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Quaternary Glaciotectonics of the Ural-Siberian North[1]

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Abstract—This is a review of previous works on glaciotectonics and recent epeirogenesis of the northern West Siberian sedimentary basin and adjacent parts of the Urals and the Siberian Craton. It is supported by the addition of detailed structural profiles of the disharmonic dislocations around Malyi Atlym settlement on the Lower Ob' never published before. The collected data highlight sources and results of neotectonic phenomena in the north of West Siberia and their impact on distribution of hydrocarbon deposits. The rugged topography of the northern Urals and Mid-Siberian Plateau, discordant with the regional tectonic structure, is generated by compensation uplifts along the margins of thick ice sheets in the West Siberian North. Ice load vacillations were an important factor of geographical separation of hydrocarbons liquid and gaseous phases. This is evident from the west–east zonation of petroleum deposits, discordant with the south–north strike of ancient structures but concordant with thickness zonation of ice sheets. The structure of the alpine-type dislocations penetrating up to 400 m into the sedimentary basin on the Lower Ob' reveals that the variations of their tectonic style do not fit the mechanical properties of thawed Paleogene rocks. However, they are more understandable assuming their origin from deviatoric stress in pressurized perennially frozen Paleogene rocks. Such conditions are feasible at the base of a growing thick ice sheet. Ice sheets did significant work of glaciotectonic erosion of soft Paleogene rocks of the perennially frozen substrate soldered with glacial ice. This type of erosion is evident in the Ob' catchment area where whole blocks of intact sand and clay were transported by glaciers over hundreds of kilometers. Glaciotectonic erosion of glacier substrate is sufficient for explaining the well-known stratigraphic hiatus between Quaternary and Upper Cretaceous formations of the Siberian Arctic instead of the popular but illogical tectonic inversion of the sedimentary basin.

Keywords: glaciotectonics, distribution of petroleum deposits, West Siberia, northern Urals, Putorana Plateau

INTRODUCTION

Recent tectonic history of northern sedimentary basins is deeply influenced by Quaternary glaciations. Comparing the structure of a large sedimentary basin against the confining highlands could be instructive for understanding the scale and imprint of glacial processes on the regional tectonic evolution. The major petroleum province of Russia, the West Siberian basin (Fig. 1) located between the Uralian Mountains and the Central Siberian Plateau, presents such an exemplary case. In order to assess the nature of recent tectonics and its significance this paper offers a short overview of the macroscopic neotectonic features of the region accompanied by a detailed cross-section of the largest mesoscopic structure. The data available on features of different scales are presented and discussed separately. Their basically glaciotectonic nature is considered as indications of deep influence of Quaternary glaciation on the recent history of the Russian North and as material for comparison with other northern sedimentary basins.

There are popular definitions of glaciotectonics as related "to the processes of glaciotectonic deformations" (Aber and Ber, 2007, p. 6) and "Glaciotectonics is glacially induced structural deformation of bedrock or sediment masses as a direct result of glacier-ice movement or loading" (Aber and Ber, 2007, p. 7). I prefer a broader option relating to glaciotectonics as any changes in geological structure best explained by ice load applied vertically and tangentially. Such changes, as will be shown, are not limited to glacioisostatic movements or thin-skinned deformations of sediments.

GEOLOGICAL SETTING

The West Siberian Plate stretching between 55° and 73° N is the world greatest sedimentary basin of more than 2.2 mln km^2 in area (Figs. 1, 2). Its basement is a consolidated system of Paleozoic folded rocks including Precambrian blocks. The last paroxysm of tectonics produced a system of south–north striking Triassic rifts filled with terrigenous rocks and basalt lavas. The overlying unconsolidated Mesozoic–Cenozoic strata, commonly 3–4 km thick but up to 9 km thick in the Arctic, is the body of the West Siberian hydrocarbon province containing more than 50% of Russian petroleum and natural gas reserves (Kontorovich

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et al., 1975; Ulmishek, 2003). Its topographic manifestation, the West Siberian Plain, is a swampy flatland descending northwards from 300 m to 100 m a.s.l. to eventually merge with the Kara Sea shelf. The northern half of the basin is covered by glacigenic and marine Quaternary formations up to 400 m thick. The flat relief and poor accessibility of the swampy boreal forest and perennially frozen tundra led to many controversial interpretations of Quaternary history (e.g., Zubakov, 1972).

The petroleum is discovered in permeable Mesozoic strata composing gentle elongated undulations striking parallel to the Paleozoic frame of the Urals and Central Siberia. The common petroleum traps are very gentle brachyanticlines formed by sedimentary strata draping basement salients less than 2°–3° steep and sealed by Upper Cretaceous clayey formations. A good deal of folds amplitude is due to consolidation and sagging of thick marine clays (Kontorovich et al., 1975). The local synsedimentary anticlines show practically no post-Oligocene growth. They normally flatten upwards from the Middle Jurassic strata to horizontally lying Paleogene clays, excluding the arctic terrains where structural traps in places show a late Cenozoic amplitude growth ~20–50 m (Kuzin, 1983). According to geochemical studies, the explored petroleum reserves were formed mostly during the Neogene–Quaternary (Ryl'kov et al., 1976), which stimulates the interest in recent tectonics.

NEOTECTONIC MACROSTRUCTURE

Distribution of macroscopic features. The neotectonic pattern of the West Siberian Plain shows a sublatitudinal zonality that is transverse to the principal south–north strike of major structures of the sedimentary basin. Such a zonality is especially pronounced in the regional trend and in the pattern of the largest structures. Only in the south of the basin all Cenozoic formations are evenly spread as thin blankets. In the north, the Pleistocene cover is ~100 m, in places even 300–400 m thick, whereas Neogene and upper Paleogene strata are mostly absent (Kontorovich et al., 1975). The age of sub-Quaternary sand, clay and diatomite formations appear progressively older towards the Kara Sea concurrently with the descent of the surface, i.e., the pre-Quaternary stratigraphic gap widens northwards (Fig. 2).

Along the borders of the plain there are some south–north striking depressions outlined by fault escarpments. The most pronounced is the Yenisei Depression, which is seen in satellite imagery as a young graben expanding northwards (Fig. 3, and object 8 in Fig. 4). The Quaternary is up to 342 m thick there as measured in a borehole at the southern end of this rift-like trough (Zubakov, 1972; Arkhipov et al., 1976).

Another characteristic feature is young clay diapirs involving Paleogene–Neogene marine clays, opokas and diatomites. Beyond the drift limit, their amplitudes are barely few meters, maximum first tens of meters, which is accountable by gravitational adjustment along fluvial escarpments commonly 50–60 m high. However, north of the drift limit the diapirs can be hundreds of meters high (Generalov, 1987). These large diapirs without deep roots may be explained only by much higher gradients of lithostatic and fluid pressure, probably caused by disjointed slabs of stagnant glacier ice (see next section).

It is noteworthy that the south–north change of the sedimentary basin is concurrent with changes in the neotectonic macrostructure of the adjacent highlands. A prominent ex-

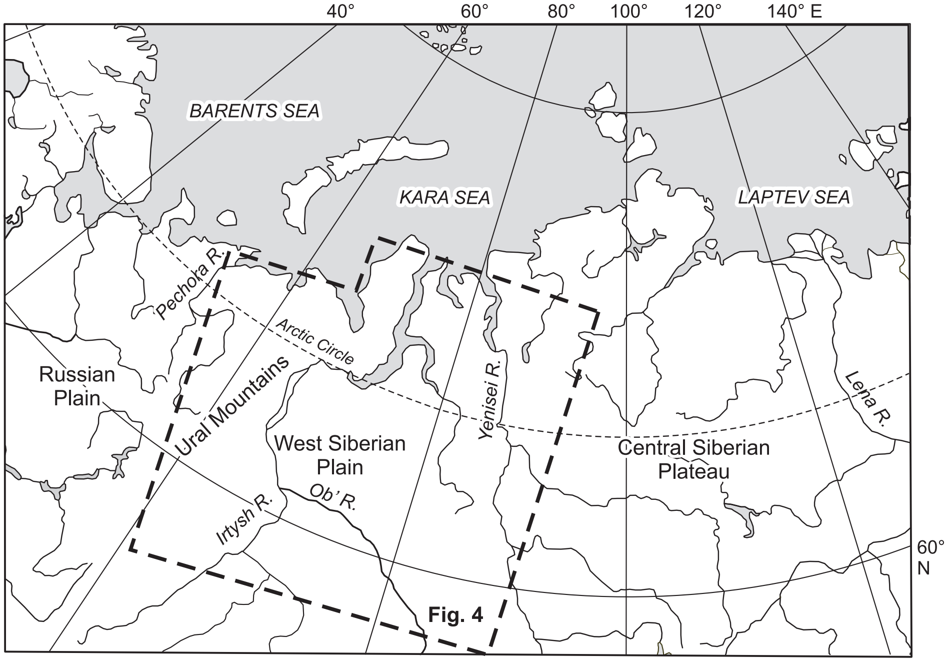

Fig. 1. Location map; study area (Fig. 4) is marked by broken line.

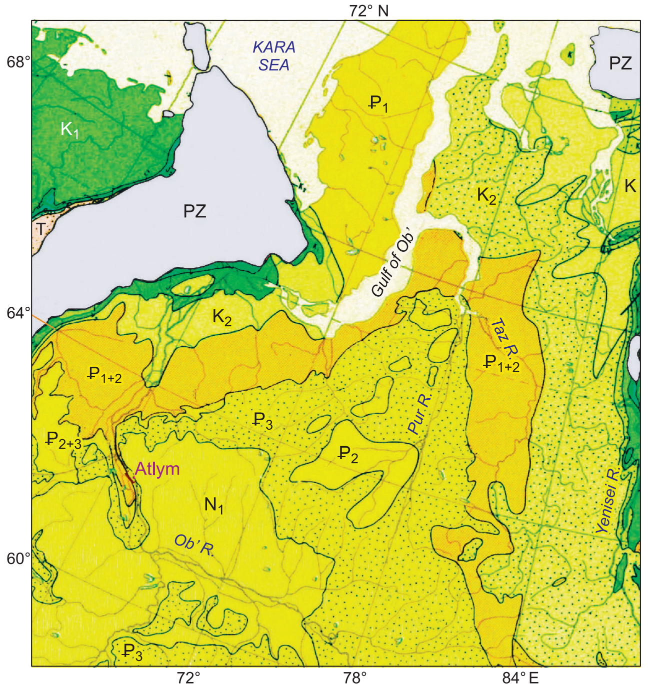

Fig. 2. Schematic geological map of the northern sedimentary basins. Pz, consolidated Paleozoic rocks of the Uralian and Central Siberian borderland ridges. Mesozoic and Cenozoic sedimentary formations: J, Jurassic sands overlain by clay; K$_1$, Lower Cretaceous shales with sandstone interlayers; K$_2$, Upper Cretaceous sandstones and shales; ₽$_1$, Paleocene clays; ₽$_{1+2}$, Paleocene and lower Eocene clays; Pg$_2$, Eocene opokas, diatomites and clays; ₽$_{2+3}$, upper Eocene–lower Oligocene clays with siderite and sand interlayers; ₽$_3$, Oligocene sands and silts; N$_1$, Miocene silty rhythmites. Red strip along the Ob' valley is the synthetic profile of Atlym disturbances in Fig. 10.

