Age and Sources of Metasedimentary Rocks of the Galam Terrane in the Mongol–Okhotsk Fold Belt: Results of U–Pb Age and Lu–Hf Isotope Data from Detrital Zircons

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Abstract—The Mongol–Okhotsk fold belt is one of the major structural elements of East Asia. In this article, we present U–Pb age and Hf isotope data for detrital zircons from metasedimentary rocks of the Galam Terrane. Our new data confirm that these rocks contain a significant amount of Archean and Paleoproterozoic zircons: most grains, regardless of age, have negative $\epsilon_{\text{Hf}(t)}$ values from -30.0 to -10.0 and model age $t_{\text{Hf}(C)} > 2.2$ Ga. The main sources of detrital material for the metasedimentary rocks of the Galam Terrane were igneous and metamorphic complexes of the southeastern margin of the Siberian Craton. Some of the Devonian and Carboniferous zircons have slightly negative and positive $\epsilon_{\text{Hf}(t)}$ values of -7.4 to $+6.9$ and younger $t_{\text{Hf}(C)}$ ages of 1.46 – 0.90 Ga. These zircons were derived from eroded island arcs in the Mongol–Okhotsk Paleoocean. Our results suggest that the Galam Terrane is a Paleozoic accretionary complex of the Siberian Craton.

Keywords: detrital zircon, U–Pb and Hf isotope data, provenance, Mongol–Okhotsk Paleoocean, Galam Terrane

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INTRODUCTION

The Mongol–Okhotsk fold belt is one of the main structural elements of East Asia and is probably the youngest orogenic belt within the Central Asian fold belt [74, 85]; it stretches for more than 3000 km north-east of central Mongolia through northern Mongolia, northeastern China, and eastern Russia to the Sea of Okhotsk (Fig. 1). At present, it is assumed that the Mongol–Okhotsk belt is a relic of the ocean of the same name, the closing of which occurred from west to east during collision of the Amur Superterrane and the margin of the Siberian Craton [33, 51, 71, 74, 75, 85].

The modern structural plan of the Mongol–Okhotsk belt is a complex collage of numerous fusiform tectonic blocks, which are probably fragments of accretionary wedges [33, 51, 59]. Paleozoic supra-subduction ophiolite and gabbro–granite bodies located in the Mongol–Okhotsk belt, as well as Paleozoic and Mesozoic intrusions in its southern and northern frames, indicate repeat subduction processes in the northern and southern directions (in modern coordinates) during its formation [2–4, 6–8, 19, 23, 27, 29, 30, 33, 34, 38, 47, 51, 54, 69–71, 74, 82]. However, many aspects in the evolution of the Mongol–Okhotsk belt remain unclear, including the timing and mechanisms of accretion and collision processes.

One of the keys to tectonic reconstruction of the Mongol–Okhotsk belt is systematic U–Pb geochronological and Lu–Hf isotope studies of detrital zircons. Such data make it possible to determine the lower age limit of sedimentation, as well as to characterize the age of detrital material and its source. Sedimentary deposits of the Mongol–Okhotsk belt, as a rule, are depleted in fossil flora and fauna, and therefore, geochronological data for detrital zircons are the main source of information on the age of these deposits [33, 51].

U–Pb and Lu–Hf isotope studies were performed for some objects of the Adaatsag, Doshgol, Khangai-Khentei, and Erendav terranes of the western part of the Mongol–Okhotsk belt, as well as in combination with Sm–Nd studies for objects of the Yankan, Tukuringra, Un’ya-Bom, and Dzhangdy terranes in the eastern part of the belt [22, 46, 49, 50, 62, 66]. The results of these studies show that in the structure of the Yankan terrane, metasedimentary rocks belonging to accretionary complexes formed above subduction zones with different polarities are spatially superposed [69]. It is assumed that one accretionary complex was formed in the Paleozoic in front of the southeastern margin of the Siberian Craton, and the other, in front of the northern margin of the Amur Superterrane. The similar interpretation was proposed for metasedimentary

Fig. 1. Geological sketch map of Galam Terrane (compiled after [20] with changes and additions). Asterisk denotes study area. Inset: tectonic sketch map of Mongol–Okhotsk belt and main structures of East Asia (compiled after [33], with changes and additions). 1, Siberian Craton; 2, collage of terranes of southeastern frame of Siberian Craton; 3, Mongol–Okhotsk fold belt; 4, Amur Superterrane; 5, Sikhote-Alin orogenic belt; 6–7, deposits: 6, Holocene; 7, Pleistocene; 8, Early Cretaceous granites; 9, Late Cretaceous volcanics; 10, Late Triassic–Jurassic, Early Cretaceous sedimentary rocks; 11, Permian granites; 12, major faults; 13, sampling sites; 14–20, sedimentary formation of the Galam Terrane: 14, Permian, 15, Early Carboniferous; 16, Late Devonian; 17, Middle, Middle–Late Devonian; 18, Early, Early–Middle Devonian; 19, Early Silurian; 20, Cambrian; 21, Early Paleozoic granites; 22–25, adjacent (bordering) terranes: 22, Lan; 23, Tokur, 24, Selendzha; 25, Ul’ban; 26, Late Mesozoic formations of southern frame of Siberian Craton.

rocks of the western part of the Mongol–Okhotsk belt [46, 50]. Also, U–Pb geochronological data led to the conclusion that metasedimentary rocks of the Tukuringra and Dzhagdy terranes are of Mesozoic age, not Paleozoic, as previously assumed, and they are a fragment of the Early Mesozoic accretionary complex in front of the margin of the Amur Superterrane [22, 36, 66].

