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The Eastern Flank of the Caspian Basin: Sedimentary Complexes and Sedimentation Conditions in the Early–Middle Carboniferous

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Abstract—Carboniferous and Lower Permian Carbonate and terrigenous rocks with the total thickness of >4000 m serve as the productive units in the Paleozoic subsalt complex at the eastern flank of the basin surrounding the northern area of the present-day Caspian Sea (hereafter, Caspian Basin in the broad sense). In recent years, several large oil and gas-condensate fields were discovered in these rocks. The complexity of geological evolution of this region, which is situated at the junction between the East European Platform and the Ural orogen, as well as multiple changes of sedimentation conditions during the Middle and Late Paleozoic, are reflected in the diversity of types of terrigenous and carbonate sediments and their facies alterations. Reconstruction of these environments makes it possible to elucidate specific features of the location of reservoir rocks in vertical and horizontal sections, as well as regularities of variations in their filtration-capacitive properties.

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INTRODUCTION

The thickness of the Paleozoic subsalt complex is not less than that of the Kungurian alts and suprasalt deposits, which are distinguished in the sedimentary cover of the eastern flank of the Caspian Basin (Yanshin et al., 1975). The subsalt complex includes rocks of four tectonosedimentary cycles composed of active and passive tectonic phases. The base of the sedimentary cover (first cycle) includes thin Ordovician–Silurian carbonate–terrigenous rocks overlain by the Devonian carbonate sequence. They accumulated during the opening of the Ural paleocean. The second cycle was produced by the collision of the East European Platform margin with the North Ustyurt continental block. The collision was accompanied by the subsidence of large crustal blocks in the eastern part of the Caspian Basin and the transportation of large volumes of clastic material. The clastic material makes up a thick lens (up to 3000 m) of proluvial-deltaic, coastal-marine, and submarine-slope sediments of Lower Carboniferous graywacke and subgraywacke formations. The subsidence, which continued after termination of the input of terrigenous clastic material, favored the development of carbonate buildups, bioherms, and biostromes on the paleoshelf break and the near-shore zone. At present, hydrocarbon deposits are known in terrigenous and carbonate sediments. The largest deposits are confined to buried bioherms and biostromes in the Early–Middle Carboniferous carbonate platform.

The overlying (third) cycle reflects events related to the tectonic activation at the boundary between the basin and the Kazakhstan block in the early Podolian time. Terrigenous (mainly, clayey) material transported from this area makes up the so-called “intercarbonate sequence” (ICS). The overlying carbonates are composed of shallow-water and lagoonal limestones and dolomites, which are replaced westward by thin organic-rich clayey-carbonate-siliceous sequences. They are considered oil source rocks. Moreover, they can contain hydrocarbon accumulations. However, the largest oil pools were found in Late Carboniferous carbonate rocks.

The fourth tectonosedimentary cycle corresponds to the final evolutionary stage of the Ural–Mugodzhary foldbelt. This cycle includes Sakmarian–Artinskian terrigenous rocks and the Kungurian saliferous sequence, which serve as the regional screen for fluids. The present work reports results of the study of terrigenous and carbonate rocks corresponding to the Early and Middle Carboniferous cycle.

TECTONIC SETTING OF THE EASTERN FLANK OF THE CASPIAN BASIN

The major part of the Caspian Basin distinguished within the salt dome domain is occupied by the Central Caspian Depression. The available seismic sections show that the basement along its border with the Urals and Mugodzhary orogens is crosscut by deep faults into separate blocks. The Utybai, Zharkamys, Akkum, Shukat-Koskul, Karaulkel'dy, Shubarkuduk, and Ashchisai blocks are the most prominent structures (Fig. 1). These blocks, in turn, are subdivided into smaller segments that form a semicircular flank around the Central Caspian Depression in the east.

The Zharkamys block is one of the largest structures of the eastern flank. Its dimension (at 7.5 km contour line) is 90 × 50 km. The top of this NE- to SW-striking swell is outlined by the 7-km contour line. The analysis of seismic materials and deep drilling data allows us to subdivide the Zharkamys Swell into three (Zhanazhol, Tortkol, and Zharkamys) tectonic zones. In each of these zones, the top of the Paleozoic subsalt blocks dip toward the central depression in the form of steps and the structures are complicated by near-meridional arc-shaped uplifts (Tortkol, Laktybai, Karatuybe, and others).

The structure of the Paleozoic subsalt complex is characterized by the position of four key seismic reflectors: F, P^3, P^2, and P^1. The stability of individual blocks of the basement and their gradual involvement in subsidence at different stages of the Paleozoic evolution predestined the composition and stratigraphic sequence of rocks within different segments of the swell. For example, well G-5 (Zharkamys zone, Eastern Akzhar field) penetrated basement rocks at a depth of 5810 m and recovered Ordovician–Silurian carbonate–terrigenous rocks (reflector P_3) and the overlying Devonian carbonates (Akhmetshina et al., 1993). In the Zhanazhol and Tortkol zones, the presence of these rocks was not proved by drilling.

The Carboniferous sequence starts with Tournaisian and Visean terrigenous rocks (graywacke and subgraywacke). The top and bottom of this sequence correspond to reflectors P_2^D and P_2^1 (Fig. 2). This sequence is not thick at the crest of the Zharkamys Ridge (Dal'yan, 1996). The thickness increases eastward from 1285 m in the Tereshkovo field (well 17) to 1510 m in the Zhanatan field (well 5), 1891 m in the Kozhasai field (well PGS-1) (Fig. 3), and up to 2806 m in the Teresken field (well 1-P). According to CDP seismic data, the depth reaches 7500 m near the Ashchisai fault. Oblique-bedded rock units, which are well traced in seismic sections, compose clinoforms in the apron of terrigenous sediments filling near-flank areas of the adjacent depressions. At the transition from the slope zone to deeper-water sediments lying on the ancient marginal trough, their dip angle is small and relatively constant. This transition is recorded on western slopes of the arc-shaped uplifts (Western Kozhasai, Zhanatan-1, Laktybai, Northern Tuskum, and Eastern Tobusken).

The overlying structural complex includes the lower carbonate sequence (CS-II) of the upper Visean–lower Moscovian substage. They are marked at the top and bottom by reflectors P_2^1 and P_2, respectively. The structural complex includes a late Visean–Bashkirian carbonate massif that stretches along the Sakmara–Kokpekti fault and terminates as an escarpment facing the Central Depression. Large organogenic buildups, such as Bashenkol, Southern and Eastern Mortuk, are distinguished in this massif.

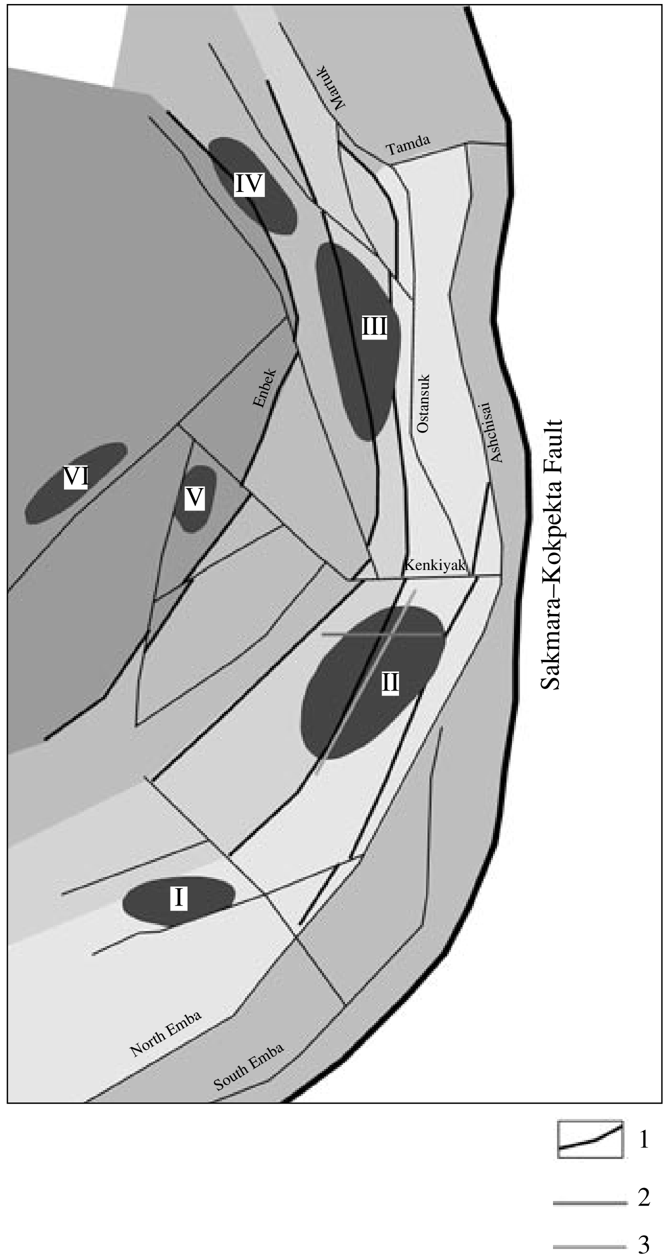

Fig. 1. Tectonic scheme of the eastern flank of the Caspian Basin (after Yanshin et al., 1975). (1) Faults; (2) seismic geological profiles; (3) swells (basement uplifts): (I) Utybai; (II) Zharkamys; (III) Enben; (IV) Ashchisai; (V) Karaulkel'dy; (VI) Kyzylzhar.

