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Detailed Stratigraphy of the Vendian Tira and Lower Danilovka Horizons in the Southwestern Siberian Platform

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Abstract—A member and bed-by-bed division of the Upper Vendian formations in the boreholes drilled in the Baikit anteclise and the Angara fold zone in the west of the Siberian Platform has revealed sedimentation gaps above the Danilovka Horizon and above and within the Tira Horizon as well as amplitude erosion of the sediments. Lower beds appear in the above-gap Il'bokich basal argillaceous-dolomite-marl member of the Katanga Formation of the Danilovka Horizon. The thicknesses of all beds gradually increase from north (Baikit anteclise) to south in the Angara fold zone. The upper members of the Tira Horizon did not accumulate below the gap in the north. The Yurubchen Plateau (uplift) was in this area. South of it, the formation thicknesses increase; there are apparently no gaps in the Beryambinskaya area of the Angara fold zone. The Il'bokich member makes up the top of the Moshakovka Formation but is part of the Danilovka Horizon. The Moshakovka Formation spans the top of the Tira Horizon and the bottom of the Danilovka Horizon. In general, stratigraphic bodies in areas with a rapid increase in the tectonic-downwarping amplitudes have a typical geologic structure.

Keywords: regocyclite, gaps, erosion, Baikit anteclise, Angara fold zone

INTRODUCTION

Vendian stratigraphic charts of the Siberian Platform (Kontorovich et al., 1981; Decisions…, 1989; Mel'nikov et al., 2005; Shemin, 2007; Mel'nikov, 2009) have been constantly improving. The basis of these schemes is the Regional Vendian Stratigraphic Chart of the Siberian Platform Internal Regions. Composed in 1986 and approved by the Interdepartmental Stratigraphic Committee in 1988, it traces Vendian formations along three regional stratigraphic horizons: Nepa, Tira and Danilovka (Decisions…, 1989). The Nepa and Danilovka Horizons have a number of subhorizons. The regional stratigraphic division has been set up based on the following sedimentation properties:

– lithological continuity in huge territories that is confirmed by tracing of markers and members;

– the stratigraphic discontinuities and gaps regarded as regional ones by many researchers;

– the cyclic nature of these Vendian formations allows one to distinguish and trace larger cyclic stratigraphic units (regocyclites).

These properties of Vendian formations have their representation in well-logging data, as the main source of information available to researchers, unlike core sampling that is mainly performed in productive horizons. Nevertheless, well logging and coring have remained the main techniques to specify formation positions in the horizons and subhorizons, since the available paleontological data have been unable to produce the required accuracy in correlation of stratigraphic sections and cannot be used for producing a standard stratigraphic chart of the Siberian Platform inland.

As for geochronological data, they have only allowed researchers to estimate the age of the upper Vendian boundary, while its lower boundary and sections remain a subject for discussion. The current state of research makes us accept the dates offered in (Zhamoida, 2006) saying the Vendian age started at 600 Ma, the Upper–Lower Vendian boundary is at 570–550 Ma, and the Vendian top is 535 ± 1 Ma.

In other words, age determination remains a problem for the Vendian horizons since it does not have sufficient geochronological and paleontological grounds. However, there is yet another approach that allows one to determine the formation duration of the Vendian horizons and subhorizons that is based on analysis of the cyclicity of the large sedimentation stages that are related to eustatic sea level and oceanic bottom depth changes (Mel'nikov, 1981). From this perspective warping movements of each degree are similar in terms of their duration. Warping motions of averaged duration result in the formation of regocyclites (Karogodin, 1990), which enables one to use such motions as a unit of geological time for the Vendian age of the Tunguska region (Mel'nikov, 2009).

In order to carry out the cyclicity analysis, it is required:

– to determine the number of the regocyclites comprising the Vendian part of the Vendian–Cambrian nexocyclite (Mel'nikov, 2009);

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System	Series	Horizon	Oscillatory motion	Start, Ma	Regocyclite	Duration, Myr	Gap	Duration, Myr
Cambrian	Lower	Usol'e	Late Danilovka–Early Usol'e	535	Tetere–Lower Usol'e	10	No	
Vendian	Upper	Danilovka	Middle Danilovka	540	Soba	10	No	
			Early Danilovka	550	Katanga	7–10		
							Pre-Danilovka	0–3.0
								0–4.0
		Tira	Late Tira	560	Upper Tira	5–10		
							Intra-Tira	
			Early Tira	570	Lower Tira	8–10		0–2.0
							Pre-Tira	0–3.0
	Lower	Nepa	Late Nepa	580	Upper Nepa	7.5–10		
							Intra-Nepa	
			Early Nepa	590	Lower Nepa	7.0–10		0–2.0
							Pre-Nepa	0–2.0
								0–3.0
		Vilyuchan	Vilyuchan	600	Vilyuchan	7.0?		
							Pre-Vilyuchan	0–2.0
								>10

Table 1. Vendian cyclometric scale of the Tunguska region of the Siberian Platform.

– to assign similar formation duration for all the determined Vendian regocyclites based on the similar averaged duration of their warping movements.

– to assume that the regional gaps are widespread in positive superorder structures, while in negative ones are either absent or cannot be determined from well data.

The obtained results of cyclicity analysis in combination with regional gaps became the basis of a cyclometric Vendian and Cambrian geological time scale for the Siberian Platform (Mel'nikov, 2009). According to the scale, the obtained duration of the Vendian regocyclites was 5 Ma, and the duration of the gaps was assumed to be 5 Ma as well. The results of member and bed-by-bed Vendian sections correlation presented in this paper have demonstrated that the gaps have not appeared in the biggest negative Vendian structure covering the southern part of the Angara fold zone (Table 1).

Detalization of the regional horizons structure and elaboration of their formational and member division have made it possible to estimate the duration and propagation of regional gaps, and the erosion degree of the units below the stratigraphic discontinuity (Vorob'ev, 1982; Mel'nikov, 1994, 1996, 2009; Shemin, 2007). What follows is such a study to investigate the middle part of the Vendian system that covers the southern part of the Baikit anteclise and spreads eastward of the Angara fold zone.

Most of the wells drilled in the southern part of the Baikit anteclise have penetrated the Vendian sediments, and eastward of the Angara fold zone the system has been fully penetrated by the 5 wells drilled in the Il'bokichskaya area and by the 2 wells drilled southward of the area (Agaleevskaya-4 and Beryambinskaya-2). The obtained coring and well logging data were sufficient for stratigraphic profiling of the Tira Horizon of the Vendian system. The profiling was carried out for two areas (Fig. 1): western (Omorinskaya, Yurubchenskaya, Kamovskaya and Platonovskaya areas) and eastern (Il'bokichskaya area and Agaleevskaya-4, Beryambinskaya-2, Kolymovskaya-139, Nizhnemodashenskaya-138, Khorkichskaya-1, Podporozhnaya-106 wells) ones. The results obtained for the eastern area became the basis for member and bed-by-bed breakdown of the Vendian system, localization of the regional gaps and associated erosions of the units below the stratigraphic discontinuity (Mel'nikov, 2009). As a result, a detailed stratigraphic chart of the middle part of the Vendian system has been produced for the described territory. The performed profiling included the following works: sections correlation, indication of gaps, and estimation of erosion amplitudes.

CORRELATION OF THE BOTTOM SECTIONS OF THE DANILOVKA AND TIRA HORIZONS

Using gamma-ray (GRL) and neutron gamma-ray (NGRL) logging data was enough to break down the Vendian system into members and beds, while in complex sec-