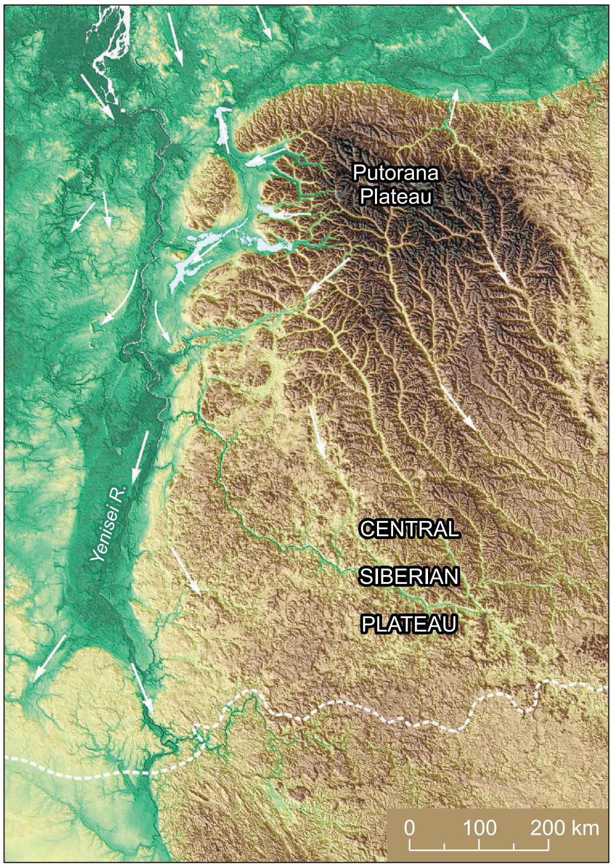

Fig. 3. Digital terrain model of eastern West Siberia and Central Siberian Plateau margin. The broken line is the glacial drift limit, arrows indicate former ice flows. Change of green shades of boreal forests in the south to brownish colors of montane tundra in the Arctic reflects gradual increase of elevations from 300 to 1300–1700 m contrary to the deepening of the Paleozoic–Triassic basin.

ample is presented by the Central Siberian Plateau along the eastern border of the plain. Its height steadily increases from 250–350 m a.s.l. close to the drift limit and up to 1300–1700 m in the arctic Putorana Plateau (Fig. 3). The latter is deeply dissected by rectilinear network of fjord-like valleys, which reflects a system of extension fractures and faults caused by a young dome-like uplift (Fig. 4). The Putorana Plateau is a clearly astructural antiform located in the deepest Paleozoic–Triassic depression of the north-western corner of the Siberian Craton called the Tunguska Basin (Staroseltsev, 1985). The fresh tectonic escarpments cutting young glacial features are a probable source of the Holocene seismicity there (Maksimov, 1970).

Another spectacular example of the south–north neotectonic change is presented by the Ural Mountains along the western border of the plain. Independently of the persistent south-north strike of all Paleozoic structural and formational zones of the Urals, the mountain chain steadily grows northwards from the drift limit (Fig. 4). South of this line the Urals are mostly gentle hills with many monadnocks and very wide pre-Quaternary valleys. The Middle Urals close to the city of Yekaterinburg merge imperceptibly with peneplanated piedmonts and display only rare summits exceeding 450 m a.s.l. The most salient feature of the Middle Urals is the lack of topographic contrast between the Urals and adjacent Cis-Uralian and Trans-Uralian plains of similar altitudes (Rozhdestvenskii, 1971). Actually, the Middle Urals are hardly noticeable from the air when jet-flying across the range. The Southern Urals are considerably higher (1000–1500 a.s.l.) but consist mostly of gentle ridges with concave slopes built of most resistant rocks such as quartzites. The subdued ridges are separated by much wider longitudinal valleys, which are too large for the extant rivers. The well graded slopes with patches of weathering mantles and Paleogene sediments indicate that the major elevations of southern mountains belong to pre-Quaternary erosional cycles. Pleistocene fluvial erosion left only narrow valleys less than 100 m deep (Bashenina, 1948).

The general subdued appearance of the old relief of the Southern and Middle Urals changes to quite a different aspect of alpine topography in the much higher Sub-Polar and Polar Urals reaching 1400–1800 m a.s.l. The principal difference in the age of landscapes of southern and northern Urals is evident from comparison of volume of negative and

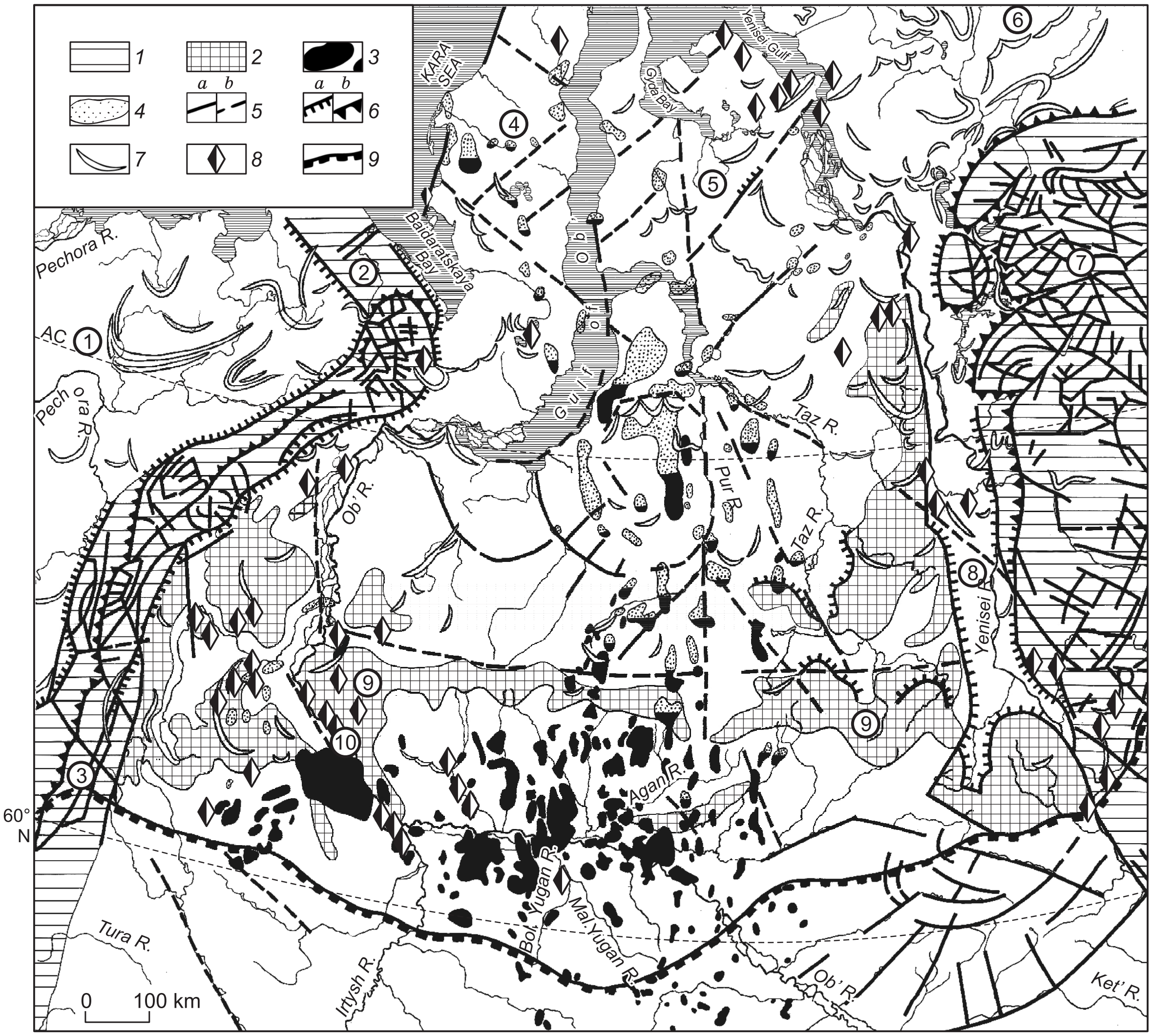

Fig. 4. Glaciotectonic map of West Siberia and adjacent uplands, modified after (Astakhov, 1986). Geological and geomorphological features: *1*, Paleozoic uplands; *2*, Quaternary uplands within West Siberian Plain; *3*, oil fields; *4*, natural gas deposits; *5*, large lineaments observable in satellite imagery: *a*, orohydrographic, *b*, discontinuously traced in the landscape; *6*, tectonic escarpments: *a*, tens of meters high, *b*, hundreds of meters high; *7*, fold-and-thrust imbricate assemblages of sedimentary cover rocks topographically expressed as ridges on the surface; *8*, large detached blocks of unconsolidated rocks; *9*, southern limit of glacial Quaternary. Physiographic elements indicated by circled numbers: 1, Pechora Lowland; 2, Pai-Khoi Range; 3, Urals; 4, Yamal Peninsula; 5, Gydan Peninsula; 6, Taimyr Peninsula; 7, Putorana Plateau; 8, Yenisei Depression; 9, Siberian Hills; 10, Atlym dislocations profile on Figs. 8 and 9.

positive landforms: old gentle-sloped valleys of Paleogene–Neogene erosion cycles make the general picture in the south, whereas positive features such as uplifted alpine blocks dominate the northern landscapes. In short, the southern part of the Urals is a residual range and the northern part is rejuvenated low mountains (Astakhov, 1986).