Thus, the results of U–Pb, Lu–Hf isotope studies of detrital zircons from weakly metamorphosed sedimentary complexes of the Mongol–Okhotsk belt, in addition to widespread intrusive rocks along the northern and southern continental frames of the belt (in modern coordinates), suggest that the Mongol–Okhotsk ocean hosted subduction zones of opposite polarity in the Paleozoic and Mesozoic. To confirm

this assumption, we carried out U–Pb geochronological and Lu–Hf isotope studies of detrital zircons in Paleozoic metasedimentary rocks of the Galam Terrane in order to determine the age, provenance areas of terrigenous material, and tectonic nature of this terrane (Fig. 1). Because the Galam Terrane is one of the largest of the Mongol–Okhotsk orogenic belt, these data are a key for understanding the evolutionary history of the entire belt.

STRUCTURE OF THE GALAM TERRANE

The Galam Terrane is wedge-shaped (Fig. 1). In the northwest, it borders the Dzhugdzhur–Stanovoy superterrane of the southern margin of the Siberian Craton and is separated along the Uligdan fault zone from the Lan terrane of the Mongol–Okhotsk belt. In the south and southeast, the Galam terrane along the Mariinsk and Tugur fault systems borders on the Tokur, Selemdza, and Ul'ban terranes of the Mongol–Okhotsk belt. The structure of the Galam Terrane includes weakly metamorphosed terrigenous deposits, metabasalts, and limestones from the Early Cambrian to the Late Permian. According to geological mapping, the Galam Terrane consists of several structural

Fig. 2. Stratigraphic core of studied sedimentary deposits (compiled after [20] with changes and additions). International stratigraphic scale was used (after [86]). Asterisk denotes sampling site. P_{1–2}nk, Nel'kan group: metasandstones, metasiltsstones, gravelstones; C₁tm, Torom–Makit Formation: metasandstones, metasiltsstones; C₁mš, Malo-Shantar Formation: metasandstones, metasiltsstones; C₁čm, Chumavrin Formation: metasandstones, metasiltsstones, metabasalts; C₁lm, Lam Formation: metabasalts, jaspers; C₁lč, Levochumavrin Formation: metasandstones, metasiltsstones; D₃kv, Kovakh Formation: metasandstones, gravelstones; D₃kr, Korel Formation: metasiltsstones, metabasalts; D₃lg, Lindgol'm Formation: metasandstones, metasiltsstones, metabasalts; D₃mk, Maksin Formation: metasandstones, metasiltsstones; D_{2–3}nm, Nimi Formation: metasandstones, metasiltsstones, metabasalts; D₂vn, Vnutrennii Formation: metasandstones, metasiltsstones, metabasalts; D₂ak, Akrinda Formation: metasandstones, metasiltsstones; D₂it, Itmata Formation: metasandstones, metasiltsstones; D_{1–2}tk, Taikan Formation: metasandstones, metasiltsstones; D₁?el, Elgakan Formation: jasper, metabasalt, mudstone; D₁on, Onnetock Formation: metasandstones, metasiltsstones, jasper; D₁ig, Ir-Galam Formation: jaspers, metabasalts, mudstones; D₁ml, Molukan Formation: metasandstones, metasiltsstones, mudstones; D₁gr, Gerbikan Formation: metasandstones, metasiltsstones, mudstones; D₁br, Borollak Formation: metasandstones, metasiltsstones; S₂?kn, Kunnikit Formation: jasper, mudstones, metasiltsstones; S_{1–2}dž, Dzhyalak Formation: jasper, metabasalts, metasandstones, metasiltsstones; S₁?tl, Tyalakchan Formation: mudstones, jaspers, metabasalts; S₁lg, Lagap Formation: metabasalts, metasandstones; S₁bg, Burgali Formation: metabasalts, metasandstones; E₃?ir, Ir Formation: jaspers, metabasalts, mudstones; E_{2–3}dž, Dzhavodi Formation: limestones, jaspers, metabasalts; E_{1–2}tl, Ty'lsk Formation: limestones; E_{1–2}kr, Kurum Formation: jasper, mudstone, metabasalt; E₁ut, Ust'-Tok Formation: jasper, mudstones, metabasalts; E₁mut, Maloutonak Formation: limestones, metasandstones, metasiltsstones.

Period	Galam Terrane			
	Galam Block	Tyl'sk Block	Tugur Block	Selitkan Block
Permian	P _{1–2} nk			
Carboniferous		C ₁ tm C ₁ čm		
			C ₁ mš	
		C ₁ lč	C ₁ lm	
		D ₃ kv	D ₃ kr	D ₃ mk
			D ₃ lg	
		D _{2–3} nm		D ₂ ak V-126 ★
		?	D ₂ vn	D ₂ it
			D ₂ bl	?
		D _{1–2} tk		
		D ₁ ?el		
Devonian		D ₁ on V-131 ★		
		D ₁ ig V-118 ★	D ₁ ml	
		D ₁ gr	D ₁ br	
Silurian	S _{1–2} dž V-138 ★	S ₂ ?kn		
		S ₁ ?tl		
	S ₁ lg	?		
	S ₁ bg			
Cambrian				
	E ₃ ?ir			
	E _{2–3} dž	E _{2–3} dž		
	E ₁ ut + E _{1–2} kr	E _{1–2} tl		
		?		
		E ₁ mut		
		?		

zones or tectonic blocks: the Galam, Tyl'sk, Tugur, and Selitkan blocks [16] (Fig. 2).

