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GEOLOGY

Isotope Sm–Nd Data on the Late Silurian–Early Devonian Age of Dynamometamorphism at the Base of Ophiolitic Allochthon in the Sakmara Zone of the Southern Urals

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Most ophiolitic complexes occur in present-day structures as allochthonous sheets that are thrust over only slightly metamorphosed sedimentary and volcanic complexes of continental margins [10]. The base of such thrusts is commonly composed of high-grade metamorphic rocks up to granulites. The inverted metamorphic zoning at the base of nappes demonstrates the increase in *PT* gradients from bottom to top approaching ultramafic rocks. Another important attribute of such complexes is development of recumbent, isoclinal, and disharmonic drag folds. The thickness of metamorphic rocks at the base of allochthons does not exceed 1–2 km. While the relatively young and still hot oceanic crust is participating in thrusting, the thermal gradients in the metamorphic base reach 1000°C/km or more. There is every reason to suggest that the age of high-gradient metamorphism corresponds to the age of thrusting. Because isotopic dating of ophiolites meets methodological difficulties, the timing of metamorphism at their base may be used for estimation of the age of thrusting. Precisely this problem has been set and solved for the metamorphic aureole at the base of the Khabarny mafic–ultramafic allochthon in the Sakmara Zone of the southern Urals.

The Khabarny and Kempirsai ophiolitic allochthons are among the largest structures in the southern Urals. They are constituents of the Sakmara Zone situated to the west of the Main Ural Fault (Fig. 1). This zone is a complex packet of tectonic sheets that are thrust westward over the margin of the East European paleocontinent [4, 9, 10]. Ophiolites occupy the uppermost position in this packet. The Khabarny mafic–ultramafic allochthon (~400 km^2 in area) is located 30 km west of the city of Orsk. In the section, this allochthon is a synform reaching 1.5 km in thickness. The dynamometamorphic rocks that underlie ultramafics as an element of the allochthon crop out in the northwestern, northeastern, and eastern blocks (Fig. 2). Amphibolites of the northwestern block were studied in detail by Sobolev and Paneyakh [12] who have shown that the rocks correspond to the epidote–amphibolite facies ($T = 400$–450°C, $P = 3$–4 kbar) and are metamorphosed subalkali oceanic basalts. The age of metamorphism was not discussed because of the lack of data. The metamorphic complex that underlies the allochthon in the east has not been studied until now. According to our data, this complex consists of the foliated uniform amphibolite in the footwall and gneiss–amphibolite unit in the hanging wall (Fig. 3). The variation of *PT* parameters through the section demonstrates typical inverted zoning with upward (westward) increase in the metamorphic gradient with the approach to gabbroic and ultramafic rocks. The intensity of deformation increases in the same direction as well.

Garnet amphibolite from the upper reaches of the Kholodny Klyuch ravine located approximately 6 km southwest of the Settlement of Khabarny was chosen as an object of isotopic dating. Garnet amphibolite occurs in the hanging wall of the metamorphic complex and intercalates with common amphibolite and quartzitic gneiss (Fig. 3). The metamorphic rocks bear signs of anatectic melting with segregation of quartz–feldspar leucosome and crosscutting plagiogranite veins. The bluish green high-Fe (f = Fe/(Fe + Mg) = 0.80–0.85) hastingsite (30–50 vol %), brownish red almandine-rich garnet (10–20 vol %), andesine (20–30 vol %), quartz (5–10 vol %), and ilmenite (4–5 vol %) are major minerals of garnet amphibolite. Apatite and zircon are accessory minerals. Relict ferroaugite and grunerite were identified as inclusions in hastingsite. As

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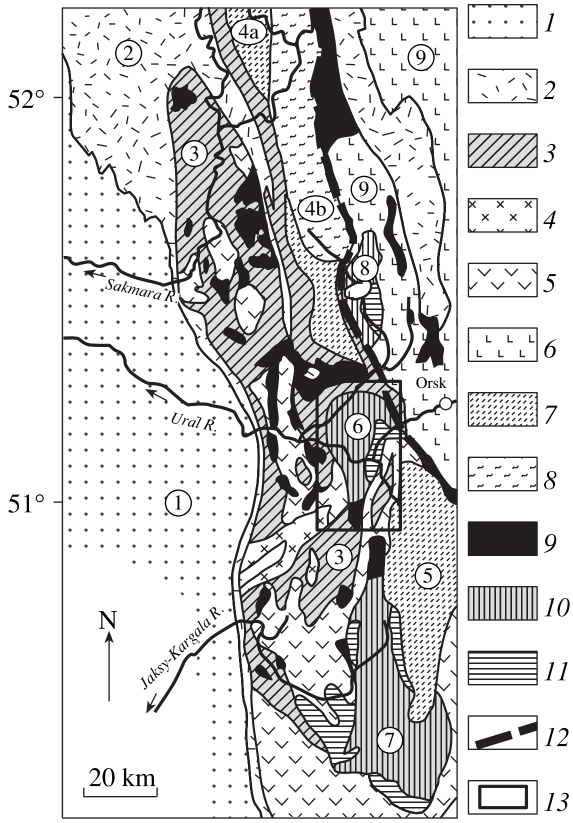

