directions similar to an ideal one, though displaced toward higher K2O concentrations. Potassium enrichment is typical for diagenetic and/or later hydrothermal processes.

In the diagram CaO+MgO – Na2O+K2O – SiO2/10 (after Taylor and McLennan, 1988), Permian–Triassic rocks of the Verkhoyansk region form two fields (Fig. 16b). In one of them, the rocks point to a granite source. Another field corresponds to basalts. Moreover, they demonstrate differently directed compositional changes through the section from the base upward. In the first case, the content of CaO+MgO content increases from proximal to distal parts of the margin, while in the second one, no regular changes are observed in the sandstone lithology. Such distributions of oxides in sandstones suggest different provenances.

In the DF1–DF2 diagram (after Roser and Korsch, 1988), Permian and Lower Triassic sandstones of the southern Verkhoyansk region and Upper Triassic rocks of the distal part of the margin are located in the field of the intermediate and quartzose sedimentary provenance (Fig. 16b). The sandstones of the Kular–Nera terrane correspond to the field of mafic rocks.

The index CIA calculated for Permian–Triassic rocks of the Verkhoyansk basin shows that they are immature in composition, i.e., the degree of weathering in the provenance was insignificant (Fig. 16b). The CIA determined for Permian sandstones is similar to that inferred for their Triassic counterparts. Therefore, it may be concluded that sandstones of the Verkhoyansk region are characterized by the trend opposite to maturation (Fig. 16b). This may be explained only by mixing of clastic material from different sources and different duration of its transportation, which prevented maturation in the provenance.

The SiO2/Al2O3 ratio, which is sensitive to fractionation of terrigenous material during its transportation and deposition, represents another indicator of maturity. For the Permian–Triassic rocks of the Verkhoyansk region, this ratio is highly variable ranging from 2.6 to 10.3. Moreover, synchronous rocks may be characterized by different fractionation levels. The SiO2/Al2O3 ratio in Chukotka sandstones increases from 2.5–4.0 in the Lower Triassic to 6–8 in Upper Triassic parts of the section (Tables 2a, 2b). These data point to substantially lower fractionation of clastic material during its transportation to the Chukotka basin in the Early Triassic as compared with that in the Late Triassic.

Figures 17a and 17b present diagrams that allow the composition of rocks in provenances to be evaluated. They are based on proportions of minor elements in sedimentary rocks, which are less sensitive to post-sedimentary transformations of clastic rocks as compared with oxides. In the Ti –Zr diagram, Triassic sandstones of Chukotka form a very uniform field, which characterizes erosional products of andesites (Fig. 17a). In the other diagram based on Co/Th–La/Sc ratios, the Chukotka sandstones correspond to erosional products of rocks lithologically close to average composition of the continental crust. Nevertheless, the transition from Lower to Upper Triassic sandstones is marked by a slight tendency for growth of the granodiorite constituent (Fig. 17 a). The Th/Sc versus Zr/Sc diagram demonstrates the recycling trend from the Early to Late Triassic (Fig. 17a).

The same diagrams (Ti–Zr, Co/Th–La/Sc, Th/Sc versus Zr/Sc) available for the Verkhoyansk region exhibit gradual increase in the role of basic components in the Permian to Upper Triassic sandstone succession. It should be noted, however, that the influence of rocks compositionally close to the continental crust is sufficiently high for Co/Th and Zr/Sc ratio in both the Verkhoyansk and Chukotka basins. The distinct compositional evolution of sandstones is also evident from the Cr/V–Y/Ni diagram. The "granite" composition of clastic material in the Permian sandstones gives way to the significant role of the mafic constituent in the Lower and Middle Triassic sandstones (Fig. 17b). In the Th/Sc versus Zr/Sc diagram, sandstones of the Verkhoyansk region demonstrate a tendency opposite to maturation (Fig. 17b).

Geochronology

The age of detrital zircons in sandstones provides important information for defining their provenances. In this work, we use the U–Pb dating of detrital zircons by the ICPMS-LA and Sm–Nd isotope ratio methods for rocks with a wide grain-size spectrum. For correlating populations of detrital zircons, the published (Miller et al., 2006; Prokopiev et al., 2007) and original data (Tables 3, 4) are used.

Distribution of ages obtained for detrital zircons from Upper Triassic sandstones of the Verkhoyansk region demonstrate peaks at 331, 353, 381, 422, and 470 Ma (Sample JT25). The peaks corresponding to 292, 321, 439, and 483 Ma are recorded for Sample JT26 and to 292, 308, 459, 485, and 517 Ma for Sample Jt29. In the sample from the Lower Permian section (00JT18), the peaks for zircons are documented at 288, 494, 782, and 854 Ma (Prokopiev et al., 2008). All three Triassic samples contain populations of ancient zircons with ages of approximately 1832 Ma; in the Permian sample, the zircon population is much older: 1863 Ma (Prokopiev et al., 2008). The Paleozoic population demonstrates two notable peaks: at 288 and 482 Ma.

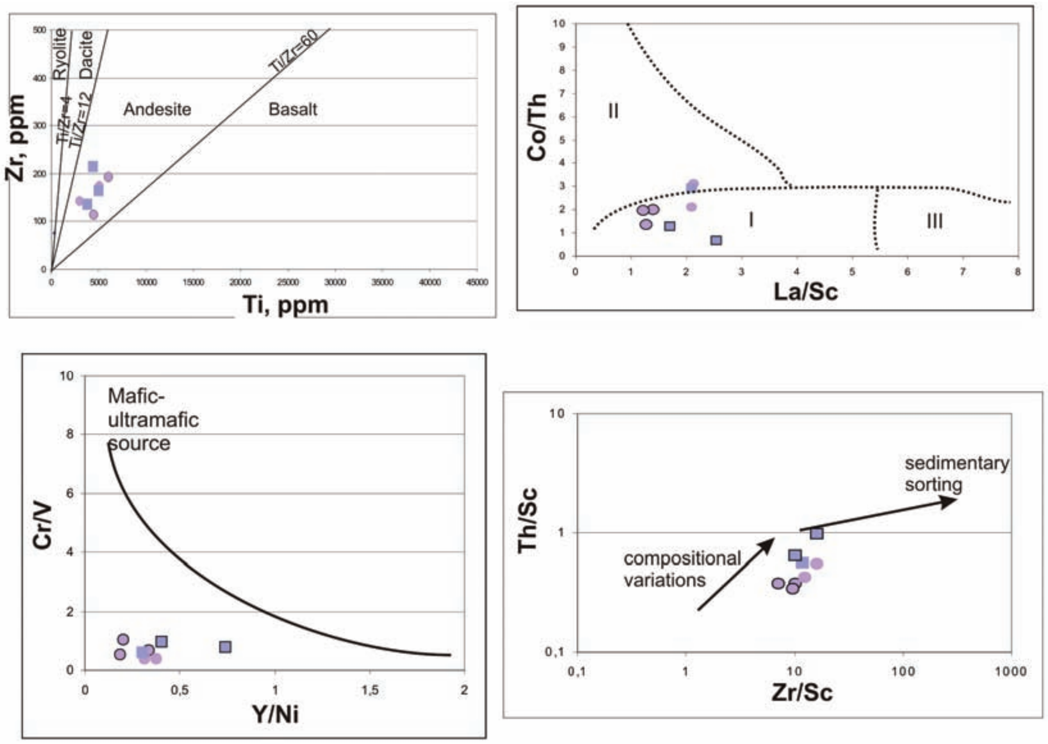
The association of detrital zircons from the Upper Triassic sandstones of the Anyui subterrane includes several populations 235–265, 321–399, 425–545, 545–011, 1061–1273, and 1606–2725 Ma old (Miller et al., 2006). The young population is represented by zircon grains dated back to 236–265 Ma (Miller et al., 2006). No such ages were recorded for sandstones from the Verkhoyansk region. The Upper Triassic sandstones from Wrangel Island yield ages ranging from 215 to 260 Ma (Miller et al., 2009).