The most ancient in the Galam Terrane are the Maloutannak (2900 m), Dzhavodi (1800 m), Ust'-Tok (1400 m), Ir (1250 m), Kurum (450 m), and the Tyl'sk (390 m) formations, which are mainly represented by siliceous rocks, metabasalts, fine-grained sandstones and siltstones, and limestones (Fig. 2). According to V.Yu. Zabrodin et al. [20], limestones contain a diverse Cambrian fauna of archaeocyathids (*Ladaecyathus* sp., *Erbocyathidae* gen. et sp. indet., *Tumuliolynthus* sp., *Capsulocyathus* (?), *Fransuasaecyathus* sp. indet., *Ajacyathus* sp., *Nochoroicyathus lenaicus* Zhuravl., *Tumuliolynthus* sp., *Archaeolynthus* sp.); trilobites (*Alokistocare*? sp. nov., *Ptychoporiidae* gen. et sp. nov., *Glyptagnostus* ex gr. *reticulatus*); and brachiopods (*Obolella* aff. *chromatica* Billings., *Lingulella minuscula* Sob., *Acrothele horida* Sob., *Dictyonina hexagona* Bell., *Acrotretidae* den. et sp. indet., *Angulotrete triangularis* Palmer, *Opisthotretadepressa* Palmer). Cambrian radiolarians *Polyentactinia dzhagdiensis* Naz. and *Entactinia iriensis* Naz. have been found in cherts.

The Silurian Burgali (2600 m), Tylakchan (2250 m), Lagap (1910 m), Dzhyalak (1200 m), and Kunnikit (500 m) formations are lithologically close to Cambrian deposits (Fig. 2). Terrigenous rocks contain corals *Palaeofavosites alveolaris* (Goldf.), *Multisolenia tortuosa* Fritz., *Multisolenia ninae* (Tchern.), *Favosites gothlandicus* Lam., *Miculiella annae* Ivnsk., brachiopods *Eospirifer radiatus* (Sow.), *Clorinda substantiva* Kulk., and *Protatrypa septentrionalis* (Nikif.) [20].

The Devonian Gerbikan (4240 m), Ir-Galam (3590 m), Onnetock (3100 m), Nimi (2900 m), Korel (2800 m), Taikan (2530 m), Molukan (2360 m), Imata (2125 m), Elkagan (1620 m), Kovakh (1525 m), Borol-lak (1500 m), and Maksin (1200 m), formations, as well as the Akrinda (to 5000 m) and Cape Vnutrenniy (2100 m) formations, are represented by sandstones, siltstones, clay shale, calcareous rocks, jasper, and basalts (Fig. 2).

Sedimentary rocks contain plant remains and spore-pollen complexes of *Taeniocrada* cf. *decheniana* (Goepp.) Kr. et W., *Drepanophycus spinaeformis* Goepp., *D.* cf. *gaspianus* (Daws.) Stock., *Eogaspesia gracilis* Dab., *Psilophyton* cf. *princers* Daws., *Aphyllopteris* sp., *Dicranophyton* sp., *Dawsonites* sp., *Protolepidodendron* cf. *scharyanum* Kr., *P. protolepidodendron scharyanum* Kr., *Aneurophyton germanicum* Kr. et W. Various stromatoporoid complexes were found in limestones: *Stromatopora boiarschynoi* J. a vor., *Simhlexodictyon coninconicum* Khrom., *Tabulata Corolites* sp., *Pachyfavosites* sp., *Oculipora* sp., *Alveolites* sp., *Alveolitella* sp., *Crassialveolites* aff. *crassus* (Les.), *Placacoen-jenites* ex gr. *orientalis* Eichw., Bryozoan *Semicoscium raskovskii* Nekh., *S. graniferum* (Hall), *Fenestella vera* Ulrich., *Atrypa devoniana descrensens* F. et F., *A. matutinalis* Khud., *Vagrana kolymensis* (Nal.) V. cf. *koly-mensis* (Nal.) Var. *intermediafera* (Khud.), *V. (Mina-*

trypa) flabellata (Roem.), *Lasutkina* sp., crinoids *Cupressocrinites* cf. *minor* Yelt., *C. gracilis* Goldf., *Mediocrinus* cf. *medius* (Yelt.), *M. persimilis* (I. Dubat.), *Pentagonacyclis petrovensis* Schisch [20].

The Lower Carboniferous Chumavrin (3500 m), Levochumavrin (2750 m), Lam (1600 m), Malo-Shantar (1200 m), Torom-Makit (800 m), as well as Devonian formations, are represented by terrigenous-carbonate and volcanogenic-siliceous (jasper) rocks (Fig. 2). Siltstones and limestones contain bryozoans *Rhombopora* sp., *Nikiforovella* sp., *Sulcoretepora* aff. *astepnata* Nekh., *Fenestella* sp. (aff. *F. rudis* Ulr.), Crinoids *Platycrinites* (?) *texanum* (M. et Jeff.), *Pentagonocyclis priscus* Sfuk. The following conodonts have been established in jasper: *Siphonodella* cf. *obsoleta* Hass., *Polygnathus* ex gr. *inornatus* Br. et M., *Siphonodella* sp. aff. *S. crenulata* (Cooper), *S.* sp. aff. *S. lobata* (Br. Et M.), *S.* sp. aff. *S. sulcata* (Huddle), *Scaliognothus* cf. *anchoralis* Br. et. M [20].

