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Early–Middle Ordovician nappe tectonics of the junction between the Kokchetav HP-UHP metamorphic belt and the Stepnyak paleoisland arc (*northern Kazakhstan*)

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Abstract

The North Kokchetav tectonic zone is located between the Kokchetav HP-UHP metamorphic belt and the Stepnyak zone of Ordovician island arc and oceanic complexes. The Kokchetav zone is a collage of nappes (thrust sheets) that consist of basement gneiss and sedimentary rocks of the Kokchetav microcontinent, granite gneiss, mica schists with eclogite blocks, the Shchuch'e ophiolite, Middle Proterozoic felsic volcanics, and Arenigian siliceous-terrigenous sediments with olistostromes. The latter are of gravity-sliding origin and their clastic material includes quartz-muscovite and quartz-garnet-muscovite schists, gneiss, dolomite, and amphibolite. The sheet boundaries are marked by mylonite and Early Ordovician mica schists ($^{40}Ar/^{39}Ar$ ages of syntectonic muscovite are 489–469 Ma). The North Kokchetav collage of compositionally diverse thrust sheets can be interpreted as a collisional zone. According to geological evidence, tectonic activity in the zone lasted as late as the Middle Ordovician. Syncollisional thrusting in the North Kokchetav zone was coeval with the latest dynamic metamorphic event in the history of the Kokchetav belt. All events of retrograde metamorphism and exhumation of HP and UHP rocks in the belt have Cambrian ages, i.e., the rocks had been exhumed prior to the Early–Middle Ordovician collisions and the related orogeny.

Keywords: North Kokchetav tectonic zone; Kokchetav metamorphic belt; olistostrome; thrust sheet; high-pressure rocks; collision; exhumation; $^{40}Ar/^{39}Ar$ dating; Early Paleozoids of Kazakhstan.

Introduction

Complexes of high- and ultrahigh-pressure (HP and UHP) rocks metamorphosed in the fields of coesite and diamond stability have been most often interpreted as metamorphic terranes that have fault boundaries with deformed but unaltered sedimentary and igneous complexes (Chopin, 2003; Liou et al., 2004). The ultrahigh-pressure (UHP) terranes occupy a certain place in the structure of orogenic areas (Dobretsov, 2000) being common constituents of accretionary-collisional zones associated with subduction of continental crust. Eclogite-blueschist complexes of mainly ultramafic compositions mark subduction of oceanic crust with oceanic islands (e.g., Petrov et al., 2009), whereas eclogite-gneiss complexes dominated by felsic and sedimentary metamorphic rocks rather represent subduction of continents. Boundaries of UHP metamorphic terranes with unaltered or low-grade complexes are especially important objects as they can provide clues to the settings and time of tectonic juxtaposition.

The Kokchetav metamorphic Belt (KMB) is a typical UHP terrane within the Neoproterozoic–Early Paleozoic orogen of Northern Kazakhstan. The belt runs from west to east for abut 150 km being 10–15 or up to 30 km wide. KMB consists mainly of gneisses and schists that enclose eclogite, garnet amphibolite, and marble boudins, as well as less abundant garnet and spinel peridotite, pyrope-talc-phengite schists, carbonate-siliceous and garnet pyroxene rocks; exposures of UHP rocks are assigned to the Zerenda Group.

The belt structure and the petrology of diamond-bearing rocks in it have been largely studied (Claoue-Long et al., 1991; Dobretsov et al., 1998, 2006; Dobrzhinetskaya et al., 1994; Maruyama and Parkinson, 2000; Ota et al., 2000; Theunissen et al., 2000; etc.). Mineral parageneses from different parts of the belt, together with structural data (Theunissen et al., 2000; Sitnikova and Shatsky, 2009), characterize the belt as a collage

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of nappes (thrust sheets) and imbrices dissimilar in petrography of rocks and in their structural and metamorphic history (Dobretsov et al., 2006). The metamorphic belt originated as a consequence of the Cambrian subduction of the Kokchetav microcontinent and several exhumation events in the Cambrian–Early Ordovician.

According to recent geological and geochronological data, the Kokchetav microcontinent existed as an isolated continental block within the Paleoasian ocean in Late Precambrian and Cambrian time. Its continental crust had a structure similar to that of Precambrian cratons, with a granite gneiss basement overlain by carbonate-terrigenous sediments. The oldest basement complexes originated in the Paleoproterozoic (2.6–2.0 Ga), the crust consolidation completed by the Neoproterozoic (1.3–1.1 Ga), and was followed by deposition of the sedimentary cover (Shatagin et al., 2001). The sedimentary complexes include quartzite-schist and carbonate-terrigenous rocks of the Late Cambrian Ilekty Group (Goncharenko, 1974; Degtyarev et al., 1998; Lydka and Filatova, 1982). The lower section of the Group composed of black shale and dolomite marble has been distinguished as the carbonate-terrigenous Sharyk Formation (Goncharenko, 1974). The Group's upper part corresponds to the Kokchetav Formation of quartz-chlorite-sericite schists, quartzite, and metamorphic quartz sandstone. The age of the Sharyk Formation has biostratigraphic constraints from poorly preserved microphytoliths of the Late Precambrian *Osagia* Twench, *Vesicularites* Reitl., and *Volvatella* Nar. taxa (Kharlamov et al., 1971), as well as from columnar stromatolite identified (by M.E. Raaben) as typically Late Riphean (Late Precambrian) *Minjaria* ex. gr. *uralica* found in a sample of dolomite marble near Lyubotino Village. The same Late Precambrian age can be assumed for the Kokchetav Formation proceeding from geological data and from the absence of detrital zircon younger than 850 Ma (Letnikov et al., 2001; Rozen, 1972).

The Kokchetav belt borders Late Ordovician intrusions of the Zerenda complex in the south, which have partly eliminated older structures of the belt's southern margin. In the north there are Ordovician volcanic and sedimentary complexes of the Stepnyak zone. The latter has been viewed as an Early Ordovician island arc system (Peive and Mossakovskii, 1982; Zonenshain et al., 1990) deformed during collisional events. The Upper Arenigian–Caradocian island arc volcanics and flysch overlie Upper Cambrian–Lower Ordovician volcanic (Degtyarev et al., 2008) and volcanic-sedimentary rocks (Ivanov et al., 1988; Nikitin, 2002; Spiridonov et al. 1988). Paleotectonic reconstructions present the latter either as backarc basin complexes similar to their present counterparts in the western Pacific continental margin (Nikitin, 2002; Nikitin et al., 1990) or as complexes of primitive island arcs and oceanic islands (Spiridonov et al., 1988).

The junction between the Kokchetav belt and the Stepnyak zone is occupied by the North Kokchetav tectonic zone (NKTZ) that runs along the northern and eastern KMB periphery from the Chaglinka River west of Kokchetav city and continues eastward parallel to the Kylshakty Valley to Aleksandrovka Village and northeastward as far as Zhanatalap Village where it bends sharply to the south (Fig. 1). The North Kokchetav zone roughly corresponds to the Kokchetav fault zone which was distinguished in the course of 1:200,000 surveys, sheets N-42-XXVIII and N-42-XXIX (Babichev et al., 1968; Rozen and Bogoyavlenskaya, 1962; Zhukov and Rakhimbaev, 1964). In most regional studies, the complexes we distinguish within NKTZ have been assumed to be part of the Kokchetav Massif, specifically, its northeastern margin (Peive and Mossakovskii, 1982), but not part of the respective metamorphic belt (Dobretsov et al., 1998).

The North Kokchetav zone is a collage of thrust sheets that consist of sedimentary (quartz-sericite schists and dolomite of the Ilekty Group) and basement (granite gneiss with amphibolite lenses) complexes of the Kokchetav microcontinent, the Shchuch'e ophiolite complex (gabbro, gabbro-dolerite, basalt, serpentinite melange, and schists), Early Ordovician siliceous-terrigenous sediments with olistostromes, as well as late Precambrian basaltic andesite and rhyolite lavas and tuff interbedded with conglomerate and sandstone. The sheets have fault boundaries marked by quartz-chlorite-muscovite schists that occasionally contain garnet. Mica schists and mylonitic biotite gneiss host eclogite produced by HP retrograde metamorphism (Zhimulev et al., 2010). The sheets with HP rocks border those composed of igneous and sedimentary complexes that did not experience HP metamorphism. Therefore, the observed relations among rock complexes and the isotope ages of tectonites in fault zones bear signature of the time and settings of events responsible for the juxtaposition of subcrustal and upper crustal rocks. The structure, age, and formation history of the North Kokchetav zone lying between the Kokchetav metamorphic belt in the south and the Stepnyak low-grade volcanic-sedimentary complexes in the north have implications for the setting of late exhumation events in KMB.

All known HP and UHP metamorphic terranes are associated with collisional zones which are deformed collages of thrust sheets (Liou et al., 2004). The latter show up in the presence of olistostromes or syntectonic mixtite (Leonov, 1981). Olistostromes, though being well known among Neoproterozoic–Early Paleozoic rocks of Northern Kazahstan, have been never reported from NKTZ, except for their hypothetical occurrence near Zhanatalap Village (Abdulkabirova, 1987). Bulygo (1987) also mentioned breccias, boulders, and pebbles of gabbro, granite, and siliceous rocks existing as lenses among the Lower–Middle Ordovician Zhansui Formation of siliceous and fine-clastic terrigenous sediments in the Stepnyak zone along the northern border of the Kokchetav Massif. However, there has been no special study of the coarse clastic rocks.

We investigated those lenses and found them to be of syntectonic origin related to thrusting and to fit the features of olistostromes according to (Leonov, 1981).

The aim of this paper has been to provide a systematic overview of the NKTZ geology and tectonic setting, to estimate its age, and to characterize olistrostromes within it. Below we describe five sites in the zone (Fig. 1): Chaglinka, Zheilyau, Aleksandrovka, Borovoe, and Zhanatalap.