Y.Hayasaka (Hiroshima University) and A. Moiseev (Geological Institute Russian Academy of Science, GIN RAS) have dated two samples of the Triassic sandstones from the Chaun subterrane by the ICP-MS LA method. Sandstone sample 09/358 was taken in the Ploskaya River basin (locality 4 in Fig. 3) from the Lower Triassic sequence of alternating siltstones and sandstones with tuff intercalations. Sample 09/321 was collected from the Upper Triassic (?) member of alternating sandstones and siltstones (Mount Lukovaya, Table 2). The first sample contains zircon populations with peaks at 272–286, 435–613, 671–793, and single older grains dated back to 1000–1969, 2397, and 2672 Ma. Zircons from Sample 09/321 exhibit only two peaks at 255–295 and 424–548 Ma; a small population yielded older ages of 1669–1986 Ma (Fig. 18).

It should be noted that both samples are barren of the young population 235–265 Ma old that is characteristic of the Upper Triassic rocks from the Anyui subterrane (Miller et al., 2006) and Wrangel Island (Miller et al., 2009) despite the occurrence of tuff intercalations and gabbro–dolerite sills in the relatively shallow-water Ploskaya River section. The young zircon population is missing also from the coeval Sadlerochit Group and Blind Fiord Formation sandstones of the Sverdrup basin (Miller et al., 2006; Omma et al., 2011).

The ancient zircon populations of the Verkhoyansk and Chukotka regions demonstrate certain differences as well. The sandstones from the Verkhoyansk region are barren of zircons with ages ranging from 900 to 1700 Ma (Sample JT25); samples JT26 and JT29 each yielded the only zircon grains dated back to 988.6 ± 18.0 and 1234 ± 90 Ma (Miller et al., 2006). Three sandstone samples from Verkhoyansk contain 6, 20, and 22 zircon grains. It is noteworthy that the sample of the Lower Triassic sandstones from the Sadlerochit Mountains (Sample 96DH102) appeared to contain 17 grains with similar ages. The Lisburne Hills Sandstones yielded 4 and

a.



b.

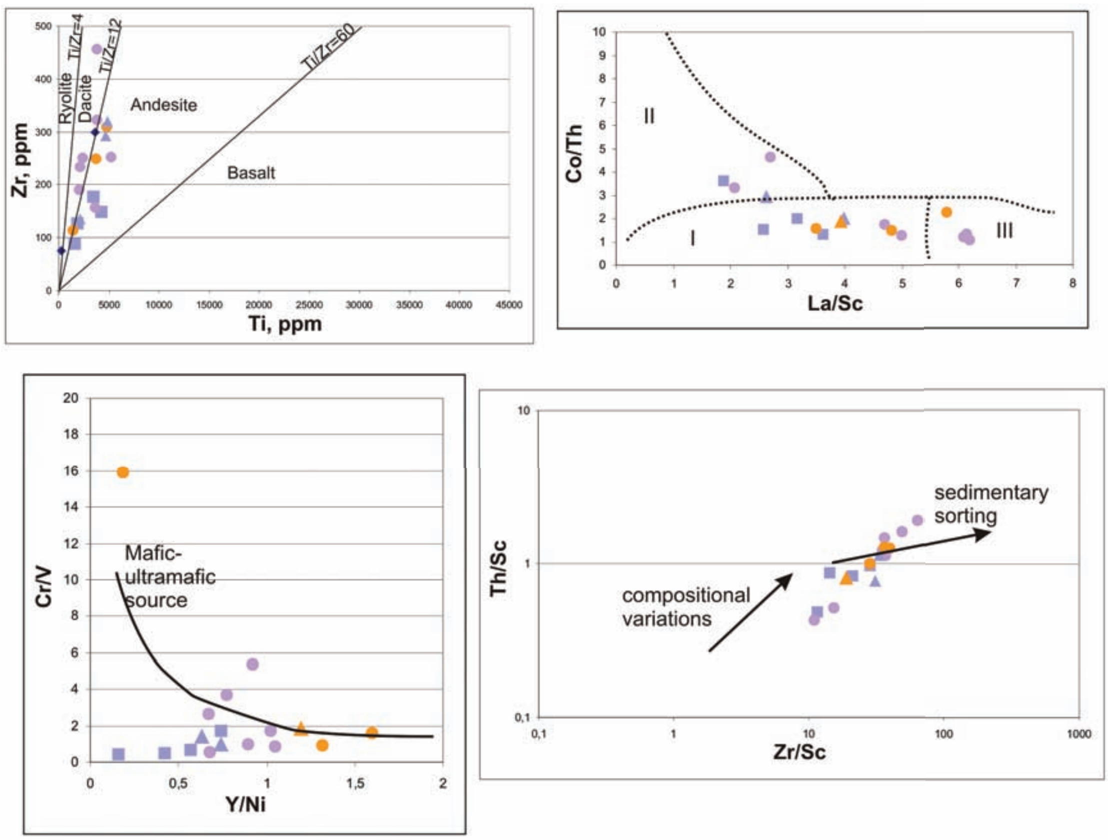


Fig. 17a. Diagrams illustrating the compositions of assumed provenances for Triassic deposits of the Anyui–Chukotka fold belt, diagrams by Roser and Korsch (1989), McLennan (1988), McLennan et al., (1993).For legend, see Figure 16. **17b.** Diagrams illustrating the compositions of assumed provenances for Triassic deposits of the Verkhoyansk–Kolyma fold belt. For legend, see Figure 16.