Most revealing are the borders of the West Siberian Plain. South of the drift limit, they are poorly expressed, both in the west and east. Only in the glaciated area they appear as tectonic escarpments growing northwards from tens to hundreds of meters concurrently with the gradual descent of the plain (Fig. 4). The result is the scissor faults with offsets up to 1000 m separating the northern highlands from the adjacent lowlands whereas the unglaciated Urals and Central Siberian Plateau merge gradually with the Russian and West Siberian Plains.

In the West Siberian Plain large hummocky uplands 200–300 m a.s.l. built of thick Quaternary sands and diamicts occur only north of the 60°–61° N. In plan view, they compose a huge horseshoe of the Siberian Hills roughly parallel to the glacial drift limit recognized early in the XX century (Fig. 4). These uplands are in places bordered by linear escarpments several tens of meters high coinciding with deep-seated geophysical lineaments. The mapping geologists interpreted the lineaments as basement faults reactivated by Pleistocene glacioisostasy (Samoiluk and Lavrov, 1986; Zaitsev and Meshalkin, 1987).

Discussion. The popular idea for the origin of the large transverse landforms and the Neogene stratigraphic gap in the north has long been invoking a late Cenozoic tectonic inversion which presumably affected the northern part of the basin. Many geologists believed that the northern, most depressed part of the basin was suddenly uplifted in the Neogene to subside again in the Quaternary (e.g., Rudkevich, 1974). This hypothesis of the regional oscillations of deep-seated tectonics seems hardly compatible with the stable subsidence of the basin inherited since the Jurassic and with the numerous erosional remnants of Oligocene–Miocene sands and clays north of 64° N (Fig. 2). Besides, in the south of the Plain a thick cover of correlative terrigenous sediments commensurate with the hypothetical Neogene uplift of the north is absent.

The distribution of the Pleistocene formations against the background of the large landforms suggests an alternative explanation for the neotectonic macrostructure of the West Siberian Plain. The decades of geological mapping and studies of glacial erratics and thick diamictic formations have reliably established that the West Siberian north was at least 5 times covered by Middle and Late Pleistocene ice sheets (Arkhipov et al., 1976, 1986; Astakhov, 1977, 2004, 2011, 2013; Sukhorukova et al., 1987). Paleoglaciological estimates based on mapped ice limits give maximum Middle Pleistocene ice thickness 3.8 km in the central West Siberian Arctic (Voronov, 1968) and up to 4.5 km for the ice dispersal center on the Kara Sea shelf (Lambeck et al., 2006). For the northern part of the sedimentary basin this means isostatic subsidence ~1 km with the commensurate compensation uplift of adjacent borderlands. This value is close to the amplitude of the entire Paleogene subsidence. The regional glacioisostatic subsidence should have been followed by a rebound of a comparable magnitude. Also, the ice flow and static pressure would have caused large-scale lateral redistribution of the non-consolidated substrate rocks in the form of voluminous glaciotectonic dislocations.

The glacial origin of the large-scale geomorphic aspect of the northern part of the West Siberian Plain is also clearly demonstrated by the south–north change of the Quaternary thickness as observed in several drilling profiles across the valleys of the Ob' catchment (Astakhov, 1991). The data were obtained by Soviet geotechnical projects of Hydroproject Corporation exploring possible routes for diversion of Ob' water to the southern deserts (Fig. 5). The Quaternary sediments, normally 30–40 m thick in the south, drape the smooth northbound profiles of the former and present waterways. However, north of the drift limit Quaternary sediments filling the buried valleys suddenly increase their thickness up to 100–300 m. The even and smoothly graded concave bottom of the Tobol–Irtysh stem valley of the periglacial area plunges abruptly below sea level in the glaciated area. Downstream, along the river Ob', the pre-Quaternary bedrock profile is obviously complicated with big humps. All this suggests that the buried valleys of the West Siberian north are excavated not by fluvial but glacial processes. The form of the Ob' buried valley in Fig. 5 is very similar to bumpy subglacial tunnels of northern Europe and America attributed to discharge of over-pressurized subglacial meltwater (Kehew et al., 2012).

The available evidence of the recent tectonics indicates that only rare features inherit ancient structural directions whereas the general pattern is the zonality transverse to the ancient south–north trends. This "geographical" or rather paleogeographical zonality of the topography and recent tectonics mirrors the zonality of Pleistocene ice thickness. The process of the slow adjustment of basement blocks to the increasing sedimentary load during the Mesozoic–Cenozoic was drastically accelerated in the Pleistocene when the rapid ice accumulation disturbed the system of isostatically

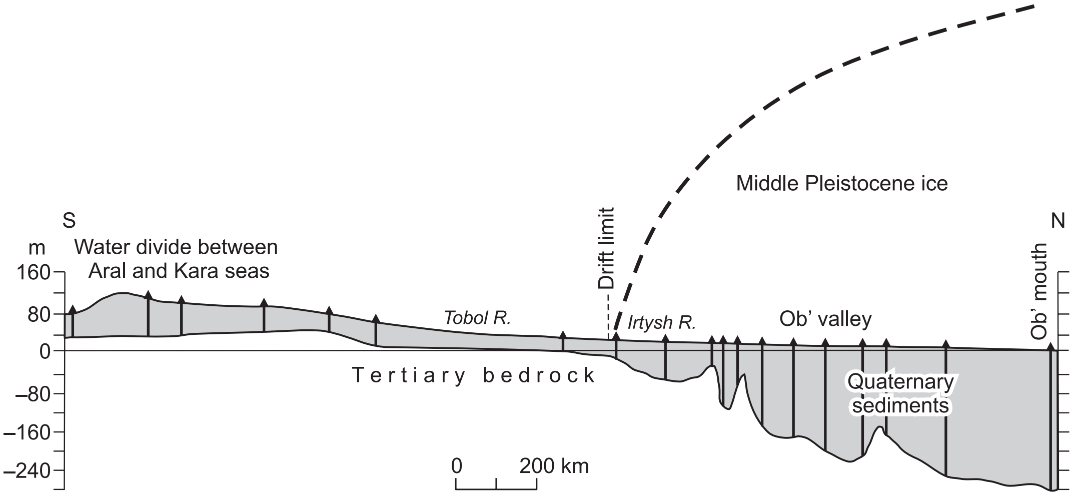

Fig. 5. Distribution of Quaternary cover thickness along the south–north striking river valleys of the Kara Sea and Aral Sea catchments according to transverse drilling profiles (black triangles) of Hydroproject corporation, after (Astakhov, 1991). Note the sudden increase of Quaternary thickness north of the drift limit.

balanced blocks. The rapidly applied load is the most probable explanation of the high-amplitude Pleistocene faults incongruous with the stable plains and old residual mountains (Astakhov, 1986).

Glacioisostatic effects in the Ural-Siberian north demonstrate a cardinal difference with the Fennoscandian pattern. Forebulges, i.e., peripheral compensation uplifts, that used to form around the former ice sheet, now are almost extinct in Fennoscandia. They are replaced by a gentle circular trough commensurate in volume with the central glacioisostatic dome (Mörner, 1979). These epeirogenic oscillations imply elastic deformation of the lithosphere. In the Ural-Siberian North, on the contrary, most conspicuous are marginal compensation uplifts of the isostatic horsts of the Urals and Putorana, and probably also the Siberian Hills in the center of the West Siberian Basin. These uplifts matched by the persisting subsidence of ice-loaded arctic West Siberia are evidence of residual deformation of the lithosphere (Astakhov, 1986).

The residual deformation versus elastic rebound is probably due to the antithetical structure of the deep-seated lithospheric layers of the Ural-Siberian region in contrast to Fennoscandia. It can be judged from the depth of the horizon of the sharp change of seismic velocities called Moho which geophysicists commonly take for the bottom of the "crust". In Fennoscandia the Moho boundary plunges down to the center of the isostatic dome from 30 to 47 km (Mörner, 1979). Conversely, in West Siberia the seismic M boundary is deepest (47 km) under the marginal highlands whereas at the inferred ice dispersal center in the arctic lowlands the M level is only 35–40 km deep (Karus et al., 1984).

RADIAL GLACIOTECTONICS AND HYDROCARBON RESERVES

The concept of the structural reorganization of the sedimentary basin by glaciotectonics may be useful for solving some problems of petroleum geology in West Siberia such as origin of anomalous fluid pressures, explanations of geothermic peculiarities, saturation of traps, etc. For example, the glacial interpretation of the neotectonic macrostructure can be applied to a solution of the old puzzle of the geographical separation of natural gas and oil deposits. The major oil fields discovered in Upper Jurassic–Lower Cretaceous strata at depths of 1.5 to 3 km are located within a west–east striking belt in the center of the plain (60°–63° N) which is transverse to the general south–north strike of the main Mesozoic structures. The subarctic belt to the north of the Siberian Hills contains a motley of oil, gas-condensate and gas deposits. Huge gas fields sealed by Paleogene clay formations decidedly predominate in the Arctic (Fig. 4).

There were attempts to explain the geographic separation of gas and oil reserves by changes of hydraulic pressure in petroleum-bearing strata caused by the fluctuations of sea level (Kuzin, 1983). However, the fluid pressure drop of ~20–30 atmospheres that could be provided by a hypothetical Pliocene regression of the Arctic Ocean is too small for degassing of ground water of Mesozoic aquifers. The rate of fluid pressure decrease in such a case would be insufficient for generation of the giant gas fields of West Siberia such as the Urengoi pool ~120 km long (Korzenstein, 1970), to say nothing of the dubious geological evidence of such a regression.

The alternative hypothesis sees the reason for the geographical separation of different types of hydrocarbons in lateral migration of fluids within aquifers under glacial load and in enhanced gas generation in the perennially frozen zone of hydrate formation (Trofimuk et al., 1979). Unfortunately, this model employed an outdated reconstruction of ice sheets which were presumably thinning towards the south–north axis of the basin which is hardly compatible with the actual distribution of petroleum reserves (Fig. 4). Also, the deepest Pleistocene permafrost is found not in the arctic zone of the main gas accumulation but in the oil belt some 600–700 km to the south. This hypothesis is also rejected by petroleum geologists because a lateral migration of viscous oil through compact sandstones over distances of hundreds of kilometers is hardly feasible.