The subordiante lower Moscovian limestones and dolomites lie with a prominent erosion unconformity on the early Bashkirian limestones. The thickness of the lower Moscovian rocks varies from some tens to a few hundred meters (162 m in well G-1 in the Sinel'nikovo field). In the Zhanazhol zone, they form the so called

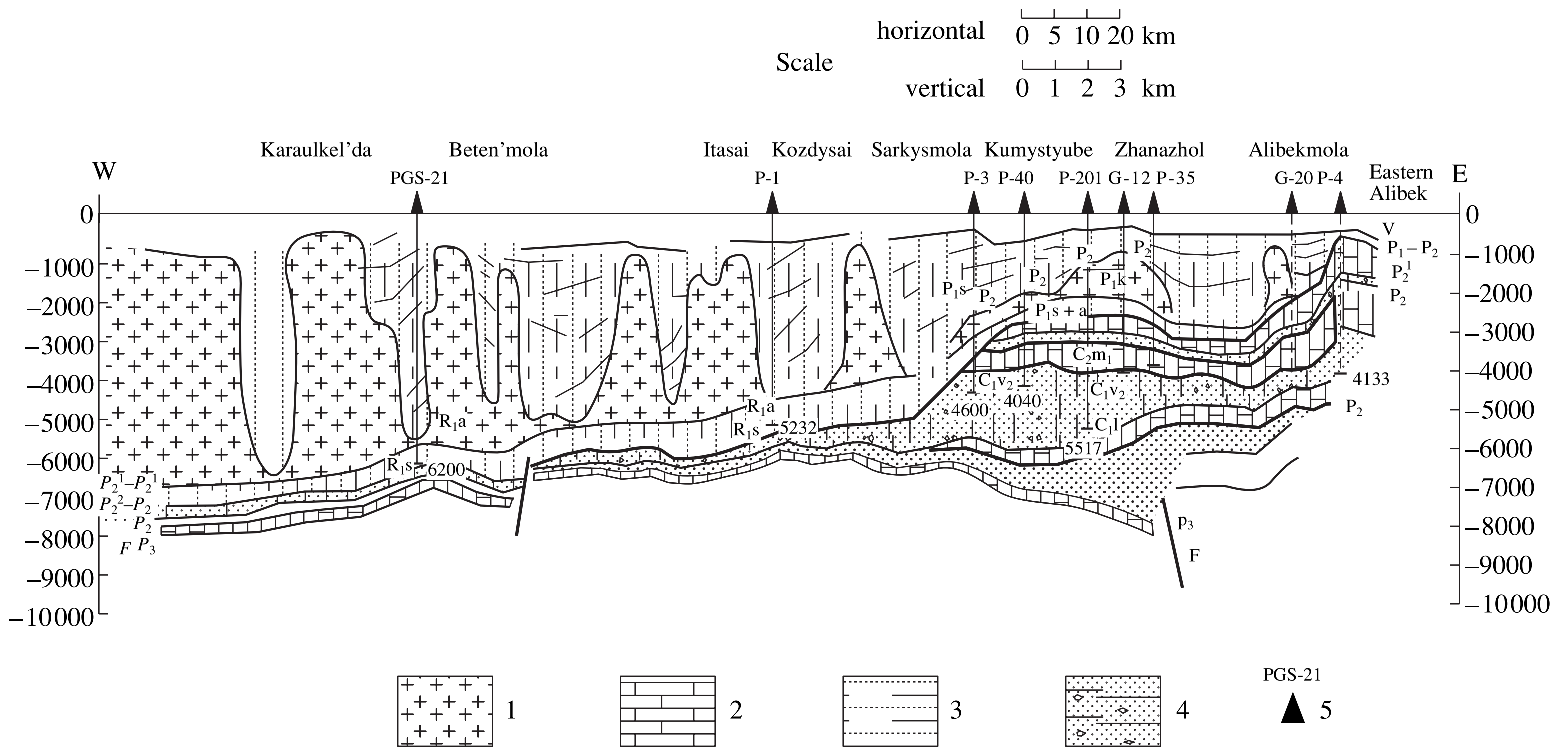

Fig. 2. Seismic geological profile across the northern part of the Zharkamys Swell. (1) Evaporites (Kungurian); (2) carbonate rocks (Devonian and Carboniferous); (3) terrigenous rocks: alternation of sandstones, siltstones, and mudstones (Middle Carboniferous and Lower Permian); (4) terrigenous rocks: alternation of sandstones, conglomerates, and gritstones with siltstones and mudstones (Early Carboniferous); (5) well numbers. (F, P_1, P_2, P_2^1, P^3, and V) Reflectors.

carbonate knolls (domes) that are characteristic of marginal part of the paleoshelf.

The problem of the Caspian Basin origin is still under discussion. According to the most reasonable hypothesis, the basin formed during the Riphean passive rifting with the subsequent emplacement of eclogites into the lower levels of Earth's crust and involvement of the central part of the depression in prolonged subsidence (Volozh and Antipov, 2004). Collision of the southeastern margin of the Russian Plate with the North Ustyurt continental block at the Devonian–Carboniferous boundary was accompanied by the foundation of a foredeep, which was filled with terrigenous material delivered from the rising mountains. According to (Volozh and Antipov, 2004), precisely this period was marked by subsidence of the Earth's crust in the central part of the Caspian Basin and the formation of an isolated deep-water basin, which expanded in the Early Carboniferous.

LITHOLOGICAL COMPOSITION OF LOWER AND MIDDLE CARBONIFEROUS ROCKS

The Lower Carboniferous terrigenous sequence, which can be attributed to the graywacke formation, includes sandstones, siltstones, and clayey rocks with the participation of gritstones and conglomerates. Sections of wells drilled in the Kozhasai, Laktybai, Zhanatan, Eastern Akzhar, Tereshkovo, Teresken, and Urikhtau fields include up to ten units of sandstones and conglomerates with a thickness of 20–80 m. The thickest Tournaisian and Visean terrigenous sequences (1206 and 1600 m, respectively) are recorded in the Teresken field (well P-1). In the Laktybai field, where rocks of the late Visean were recovered, their thickness varies from 400 to 1340 m. In other fields, the recovered thickness varies from 195 to 920 m.

Conglomerates were described in wells drilled in the Laktybai (well 16), Eastern Akzhar (well G-5), Teresken (P-1), and Tortkol (G-2) fields. They form thin interlayers among mudstones and sandstones. The conglomerates occur as gray (or dark gray) dense and hard fine- to medium-pebble (rarely, coarse-pebble) unsorted sandy rocks containing pebbles of quartz, diabases, quartzites, siliceous shales, dark-colored effusive rocks, as well as tuffs of acid composition. The predominant rounded or semirounded Pebbles (95%) are cemented by chloritic, calcareous–clayey, clayey–siliceous, and secondary calcitic matrix. of the porous, contact-porous, and corrosive-porous types. In addition to the rocks described above, conglomerates of the Laktybai field include fragments of carbonate rocks (micro- and fine-grained biomorphic limestones and dolomites), as well as remnants of crinoids and foraminifers. Inclusions of xenomorphic pyrite are also noted.

Gritstones are encountered in Lower Carboniferous sequences in the Laktybai, Kozhasai, Tortkol, Teresken, Zhanatan, Eastern Akzhar, Tereshkovo, and Urikhtau fields. Usually, they form thin interlayers in sandstones and are sometimes replaced by the sandstones. The gritstones consist of gravel-sized gray and white particles, rare varicolored pebbles, and calcareous cement. Semirounded and rounded grains predominate, although some of them have an irregular shape. The rocks are most frequently poorly sorted. They contain quartz grains and siliceous (more rarely, clayey and effusive) rock fragments 1.0–5.0 mm in size (generally, 1–2.5 mm). Gravel particles are frequently ferruginated and chloritized. The medium- to fine-grained sandy matrix is dominated by quartz, although rock and feldspar fragments, as well as mica and chlorite flakes, are also present. Lenslike inclusions of clayey–coaly material are also found. Porous, contact-porous, and pellicular-porous types of cement with the carbonate composition are characteristic of the gritstones.

Sandstones are developed in Lower Carboniferous (Visean) sediments of the Eastern Akzhar, Laktybai, Teresken, Tortkol, Urikhtau, Kozhasai, and other fields. They occur as dark gray dense hard medium-sorted (sometimes poorly sorted) rocks. Fine- to medium-grained, as well as medium- to coarse-grained and varigrained, varieties are encountered in some places. They mainly consist of semirounded and angular fragments. In some places, one can see oval grains with a coating of concentrically layered crusts of the calcareous–clayey composition. In terms of composition, these rocks are polymictic aggregates dominated by clasts of the clayey, effusive, siliceous, and other rocks with the subordinate quartz and feldspars (feldspar–quartz graywackes) (Fig. 4). Grains of chalcedony, chlorite, micas, pyrite, as well as accessory minerals (magnetite, ilmenite, apatite, and zircon) are found.

Researchers have also reported sandstones made up of quartz grains and variable-sized fragments of quartzites, cherts, and sericite–siliceous, and siliceous schists. Tissue elements of carbonate-building organisms are frequently present in these rocks. The structure of the sandstones is usually massive, but sometimes one can observe obscure bedding, which is emphasized by the layered concentration of dark clayey material and coalified plant detritus. The clastic grains have irregular shapes. Many grains show traces of secondary alterations (corrosion, dissolution, intrusion, and mutual penetration). In thin sections, one can clearly see the initial rounded or spherical shape of clastic grains. Regenerated rims are most frequently formed around quartz and feldspar grains. The corroded grains have serrate-sinuous contours. Their primary material is usually replaced by secondary calcite and siderite crystals growing in the pore space.