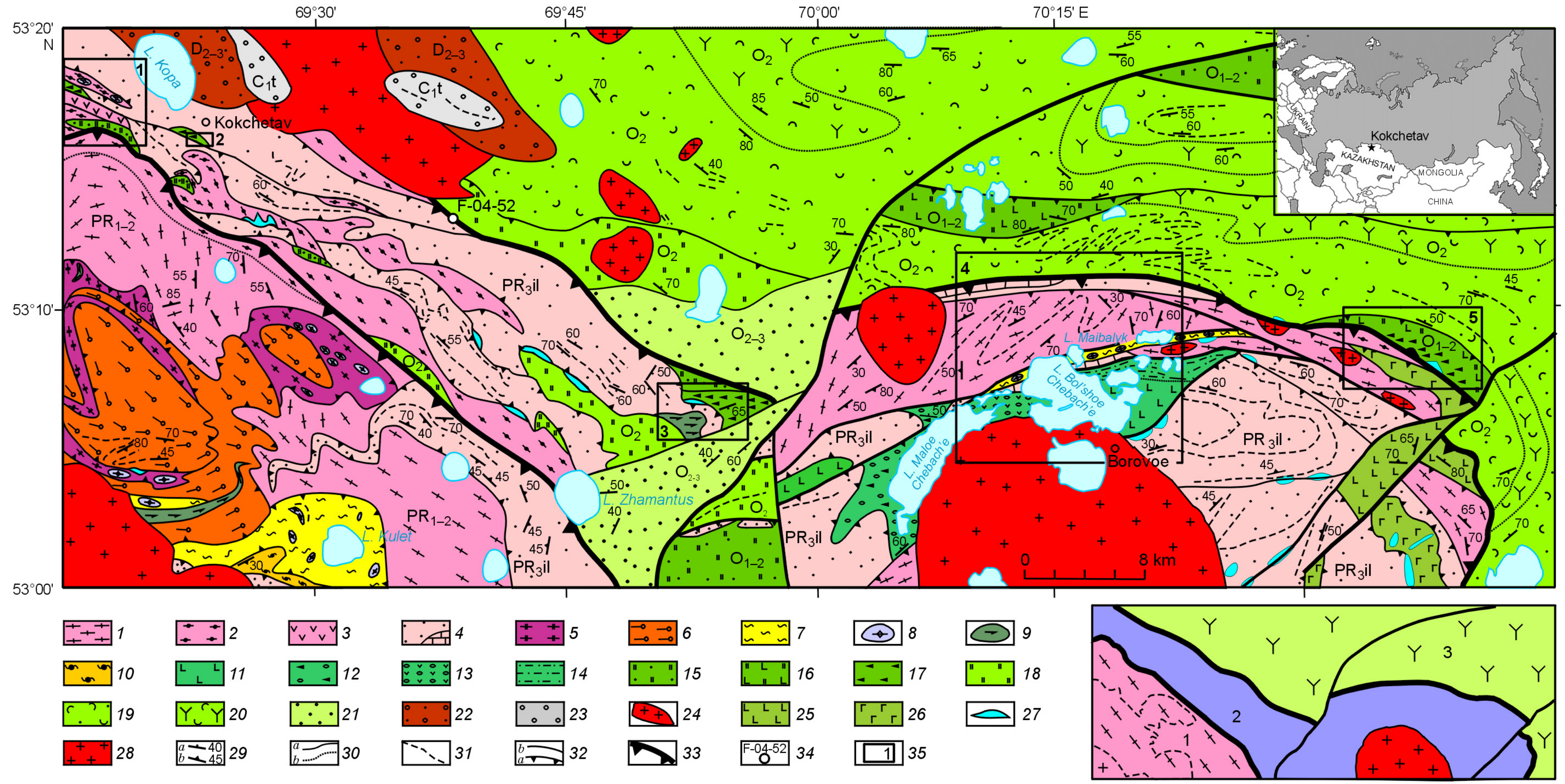

Fig. 1. Generalized geology of North Kokchetav tectonic zone. *1–4,* complexes of Kokchetav microcontinent: *1*, Early–Middle Proterozoic basement gneiss; *2*, mylonitized and blastomylonitized Proterozoic basement gneiss; *3*, Middle Proterozoic quartz-feldspar porphyry; *4*, Late Proterozoic Ilekty Group of quartz-sericite schists, metasandstone, and dolomite of sedimentary cover; *5–9*, rocks of Kokchetav metamorphic belt: gneiss with eclogite boudins (*5*), garnet-kyanite schists with boudins of garnet amphibolite (*6*), quartz-garnet-muscovite (phengite) schists with eclogite boudins (*7*), eclogite, large bodies and assemblages of bodies (*8*), amphibolite (*9*); *10*, andalusite-cordierite-biotite schists (Daulet Formation); *11–14*, rocks of pre-Ordovician island arc (?): greenstone basalt porphyry (*11*), bouldery conglomerate with enclosed blocks (*12*), andesitic aglomerate (*13*), mudstone, siltstone, sandstone (flysch) (*14*); *15–17*, Early–Middle Ordovician deposits: sandstone, silicified mudstone and siltstone, jaspers, and breccias (*15*), basalt, red siliceous siltstone, and jaspers (*16*), Arenigian olistostrome (*17*); *18–20*, Middle Ordovician deposits: gray siliceous shale and microquartzite (18), volcanic-sedimentary flysch (*19*), basaltic andesite and its tuff (*20*); *21*, Middle–Late Ordovician conglomerate and sandstone; *22*, Middle–Late Devonian red sandstone and conglomerate; *23*, Tournaisian gray sandstone, siltstone, and pinkish-gray limestone; *24*, Proterozoic granite; *25–27*, (Cambrian?) Shchuch'e ophiolite belt: basaltic porphyry (*25*), gabbro (*26*), serpentinite (27); 28, Paleozoic (O_3, S, D_1) granite; *29,* bedding (*a*) and schistosity (*b*); *30*, geological boundaries between units of different ages (*a*) and between bodies of different compositions within these units (*b*); *31*, exposed marker beds; *32*, thrusts (*a*) and other faults (*b*); *33*, NKTZ master thrust faults; *34*, sampling site of sample F-04-52 for Ar-Ar dating; *35*, sites discussed in text, with Arabic numerals standing for their names: 1, Chaglinka, 2, Zheilyau, 3, Aleksandrovka, 4, Borovoe, 5, Zhanatalap.

Inset in right-hand bottom corner is a sketch of main tectonic units (Arabic numerals): 1, Kokchetav microcontinent, 2, NKTZ, 3, Stepnyak zone. Dashed line is KMB boundary.

$^{40}Ar/^{39}Ar$ dating

We investigated the history of NKTZ using $^{40}Ar/^{39}Ar$ dating of muscovite from quartz-sericite schists of the Kokchetav Formation (Ilekty Group) and from mylonitized gneiss. Some dates were reported earlier (Dobretsov et al. 2005a), and those for samples F-04-30, F-04-31, F-04-52, and Zh-03-63 are new. The samples were analyzed at the Analytical Center of the Sobolev Institute of Geology and Mineralogy (F-04-30, F-04-31, F-04-52) and at Stanford University (Zh-03-63).

Muscovite aliquots (0.2–0.5 mm) from samples F-04-30, F-04-31, and F-04-52, together with monitor aliquots (MCA-11 N 129-88 biotite), were wrapped in aluminum foil, placed in fused silica ampoules, and sealed in vacuum. The MCA-11 biotite prepared in 1988 as a K/Ar standard sample was certified as an $^{40}Ar/^{39}Ar$ monitor against the international standards of Bern 4m muscovite and LP-6 biotite, and its total gas age was estimated as a calibrated mean to be 311.0 ± 1.5 Ma. The ampoules were irradiated in the cadmium-shielded carrier of a WW research reactor at Tomsk Technological Institute, at a neutron flux gradient within 0.5% sample size. The incremental heating experiment was performed in a quartz reactor with an external furnace. The ^{40}Ar blank (10 min at 1200 °C) did not exceed 5×10^{-10} ncm^3. Argon was purified with Ti- and ZrAl SAES getters. The Ar isotope composition was measured on a *Micromass* Noble gas 5400 mass spectrometer (UK), to uncertainty quoted in text, tables, and figures at the one-sigma level.

Sample Zh-03-63 was dated using about 1–2 mg pure (free from inclusions) muscovite with ~0.1–0.2 mm flakes, on a reactor at Oregon University, using rhyolite with a $^{40}Ar/^{39}Ar$ age 27.92 ± 0.17 Ma (USGS 85G003) for standard. The incremental heating procedure was performed at Stanford University, and Ar isotope composition was measured on a MAP 216 mass spectrometer (Tables 1 and 2).