Fig. 1. Geology of the Sakmara Zone (after [4]). (*1*) Lower Carboniferous–Permian carbonate sequences and molasse; (*2*) Upper Devonian–Lower Carboniferous graywacke flysch of the Zilair Group; (*3*) Ordovician–Lower Carboniferous terrigenous and cherty rocks of the continental slope; (*4*) Early Devonian alkali basaltoids; (*5*) Ordovician–Middle Devonian volcanic and volcanosedimentary rocks (volcanic and tuffaceous types of sections in the Sakmara Zone); (*6*) Devonian volcanic and volcanosedimentary rocks of the West Magnitogorsk Zone; (*7, 8*) metamorphic rocks: (*7*) quartzite and schist, (*8*) zone of glaucophane metamorphism; (*9*) serpentinite melange; (*10*) dunite–harzburgite allochthon; (*11*) gabbroic rocks and amphibolites; (*12*) Main Ural Fault; (*13*) Khabarny mafic–ultramafic allochthon and its framework. Numerals in circles: (1) Ural Foredeep; (2) Zilair Synclinorium (southern part); (3) Sakmara Zone; (4) Uraltau Zone: (a) Suvanyak quartzite–schist greenschist-facies complex; (b) Maksyutovo eclogite–glaucophane complex; (5) Ebety Anticline; mafic–ultramafic complexes (6–8): (6) Khabarny, (7) Kempirsai, (8) Khalilovo; 9, West Magnitogorsk Zone.

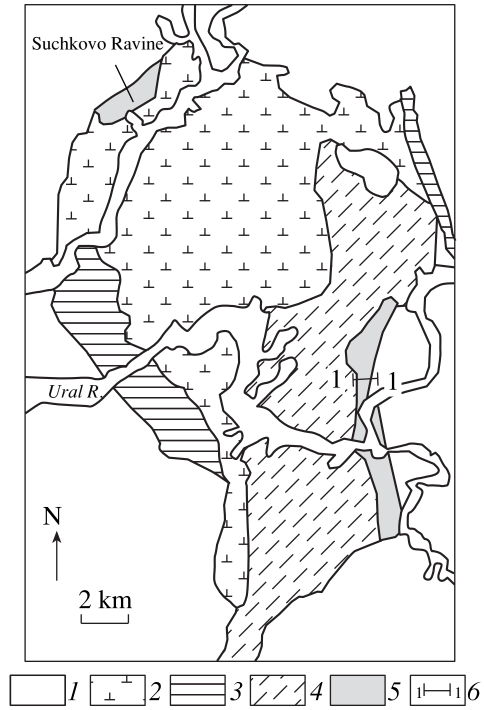

Fig. 2. Geology of the Khabarny mafic–ultramafic allochthon (based on data reported by Orenburggeologiya Territorial Geological Survey). (*1*) Paleozoic volcanosedimentary and metamorphic rocks of the framework; (*2*) ophiolitic dunite–harzburgite complex; (*3*) complex of parallel dolerite dikes and the layered mafic–ultramafic series (Akkerman Complex); (*4*) East Khabarny dunite–clinopyroxenite–websterite–gabbronorite complex; (*5*) amphibolite and other metamorphic rocks at the base of the allochthon; (*6*) studied geological section with garnet amphibolite (see Fig. 3).

is known, grunerite readily replaces orthopyroxene during retrograde metamorphism of granulites under amphibolite-facies conditions, so that garnet amphibolite could have been formed as a product of alteration of two-pyroxene crystalline schist.

In chemical composition, garnet amphibolite differs from basic igneous rocks, being characterized by elevated silica content (53–58 wt %); enrichment in TiO_2 and FeO_{tot} (3–4 and 20–22 wt %, respectively); and depletion in Al_2O_3, CaO, and MgO relative to the basaltic cotectic (table). The FeO mole fraction (f) reaches 0.7–0.8, and this value is obviously higher than in basic igneous rocks. Garnet amphibolite reveals a near-horizontal chondrite-normalized REE pattern at the level of 50–70 chondritic units, and this also distinguishes it from igneous rocks. The normative mineral composition (CIPW) of garnet amphibolite corresponds to two-pyroxene–quartz–plagioclase crystalline schist containing up to 20 wt % quartz, ~40% andesine, up to 25% pyroxenes, and 4–5% ilmenite in support of the granulitic protolith of amphibolite. A Fe-rich sedimentary rock (melanocratic wacke) might have been a protolith of garnet amphibolite or the preceding two-pyroxene schist. The parameters of metamorphism fit the upper amphibolite facies of moderate pressure (T = 650–850°C, P = 5–6 kbar) [2].

