

Lithology and Formation Conditions of Paleogene Rocks in the Dongying Depression (Bohai Bay Basin, China)

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Abstract—The Dongying Depression is one of the largest depressions in terms of hydrocarbon reserves not only within the Bohai Basin, but also in the whole Pacific region. This is related to the inherited pattern of geological evolution, as well as the optimal combination of oil source rocks, reservoirs, and caprocks, which alternate in both lateral and vertical directions. Diversity of the lithofacies composition of Eocene and Oligocene sediments in thick (proluvial, deltaic, fan deltaic, and deep-water) hemipelagic and gravitational deposits in the composition of various fans, predetermined the wide distribution of sandstone and gritstone beds with good filtration-capacity properties. The beds were filled with hydrocarbons that migrated from the adjacent layers of oil shales and clays. The role of the principal reservoirs was played by sandstones, which were deposited in distributary channels of Eocene deep-water fans. The detailed study of these underwater fans will make it possible to expand the reserves of hydrocarbons explored now in the Dongying Basin.

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The Bohai Bay Basin is located in the eastern half of the North China Platform. The basin is bounded by the Yean-Shan Range in the north, the Zhaoliao Uplift in the east, the Shanxi Ridge in the west, and the (Lushan) Taikang Uplift in the east. Its eastern boundary is represented by the Liaodung and Jiaodung uplifts. The basin is elongated in a near-meridional direction for 700 km (width 300–400 km and area ~200 000 sq. km). The basement of the North China Platform includes Archean and Lower Proterozoic metamorphic rocks of three metamorphic complexes. The oldest complex (2.35–2.55 Ga) consists of initially clastic and volcanic rocks in the Fuping, Siayi, Anshang, and Taishan groups, which subsequently underwent migmatization and granitization.

GEOLOGICAL STRUCTURE OF THE DEPRESSION

The Bohai Basin represents a typical rift (Geodekyan et al., 1988; Limonov and Burlin, 1988) of two evolution stages. The Paleozoic platform stage was marked by the accumulation of predominantly marine carbonate sediments. The Mesozoic–Cenozoic rifting stage was dominated by terrigenous sedimentation in the region (Milanovskii, 1991). According to Chinese geologists, the total thickness of sedimentary rocks accumulated during the Late Proterozoic and Phanerozoic, can reach 10 000 m (Wang Shangwen et al., 1994). The thickness of the Earth's crust in the Bohai Basin is 28–32 km, which is approximately 5–10 km less in comparison with 34–40 km in the framing areas. The high conductivity layer, which allegedly hosts the

top of asthenosphere, is generally located at a depth of 45–60 km (maximum 80 km), as compared with 100–150 km in the adjacent parts of the North China Platform.

The Bohai Bay Basin incorporates numerous large and small blocks of the Earth's crust, which are subsided along large faults to different depths. Activation of these faults in the Eocene was accompanied by the origination of grabens and semigrabens, a system of tilted blocks separated by synsedimentary faults. Depressions originated along the subsided limbs of the largest grabens served as depocenters for predominantly deep-water sediments. The area of 200 000 sq. km includes 80 such depressions (Fig. 1). The largest depression occupies an area of 8800 sq. km, while the smallest one has an area of 750 sq. km. Areas of the majority of depressions vary within a range of 1000–2000 sq. km. The amplitude of subsidence in these depressions could reach 6–9 km.

Structures in the peripheral parts of the basin are oriented in the northeastern direction dictated by the orientation of the Tang-Lu Fault, which represents a transcontinental sinistral strike-slip zone. This zone crosses eastern areas of the Asian subcontinent over 3600 km (Li Yuan et al., 2004) from southern China to the northeastern Songliao Plain and the Russian Far East. Recent activity of this zone is testified by frequent earthquakes and deformations of Quaternary sediments along the fault strike. Since XV century, at least 10 catastrophic earthquakes have occurred here.

The Dongying Depression belongs to the Ziyang Subbasin, which is located at the southeastern periph-

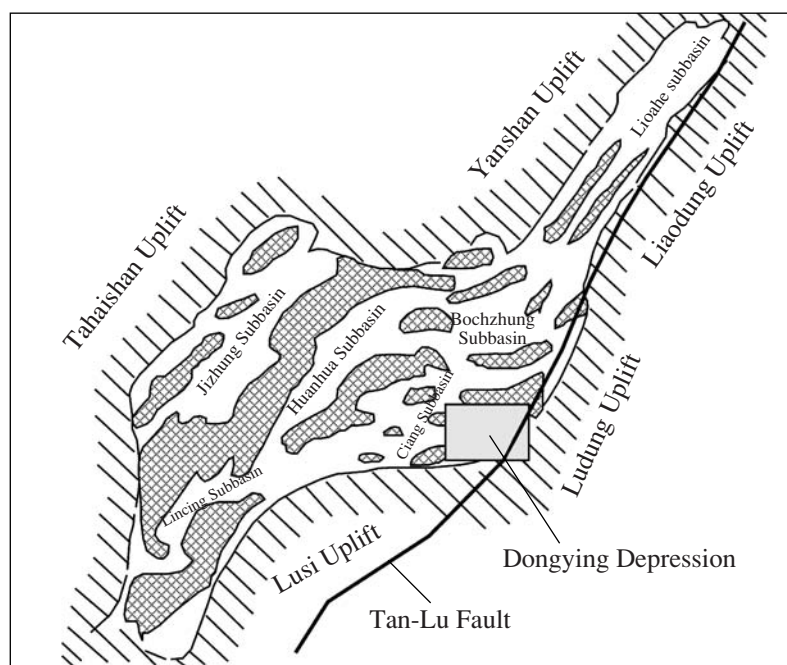


Fig. 1. Tectonic structure of the Bohai Bay.