The sandstones are characterized by contact-porous, pellicular-porous, contact, and semiporous types of the clayey (from 2–10 to 17%) cement. The clayey, probably syngenetic and diagenetic, material forms a coating around clastic grains or fills a part of the pore space. In

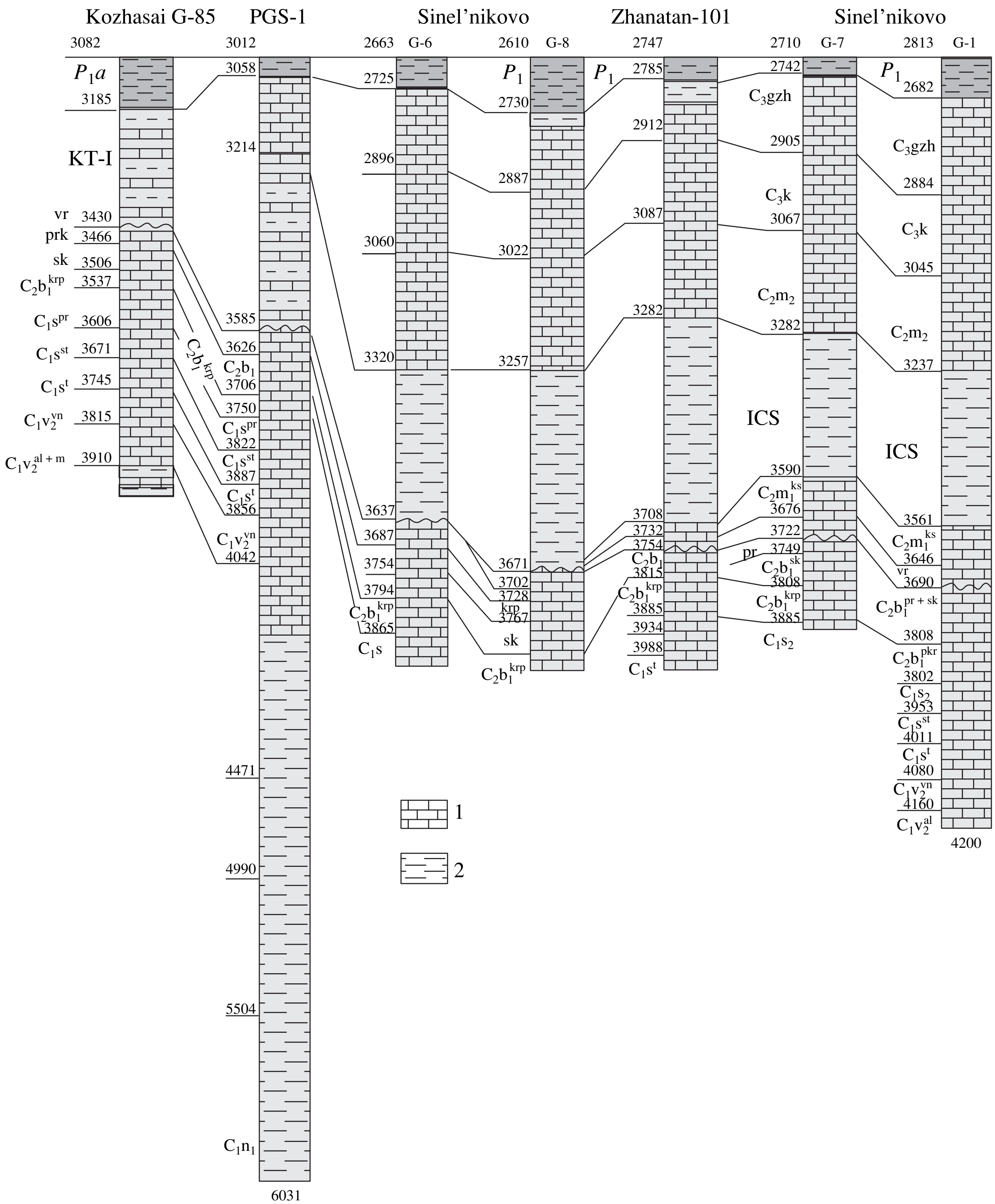

Fig. 3. Correlation scheme of Paleozoic subsalt rocks of the Zharkamys Swell. (1, 2) Rocks: (1) carbonate; (2) terrigenous.

thin sections, the yellowish brown cement is observed as a poorly crystallized microaggregate with low birefringence. The cement includes kaolinite, chlorite, sericite, and occasional smectite. The carbonate (calcite and siderite) cement is less common. The calcite originated in the process of sediment accumulation, whereas the siderite formed during diagenesis. The content of carbonate cement varies from 2 to 15% (commonly, not more than 2–10%). The sandstones, weekly cemented by $CaCO_3$ and clayey material, easily break up into small fragments and can be ground to powder by fingers. However, one can also see some hard varieties with complex conformable-incorporative textures that originated at the contacts between clastic grains. Convexo-concave and suture-like contacts predominate in these rocks. Aggregates of regenerated grains are observed in the case of irregular arrangement of fragments. They are characterized by serrate structure and close packing. Therefore, these rocks have a patchy-mosaic (quartzitelike) conformable-regenerative texture.

Siltstones form thin interlayers in mudstones and sandstones (Tereshkovo, Nikolaev, Tobusken, Borzher, and other fields). We can also see coarse- and fine-grained dense hard (generally, unsorted) polymictic varieties with the predominance of quartz and feldspars grains. The clayey and clayey–carbonate cement has porous and basal-porous structures. In terms of composition and texture, the siltstones resemble the sandstones and contain an admixture of fine sandy material. The content of micas and chlorites is slightly increased in the clastic constituent, and the cement is mostly saturated with clay chlorite.

Mudstones are observed as black and dark gray (usually, silty and micaceous) thin-bedded and platy rocks that are split along smooth planes parallel to bedding. Massive varieties are only found at the lowermost part of the sequence. These hard calcareous and noncalcareous rocks with coalified plant remnants, as well as brown inclusions of organic matter, were reported from Lower Carboniferous rocks in the Kuantai, Eastern Akzhar, Kara-Tyube, Northern Tuskum, Tortkol, and Eastern Tobusken fields. The siltstones are mainly composed of micrograined and flaky clay particles oriented along bedding. They contain pyrite and coaly matter inclusions.

The mudstones are mainly composed of chlorite and illite with an admixture of silt- and even sand-sized grains. They often chaotically alternate with sandstones and gritstones. The silty admixture is represented by acute-angled and semirounded grains of quartz, feldspar, chlorite, ore minerals, and the subordinate muscovite and biotite flakes irregularly dispersed in the rock. Flakes of clay minerals and small flattened clastic grains are oriented parallel to long axes. This is expressed as direct and simultaneous extinction. The rock has pelitic oriented texture.

Silty sandstones are nearly ubiquitous in the terrigenous part of the Visean sequence in the Zhanazhol and Tortkol zones. The grain size in these rocks varies from 0.03 to 0.63 mm. The clastic material is unsorted. The composition of these rocks is close to that of graywackes (quartz and rock fragments with an admixture of feldspars). Rock fragments are semirounded, subhedral, and irregular. The cement is composed of basal clayey material. Coalified plant remnants are subordinate.

Carbonate rocks compose the upper Visean, Serpukhovian, Bashkirian, and lower Moscovian units in sequences of the Zharkamys Swell. They formed under different, frequently changing conditions. The principal lithological types are represented by biogenic and biochemogenic varieties, including the biohermal, biomorphic, biomorphic-detrital, detrital (bioclastic), oolitic, oncolitic, spherical-patterned, and micrograined limestones and dolomites.

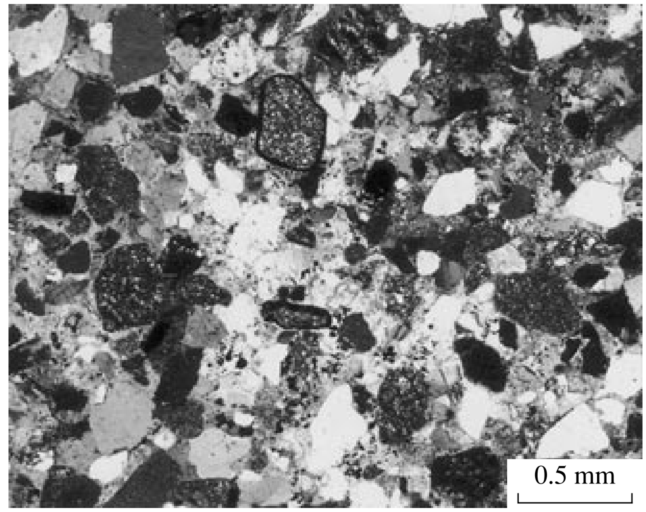

Fig. 4. Medium- and fine-grained petroclastic feldspar–quartz sandstones (thin section). Kozhasai field, well PGS-1, int. 5100–5107 m (Lower Carboniferous, Visean).

Biohermal limestones form organogenic buildups in the Alibekmola, Kozhasai, Zhanazhol, Urikhtau, Sinel'nikovo, and other fields. In the Early Carboniferous sequence, biohermal limestones are mainly represented by algal varieties. Together with algafloral thalluses, they contain peloids and foraminiferal shells. Fragments of echinoids, ostracods, brachiopods, and bryozoans are present as admixture. Based on the algafloral species composition, the algal limestones can be subdivided into the schartimoficus (Fig. 5), ungdarella, calcifolium, and predonetsellid varieties. The suspended matter was trapped and settled between algal thalluses that make up the rock frame. Taluses of algae are well preserved. In thin sections, one can see cross-sections of thallus (>5%), indicating burial of the algoflora in its life time. The biohermal limestones contain abundant paleonubecularian shells.

During the Serpukhovian, the composition of the algoflora was dominated by schartimoficuses, predonetsellids, and calcifoliums. The space between their stems was filled with carbonate micrite and detritus of different organisms: echinoids, brachiopods, ostracods, and others. High hydrodynamic activity in the sedimentation basin favored the formation of small buildups (bioherms and biostromes) at the shelf break.