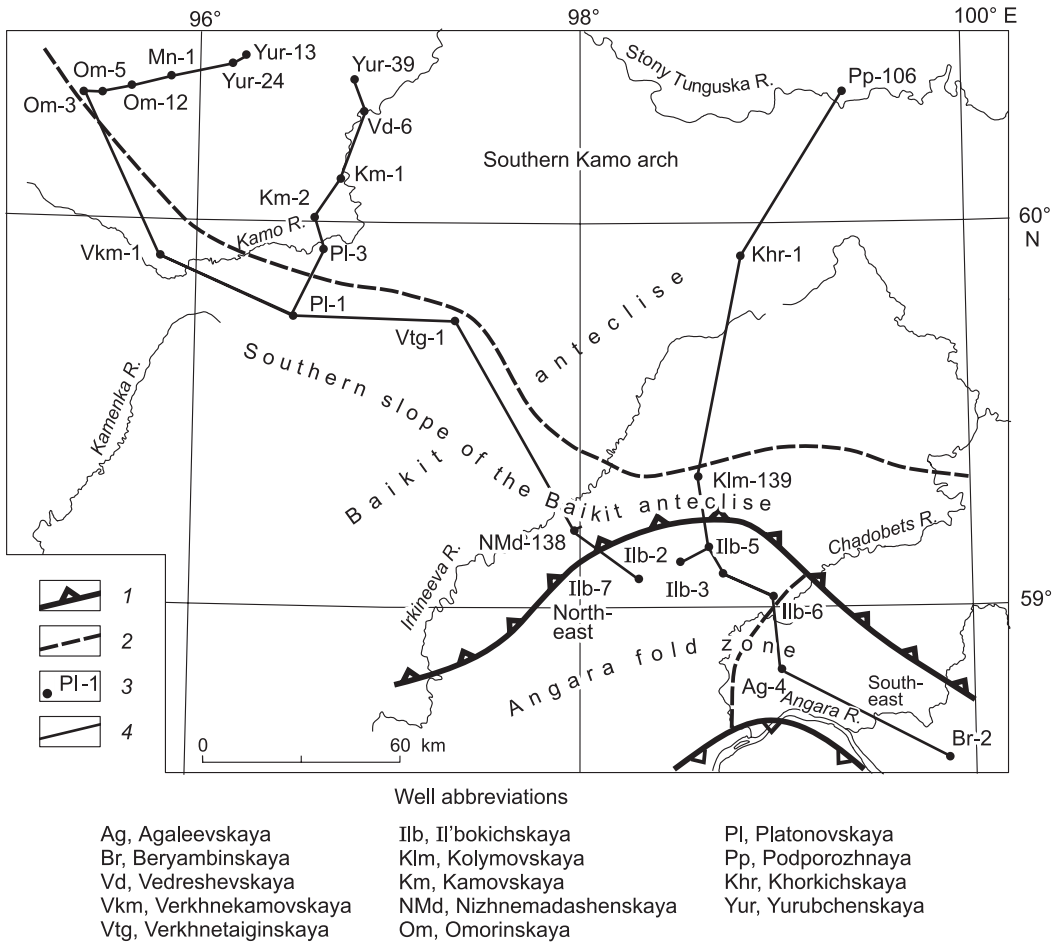

Fig. 1. Profile positioning in the southern part of the Baikit anteclise and the eastern part of the Angara fold zone. *1*, *2*, boundaries: *1*, Angara fold zone, *2*, structural; *3*, well and its number; *4*, profile lines.

tions additional data from acoustic, lateral and caliper logging were used. A detailed description of the applied correlation method can be found in (Mel'nikov, 2009, 2013).

The available well sections were correlated to the level of members, and the regional gap intervals—to the level of beds in members (Table 2). The obtained correlation is given in the figures covering the territories of the southern part of the Baikit anteclise and eastwards of the Angara fold zone. It is based on the available GRL and NGRL data and its cross-section is formed of the members and beds of the Katanga, Oskoba, Moshakovka and Chistyakovka Formations.

The well data obtained in the Il'bokichskaya area were used to form a typical section of the bottoms of the Danilovka and Tira Horizons. The area is located in the northwestern part of the Angara fold zone where it adjoins the Baikit anteclise. The area extends as far as the right tributaries of the Chadobets River (Fig. 2) and includes seven wells, five of which have been drilled in recent years, to reach its gas reservoir. These are the wells that have enabled performing the discussed member and bed-by-bed breakdown to correlate the Katanga and Oskoba Formations, localize the regional gaps and estimate their duration, and erosion amplitudes.

In the Katanga Formation, its bottom part was considered to be composed of two members: Il'bokich argillaceous-dolomite and overlaying Preobrazhenka dolomite ones.

The Il'bokich member is divided into four beds (Fig. 2), the two bottom beds are made of siltstones and marls subdivided by a meter-thick interbed of dolomites. Bed 1 (bottom) was indicated only in southeastern wells Ilb-3 and Ilb-6. It is 7 and 13 meters thick, the thickness increases in the vicinity of Ilb-6. In this well, bed 1 belongs to the Moshakovka Formation. Unlike bed 1, bed 2 can be traced in all the wells, its thickness changes little within 5–6 m. In wells Ilb-5 and Ilb-6, bed 2 belongs to the Oskoba Formation. Bed 3 is formed of loamy dolomites, and its middle part – of marls, mudstones and dolomite siltstones. The bed thickness changes from 10 to 15 m and increases in the vicinity of Ilb-6. The fourth (top) bed of the formation is mainly composed of marls and loamy dolomites, its thickness varies from 10 to 13 m.

The thickness of the whole Il'bokich member changes from 25 to 45 m, the thinnest part (25–28 m) belongs to the

Horizon	Baikit anteclise						Angara fold zone						Horizon
	Conventional (Mel'nikov, 2013)			Proposed			Northeastern			Southeastern			
							Proposed						
	Formation	Member	Bed	Formation	Member	Bed	Formation	Member	Bed	Formation	Member	Bed	
Danilovka	Katanga	2 Preobrazhenka		Katanga	2 Preobrazhenka	2	Katanga	Preobrazhenka		Katanga	Preobrazhenka		Danilovka
						1							
		1			Il'bokich	4		Il'bokich	4		Il'bokich	4	
						3			3			3	
						2			2			2	
						1			1			1	
Gap	Gap			Pre-Danilovka gap						Moshakovka	4		Tira
											3		
											2		
											1		
Tira	Oskoba	4		Oskoba	7		Oskoba	7		Chistyakovka	7		
		3	3-3		6	6-2		6			6		
			3-2			6-1							
			3-1		5			5			5	5-2	
												5-1	
		2	2-3		4	4-2		4	4-2		4	4-2	
			2-1, 2-2			4-1			4-1			4-1	
		1	1-4		3			3			3		
			1-3		2			2			2	2-2	
												2-1	
			1-2		1			1			1	1-2	
												1-1	

Table 2. Accepted and suggested stratigraphic divisions of the Tira and Danilovka (bottom) horizons of the southern part of the Baikit anteclise and the eastern part of the Angara fold zone of the Siberian Platform.

northwestern part of the Il'bokichskaya area, and the thickest (37–45 m)—to the southeastern one.

The Preobrazhenka member is mainly composed of calcareous dolomites, its thickness changes from 18 to 23 m.

The Preobrazhenka member and Il'bokich member bed thickness continuity and the directionality of their changes along the area make it possible to conclude that Il'bokich member beds formed after the end of the pre-Danilovka sedimentation gap. In the well sections, the gap interval belongs to the bottom of bed 2 in the northeastern part of the Il'bokichskaya area and the bottom of bed 1 in the east.

The Moshakovka Formation of the Taseeva Series was found only in the southeastern termination of the Il'bokichskaya area, in well Ilb-6, where its thickness comprises 35 m (Fig. 2). Considering the Moshakovka Formation thickness (160 m) in well Agaleevskaya-4, in Ilb-6 only the bottom part of the formation has preserved that includes members 2 and 3 (mudstones) with siltstone interbeds.

According to the well-logging and coring data, the Oskoba Formation breaks down into 7 members (Fig. 2). While the bottom member is an alternation of mudstones and siltstones, the top ones have sandstone interbeds. In member 2 mudstones prevail, in member 3—sandstones (bottom and top parts) and mudstones (middle part). In member 4 sandstones concentrate in the top part, and loamy rocks—in the bottom one. Member 5 is composed of sandstones and siltstones in the western part and of loamy rocks – in the eastern part of the area. Member 6 is mainly sandstone. Member 7 serves as a marker and makes the top of the Oskoba Formation. It is an alteration of anhydride-dolomite beds and loamy-dolomite interbeds. In Ilb-6, the member thickness reaches 12 m. In Ilb-3 pre-Danilovka gap erosion left 4 m the seventh member bottom (Fig. 2). In wells Ilb-2 and Ilb-5 the above-gap Il'bokich member overlays the residues (12–14 m) of the bottom parts of member 6 of the Oskoba Formation. In the begging of the Tira and the end of the Danilovka period, it was a piece of land (Mel'nikov, 2011).