ery of the Bohai Bay Basin. This depression is one of the largest structures in terms of petroleum potential in the study region. Its northern and southern borders are represented by ridges of the Qenjiazhuang and Lusi, respectively, buried under Pliocene–Quaternary sediments. In the west and east, it is bounded by the Cinchong and Kendung–Cingtozy uplifts, respectively, with their tops covered by a layer of recent sediments. The Dongying Depression incorporates slightly subsided peripheral zones and a depression with the steep northern and gentle southern flanks (Fig. 2a). The depression is divided by the uplifted Qyunhua–Dungan zone into the western and eastern parts. The asymmetric structure of the Dongying Depression is best manifested in near-meridional profiles, such as A–A (Fig. 2b).

The northern flank was formed along large synsedimentary faults dipping southward at 15° – 30° . This flank, located between the Qenjiazhuang and Binxian uplifts in the north, the Cingtozy Uplift in the east, the Linfanja Uplift in the west, stretches over 100 km from west to east. Its width does not exceed 15 km, and the area is about 1500 sq. km. The presence of buried hollows and canyons suggests that in the Paleogene this area included a submarine slope merged with the Lijyin and Minfeng depressions in the south. This slope had a stepwise structure complicated by small anticlinal uplifts, which originated within the subsided blocks and represented reverse drag folds. Tops of the folds were composed of packages of Paleogene–Neogene gravel sandstones and covered by clays. These buried uplifts frequently played the role of oil traps.

The southern flank is a monocline slightly inclined toward the center of the depression (dip angle does not exceed 5° – 10°). It is composed of several anticlinal structures with a stepwise pattern in some areas. From the paleotectonic point of view, this flank represented a gentle slope (Buke et al., 2000), as evidenced by the presence of ancient canyons and underwater channels incised into the top of Eocene sequences. They are particularly numerous in the lower half of the southern flank.

The central part of the Dongying Depression is crossed by a large fault belt that stretches over 60 km in the northeastern direction. The width is 12 km and the area is 600 sq. km. This belt is framed by small depressions (sags): Mingfeng Sag in the north, Licing Sag in the west, and Liuzhang Sag in the south. They are complicated by buried domes and anticlinal folds. The majority of Chinese geologists suppose that the formation of this fault belt is related to the growth of salt domes, because drilling in this part of the basin recovered samples of gypsum and rock salt.

LITHOLOGY OF MESOZOIC–CENOZOIC ROCKS

According to the drilling, seismic, and paleontological data on cores from many wells drilled in the Bohai Basin, the sedimentary cover here lacks Proterozoic, Upper Ordovician, Silurian, Devonian, Lower Carboniferous, Upper Permian, and Triassic rocks, whereas rocks of other representatives of the Paleozoic, Mesozoic, Cenozoic, and Quaternary periods are present.

Lower Paleozoic rocks include predominantly coastal-marine carbonate varieties. The Upper Paleo-