However, the huge ice load that produced some 200–300 atmospheres of additional pressure should have inevitably affected the underground hydraulic system. Some immediate effects of unevenly applied recent ice load can be directly measured in the drilled petroleum fields. Measurements in boreholes down to the depth of 2.7 km revealed that aquifer porosity in the Arctic is 5–7% lower than that of the same sandstones in central regions along the transverse Ob' River (Fig. 6). This fact is explained by thicker and more persistent glacial ice of the Arctic whereas close to the drift limit on 60° N only a minor ice load was sporadically applied (Gorelov, 1975).

However, glacially induced lateral migration is quite possible for ground water with gaseous hydrocarbons. A glacial effect is felt in northward inclination of water/hydrocarbon contacts in petroleum traps. The inclination of petroleum/water contact is also known in petroleum fields of the Norwegian shelves. In that case glacioisostasy was considered responsible for depth changes, tilting of the traps and expansion of formation gas being used for estimates of Pleistocene spillage and loss of petroleum from the traps during the Pleistocene (Zieba and Grøver, 2016).

In an ideal environment the free-water level in a trap is horizontal. In a real situation this level is tilted because the buoyant force is interfered with by the hydrodynamic force. For example, water/oil contacts may have been tilted up to 1:10 with gas in reservoirs compressed (Forsberg, 1996). Whatever the mechanism, the northward inclination of water/oil interface and piezometric surfaces of water-bearing strata was directly measured in boreholes of all major petroleum fields of central West Siberia in the area of middle Pleistocene ice sheets (Tsarev, 1976).

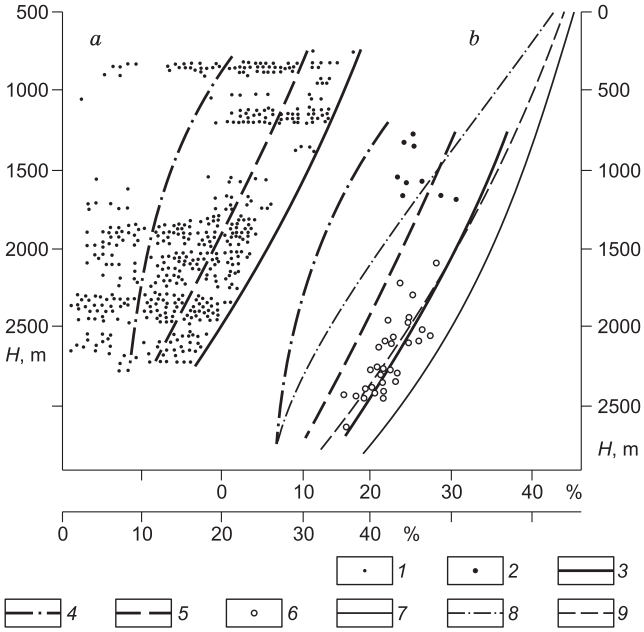

Fig. 6. Open porosity of Cretaceous rocks (percentage) against depth of samples in Arctic West Siberia (*a*) and in the transverse Ob' region (*b*) (Gorelov, 1975). *1–5* for *a*, *6–9* for *b*; *1*, single measurements; *2*, *6*, mean values used for calculating oil reserves; *3*, *7*, weakly-cemented sandstones; *4*, *8*, clayey sandstones; *5*, *9*, mean porosity of oil-reservoir sandstones.

Taking into account the modern data on the ice limits and geographical distribution of the Pleistocene ice thickness (Astakhov, 2013) a simpler explanation of the Quaternary separation of the oil and gas reserves in West Siberia is possible. The sharp vertical oscillations of the arctic part of the basin on the order of hundreds of meters pressurized by periodical ice load should have caused fast changes of underground thermobaric situation. This would result in vertical shifts of zones of generation of different phases of hydrocarbons with irreversible replacement of the liquid phase by the gaseous phase. Gas volume is influenced by pressure both through compression and dissolution when ice load is applied. Conversely, when the ice load is removed gas volume in aquifers is instantly increased by dilatation and degasification.

Thus, an abrupt drop of formation pressure during ice sheet disintegration would result in mass degasification of ground water similar to the effect of the champagne cork. Recurrent changes of formation pressure due to intermittent ice load of Pleistocene glacials and interglacials should have been by an order higher than the pressure drop connected with the hypothetical Pliocene sea regression. This mechanism is called the "ice pump" (Riis, 1992).

In the view of this simple mechanism far-distance lateral migration of petroleum is not necessary for spatial separation of oil and gas reserves. Vertical migration of fluids would concentrate the gaseous phase closer to the surface with liquid phase lagging in deeper strata. The southern petroleum belt contains mostly oil in shallow anticlines of Lower Cretaceous and Upper Jurassic rocks within the depths of 3 to 1.5 km (Kontorovich et al., 1975). The shallow gas deposits must have already dissipated there through not very reliable seals. In the Arctic predominating natural gas is found in more expressive structural traps sealed by thicker Paleogene clays and monolithic permafrost at depths of 0.7 to 1.2 km whereas oil deposits occur sporadically and much deeper.

It is significant that the arctic region of gas fields is located mostly in the area of the last glaciation and of maximum thickness of preceding ice sheets. Therefore, the amplitude of oscillations of reservoir pressure was probably highest in the extreme north where it more significantly facilitated periodic degassing of ground water with formation of the huge gas bubbles close to the surface (Fig. 4). This process was not that powerful in the southern belt with lower ice thickness and less frequent ice advances. Besides the last ice sheet along the drift limit occurred by 100–150 ka earlier than in the Arctic. Therefore, shallow gas pools of the southern belt had ample time to disappear by gradual dissipation through unreliable seals of the patchy permafrost and discontinuous clay formations.

Thus, the peculiar distribution of oil and gas reserves of West Siberia is probably due to pumping the ground fluid system by recurrent Pleistocene ice sheets which greatly enhanced release of hydrocarbons and their vertical migration to the actual structural traps.

IMBRICATE MESOSTRUCTURES

General pattern. The most disputable features of arctic and subarctic lowlands are thick imbricate assemblages of distorted and steep-dipping surficial formations of Meso-Cenozoic soft rocks appearing in plan as large bow-like curvatures. These epidermal disharmonic dislocations of Meso-Cenozoic rocks known as "exotectonic dislocations" (Zakharov, 1968) have been mapped practically everywhere within the drift limit (Rostovtsev, 1982). In places they are not visible on the surface being overlain by the thick Quaternary cover. But more often they are expressed in topography as systems of parallel ridges sticking out due to selective erosion of steeply dipping alternating sands, clays, sometimes opokas and diatomites of any age. They are framed on a deep eroded depression from the concave side (Zakharov, 1968).

In the international literature they are commonly described as composite ridges or hill-hole pairs if such landforms are steep enough (Aber and Ber, 2007). In West Siberia and in the Pechora Basin such features range from hill-hole pairs first kilometers long (Astakhov, 1979, 2004) to composite ridges of record length up to 220 km and width up to 25 km (Fig. 4). The arcs of parallel ridges and hill-hole pairs are generally open to the north, sometimes to the west or east but never to the south (Astakhov, 2013). Their map pattern is clearly concentric in relation to the arctic lowlands and Kara Sea shelf (Fig. 4).

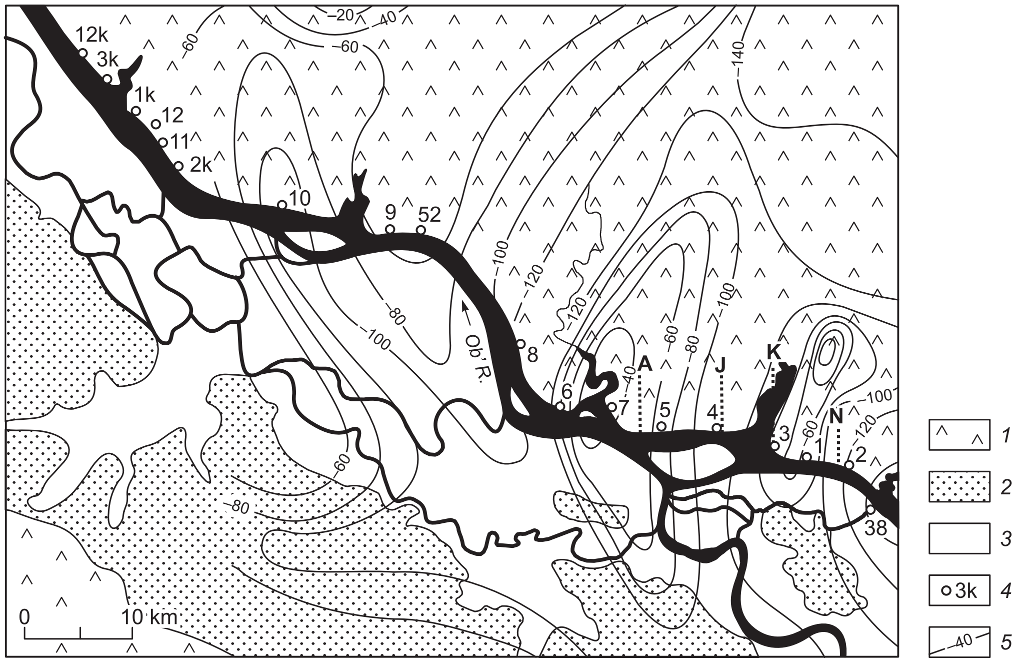

Fig. 7. Location map of the Atlym area in river Ob' valley (see Fig. 2 for geological background). *1*, interfluvial plain with altitudes 120 to 180 m; *2*, terraces of Ob' River; *3*, floodplain; *4*, borehole of Glavtyumengeologiya and its number; *5*, roof of Tavda Formation clays (₽$_{2-3}$tv); dotted lines indicate end points of detailed profiles A–J and K–N (Fig. 8).

