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GEOLOGY

Geological History of the Late Precambrian Patom Supergroup (Central Siberia)

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The Patom Supergroup, which constitutes the outer arc of the Patom fold zone, represents one of the thickest and most complete Late Precambrian sections in the Siberian Platform framing. This section is of key importance for understanding the geological history of the northern Baikal orogenic region and for dating Late Precambrian glaciation of Siberia. The Patom Supergroup is subdivided into three groups and nine formations (figure). Its stratotype is located in the eastern branch of the outer arc in the Zhuya River. Based on marker members and successive correlation of sections, analogues of all stratotype units are traced to the northeast up to the transverse Ura Uplift [1], to the east up to the western slope of the Aldan Shield [2], and to the west up to the Bodaibo Synclinorium [3–5]. This correlation was confirmed with some refinements by many specific works and standard geological surveys (scale 1: 200 000 or larger). The results of these works are summarized in [6].

Since the early 1960s, the Patom Supergroup was referred to the Middle and Upper Riphean based on the study of stromatolites, catagraphs, and oncolites [7]. The Ballaganakh and Dal'nyaya Taiga groups were referred to the Middle Riphean, whereas the Zhuya Group was referred to the Upper Riphean. Subsequently, the Dal'nyaya Taiga Group was correlated with the Middle–Upper Riphean [6], or the entire Patom Supergroup was referred to the Upper Riphean [8]. All researchers referred the Zherba and Tinnaya formations, which overlie the supergroup, to the Vendian. This is confirmed by finds of small shell fossils of the Nemakit–Daldyn Horizon in the upper part of the Tinnaya Formation and faunal remains of the Lower Cambrian (Tommotian) *Ajacicyathus sunnaginicus* Zone in basal layers of the overlying Nokhtuisk Formation [9].

In [10], Sovetov put in doubt the Riphean age of the two upper groups of the Patom Supergroup and referred them to the Vendian. He arrived at this conclusion based on interregional correlation and paleogeographic reconstructions. Recent studies yielded new data suggesting that the major part of the supergroup is younger than the Riphean. First, the analysis of carbon isotopic composition in carbonate rocks of the supergroup (from the Marinsk to Chena formations) revealed anomalous variations in $\delta^{13}C$ (from +8.1 to –12.5‰ [11]) that are only typical of the terminal Late Proterozoic (750–545 Ma). Minimal $^{87}Sr/^{86}Sr$ values in carbonates of the Dal'nyaya Taiga and Zhuya groups (0.70725–0.70799) specify the age for this part of the Patom Supergroup up to the range of 660–580 Ma [11].

Second, the younger-than-Riphean age of the supergroup is evidenced by microfossils from the Ura Formation, which corresponds to the lower part of the Valyukhta Formation in the stratotype. Our sample collection from the Ura Formation yielded a diverse microfossil assemblage. According to determination by N.G. Vorob'eva and subsequent confirmation by V.N. Sergeev (private communication, 2005), the assemblage contains abundant acanthomorphic acritarchs of *Ericiasphaera, Echinosphaeridium*, and *Tanarium,* and new genera with features typical of Lower Vendian taxa.

In addition, the assemblage contains smooth-walled vesicles with peculiar structures and filamentous microfossils. As a whole, this microbiota is close to the Pertatatka-type microfossils described from the upper part of the postglacial (post-Marino) Ediacaran Pertatatka Formation (Central Australia), Doushanto Formation (China), Scotia Formation (Spitsbergen), Infrakrol Formation (India), and upper part of the Nepa Horizon in the Siberian Platform. Nagovitsyn et al., who were first to describe the Ura microfossil assemblage [13], dated it back to the Late Riphean based on the presence of some forms similar to Riphean taxa.