After the Il'bokichskaya area, the beds and members were traced in the northern wells such as Kolymovskaya, Khorkichskaya, and Podporozhnaya of the Baikit anteclise,

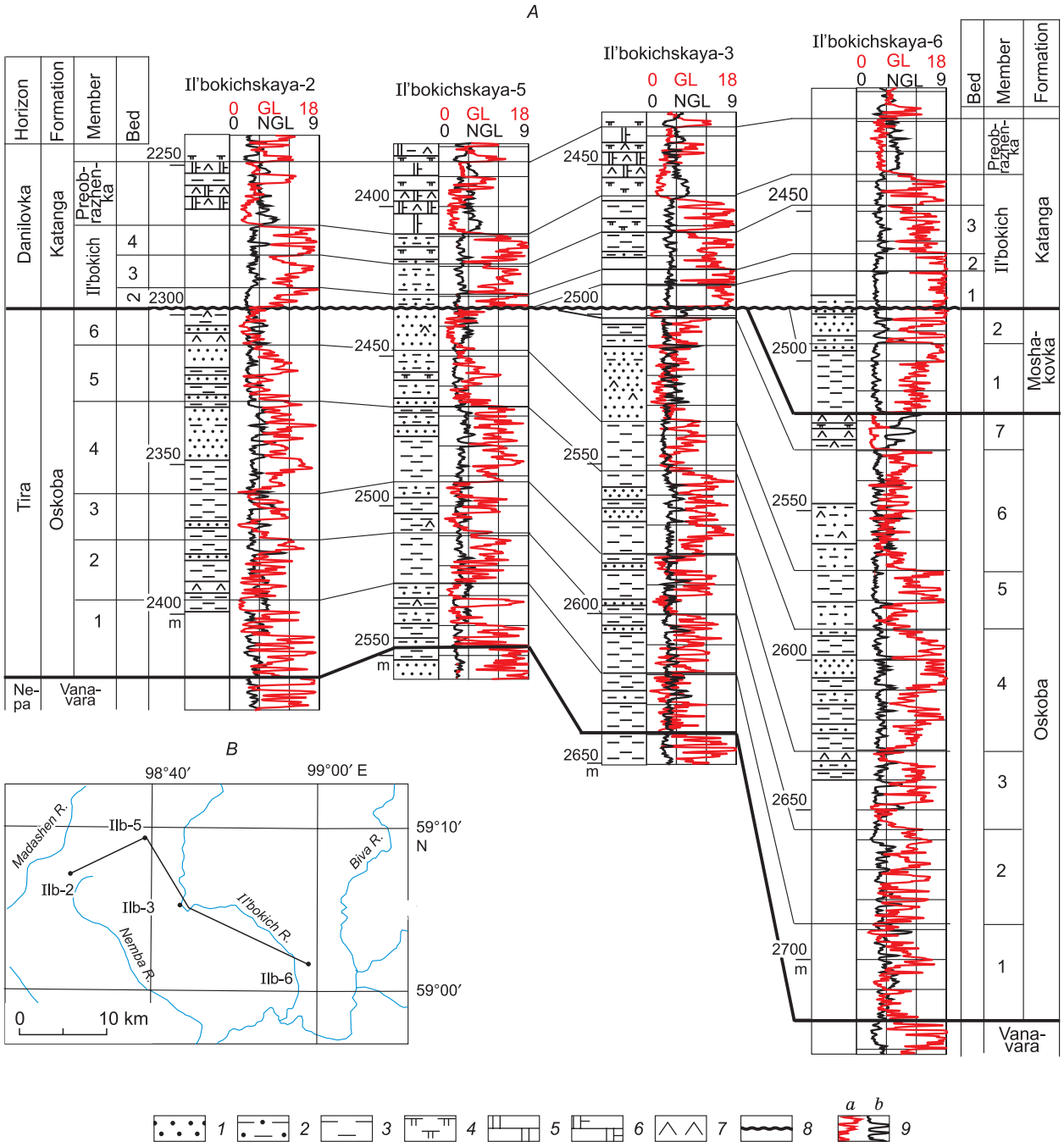

Fig. 2. Detailed correlation of the Tira and Danilovka (bottom) horizons for the Vendian Il'bokichskaya area (*a*) and well localization (*b*). Core-based lithology: *1*, sandstone, *2*, siltstone, *3*, mudstone, *4*, marl, *5*, dolomite, *6*, limy dolomite, *7*, anhydrite, *8*, pre-Danilovka gap line, *9*, here and in Figs. 3, 6, 7: well-logging curves: *a*, GRL (μR/hr), *b*, NGRL (c.u.).

and the southern ones such as Agaleevskaya-4 in the Angara fold zone (Fig. 1).

In Kolymovskaya-139 well in the bottom of the Katanga Formation, the same Preobrazhenka and Il'bokich members were found (Fig. 3). The Preobrazhenka member thickness reduces to 20 m, and that of Il'bokich member—to 16 m. Il'bokich member is subdivided into beds 3 and 4 that are traced from the Il'bokichskaya area. The pre-Danilovka gap is located in the bottom bed of well Ilb-3.

The Katanga Formation in underlaid by the Oskoba Formation. The latter is subdivided into 5 members that are correlated with members 1–5 of the Chistyakovka Formation of the Agaleevskaya area. In this way, the simultaneous accumulation of the Chistyakovka Formation of the Angara fold zone and the Oskoba Formation of the Baikit anteclise has been confirmed (Mel'nikov, 2013).

In wells Khorkichskaya-1, Podporozhnaya-106 of the Kamo arch of the Baikit anteclise, the Il'bokich member

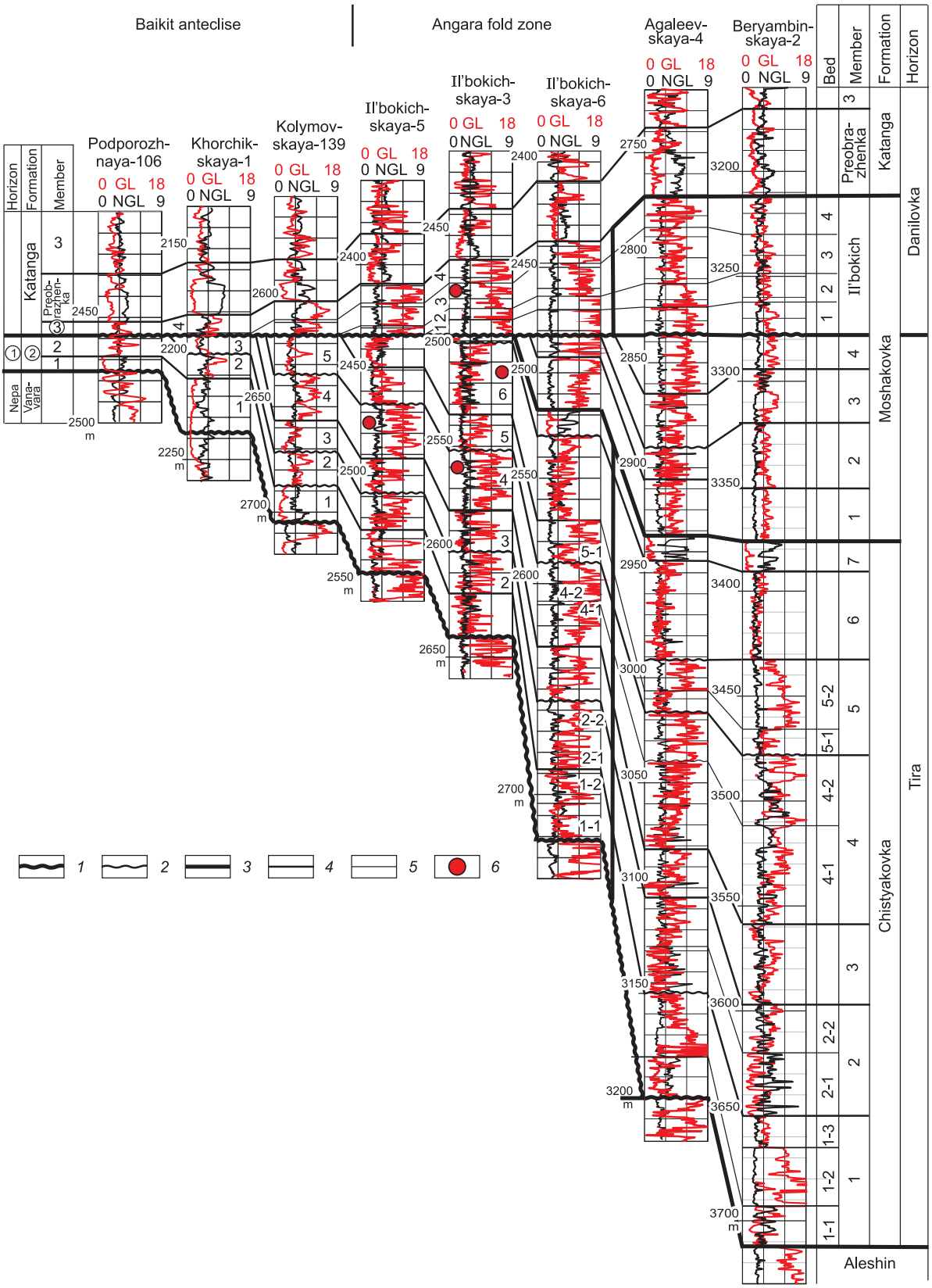

Fig. 3. Detailed correlation of the Tira and Danilovka (bottom) horizons for the Vendian southern part of the Baikit anteclise and eastern part of Angara fold zone: Submeridional section (profile Br-2–PPr-106). *1*, localization of pre-Danilovka and pre-Tira gaps in well sections; *2*, localization of the intra-Tira gaps; *3–5*, boundaries: *3*, formations, *4*, members, *5*, beds, *6*, gas influx. Circled numbers: 1, Tira Horizon, 2, Oskoba Formation, 3, Il'bokich member.