Biomorphic limestones developed in the study region are characterized by a significant variability. They often include algal-foraminiferal varieties, which always contain shells of small foraminifers (tuberitina and palaeonabecularia) along with algae. Another type

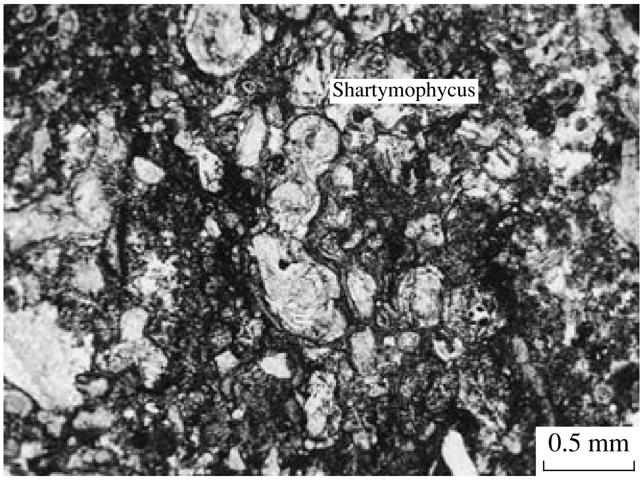

Fig. 5. Biohermal schartimoficus limestone (thin section). Alibekmola field, well 4, depth 3818–3823 m (lower Carboniferous, Serpukhovian).

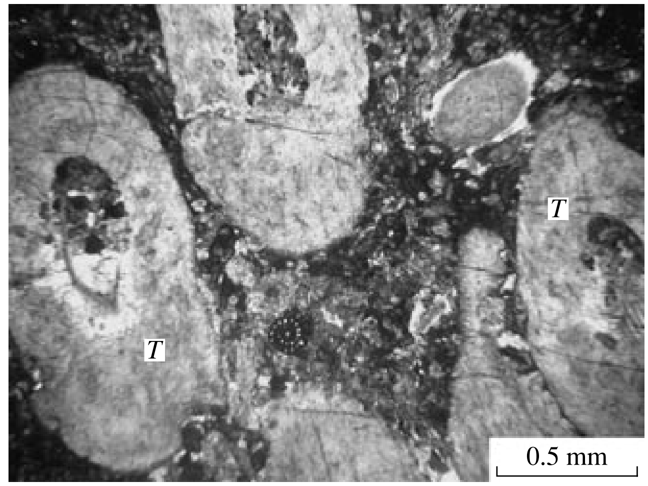

Fig. 6. Biomorphic and tabulatomorphic limestones, Multithecopora coral (thin section). Alibekmola field, well 58, depth 3338.5 m (Middle Carboniferous, Bashkirian).

is represented by biomorphic limestones with the frame consisting of branches of rugose corals (Fig. 6) and tabulatomorphic corals (Multithecopora). The space between remnants of frame-building organisms is filled with fine- and micro-grained carbonate cement with lumps and peloids. The surface of the rock-forming elements is often covered by pseudosparite shells and films. Newly formed sparite developed in pore space is rather abundant.

Some types of biomorphic limestones are characterized by significant porosity. Pores inherited from the initial structure of sediment expanded, and new ones appeared in the process of leaching and dolomitization. Faces of calcite crystals, which make up the cement, and surfaces of bioclasts served as walls of the newly formed pores. Caverns and pores have irregular, ellipsoid, and crevicelike shapes. The size of caverns and pores is 1.2–4.0 and 0.05–1.0 mm, respectively.

Processes of recrystallization activated during catagenesis were accompanied by the infilling of intergranular pores with newly formed sparite.

The Serpukhovian sequence contains *microbial-algal limestones*, i.e., rocks with fenestral or layered-fenestral texture mainly consisting of pelitomorphic and micrograined calcite (70–80%) with dissemination of bryozoan fragments. The limestones form the lower part of the so-called knolls or domes, which originated in the back-reef area of lagoons (James and Bourque, 1992). One can distinguish several (microbial, skeletal, and mud) varieties of such knolls (domes). The initial stage of the formation of the Bashenkol reef was marked by the growth of the "skeletal" knoll, where thin particles were trapped by numerous bryozoans. Their tissue elements are preserved in the limestone structure and usually dispersed in well-crystalline sparite (well 6, Bashenkol field). Microbial incrustations and stromatactis structures can be observed in thin sections.

The lower Serpukhovian sequence of the Zhanazhol zone contains limestones consisting of numerous spheres (shells of single-chamber foraminifers and calcispheres). In scientific literature, they are described as *spherical-patterned limestones* (Chuvashov and Shuiskii, 1988; Maksimova and Rozanova, 1981). This rock is composed of micrograined calcite with abundant dissemination of spheres ("spherical algae"). Porosity in the spherical-patterned limestones is intragranular and, as a rule, very low.

Biomorphic-detrital and detrital (bioclastic) limestones. The destruction of organic buildups, which formed positive features in the seafloor relief, by waves promoted the wide distribution of detrital and polydetrital limestones. They include fragments of shells and other tissue elements of different grades of preservation, the size of which was governed by hydrodynamic activity of the medium (Fig. 6).

The "fore-reef" facies is generally represented by limestones with coarse-detrital texture (particle size more than 2 mm) and micritic or sparite cement. Detrital limestones form wide taluses in front of carbonate buildups. When moving away from them, coarse-grained varieties are replaced by fine-grained ones.

Fragments of foraminifers, brachiopods, crinoids, algae, ostracods, and bryozoans are the principal rock-forming elements in the biomorphic-detrital limestones that are widespread in the upper Visean and Serpukhovian rocks. These gray to dark gray rocks are characterized by parallel-horizontal or near-horizontal bedding related to the layer-by-layer enrichment in brachiopod shells or other tissue elements. The good preservation of brachiopod shell in many cases can be explained by their in situ burial.

Carbonate fragments in polydetrital varieties of these limestones are frequently represented by ossicles of siphon algae. They are noted for good sorting, roundedness, and variation in size from 0.1 to 1 mm. Micrite (sparite in some cases) serve as cement. The cement is porous (less frequently, basal-porous and basal; rarely, contact-porous). The bioclastic limestones probably accumulated within a wide range of waterdepths on shore slope (from lower littoral to open shelf). At the same time, the size of particles decreased with depth, and components related to the vital activity of green algae gradually disappeared. Simultaneously, the content of mud particles increased, the degree of sediment compaction increased, and traces left by ichtiofauna (Zoophycos), increased.

Peloid-bioclastc limestones form thin interlayers. The limestones are gray and light gray, massive, dense or porous, and sometimes fractured. They are composed of various bioclasts and colloidal-micrograined lumpy components (pellets and peloids) (Fig. 7). The proportion of these components is very different. Bioclasts are represented by remnants of foraminifers, ostracods, gastropods, and brachiopods, as well as fragments of crinoids and the subordinate algae, bryozoans, and corals. The shape of fragments is clearly expressed, often with signs of roundness. According to (Mckee and Gutschiick, 1969), the peloid particles are detrital grains of the psammitic size (average 100–500 μm). These structureless particles have rounded, spherical, or ellipsoidal shape with signs of roundedness. It is probable that peloids are the product of granulation of remnants of carbonate-forming organisms favored by the vital activity of endolithic algae. The final result of this activity was the complete loss of initial structure of bioclasts (Bathurst, 1975). The peloid particles may represent fragments of fine-grained algal nodules (Wolf, 1965), fossilized cells of cyanobacteria, or lithified lumps of carbonate mud. The faecal origin of these particles cannot also be excluded, especially for particles with egglike shape characterized by variation of the ratio of long and short axes from 1.5 to 3. Various "wrapped grains" (oncoids and cortoids) are frequently observed in the peloid-bioclastic limestones.

The content of peloids and carbonate detritus in peloid-bioclastic limestones reaches 75–80%, whereas the primary micrite makes up not more than 5–25%. The cementation type varies from the porous to pellicular-porous, semiporous, and coating varieties. The basal-porous cement is less common. Conditions favorable for the accumulation of peloid-bioclastic limestones existed in wave-resistant lagoons with moderate hydrodynamic activity (probably, littoral and sublittoral zones).

Lumpy limestones are primarily developed in Serpukhovian rocks with lumpy disordered bacterial microtexture and sparite cement, which includes small peloids with obscure margins. The lumps often merge to form shapeless patches. They include rare remnants of foraminifers, brachiopods, algae, and echinoids, as well as peloids with a prominent oval shape (Fig. 8). The intertissue space of lumpy and peloid-lumpy limestones is filled with micro- or fine-grained calcareous material. In low-porous varieties, the content of cement can reach 25 vol %.

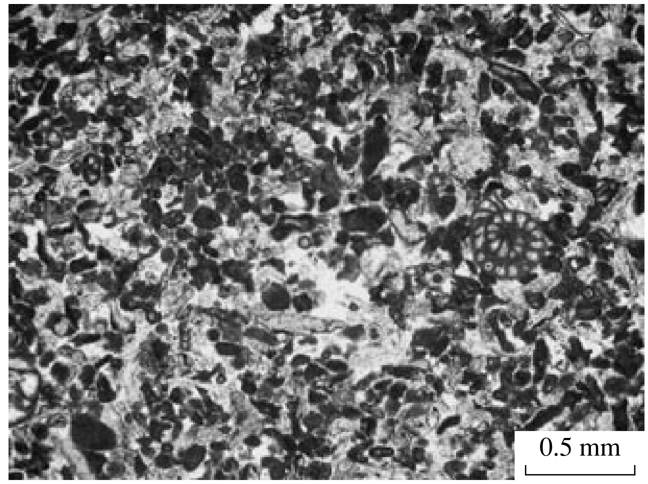

Fig. 7. Peloid-bioclastic limestone (thin section). Alibekmola field, well 53, depth 3443.7 m (Middle Carboniferous, Bashkirian).