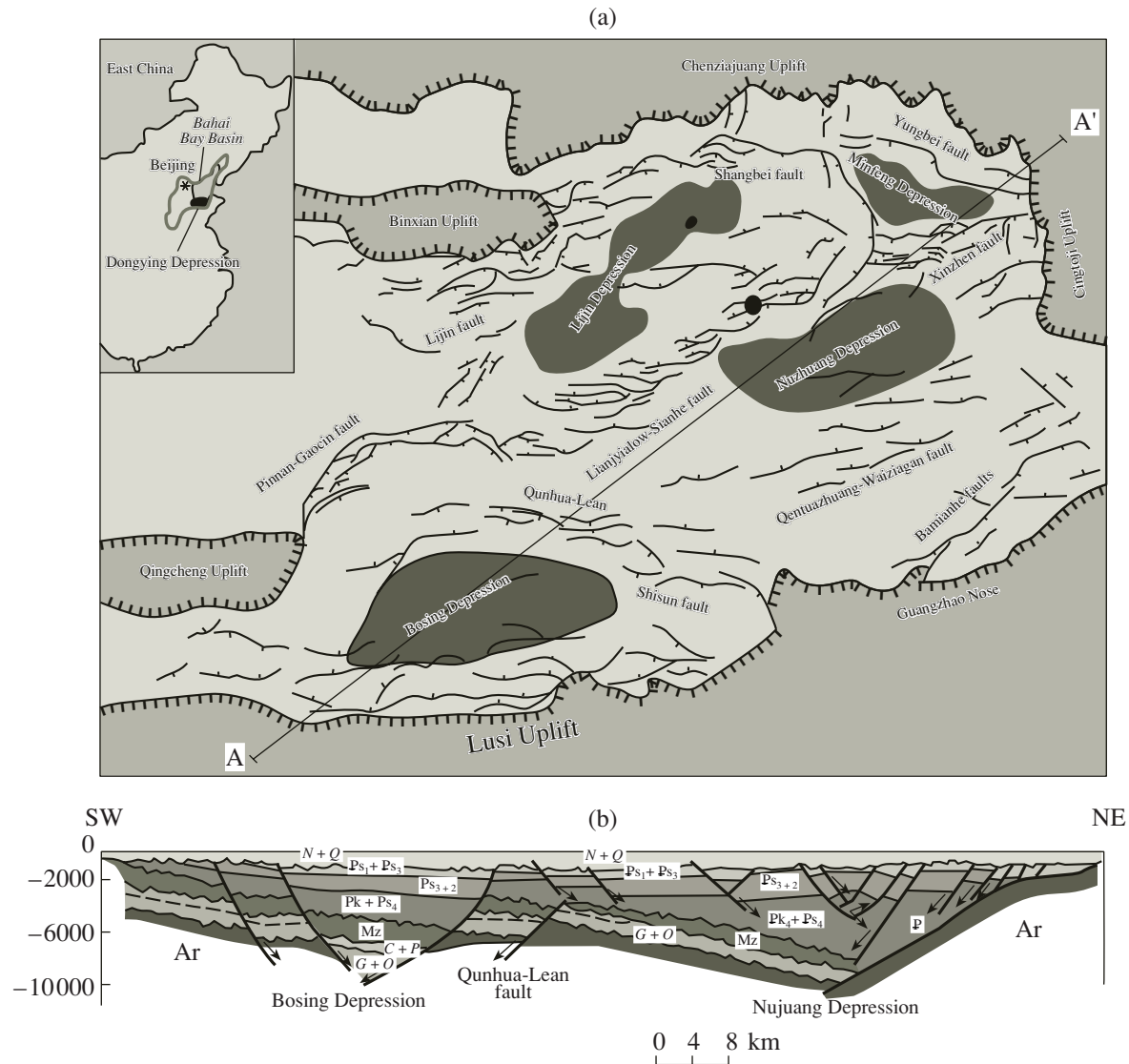


Fig. 2. Tectonic scheme of the Dongying Depression (a) and meridional seismic-geological profile of its central part (b).

zoic is represented by terrigenous clastic rocks accumulated both under marine and continental conditions. The Mesozoic section is mainly dominated by alluvial clastic rocks with coal interlayers. Igneous rocks are also encountered. The Cenozoic part of the section begins with Paleocene rocks developed in local areas. In contrast, Eocene and Oligocene sediments (predominantly terrigenous-lacustrine clastic varieties with interlayers of carbonate rocks, rock salt, gypsum, and volcanic in some localities) are extremely widespread (Feng Youliang, 1999). The composition of Neogene and Quaternary sediments is dominated by terrigenous (mainly alluvial) clastic sediments with rare interlayers of marine sediments (Fig. 3).

The study of the core material from numerous wells drilled during the last years significantly supplemented

and refined the previous ideas about the lithological composition of Cenozoic rocks.

Terrigenous rocks are widespread among the Mesozoic and Cenozoic deposits. Moreover, they absolutely dominate in Paleogene and Neogene sections, except the Lower Eocene. Their lithotypes are represented by conglomerates, gritstones, sandstones, siltstones, mudstones (clays), mixed rocks, and transitional varieties.

Lithology of terrigenous rocks in the Bohai Basin is characterized by significant variability and defined by the remoteness of individual depressions from the provenance, composition of eroded ancient rocks, hydrodynamic regime in the lacustrine basins, climate, and other factors. Rock fragments played a significant role in the composition of conglomerates, gritstones, and sandstones. In different parts of the Dongying Depression, they are represented by clasts of effusive and