Horizon
Formation
Member
Regocyclite
Oscillatory motion, Ma
Baikit anteclise
Southern Kamo arch
Southern slope
Angara fold zone
Northeastern
Southeastern
Il'bokichskaya
Podpo-rozh-naya-106
Khorioch-skaya-1
Kolymov-skaya-39
5
3
6
Agaleev-skaya-4
Beryam-bin-skaya-2
Bed
Member
Formation
Horizon
Regocyclite
Danilov-ka
Katanga
Tira
Oskoba
Katanga
Late Tira
Early Tira
Pre-Tira gap
Pre-Danilovka gap
Yurubchen Plateau
Il'bokich
Danilovka
Moshakovka
Chistyakovka
Tira
Katanga
Upper Tira
Lower Tira
550
560
570
1
2
3
4
5
6

Fig. 4. Detailed stratigraphy of the Tira and Danilovka (bottom) horizons for the Vendian southern part of the Baikit anteclise and eastern part of Angara fold zone. Submeridional section. *1*, gap periods; *2*, eroded sediments; *3*, gap and washout boundaries; *4*, zonal gap boundaries; *5*, formation boundaries, *6*, members, beds: top-bottom depth (m), thickness (m). See legend in Fig. 3. Circled numbers: *1,* Katanga Formation; *2*, Preobrazhenka member; *3*, Il'bokich member; *4*, Lower Tira regocyclite.

thickness keeps reducing, so the sections contain only a part of bed 4 (6–10 m), which is due to the late ending of the pre-Danilovka gap. In Podporozhnaya-106 well, the section of the Oskoba Formation contains only member 1 and the lower part of member 2. This fact has been interpreted as an erosion of the Oskoba Formation in the land part of the Yurubchen Plateau.

Southwards of Il'bokichskaya well is the Agaleevskaya-4 well (Fig. 1). In this well, the bottom part of the Katanga Formation is composed of only the Preobrazhenka member, which lays at the depth of 2772 m (Fig. 3). It is underlaid by the Moshakovka Formation (2772–2932 m) that is mainly loamy rocks. In Ag-4 its thickness comprises 160 m. Beds 1–4 of the Il'bokich member form the upper part of the Moshakovka Formation.

The underlying Chistyakovka Formation is subdivided into the same 7 members, as the Oskoba Formation of the Il'bokichskaya area. Member 7 (top) is 12 m thick, formed by dolomites and serves as a marker. The other members are similar to those in the Il'bokichskaya area but have greater thickness.

In summary, beds 1–4 of the Il'bokich member of the Moshakovka Formation in well Ag-4 are the same beds of the Il'bokich member of the Katanga Formation in the wells of the Il'bokichskaya area. However, the gap in the member's bottom traced in the Agaleevskaya area has not been traced here, so the Il'bokich member of the Agaleevskaya area should be related to the Moshakovka Formation, but to the regional Danilovka Horizon (Fig. 3).

Correlation of the sections of Agaleevskaya-4 and Beryambinskaya-2 wells has demonstrated there is a thickness continuity of the Il'bokich member (65–66 m) and the bottom (Tira) part of the Moshakovka Formation (97–98 m) (Fig. 3). Such continuity of the horizons under (Danilovka) and above (top Tira) the stratigraphic discontinuity allows for the conclusion that the Agaleevskaya and Beryambinskaya areas either do not include the pre-Danilovka gap, or it did not manifest itself with the erosion of the beds that had formed earlier (Fig. 4).

In the wells of the Beryambinskaya area, the Chistyakovka Formation is subdivided into the same seven members, as it is in the Agaleevo Formation. The top member (7) of 12 m thick is made of dolomites and serves as a marker. The underlying members are an alternation of mudstones, siltstones and sometimes sandstones.

Detalization of the Chistyakovka Formation was performed based on the data from Beryambinskaya-2 well that had penetrated the thickest and most complete section of the Tira Horizon (Fig. 3). As a result, the beds of the members of the Chistyakovka Formation were determined (beds 1, 2, 3 in members 1 and 4; beds 1 and 2 in members 2 and 5). This member and bed-by-bed division as well as the disappearance of a number of the beds was traced along the eastern part of the Angara fold zone to indicate gaps in relation to disappearance of the top parts of beds 1-2, 2-2, 4-2, 5-2 in the members of the Chistyakovka Formation (Fig. 4).

In the sublatitudinal profile that crosses the southern slope of the Baikit anteclise (Fig. 5), the same members of the Oskoba Formation and the beds of the Il'bokich member of the Katanga Formation were traced. The only absent bed was bed 1 (bottom) of the Il'bokich Formation, while member 7 of the Oskoba Formation spanned along the western part of the profile. Underlying member 6 is subdivided into two beds. Figure 4 demonstrates the gaps in the bottoms of members 5, 3; and 2 in Fig. 6.

The pre-Danilovka and intra-Tira gaps were traced in wells NMd-138 and Ilb-7and from correlation between the members and wells Ilb-2 and Ilb-3. If there had not been those well, there would not have been any signs indicating the presence of said gaps in the sublatitudinal profile, because only the wells that are placed transversely to formation isopachs in this territory are able to indicate both regional and zonal gaps in the Vendian sedimentation.

The two profiles in the western part of the Baikit anteclise turned out to be more informative (Fig. 7). The first one goes from Platonovskaya-1 well (south) to Yurubchenskaya-39 well (north) (Fig. 1). In the southern part of the profile, a complete section of the Oskoba Formation of 130 m thick was stripped (members 1–7), while member 4 that left in the northern part was only 13 m thick. In the section, members 1–3 adjoin the top of the Riphean beds; members 6 and 7 were washed out in the pre-Danilovka time, and member 5 adjoins to the surface of the Yurubchen Plateau. The member thicknesses remain almost the same in the vicinity of the plateau (Fig. 8), and in the sandstone beds 4-2 in well Kamovskaya-1 an oil reservoir was discovered.

In general, the western part of the Baikit anteclise demonstrates a similar pattern of beds distribution in the Il'bokich member and the Oskoba Formation (Fig. 7). The thickness of the Il'bokich member changes from 26 m (beds 2, 3, 4) in the southern part of the profile to 13 m—in the northern part (beds 3, 4). The Preobrazhenka carbonate member is absent being replaced by member 2 of the Katanga Formation, composed of argillaceous (bottom) and argillaceous carbonate beds (top).

As in Fig. 8, members 1–3 of the Oskoba Formation adjoin the top of the Riphean beds in the northern part of the profile, while members 6 and 7 sequentially end before the Yurubchen Plateau (Fig. 9).

Thus, in the Late Tira and the Early Katanga period, there was a piece of land (Yurubchen Plateau) in the central part of the Baikit anteclise (Mel'nikov, 2015). Beyond this piece, in the western part of the studied territory, the thicknesses of the Tira Horizon reach 154 m (Verkhnekamovskaya-1 well); 140–110 m in the eastern part (Il'bokichskaya wells); and 360–420 m in the southeastern part (Agaleevskaya and Beryambinskaya wells). In the Yurubchen Plateau in the central and eastern parts of the Kamo arch (Kontorovich et al., 1988), the Tira Horizon absent almost completely, except for 15–20 m of the Oskoba Formation that disappears in the northern part. The absence of the Il'bokich member of the Katanga Formation indicates the presence of land. The southeastern part of the Angara fold zone most likely does not include the pre-Danilovka and intra-Tira gaps.

UNERODED PARTS OF REGOCYCLITES

The studied territory embraces the bottom part of the Katanga regocyclite, and Upper Tira and Lower Tira regocyclites.

The bottom part of the Katanga regocyclite is located in the southern part of the Baikit anteclise and the Angara fold zone. It is composed of siltstones, mudstones, marls (Il'bokich member), sulfated dolomites, loamy and marl interbeds (Preobrazhenka member). The two members form the bottom of the Katanga Formation except for the southeastern part of the Angara fold zone where they comprise the top of the Moshakovka Formation, while the Katanga Formation bottom is formed by the Preobrazhenka member (Figs. 3, 4).

The Il'bokich member consists of four beds, its complete sections belong to the Angara fold zone. Beds 1, 2 and 3 successively disappear in the western and northern directions, so the underlying sediments are overlaid by the different beds of the Il'bokich member. This bed distribution means the Il'bokich member overlays the stratigraphic discontinuity and got formed during successive spreading of the sedimentation area in the northern direction when the forth (top) bed of the member formed.