Some varieties of lumpy limestones have fenestral structure, which defines the volume of pore space. Such structures are presumably related to the decomposition of algal pillows, covered by sediment (Tebutt et al., 1965). Compaction of carbonate mud fosters the preservation of gas- or water- filled cavities therein. They were partially filled with crystalline calcite during dia- and catagenesis, and the size of cavities increased during leaching. Despite the small dimension of these pores (generally, up to 0.02–0.08 mm), they are very well communicated. It should be noted that porous varieties of lumpy limestones are characterized by a low content of the contact-porous or semiporous cement.

Oolitic limestones are developed in the upper part of the Serpukhovian sequence. In addition to ooids, they contain peloids and well-rounded bioclasts, as well as lumps with detrital components. Ooids are usually covered by several shells of micritic and fine-grained calcites. The nuclei of ooids are represented by fragments of foraminifers, algal micronodules and other remnants, as well as small pelitomorphic lumps and calcite crystals. The shell has a radial-fibrous (Fig. 9) and the subordinate tangential or chaotic structure. Initially, it was composed of aragonite that was replaced by calcite. Ooids with the tangential shell formed under conditions of high hydrodynamic activity and mutual friction of grains (Davies et al., 1978; Ferguson et al., 1978). Pseudoolitic limestones are also encountered. The components of such limestones are similar with ooids in terms of shape and size, but they are composed of fine-grained calcite that makes up thick radiated

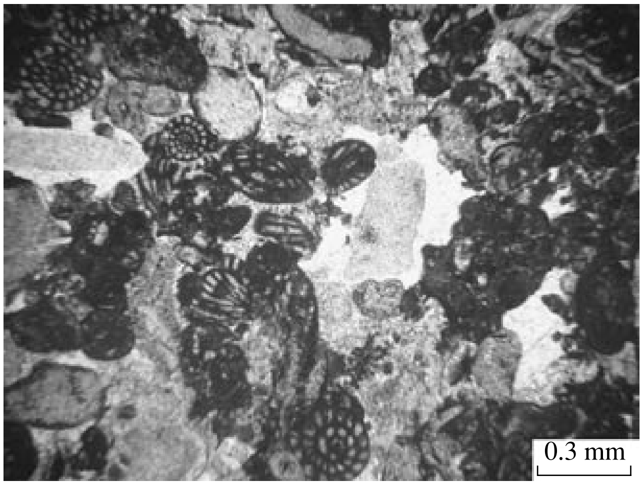

Fig. 8. Lumpy-detrital limestone (thin section). Alibekmola field, well 8, depth 3456 m (Middle Carboniferous, Moscovian).

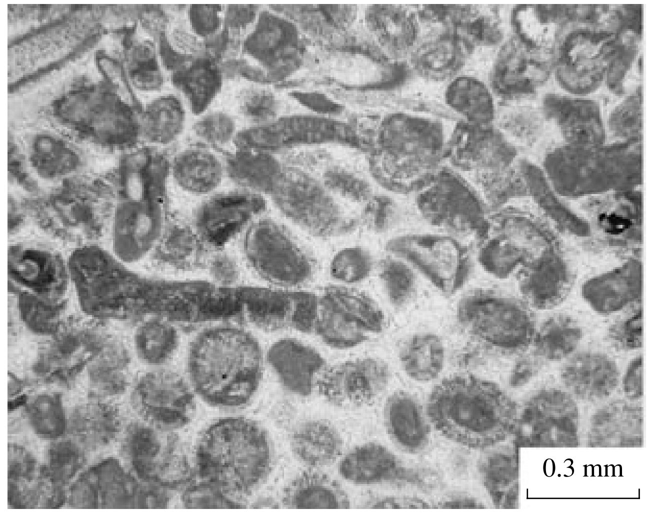

Fig. 9. Oolitic limestone with radial-fibrous shells (thin section). Kozhasai field, well 87, int. 3331–3338 m (Middle Carboniferous, Bashkirian).

shells. The pseudoolites lack the nucleus and are characterized by chaotic microtexture, probably, as a result of the influence of endolithic microorganisms.

The oolitic limestones are noted for good sorting of grains. The size of ooids varies from 0.3 to 0.8 mm (rarely, up to 1.5 mm in diameter). The limestones include two types of cement generation. The initial cement is developed as isopachous allochem incrustations, whereas the secondary (fibrous or sparitic) cement has a porous, pellicular-porous, crustification-porous, or semiporous structure.

Micrograined limestones sporadically encountered mainly in Early Carboniferous rocks are characterized by homogeneous structure and insignificant content of tissue elements (usually, not more than 2 mm in size). The limestones are represented by irregular carbonate detritus, lumps, and clots originated in the process of sediment recrystallization. The irregular-lumpy texture is characteristic of these rocks. The carbonate mud, which was consequently transformed into fine-grained limestone, accumulated in lagoons and outer shelf areas under quiet conditions.

The environment of carbonate mud accumulation can be reconstructed on the basis of faunal remnants. The lagoonal varieties are dominated by ostracod and small foraminifer tests, as well as micronodules of green and green-blue algae. Intense granulation of skeletal particles is noteworthy. The fine-grained lagoonal limestones usually contain traces of dolomitization. Sponge spicules, thin-walled shells of brachiopods, ostracods and radiolarians, and tissue elements of bryozoans are frequently encountered in the mud deposited on the open shelf or submarine slope. In the micrograined limestones formed at the boundary of storm wave action, the bulk micritic mass shows lenses and laminas consisting of fragments of thin shells of brachiopods, echinoids, and other marine fauna. Sometimes, one can see signs of graded bedding. Such structures are characteristic of distal parts of storm facies, i.e., distal tempestites.

The micrograined limestones are mainly observed as dense rocks significantly subjected to stylolitization and cracking. The density of stylolites changes from 20–25 to 150–160 units per meter; the density of open fractures, from some units to 100 units per meter.

Dolomites are typical of the Serpukhovian sequence. From the genetic point of view, one can distinguish two (sedimentary and catagenetic) groups of dolomites. The sedimentary dolomite is formed during enrichment of marine bottom waters in Mg, whereas the catagenetic dolomite is formed during the metasomatic replacement of calcite by dolomite in limestones with the participation of Mg dissolved in groundwaters (Strakhov, 1962).

Sedimentary dolomites are represented by micrograined rocks (crystal size 10–100 μm) and micro- fine-grained varieties (crystal size 50–200 μm). Fine-grained idiomorphic and hypidiomorphic crystals contain different amounts of clayey admixture. In drill cores, they occur as light brown dense, hard, and frequently fractured rocks. Syngenetic intercrystalline pores filled with clayey material are encountered in some places. Remnants of organisms are absent.

Dia- and catagenetic dolomites form massive irregular bodies and interlayers up to several meters in size. Their brownish gray color with dark brown and black patches is related to the presence of bitumen. The dolomites have irregular porous and cavernous structures with rare microfissures and fine-grained (0.05–0.25 mm) or the subordinate medium- and coarse-grained (0.25 to 0.8 mm) textures. Idiomorphic (less commonly, hypidiomorphic) dolomite crystals, which

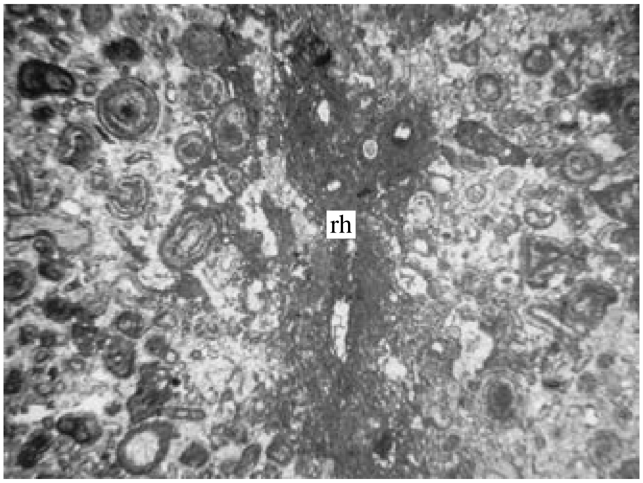

Fig. 10. Rhizolites (thin section). Alibekmola field, well 51, depth 3463 m (Middle Carboniferous, Bashkirian).

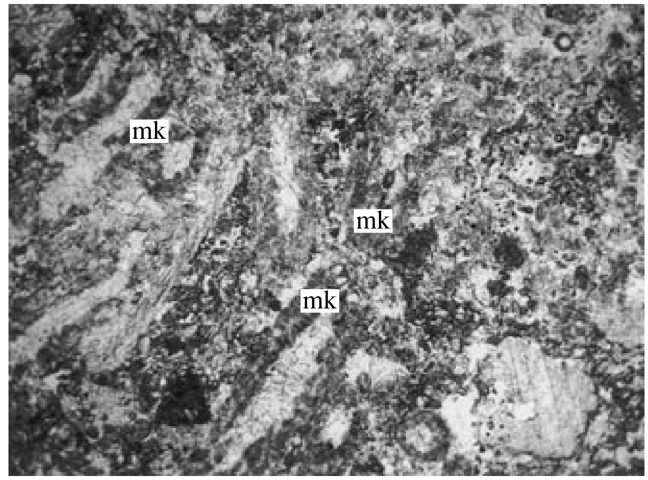

Fig. 11. Microcodiaceans (thin section). Alibekmola field, well 51, depth 3463 m (Bashkirian).

often contain clayey and dustlike inclusions, as well as pelitomorphic calcite, are abundant. Relicts of primary rocks (shells and algae thallus) are also present. Tissue elements are usually dissolved. Therefore, only their imprints and casts are preserved. In the case of incomplete dolomitization, the space between orthorhombic dolomite crystals is filled with sedimentary pelitomorphic calcite.

Drop of sealevel and tectonic movements in the Paleozoic were repeatedly accompanied by the draining of vast areas of the Carboniferous marine basin. Moreover, the influence of atmospheric precipitation promoted the leaching of poorly lithified carbonate sediments and the consequent formation of caverns, karst hollows, and breccias. Calcretes originated during the prolonged exposition of sediments above the sealevel. Frequently, the carbonate sediments served as a substratum for the formation of soil cover. This is evidenced from relict structures, such as rhizolites, worm traces, microcodies, and lamina bends beneath plant roots (alveolar-septal structure) preserved in carbonate rock beds at different levels of the Lower–Middle Carboniferous sequence.