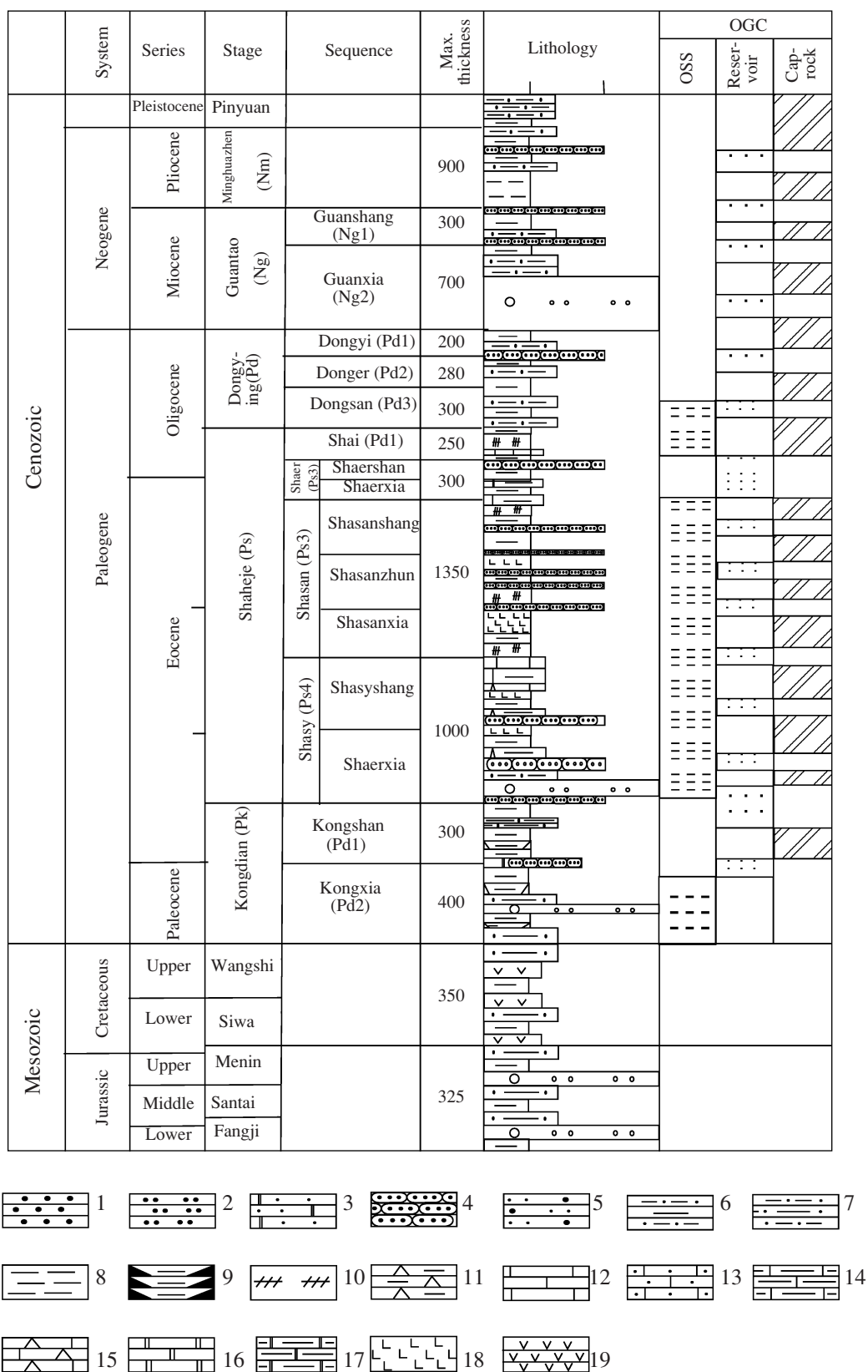


Fig. 3. Lithofacies profile of Mesozoic–Cenozoic deposits in the Dongning Depression. (1–8) Terrigenous rocks: (1) conglomerates, (2) gritstones, (3) dolomitic gritstones, (4) sandstones, (5) gravelly sandstones, (6) clayey sandstones, (7) siltstones, (8) clayey rocks; (9) coaly–clayey shales; (10) oil shales; (11) clayey rocks with anhydrite; (12) limestones; (13) sandy limestones; (14) clayey limestones; (15) anhydrite limestones; (16) dolomites; (17) clayey dolomites; (18) evaporites; (19) andesites. (OGC) Oil- and gas-bearing complex; (OSS) oil source sequence.

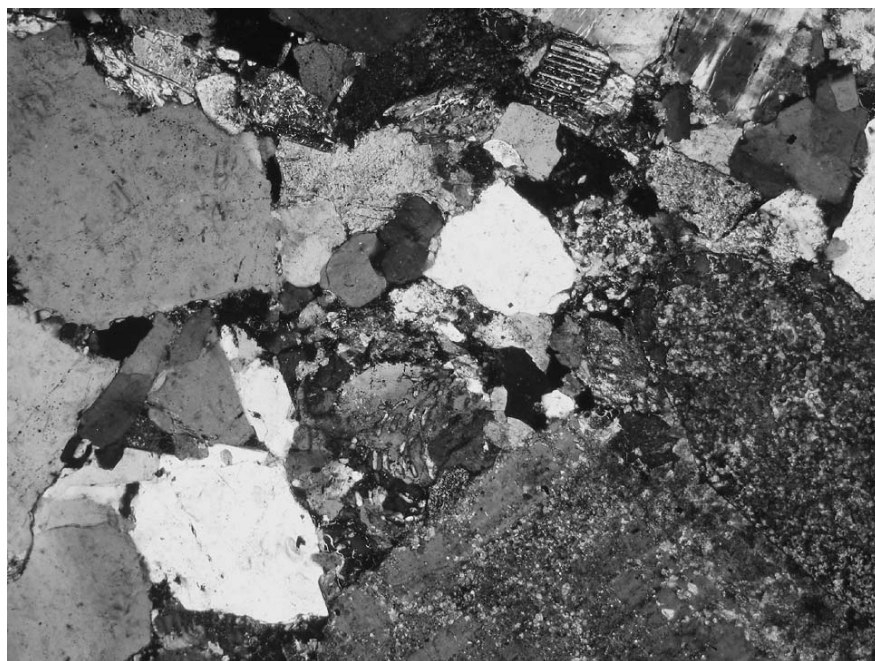


Fig. 4. Gravelly inequigranular sandstone (quartz–feldspar graywacke, Es₄), Well Yun 920, depth 3372.5 m, the northern slope of the Dongying Depression. Magnification 50.

intrusive rocks, metamorphic and ancient sedimentary rocks, including quartzites, gneisses, limestones, dolomites, anhydrites, and shales.