The Tira Horizon is composed of two regocyclites, namely Upper and Lower Tira. Eastwards, the Upper Tira regocyclite includes members 5–7 of the Chistyakovka For-

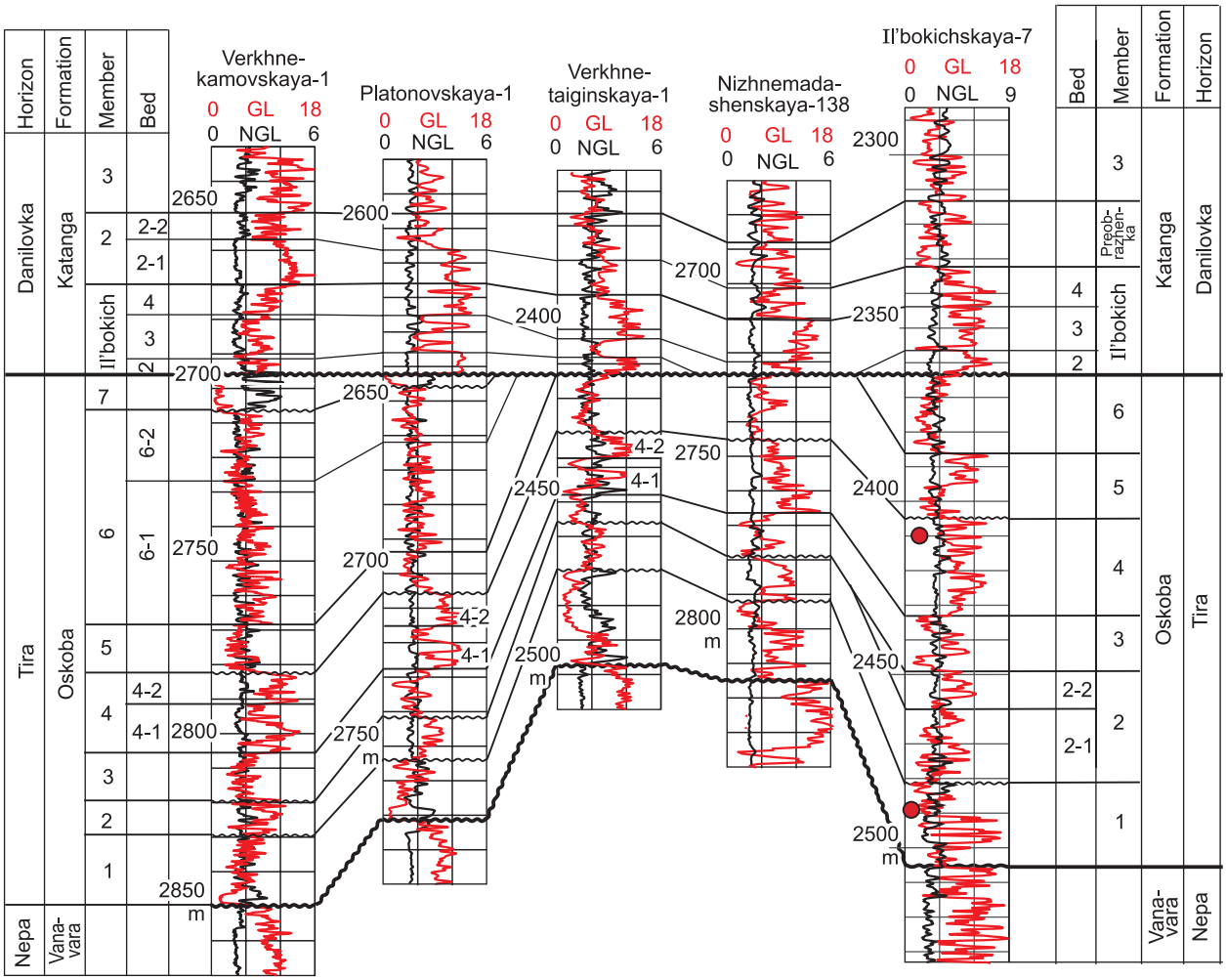

Fig. 5. Detailed correlation of the Tira and Danilovka (bottom) horizons for the Vendian southern part of the Baikit anteclise. Sublatitudinal profile. See legend in Fig. 3.

Fig. 6. Detailed stratigraphy of the Vendian (bottom) of the southern part of the Baikit anteclise. Sublatitudinal profile. See legend in Fig. 3 and 4.

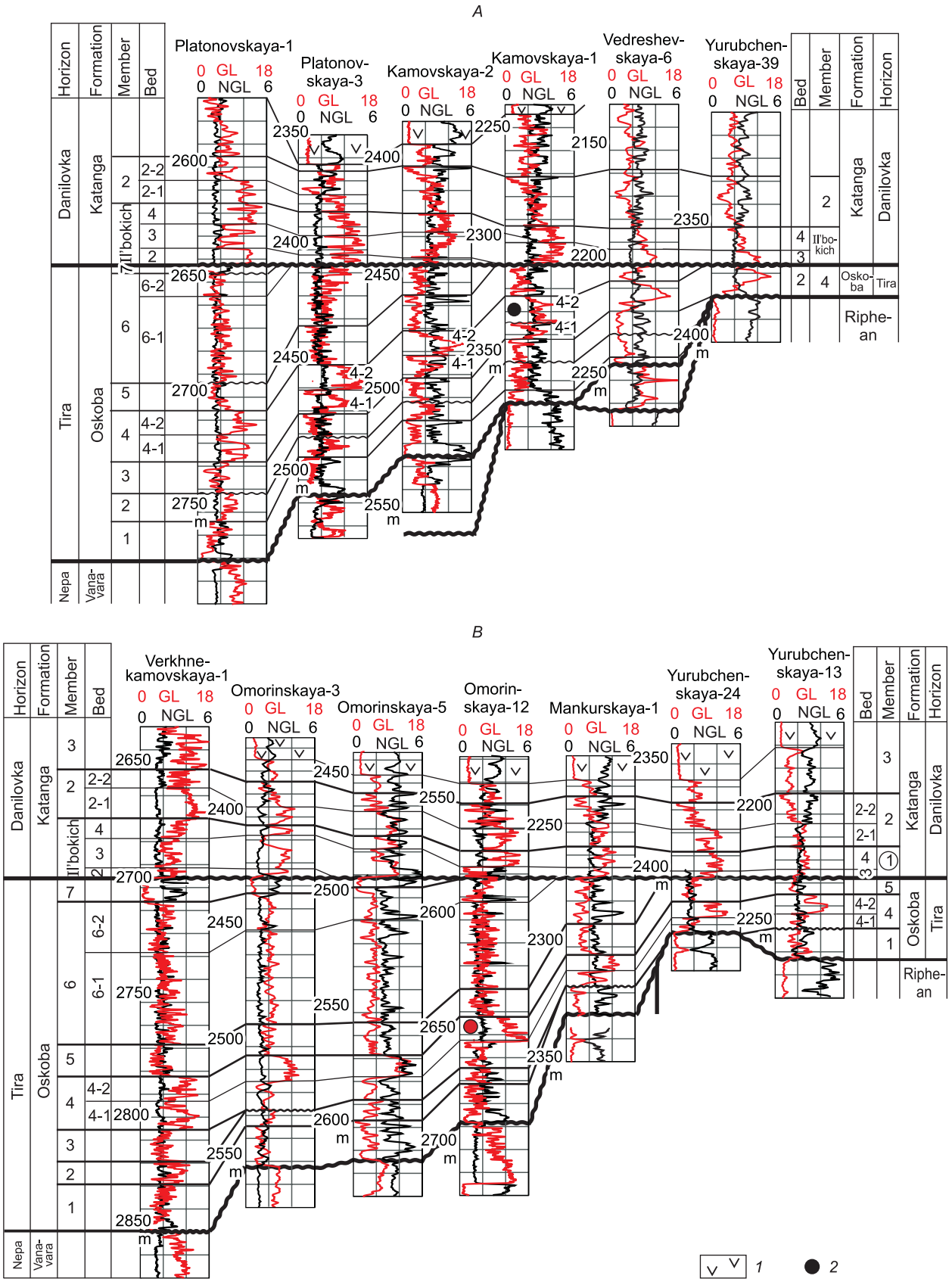

Fig. 7. Detailed correlation of the Tira and Danilovka (bottom) horizons for the Vendian southern part of the Baikit anteclise. *A*, submeridional profile, *B*, western profile. *1*, dolerite intrusion, *2*, oil influx. For the rest of the legend see Fig. 3. Circled numbers: 1, Il'bokich member.