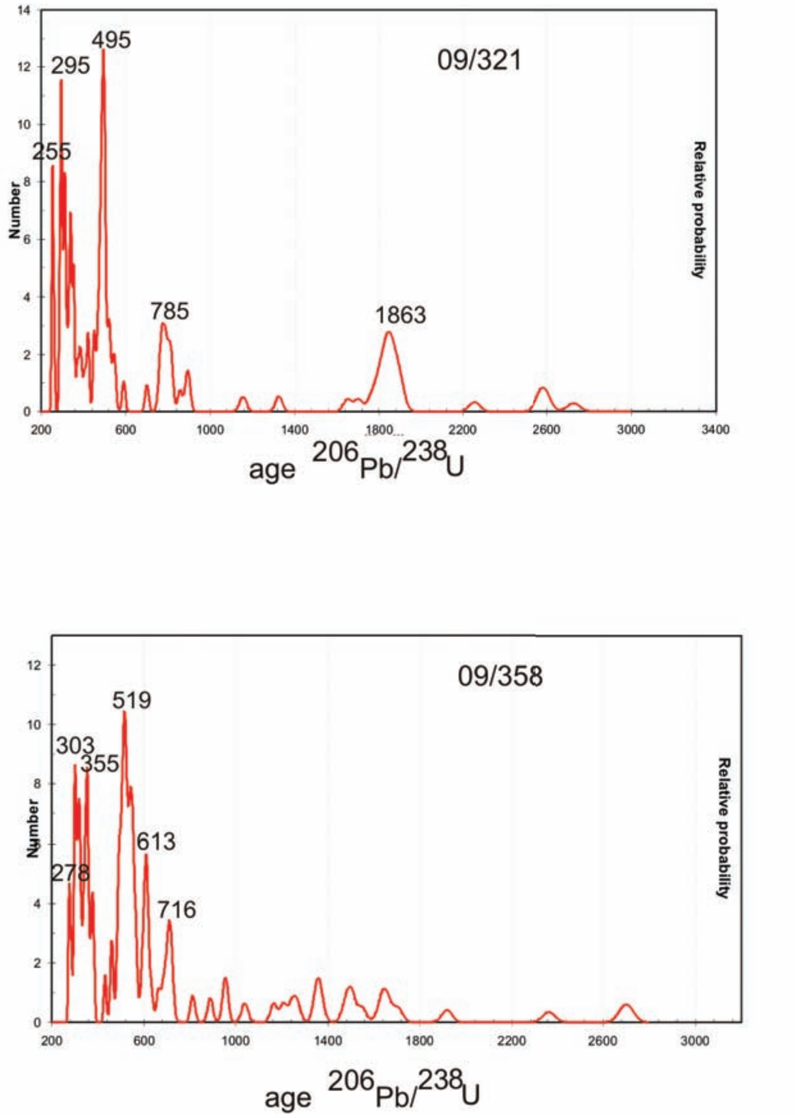


Fig. 18. Zircon populations from the Triassic sandy rocks of eastern Chukotka, samples 09/321 and 09/358. The positions of samples and zircon ages are shown in Tables 2 and 3, respectively.

11 grains with similar ages. Thus, the sandstones of Alaska and Chukotka are close to each other by this parameter.

The Sm-Nd isotopic system of sandstone samples was studied in the Institute of Geology and Geochronology of Precambrian. The Nd isotopic system is widely used in recent studies of sedimentary rocks. It is assumed that the chemical fractionation of Sm and Nd occurs mostly during differentiation of mantle material and formation of the continental crust and that these elements avoid fractionation during sedimentation and diagenesis (Taylor and McLennan, 1988). For sediments, the Nd model age offers an opportunity to determine the crust formation age of the provenance. The samples from the Verkhoyansk region imply erosion of the old continental crust with the εNd varying from -5 to -20 (Fig. 19). In Chukotka rocks, the content of eroded juvenile material is slightly higher; therefore, they occupy the higher position in the diagram. Consequently, erosion in the Chukotka provenance involved an ancient orogen with relicts of the oceanic crust. The Sm–Nd ages of zircons range from 1033 to 2297 and from 1038 to 1785 Ma for sandstones from the Verkhoyansk and Chukotka regions, respectively (Table 4).

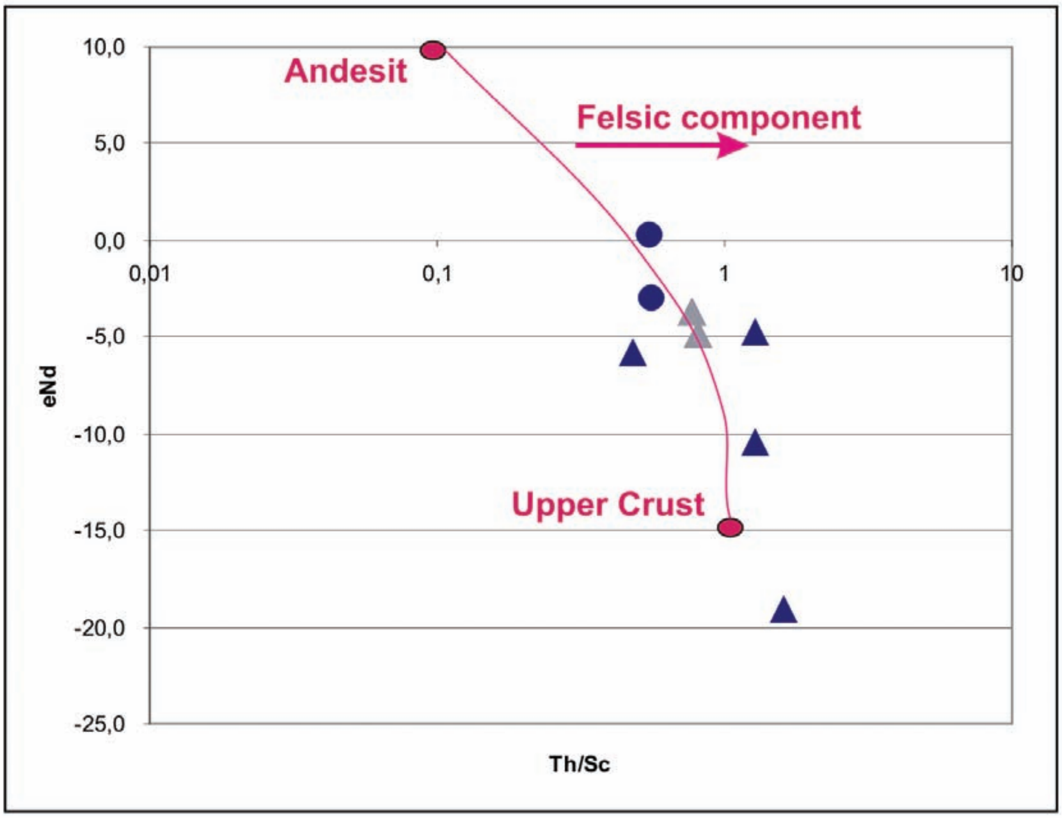


Fig. 19. eNd – Th/Sc systematic in the Permian-Triassic rocks of the southern (dark triangles) and western (gray triangles) Verkhoyansk region. Circles designate Triassic rocks of Chukotka.

STRUCTURAL STYLE

Collisional deformation in the West Verkhoyansk region began in Late Jurassic time and was most active during Early Cretaceous. In the Chukotka fold belt the main phase of collisional deformation took place at the end of Early Cretaceous (Hauterivian-Barremian). It is notable that the well-known Tithonian-Neocomian clastic sequence of Myrgovaam/Rauchua area of Chukotka is traditionally regarded as synorogenic/syncollisional (Bondarenko et al., 2003; Miller et al., 2008, and references therein). Nevertheless the unit still lacks any identified intra-formational unconformities or evidence of synsedimentary contractional deformation, although the some slump folds were described. It means that strictly speaking we do not have enough data to state that the deposition of Tithonian-Neocomian clastic sequence took place in a compressional collision-related setting. Nevertheless the earlier (pre-Neocomian) stage of contraction (?) certainly took place and caused the deformation of Triassic strata (in Early Jurassic?) and general uplift of the entire area (Tuchkova et al., 2007). The latter in turn caused very limited occurrence of Lower Jurassic and total absence of Middle Jurassic sequences. Another principal difference between these two regions is that the main collisional stage in Verkhoyansk area lasted significantly longer (up to Late Cretaceous) than those of Chukotka (was pretty much over prior Aptian). It is also notable that collisional deformations in the South Verkhoyansk region was completed much earlier, before Tithonian-Neocomian time (Prokopiev and Deikunenko, 2001). The predominant west-vergent fold-and-thrust structural pattern of West Verkhoyansk region is cut by post-kinematic granite plutons of Main Batholith Belt of and Northern Batholith Belt with 40Ar/39Ar age of 160-134 Ma (Oxfordian-Valanginian) and 127-120 Ma (Barremian-Aptian) respectively (Layer et al., 2001; Prokopiev and Deikunenko, 2001). In general the age of deformation becomes younger westward, established by post-kinematic granite

Table 3. Sample data for sandstones analyzed for detrital zircons

Sample number	Area	Latitude	Longitude	Age
09/321	Eastern Chukotka	66^{o} 41 53.6	W176^{o}43 40.9	Upper Triassic
09/358	Eastern Chukotka	67^{o}09 27.6	W178^{o}08 29.5	Lower-Middle Triassic

Table 4. Interpreted zircon ages. Ages are in Ma.