In thin sections, the rhizolites commonly occur as tubular bodies, up to 1 mm thick, with a cutan-shaped halo and central cavity filled with alveolar-septal tissue. In the micritic substrate with vague bedding and lumpy structures, one can see sinuous channels and vugs that can be considered as sections of small roots (Fig. 10). They form a porous medium around the rhizolites. The contact of rhizolite shell with the host rock is usually very sharp, most probably, due to the decay of roots in the cavity initially occupied by them (Wright and Tucker, 1991).

During the study of thin sections of late Visean and Bashkirian rocks, Kan detected and described accumulations of Microcodium (well 71, Kozhasai field; well 28, Alibekmola field; and well 5, Zhanatan field) (Kan, 2005; Kan and Akhmetshina, 2004). These represent trapeziform or cylindrical calcite grains (100–850 μm long and up to 300 μm wide) having light brown color in transmitted light. Aggregates of Microcodium are characterized by tubular shape, which becomes ring-shaped or ellipsoidal in the cross-section. At high magnification, the grains contain black opaque inclusions with radial or fibrous structures (Fig. 11).

ACCUMULATION SETTING OF LOWER AND MIDDLE CARBONIFEROUS SEDIMENTS

The composition and structural–textural features of Tournaisian and Visean terrigenous rocks testify to their accumulation in different settings ranging from foothills and coastal plains in eastern areas of the Zharkamys Swell to marginal shelf and submarine fans on the western steep submarine slope. For example, the lower Visean sequence in the Zhonazhol zone includes several units of mudstones, siltstones, and sandstones containing interlayers of coarse sandstones and gritstones with coal seams. One can see ripple marks on stratification planes. These sediments probably accumulated in proluvial fans and deltas of small rivers that transported the clastic material from a mountainous provenance situated in the east.

Coeval rocks penetrated by wells in the Laktybai area in the western part of the swell have another appearance. They occur as massive graywacke sandstones, which lack structures typical of the wave agitation zone show elements of graded bedding. Generally, they lie on the erosion surface of the underlying rocks. Similar were reported by Selley (1978) from the Mexico Gulf. The clastic material was probably transported by grain and mud flows originated in the marginal part of the shelf. These sediments can be interpreted as tur-

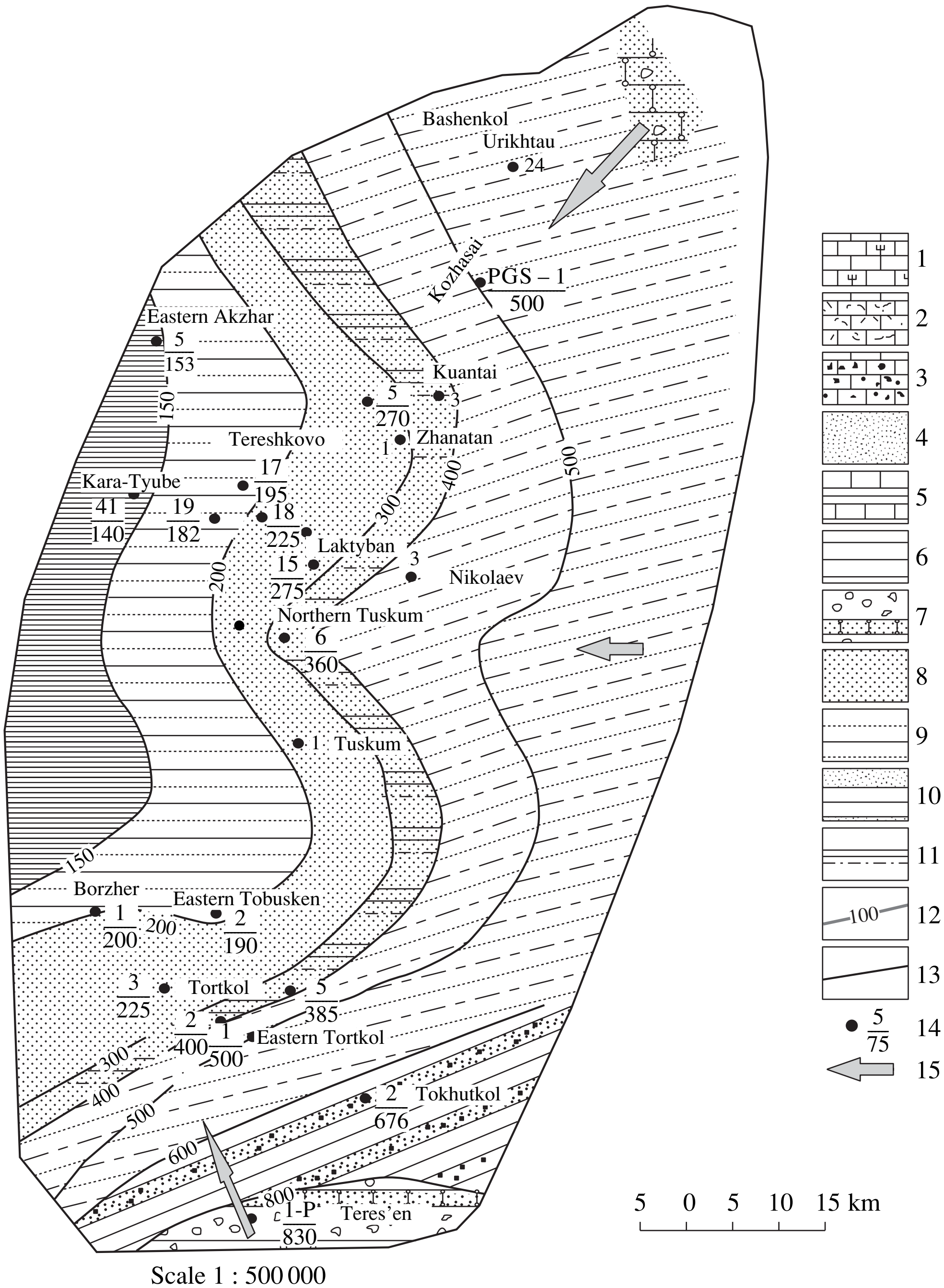

Fig. 12. Lithofacies scheme of the distribution of lower Visean terrigenous rocks. (1–11) Rocks: (1–4) carbonate (limestones): (1) biohermal, (2) biomorphic and biomorphic detrital, (3) detrital fine-grained and micritic, (4) oolitic and peloid-bioclastic; (5–11) terrigenous: (5) alternation of mudstones and limestones, (6) clays and mudstones, (7) conglomerates with sandstone interlayers, (8) sandstones, (9) fine-grained sandstones with mudstone interlayers, (10) fine-grained sandstones with siltstones interlayers, (11) alternation of mudstones, siltstones, and fine-grained sandstones; (12) isopachs; (13) boundaries of facies zones; (14) well numbers (numerator) and thickness of recovered rocks (denominator); (15) direction of clastic material transportation.

bidites, which accumulated on the continental slope in submarine fans (Fig. 12).

Changes in tectonic regime in the adjacent areas in the late Visean are reflected in the composition of sediments. Sediments are gradually enriched in clays and carbonates. Thick clayey members alternate with horizons of clastic rocks. The late Visean sequence includes several large cyclites. Coarse-grained rocks at the base give way upsection to medium- and fine-grained rocks, which are sometimes overlain by micrograined limestones at the top. Clastic limestones contain reworked fauna and fragments of carbonate rocks. The limestones usually include an admixture of terrigenous particles. The composition of the cement of terrigenous clastic rocks also changes. For example, the lower Visean graywackes are dominated by fine-grained silty cement containing clayey material of the chlorite-illite composition, whereas the upper Visean sandstones are characterized by the calcitic cement.

The upper Visean sandstones have mainly petroclastic quartzose composition. They are better sorted in comparison with analogous rocks from the lower Visean sequence. The appearance of mesomictic sandstones is probably related to the rewashing of the previously deposited sandy sediments by waves and alongshore currents. Such sandstones make up massive horizons with sharp contacts at the top and base, and they lack the graded bedding. The fine-grained silty sandstones and silty sandstones are characterized by stratification related to the concentration of carbonaceous plant detritus and mica in separate layers. It is possible that the sediments accumulated in channels and underwater furrows of a prodelta, in the course of rewashing and partial destruction of levees. This is evident from the presence of clay lumps (10–20 mm in size) buried together with sand.

Cores recovered from the Laktubai field (wells 27, 34, and 37) contain gravelly and pebbly mudstones containing isolated gravel fragments in the clayey matrix, as well as mudstones with inclusions of sandy and gravelly material. The rocks demonstrate traces of the creep of the initial friable material. Together with grain flows, these traces indicate processes of sedimentation over a vast area of the submarine slope embracing the Laktybai, Zhanatan, and Northern Tuskum fields (Fig. 12).

In the Tortkol zone, the clastic portion of gray coarse-grained polymictic and unsorted rocks (conglomerates and gritstones) is composed of fragments of cherts and intermediate and basic volcanic rocks the subordinate mudstones and shales, and quartz grains. The cement is composed of the sandy–clayey, carbonate–clayey, and occasional chloritic material. The gray homogeneous massive polymictic fine- to coarse-grained sandstones contain an admixture of both calcareous and noncalcareous gravel grains. Clastic particles are poorly rounded. Coaly inclusions, 1.5–2.0 cm across, are encountered in some places. The cement is composed of the clayey-chloritic, clayey–calcareous, and clayey material. In terms of composition, the sandstones can be attributed to the typical graywacke.