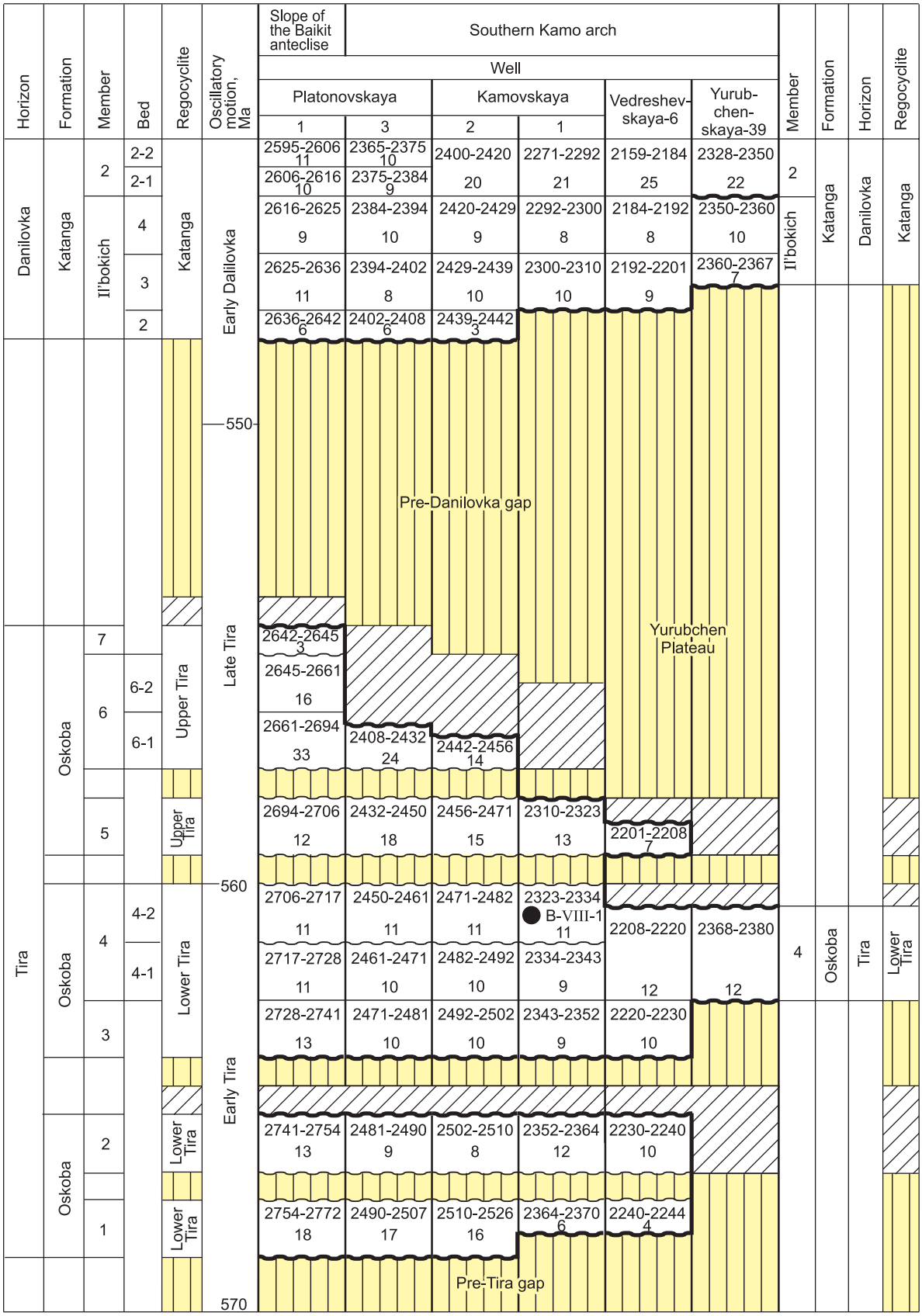

Fig. 8. Detailed stratigraphy of the Tira and Danilovka (bottom) horizons for the Vendian southern part of the Baikit anteclise. Submeridional profile. See legend in Fig. 4.

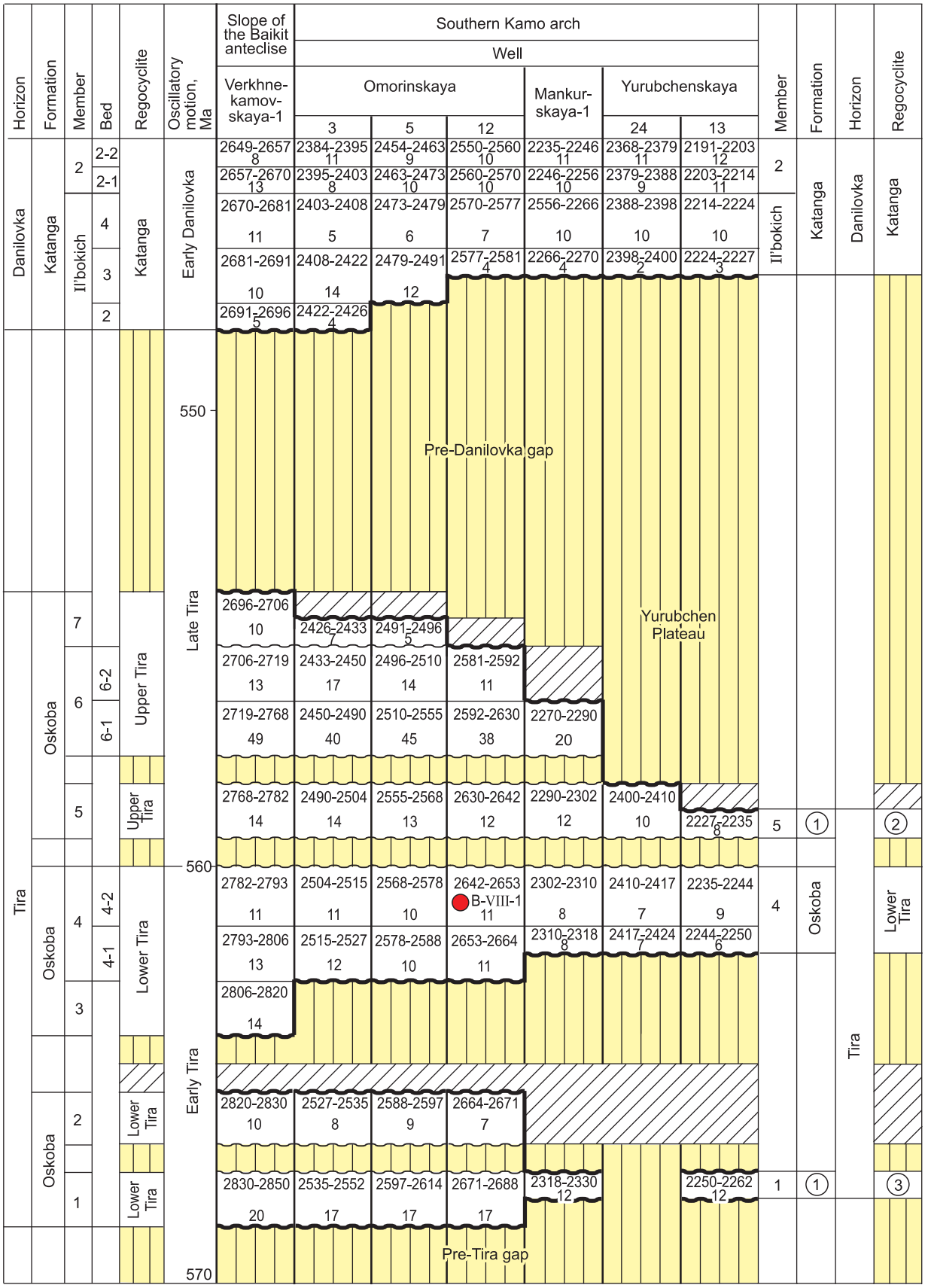

Fig. 9. Detailed stratigraphy of the Vendian (bottom) of the southern part of the Baikit anteclise. Western profile. See legend in Fig. 3 and 4. Circled numbers: 1, Oskoba Formation, 2, Upper Tira regocyclite, 3, Lower Tira regocyclite.

mation, and westwards—members 5–7 of the Oskoba Formation. Under the regocyclite is an intra-Tira gap, when the members of the Moshakovka and Oskoba Formations disappear sequentially from the sections of the Upper Tira regocyclite in the direction from the south to the north (to the Kamo arch). They are eroded and adjoin the surface of the Yurubchen Plateau.

The Lower Tira regocyclite is composed of members 1–4 of the Oskoba and Chistyakovka Formations. This regocyclite is characterized by the gaps of 0.5 Ma in duration that separate its members. Considering the thicknesses of the absent beds the duration of such gaps was several times smaller than the formation duration of these members (Figs. 6, 8, 9). For that reason, it remains unclear whether the underlaying beds were affected by erosion while the gaps were forming. As for the gaps themselves, they should be characterized as those of zonal rather than of regional character.

LOCALIZATION OF GAPS AND ESTIMATION OF EROSION AMPLITUDES

The results of gap localization and estimation of erosion amplitudes have been presented in many publications that are shortly described in (Mel'nikov, 2009). In all these publications the presence of a gap or a washout has been justified by detailed correlation of well sections.

A significant part of the Vendian is occupied by sedimentation gaps of different degree. However, the stratigraphic charts mark only those that were accompanied by erosion of the underlying beds, members and formations.