Lukovaya mountains Sample 09/321		Ploskaya River Sample 09/358	
Used Age±2σ			
09-321-01	252,33±6,79	09-358-01	275,22±7,26
09-321-02	253,61±7,09	09-358-02	278,17±7,39
09-321-03	254,73±7,05	09-358-03	285,48±7,62
09-321-04	257,25±7,87	09-358-04	298,64±8,24
09-321-05	262,12±7,77	09-358-05	298,92±7,74
09-321-06	286,63±7,52	09-358-06	302,03±8,00
09-321-07	292,17±7,93	09-358-07	303,97±8,18
09-321-08a	293,55±7,80	09-358-08	307,00±8,17
09-321-08b	294,26±7,86	09-358-09	312,18±8,75
09-321-09	294,91±7,80	09-358-10	314,96±8,46
09-321-10	297,51±7,97	09-358-11	318,43±8,41
09-321-11	297,99±7,72	09-358-12	320,18±8,51
09-321-12	303,47±8,16	09-358-13	324,47±8,87
09-321-13	308,65±8,29	09-358-14	327,00±8,97
09-321-14	310,89±8,26	09-358-15	335,65±8,82
09-321-15	311,49±8,26	09-358-16	342,74±9,35
09-321-16	314,57±8,24	09-358-17	343,72±9,29
09-321-17	316,89±8,52	09-358-18	348,67±9,54
09-321-18	323,86±8,58	09-358-19	353,81±9,81
09-321-19	331,5±8,708	09-358-20	354,24±9,78
09-321-20	337,16±8,86	09-358-21	355,79±9,80
09-321-21	339,78±9,04	09-358-22	355,87±9,29
09-321-22	339,92±9,16	09-358-23	365,33±9,99
09-321-23	343,50±9,07	09-358-24	374,79±10,19
09-321-24	351,94±9,13	09-358-25	377,73±10,09
09-321-25	354,77±9,67	09-358-26	382,99±9,99
09-321-26	355,66±9,60	09-358-27	432,23±11,27
09-321-27	371,38±9,89	09-358-28	459,25±12,00
09-321-28	382,44±10,00	09-358-29	463,74±12,46
09-321-29	391,36±10,90	09-358-30	485,65±13,11
09-321-30	406,56±12,00	09-358-31	491,94±12,54
09-321-31	420,67±11,9	09-358-32	492,05±12,79
09-321-32	424,18±11,28	09-358-33	497,69±13,26
09-321-33	450,95±11,95	09-358-34	499,38±12,85
09-321-34	452,24±11,92	09-358-35	504,90±13,02
09-321-35	466,23±12,00	09-358-36	508,34±13,00
09-321-36	471,55±12,47	09-358-37	509,82±12,99
09-321-37	479,61±12,37	09-358-38	513,65±13,71
09-321-38	480,44±12,43	09-358-39	514,79±13,81
09-321-39	482,34±12,59	09-358-40	515,80±13,29
09-321-40	483,49±12,58	09-358-41	518,23±13,35
09-321-41	487,96±12,83	09-358-42	518,35±13,39
09-321-42	491,67±12,50	09-358-43	521,65±13,33
09-321-43	493,16±13,04	09-358-44	526,01±13,72
09-321-44	493,34±12,94	09-358-45	526,73±13,41
09-321-45	494,40±13,01	09-358-46	528,93±13,79
09-321-46	495,12±13,02	09-358-47	534,99±13,65
09-321-47	495,20±13,37	09-358-48	539,13±14,12
09-321-48	499,78±13,19	09-358-49	540,12±13,80
09-321-49	500,16±13,12	09-358-50	543,23±14,00
09-321-50	501,30±13,34	09-358-51	545,05±14,73
09-321-51	501,84±13,02	09-358-52	550,63±14,86
09-321-52	503,81±13,10	09-358-53	551,78±14,79
09-321-53	518,69±13,53	09-358-54	553,38±15,01
09-321-54	521,19±13,67	09-358-55	555,00±15,76
09-321-55	527,52±13,99	09-358-56	565,95±14,42
09-321-56	542,26±14,10	09-358-57	566,46±15,17
09-321-57	550,01±14,69	09-358-58	593,33±15,72
09-321-58	591,87±15,50	09-358-59	603,10±16,29
09-321-59	701,59±17,73	09-358-60	604,39±23,70
09-321-60	762,61±19,82	09-358-61	609,45±15,35
09-321-61	771,31±20,67	09-358-62	612,63±17,08
09-321-62	773,25±19,73	09-358-63	614,07±15,62
09-321-63	783,22±23,47	09-358-64	615,72±16,24
09-321-64	790,44±20,16	09-358-65	632,76±16,85
09-321-65	790,68±20,63	09-358-66	663,96±16,94
09-321-66	806,76±20,68	09-358-67	684,03±18,18
09-321-67	813,98±20,86	09-358-68	697,20±17,71
09-321-68	816,93±20,68	09-358-69	707,30±17,77
09-321-69	859,08±22,08	09-358-70	712,93±17,98
09-321-70	893,28±22,10	09-358-71	715,65±18,07
09-321-71	896,84±23,15	09-358-72	725,01±18,32
09-321-72	1785,97±42,63	09-358-73	813,26±20,52
09-321-73	1827,73±43,67	09-358-74	889,69±22,18
09-321-74	1841,32±44,38	09-358-75	953,38±23,69
09-321-75	1850,11±42,76	09-358-76	957,14±23,70
09-321-76	1858,55±42.56	09-358-77	1052,68±76,06
09-321-77	1863,32±44,56	09-358-78	1196,20±44,81
09-321-78	1863,36±45,72	09-358-79	1241,42±47,65
09-321-79	1868,24±40,97	09-358-80	1296,59±52,02
09-321-80	1871,57±46,21	09-358-81	1302,27±46,09
09-321-81	1879,76±44,89	09-358-82	1319,81±45,55
09-321-82	1885,36±43,96	09-358-83	1351,16±46,19
09-321-83	1889,77±68,34	09-358-84	1453,72±47,51
09-321-84	1891,58±43,27	09-358-85	1489,24±55,47
09-321-85	1897,15±50,53	09-358-86	1524,98±46,93
09-321-86	1961,13±45,66	09-358-87	1547,96±46,59
09-321-87	1982,78±42,15	09-358-88	1653,46±42,63
09-321-88	2025,60±39,35	09-358-89	1687,73±61,75
09-321-89	2366,22±42,46	09-358-90	1696,75±42,59
09-321-90	2576,94±40,17	09-358-91	1703,02±40,96
09-321-91	2585,71±65,94	09-358-92	1852,75±44,13
09-321-92	2601,71±40,78	09-358-93	1855,34±45,34
09-321-93	2615,60±40,53	09-358-94	2584,56±42,76
09-321-94	2846,59±39,60	09-358-95	2660,44±39,28
09-321-95	3593,07±60,22	09-358-96	2698,26±36,18