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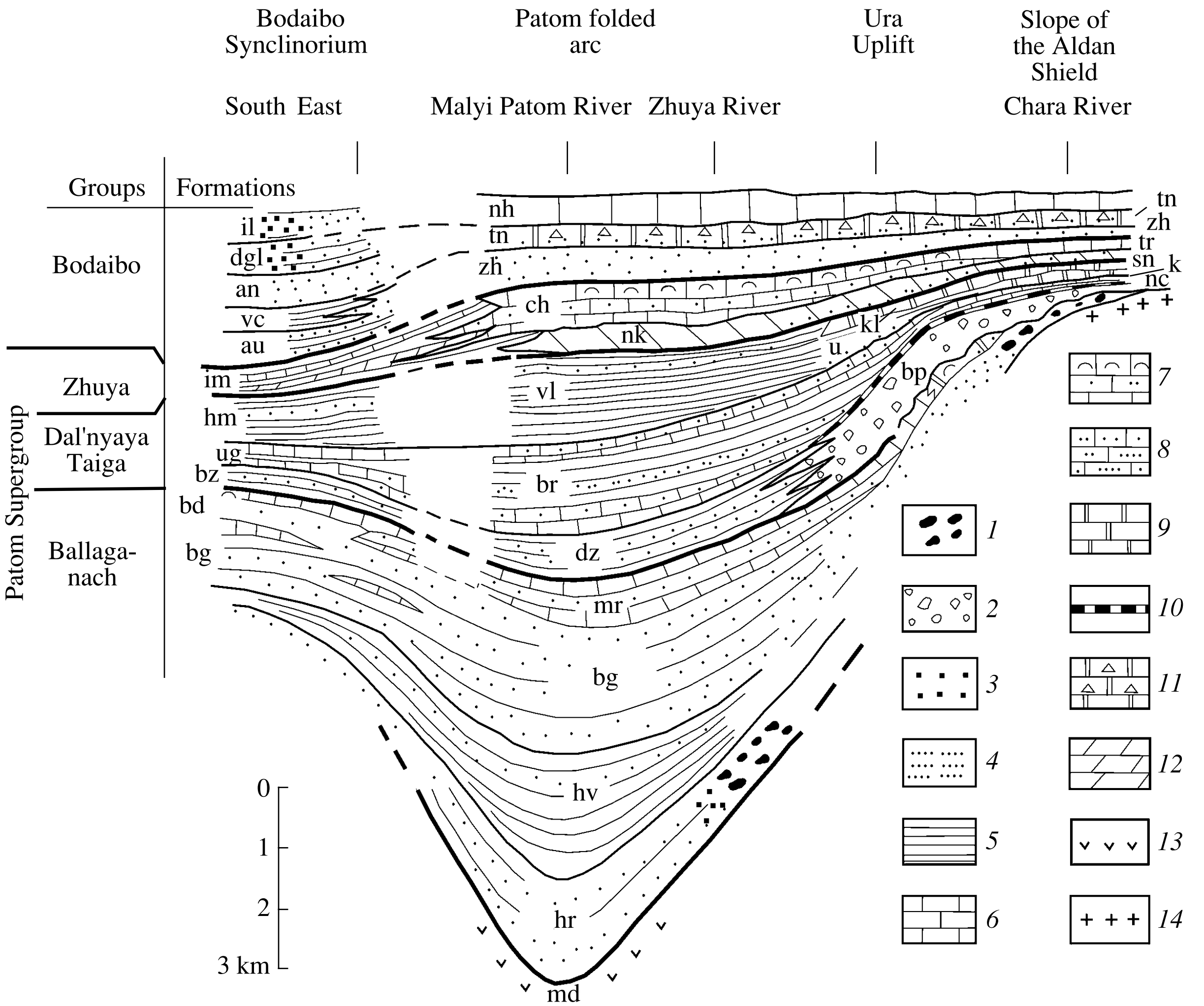

Structure and major facies of the Patom Supergroup and Bodaibo Group. (*1*) Conglomerate; (*2*) glaciogenic sediments; (*3*) sandstone and gritstone; (*4*) sandstone; (*5*) shale and siltstone; (*6*) limestone; (*7*) stromatolitic and oolitic limestones; (*8*) sandstone members in carbonate rocks; (*9*) dolomite; (*10*) cap dolomite; (*11*) dolomitic breccia; (*12*) marl; (*13*) sedimentary and volcanogenic rocks; (*14*) Archean crystalline rocks. Lower Cambrian: (nh) Nokhtuisk Formation; Vendian formations: (tn) Tinnaya, (zh) Zherba, (ch) Chencha, (nk) Nikol'sk, (vl) Valyukhta, (kl) Kalancha, (ur) Ura, (br) Barakun, (dz) Dzhemkukan, (bp) Bol'shoi Patom, (il) Iligir, (dgl) Dogaldyn, (an) Anangra, (vc) Vacha, (au) Aunakit, (im) Imnyakh, (hm) Homolkho, (ug) Ugakhan, (tr) Torgo, (sn) Sen, (k) Kumakh-Ulakh, (nc) Nichatka; Vendian–Upper Riphean(?) formations: (mr) Mariinsk, (bg) Bugarikhta, (hv) Haiverga, (hr) Horlukhtakh, (bd) Bodaibokan; (md) Riphean(?) Medvezh'ya Formation.