Conglomerates and gritstones are mainly widespread near the provenances on the northern slope of the Dongying Depression. The distance of transportation was very short. Therefore, the composition of conglomerates and gritstones is dominated by angular and subrounded fragments of effusive rocks, granites, and anhydrite. Like quartz grains, they are poorly sorting. The color of these rocks changes from light gray and gray to brown.

In Early Eocene (Shasyxia Stage) deposits, the coarse-grained fraction of conglomerates is mainly composed of pebbles of Paleozoic limestones, which sometimes contain remnants of trilobites, urchins, and other fauna. After the washout of the most part of the Paleozoic deposits, basement rocks of mainly Archean age were also eroded. Therefore, pebbles are dominated by fragments of granites and gneisses with the subordinate clasts of anhydrite and gypsum. The maximum size of the pebbles reaches 5 cm. The size of gravel grains varies from 1 to 10 mm (commonly, 3–8 mm). The intergranular space of rocks is usually filled with silt and clay material. The basal-porous and contact-porous cement is typical.

Porosity of these rocks (1–8%) is governed by the presence of pores and fractures. The pores are divided into the intergranular, dissolution (along pebble surfaces, and less frequent intrapebble) types. The fractures are also divided into the dissolution (along pebble surfaces) and tectonic types. In some places, the frac-

tures fractures are not filled with secondary minerals. Such fissures can serve as channels for the filtration of oil and gas fluids.

Sandstones are widespread in different parts of the Dongying Depression. Based on the grain size composition, one can distinguish gravelly, granular (coarse-, medium-, fine-grained varieties), and inequigranular sandstones, as well as silty and clayey–silty varieties. The grain size varies from 0.12 to 1.2 mm. The color varies from grayish white to brown. The rocks are mainly composed of semirounded and angular, poorly or weakly sorted grains and clasts. In terms of composition, the sandstones mainly belong to graywackes (Fig. 4) and arkoses (Fig. 5). The graywackes are represented by both quartz–feldspar and feldspar–quartz varieties.

The content of quartz in the sandstones is commonly less than 50%, whereas feldspars are up to 14–50% (average 25.7%). Grains of potassic feldspars and plagioclases are present in almost equal proportions. The content of rock fragments varies from 10 to 55% (39.3%, on the average). They are represented by various proportions of clasts of metamorphic, magmatic, carbonate, and other rocks. For instance, the average content of metamorphic rock fragments is 17.2% (maximum 46%).

Different types of cement are found in the sandstones. However, one can usually observe basal, contact-porous, or porous cement with pointed or pointed-linear contacts between grains. Sometimes, concave-convex contacts are observed. The cement has the clayey or carbonate composition. The clayey cement

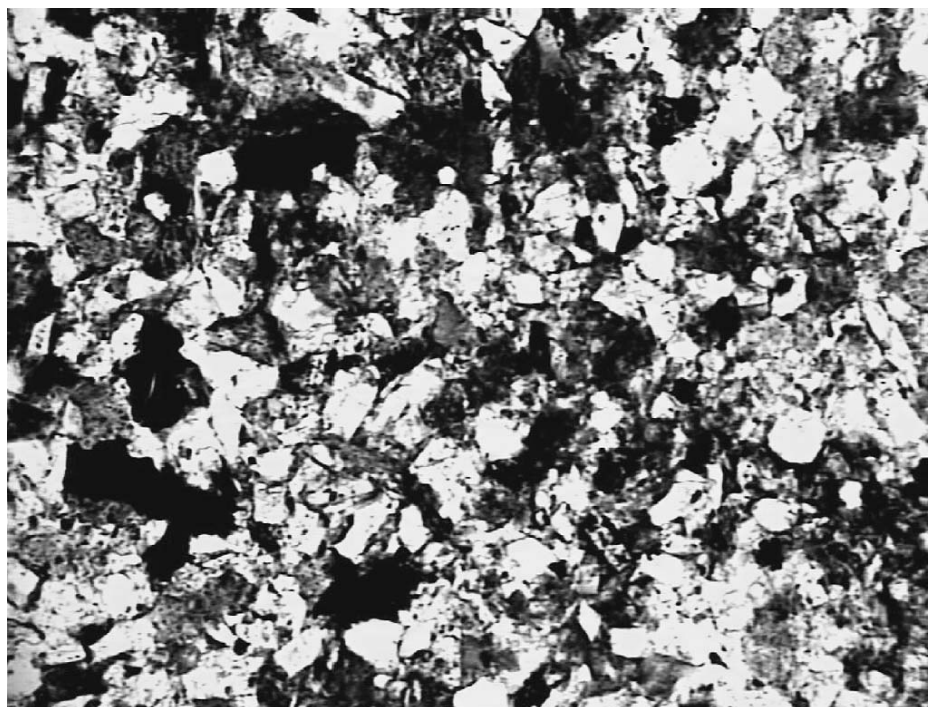


Fig. 5. Arkosic sandstone (Es₃), Well To 35-11, depth 2010 m, the northern slope of the Dongying Depression. Magnification 100.

mainly includes hydromicas. Their concentration varies from 5 to 16 vol %. The carbonate cement can contain calcite, dolomite, ferruginous calcite, and ferruginous dolomite (6–10%, up to 20% in some places).