Table 1. $^{40}Ar/^{39}Ar$ data for muscovite from rocks in western North Kokchetav tectonic zone

T, °C	^{40}Ar(STP)	$^{40}Ar/^{39}Ar$	± 1σ	$^{38}Ar/^{39}Ar$	± 1σ	$^{36}Ar/^{39}Ar$	± 1σ	Σ^{39}Ar, %	Age, Ma	± 1σ
F-04-30 muscovite, aliquot 42.7 mg, J = 0.003390 ± 0.000030										
500	$28.82 \times e^{-9}$	64.138	0.215	0.0487	0.0043	0.0302	0.0037	0.9	309.5	6.2
600	$90.01 \times e^{-9}$	88.333	0.155	0.0167	0.0009	0.0048	0.0014	3.1	465.9	4.2
700	$212.08 \times e^{-9}$	91.554	0.076	0.0152	0.0010	0.0038	0.0009	8.0	482.4	4.0
800	$729.47 \times e^{-9}$	91.396	0.048	0.0171	0.0002	0.0021	0.0001	24.7	484.0	3.8
850	$744.82 \times e^{-9}$	91.009	0.046	0.0160	0.0002	0.0006	0.0001	41.9	484.3	3.8
900	$432.16 \times e^{-9}$	90.992	0.047	0.0173	0.0002	0.0007	0.0002	51.9	484.1	3.8
950	$324.74 \times e^{-9}$	90.939	0.072	0.0167	0.0005	0.0023	0.0002	59.4	481.7	3.8
1030	$526.58 \times e^{-9}$	91.042	0.050	0.0172	0.0002	0.0008	0.0001	71.6	484.2	3.8
1080	$555.16 \times e^{-9}$	91.105	0.055	0.0165	0.0001	0.0006	0.0002	84.4	484.7	3.8
1130	$675.76 \times e^{-9}$	91.056	0.043	0.0161	0.0003	0.0001	0.0001	100.0	485.1	3.8
F-04-31 muscovite, aliquot 43.9 mg, J = 0.003354 ± 0.000030										
500	$48.71 \times e^{-9}$	58.031	0.066	0.0428	0.0015	0.0171	0.0017	2.4	295.0	3.6
600	$138.81 \times e^{-9}$	76.635	0.084	0.0195	0.0011	0.0032	0.0009	7.6	408.2	3.5
650	$136.73 \times e^{-9}$	78.973	0.097	0.0168	0.0014	0.0006	0.0006	12.5	423.1	3.5
700	$180.69 \times e^{-9}$	81.281	0.084	0.0184	0.0002	0.0039	0.0003	18.9	429.4	3.5
800	$669.65 \times e^{-9}$	87.765	0.038	0.0173	0.0004	0.0028	0.0002	40.7	461.7	3.7
850	$463.14 \times e^{-9}$	89.131	0.061	0.0168	0.0003	0.0007	0.0002	55.6	470.9	3.7
875	$249.92 \times e^{-9}$	89.085	0.079	0.0183	0.0005	0.0021	0.0004	63.6	468.7	3.8
900	$155.15 \times e^{-9}$	89.030	0.103	0.0195	0.0014	0.0026	0.0013	68.6	467.9	4.1
950	$174.59 \times e^{-9}$	88.747	0.065	0.0196	0.0005	0.0031	0.0009	74.2	465.9	3.9
1000	$273.81 \times e^{-9}$	89.285	0.056	0.0177	0.0006	0.0035	0.0006	82.9	467.7	3.8
1050	$443.28 \times e^{-9}$	90.339	0.077	0.0155	0.0006	0.0030	0.0008	97.0	473.4	3.9
1130	$90.99 \times e^{-9}$	85.996	0.213	0.0196	0.0015	0.0034	0.0015	100.0	452.5	4.2

(*continued on next page*)

Table 1 (*continued*)

T, °C	^{40}Ar(STP)	^{40}Ar/^{39}Ar	± 1σ	^{38}Ar/^{39}Ar	± 1σ	^{36}Ar/^{39}Ar	± 1σ	Σ^{39}Ar, %	Age, Ma	± 1σ
F-04-52 muscovite, aliquot 23.6 mg, J = 0.003208 ± 0.000027										
600	$71.80 \times e^{-9}$	80.812	0.118	0.0301	0.0018	0.0131	0.0014	3.4	398.0	3.6
700	$213.75 \times e^{-9}$	95.799	0.094	0.0180	0.0007	0.0041	0.0006	12.0	478.0	3.6
800	$436.07 \times e^{-9}$	95.841	0.073	0.0179	0.0004	0.0026	0.0003	29.6	480.2	3.6
850	$569.18 \times e^{-9}$	95.460	0.056	0.0173	0.0002	0.0006	0.0002	52.6	481.2	3.6
900	$450.83 \times e^{-9}$	95.586	0.057	0.0167	0.0003	0.0018	0.0005	70.8	480.2	3.6
950	$348.43 \times e^{-9}$	95.624	0.051	0.0175	0.0003	0.0012	0.0002	84.9	481.1	3.6
1000	$178.79 \times e^{-9}$	95.143	0.075	0.0185	0.0013	0.0014	0.0008	92.2	478.7	3.7
1130	$193.65 \times e^{-9}$	95.282	0.067	0.0197	0.0003	0.0031	0.0005	100.0	477.1	3.6

Note. Here and in Table 2: J is irradiation parameter. Each heating step is 10 min.

Table 2. ^{40}Ar/^{39}Ar data for muscovite from rocks of Aleksandrovka site of North Kokchetav tectonic zone

T, °C	^{40}Ar/^{39}Ar	±1σ	^{36}Ar/^{39}Ar	±1σ	Σ^{39}Ar, %	Age, Ma	±1σ
Zh-03-63 muscovite, J = 0.002339 ± 0.000009							
700	78.437	0.366	0.0445	0.0010	2.7	256.4	1.8
800	124.693	0.204	0.0092	0.0007	7.1	452.9	1.8
850	129.525	0.211	0.0061	0.0006	11.8	471.6	1.8
900	130.187	0.158	0.0056	0.0004	19.5	474.2	1.7
950	129.521	0.084	0.0041	0.0001	41.5	473.5	1.6
1000	129.021	0.117	0.0024	0.0001	63.6	473.5	1.6
1025	129.280	0.135	0.0036	0.0003	73.2	473.2	1.7
1050	128.847	0.164	0.0039	0.0005	79.0	471.5	1.7
1075	129.255	0.241	0.0041	0.0006	83.7	472.6	1.9
1100	130.124	0.296	0.0031	0.0007	87.4	476.4	2.0
1120	129.976	0.300	0.0025	0.0009	90.4	476.5	2.1
1140	130.488	0.331	0.0052	0.0011	93.1	475.6	2.2
1170	129.950	0.471	0.0042	0.0013	95.3	474.8	2.5
1200	129.698	0.537	0.0034	0.0018	96.9	474.8	2.9
1250	128.805	0.764	0.0036	0.0025	98.0	471.6	3.8
1300	129.200	1.006	0.0005	0.0034	98.8	475.9	4.9
1400	131.068	0.716	0.0021	0.0024	100.0	480.4	3.6

Chaglinka site

The Chaglinka site (Fig. 2) is located on the right bank of the Chaglinka river, south of Chaikino and Krasnyi Yar Villages. The local tectonic framework consists of several folded sheets composed of quartz-sericite schist (Kokchetav Formation, Ilekty Group), porphyroblastic augen gneiss with lenses of amphibolitized eclogite, and Arenigian siliceous-terrigenous sediments that host olistostromes (Zhansui Formation), quartz porphyry, tuff, and felsic volcanic breccias. Igneous zircon from felsic volcanics in the latter gave a Mesoproterozoic age of 1136 ± 4 Ma (Tret'yakov et al., 2009). The sheets have fault boundaries evident from positions of the bodies across their interior structure, from their strong thickness variations, and from different metamorphic grades of juxtaposed rocks. Rocks along the sheet margins are rich in mica and have 487.6 ± 3.5 Ma and 478.5 ± 4.4 Ma ^{40}Ar/^{39}Ar ages (samples K02-2 and K02-3, respectively, from quartz-muscovite schists of the Kokchetav Formation) (Dobretsov et al., 2005a,b). The volcanic-sedimentary sequence includes quartz and feldspar porphyry and aphyric volcanic rocks, with less abundant felsic volcanic breccias and tuff. The Kokchetav quartz-sericite schists are steeply folded and form sheets with their thicknesses increasing eastward.