Detailed correlation of well sections within a studied territory usually allows for separation of two bed (member) complexes. The bed sequence of the upper complex does not change, which means the complex overlays the stratigraphic discontinuity. The top beds of the lower complex successively wedge out on the top of the upper complex bottom. After their cut-off is indicated, it is normally interpreted as erosion of older rocks within a gap. Such studies can be performed in areas where enough (at least 5) wells have been drilled, and their results are determination of gaps in well sections; basal beds above the stratigraphic discontinuity; thicknesses of the eroded beds underlying the stratigraphic discontinuity; gap duration in relation to the thicknesses of absent section intervals (members and beds). During the gaps, short-term downwarping and deposit accumulation took place, but these sediments were washed out during the upwarping that followed.

To justify sedimentation gap localization and the erosion amplitude in the beds underlying the stratigraphic discontinuity one has to indicate deviations from a standard succession of beds and members in a formation section, which manifests itself in a number of beds and members disappearing from the section. If this deviation is true for a number of wells, it is considered to be a sedimentation gap, and the number of missing beds allows one to determine the erosion degree within the gaps and its variation throughout a studied territory. In the presented study, such gaps and washouts were clearly observed in the geological sections composed for a number of wells, and the thinner were the thicknesses of the disappearing beds and members, the more precise was the localization of the gaps (Mel'nikov, 2011).

The detailed correlation of well sections in the studied territory determined the presence of two regional gaps—pre-Danilovka and pre-Tira ones—first justified for the Il'bokichskaya area (Fig. 2). The structure of Vendian deposits in the area allowed tracing its bed-by-bed and member breakout and verifying gaps and erosion amplitudes in the sections of the Moshakovka and Oskoba Formations. It turned out the bottom of the Il'bokich member of the Katanga Formation was a localization of the top of the pre-Danilovka gap.

Correlation of the sections of submeridional profile Br-2–PPr-106 (Fig. 3) demonstrated that the thicknesses of the Il'bokich member and those of the Tira Horizon (Chistyakovka and Oskoba Formations) successively decreased. For example, the thickness of the Il'bokich member reduced from 64 to 4 m, and the member's section lost beds 1, 2, 3 that adjoined the gap top (without deposition).

The changes in the Il'bokich member affected its underlaying bedding. In the south-eastern part of the Angara fold zone, bed 1 of the Il'bokich member is underlaid by member 4 of the Moshakovka Formation. In the northern part, beds 1–3 the Il'bokich member overlay members 6 and 7 of the Oskoba Formation. Further, in the southern slope of the Baikit anteclise, bed 3 of the Il'bokich member overlays members 5 and 4 of the Oskoba Formation, and in the southern part of the Kamo arch, bed 4 of the Il'bokich member covers members 3 and 2 of the Oskoba Formation. This structure if the section proves the pre-Danilovka gap extends northward in the Baikit anteclise (Figs. 3, 7)

In the southeastern part of the Angara fold zone, the correlation determined gaps in the bottom of members 6, 5, 3 and 2. The presence of these gaps is justified by the disappearance of beds 5-2, 4-3, 1-3 in well Agaleevskaya-4. The gap tops adjoin the bottoms of members 6, 5, 3 and of beds 4-2, 2-1 (Figs. 3, 4). The gaps in the bottom of member 5 are accompanied by frequent washouts of undelaying bed 4-2. This gap had been traced in the other profiles as well, but then it was regarded as a starting point of late Tira warping (Figs. 4, 6, 8, 9).

The members of the Tira Horizon disappeared in the following sequence. Members 1 and 2 are found all over the studied territory and reflect its lowstand. Members 3, 4 and 5 are absent at the top and the northern part of the Kamo arch. Most probably, they were eroded during the initial stage of the pre-Danilovka gap. Members 6 and 7 are limited by the propagation of the Baikit anteclise and the northeastern part of the Angara fold zone. Probably, their formation area was bigger, but they were washed out in the territories where the pre-Danilovka gap kept developing.

Thus, during the times of pre-Danilovka gap, the Yurubchen Plateau in the southern part of the Baikit anteclise and the eastern part of the Angara fold zone was successively (from the south to the north) deposited.

The pre-Tira gap has a regional degree and this study concerns its final stage of up to 1–2 Ma in duration. This gap is probably absent in the southeastern part of the Angara fold zone. In the remaining part of the zone and in the Baikit anteclise (where bed 1-1 is absent) its final stage lasted 1 Ma, and in the Kamo arch—2 Ma.

DETAILED STRATIGRAPHIC CHART

The obtained data on regocyclite structure, regional and zonal gaps, and the erosion degree of the beddings beneath the stratigraphic discontinuity were put together into a detailed stratigraphic chart of the Tira and Danilovka (bottom) Horizons that covers the Vendian system in the southern part of the Baikit anteclise and in the eastern part of the Angara fold zone (Fig. 10).

The chart covers the territory in whose northern part (the central part of the Kamo arch) there is an insignificant bedding of the Tira Horizon (it is either absent or does not exceed 5–7 m in thickness), and the top bed of the Il'bokich member of the Danilovka Horizon bottom; while its southeastern part contains the sections of the Tira and Danilovka Horizons without regional gaps.

At the bottom of the chart lies the final stage of the pre-Tira gap that lasted 1–2 Ma in the Kamo arch and 1 Ma in the southern slope of the Baikit anteclise and the northeastern part of the Angara fold zone. In the southeastern part of the zone, the gap did not manifest itself, as it was probably absent in the Nepa Horizon and so it cannot be associated with the eroded top of the Nepa Aleshin Formation.

This above-gap Lower Tira regocyclite started to form in the southeastern part of the Angara fold zone (basal bed of member 1 of the Chistyakovka Formation), while the rest of its territory was taken by a sedimentation gap (Fig. 10). In its main part, the regocyclite is formed by members 1–4 of the Oskoba and Chistyakovka Formations, the members alternate with zonal sedimentation gaps. A section without gaps was only found in the Beryambinskaya area. The regocyclite is also absent in the northern and, sometimes, in the central part of the Kamo arch. At that time, it was the top of the Yurubchen Plateau (Mel'nikov, 2015).

Oil and gas reservoirs and gas influxes in some of the wells were discovered in the sandstone beddings of beds 4-2 of the Oskoba Formation in the Omorinskaya, Kamovskaya, and Il'bokichskaya areas (bed B-VIII-1 according to the general classification). Gas influxes were observed in singular wells in the Omorinskaya and Il'bokichskaya areas from member 1 (siltstone, bed B-IX). Bed 4-2 of the Oskoba Formation should be considered as another productive bed in the Baikit hydrocarbon region and Nizhneangarsk independent gas region.

The Upper Tira regocyclite, next in the section, is separated from the Lower Tira by the intra-Tira gap of up to 1 Ma in duration. Under the gap, one can observe bed 4-2, which includes a productive sandstone bed (B-VIII-1).

The Upper Tira regocyclite is composed of members 5–7 of the Oskoba Formation in the western and northeastern part of the territory, including member 5 in its central part. The complete section of the regocyclite was found only in the southeastern part of the Angara fold zone and includes members 5–7 of the Chistyakovka Formation and members 1–4 of the bottom part of the overlaying Moshakovka Formation.

Members 1–4 of the Moshakovka Formation are absent in the Baikit anteclise and the northeastern part of the Angara fold zone, probably because they did not deposit in the Baikit anteclise due to an upheaval that formed at that time and produced the pre-Danilovka gap.

The Upper Tira regocyclite is absent in the central part of the Baikit anteclise for this is the place where the Yurubchen Plateau started to form simultaneously with washing out of the top beds and members of the regocyclite.

The pre-Danilovka gap preserved throughout the end of late Tira–Early Danilovka warping (Fig. 10). In the late Tira gap that according to the cyclometric chart continued up to 4 Ma, an upheaval formed in the southern part of the Baikit anteclise. In the Early Danilovka time of the gap, the beds of the Il'bokich member started cover the Yurubchen Plateau. This gap continued for 6.0–6.5 Ma (cyclometric measurements) in the central part of the Baikit anteclise, and 5 Ma in the southern slope of the anteclise and the northeastern part of the Angara fold zone. The gap did not manifest itself in the southeastern part of the zone, but we do not have enough well drilling data to say why.

The Katanga regocyclite started to form during the times of the pre-Danilovka gap in a negative superorder structure known as the Sayan–Yenisei syneclise, whose formation history and structure remains understudied. However, during the Vendian, the northern part of the syneclise was located in the place of the modern Angara fold zone, where the maximum Vendian thicknesses have been registered, and which has its own stratigraphic divisions such as the Aleshin Formation (Nepa Horizon), the Chistyakovka Formation, and the bottom part of the overlaying Moshakovka Formation (Tira Horizon).

The top part of the formation was regarded as a part of the Danilovka Horizon (Il'bokich Formation). The Katanga Formation here starts with the Preobrazhenka member. Specifying both the number and volume of the formations has long been felt needed, but this issue is beyond the scope of this paper. For this reason, the Il'bokich member being the bottom of the Katanga regocyclite has been marked as the bottom of the Katanga Formation in the Il'bokichskaya wells, and as the top of the Moshakovka Formation in the Agaleevskaya and Beryambinskaya wells (Fig. 10).