These forms are either transient or distinguished in some characteristic features from their Late Riphean counterparts. Therefore, we can conclude that the Ura microfossil assemblage points to the postglacial Early Vendian age of host rocks, which can be correlated with the pre-Redkino level of the Early Vendian in the Russian stratigraphic scheme or with the Early Ediacaran in the international scale. Thus, biostratigraphic data support the chemostratigraphic inference on the Vendian age of the two upper groups of the Patom Supergroup. The Zherba Formation, which overlies this supergroup, probably correlates with terminal horizons of the Vendian, whereas the overlying Tinnaya Formation correlates with the Nemakit–Daldyn Horizon of the Vendian.

The inference on the Vendian age of the two upper groups of the Patom Supergroup makes it possible to refine existing views on the geological history of the Patom fold zone and age of Siberian glaciation. The supergroup overlies unconformably older rift structures and represents a typical cyclic-progradation prism of sedimentary rocks at the passive margin of the Siberian Platform. This is evident from the structure and facies variations in the Patom supergroup. The history of prism accretion can be divided into three major cycles, which correspond to three groups of the supergroup. Each group begins with a conglomerate or sandstone sequence, which grades into alternating shales and carbonate rocks and, then, into the crowning carbonate sequence. In the inner part of the Patom arc, the rock groups are characterized by great thickness; conformable interrelations; and prevalence of flyschoid (often anoxic) rocks, such as black carbonaceous shales and limestones. In the outer part of the arc and at the platform margin, the thickness of groups decreases and they overlie older formations with marginal unconformities. The crowning carbonate formations are represented there by typical sediments of carbonate platforms (stromatolitic, oncolitic, and oolitic dolomites; limestones; and products of their redeposition). At the same time, carbonate platforms in each successive group gradually shifted toward the most subsided part of the basin. The lack of volcanic groups in the Dal'nyaya Taiga and Zhuya groups is inconsistent with the concept proposed in [8], according to which the Patom basin was transformed into a back-arc basin during the accumulation of ashes.

In the central and southern parts of the Patom fold zone, the Patom Supergroup is conformably overlain by the terrigenous Bodaibo Group consisting partly of flyschoid anoxic sediments. Researchers have proposed different versions for correlation of the Bodaibo Group with sections of the outer fold arc, but most of the researchers correlate the entire group [3, 4, 6] or its major (upper) part [8, 9] with the Zherba; Tinnaya; and, sometimes, Nokhtuisk formations [6].

The Patom passive margin of the Siberian Platform bordered the Baikal–Vitim Ocean in the north [8]. The main formation stage of this margin corresponded to the accumulation period of the Patom Supergroup and the lower part of the Bodaibo Group. Their integral thickness in the inner zone of the fold arc amounts to 10–12 km. Hence, we can conclude that the Baikal–Vitim Ocean existed and actively developed until the terminal Vendian. Only during accumulation of the upper part of the Bodaibo Group in the latest Vendian did the southern part of the Patom basin start to receive regularly terrigenous polymictic material from the south [6, 8]. This probably indicates that the Patom passive margin began to transform into an active one due to subduction of the adjacent branch of the Baikal–Vitim Ocean and formation of uplifts along the continental margin in the terminal Vendian. The uplifts included, probably, island arcs, because some signs of tuff sandstones are present in the uppermost Bodaibo Group [6].

The age of folding in the Patom zone is highly debatable. In the early 1930s, N.S. Shatsky assumed that the Baikal–Patom region was subjected to folding in the terminal Middle–initial Late Cambrian. As is shown below, this standpoint is supported by recent data with correction for the Early Cambrian age of the Lenan limestones, which were considered Middle Cambrian rocks at that time. In the mid-1950s, E.V. Pavlovskii surmised the Late Caledonian (Devonian) age of folding in the Baikal–Patom region. Recently, this viewpoint has gained wide recognition. Based on geological [6] and paleomagnetic [13] data, some authors presume that folding in the Patom zone occurred in the Middle or, even, Late Paleozoic. The discrepancy in the dating of folding is explained by the fact that the region consists of folded structures of different ages, and, thus, it is impossible to imagine that the entire structural ensemble of the Patom zone and its framing formed during a single tectonic epoch.