The Sm–Nd isotopic dating was performed on a Finnigan MAT-262 (RPQ) multicollector thermoionization mass spectrometer in the static regime at the Geological Institute, Apatity. The chemical decomposition of rocks and minerals was carried out following the technique described in [3]. The Re filaments were used as ionizers. Samples were placed on Ta filaments along with a microdroplet of diluted H_3PO_4. The uncertainty of reproducibility in determining the Nd isotopic com-

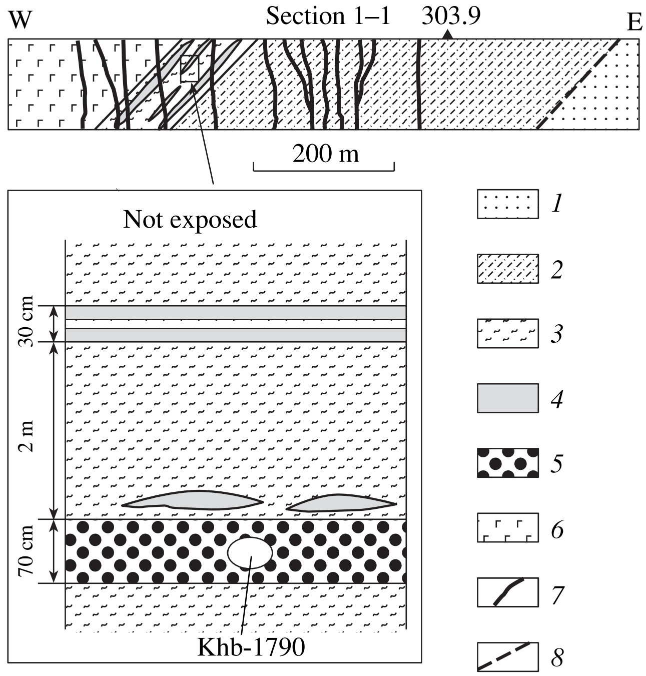

Fig. 3. Simplified geological profile 1–1 (Fig. 2) with a detailed sketch of the garnet amphibolite outcrop (sample Khb-1790). (*1*) Lower Ordovician arkose sandstone and conglomerate of the Kidryasy Formation (autochthon); (*2–5*) base of allochthon: (*2*) foliated amphibolite, (*3*) thin-banded deformed amphibolite alternating with quartzite and quartzose gneiss, (*4*) amphibole–garnet quartzite and quartzose gneiss, (*5*) garnet amphibolite; (*6*) gabbronorite of the East Khabarny Complex; (*7*) gabrodolerite dike; (*8*) thrust fault.

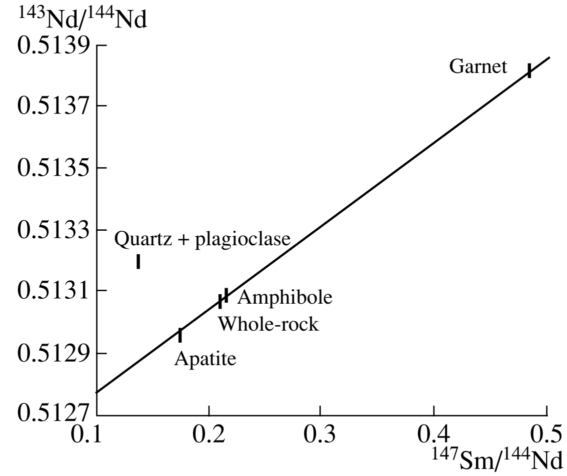

Fig. 4. Isochron diagram $^{143}Nd/^{144}Nd$–$^{147}Sm/^{144}Nd$ for garnet amphibolite (sample Khb-1790) and monomineral fractions of apatite, amphibole, garnet, and quartz–feldspar concentrates separated from this rock. $T = 415 \pm 8$ Ma; $\varepsilon_{Nd}(T) = +7.7$; MSWD = 1.3.

position of the La Jolla standard (0.511833 ± 6) equals 0.0024% (2σ, $N = 11$). The same uncertainty was estimated by parallel analyses of the Japanese standard $JNd_i1 = 0.512072$ (2σ, $N = 44$). An error in the $^{147}Sm/^{144}Nd$ ratio was accepted at 0.2% (2σ) from statistical counting of the Sm and Nd concentrations in BCR-1 standard (average of seven measurements). The procedure blank is 0.3 ng for Nd and 0.06 ng for Sm. The measured Nd isotope ratios were normalized to $^{148}Nd/^{144}Nd = 0.241570$ and then recalculated to $^{143}Nd/^{144}Nd$ = = 0.511860 in the La Jolla standard. The whole-rock sample, garnet, amphibole, and apatite, as well as a quartz–feldspar concentrate were used for Sm–Nd dating (table). The Sm–Nd mineral isochron calculated for 4 points corresponds to the age of 415 ± 8 Ma ($\varepsilon_{Nd}(T) = +7.7$; MSWD = 1.3) (Fig. 4). The point of quartz–feldspar concentrate was omitted because of inferred disturbance of the Sm–Nd system.