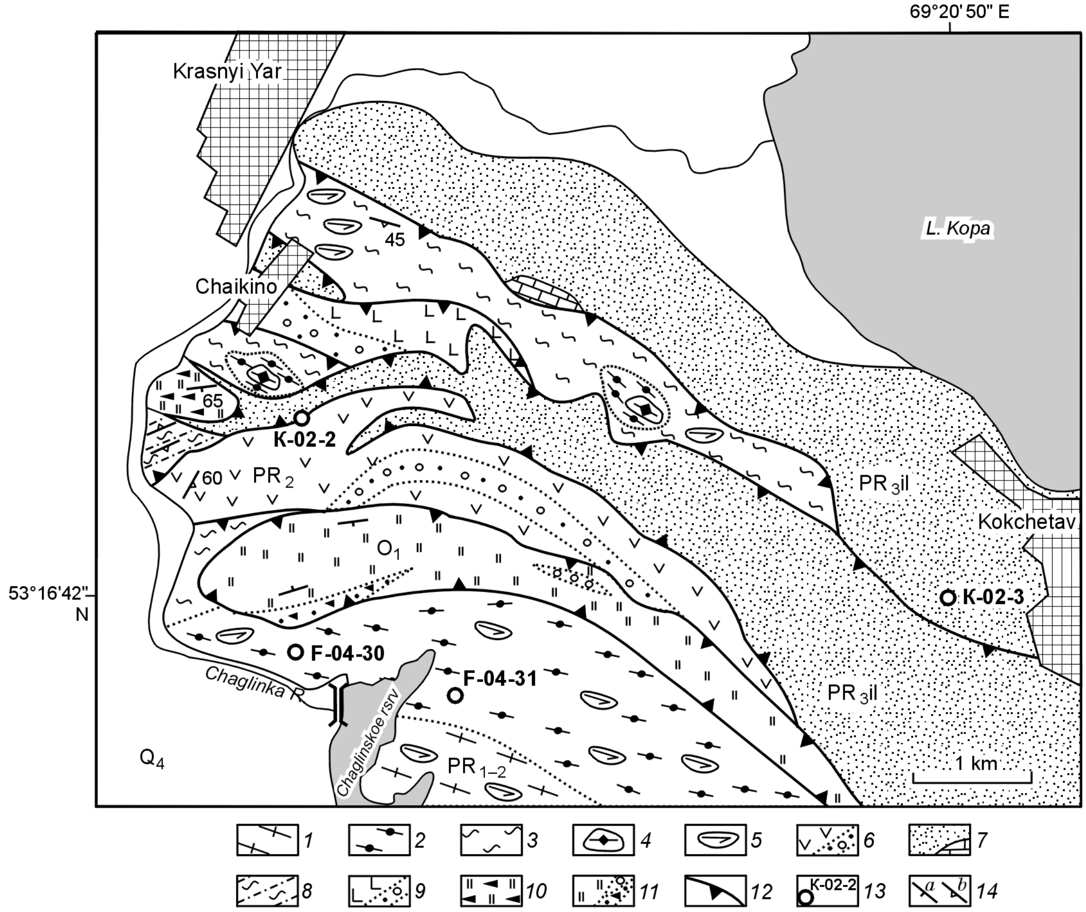

Fig. 2. Generalized geology of Chaglinka site. *1–5*, metamorphic basement of Kokchetav microcontinent, including rocks subjected to Paleozoic metamorphism: Early–Middle Proterozoic granite gneiss (*1*), blastomylonitized granite gneiss (*2*), granite gneiss subjected to greenschist retrograde metamorphism (*3*), eclogite (*4*), amphibolite (*5*); *6*, *7* volcanic-sedimentary cover of Kokchetav microcontinent: Middle Proterozoic quartz and feldspar porphyry (*6*), quartz-sericite schists with scarce lenses of dolomite, Late Proterozoic Ilekty Group (*7*); *8*, metaterrigenous greenschist of uncertain age; *9–11*, Ordovician sedimentary and volcanic rocks: plagioclase porphyry, sandstone, conglomerate (*9*), Arenigian siliceous-terrigenous sediments with olistostromes (*10*), Ordovician rather siliceous sediments, lenses of fine clastic breccias and sandstone; *12*, fault boundaries of thrust sheets; *13*, sampling sites and numbers of samples for Ar-Ar dating.

A greenschist sheet within the site encloses boudins of amphibolitized eclogite exposed 150 m south of Chaikino Village and in the site's eastern part. Both eclogite bodies occur among porphyroblastic (augen) gneiss smoothly grading into the greenschist rocks. According to our estimates (Zhimulev et al., 2010), the *PT*-conditions of eclogite formation were T = 800–850 °C and P = 18–20 kbar.

The Lower Ordovician sedimentary section assigned to the Zhanasui Formation (Bulygo, 1987) was documented in outcrops of the Chaglinka's bluffy right bank, 400 m south of Chaikino Village. Ordovician rocks make up a fault-bounded sheet cut by the river valley almost across the strike of the Zhanasui Formation. Outcrops in the steep valley sides perfectly expose the relations among different units of the sequence. The layers dip to the south (dip azimuth 170°, dip angle 65°). The section of the sheet, 150 m of total thickness, consists of (from bottom to top):

(1) yellow siliceous rocks interlayered with mudstone, siltstone, and sandstone . . . . 20 m;

(2) red siliceous rocks interlayered with siliceous siltstone . . . . 5 m;

(3) yellow siliceous rocks interlayered with siliceous siltstone and sandstone enclosing lenses and interbeds (up to 20 cm) of fine clastic breccias at layer bottoms . . . . .45 m;

(4) diamictites with a sand-clay matrix, up to 30 m, including several beds (upsection):

(a) bed with amphibolite and plagioclase-amphibole schist olistoliths (5 m long and 1.5 m high) . . . . .10 m;

(b) bed with olistoliths (3 m long and 0.6 m high) of quartzite, chlorite-sericite schists, marbled carbonates, gneisses, blastomylonite and mylonite, and quartz sandstone . . . . 5 m;

(c) breccias, ... 2 m;

(d) bed with quartz sandstone and quartzite pebble . . . . . . 3 m;

(e) garnet-muscovite breccias . . . . 1 m;

(f) same as (b) . . . . 2 m;

(g) bed of quartzite breccias with a quartzite olistolith (exposed length over 10 m, height 4 m) . . . . 8 m;

(5) interlayered red siltstone and mudstone . . . . .12 m;

(6) diamictites with small angular clasts and olistoliths of quartzite, quartz sandstone, carbonates, chlorite-sericite schists, amphibolite, and gneiss in their sand-clay matrix . . . . .10 m;

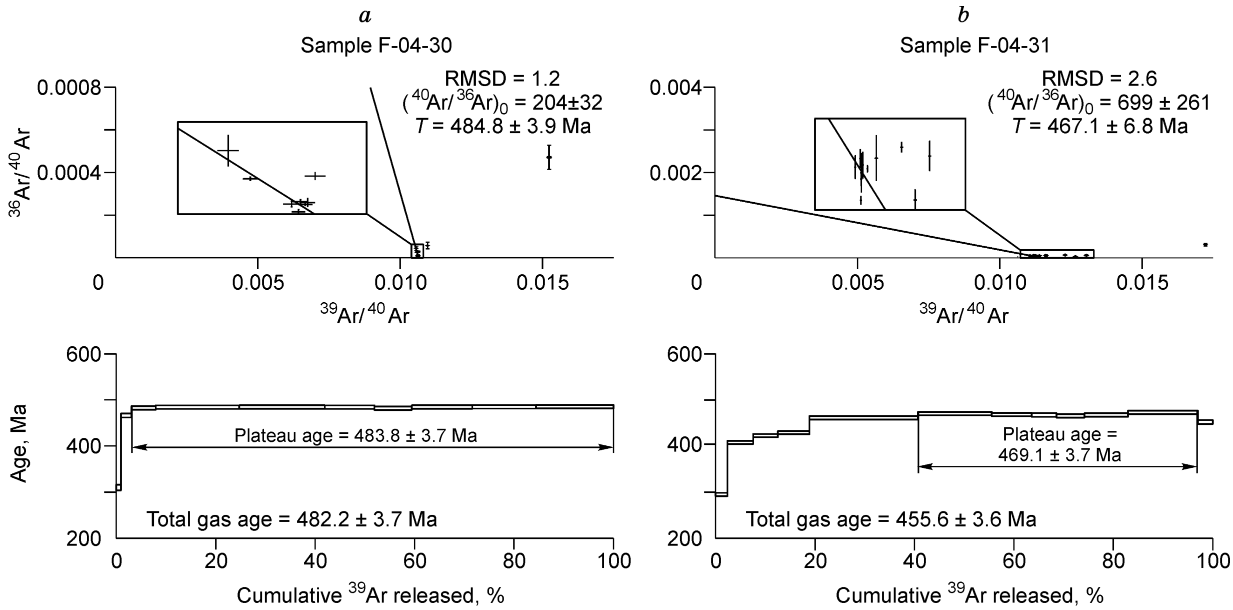

Fig. 3. $^{40}Ar/^{39}Ar$ spectra and isochron diagrams of muscovite from mylonitized gneiss of Chaglinka site. Dated by A.V. Travin at IGM, Novosibirsk.

(7) diamictites with a siliceous-terrigenous matrix and siliceous concretions. Clasts contain siliceous siltstone and mudstone, in addition to same rocks as in (4) . . . . 6 m;

(8) interlayered red siliceous mudstone, siltstone, and fine sandstone containing lenses and thin layers of fine clastic breccias, ... 11 m;

(9) interlayered yellowish-gray siltstone and fine sandstone . 8 m.

The Argenigian age of the sequence has been constrained by conodonts from yellow chert and lilac siliceous siltstone in the described section. A similar conodont-radiolarian assemblage was found above and below diamictites (Obut et al., 2006; Tsai et al., 2001). Diamictites are massive, have no bedding, and are jointed. The diamictite beds lie concordantly with other sedimentary beds below and above in the section. The quartzite olistolith reaching a thickness of 4 m and a length over 10 m in the thickest diamictite bed (4g) is parallel to the bedding of the host sediments. The clasts are nonrounded, mostly from a few cm to tens of centimeters, and far exceeding the volume of the matrix which only fills interstitials between adjoining clasts.

One diamictite lens has its boundary, well exposed in a vertical outcrop, as a gradual transition from breccias through fine clastic breccias and coarse sandstones to thinly laminated lilac siltstones. The transitional zone from the breccia to the siltstone is no thicker than 1 m. Siliceous siltstone and sandstone in beds 1–3 of the section also host fine clastic breccias consisting mainly of quartzite and chlorite-mica schists, as well as less abundant mylonitized gneiss and isolated clasts of limestone and typical KMB rocks (amphibolite, plagioclase-amphibole and quartz-garnet-muscovite schists). These rocks are of broad occurrence 5–15 km south and southwest of the site. Judging by their structures and textures, position in the section, and the compositions of diamictite, the rocks belong to olistostromes produced by gravity sliding during a tectonic event.

Strongly mylonitized granite gneisses are exposed in the southern part of the site, near the dam across the Chaglinka and in the bluffs of its water reservoir. The gneisses consist of microcline, plagioclase, quartz, and muscovite, are fine grained and thinly banded. During mylonitization, muscovite substituted for biotite along cleavage planes. We dated muscovite from two granite gneiss samples (F-04-30, 53°16′27.18″ N, 069°15′47.4″ E, and F-04-31, 53°16′11.58″ N, 069°16′40.74″ E, Fig. 3, Table 1) and obtained plateau ages of 483.8 ± 3.7 Ma and 469.1 ± 3.7 Ma, respectively. Igneous zircon from granite gneiss gave an age of 1148 ± 16 Ma, and the T_{Nd}(DM) rock model age was estimated at 2.3–2.4 Ga (Turkina et al., 2009). Thus, the primary granite (transformed into gneiss) was derived from felsic rocks of the Paleoproterozoic basement.

The rocks juxtaposed along faults within the site differ strongly in ages and formation depths, which is evidence of a large amount of displacement. The deformation occurred in the Early Ordovician (according to $^{40}Ar/^{39}Ar$ ages), both in basement granite gneiss and in metasandstone. The presence of olistostromes prompts that faulting was coeval with Early Ordovician siliceous-terrigenous deposition.