The Permian Nel'kan (3650 m) group consists of coarse-grained terrigenous sediments containing bivalvia *Neoschizodus* sp., *Chaenomya* (?) sp., *Edmondia* (?) sp., Angarian flora *Paracalamites* cf. *vicinalis* Radcz., *P.* cf. *angustus* Such., *Noegatheriopsis* cf. *derzavini* Neub., *N. tschirkovae* Zal [20] (Fig. 2).

Plagiogranite intrusions occur along the Uligdan Fault, which separates the Galam Terrane from the metamorphic complexes of the southern margin of the Siberian Craton (Fig. 1). On the modern geological map, these rocks are attributed to the Lower Devonian (?) Maloelga Complex [20]. According to Sun et al. [67], plagiogranites are of Cambrian age (511 ± 3 Ma, U-Pb method based on zircons).

Upper Cretaceous granitoids and volcanic rocks are widespread within the Galam Terrane (Fig. 1). They formed after closing of the Mongol-Okhotsk belt and are associated with tectonic processes along the Pacific margin of Asia.

The concepts of the geodynamic nature of the Galam Terrane are significantly different. B.A. Natal'in [32] believed that the Galam Terrane is an accretionary complex of the Siberian Craton, which is a complex thrust structure. In the structure of the terrane, he identified three rock associations:

- basalts and siliceous rocks;
- terrigenous-layered deposits;
- olistostromes.

It was shown that these rock associations make up separate tectonic plates, but they do not form a single sedimentary formation [32]. A.I. Khanchuk [15, 51] proposed a model according to which the Galam Terrane is a displaced fragment of the Okhotsk-Koryak orogenic belt, not a component of the Mongol-Okhotsk belt. This model is based on the similarity of the Cambrian fauna of the Galam Terrane and Okhotsk-Koryak belt.

Fig. 3. Micrographs of samples (a) V-126, (b) V-131, (c) V-118, and (d) V-138. Indicated (abbreviations): Pl, plagioclase; Q, quartz; Ser, sericite.

In order to refine the geodynamics of the Galam Terrane, we carried out U–Pb geochronological and Lu–Hf isotope studies of detrital zircons from:

- metasilstone of the Dzhyalak Formation (sample no. V-138);
- metasandstone of the Ir-Galam Formation (sample no. V-118);
- metasandstone of the Onnetock Formation (sample no. V-131);
- metasilstone of the Akrinda Formation (sample no. V-126).

The sampling sites and micrographs of thin sections are shown in Figs. 1 and 3 and Table 1.

ANALYTICAL METHODS

U–Pb Geochronological Studies

Detrital zircons were isolated from metasedimentary rocks in the mineralogical laboratory of the Institute of Geology and Mineralogy, FEB RAS (Blagoveshchensk, Russia) using heavy liquids. Next, the zircons, together with standard zircons (FC, SL and R33), were mounted in an epoxy block and polished to expose mid-grain sections. The internal structure of zircon grains was studied in the CL and BSE modes using a Hitachi S-3400N scanning electron microscope (Hitachi High Technologies America Inc.) equipped with a Gatan Chroma CL2 detector (Gatan Inc., USA). Prior to isotope analyses, zircons were

purified in an ultrasonic bath with 1% HNO₃ and 1% HCL to remove any residual total lead from the surfaces of the zircons. U–Pb geochronological studies of zircons were carried out at the Geochronological Center of the University of Arizona (Arizona Laser-Chron Center, Tucson, Arizona, USA) using a Photon Machines Analyte G2 laser ablation system (Photon Machines Inc., USA) and an ICP Thermo Element 2 mass spectrometer (Thermo Fisher Scientific Inc., Germany). The crater diameter was 20 µm and the depth was 15 µm. Calibration was done according to the FC standard (Duluth Complex, 1099.3 ± 0.3 Ma [60]). Zircons SL (Sri Lanka) and R33 (Bainbrete complex) [43] as secondary standards for the control of measurements. The age values based on the ²⁰⁶Pb/²³⁸U and ²⁰⁷Pb/²⁰⁶Pb ratios for the SL standard during measurements was 557 ± 5 and 558 ± 7 Ma (2σ), respectively, which agrees well with the values obtained by G. Gehrels with the ID-TIMS method [48]. The average ages based on the ²⁰⁶Pb/²³⁸U and ²⁰⁷Pb/²⁰⁶Pb ratios for the R33 standard were 417 ± 7 and 415 ± 8 Ma, corresponding to the recommended ones [43, 56]. Systematic errors are 0.9% for the ²⁰⁶Pb/²³⁸U ratio and 0.8% for the ²⁰⁶Pb/²⁰⁷Pb ratio (2σ). Corrections for common Pb were introduced based on ²⁰⁴Pb corrected by ²⁰⁴Hg, in accordance with the model values. A detailed description of the analytical procedures is presented on the website of the University of Arizona Geochronological Center [87]. Concordant ages were calcu-

Table 1. Determination of age, sampling site, and rock composition in samples (%)