There are several fragmentary descriptions of such imbrications in the literature but the described natural cross-sections are never more than several hundreds of meters long. To better understand peculiarities of epidermal tectonics in West Siberia it seems more useful to consider the structure of the much longer cross-section of well exposed Atlym dislocations of Cenozoic rocks on the Lower Ob' River (Fig. 2) which presents an outstandingly instructive case.

Atlym dislocations. A strip of alpine-type dislocations of soft Paleogene and Quaternary sediments up to 25 km wide has long been known in bluffs of the eastern bank of the Ob' River near Malyi Atlym settlement (Atlym in Fig. 2) (Li and Kravchenko, 1959; Nalivkin, 1960). The strip of Atlym dislocations is of considerable interest because of its large size embracing all major types of local Cenozoic formations from Eocene marine clay to Pleistocene diamictons and fluvial sands. This is the reason why they were investigated by a profile of mapping boreholes (Fig. 7) which penetrated the disturbed zone down to the horizontally laying strata. The disturbed rocks are truncated with a pronounced unconformity by a basal till containing slabs of loose Oligocene sand. The diamict and outwash formations farther upstream on the river Ob' proceed southwards to the limit of the middle Pleistocene glaciations over undisturbed Paleogene strata. The subsequent study of the Atlym dislocations shed a new light on their origin and on general glaciotectonic situation in the West Siberian basin (Astakhov et al., 1996).

The detailed profiles in cross-section (Fig. 8) have not been published previously but they contain a large amount of clear indications of alpine-type glaciotectonics endemic for northern West Siberia. The profiles were obtained by measuring attitude of contacts and fault planes in the bluffs 15 km long on the northern bank of the river Ob'. The measurements were controlled by continuous photography from a boat which was a regular practice before the era of GPS. The measured contacts of the local sedimentary formations have been extrapolated below the river level using cores of boreholes drilled by Glavtyumengeologia for geological mapping. The resultant generalized profile shows a complicated zone of deep crumpling of the Paleogene strata ca 35 km wide between wells 2 and 10 (Fig. 9).

The most salient features of the cross-section pictured in Fig. 8 is the dominant western inclination of the structural elements with increase of the dip angles and ratio of shear strain eastwards. The western dips are recorded for overturned folds, thrust planes, imbricated slices and clay injections. The most common features identified by the detailed structural survey are numerous listric faults growing steeper and more tightly spaced upstream, i.e., eastwards. In the western, i.e., upglacier direction the structure gradually becomes simpler, with gentle slightly asymmetric folds prevailing and only occasional upthrusts and clayey injections breaking through the overlying Oligocene sand (Fig. 9).

In the downglacier direction harmonic or slightly asymmetric folds change into tight recumbent folds with numerous zones of mylonitization and injections of the Eocene clay. At the very end of the detailed profile the intensely deformed subvertically dipping and heavily foliated Paleogene rocks are suddenly replaced by subhorizontal strata lying in the normal stratigraphic order upon the Eocene clay which is positioned 250 m below the surface (station 18.4–18.8 km in Fig. 8*b*). About 67° E (right of Fig. 9) the zone of alpine folding abruptly terminates, and farther upstream the river bluffs display only horizontally layered upper Oligocene–lower Miocene sands and rhythmites covered by Quaternary sands and diamicts about 12 m thick. These relations indicate that the shear strain increasing downglacier in incompetent rocks was met by a solid competent dam (Astakhov et al., 1996).

The mean thickness of the Tavda Eocene–upper Oligocene clay as traced in boreholes along the general cross-section is 170 m (borehole 36). However, upglacier it is getting abnormally thin (ca. 100 m) whereas downglacier its thickness increases up to 200–250 m (boreholes 1 to 6). This feature looks as a result of extension upglacier and injection of pressurized clay downglacier. In borehole 3 the deformed Eocene clay with slickensides was observed down to the depth of 310 m below the river level (Fig. 9). Therefore, the entire zone of the disturbed soft rocks is ca. 400 m thick which is probably the world record for epidermal glaciotectonics. The underlying Paleocene and Mesozoic strata beds down to the Paleozoic basement, which is 2.8 km deep, in seismic profiles are basically horizontal with only minor undulations (Li and Kravchenko, 1959).

Discussion. The epidermal alpine-type deformations of West Siberia on account of their size have been perceived by some geologists as rootless neotectonic structures and manifestations of deep-seated tectonics (e.g., Krapivner, 1986). However, after many drilling projects and seismic profiling of 1960–1980s it became clear that these arches reflect disharmonic folds and thrusts accompanied by large detached blocks of soft rocks and usually cannot be traced deeper than 200–300 m (e.g., Arkhipov et al., 1976, 1986; Astakhov, 1986, 2011). The disharmonic dislocations of West Siberia are structurally very similar to ice-pushed ridges or thrust moraines in glaciated sedimentary basins of northern Europe and America where they are related to tangential glaciotectonics, i.e., to subglacial deformation of soft rocks (Levkov, 1980; Aber and Ber, 2007). The most revealing is their orientation which is discordant to the Mesozoic–Paleogene structural plan but quite consistent with the margins of reconstructed ice sheets in the arctic lowlands and on the Kara Sea shelf (Astakhov, 1977, 1986). Thus, the glacial origin of epidermal dislocations in Cenozoic rocks of northern West Siberia seems highly probable.

The largest and best exposed Atlym dislocations can shed more light on glaciotectonics in West Siberia. Originally the geologists described the structure as basically folded with complications of minor faults. They explained the Atlym dislocations either by unspecified glaciotectonics (Li and Kravchenko, 1959) or were cautious about genetic implications (Nalivkin, 1960). A dissenting view ascribed this crumpling of Cenozoic rocks as produced by a deep-seated slip-strike fault (Krapivner, 1986). The latter idea was not adopted by local geologists because numerous seismic exploration profiles clearly demonstrated that the deeper Jurassic-Cretaceous sedimentary strata were lying horizontally over the Paleozoic basement with very rare faults (Kontorovich et al., 1975).

The crucial feature for understanding the origin of the Atlym dislocations is the difference of the deformation styles of the mechanically diverse Paleogene rocks which is evident in minor structural complications of the maximally deformed downglacier part of the Atlym profile. The middle Oligocene Atlym sand displays only brittle deformations without minor folds or crenulation or any other ductile structures. Commonly it is broken into sharp-edged blocks divided by listric upthrusts, sometimes stacked into a pile of "chips" (Fig. 10*a*). The extreme brittle deformation is observable in typical fault breccia consisting of small angular splinters (Fig. 10*b*). Such deformations normally develop in competent rocks such as cemented sandstones whereas presently the Oligocene sand is completely loose. The only possible cement during the deformation in this case was ice. This is also suggested by the 120 m long undisturbed raft of the middle Oligocene sand below the basal till visible atop of the distorted upper Oligocene rhythmites (station 17.8 km in Fig. 8*b*). The presently thawed sand raft, piggyback riding on the younger sediments, shows no strong internal deformation and was probably incorporated into glacial ice prior to the maximum compression.

More ductile deformations are visible within the overlying Novomikhailovka sand, silt, clay and lignite interbedded together with Turtas and Abrosimovka silt/clay rhythmites. In the downstream, i.e., upglacier end of the profile (Fig. 8*a*) these rocks commonly occur in harmonic, slightly asymmetric folds eastwards changing into overturned folds (Fig. 10*c*). Farther eastwards subhorizontal stress obviously increases to produce recumbent folds with crenulated bedding and listric upthrusts (Fig. 10*d*), or even glaciotectonic mélange (Fig. 10*e*). These formations also must have been frozen as indicated by their position atop of the perennially frozen middle Oligocene sand (Astakhov et al., 1996).

Finally, the extreme deformations are displayed by the Eocene montmorillonite marine clay of the Tavda Formation which is everywhere exposed as tabular injections up to 200 m thick (station 12–12.2 km in Fig. 8*b*) or clastic dikes 0.3–1 m thick (station 14.2 km). The Tavda clay pierces all younger Oligocene formations which is evident from the color difference between the greenish clay with brown siderite lenses and white sand of the overlying middle Oligocene Atlym Formation (Fig. 10*f*).

Such protrusions could also develop in thawed clays which the thin apophyses seemingly indicate. But in this case the thaw state is unlikely because the internal structure of the injected clay is not just flow foliation but crenulation cleavage. Second, the clay dikes contact with the surrounding sand by flat slickensides with practically no sand xenoliths incorporated into the protrusions. And third, the pulled apart siderite bands in several places are bent into small tight folds which are normally formed not in liquid but in rela-