plutons dating from 132 Ma (Hauterivian) on the east to 98 Ma (Cenomanian) on the west (Prokopiev and Deikunenko, 2001; Layer et al., 2001). On the western margin of the Verkhoyansk belt the youngest rocks involved in contractional deformation are Cenomanian and Turonian (100-89 Ma) (Khudoley and Prokopiev, 2007). Post-collisional (undeformed) granite plutons of Chukotka were recently dated by U-Pb (SHRIMP) as Aptian-Albian, i.e. ~ 117-108 Ma (Katkov et al., 2007; Miller et al., 2009). These ages are in a better agreement with those of the Northern Batholith Belt.

The general structural style of the Verkhoyansk region is a fold-and-thrust belt with thin-skinned tectonics. It was also noted that in the outer (west) zones thrust tectonics predominates whereas in the inner (east) the open folds are more common (e.g., Parfenov et al., 1995; Prokopiev and Deikunenko, 2001; Khudoley and Prokopiev, 2007). The recent application of the critical wedge model to the Verkhoyansk fold-and-thrust belt led to the conclusion that inner and outer zones of the belt corresponds to two different thrust wedges instead of single one (Khudoley and Prokopiev, 2007). The boundary between these two wedges was interpreted by the cited authors as the eastern limit of North Asian cratonic basement. The authors also proposed that structural and stratigraphic peculiarities of the inner fold belt (likely underlain by blocks with transitional continental crust separated by rifted basins) require a basal detachment related to salt and evaporate deposits of Middle and Upper Devonian(?).

The tectonic basement of the Chukotka fold belt is not exposed over most of the area and the number and quality of published deep seismic lines is extremely poor. So we do not have enough data to understand whether we have a regional predominance of thick-skinned or thin-skinned tectonics in Chukotka. On the other hand thick-skinned tectonics is identified on Wrangel Island where the metamorphic basement of Paleozoic-Triassic sedimentary cover (Neoproterozoic Wrangel complex) is certainly involved in the thrust and fold deformation (e.g. Kos’ko et al., 1993; 2003). Nevertheless the majority of the thrusts and folds (up to isoclinal and recumbent) of mainly northern and east-northeastern vergence were identified and mapped for the onshore Chukotka fold belt, including Wrangel Island (Sokolov et al., 2002; 2009; Kos’ko et al., 1993; 2003). Recently some seismic lines demonstrated the occurrence of low-angle north-vergent thrust faults within the Late Mesozoic tectonic basement of the southern part of Russian Chukchi Sea (Verzhbitsky et al., 2008; 2010).

Imbricate thrust fans normally characterize the frontal ranges of the Verkhoyansk fold-and-thrust belt (e.g., Parfenov et al., 1995; Prokopiev and Deikunenko, 2001; Khudoley and Prokopiev, 2007), whereas the Chukotkan deformation front of (revealed by offshore seismic only) demonstrate transpressional (pop-ups, positive flower-like) structural pattern (Verzhbitsky et al., 2008; Drachev et al., 2001; Drachev, 2011).

DISCUSSION: CORRELATION OF SEDIMENTOLOGIC AND TECTONIC EVENTS

Typical passive margins are characterized by rift-related volcanism and thick sedimentary successions consisting of material transported by major rivers and/or carbonates. Passive margins usually occupy wide areas with similar sedimentary histories, and significant stratigraphic unconformities and/or lithological complexes are traceable throughout the wide area related to a continental margin.

The Permian–Triassic sedimentary basins of the Verkhoyansk and Chukotka regions were formed on passive margins (Til’man, 1980; Parfenov, 1984; Zonenshain et al., 1990; Parfenov et al., 1993; Nokleberg, 1994). For convenience in comparison between geological events, the tectono-stratigraphic units of both regions are correlated with units of the North America scale: Ellesmerian, Beaufortian, and Brookian megasequences (Bird et al., 2001).

As follows from published data and that presented here, the sedimentary and tectonic evolution of the Ellesmerian and Beaufortian stages in the Chukotka and Verkhoyansk basins are different. The sections of the Chukotka passive margin are characterized by two major unconformities at the base of the Anyui Complex (Triassic) and the Upper Jurassic sequences (Figs. 20, 21). The Middle Jurassic deposits are missing from the region under consideration, while thin Lower Jurassic strata are developed only in the Rauchua River basin. The total thickness of the Triassic section is approximately 4–5 km.

On the Siberian passive margin, the Verkhoyansk complex forms a continuous Lower Carboniferous–Jurassic section 14–16 km thick in total. Its Permian–Triassic part constitutes approximately 7 km (Khudoley and Prokopiev, 2007).

The Triassic section in both fold belts is characterized by the regressive structures implying general shoaling of the sea basin up to deposition of shallow-water–shelf and terrestrial sediments in the Chukotka and Verkhoyansk basins, respectively (Figs. 9, 13).

The river systems that controlled the influx of clastic material in both basins demonstrate different delta structures. In the Chukotka basin, the deltaic system may be attributed to fine-grained deltas (Nichols, 2009). Such deltas are characterized by a mixed feeding mode and accumulation of fine-grained sediments in their frontal parts with development of small mouth sand bars probably grading into slope sediments and turbidites. In the Verkhoyansk basin, the delta belonged to the coarse-grained type (Nichols, 2009). Coarse-grained deltas are fed by solid bottom material and characterized by a proximal mouth gravelly bar. The distal mouth