Zheilyau site

The Zheilyau site is located in the southwestern outskirts of Kokchetav city (Zheilyau neighborhood) (Fig. 4). The local geology includes olistostrome-bearing Ordovician sediments existing as a relatively small lens-shaped block (200 × 80–100 m) and long sheets of quartzite and quartz-sericite schists of the Kokchetav Formation exposed north and south of the sedimentary block. Outside the site, 1 km to the south, there are exposures of blastomylonitized gneiss and mylonitized granite gneiss.

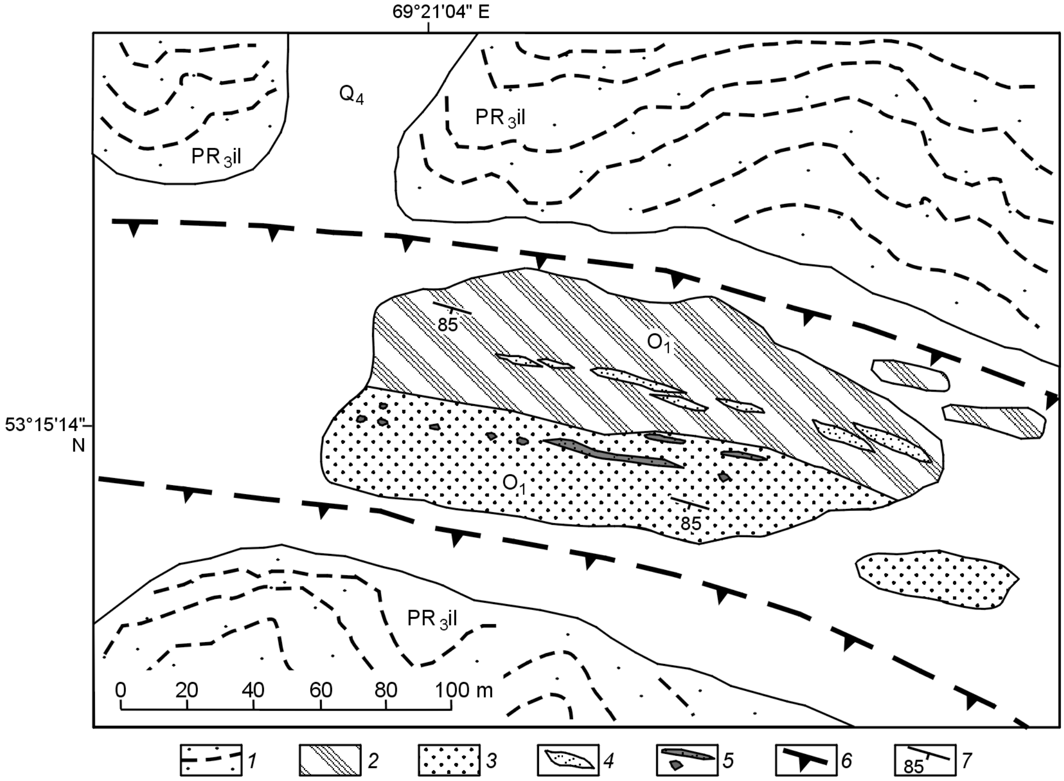

Fig. 4. Generalized geology of Zheilyau site. *1*, quartz-sericite schists of Late Riphean Kokchetav Formation; *2*, *3*, Early–Middle Ordovician deposits of Zhanasui Formation with olistostromes: siltstone and sandstone (*2*), sandstone and fine clastic breccias (*3*); *4*, breccias composed of mylonitized gneiss clasts; 5, breccias composed of quartzite clasts and isolated quartzite blocks; *6*, faults; *7*, bedding.

The sequence of Ordovician sediments strikes at 105° and dips southward at 85°. The rocks are green or brownish-purple foliated siltstone and sandstone changing in color and grain sizes along the strike, with numerous inclusions of coarser clastic material and fine clastic breccias. The clastic material in the latter consists of mylonitized gneiss. Olistoliths are nonrounded isometric or elongate quartzite blocks, up to 3–4 m across. The elongate blocks have their long sides parallel to the host sedimentary bedding, whereas the bedding of quartzite is oblique (40–45°) to that of the matrix. The quartzite blocks together make up a chain parallel to the host sedimentary bedding. South of Kokchetav there are quite small (tens to hundreds of meters) lenses of Early–Middle Ordovician sediments (Rozen and Bogoyavlenskaya, 1962; Tsai, 2001): siliceous shale, limestone, sandstone, and conglomerate. The Ordovician sediment lenses alternate in the plan view with larger exposures of the Kokchetav quartz-sericite schists or mylonitized gneiss, and are apparently parautochthonous fragments involved in thrusting. This inference is consistent with the lenticular geometry of the exposed fault-bounded bodies, the steep dip of the layers, and with the composition of clastics in conglomerate strongly different from that of the surrounding rocks.

A large part of NKTZ south of Kokchetav is composed of blastomylonitic gneiss, which was for a long time assigned to the Kuuspek Formation of the Borovoe Group, a porphyric complex presumably produced by progressive metamorphism of a Late Proterozoic (?) (Rozen, 1972) volcanic-sedimentary sequence at base of the sedimentary cover of the Kokchetav Massif. The isotope age constraints of the formation were obtained for a site south of Kokchetav, near Galcheva Sopka Mountain (Tugarinov et al., 1970). Having studied the petrography of rocks and the local geology between Kokchetav and Galcheva Sopka, we concluded that the rocks described in (Tugarinov et al., 1970) were blastomylonitized and mylonitized Proterozoic gneiss from the basement of the Kokchetav microcontinent. Blastomylonite (Fig. 5) is gray-green, light-gray massive or occasionally foliated and consists of quartz, K-feldspar, plagioclase, and mica, often with substitutions of sericite for plagioclase-albite and muscovite for biotite. The accessories are apatite, zircon, titanite, and tourmaline. The rock has a banded structure, with prominent banding-parallel feldspar and quartz porphyroclasts, and a porphyroblastic or a blastoclastic texture. The porphyroclasts composed of K-feldspar (microcline), less often coexisting with quartz, garnet, allanite, and biotite occur as separate blocks, have sericite rims, and are sheared with formation of angular clasts. They likely were tectonically rounded, judging by traces of rotation and bended foliation of the matrix near their margins. The matrix is lepidogranoblastic or sometimes microblastic. No blastoporphyric, blastopsammitic, or other textures typical of volcanic or sedimentary metamorphic rocks are evident. Blastomylonite contains lenses of slightly altered granite gneiss with smooth boundaries, as well as boudins of chloritized amphibolite. The rocks have α-Pb zircon ages of 1050 ± 50 Ma (Tugarinov et al., 1970), the same as for

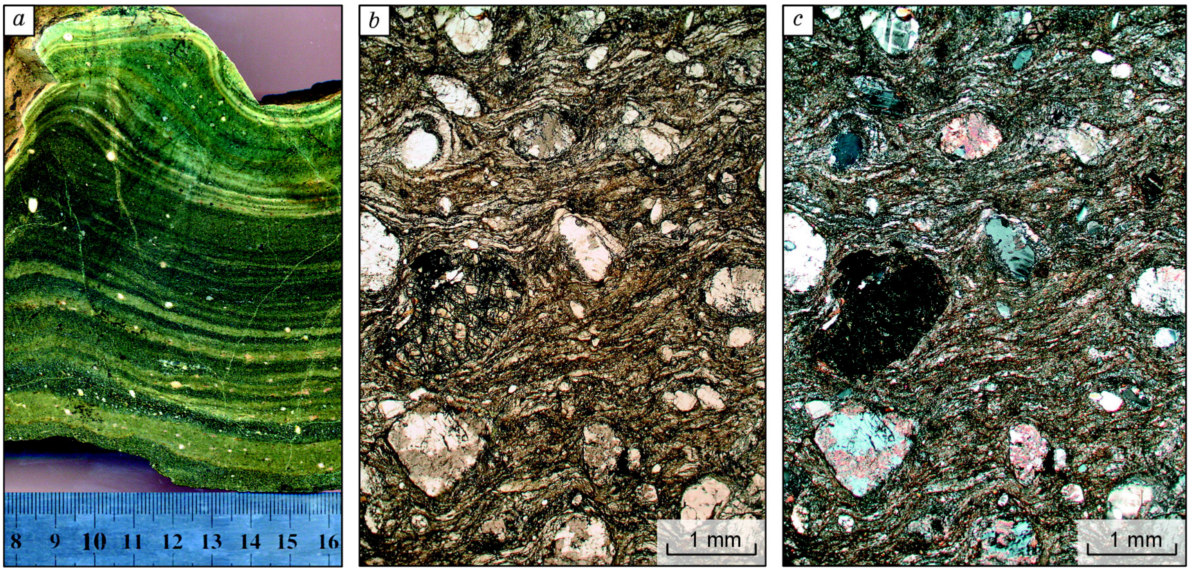

Fig. 5. Blastomylonitized gneiss. *a*, Polished section; *b*, photograph of thin section, parallel nicols; *c*, photograph of thin section, crossed nicols.

gneisses of the Zerenda Group (Rozen and Krasnobaev, 1966). In total, the available semiquantitative α-Pb zircon ages are from 920 ± 85 to 1220 ± 100 Ma for the Zerenda gneiss (Rozen, 1972; Rozen and Krasnobaev, 1966) and from 1300 ± 130 to 775 ± 70 Ma for the Kuuspek porphyric rocks (Rozen, 1971), with many dates about 1000 Ma in both groups. Thus, the porphyric rocks of the Kuuspek Formation are similar to the Zerenda gneiss according to α-Pb ages. New U-Pb SHRIMP dates of igneous zircon from granite gneiss are 1148 ± 16 Ma (Turkina et al., 2009) and likewise correspond to the Late Mesoproterozoic. Blastomylonitized Proterozoic gneiss and granite gneiss that belong to the basement of the Kokchetav microcontinent are widespread southeast of Kokchetav and constitute a large part of the NKTZ volume.