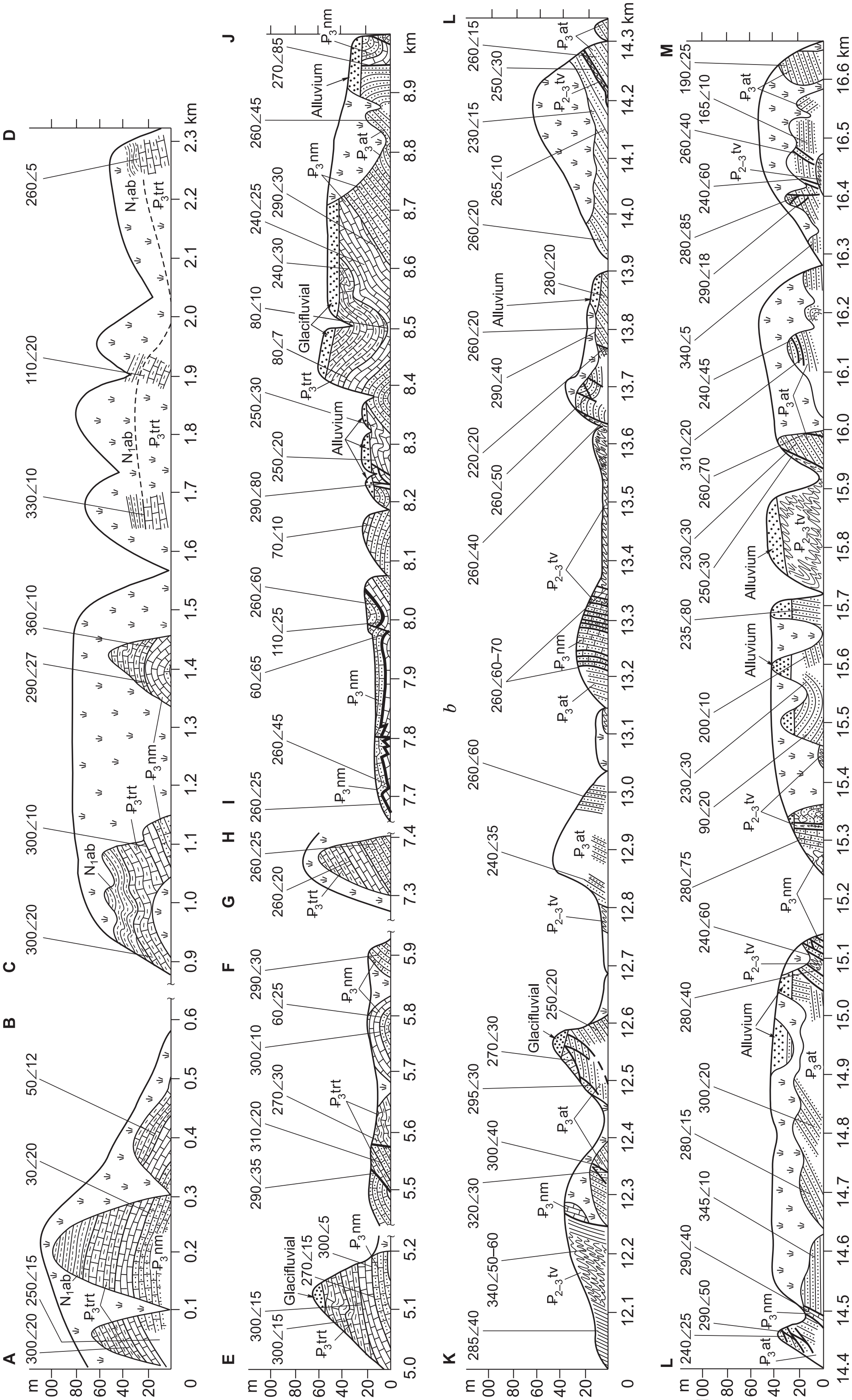

Fig. 8. (*to be continued*).

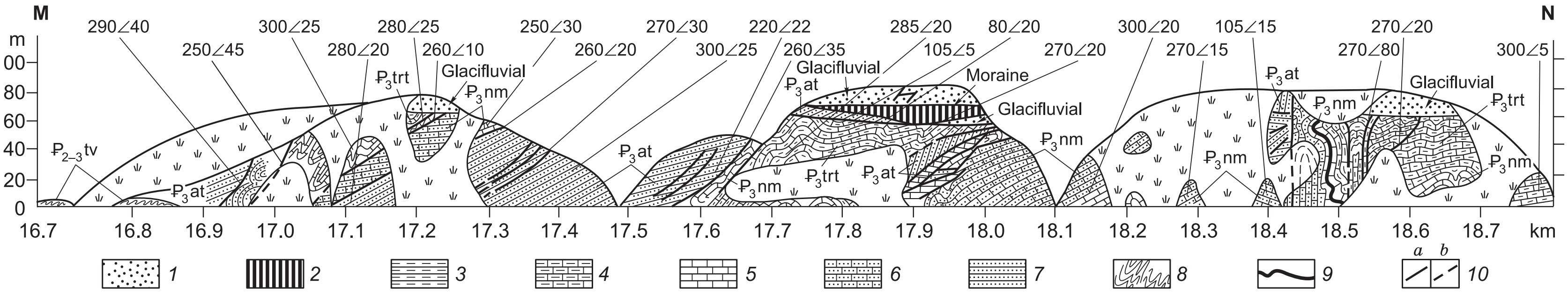

Fig. 8. Detailed geological profiles of the right bank of the Ob' River between E 66°46.5′ and 67°4.5′. Profile A–J (*a*) is west of Malyi Atlym creek, profile K–N (*b*) is east of it. Distances are given from point A, altitudes are from low river Ob' at 15 a.s.l. Attitudes of structural planes are indicated above the sections as dip azimuth (1st number) and dip angle (2nd number). *1*, Quaternary fluvioglacial and alluvial sands; *2*, diamictons of Pleistocene moraines; *3*, silty rhythmites of the Abrosimovka Formation (N_1ab); *4*, silt-clay rhythmites of the Turtas Formation (Ꝑ$_3^3$trt); *5*, silty clay interbedded with sand and lignite of the upper Novomikhailovka Formation (Ꝑ$_3^2$nm); *6*, sands with clay interlayers of the lower Novomikhailovka Formation (Ꝑ$_3^2$nm); *7*, sands of the Atlym Formation (Ꝑ$_3^2$at); *8*, shaly clay with siderite lenses of the Tavda Formation (Ꝑ$_2^3$–Ꝑ$_3^1$tv); *9*, lignite marker layer; *10*, faults: *a*, measured, *b*, inferred.

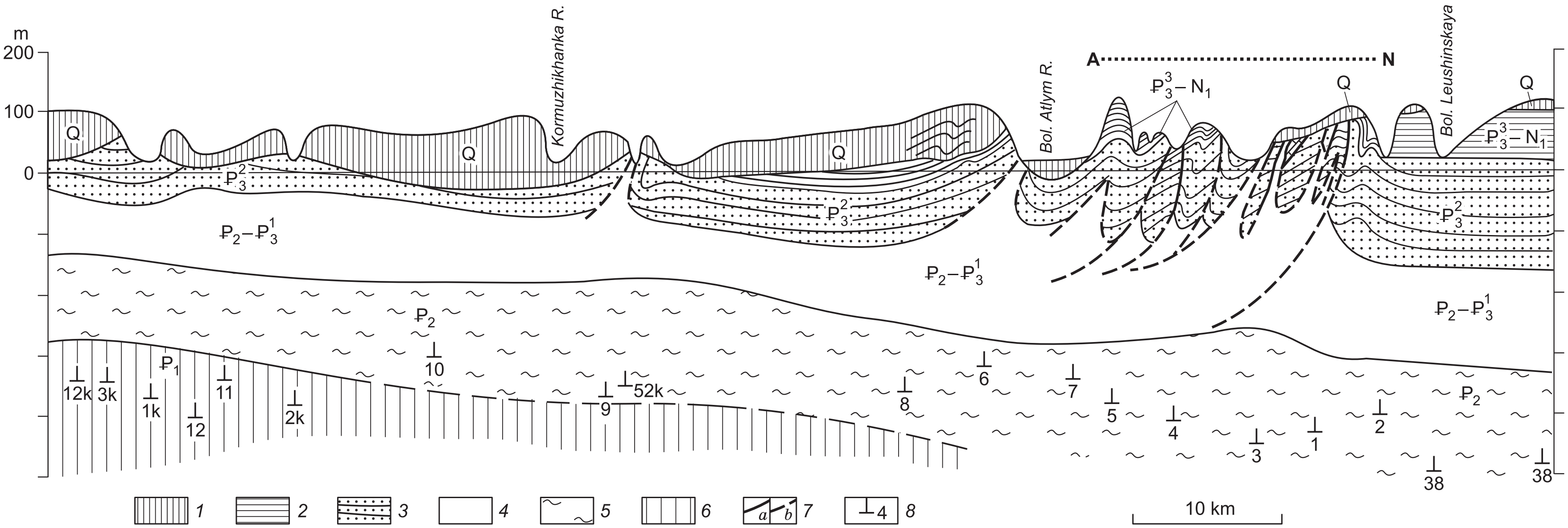

Fig. 9. Synthetic profile of Cenozoic formations along the Lower Ob' River based on Fig. 8 cross-sections controlled by boreholes between 65°40′ E/62°40′ N and 67°15′ E/62°04′ N, after (Astakhov et al., 1996). Continental formations: *1*, Quaternary sediments; *2*, upper Oligocene–lower Miocene silt-clay rhythmites; *3*, middle Oligocene sands with silty clay and lignite interlayers. Marine formations: *4*, upper Eocene–lower Oligocene shaly clay with siderite lenses; *5*, Eocene opokas, diatomites and clays; *6*, Paleocene clay; *7*, faults: *a*, observable, *b*, inferred; *8*, bottoms of numbered boreholes. Broken line A–N indicates location of detailed profiles.