Period (System)	Sample no.	GPS (x°x'x'')	Formation	Rocks composition in samples
<i>Galam Terrane</i>				
Middle Devonian (?)	V-126	134°29'37.4" E 53°14'09.2" N	Akrinda Formation	Gray schistose metasiltstones 0.02–0.10 mm, angular and subrounded: 25–30% quartz, 8–10% clastic rock, 30–35% plagioclase, 10–15% sericite
Early Devonian (?)	V-131	133°47'16.7" E 53°45'02.7" N	Onnetock Formation	Gray massive metasandstones 0.15–0.20 mm angular and subrounded: 30–35% quartz, 7–9% clastic rock, 38–45% plagioclase
Early Devonian (?)	V-118	132°38'30.0" E 53°22'05.1" N	Ir-Galam Formation	Gray massive metasandstones 0.15–0.20 mm angular and subrounded: 20–25% quartz, 8–12% debris, 40–47% plagioclase, 2–3% sericite
Silurian (?)	V-138	133°51'15.5" E 54°00'43.9" N	Dzhyalak Formation	Massive gray metasandstones 0.15–0.20 mm angular and subrounded: 20–25% quartz, 8–10% clastic rock, 35–42% plagioclase, 5–7% sericite

lated using Isoplot software (v. 3.6) [55, 68]. The following were excluded from the final age calculations:

- data for which it was impossible to calculate concordant ages;

- concordant ages that correspond to a 95% confidence level, but for which MSWD > 1;

- $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ratios with errors >3%, since they exceed the accuracy of the LA-ICP-MS method.

The AgePick program [87] was used to calculate the values of the peaks on the age probability curves.

Lu–Hf Isotope Studies of Zircons

Lu–Hf isotope analyses of zircons were performed at the University of Arizona Geochronological Center (Arizona LaserChron Center, Tucson, Arizona, USA) using a Nu High-Resolution Multi-Collector Induction-Coupled Plasma Mass Spectrometer (MC-ICP-MS) (Nu Instruments, UK) and an Analyte G2 excimer laser (Teledyne CETAC, UK). Standard solutions JMC475, Spex Hf and Spex Hf, Yb and Lu, as well as standard zircons Mud Tank, 91500, Temora, R33, FC52, Plesovice and SL, were used to adjust and check the quality of analyses.

Lu–Hf isotope analyses were performed at the same point as U–Pb analyses. The laser beam diameter was 40 μm , the laser power was about 5 J/cm², the frequency was 7 Hz, and the ablation rate was about 0.8 $\mu\text{m/s}$. Details of the analytical methodology are presented on the website of the University of Arizona Geochronological Center [87].

To calculate $\epsilon_{\text{Hf}(t)}$ the decay constant ^{176}Lu ($\lambda = 1.867 \times 10^{-11}$) was used after [63]. When calculating $\epsilon_{\text{Hf}(t)}$, the following chondrite ratios were used: $^{176}\text{Hf}/^{177}\text{Hf}$ (0.282785) and $^{176}\text{Lu}/^{177}\text{Hf}$ (0.0336) [45]. Crustal Hf-model ages $t_{\text{Hf}(C)}$ were calculated by taking the average ratio $^{176}\text{Lu}/^{177}\text{Hf}$ in the continental crust of 0.0093 [42, 73]. To calculate the isotope parameters of the depleted mantle, the modern ratios $^{176}\text{Hf}/^{177}\text{Hf} = 0.28325$ and $^{176}\text{Lu}/^{177}\text{Hf} = 0.0384$ [44, 64] were used.

RESULTS

U–Pb Geochronological Studies

The results of U–Pb geochronological studies are given in Fig. 4 and Table S1 of Supplement 1. Cathodoluminescence (CL) images of individual detrital zircons from the youngest populations are shown in Fig. 5.

Fig. 4. Relative U–Pb age probability curves for detrital zircons from metasedimentary rocks of Galam Terrane. (a)–(d) samples: (a) V-138 (metasandstones of Dzhyalak Formation); (b) V-118 (metasandstones of Ir-Galam Formation); (c) V-131 (metasandstones of Onnetock Formation); (d) V-126 (metasiltstones of Akrinda Formation).

Sample V-138 (metasandstone of the Silurian Dzhyalak Formation (Fig. 3d; Table 1)). Of the 145 analyzed detrital zircons, a concordant age was obtained for 120 grains (Fig. 4a; Supplement 1: Table S1). Zircons are predominantly Paleoproterozoic (peaks on the age

probability curve at 2121, 1982, and 1900 Ma), less often Archean (peak at 2514 Ma) and Early Paleozoic (peak at 512 Ma). In addition, there is an insignificant amount of Neoproterozoic zircons with ages of 877 ± 5 , 827 ± 5 , 798 ± 8 , 797 ± 4 , and 586 ± 4 Ma. The ages

Fig. 5. Representative (CL) Images of detrital zircons from youngest populations from metasedimentary formation of the Galam Terrane.

of the youngest zircons are 511 ± 4 , 508 ± 3 , 486 ± 3 , and 480 ± 4 Ma, while the concordant age of the youngest group of three grains cannot be calculated.

Sample V-118 (metasandstone of Lower Devonian Ir-Galam Formation (Fig. 3c; Table 1)). One hundred nine concordant age estimates were obtained from 124 analyzed detrital zircons (Fig. 4b; Supplement 1: Table S1). Most of the grains are Paleoproterozoic (peaks on the probability age curve at 1976 and 1887 Ma) and Devonian (peak at 380 Ma). In addition, there are a number of Archean zircons (peaks at 2735 and 2537 Ma), as well as seven grains with concordant ages in the interval of 870–502 Ma. The concordant age of the youngest zircon is 368 ± 5 Ma; the concordant age of the youngest group of three grains is 371 ± 3 Ma.