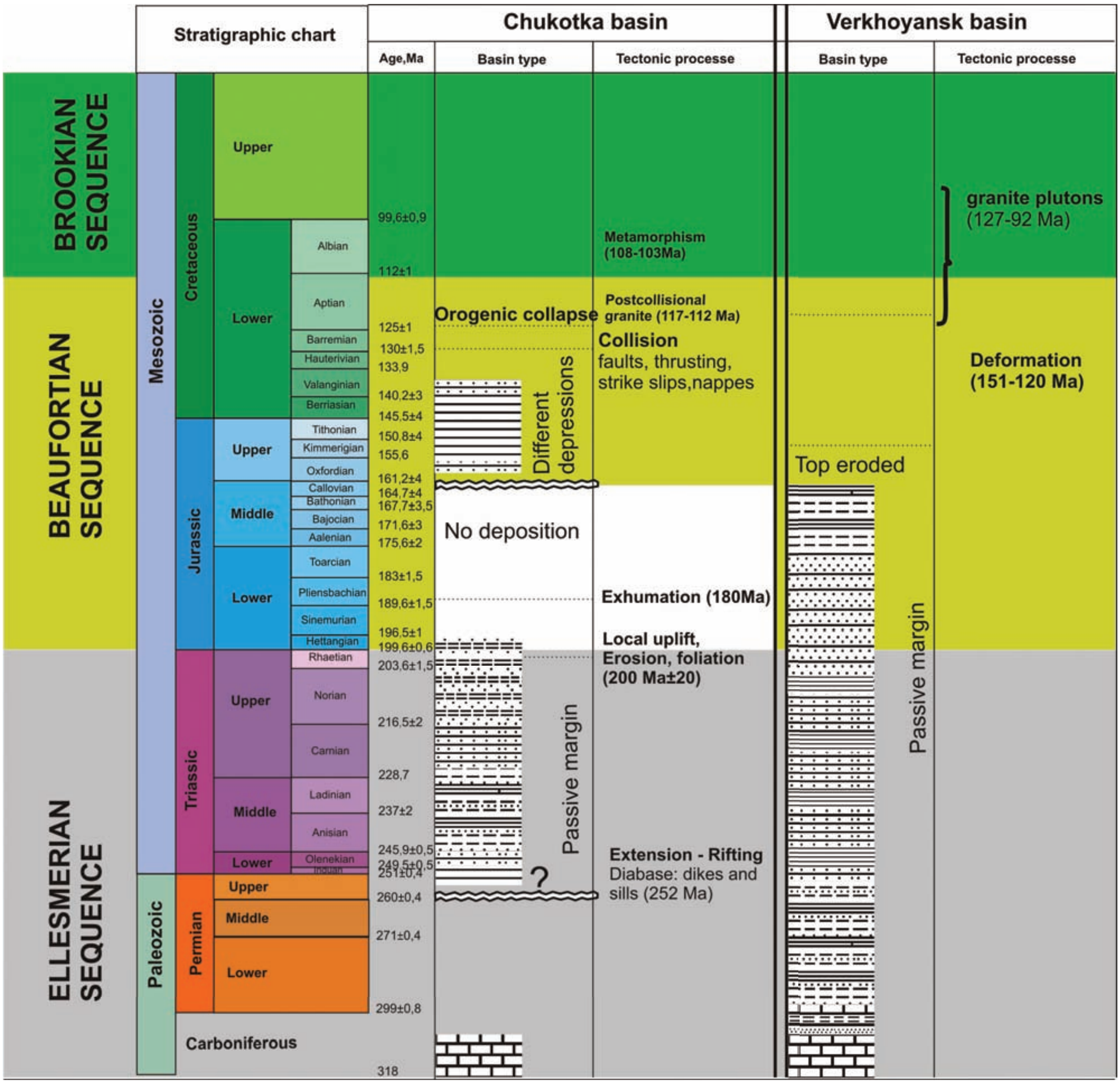


Fig. 20. Correlation between sedimentological and tectonic events in the Verkhoyansk–Kolyma and Anyui–Chukotka fold belts.

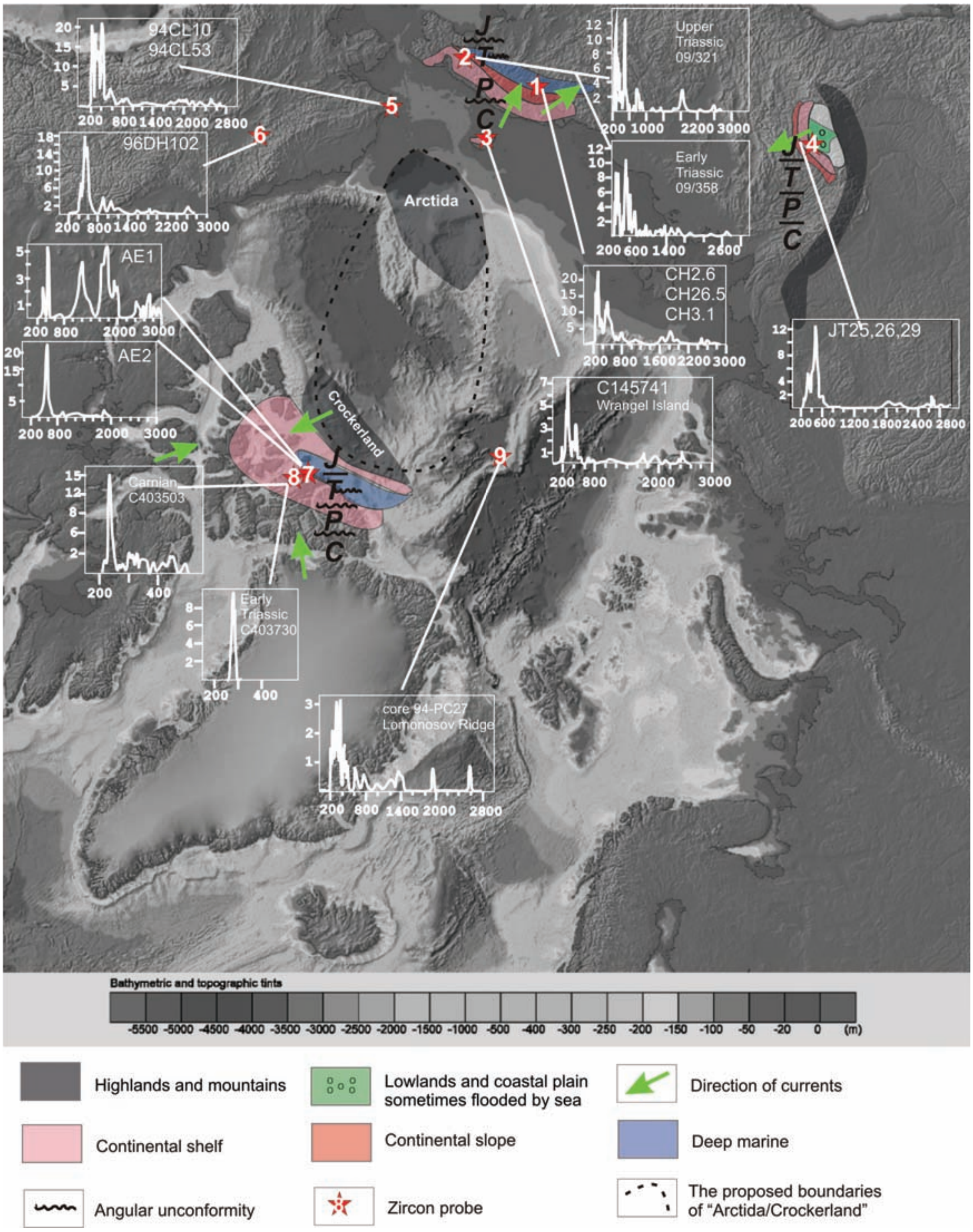


Fig. 21. The schematic position of paleogeographic zones in the present-day geography of the Arctic region. The positions of deltaic and prodelatic systems are consistent with the directions of the clastic material transport. It is seen that the material transport for the Permian-Triassic deposits of the Verkhoyansk and Chukotka regions was characterized by almost opposite directions. The dashed line shows the contour of the hypothetical microcontinent (Arctida?, Crockerland?). Asterisks with numbers designate positions of samples with detrital zircons discussed in the text.