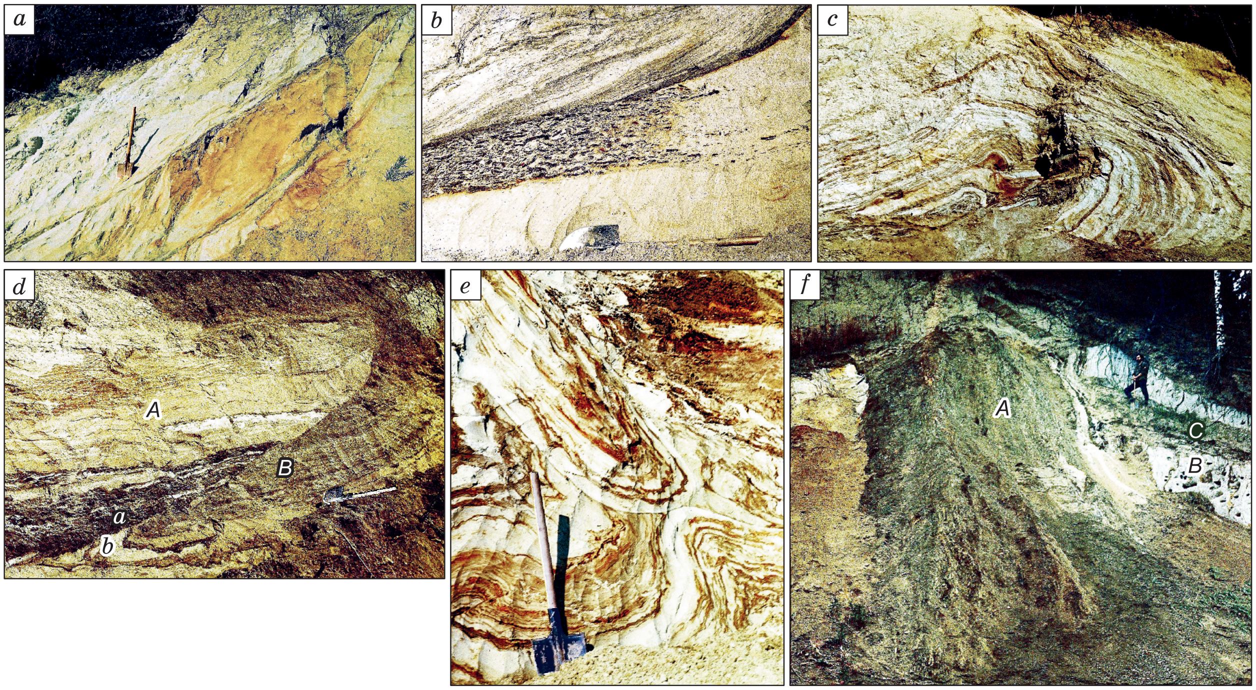

Fig. 10. Deformation structures of Tertiary formations in northern bank of the Ob' River near Malyi Atlym settlement; one meter shovel for scale. *a*, Upthrusted "chips" of the middle Oligocene Atlym sand; station 12.5 km in Fig. 8*b*; *b*, fault friction breccia of silt splinters in the footwall block under a listric thrust in middle Oligocene Atlym Formation sand; station 12.5 km in Fig. 8*b*; *c*, middle Oligocene Novomikhailovka Formation interbedded silt and sand in disharmonic fold overturned eastwards; station 1 km in Fig. 8; section appr. 12 m wide; *d*, middle Oligocene Novomikhailovka Formation (*A*) with lignite layer (*a*) upthrusted along a listric fault over upper Oligocene Turtas rhythmites (*B*) with a drag fold in the footwall block (*b*); 5.5 km in Fig. 8*a*; *e*, glaciotectonic mélange of the folded Novomikhailovka interbedding sands, silts and clays; station 9 km in Fig. 8*a*; *f*, subvertical clastic dyke of the Eocene Tavda clay with siderite lenses (*A*) piercing overlying middle Oligocene sand of the Atlym Formation (*B*); C, parallel clay apophyses, station 15.3 km in Fig. 8*b*. Top right is person for scale.

tively competent medium to translate the stress necessary for loaded flexion of hard rock (Astakhov et al., 1996).

These and other similar features tell us that the Tavda clay was also frozen when it pierced through the overlying hard-frozen sandy sediments. Water saturated clayey sediments can retain their plasticity in a wide range of negative temperatures due to preservation of combined water in liquid state. The elastoviscous behavior of the frozen clay is normal because it always retains interstitial liquid water. Its shear strength is more time-dependent than that of crystalline ice and it is reduced by an order with prolonged stress applied. Numerous experiments indicate that frozen clay at least up to –7 °C shows dynamic viscosity lower than pure ice, i.e., after initial resistance is overcome the stressed frozen clay would creep faster than pure ice (Tsytovich, 1973; Williams and Smith, 1989). The implication is that the maximum deformation of the glacier/frozen clay couplet would occur below the ice/rock interface with resultant squeezing out of the clay upwards and with the glacier floating upon a thick clay pillow (Astakhov et al., 1996).

Model of Atlym dislocations. The observable mode of deformation of the Paleogene sediments in the Ob' valley is markedly different from what might be expected from their mechanical properties in the present thawed state. Therefore, the glacier bed at Atlym must have been frozen during the deformation. This means that perennially frozen substrate ca. 300 m thick under a thick middle Pleistocene glacier existed ca. 300 km up-ice from the drift limit. The development of the Atlym dislocations summarized in profile Fig. 9 is schematically shown in Fig. 11. Possible sedimentological and structural consequences were discussed earlier (Astakhov et al., 1996) and are briefly listed below.

Stage 1 pictures a glacier advance over perennially frozen Paleogene sedimentary substrate initially supporting not very thick ice.

At *Stage 2* with ice thickening the shear resistance limit is first overcome in less competent clay formations below the base of the ice. The *dynamic sole* of the glacier—a subhorizontal zone in which the maximum deformation occurs—is established in this thick clay formation. This means that the sliding component of ice advance plunges into the frozen clay which is capable of faster deformation than ice itself. The monocline of the Oligocene frozen sand provides two different situations: (i) upglacier where the thinner and brittle frozen sand over the stretching clay and under the increasing ice load breaks to produce slabs and (ii) downglacier where the flow of compressed clay is terminated by a competent dam in the form of the thicker sand.

Stage 3 accounts for the maximum ice thickness when the dynamic sole was already firmly established within the

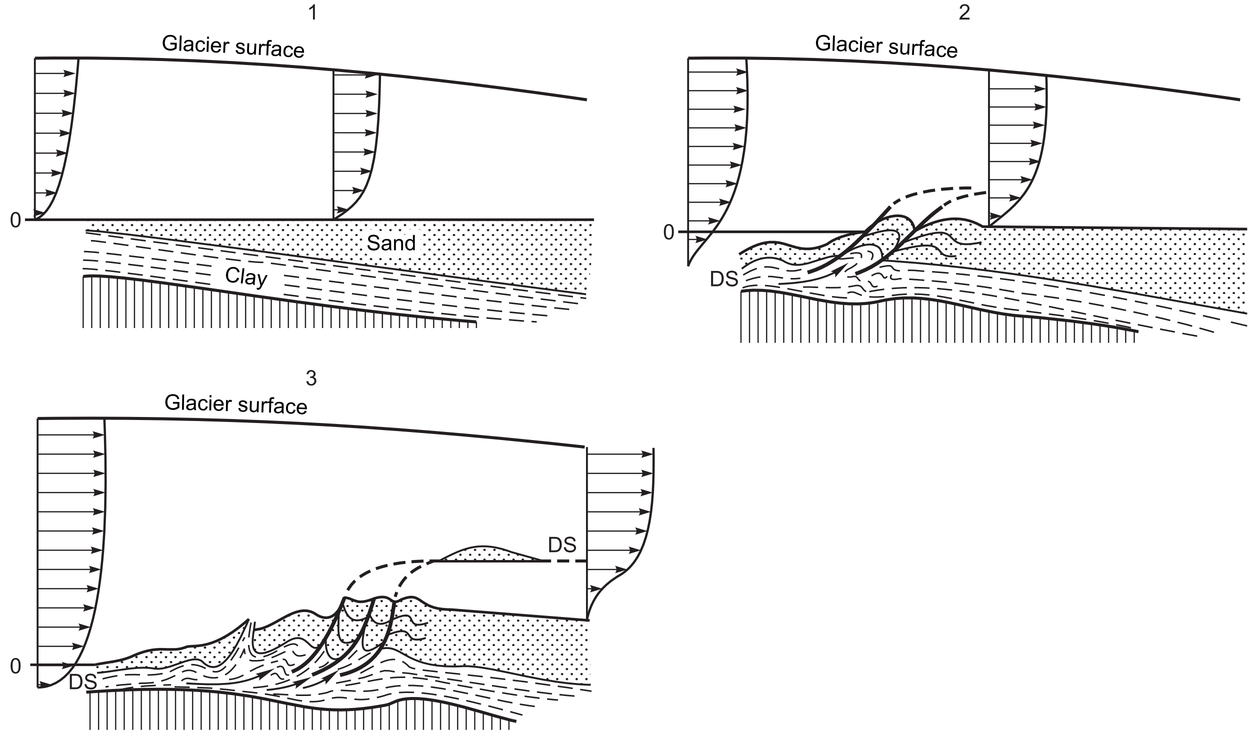

Fig. 11. Idealized stages of deformations of frozen sand and clay under thickening ice sheet as inferred from the Atlym disturbances. Parallel arrows show vertical distribution of summary velocities within ice/permafrost couplet. DS is dynamic sole of the glacier (Astakhov et al., 1996).

underlying frozen clay. The viscoelastic creep of the sheared frozen clay takes most of the basal stress and supports movement of the entire glacier with the frozen sand attached to its base. The breakage of the competent sand roof terminates in the eastern end of the profile (Fig. 9) where the east-dipping sand formation is thick enough to resist any glacial stress. This implies a sudden reduction of the effective velocity of the clay creep and its pillow-like thickening against the sand obstacle with steep listric thrusts penetrating into the ice/sand couple. Kinematically it would mean a leap of the dynamic sole upwards into media with another low shear strength, i.e., into pure solid ice above. The underground dynamic sole in the form of the creeping clay transforms into a plane of décollement in the glacier ice over which the thick glacier slides as a whole block. Thus, the dynamic sole is split into two levels: subglacial, within the frozen clay and englacial one, within the pure ice above.

A likely result of the higher position of the dynamic sole is englacial sliding of large rafts of frozen sand. Gradually descending, such rafts would eventually join the basal debris-laden ice closer to the drift limit resulting in their stagnation and deposition together with frozen diamicts, according to Lavrushin's model (1976). Rafts of Paleogene sand are found atop of diamict formations on the Irtysh River some 200 km to the southeast (Kaplyanskaya and Tarnogradskii, 1974).

The model in Fig. 11 purports to explain major glaciotectonic dislocations which are positioned distally from the ice margin but still within the thick subglacial permafrost. The dislocations of the Atlym type, namely the great width and the record depth of the distorted zone, demand high hydrostatic pressure of ice at least 1 km thick. In this case rugged subglacial topography is not necessary for large-scale deformations of the substrate and entrainment of large erratic blocks. What is really necessary is a downglacier decrease of ice thickness providing deviatoric stress at the ice base plus rheologically contrasting sedimentary formations which are available everywhere in the basin. In the Atlym case an important role was played by the monoclinal structure of the Paleogene–Neogene rocks, which provided the downglacier thickening of the competent sandy sediments and termination of clay creep by a frozen sand dam.

In general, within the realm of cold-based glaciers the instability of the dynamic sole of the glacier caused by diverse rheologies of the substrate seems the main reason for detachment and downglacier transportation of large slabs of frozen sediments. Thus, a dry-based glacier can erode and tectonize large volumes of sedimentary rocks by splitting its dynamic sole which may vacillate between its englacial, basal, and subglacial positions (Astakhov et al., 1996). Judging by the numerous hill-hole pairs of West Siberia (e.g., Astakhov, 2004) the mechanism of glaciotectonic excavation and upthrusting exemplified by the Atlym dislocations can readily account for the wide stratigraphic gap with the lack of Neogene and upper Paleogene formations (Fig. 2) eroded in arctic and subarctic West Siberia and transformed into thick sheets of fine-grained diamictons.