Sample V-131 (metasandstone of the Lower Devonian Onnetock Formation (Fig. 3b; Table 1)). Of the 120 analyzed grains of sample V-131, 104 concordant age estimates were obtained (Fig. 4c; Supplement 1: Table S1). The age of most grains are Archean (peak at 2618 and 2489 Ma), Paleoproterozoic (peak at 1907 Ma), and Paleozoic (peaks at 493, 442, and 387 Ma). Several Neoproterozoic zircons are present (peak at 796 Ma). The concordant age of the youngest

zircon is 372 ± 5 Ma, and the concordant age of the youngest group of three grains is 374 ± 3 Ma.

Sample V-126 (metasiltstone of the Middle Devonian Akrinda Formation (Fig. 3a; Table 1)). A total of 128 detrital zircon grains from this sample were analyzed, of which concordant values were obtained for 116 grains (Fig. 4d; Supplement 1: Table S1). The overwhelming majority of zircons are Paleoproterozoic (the peaks on the probability age curve at 1967 and 1892 Ma), Neoproterozoic (peaks and 901, 805, 590, and 575 Ma) and Paleozoic (peaks at 508, 360, and 334 Ma). The concordant age of the youngest zircon is 324 ± 5 Ma; the concordant age of the youngest group of three grains is 378 ± 3 Ma.

Lu–Hf isotope studies of zircons

The results of Lu–Hf isotope studies of zircons are shown in Fig. 6 and Supplement 1: Table S2.

Lu–Hf isotope studies were performed for:

- 22 zircon grains from metasiltstone (sample no. V-138) of the Silurian Dzhyalak Formation;
- 19 zircon grains from metasandstone (sample no. V-118) the Lower Devonian Ir-Galam Formation;

— 22 zircon grains from metasandstone (sample no. V-131) of the Lower Devonian Onnetok Formation;

— 20 zircon grains from metasilstone (sample no. V-126) of the Middle Devonian Akrinda Formation.

According to the results obtained, Archean and Paleoproterozoic zircons have negative and weakly positive $\epsilon_{\text{Hf}(t)}$ values from -20.3 to $+3.4$, and two-stage Hf-model ages ($t_{\text{Hf}(C)}$) > 2.2 Ga (Fig. 6; Supplement 1: Table S2).

Neoproterozoic and Cambrian grains have higher $\epsilon_{\text{Hf}(t)}$ values from -5.2 to $+11.5$ and younger values of Hf-model ages $t_{\text{Hf}(C)} = 1.61$ – 1.01 Ga (Fig. 6; Supplement 1: Table S2).

The $\epsilon_{\text{Hf}(t)}$ values and Hf-model ages of Ordovician, Silurian, Devonian and Carboniferous zircons are very different. They can be divided into two groups. The first is characterized by extremely negative $\epsilon_{\text{Hf}(t)}$ values from -33.0 to -12.1 with Archean and Paleoproterozoic model ages $t_{\text{Hf}(C)}$ 2.82– 1.76 Ga. The second group is characterized by weakly negative and positive $\epsilon_{\text{Hf}(t)}$ values from -7.4 to $+6.9$ and younger (Mesoproterozoic–Neoproterozoic) model ages $t_{\text{Hf}(C)}$ 1.46– 0.90 Ga (Fig. 6; Supplement 1: Table S2).

DISCUSSION

Sedimentation Boundary Conditions of the Galam Terrane

Zircons, which make up the youngest age populations in the studied samples, have oscillatory zoning, indicating their magmatic origin (Fig. 5). In addition, these zircons are characterized by a Th/U ratio of 1.1–0.2, which is also typical of magmatic zircons [61, 76].

The concordant age of the youngest zircon from metasilstone (sample no. V-138) of the Dzhyalak Formation is 480 ± 4 Ma, and the youngest peak on the age probability curve corresponds to 512 Ma (Fig. 4a). These data indicate the age boundary of the deposits of this formation from Middle Cambrian to Early Ordovician. Thus, our results agree with the Silurian age of the Dzhyalak Formation, determined by the fossil fauna [20].

In metasandstone (sample no. V-118) of the Ir-Galam Formation, the concordant age of the youngest zircon is 368 ± 5 Ma, and the youngest peak on the age probability curve corresponds to 380 Ma (Fig. 4b). These data indicate that the lower sedimentation boundary of deposits of the Ir-Galam Formation is Late Devonian, which does not correspond to the age of this formation established from the fossil flora [20]. This could mean:

— there is a need to revise the age of the Ir-Galam Formation;

Fig. 6. Diagram of $\epsilon_{\text{Hf}(t)}$ age (Ma) for zircons from metasedimentary rocks of the Galam Terrane. 1–4, samples: 1, Dzhyalak Formation (sample no. V-138); 2, Ir-Galam Formation (sample no. V-118); 3, Onnetok Formation (sample no. V-131); 4, Akrinda Formation (sample no. V-126)

— the sample studied by us belongs to another (younger) thicker formation.

Currently, both causes are equally likely.