The obtained Late Silurian–Early Devonian age of garnet amphibolite at the base of the Khabarny mafic–ultramafic allochthon is consistent with the previously reported K–Ar age of this amphibolite (415 ± 5 Ma) [7]. The age of 410 ± 6 Ma was recently determined with the LA-ICP-MS method for zircons from migmatized amphibolite in the Zharly-Butak Depression near the southwestern contact of the Kempirsai ophiolitic allochthon [5]. A single K–Ar age determination of amphibole at 427 Ma was pointed out in review [6]. All these results coincide with one another within the error limit. Thus, we may speak with confidence about the Late Silurian–Early Devonian age of dynamometamorphism related to the obduction of giant ophiolitic allochthons in the Samara Zone of the southern Urals.

The above data on the time of metamorphism in the framework of ophiolitic allochthons in the Sakmara Zone are close to the age of peridotite: the oldest dates are not older than 427 Ma [13]. The geochronological evidence indicates that endogenic activity in ophiolitic complexes continued up to the Middle–Late Devonian (380–370 Ma), the time of high-pressure metamorphism in the Main Ural Fault Zone [9] and final episodes of mantle magmatism that sealed up ophiolitic nappes [8, 13]. The Early Devonian level at 400 Ma is considered [1] as a transition to the epoch of collision of older oceanic and island-arc complexes with the margin of the East European paleocontinent and related metamorphism.

The Late Silurian–Early Devonian age of amphibolite-facies dynamometamorphism comes into conflict with a concept assuming that no tectonic nappes were formed in the Sakmara Zone from the Late Ordovician to the Middle Devonian because of relatively quiet sedimentation in different facies settings [4, 9]. However, Ruzhentsev [10] suggested that compression in the southern Urals began already in the Late Silurian and predated the thrusting of oceanic complexes over the margin of the East European Platform. The studies performed recently by Ryazantsev et al. [11] convincingly demonstrate that the widespread Middle Ordovician volcanism in the Sakmara Zone was related to the activity of the Guberlya arc. In their opinion, this arc became

Chemical composition of garnet amphibolite (sample Khb-1790), representative analyses of amphibole and garnet, measured Sm and Nd contents and isotope ratios

Component	Garnet amphibolite	Hastingsite	Garnet	Apatite	Quartz + plagioclase
SiO_2	52.52	42.39	37.60		
TiO_2	3.241	1.87	0.07		
Al_2O_3	9.00	9.86	20.82		
FeO*	19.36	26.63	30.86		
MnO	0.33	0.26	1.82		
MgO	2.92	4.19	1.96		
CaO	7.86	10.09	7.32		
Na_2O	2.2	1.86			
K_2O	0.40	0.35			
P_2O_3	0.62				
L.O.I.	1.00				
Total	99.44	97.50	100.54		
Fe/(Fe + Mg)	0.79	0.78	0.90		
Sm, ppm	12.687	19.149	7.454	163.400	0.08
Nd, ppm	36.411	53.794	9.311	565.264	0.371
$^{147}Sm/^{144}Nd$	0.210637	0.215187	0.483983	0.174745	0.129473
$^{143}Nd/^{144}Nd$	0.513069 ± 5	0.513090 ± 22	0.513812 ± 12	0.512966 ± 10	0.513205 ± 54

Note: (FeO*) Total iron as FeO. The rock composition was determined with the XRF method on a CPM-18 spectrometer; chemical compositions of minerals were determined with a JXA-5 microprobe at the Institute of Geology and Geochemistry, Yekaterinburg. Sm and Nd contents and isotope ratios were measured at the Geological Institute, Apatity (see text).

extinct in the Silurian, and the appearance of a new west-verging subduction zone in the east promoted the formation of the Magnitogorsk island-arc system in the Devonian. According to geological observations, the volcanic and sedimentary rocks of the Guberlya Formation in the northern framing of the Khabarny allochthon plunge beneath peridotites. Making allowance for diverse composition of metamorphic rocks at the base of the Khabarny allochthon [2] and the occurrence of metaterrigenous and tuffaceous sedimentary complexes of the island-arc type, the Guberlya block can be a fragment of an accretionary prism obducted in the Late Silurian–Early Devonian by ophiolitic allochthons of the Sakmara Zone. The accretionary prism probably was a part of the Guberlya island arc, whose Ordovician age does not contradict such an interpretation.

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