Irregular forms are characteristic of detrital grains. Many grains show traces of secondary alternations (corrosion, dissolution, injection or mutual penetration). They are particularly typical of deposits of the Shasy and Shasan epochs. Corrosion and dissolution affected both the rock-forming matrix (quartz, feldspars, and rock fragments) and calcite in the cement. At the first stage, the dissolution took place at contacts between grains, resulting in the origination of convex-concave contacts and irregular grains. Regenerative fringes (3–5 vol %) are frequently produced around quartz grains.

Additionally, metasomatic alterations (for example, the replacement of quartz by calcite) are also noted in the sandstones. One can frequently observe the dolomitization of calcite, feldspars, and rock fragments, as well as the development of kaolinite flakes on surfaces of feldspar grains.

The filtration-capacity of the sandstones is mainly governed by pores (more rarely, by fractures). From the genetic point of view, primary and epigenetic pores can be distinguished. The first variety is mainly represented by the intergranular pore. The secondary pores are related to the leaching, metasomatism, and recrystallization.

In general, the grain size composition of sandstones predetermined the peculiarities of development of

diagenetic and catagenetic processes. For example, feldspar dissolution pores prevail and intergranular dissolution are subordinate in the coarse-grained sandstones. Fractures along contours of clastic grains and diagenetic reticulate fractures are recorded. In the medium- and fine-grained sandstones, intergranular and dissolution pores predominate and microfractures are less developed. Clayey sandstones are characterized by dissolution pores in the cement. Branched diagenetic fractures are also observed.

Analysis of the ternary diagram (Fig. 6) shows an appreciable variation of the sandstone composition when passing from one sector of the Dongying Depression to another sector. The least “mature” varieties (quartz–feldspar graywackes) are concentrated in the northern near-slope part of the depression, whereas the sandstones (mainly feldspar–quartz graywackes and graywacke arkoses) are accumulated on the gentle southern slope. The most “mature” composition is typical of sandy rocks deposited by gravity flows in the central depression at the extension of ancient river deltas. They are mostly represented by graywacke arkoses, but some varieties can be attributed to arkoses.

Gradual destruction of low stable components during the transportation of clastic sandy material from the lacustrine shoals to deep-water areas is indicated by the composition of sandstones, which were accumulated at the base of steep and gentle paleoslopes, as well as in the central depression. For example, sandstones recovered by drilling at the base of the northern steep paleoslope contain rock fragments, quartz and feldspar grains

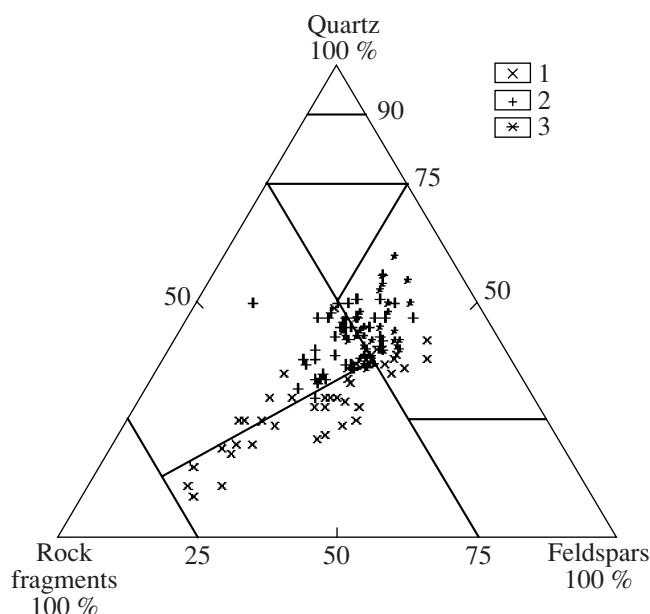


Fig. 6. Mineral composition of Paleogene sandstones in different sectors of the Dongying Depression. (1) Northern steep slope; (2) southern gentle slope; (3) central depression.