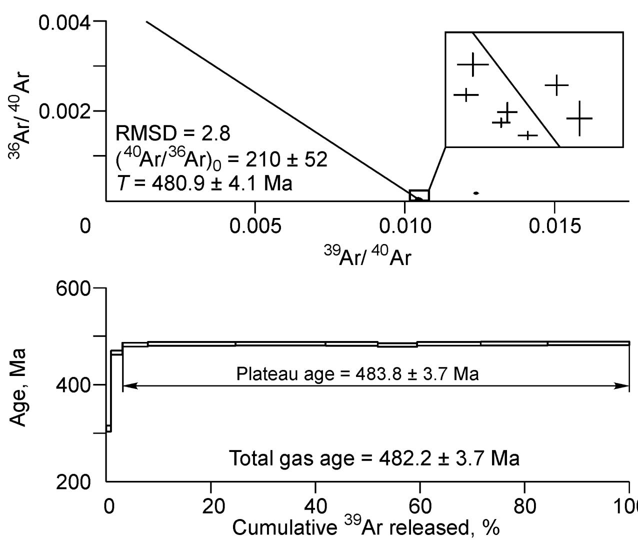

Fig. 6. $^{40}Ar/^{39}Ar$ spectra and isochron diagrams of muscovite from sample F-04-52. Dated by A.V. Travin at IGM, Novosibirsk.

A fault boundary between quartz-sericite schists of the Kokchetav Formation and Middle Ordovician schists and microquartzite is exposed 15 km south of Kokchetav, where the Kokchetav–Astana highway crosses the railway. The zone, about 30 m thick, includes heavily brecciated quartz-muscovite schists with scarce garnet porphyroblasts. We interpret the fault as a northern border of NKTZ (Fig. 1) taking into account the absence of exposures of the Kokchetav quartzite or other microcontinent-related rocks north of the site (a continuous field of Ordovician sediments of the Stepnyak zone). Muscovite from that fault zone (sample F-04-52, 53°13′10″ N and 69°38′29″ E) gave an $^{40}Ar/^{39}Ar$ plateau age of 483.8 ± 3.7 Ma (Fig. 6, Table 1).

Aleksandrovka site

The nappe tectonics of the North Kokchetav zone is especially prominent in the vicinity of Aleksandrovka Village (Kenesary), on the right bank of the Kylshakty River (Fig. 7). The zone includes two sheets (amphibolite below and Kokchetav quartzite above) thrust over the Lower Ordovician siliceous-terrigenous deposits of the Stepnyak zone. The upper frontal thrust shows up as a thick zone of quartz-muscovite schists and tectonic breccias with a chlorite-sericite matrix. The $^{40}Ar/^{39}Ar$ age of muscovite from the zone is 489.7 ± 3.1 Ma (sample K 02-6, Fig. 7) (Dobretsov et al., 2005a). Quartzite is foliated at the contact with amphibolite and bears muscovite, as much as to be quartz-muscovite schist. The plateau age of 473.4 ± 3.9 Ma we obtained for muscovite from this schist sampled along the amphibolite-quartzite boundary (sample Zh-03-63, 53°06′33″ N, 69°51′28″ E) agrees with the isochron age of 472.2 ± 5.8 Ma (Fig. 8, Table 2).

The contact between siliceous-terrigenous sediments and quartzite dips southwest at 45° to 80° and is marked by sediment deformation in its vicinity and presence of ser-

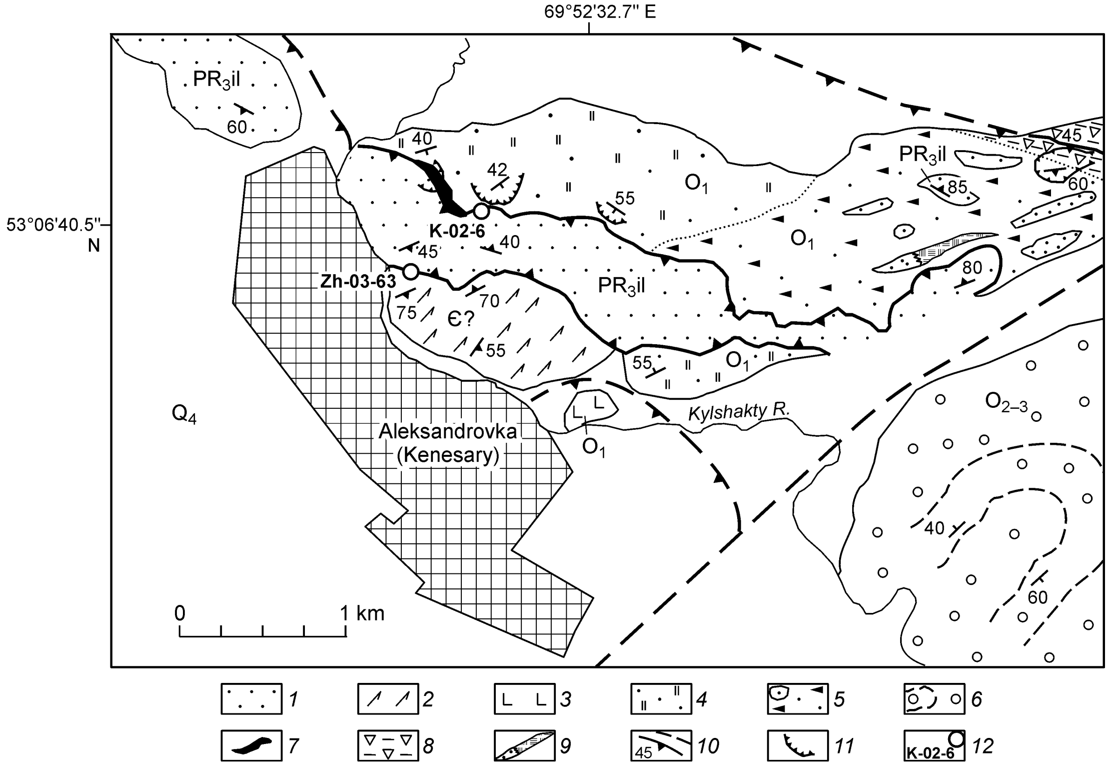

Fig. 7. Generalized geology of Aleksandrovka site. *1*, quartz-sericite schists and quartzite, Ilekty Group; *2*, amphibolite; *3*, Early Ordovician (?) basalt pillow lavas; *4*, Arenigian siliceous shale, jasper, siltstone; *5*, Early Ordovician siliceous-terrigenous sequence with olistoliths of Ilekty quartzite; *6*, Middle–Late Ordovician conglomerate and sandstone; *7*, serpentinite of Shchuch'e ophiolite belt; *8*, tectonic breccias; *9*, olistolith of quartzite replaced by breccias on strike; *10*, observed and inferred faults and dips of their planes; *11*, quarries; *12*, sampling sites and numbers of samples for Ar-Ar dating.

pentinite schists. The sedimentary sequence with olistostromes is exposed in quarries as consisting of red, or less often yellow, siliceous siltstone and fine sandstone, and massive lilac or dark-red chert with conchoidal fracture. Siliceous rocks bear

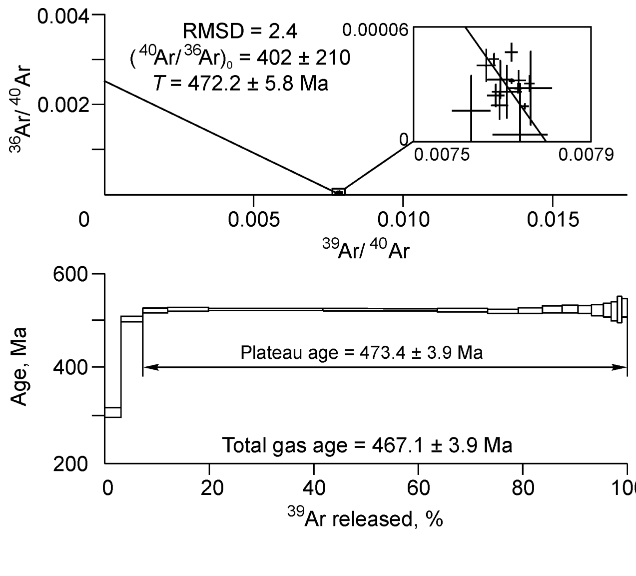

Fig. 8. $^{40}Ar/^{39}Ar$ spectra and isochron diagrams of muscovite from quartz-muscovite schist (sample Zh-03-63) in contact between amphibolite and quartzite sheets at Aleksandrovka site. Dated by J. de Grave at Stanford University, US.

Early Ordovician conodonts (Tsai et al., 2001) and abundant, though poorly preserved, radiolarians (Bulygo, 1987). A lithologically identical bed of lilac and dark red cherts, which crops out 12 km south of Aleksandrovka Village in the outskirts of Igylyk Village, contains an Early–Middle Ordovician radiolarian assemblage with *Proventocitum procerulum* (Nazarov), *Inanigutta* sp. cf. *I. unica* (Nazarov), *Inanigutta* sp. and *Periodon flabellum* Lindström, *Paroistodus originalis* (Sergeeva), as well as *Protopanderodus rectus* (Lindström) conodonts characteristic of the Middle–Upper Arenigian conodont zones B. navis—lower Par. originalis (Obut et al., 2006).

Furthermore, the sedimentary rocks host chaotically scattered elongate blocks, from a few meters to hundreds of meters long, composed of quartzite and quartzitic sandstone, mylonitized granite gneiss and garnet-mica schists, with schistosity commonly parallel to the long side of the blocks. Especially abundant are relatively well exposed blocks of white quartzite (or less often brownish jaspilite) that occasionally reach 200 m across and form small hills on the surface. Between the quartzite blocks there are bedrock exposures and debris of siliceous-terrigenous sediments that host breccia lenses, about 3 m thick and up to 25 m long. Clasts in the breccias are mainly quartzite, with less abundant amphibolite and garnet-muscovite schists, as well as red chert; they are mostly nonrounded and as small as a few centimeters, though some reach sizes of 20 cm.