In the Zharkamys zone (Eastern Akzhar and Tereshkovo fields), boreholes penetrated the thick undifferentiated lower Visean sequence of interstratification of clayey and terrigenous clastic rocks. These rocks can be identified as the sandy–clayey subgraywacke formation. The lower part of the sequence includes alternation of terrigenous clastic and clayey rocks with rare interlayers of carbonate and siliceous sediments. The predominant clastic rocks include varieties ranging from siltstones to gritstones and small-pebble conglomerates. Medium- to fine-grained sandstones with siltstone interlayers are most widespread. They correspond to graywackes in terms of the petrographic composition. The clastic portion is mainly composed of poorly rounded fragments of siliceous, clayey-siliceous, and volcanic rocks with quartz and feldspar grains, as well as mica and chlorite flakes. The role of thin- and thick-bedded bituminous limestones with remnants of siliceous and calcitic radiolarians increases toward the top of the sequence. Rocks have horizontal thin- and thick-bedded (less commonly, oblique-bedded) wavy structures with erosion grooves. Mudstones interlayers in the sandstones are enriched in coalified plant detritus.

These rocks are overlain by sandy–clayey rocks with a thickness of 60–100 m. They consist of dark gray mudstones alternating with sandstones, siltstones, gritstones, small-pebble conglomerates, and the subordinate limestones. This sequence is characterized by chaotic interstratification of fine- and coarse-grained sediments. The mudstone-dominated intervals contain interlayers of varigrained gravelly sandstones and siltstones, along with the less common gray and dark gray breccia-type limestones. The mudstones are represented by dense low-carbonate illite–smectite rocks. They usually contain an admixture of clastic material (quartz, cherts, feldspars, chlorite, micas, fragments of effusive rocks, and limestones with particle size ranging from 0.01 to 10–50 mm). Grains and fragments have acute-angled or angular shape. The mudstones have platy and flat-bedded structures.

Siltstone and sandstone interlayers in mudstones are characterized by graywacke and subgraywacke compositions and low grade of sorting. Varisized coarse-bedded gritstones are made up of fragments of dark-colored siliceous and effusive (less commonly, carbonate) rocks and quartz grains. Their pore space is frequently filled with silt- and sand-sized grains and fragments with the composition similar to that of the larger clasts. The cementation is porous and basal-porous. Limestones found in this part of the sequence are represented by fine-crystalline biomorphic-detrital (often breccia-type) varieties.

Analysis of the composition and structural–textural features of the rocks described above indicates their formation in submarine canyons of a paleoslope owing to the action of grain flows and possibly turbidity (mud) flows. This is testified by the occurrence of conglomerates, gritstones, and sandstones on the erosion surface of the previously accumulated sediments. This is typical of sediments related to such flows. We believe that the lower Visean rocks, which are characterized by alternation of fine-grained graywacke sandstones with mudstones and unusual structures (flat-bedded at the bottom and with hollows and furrows at the top), represent turbidites.

The end of the Visean was marked by attenuation of tectonic movements in the adjacent continental realms and the consequent replacements of terrigenous sediments by carbonate ones on the eastern flank of the Caspian Basin. In the Zhonazhol and Tortkol zones, these rocks overlie a flat surface of terrigenous rocks. Carbonate rocks accumulated in the Mikhailov–Venev time are almost barren of the terrigenous admixture, and they bear traces of sedimentation in shallow-water marine conditions. The accumulation of these carbonate sediments was only occasionally interrupted by terrigenous sedimentation in the Alibekmola field.

The upper Visean sequence includes algal biohermal, bioclastic, and microbial-detrital limestones. The late Visean is characterized by a wide distribution of red algae (Praedonezella), as well as codiacean and verticillate siphon algae (Calcifolium and Koninckopora). Oolitic limestones containing grains of Microcodium are present in the upper part of the sequence. They mark uplifted areas of the carbonate shelf, where sediments were subjected to wave action and rip currents (well 6, Bashenkol field). Such areas were occasionally located above the sealevel and leached. This is suggested by the presence of calcretes and beachrocks (well 5, Zhonatan field). Rocks of the Oka Superhorizon contain traces of dolomitization and recrystallization.

In western areas of the Zharkamys Swell, shallow-water carbonates are replaced by dark gray and black bioclastic limestones consisting of unsorted remnants of tissue elements. These bedded, silicified, and pyritized rocks contain intensely altered organic matter and clay interlayers. Thus, the available facts suggest that the sediments described above accumulated under deeper-water conditions relative to the Zhonazhol and Tortkol zones, probably, on the outer part of carbonate shelf (Fig. 13). The top of the Visean sequence contains dark gray and black bedded detrital micrograined limestones with an admixture of clayey material. These rocks are deep-water analogues of limestones from the Zhanazhol zone.

The lowest sealevel stand is recorded at the Visean–Serpukhovian boundary. The Serpukhovian sea coast included numerous shoals and isolated lagoons with restricted water circulation, where carbonate sediments with spherical-patterned, microlumpy, and stromatolitic textures accumulated. Rocks of the Tarusa Horizon contain nodules of blue-green algae and remnants of siphon algae (calcifoliums, paleoberesella, schartimoficuses, and koninckopors). Biomorphic-detrital varieties of the limestone are made up of foraminiferal shells and algal nodules, as well as tissue elements of brachiopods, crinoids, and solitary corals. Some areas of the ancient carbonate platform are composed of lumpy, fine-detrital, and microlaminated limestones pigmented by organic matter (well G-5, Alibekmola field). Carbonate buildups were formed in the western sector, where the outer shelf (Kozhasai and Zhanatan fields) and submarine slope (Bashenkol field) could be situated (Fig. 14). The largest structure was represented by the Bashenkol massif that included biostromes separated by biomorphic-detrital limestone layers. Their thickness attains 115 m, whereas the height of the whole massif with the top fixed at a depth of 4188 m is 583 m. The buildup base includes micritic algal-bryozoan limestones primarily composed of bryozoans.

In rocks of the Protva Horizon, red algae play a subordinate role, while blue-green and green algae (codiacean and verticillate siphon algae, stromatolites, girvanellas, and so on) are abundant. Marginal parts of the uplifts accumulated coarse-grained carbonate detritus (remnants of brachiopods, crinoids, bryozoans, and other organisms). The upper part of the sequence contains calcareous sandstones composed of rounded algal nodules, foraminiferal shells, peloids, ooids, and carotids.

Carbonate buildups were developed along the northern and western edges of the Zhonazhol zone and in the Tortkol zone. They occupied the hypsometrically highest areas of the carbonate shelf. The flat organogenic structures (n–$10n$ m high) were developed on projections of the seafloor on tops of local uplifts. The framework-forming organisms were represented by algae, such as green (schartimoficuses, calcifolium, koninckopora and others), blue-green (girvanella), red (Ungdarella), and green (Praedonecella), and less common bryozoans. Fragments of pelmata and brachiopod shells and peloids, are ubiquitous in rocks.

Granular carbonate material accumulated in the zone of reeflike structures on the western side of the shelf break. They compose clinoforms grading into basinal facies. The clinoform structures are dominated by fragments of algal nodules and unsorted faunal remnants. With increasing depth, these sediments grade from the coarse-grained variety at the foothill of large carbonate buildups to the micrite-rich fine-grained variety in distal parts of the talus. Further to the west, they give way to deep-water carbonate–terrigenous–siliceous sediments of. Black micro- and fine-crystalline bedded bituminous limestones with radiolarian shells and sponge spicules are present in the Zharkamys sequence. These limestones represent the micritic and bioclastic varieties. Nearly all of them are saturated with brown organic matter (probably, sapropel). These deep-water rocks can be defined as the deep-water analogues of carbonate rocks accumulated in the eastern areas of the Zharkamys Swell. They continued to accumulate for a long period and underwent several episodes of rewashing. Therefore, some stratigraphic horizons are missing in several well sections. Their deep-water genesis is suggested by the abundance of remnants of silica-forming organisms, such as radiolarian shells and sponge spicules.

The carbonate complex of the Middle Carboniferous (Bashkirian Stage) formed in the course of gradual marine regression. The Zhanazhol and Tortkol sectors