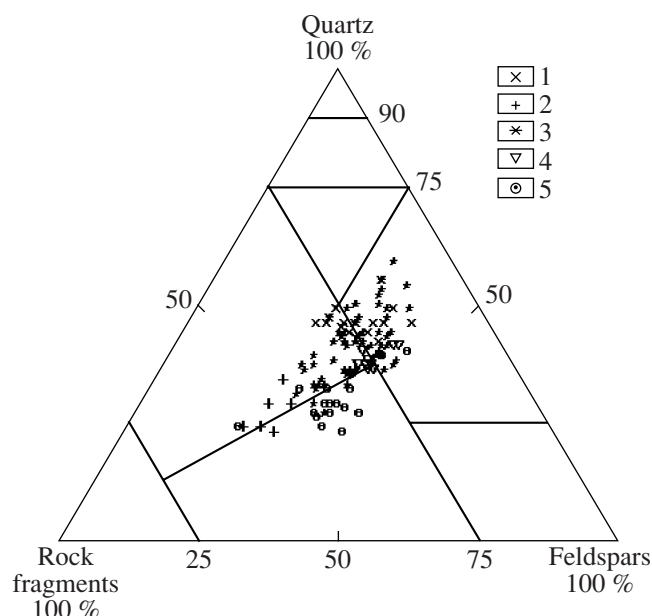


Fig. 7. Mineral composition of sandstones in different lithofacies complexes of Paleogene deposits in the Dongying Depression. (1) Sand bars on shoals; (2) proluvial fans; (3) deep-water fans; (4) river deltas; (5) fan deltas.

in approximately equal proportions. Their data points are confined to the center of the ternary diagram (Fig. 6). At the same time, the sandstones accumulated on the opposite gentle slope are depleted in feldspars. This can be related to compositional differences of rocks washed out at the tops of uplifts extending in the Paleogene along the northern and southern peripheries of the Dongying Depression. The most mature composition is typical of sandstones produced by turbidity currents in the central depression (Fig. 7), where sand bodies are hosted in clayey sediments and oil shales. Therefore, fluids derived from such rocks could promote the dissolution of low stable components.

Siltstones are most developed in distal areas. The color of these rocks varies from gray, grayish green to brown. The siltstones are characterized by a satisfactory rate of material sorting. Normally, they contain a significant admixture of sand- and pelite-sized particles (Fig. 8). Angular and subrounded grains and fragments predominate in the silt fraction (0.01–0.1 mm). Their size varies from 0.02 to 0.07 mm. The basal and basal-porous cement is characterized by pointed or pointed-linear contacts between grains. The cement is composed of irregularly distributed flakes of clay minerals (4–10%, average 7%). The carbonate cement is mainly represented by dolomite with pyrite inclusions. The dolomite content is highly variable (maximum 32%).

The siltstones are close to sandstones in terms of composition and structure. They are divided into sandy, clayey, and dolomitic varieties. Clayey varieties are observed most frequently. The siltstones include the following components: quartz 35–60%; potassic feld-

spars 12–30% (average 18.2%); and plagioclases 10–25% (average 17.1%). Magmatic and metamorphic rocks predominate among fragments. Mica flakes and pyrite and siderite grains are also encountered. Regeneration rims are frequently developed around quartz grains. Traces of metasomatic replacement of quartz by calcite are observed.

The siltstones contain box-, bay-, and slit-shaped cavities. However, fine (0.02–0.05 mm) and small (0.05–0.1 mm) pores are most common. The pores are connected via intergranular channels developed at boundaries between detrital grains and cement or at contacts between detrital grains. In some cases, they are connected via chaotically distributed sinuous open microfractures with offshoots. The distribution of pores in the rocks is irregular and they are absent at all in some places.

The share of *clayey rocks* in the Paleogene sections depends on the position of the area (relative to the sources of clastic material), the content of fine terrigenous admixture, the activity of tectonic movements, and the level of lake waters during different stages of the basin evolution. The clayey rocks are most widespread in Eocene rocks (predominantly in the Shasyshang, Shasanxia, and Shasanjung sequences), where they are represented by gray, dark gray, and less common grayish green clays and mudstones. Generally, they contain a significant quantity of dispersed organic matter and alternate with oil shales (Fig. 9). Therefore, they are considered as source rocks for liquid and gaseous hydrocarbons. In depressions of the central part of the basin, they form massive beds and thick packages.

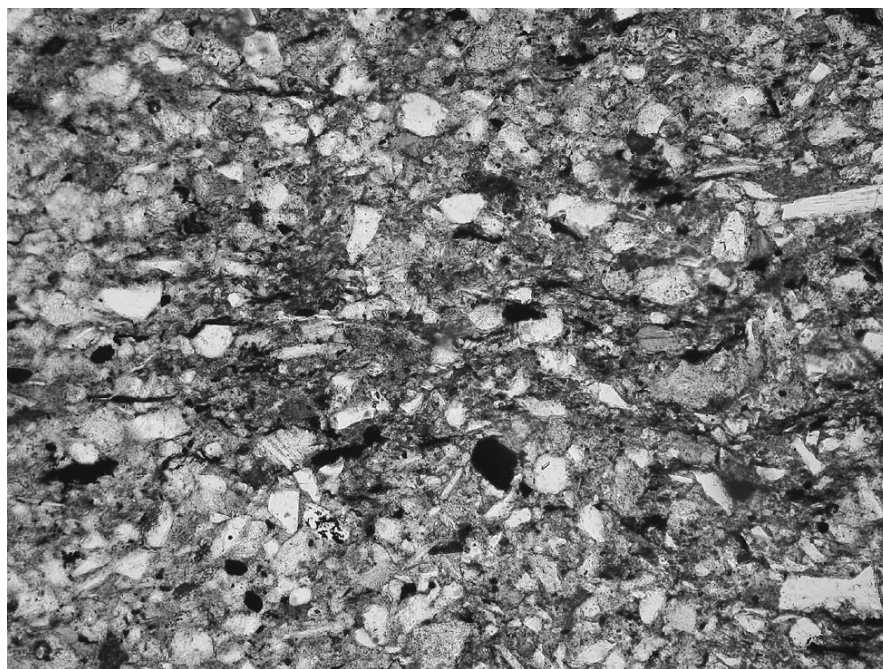


Fig. 8. Sandy petroclastic quartz siltstone (Es_3), Well Nyu 38, depth 2848 m, central depression. Magn. 100.