The eastern part of the Patom fold arc is characterized by NW- and E-inclined linear (NW- and nearly NS-striking) folds, which involve the entire Patom Supergroup, as well as the Upper Vendian Zherba and lower Tinnaya formations. Therefore, it gives the impression that the lower age limit of the linear folding is post-Vendian. The analysis of some specific folding-related textures provides a different estimate. The formation of linear folds in the eastern branch of the arc was accompanied by development of distinct cleavage of the axial surface (main cleavage). The middle Barakun Subformation (black shales, subordinate sandstone beds, black fine-oolitic limestones, and carbonate breccia) encloses numerous clastic dikes along the main cleavage planes in some places, e.g., middle reaches of the Zhuya River (1.3 km downstream of the Sof'e-Ivanovskoe Creek; between the Ambardakh and Marekta Creek mouths; upstream of the Chepok Creek mouth), the Malyi Patom River (3 km upstream of the Inokent'ev winter hut), and others. The dikes are composed of sandstones (Malyi Patom River) or black fine-oolitic limestones (Zhuya River). These rocks are lithologically identical to their counterparts that alternate with host shales. The thickness of the dikes varies from *n* cm to 1 m or more, and their observable length ranges from *n* to 50 m. The dike contacts demonstrate frequently distinct upward- or downward-oriented bends of host layers. This indicates the direction of dike material migration and excludes the possibility of passive filling of fissures from above in the case of the ascent of material. The cleavage along which dikes intruded could naturally form only after dehydration of clays up to their brittle state. In tectonically placid sedimentary basins, clays are dehydrated at depths of 1–4 km [14]. It can be assumed that dehydration can occur under tangential stress at a depth of less than 4 km in tectonically active regions, but it is impossible to estimate the impact of this factor. Therefore, we use both depth limits for the sake of greater confidence.

In our case, the formation of clastic dikes (and some carbonate breccia) is obviously related to dehydration of the Barakun clays. Similar processes are widely developed in elision basins [14]. Like in these basins, waters released in the course of dehydration in the studied regions were squeezed into beds of semilithified sands and fine-oolitic limestones. Consequently, the latter beds were diluted and injected along the newly forming fissures of the main cleavage under the impact of high formation pressure. The direct correlation between folding and cleavage, as well as rapid lithification of carbonates in elision dikes, suggest the formation of dikes during folding. The dehydration period of the Barakun Formation can be estimated proceeding from the thickness of overlying rocks. The minimal limit of the dehydration depth was achieved during accumulation of the Valyukhta Formation. The dehydration depth could reach the maximal limit of 4 km in the Malyi Patom and Zhuya river areas during deposition of the Tinnaya and Nokhtuisk formations, respectively. Thus, clays of the Barakun Formation should be dehydrated after accumulation of the Valyukhta Formation but not later than the Early Cambrian. Participation of the Tinnaya Formation in linear folds is additional evidence for synsedimentary folding of the Patom Supergroup (most likely in the initial Vendian–initial Early Cambrian). The folding was caused, probably, by a slight westward displacement of the Chara Block [8].

The Patom zone was subjected to the next tectonic phase in the terminal Early or initial Middle Cambrian. This episode was responsible for the significant hiatus and slight angular unconformity noted by some researchers between the carbonate sequence of the Lenan Stage and the Middle–Upper Cambrian Verkhnyaya Lena Formation along the periphery of the Patom zone [3]. In lower reaches of the Bol'shoi Patom River, this unconformity is distinctly observed for several kilometers upstream of the Tonus-Daban River mouth. Here, the Verkhnyaya Lena Formation rests upon breccias and the surface of brecciated Lenan limestones altered by karst processes. The angular unconformity between basal members of the Verkhnyaya Lena Formation and brecciated Lenan limestones is also recorded in the Khadar Cliff on the left bank of the Lena River.

In general, we can assume that the structure of the Patom fold arc formed in the course of two syncontemporaneous tectonic episodes: the first episode of temporally close deformations lasted from the initial Vendian to the initial Early Cambrian, whereas the second episode of tectonic deformations took place in the Early–Middle Cambrian. This point of view is close to Shatsky's concept on the age of the Baikalian folding.

The Patom fold arc is complicated and overlapped by younger NE-trending folds. In the northwest, the Patom zone is in contact with the northern part of the Angara–Lena zone characterized by the alternation of wide flat synclines and narrow anticlines. The synclines are filled with sediments of the Verkhnyaya Lena Formation, Ordovician rocks, and younger sediments in some places. The anticlines are composed of the Lower Cambrian rocks and complicated by thrusts in the northwestern direction. These folds subside and gradually disappear in the northeastern direction. In terms of strike and morphology, the folds are obviously independent of the Patom fold arc. The northeastern margin of the arc is superimposed by the transverse Ura Uplift composed of the Patom Supergroup. Both the uplift and relevant complicating folds extend and subside in the northeastward direction. Their axial planes are also inclined in the same direction. Geological and paleomagnetic data on the Middle–Late Paleozoic age of folds are valid only for NE-trending structures located in the Angara–Lena zone and Ura Uplift area [6, 13]. According to paleomagnetic data, superimposed NE-trending folding can be explained by rotation of the Aldan Block by 20° (relative to the Angara–Olenek Block) in response to the opening of the Vilyui paleorift system in the Early Devonian. Latitudinal folds at the southern margin of the Patom zone are, probably, related to the northward displacement of the Barguzin microcontinent in the Late Devonian–Early Carboniferous [13].

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