The Il'bokich member occurs over the stratigraphic discontinuity and successively sediments the remains of the pa-

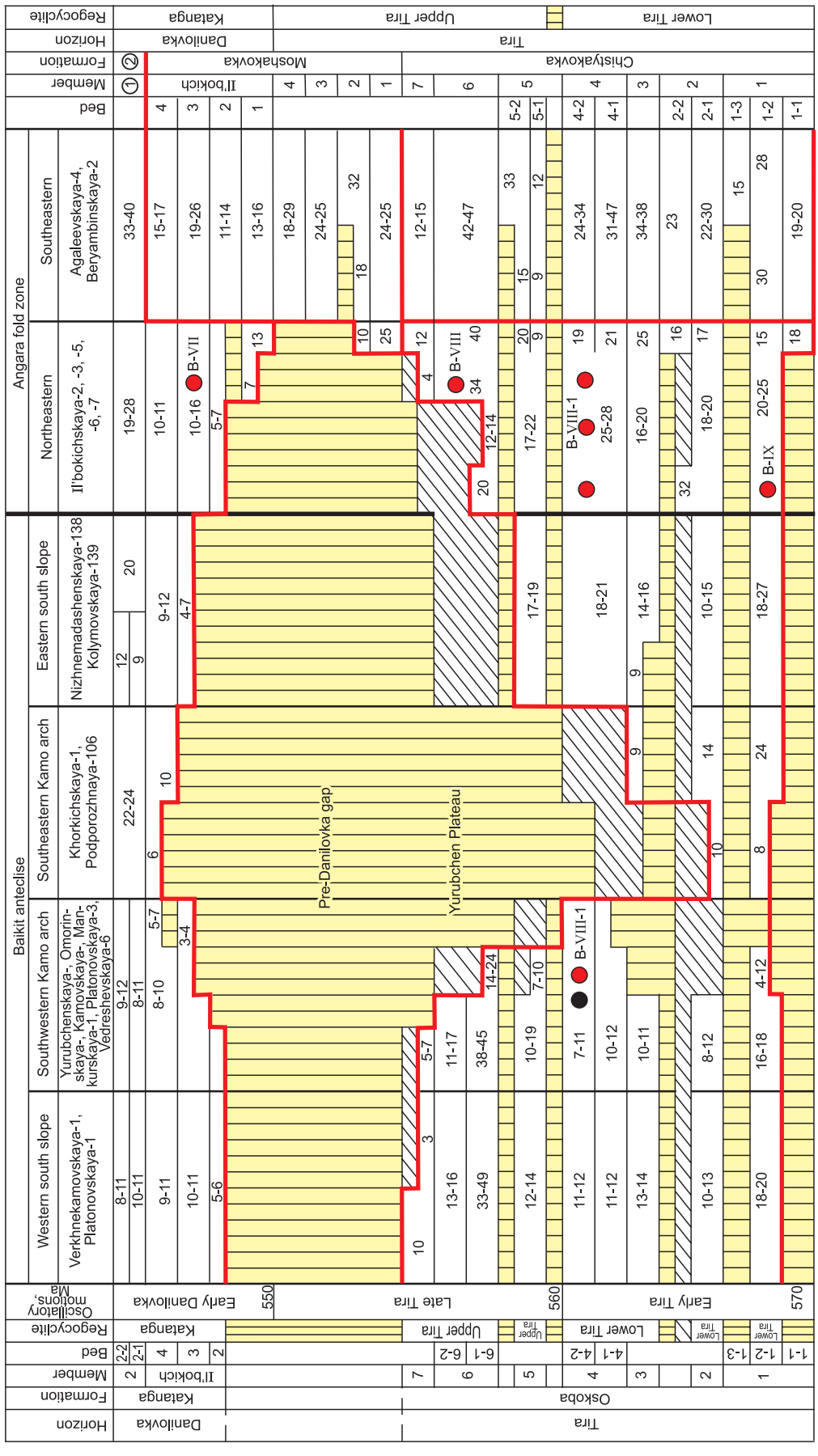

Fig. 10. Detailed stratigraphic chart of the Tira and Danilovka (bottom) horizons for the Vendian southern part of the Baikit anteclise and the eastern part of the Angara fold zone of the Siberian Platform. *1*, formation boundaries; *2*, bed and member thicknesses (m), for the rest of the legend see Figs. 3, 4, 7. Circled numbers: 1, Preobrazhensk member, 2, Katanga Formation.

leorelief (Mel'nikov, 2011, 2015) that formed in the Kamo arch in pre-Nepa and, probably, even in pre-Vendian time.

Northwards, over the eroded Vendian and then the Riphean tops in the Yurubchen–Tokhomo petroleum accumulation zone (Kontorovich et al., 1988) on the top Kamo arch over the gap is the Preobrazhenka member or its analog (member 2 of the Katanga Formation).

In well Ilb-3 from the siltstones of bed 3 of the Il'bokich member, a hydrocarbon gas influx was registered, which, probably, comes from productive bed B-VII of the Omorinskaya area.

CONCLUSIONS

The study performed to investigate the mid part of the Vendian at the level of members and beds has made it possible to compose a stratigraphic chart of this interval for the southwestern part of the Siberian Platform. The data on cyclites and warping have allowed estimating the changes in formation duration of the Tira Horizon formations, regional sedimentation gaps and erosion amplitudes during such gaps. The member based correlation within the Tira Horizon has confirmed a wide-spread occurrence of productive bed B-VIII-1 in the mid part of the Oskoba Formation along the studied territory.

The performed study has given an opportunity to forecast the areal occurrence of the members of the Oskoba Formation and to reconstruct the paleogeomorphological details of the relief during sedimentation gaps. Thus, the duration of the pre-Danilovka gap was determined by the pre-Danilovka relief of the Yurubchen Plateau.

The accumulated data have demonstrated that in the southwestern part of the Siberian Platform the thicknesses of the Upper Vendian formations increases abruptly. At the distance of 60 km northward (Baikit anteclise) and southward (Angara fold zone) the thicknesses of the Katanga Formation increase from 136 to 300 m, the thicknesses of the Moshakovka Formation from 0 to 160 m; those of the Oskoba and Chistyakovka Formations from 30 to 286 m (Figs. 3, 10). These changes were due to the presence of the Yurubchen Plateau on the Baikit anteclise, and the tectonic downwarping of the northern part of the Sayan–Yenisei syneclise during the Vendian. The syneclise seems not to have the pre-Danilovka and pre-Tira gaps, but they present regionally in the Baikit anteclise and the central part of the Lena–Tunguska petroleum province. The presence of the pre-Danilovka gap has also been confirmed for the Baikit–Katanga and Turukhan–Bakhta facial regions (Mel'nikov, 1994, 2009).

In the Angara fold zone and the northern part of the Sayan–Yenisei syneclise the Vendian terrigenous sediments are difficult to break out into the pre-Danilovka and pre-Tira Horizons. For this region, the formation breakout has been specified, and the Il'bokich members have been separated in the bottom of the Katanga Formation of the Baikit anteclise and in the top of the Moshakovka Formation of the Angara fold zone.

The disappearance of the washouts, pre-Danilovka and intra-Tira gaps in the Angara fold zone represents a typical structuring of beddings over and under the stratigraphic discontinuity where positive and negative structures contact that has been many times described in geological literature. This conclusion has made it possible to specify (Table 1) the Vendian cyclometric chart (Mel'nikov, 2009). A warping scale has been added into the chart, its duration for the Vendian is considered equal to 10 Ma. The regocyclites have been kept as independent elements for in big and the biggest positive Vendian structures, gaps formed simultaneously with the bottom of parts of the regocyclites in the biggest negative structures.

The gap duration varies from 0 to 6.5 Ma depending on the types. For that reason, the gaps have been included in the warping ranges and seem to be absent (or short-lived) in the negative structures.

The study has indicated a variety of sedimentation gaps of different degrees, determined their localization, maximum duration and absence periods. The gap duration depends on their degree: regional ones lasted 2-4, rarely up to 6.5 Ma, zonal—0.5 and rarely up to 1 Ma. This estimation has been given in relation to the durations of the Early Tira, Late Tira, and Early Danilovka warping movements during the Vendian.

The study has also demonstrated there is a standard inverted dependence between sedimentation duration and sedimentation gaps. The maximum duration of the sedimentation periods was estimated to be 6–10 Ma, the maximum measured formation thicknesses in the wells were up to 205 m (Oskoba Formation); up to 320 m (Chistyakovka Formation); 160 m (Moshakovka Formation) including the 95 m related to the Tira Horizon and 65 m to the Danilovka Horizon (Il'bokich member).

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