The concordant age of the youngest zircon from metasandstone (sample no. V-131) of the Onnetok Formation is 372 ± 5 Ma, and the youngest peak on the age probability curve corresponds to 387 Ma (Fig. 4c). These data indicate that the lower sedimentation boundary of these deposits is Middle Devonian. This contradicts the concept of the Early Devonian age of the Onnetok Formation, based on the finds of fossil flora [20], and can be explained by the same reasons given by us for the Ir-Galam Formation.

The youngest zircon from metasilstone (sample no. V-126) of the Akrinda Formation has a concordant age of 324 ± 5 Ma; the youngest peak on the relative age probability curve corresponds to 334 Ma (Fig. 4d). These data determine the lower age boundary for the deposits of this formation as the Mississippian. However, this suite contains abundant marine fauna of the Middle Devonian [20]; therefore, sample V-126 probably belongs to a younger sedimentary formation.

Characteristics of Provenance Areas of Detrital Material

The eastern part of the Mongol–Okhotsk belt is located between the southeastern margin of the Siberian Craton and the Amur Superterrane, which are potential provenance areas of detrital material for sedimentary rocks in the Mongol–Okhotsk belt (Fig. 1). These provenance areas are characterized by sharply different age and isotope characteristics.

The southeastern frame of the Siberian Craton with the Early Precambrian basement is the source of both Early Precambrian and younger zircons with

Early Precambrian Hf-model ages [1, 5, 9–14, 26, 31]. Conversely, the Amur Superterrane does not have an Early Precambrian basement and is composed of Neoproterozoic and Paleozoic and Early Mesozoic geological complexes [24, 25, 35, 37, 58, 65, 77, 80, 83, 84]. Therefore, this is the provenance area of Neoproterozoic, Paleozoic and Early Mesozoic zircons with Neoproterozoic (less frequently—Mesoproterozoic) Hf-model age.

There is a third possible provenance area of detrital material: island arcs in the Mongol–Okhotsk Ocean. Their existence is presumed in most tectonic models of the evolution of this belt [33, 51, 71, 74, 75, 85]. It is possible that Paleozoic gabbro and plagiogranite bodies are the roots of such island arcs, but geochronological and Hf isotope data for these rocks are usually lacking.

Our U–Pb geochronological data show that Paleoproterozoic zircons prevail in metasedimentary rocks of the Galam Terrane (Dzhyalak, Ir-Galam, Onnetock formations, and the Akrinda Formation), while Archean zircons are present in significant amounts (Figs. 4 and 6; Supplement 1: Table S1). These zircons are characterized by $\epsilon_{\text{Hf}(t)}$ values from -20.3 to $+3.4$ and model ages $t_{\text{Hf}(C)} > 2.2$ Ga. The only provenance areas of such zircons in the region under consideration may be Paleoproterozoic and Archean magmatic and metamorphic complexes of the southeastern frame of the Siberian Craton [1, 5, 9–13, 16–18, 26, 28, 31].

Neoproterozoic and Cambrian zircons are quite rare in metasedimentary rocks of the Galam Terrane. These zircons have weaker negative and positive $\epsilon_{\text{Hf}(t)}$ values from -5.2 to $+11.5$ and fairly young model ages $t_{\text{Hf}(C)} 1.61$ – 1.01 Ga (Fig. 6; Supplement 1: Table S2). Judging from the Hf isotope characteristics, island arcs could have been the source of these zircons. In particular, Cambrian (511 ± 3 Ma) plagiogranites of the Galam Terrane may be the root part of such an arc. This is confirmed by positive $\epsilon_{\text{Hf}(t)}$ values from $+8.8$ to $+14.8$ in zircons from these rocks [67].

Most of the Paleozoic zircons in metasedimentary rocks of the Galam Terrane are Devonian (samples V-118, V-126, and V-131) and Carboniferous (sample V-126) in age (Fig. 4; Supplement 1: Table S2). These zircons vary widely in the parameter $\epsilon_{\text{Hf}(t)}$ and the values of Hf-model ages (Fig. 6; Supplement 1: Table S2). Zircons with negative $\epsilon_{\text{Hf}(t)}$ values from -33.0 to -12.1 and Archean/Paleoproterozoic model ages $t_{\text{Hf}(C)} = 2.82$ – 1.76 Ga could have entered the sedimentation basin only from the southern margin of the Siberian Craton. Such sources could have been the following:

- granitoids of the Olekma Complex with ages of 358 ± 6 Ma [30] and 360 ± 2 Ma [12];
- granitoids of the Barguzin complex with an age of 330 – 310 Ma [38, 40].
- volcanic rocks of the Amazar–Gilyui zone with an age of 358 ± 2 Ma [38, 40].

The source of the Late Devonian zircons is unclear, but they may be intrusions of the Krestovsky and Kruchinin complexes [41].

Another group of Devonian and Carboniferous zircons is characterized by weakly negative and positive $\epsilon_{\text{Hf}(t)}$ values from -7.4 to $+6.9$ and younger (Mesoproterozoic–Neoproterozoic) ages $t_{\text{Hf}(C)} 1.46$ – 0.90 Ga (Fig. 6; Supplement 1: Table S2). The Hf isotope composition of these zircons suggests an origin of rocks without significant involvement of Early Precambrian crust in the sources of primary melts. Thus, this source cannot be located within the margin of the Siberian Craton. Consequently, these sources can be island arcs of the Mongol–Okhotsk Ocean, or complexes of the Amur Superterrane. Available paleomagnetic data indicate a large distance in the Paleozoic between the Siberian Craton and the continental massifs combined in the Amur Superterrane, which excludes the simultaneous influx of detrital material from the Siberian Craton and Amur Superterrane in the Paleozoic [51–53, 57, 72, 78, 79, 81]. Consequently, the island arcs of the Mongol–Okhotsk Ocean can be considered the main provenance areas of Devonian and Carboniferous zircons with $\epsilon_{\text{Hf}(t)}$ values from -7.4 to $+6.9$ and Mesoproterozoic/Neoproterozoic Hf-model ages. Currently, there is no evidence of Devonian and Carboniferous island arcs in the eastern part of the Mongol–Okhotsk belt. However, it is possible that tonalites with an age of 392 ± 18 Ma are examples of such arcs [67].