(1) Western Chukotka terrane, Upper Triassic sandstones, cited from Miller et al., 2006;
(2) Chaun terrane, Lower and Upper Triassic sandstones discussed in this work;
(3) Wrangel Island, Upper Triassic sandstones, cited from Miller et al., 2006.
(4) Verkhoyansk terrane, Permian and Triassic sandstones, cited from Miller et al., 2006, Prokopiev et al., 2008.
(5) Cape Lisburne, Two samples, data combined, cited from Miller et al., 2006.
(6) Sadlerochit Mts, Eastern Alaska: Ivashak sandstones, cited from Miller et al., 2006.
(7) Arctic Alaska, Canada, Sverdrup basin, cited from Miller et al., 2006.
(8) Arctic Alaska, Canada, Sverdrup basin, cited from Omma et al., 2010.
(9) Lomonosov Ridge, Grantz et al., 2001, cited from Miller et al., 2006.

bar and delta front are composed of sand material, and the muddy prodeltaic zone is narrow.

The facies analysis reveals that the Chukotka and Verkhoyansk Triassic basins deepened in opposite directions. In the Chukotka basin, sediments transformed from shallow- to deepwater varieties and the shelf zone gradually prograded from the north (northeast) southward (southwestward). The section thicknesses increase in the same direction (Fig. 5). The distal facies of Upper Triassic turbidites are known from the South Anyui suture (Sokolov et al., 2002). The eastern Lower Triassic sections (locality 4 in Figure 3) exhibit the significantly reduced thickness and imply coastal –marine depositional environments accompanied by volcanism (Ledneva et al., 2011).

In the Verkhoyansk basin, shallow-water facies are replaced by deepwater sediments in the SW–NE direction (Figs. 13, 21) and distal turbidite facies are documented in the Kular–Nera terrane (Kossovskaya et al., 1960; Parfenov, 1984; Yapaskurt, 1992; Prokopiev, Khudoley, 2007).

The analysis of paleogeographic and geochemical data provides grounds for the assumption that the provenance of the Chukotka basin was characterized by a low hilly topography without high mountains. The Triassic was marked by enhanced weathering, which is evident from the CIA trend close to the ideal one (Tuchkova et al., 2009). Hence, clastic material was subjected to weathering immediately in the provenance, not only during its mixing and transport. This resulted in the supply to the sedimentation basin of sediments with the average weighted composition. The compositional similarity between Triassic sandstones and the averaged crust as well as almost complete lack of conglomerates confirms this assumption.

Quite different Permian and Triassic paleogeographic settings are reconstructed for the Verkhoyansk basin. In the south and west the basin was surrounded by relatively high mountains which graded northward into a spacious plain with coal-bearing deposits. Numerous rivers and creeks eroded complexes with variable lithology, while no weathering occurred in the provenance, which is supported by CIA trends (Fig. 17a).

The geochemical evolution of clastic material constituting Triassic rocks of the Verkhoyansk and Anyui complexes demonstrate different trends. The sandstones of the Chukotka basin reflect the reduced influence of basic rocks, mature composition of sedimentary material, and increased role of the quartz constituent. In the Verkhoyansk basin, the influence of basic rocks becomes notable in the Upper Triassic sandstones, while their Lower Triassic and Permian counterparts are mostly characterized by quartzose composition of clastic material. The distal sandstones demonstrate the significant contribution of granites.

The assumption of the “trap provenance” requires close relations between Chukotka and Siberia. At the same time, geochemical data and composition of rock clasts indicate no influence of basic and intermediate rocks on the Carnian and Norian deposits of Chukotka. The absence of these relations in the Late Triassic is difficult to explain taking into consideration development of large river systems and continuous sedimentary succession. There are no indications of Chukotka moving or of tectonic reorganizations in the assumed provenance during the Triassic. At the same time, the typical Verkhoyansk passive margin demonstrates the opposite geochemical trend with the increased role of mafic clastic material in the Late Triassic and substantial influence of acid material in Permian and Lower Triassic deposits (Fig. 17b). Diagrams of the REE distribution constructed for both regions point to depositional environments typical of passive margins. Nevertheless, different trends of changes in the composition of sandstones in the Permian–Upper Triassic succession are notable; i.e., they point to different passive margins, and correspondingly, different provenances.

The age of detrital zircons provides important information on provenances. Despite intense Permian–Triassic trap volcanism on the Siberian Platform, no indications of their erosion are revealed in detrital zircons of the Verkhoyansk complex (Miller et al., 2006; Prokopiev et al., 2008), although the Upper Permian and Lower Triassic sections of the southern Verkhoyansk region include volcanogenic–sedimentary rocks and abundant basic pyroclastic material (Prokopiev and Ivensen, 2008). The population of detrital zircons with the peak at 288 Ma corresponds to erosion of the Angara–Vitim batholith. The main peak at 488 Ma points to the increased role of clastic material from the Altai–

Sayany region. It is also conceivable that clastic material was transported from the Suntar and Yakutsk uplifts, Aldan Shield (?) (2300–2800 Ma), northern Transbaikal and eastern Sayany regions (1863 Ma) (Kossovskaya, 1960; Prokopiev et al., 2007).

Unfortunately, it is impossible to correlate zircon age peaks and assumed provenances for the Chukotka continental margin. This is primarily explained by the underwater position of its "northern province." Among Upper Triassic detrital zircons of Chukotka and Wrangel Island, is the remarkable Permian–Triassic population (235–265 Ma), which provides grounds for considering them as originating from the Siberian traps and assuming a westerly position for Chukotka near the Urals, Taimyr, and Siberia (Miller et al., 2006). Indeed, some displacement of Chukotka in an easterly direction in response to the opening of the Eurasia Basin and rifting on the Laptev Sea shelf cannot be ruled out (Drachev et al., 2003). In addition, some displacement could be determined by dextral syncollisional shifts along strike-slip faults established in the South Anyui fold system, a result of from the oblique subduction of the Chukotka microcontinent (Sokolov et al., 2002, 2009). At the same time, the amplitude of such shifts cannot explain significant near-latitudinal AACM displacements.

Coeval zircon population dated at 220–265 Ma is known from the Upper Triassic Lisburne Hills Sandstones (Miller et al., 2006). Nevertheless, taking into consideration the shelf affinity of these sandstones, it is impossible to assume an origin for the zircon population in question from the Urals, Taimyr, or Siberia provenances.

The zircon populations with ages of 750–1000 and 1000–1300 Ma from the Triassic sandstones of Chukotka imply erosion of an ancient metamorphic complex. The lack of these populations, except several grains in sandstones (samples JT 26, JT 29) of the Verkhoyansk region (Miller et al., 2006) points to another, not "Siberian" source for the sandstones of Chukotka.

According to (Miller et al., 2006), the Triassic sandstones of the Sverdrup basin yielded 20 and 37 zircon grains aged in the interval of 959–1700 Ma. The Lower Triassic sandstones provided the population dated back to 265–290 Ma (19 grains), Mesoproterozoic zircons with ages of 959–1206 Ma (eight grains) and 1356–1497 Ma (12 grains), and single Archean grain (3100 Ma). The Paleozoic rock yielded a zircon population dated at 268–493 Ma, 34 grains with peaks at 302, 327, 348, and 447 Ma, and 21 Precambrian grains exhibiting no distinct peaks. The Proterozoic zircon population (900–1700 Ma) in sandstones of Chukotka, the Sverdrup basin, and Alaska point presumably to a single source in common. It is clear that neither Siberia nor Laurentia could serve as such a source.