A quarry in the northeastern part of the site strips brecciated schists and tectonic breccias corresponding to a fault zone. The breccias exist as a crumble mass of fine quartz, mica and clay minerals, which is limonitized, veined with quartz, and contains copper oxides and carbonaceous matter. In places, talc is rather abundant to form quartz-chlorite-talc schists. The direction of foliation indicates the fault dip to the southwest at 45°. The zone of tectonites has a thickness of at least several tens of meters. The deformation apparently affected siltstone and siliceous-argillaceous rocks of the Stepnyak zone.

Borovoe site

The Borovoe site is located north of the Borovoe Mountains, 60 km southeast of Kokchetav (Fig. 1). The tectonic pattern across NKTZ in the area of Maloe and Bolshoe Chebach'e lakes consists of five sheets (listed from north to south): (1) quartz-sericite schists and dolomite of the Ilekty Group; (2) mylonitized schists and gneisses with amphibolite lenses; (3) quartz-garnet-muscovite schists, micaceous rocks, and gneisses with eclogite boudins; (4) quartz-sericite schists and dolomite of the Ilekty Group (the sheet is thin and discontinuous)); (5) pre-Ordovician volcanic-sedimentary flysch, olistostromes, conglomerate, and plagioclase porphyry. The imbricated structure is intruded with Late Silurian (Letnikov et al., 2009a) Borovoe and Orlinaya Gora plutons of the Borovoe complex. The isometric shapes of the plutons and their position across the country rock layers indicates that the sheets had been juxtaposed prior to the granite emplacement. Being sealed by Late Ordovician (Letnikov et al., 2009b) plutons of the Krykkuduk complex on the extension of unit (5), the zone must have pre-Late Silurian or rather pre-Late Ordovician age.

The boundary between NKTZ and the Stepnyak zone exposed within the Borovoe site is of fault origin and is composed of mylonite and cataclastic rocks (a tectonite complex). The rocks of the Stepnyak zone north of NKTZ are folded Early–Middle Ordovician volcanics and sediments (Obut et al., 2006). On the regional scale, folds in the northwestern Stepnyak zone are parallel to the boundaries of the Borovoe block as part of the Kokchetav Massif, but at a closer view they are truncated by the NKTZ frontal thrust. North of Maloe and Bol'shoe Chebach'e lakes, the North Kokchetav zone strikes in the W–E direction while the Ordovician volcanic-sandstone beds in the Stepnyak fold structure have an NE strike, i.e., are oblique to the truncating fault. Thus, we infer that tectonic activity in NKTZ terminated in the Middle Ordovician proceeding from the pattern of folding, faulting, and intrusions.

HP facies at the Borovoe site is eclogite existing in boudins found among quartz-garnet-muscovite schists (sometimes almost monomineral micas). The sheet of eclogite-bearing mica schists (Fig. 1) is traceable for at least 15 km (including the segments buried under Quaternary sediments and lakes), and has a width from 0.5 to 1 km. It contacts the sheets of gneisses and quartz-sericite schists of the Kokchetav Formation and pre-Ordovician volcanic and sedimentary rocks. The *PT*-conditions for the Borovoe eclogite were estimated at T = 750–800 °C and P = 17–18 kbar, or corresponding to depths about 55–60 km. Muscovite from quartz-garnet-muscovite schists that host eclogite gave a $^{40}Ar/^{39}Ar$ age of 493 ± 5 Ma (Zhimulev et al., 2010).

Letnikov and Khalilov (1994) obtained a U-Pb zircon discordia for granite gneiss sampled at the boundary between the eclogite-mica and amphibolite-gneiss sheets near Lake Maibalyk (Fig. 1), with its upper and lower intercepts at 1.2 Ga and ~450 Ma (Late Ordovician), respectively, and interpreted it as the time of K-Si metasomatism and origin of muscovite schist. Zircons from granodiorite veins that cut the gneiss sheet gave an age of 1128 ± 12 Ma (Letnikov et al., 2007). The latter sheet bears no eclogite or other signature of HP metamorphism.

Zhanatalap site

The Zhantalap site is located near Zhanatalap Village (Fig. 9), where the North Kokchetav tectonic zone turns from the W–E to N–S strike. The site is remarkable for widespread ophiolite and coarse clastic olistostromes. The thrust sheets at the site consist of gneisses and schists of the Zerenda Group, quartz-sericite schists of the Kokchetav Formation, and gabbro and serpentinite of the Shchuch'e ophiolite suite. The thrusts, and the sheets juxtaposed along them, strike in the W–E direction. All sheets together thrust over Ordovician rocks of the Stepnyak zone lying in the north. Gneiss and mica schists with garnet and sillimanite along the sheet boundaries experienced retrograde metamorphism to become fine sericite-chlorite-quartz rocks with scarce relicts of garnet and sillimanite, while garnet amphibolite transformed into epidote-chlorite-albite metamorphic rocks. Gneiss and migmatite bear signature of mylonitization which produced cryptocrystalline sericite-chlorite-quartz aggregates cementing quartz and K-feldspar clasts.

Muscovite from quartz-mica schists of the Kokchetav Formation has an $^{40}Ar/^{39}Ar$ age of 488.7 ± 3.5 Ma (Dobretsov et al., 2005a), which corresponds to the Cambrian–Tremadocian boundary according to the Stratigraphic Code of Russia (2006).

The frontal thrust is delineated by small lenses of serpentinite and serpentinite schists coexisting with tectonites (gneiss, quartz-sericite schist, and gabbro-amphibolite). The rocks of the allochthon are altered near the fault: mica quartzite and sandstone of the Kokchetav Formation are blastomylonitized and folded; gabbro is foliated, with the lamina set in a serpentinite matrix and folded as well (1.5–2 m folds). The fold hinges strike from west to east, i.e., along the general strike of the structure. The frontal thrust plane lies nearly vertical in the present framework. The allochthon has at its base a tectonic breccia composed of angular mylonitized gneiss clasts.

The allochthon involves gabbro and peridotite serpentinite that belong to the Shchychie ophiolite. There are four mafic

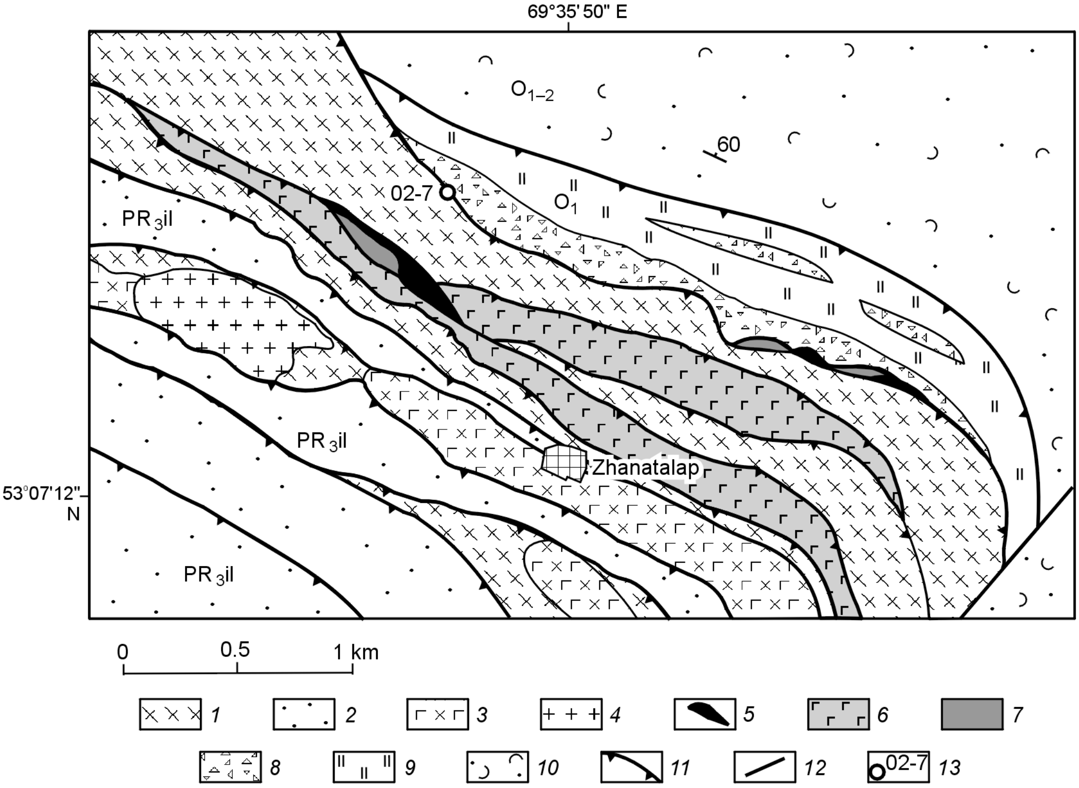

Fig. 9. Generalized geology of Zhanatalap site. *1*, gneiss with amphibolite boudins; *2*, quartz-sericite schists and quartzite, Ilekty Group; *3*, *4*, Precambrian igneous rocks: gabbro-diorite (*3*), granite (*4*); *5–7*, Shchuch'e ophiolite belt: serpentinite (*5*), gabbro (*6*), basalt (*7*); *8*, olistostrome; *9*, Arenigian siliceous-terrigenous sequence with breccia lenses; *10*, Late Arenigian (?)–Late Ordovician volcanic-sedimentary flysch; *11*, thrusts; *12*, strike slip fault; *13*, sampling sites and numbers of samples for Ar-Ar dating.

and ultramafic bodies distinguished within the site. Two larger ones consist of gabbro and gabbro amphibolite with smaller amounts of pyroxenite and hornblendite, while two smaller bodies are of serpentinite. Gabbro belongs to tectonic sheets juxtaposed with the gneiss and quartzite-sandstone sheets of the allochthon complex. Gabbro is mostly a medium-grained amphibolitized meso- and melanocratic rock, with gabbroic textures produced by tabular crystals of saussuritized calcic plagioclase and short prismatic crystals of brownish-greenish hornfels after diopside. The accessories are commonly titanite and titanomagnetite. There are also leucocratic varieties transitional to gabbro diorite, as well as small segregations of pyroxenite and hornblendite. Gabbro is locally foliated and amphibolitized along the margins of the bodies. The two smaller serpentinite lenses are located in the zone of the frontal thrust. One larger lens (~150 m long and 40 m wide) occurs 2 km east of Zhanatalap Village and consists of peridotitic chrysotile-antigorite and recrystallized antigorite with minor Cr-spinel. The rocks are locally carbonatized and bear rather large amounts of chlorite (pennine) near the lens margins.