CONCLUSIONS

– Ice Age tectonics is the final and important structural stage in the history of the great sedimentary basin and its marginal highlands.

– Glaciotectonics is a principal force constructing major landforms of the West Siberian Plain and its borderlands.

– Glaciotectonics by cold-based ice sheets applied to perennially frozen substrate is the main erosive agency responsible for the stratigraphic gap by removal of large volumes of Paleogene–Neogene sedimentary rocks from the northern part of the basin.

– Glaciotectonics is a crucial factor of the recent redistribution of oil and natural gas reserves of the northern part of the basin.

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REFERENCES

Aber, J.S., Ber, A., 2007. Glaciotectonism. Elsevier, Amsterdam.

Arkhipov, S.A., Andreeva, S.M., Zemtsov, A.A., Isaeva, L.L., Mizerov, B.V., Fainer, Y.B., 1976. Terrestrial ice sheets and the topography. Problemy Ekzogennogo Rel'efoobrazovaniya, No. 1, 7–89.

Arkhipov, S.A., Isayeva, L.L., Bespaly, V.G., Glushkova, O., 1986. Glaciation of Siberia and north-east USSR. Quat. Sci. Rev. 5, 463–474.

Astakhov, V.I., 1979. New data on the latest activity of Kara-shelf glaciers in West Siberia, in: Šibrava, V. (Ed.), IGCP Project 73/1/24 "Quaternary Glaciations in the Northern Hemisphere", Rep. 5. Czechoslovak Geological Survey, Prague, pp. 22–31.

Astakhov, V.I., 1977. The Kara center of Pleistocene glaciation as reconstructed from ancient moraines of West Siberia. Materialy Glyatsiologicheskikh Issledovanii 30, 60–69 [with English summary].

Astakhov, V.I., 1986. Glaciotectonics of West Siberia as related to petroleum prospecting problems. Geomorfologiya, No. 3, 56–64 [with English summary].

Astakhov, V.I., 1991. The fluvial history of West Siberia, in: Starkel, L., Gregory, K.J., Thornes, J.B. (Eds.), Temperate Paleohydrology. Wiley, London, pp. 381–392.

Astakhov, V., 2004. Pleistocene ice limits in Russian northern lowlands, in: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations—Extent and Chronology. Part 1: Europe. Development in Quaternary Science, Vol. 2. Elsevier, Amsterdam, pp. 309–319.

Astakhov, V., 2011. Ice margins of northern Russia revisited, in: Ehlers J., Gibbard, P.L., Hughes, P.D. (Eds.), Quaternary Glaciations—Extent and Chronology: A Closer Look. Developments in Quaternary Science, Vol. 15. Elsevier, Amsterdam, pp. 323–336.

Astakhov, V.I., 2013. Pleistocene glaciations of northern Russia—a modern view. Boreas 42 (1), 1–24.

Astakhov, V.I., Kaplyanskaya, F.A., Tarnogradsky, V.D., 1996. Pleistocene permafrost of West Siberia as a deformable glacier bed. Permafrost and Periglacial Processes 7 (2), 165–191.

Bashenina, N.V., 1948. Origin of Relief of the Southern Urals [in Russian]. Geografgiz, Moscow.

Forsberg, C.F., 1996. Possible consequences of glacially induced groundwater flow. Global Planet. Change 12, 387–396.

Generalov, P.P. The secondary tectonics in the surficial sedimentary cover of West Siberia, in: Opalites of West Siberia [in Russian]. ZapSibNIGNI, Tyumen, 1987, pp. 48–74.

Gorelov, A.A., 1975. On influence of ice sheets on porosity of sand rocks and petroleum deposits formation in the northern West Siberian Plate. Dokl. AN SSSR 221 (3), 718–721.

Kaplyanskaya, F.A., Tarnogradskii, V.D., 1974. The Middle Pleistocene of the Lower Irtysh Area [in Russian]. Nedra, Leningrad.

Karus, Y.V., Gabrielantz, G.A., Kovylin, V.M., Chernyshov, N.M., 1984. New data on the Moho boundary and upper mantle of the West Siberian Plate. Dokl. AN SSSR 276 (1), 196–198.

Kehew, A.E., Piotrowski, J.A., Jørgensen, F., 2012. Tunnel valleys: Concepts and controversies—a review. Earth-Sci. Rev. 113 (1–2), 33–58.

Kontorovich, A.E., Nesterov, I.I., Salmanov, F.K., Surkov, V.S., Trofimuk, A.A., Ervye, Y.G., 1975. Geology of Oil and Gas of West Siberia [in Russian]. Nedra, Moscow.

Korzenstein, V.N., 1970. On influence of periodical glaciations on formation of the unique gas fields of the northern Tyumen Region. Dokl. AN SSSR 191 (6), 1366–1369.

Krapivner, R.B., 1986. Rootless Neotectonic Structures [in Russian]. Nedra, Moscow.

Kuzin, I.L., 1983. Impact of neotectonic movements, sea level oscillations and climate change on formation of petroleum deposits of West Siberia, in: Logachov, N.A., Sherman, S.I., (Eds.), Regional Neotectonics of Siberia [in Russian]. Nauka, Novosibirsk, pp. 26–31.

Lambeck, K., Purcell, A., Funder, S., Kjær, K.H., Larsen, E., Möller, P., 2006. Constraints on the Late Saalian to Early Middle Weichselian ice sheet of Eurasia from field data and rebound modelling. Boreas 35, 539–575.

Lavrushin, Yu.A., 1976. Structure and Development of Ground Moraines of Continental Glaciations [in Russian]. Nauka, Moscow.

Levkov, E.A., 1980. Glaciotectonics [in Russian]. Nauka i Tekhnika, Minsk.

Li, P.F., Kravchenko, L.M., 1959. To the question of genesis of the Malyi Atlym dislocations. Trudy SNIIGGiMS 1, 36–38.

Maksimov, Y.V., 1970. Phases of former glaciation and neotectonics in the mountains of Putorana, Polar and Subpolar Urals, in: Reports of Departments and Commissions of Geographical Society of the USSR [in Russian]. Leningrad, Vol. 16, pp. 19–34.

Mörner, N.-A., 1979. The Fennoscandian uplift: geological data and their geodynamical implication, in: Earth Rheology, Isostasy and Eustasy. Chichester, Wiley, pp. 251–284.

Nalivkin, V.D., 1960. The Malyi Atlym dislocations on the Ob' River. Trudy VNIGRI 158, 256–266.

Riis, F., 1992. Dating and measuring of erosion, uplift and subsidence in Norway and the Norwegian shelf in glacial periods. Norsk Geologisk Tidskrift 72, 325–331.

Rostovtsev, N.N. (Ed.), 1982. Geological Map of the West Siberian Plain and Adjacent Regions (without the Quaternary). Scale 1:1 500 000 [in Russian]. VNIGRI, Leningrad.

Rozhdestvenskii, A.P., 1971. Some questions of structural and geomorphic development of the Urals during the neotectonic stage, in: Materials on the geomorphology of the Urals [in Russian]. Nedra, Moscow, 1971, Vol. 2, pp. 41–51.

Rudkevich, M.Ya., 1974. Paleotectonic Criteria of Petroleum Potential [in Russian]. Nedra, Moscow.

Ryl'kov, A.V., Shepetkin, Y.V., Nesterov, I.I., Kulakhmetov, N.Kh., Ushatinskii, I.N., 1976. Geological and geochemical indicators of the age of oil deposits in the Jurassic and Cretaceous formations of the central West Siberian Plain, in: Formation Time of Oil and Gas Deposits [in Russian]. Nauka, Moscow, pp. 114–121.

Samoiluk, L.A., Lavrov, A.S., 1986. Faults as reflected in glacigenic topography of the West Siberian North, in: Express Information: General and Regional Geology [in Russian]. VIEMS, Moscow, Vol. 1, pp. 1–8.

Staroseltsev, V.S., 1985. Mesozoic–Cenozoic tectonic movements of the northern Tunguska Basin as related to assessment of its petroleum potential, in: Neotectonics of the Siberian Craton and Its Impact on Its Petroleum Potential [in Russian]. Nauka, Moscow, pp. 56–64.

Sukhorukova, S.S., Kostyuk, M.A., Podsosova, L.L., Babushkin, A.E., Zol'nikov, I.D., Abramov, S.A., Goncharov, S.V., 1987. Moraines and Dynamics of Glaciations of West Siberia [in Russian]. Nauka, Novosibirsk.

Trofimuk, A.A., Cherskii, N.V., Tsarev, V.P., 1979. Influence of gas hydrate generation, glaciations and seismicity on formation of hydrocarbon reserves. Geologiya i Geofizika, No. 4, 3–18.

Tsarev, V.P., 1976. Peculiarities of Formation, Methods of Prospecting and Developing of Hydrocarbons in Permafrost Regions [in Russian]. Yakutsk. Knizh. Izd., Yakutsk.

Tsytovich, N.A., 1973. Mechanics of Frozen Soils [in Russian]. Vysshaya Shkola, Moscow.

Ulmishek, G.F., 2003. Petroleum Geology and Resources of the West Siberian Basin, Russia. U.S. Geological Survey Bulletin, 2201-G.

Voronov, P.S., 1968. Essays on Morphometric Regularities of the Global Relief of Earth [in Russian]. Nauka, Leningrad.

Williams, P.J., Smith, M.W., 1989. The Frozen Earth. Cambridge University Press.

Zaitsev, A.P., Meshalkin, K.A., 1987. Role of glacioisostasy in formation of petroleum deposits of West Siberia, in: Geology of Nonmetallic Raw Materials of Western Siberia [in Russian]. ZapSibNIGNI, Tyumen, pp. 111–115.

Zakharov, Yu.F., 1968. Exotectonic dislocations in the sedimentary cover of West Siberia. Geologiya i Geofizika, No. 6, 148–155.

Zieba, K.J., Grøver, A., 2016. Isostatic response to glacial erosion, deposition and ice loading. Impact on hydrocarbon traps of the southwestern Barents Sea. Mar. Pet. Geol. 78, 168–183.

Zubakov, V.A., 1972. Recent Deposits of the West Siberian Lowland [in Russian]. Nedra, Leningrad.

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