Thus, our data suggest that the detrital material for the metasedimentary rocks of the Galam Terrane came mainly from the southeastern (in modern coordinates) margin of the Siberian Craton, as well as from the island arcs of the Mongol–Okhotsk Ocean.

TECTONIC IMPLICATION

Based on structural studies, B.A. Natal'in and L.I. Popeko [32] showed that the Galam Terrane is a Mesozoic accretionary complex of the Siberian Craton, which explains the close spatial association of rocks of different origin (cherts, limestones, basalts, and sandstones).

Based on our U–Pb geochronological and Lu–Hf isotope–geochemical data for detrital zircons, it follows that the main provenance areas of detrital material for metasedimentary rocks of the Galam Terrane were located in the southeastern margin of the Siberian Craton. The geological material supplied by the island arcs of the Mongol–Okhotsk Paleoocean accumulated to a much lesser extent. Our data additionally confirm that the Galam Terrane is an accretionary complex (or part of it) formed in the frontal part of the southeastern margin of the Siberian Craton.

In determining the formation age of the Galam accretionary complex, the following conditions were taken into account [12, 30, 38–40]:

Fig. 7. Relative U–Pb age probability curves for detrital zircons from metasedimentary rocks of (a) Galam Terrane versus age determination of zircons from rocks of (b) Lan Terrane (according to obtained data with use of data from [21]).

— The Galam Terrane consists mainly of Silurian, Devonian, and Early Carboniferous formations;

— Permian sedimentary complexes are poorly developed and can possibly be attributed to later evolution of the Mongol–Okhotsk Ocean;

— along the southern and southeastern margins of the Siberian Craton, granitoids and volcanic rocks

(Late Devonian and Early Carboniferous) are widespread, probably associated with subduction under this margin.

Based on these data, we believe that the Galam accretionary complex is Late Paleozoic in age. However, this does not exclude the possibility that younger accretion complexes were also present along the southern margin of the Siberian Craton. In particular, the Lan Terrane is a Mesozoic accretionary complex, which consists of Late Paleozoic and Early Mesozoic formations [21] (Fig. 1). The plots of the relative ages probability curves of zircons from metasedimentary rocks of the Lan and Galam terranes, as well as the Hf isotope composition of these zircons, approach each other (Figs. 7a, 7b, 8). However, the metasedimentary rocks of the Lan terrane contain younger zircons than those in the Galam Terrane. Thus, the results of analyzing the isotope composition of zircons may indicate the existence of Paleozoic and Mesozoic subduction zones under the southern and southeastern margins of the Siberian Craton (in modern coordinates).

We cannot ignore the fact that A.I. Khanchuk's model [15, 51], which assumes that the Galam Terrane is a displaced fragment of the Okhotsk–Koryak orogenic belt, reconstructs geological processes with a high degree of reliability, but at first glance, this model contradicts the results of our studies. However, we consider it important to emphasize that the Khanchuk's research objects were the Cambrian complexes,

Fig. 8. Diagram of $\epsilon_{\text{Hf}(t)}$ age (Ma) for zircons from metasedimentary rocks of (a) Galam Terrane versus age determinations of zircons from rocks of (b) Lan Terrane (after [21]). 1–2, terranes: 1, Galam; 2, Lan.

while the objects of this study were Silurian, Devonian, and Carboniferous (?) metasedimentary complexes. Therefore, it can be suggested that the Cambrian and younger complexes have different tectonic natures and represent different tectonic plates combined in the modern structure of the Galam Terrane.

CONCLUSIONS

The data obtained and results of the research led to the following conclusions:

(1) In the studied Ir-Galam, Onnetock, and Akrinda formations, the age of the sedimentation boundary based on U–Pb dating of detrital zircons proved younger than the age established from fossil fauna.

(2) Detrital zircons in metasedimentary rocks of the Galam Terrane contain a large number of Archean and Paleoproterozoic zircons. In addition, most zircons, regardless of age, have predominantly negative $\epsilon_{\text{Hf}(t)}$ values from -30.0 to -10.0 and Hf-model ages $t_{\text{Hf}(C)} > 2.2$ billion years. These data suggest that the main provenance areas of detrital material for metasedimentary rocks of the Galam Terrane were located in the southeastern margin of the Siberian Craton.

(3) The influx of Devonian and Carboniferous detrital zircons with weakly negative and positive $\epsilon_{\text{Hf}(t)}$ values from -7.4 to $+6.9$ and younger model ages $t_{\text{Hf}(C)} = 1.46\text{--}0.90$ Ga occurred due to the breakup of island arcs in the Mongol–Okhotsk Ocean.

(4) The Galam Terrane is a Paleozoic accretionary complex (or part of it) at the southeastern margin of the Siberian Craton.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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ADDITIONAL INFORMATION

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