The new data on Chukotka show that populations of detrital zircons from Chukotka, the Sverdrup basin, and Alaska, the Sadlerochit Mountains included, demonstrate greater similarity than it was previously thought. Consequently, it may be assumed that they originate from a single source.

The data on zircon ages of gabbro–dolerite magmatism in eastern Chukotka (252 Ma. Ledneva et al., 2011) and K–Ar ages obtained for sills and small intrusive bodies (Geodynamic, Magmatism, and Metallogeny…, 2006) in Lower Triassic deposits allow the local (Chukotka), not Siberian provenance to be assumed. The presence of products of synchronous magmatism and shallow-water facies in the Lower Triassic sequences (Fig. 8 and 9) confirm this assumption. At the same time, coeval zircons appear only in the Upper Triassic strata. It is conceivable that the young zircon population originates from intrusive, not volcanic rocks, which were subjected to erosion only in the Late Triassic.

In our opinion, the assumption of the local source with synchronous magmatism is consistent with the evolution of the petrological–mineralogical and geochemical compositions in the Anyui Complex of Chukotka. The Devonian zircon population (340–390 Ma) of Chukotka and Lisburne Hills may also originate from a local magmatic source, indications of which are established in metamorphic complexes of eastern Chukotka and Alaska (Natal'in, 1999; Amato, 2009).

For solving the problem of a northern "local" source of clastic material for Triassic deposits of the Chukotka basin, the available reconstructions should be taken into consideration. The existence of a large continental block in the central Arctic region was assumed in previous works: the Hyperborean Platform (Shatsky, 1935, 1963), the Ancient Arctida (Eardly, 1948). Zonenshain et al. (1990) substantiated the existence of the Arctida continent that resulted from Rodinia break-up (Vernikovsky and Vernikovskaya, 2001). In the present-day structure, fragments of Arctida basement are preserved along the periphery of the Arctic Ocean: Kara massif, northern Taimyr, Chukotka, Brooks Range, Wrangel Island, and others. According to subsequent studies (Kuznetsov et al., 2007; Vernikovsky and Vernikovskaya, 2001), the Arctida continent included also the Barentsia and Timanides. When investigating the provenances for sediments of the Sverdrup basin, Embry (1993, 2011) assumed existence of a northerly located, hypothetical, Crockerland continent. The Sverdrup basin was formed in response to rifting in the Carboniferous, which is consistent with the Lower Ellesmere Sequence and onset of the formation of the Verkhoyansk and Anyui complexes (Fig. 21).

Figure 21 illustrates the present-day positions of the Chukotka, Verkhoyansk, and Sverdrup basins and their provenances. The sediments of the Chukotka basin and its paleogeographic zones extend now in approximately east-west direction (Fig. 8). In contrast, the paleogeographic zones of the Verkhoyansk basin are oriented in almost north-south directions (Fig. 13). The last basins are separated by major tectonic elements: SAS and cratonic and island-arc terranes of the Kolyma loop.

Two important inferences follow from this geodynamic situation. First, the facies distribution and clastic material transport for the Sverdrup and Chukotka basins point to the existence of the continental provenance north of them: Arctida (Zonenshain et al., 1990) or Crockerland (Embry, 1990, 1992; Anfinson et al., 2012). This provenance is characterized by the Mesoproterozoic and Permian–Triassic zircon populations with ages of 900–1700 and 236–263 Ma, respectively. The Arctida–Crockerland continent was subjected to most intense erosion in the post-Jurassic period after structural reorganization, which is evident from the appearance of significant peaks (at 1900–1950 Ma and single grains dated back to 2200, 2400, 2600, and 2800 Ma) in zircons from the Lower Cretaceous rocks of Chukotka (Miller et al., 2006). The ancient zircon populations (978–1978 Ma, Omma et al., 2010) appear also in Jurassic deposits of the Sverdrup basin.

Second, the displacement of Chukotka only along strike-slip faults toward Taimyr and the Urals provides no grounds for considering traps as a potential source for the Permian–Triassic zircon population (236–263 Ma). This requires also rotation of the Chukotka block by approximately 100–180º. In addition, the westward AACM displacement requires the opening of the oceanic basin in its rear part. No suture of the basin closed in the Late Cretaceous is recognizable in the present-day structure of eastern Alaska. If it is assumed that the Lisburne thrust represents such a structure then the Chukotka terrane along with the Seward Peninsula and Arctic Alaska terrane can be considered autonomous microcontinents (Grantz et al., 1990; Nockleberg et al., 1993). Such a scenario may be considered possible, when fragments of the oceanic crust are found along the Lisburne thrust.

Differences in sedimentary evolution of the Verkhoyansk and Chukotka basins are determined by their different tectonic histories. The formation of the Verkhoyansk passive margin was initiated in the Devonian (Til'man, 1980; Parfenov, 1984; Khudoley and Prokopiev, 2007). In the Chukotka basin, extension of the continental crust occurred at the Permian –Triassic transition determined by the replacement of carbonate sedimentation with a terrigenous one.

The structural patterns of the Verkhoyansk complex conform to thrust–wedge models with the western vergence of thrusts and folds. The age of deformation and intruded syncollisional granites becomes younger westward. In the east, granite plutons of the Main Batholith Belt are dated back to 135–160 Ma (40Ar/39Ar), although most plutons range in age from 136 to 144 Ma (Layer et al., 2001). The granite pluton closest to the frontal thrust yielded a 40Ar/39Ar age of 98 Ma. The folded and thrust structures of Chukotka exhibit the northern vergence (Sokolov et al., 2009; Sokolov, 2010). The Anyui complex is deformed into complex isoclinal and recumbent folds. The postcollisional granites are 115–117 in age (Katkov et al., 2007).

CONCLUSIONS

1. The comparison of sedimentary and tectonic events documented in the two regions under consideration reveals significant differences. The thick continuous section of the Verkhoyansk

complex differs from its thinner Anyui counterpart in Chukotka, which was formed during a shorter period.

2. In contrast to the Verkhoyansk region, the continental margin of Chukotka is devoid of Upper Carboniferous, Lower Permian, and Middle Jurassic deposits and its section encloses unconformities at the bases of the Anyui Complex and Upper Jurassic–Lower Cretaceous sequence.
3. The geochemical composition of sandstones from the Chukotka basin is characterized by the distinct maturation trend reflected in the lower influence of basic rocks and increased role of the quartzose constituent. For Permian–Triassic sediments of the Verkhoyansk basin an opposite geochemical trend is reported.
4. The analysis of detrital zircons reveals several similar coeval populations, though these belong to different provenances, in addition to differences in ancient populations. The compositions of provenances are shown to be different. For the Chukotka basin, the provenance was dominated by low- to medium-metamorphosed rock complexes; in the Early Triassic, the notable role belonged to basic–intermediate rocks. For the Verkhoyansk basin, dominant rocks in the provenance were represented by granitoids; beginning in the Late Triassic, they were added to by basic rocks.
5. New dates obtained for detrital zircons from the Chukotka basin are similar to those available for Alaska and the Sverdrup basin, which provides grounds for assuming a single provenance for them (Crockerland–Arctida microcontinent).

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research (project nos. 11-05-00074, 11-05-00787, 13-05-00943, 14-05-00031), 12-05-31432, project NSh-5177.2012.5, Department of Earth Sciences of RAS (program no. 10), and State contract № 01/14/20/11 and grant from St. Petersburg State University.

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