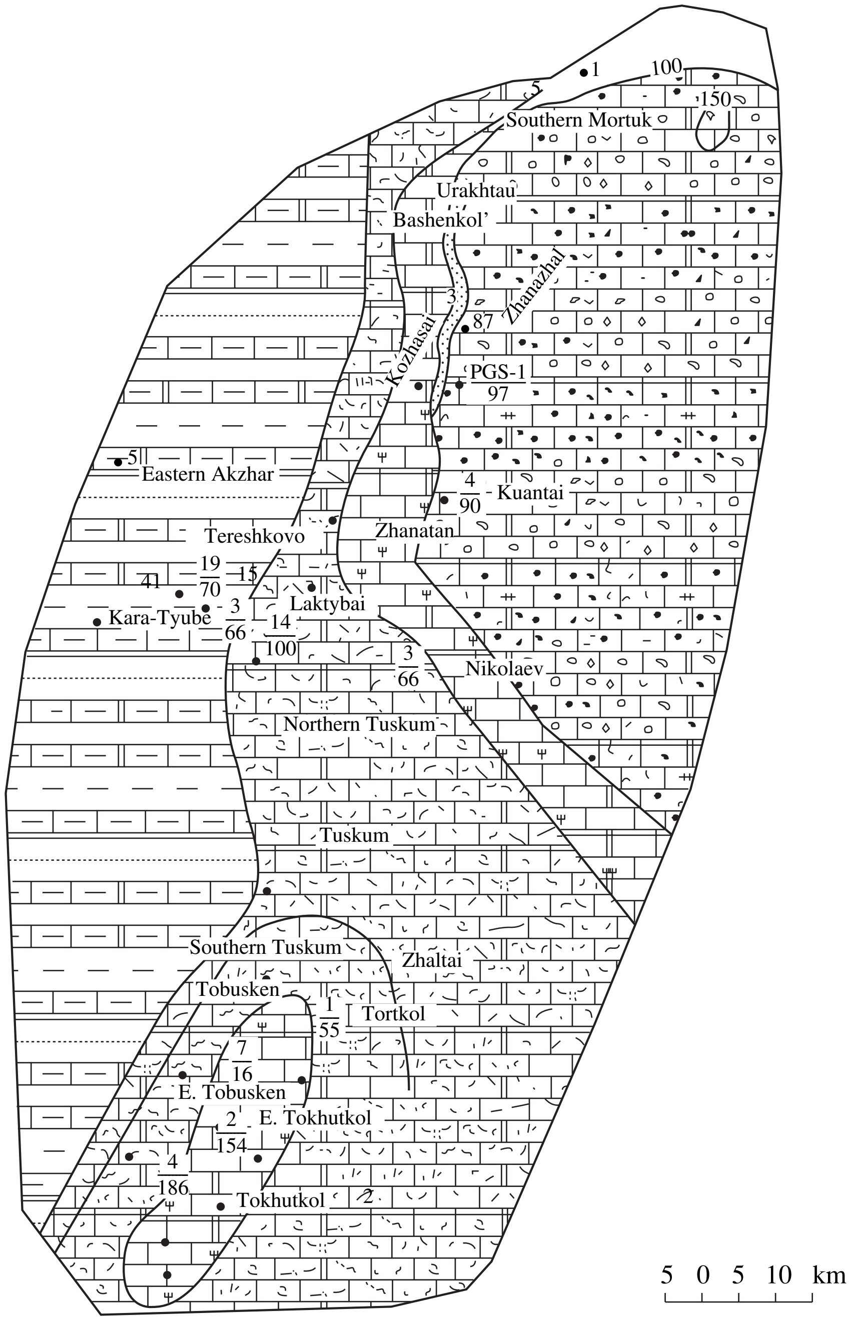

Fig. 13. Lithofacies scheme of the distribution of upper Visean carbonate rocks. See Fig. 12 for legend.

primarily accumulated shallow-water sediments characterized by the gradual concentration of sediments typical of lagoons and tidal shoals. However, well P-6 drilled in the Bashenkol field penetrated 80-m-high donecellid bioherm, suggesting that the algae buildups continued to develop in the marginal part of the paleoshelf.

Biohermal limestones make up several intervals of the lower Bashkirian sequence in the Kozhasai, Zhagabulak, Alibekmola, and Southern Mortuk fields. Well G-2 (Zhagabulak field) penetrated stromatolitic limestones with characteristic crustal and microlumpy textures. They contain algae accumulations of indefinite nature, as well as fragments of crinoids and foraminiferal shells, which are typical of the upper part of "carbonate knolls" formed in the back-reef zone of lagoons or in the littoral part of the shelf. In the Alibekmola uplift, the Bashkirian (mainly, algal) limestones consist of donecella and ungdarella–beresella nodules. Bioclastic varieties are rather rare.

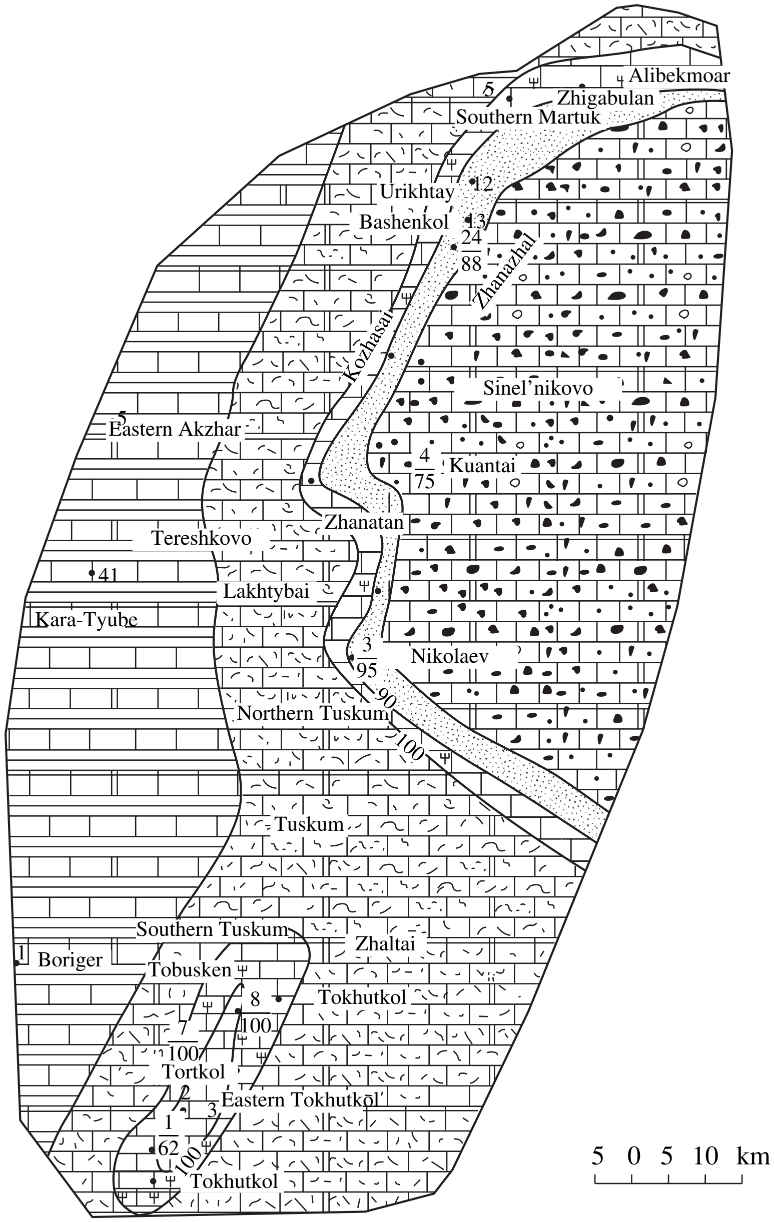

Fig. 14. Lithofacies scheme of the distribution of different types of middle Serpukhovian rocks. See Fig. 12 for legend.

Sediments of the littoral zone and shoals are represented by peloid-bioclastic and algal-polybioclastic limestones. Along with bacterial-algal carbonates containing stromatactises, they compose the upper horizons of organogenic buildups. Marine regression reached its maximum in the second half of the Bashkirian, resulting in the exhumation and washout of sediments primarily in the southern part of the Zharkamys Swell. For example, the Bashkirian rocks are absent in the Tokhutkol field (wells 2 and 3). They appear on the northern side of the uplift. Here, the thickness of the Bashkirian sequence gradually increases up to 250–290 m, and the stratigraphic section is also more complete.

The growth rate of carbonate buildups significantly decreased in the Bashkirian time. This was reflected in the volume of clastic material delivered to the submarine slope. Only at the very end of this stage, a thick bioclastic limestone sequence of various types of carbonate detritus accumulated here due to intense erosion of sediments of the carbonate platform.

The continental slope situated at the westernmost end of the Zharkamys Swell is composed of sediments accumulated under anaerobic conditions characterized by the deficit of terrigenous and carbonate material. They are represented by dark gray to black fine-laminated bituminous clayey-siliceous–carbonate rocks with pyrite inclusions. Organic-rich mudstones are also present. In some places, the rocks contain accumulations of siliceous remnants (sponge spicules and radiolarian shells). Black and dark gray fine-detrital limestones with lenses of siliceous–clayey material and black spots enriched in organic matter and fine-grained pyrite form thin interlayers. In addition to sponge spicules and radiolarian shells, the tissue elements of brachiopods and crinoids, as well as an admixture of terrigenous material, are also present in the rocks. These rocks compose the lower part of the undifferentiated member (95–130 m thick), which includes upper Visean–Asselian rocks accumulated on the submarine (probably, continental) slope.

CONCLUSIONS

The end of the Devonian and beginning of the Carboniferous were marked by important tectonic deformations that affected, first, the eastern flank of the Caspian Basin and then its central areas. This is testified by the graywacke composition and enormous thickness of the terrigenous complex accumulated on the Zharkamys Swell and adjoining structures. The predominance of fragments of siliceous and effusive rocks in the clastic portion of conglomerates, sandstones, and other detrital rocks indicates that the source was situated beyond the East European Platform. Clastic material was evidently delivered from an orogenic belt located at the eastern boundary of the Caspian Basin. The foredeep formed in front of this belt was only partially filled with terrigenous sediments. This foredeep was later transformed into an internal deep, the development of which was accompanied by an irregular subsidence of large areas of the Earth's crust at the eastern periphery of the basin and the consequent formation of a deep-water trough at the Devonian–Carboniferous boundary. The trough was bounded in east by a chain of uplifts stretching along the collision zone. The narrow shelf and rather steep submarine slope, which formed at the crest and on the western limbs of these uplifts, became depocenters of terrigenous and later carbonate sediments for a long time. The apron of terrigenous sediments, which included talus fans, mountain river deltas, and grain and turbidity flows, gradually extended toward the deep-water trough. This material turned into the substratum, on which carbonate shoals and organogenic buildups started to develop at the margin of the paleoshelf in the second half of the Early Carboniferous. In the Middle Carboniferous, lagoons and tidal flats of the littoral zone became the principal zones of accumulation of carbonate sediments. The sealevel fall in the Bashkirian time was accompanied by the partial destruction of carbonate buildups and accumulation of bioclastic and oolitic carbonate sediments. The growth of the carbonate buildups was renewed in the early Moscovian time. The formation of the carbonate platform at the eastern flank of the carbonate platform was interrupted by a new phase of tectonic movements in the early Podolian time. These movements terminated one of the most important stages in the Paleozoic history of the Caspian Basin that predetermined the formation of the principal petroliferous complex in its eastern periphery.

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