The 300–400 m thick olistostrome lying immediately before the frontal thrust includes clastic material of two types corresponding to two sources. One type (predominant) is rocks of the allochthon: gneiss, quartz-sericite schist, gabbro-amphibolite, granite, and granodiorite in angular clasts from millimeters to a few meters in size. Locally there are 20 m long and up to 2 m thick gneiss olistoliths oriented along the coarse bedding of the host deposits. They give way on strike to an apron of monomictic gneiss breccias. Rocks of the other type are less abundant well rounded 10–15 cm clasts of plagiogranite, basalt, and jaspers in a silt-sand matrix, confined to the olistrostrome base. The olistostrome contains ever more clastic material toward the allochthon, progressively looses its sand-clay matrix, and eventually becomes a tectonic mélange of breccia and cataclastic rocks in the frontal thrust zone.

The coarse clastics of the olistostrome complex grade northward, toward the autochthon, into rhythmically interlayered sandstone, siltstone, and siliceous shale in which breccia and conglomerate lenses become ever scarcer. The lenses are from tens to hundreds of meters long and from a few meters to tens of meters thick. In places, sand-clay sediments enclose nonrounded gneiss blocks up to 1.5–2 m across. The breccias have normal contacts with their hosts. Often there are gradual transitions within the outcrops from fine clastic breccias through coarse sandstone to fine sandstone (Fig. 10, *a*), with individual pebbles "sinking" in sandstone (Fig. 10, *b*). The siliceous-terrigenous sediments contain *Paracordylodus gracilis* (Lindström) and *Periodon flabellum* (Lindström) conodonts that belong to an assemblage known from the Middle Arenigian conodont zone O. evae (Obut et al., 2006). The breccia-bearing Arenigian sediments are siliceous rocks of different colors (green, red, or gray) and structures (thinly

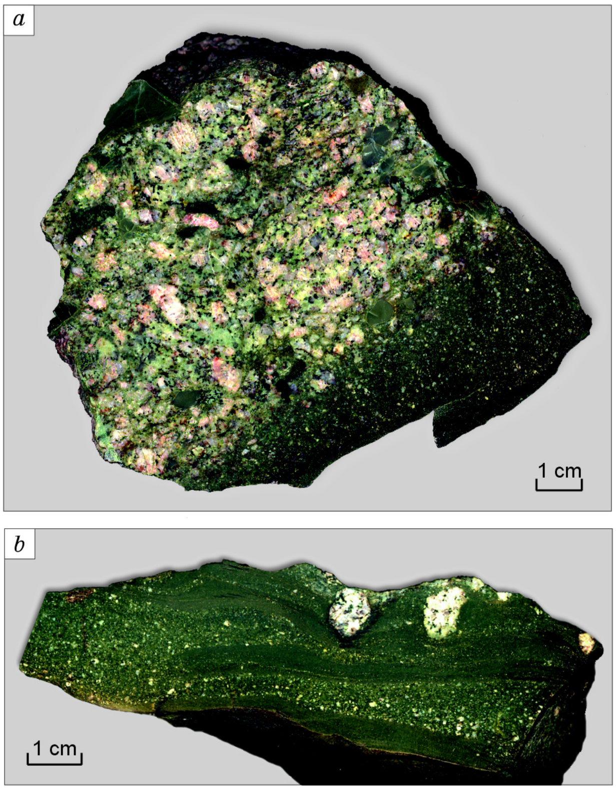

Fig. 10. Polished samples. *a*, Gadual transition from breccia in upper part, though coarse sandstone to fine sandstone in lower part. Clastic material is mostly granitic; *b*, lenses of coarse sandstone with "sinking" granitic pebbles in siltstone.

laminated, massive, brecciated, or landslide). There are also thin layers of green tuff with clasts of siliceous rocks and silty-siliceous interbeds with granitoid pebbles. The silty-siliceous interbeds consist of rhythmically alternated sand-silt and siliceous layers, the rhythms being 10–15 cm thick. Some interbeds show traces of creep folding or overturn. The Arenigian sequence is strongly variable on strike: most beds notably vary in thickness, pinch out, or change their aspect within relatively short distances (a few hundreds of meters).

The compositionally diverse Arenigian siliceous-terrigenous sequence gives way 1 km north of the frontal thrust to a volcanic-sedimentary complex of tuff, basaltic andesite lavas, and green siliceous siltstone. The contact between the Ordovician sequences is nearly parallel to the NKTZ fault border and is likewise of tectonic origin.

Discussion and conclusions

The North Kokchetav Tectonic Zone (NKTZ), a newly distinguished tectonic unit in Northern Kazakhstan, is a collage of nappes (thrust sheets) composed of rocks complexes that represent different tectonic settings. They are, namely, deformed fragments of the granitic-metamorphic basement and sediments of the Kokchetav microcontinent which were not involved in continental subduction and HP metamorphism; Mesoproterozoic continental-margin felsic volcanics; pre-Ordovician Shchuch'e ophiolite suite of basalt, gabbro, and serpentinite; Arenigian siliceous-terrigenous sediments containing olistostromes; HP amphibolitized eclogite among augen gneiss and muscovite schists.

The thrust sheets have boundaries oblique to their inner structure. A large volume of the North Kokchetav zone is occupied by tectonites of different depth facies: tectonic breccias and cataclastic rocks, as well as blastomylonite. Juxtaposition of HP and unaltered or low-grade rocks along faults indicates a large amount of displacement. At the Aleksandrovka site, NKTZ sheets thrust over rocks of the Stepnyak paleoisland-arc zone, and all contacts between the two zones are of tectonic origin. Folding in the Stepnyak zone is conformal to the NKTZ frontal fault, which characterizes the latter as a thrust (Rozen and Bogoyavlenskaya, 1962). The fact that Ordovician sediments enclose olistostromes composed of rocks of the Kokchetav microcontinent is another piece of evidence that the origin of NKTZ was associated with thrusting. Such assemblages of thrust sheets consisting of compositionally different complexes, including HP rocks, ophiolite, olistostromes, and melange normally form in collisional settings. Therefore, the North Kokchetav zone, being located between the complexes of the Kokchetav microcontinent and Early Paleozoic island-arc and oceanic rocks, can be interpreted as a collisional zone.

The $^{40}Ar/^{39}Ar$ ages of dynamic metamorphic rocks in NKTZ (mylonitized basement gneiss and quartz-sericite schists derived from sandstone sedimentary cover of the microcontinent) are in the range 489–474 Ma, or Early Ordovician, while most dates correspond to the Tremadocian (488–478 Ma) and earliest Arenigian. Olistostromes have been found in Arenigian sediments which are the youngest of the NKTZ complexes involved in tectonic activity. Geological position indicates a Middle Ordovician age of deformation. Middle–Late Ordovician sediments, though being deformed by the largest thrusts, differ markedly from Early–Middle Ordovician sediments in deformation degree and style. They fill a graben superposed over the NKTZ thrusts (area of Lake Zhamantus (Fig. 1)), and thus form a neo-autochthon. $^{40}Ar/^{39}Ar$ data place constraints on the age of mylonitization and dynamic metamorphism, i.e., deformation at depth (the closure temperature of the $^{40}Ar/^{39}Ar$ system of muscovite is ~370 °C (Hodges, 2003)). Tectonic activity in the North Kokchetav zone apparently continued in the Middle Ordovician as well, judging by truncation of folded Middle Ordovician sediments by the NKTZ frontal thrust. This geological pattern records the latest tectonic events that show up in cataclasis and brecciation of all NKTZ rocks, including Early Ordovician quartz-muscovite tectonites. According to numerous Early Ordovician dates of muscovite and phengite from rocks of the Kokchetav metamorphic belt (de Grave et al., 2006; Hacker et al., 2003; Travin, 1999), NKTZ thrusting was synchronous with the latest dynamic metamorphic event in the belt.

The reported data have important implications for the history of the Kokchetav belt. All events of UHP metamorphism show Cambrian ages in different isotope methods from SHRIMP U-Pb zircon to low-temperature $^{40}Ar/^{39}Ar$ thermochronology (Borisova et al., 1995; Hacker et al., 2003; Katayama et al., 2001; Korsakov et al., 2009; Ragozin et al., 2009; Shatsky et al., 1999; etc.). Thus, exhumation of UHP rocks had completed by the latest Cambrian (510–500 Ma). The younger Early–Middle Ordovician ages (470–490 Ma) we have obtained for large-scale collisional deformation indicate that HP rocks had been exhumed prior to the rigid collision, apparently, during ongoing continent subduction. Early Ordovician collisional deformation acted upon HP rocks which thrust onto the margin of the Kokchetav microcontinent in the Late Cambrian. The Late Cambrian thrust, whose fragments have been preserved along the southern boundary of the Kokchetav metamorphic belt, has a south vergence (Terabayashi et al., 2002). Andalusite-cordierite-garnet-biotite schists of the Daulet Formation within the thrust zone have Late Cambrian $^{40}Ar/^{39}Ar$ biotite ages (Buslov et al., 2010). Another example of HP complexes that had been exhumed prior to collisional orogeny and related deformation comes from the Himalaya and Timor areas whose tectonic setting and *P-T-t* history were investigated recently by Leech et al. (2005) and Kaneko et al. (2007), respectively.

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