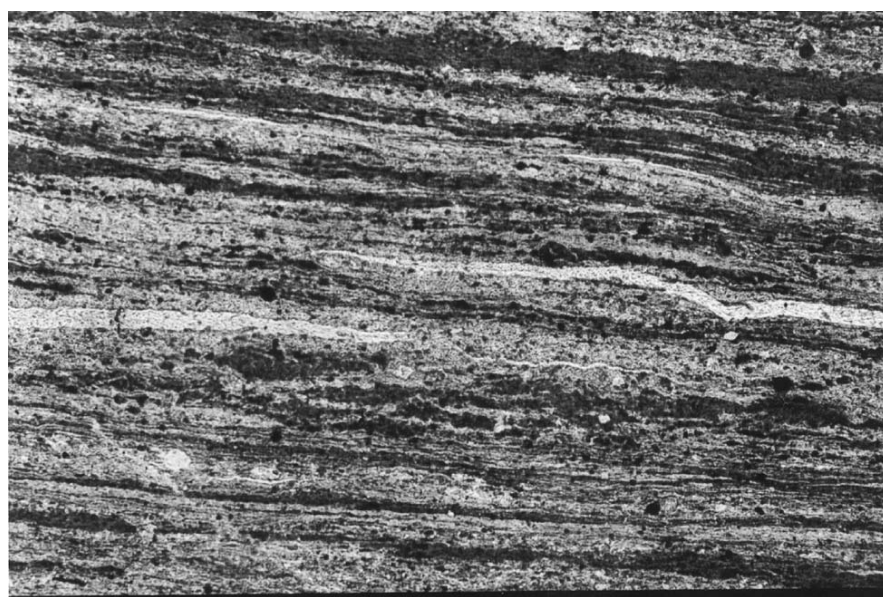


Fig. 9. Alternation of clays and silty clays with oil shales (Es_3), Well Nyu 38, depth 3365.5 m, central depression. Magn. 25.

In the peripheral parts, they are mainly distributed as thin interlayers in sandstones and siltstones. In different sectors of the Dongying Depression, clays serve as caprocks for oil and gas pools.

In clayey rocks, clay minerals are supplemented with the sand- and silt-sized material and carbonates. They also contain coal fragments, coalified plant detritus, faunal remnants (ostracod shells), and grains of phosphates, pyrite, and other ferruginous minerals.

According to the diffractometric and SEM investigation data, smectites and mixed-layered minerals of the hydromica–smectite series predominate in clays of Late Eocene and Early Oligocene (Shayi and Shaer stages) rocks. Hydromicas, kaolinite, and chlorite are subordinate. In Lower and Middle Eocene (Shasy and Shasan stages) rocks, mixed-layered smectite–illite prevail, whereas smectite, hydromicas, chlorite, and kaolinite are subordinate. The clays with mixed-layered

minerals, smectite, and hydromica are usually characterized by chaotically distributed leaflike and platy particles. Thin horizontal foliation is frequently observed in the smectite clays. They are composed of small flake-like and layered aggregates. Kaolinite occurs as leaf- and worm-shaped aggregates. Chlorite is rarely encountered as filler in small cavities in the cement of sandstones and siltstones. Aggregates of lens- and leaf-shaped forms are typical of this mineral.

Iron minerals (pyrite, siderite, ferruginous dolomite, and calcite) are widespread. Pyrite is most frequently encountered. It is present as lenslike inclusions, small aggregates, and grains. Its content is especially high in the oil shales and dark gray mudstones. Siderite forms massive aggregates oriented along layering in the clays. Ferruginous dolomite and calcite occur in carbonate clays and oil shales, respectively.

The clayey rocks have massive or layered structure. The layered structure is related to the layer-by-layer concentration of silt, fine sand, carbonates, or carbonaceous plant detritus in the clays.

Massive silty mudstones are widespread in rocks of the Shasan Epoch. Their color changes from gray and greenish gray to dark gray. In general, the layering is not expressed. The content of silt material is 16–26%. They also contain a small admixture of fine sand, coal particles, as well as grains and crystals of calcite, dolomite, and gypsum. Siderite and microfaunal remnants are less common. Terrigenous admixture and other minerals are usually oriented along the layering.

The layered silty mudstones are characteristic of the Shasi, Shasan, and Shayi epochs. Their color is gray, grayish green, brownish gray, dark gray, and brown. The clastic part is mainly represented by quartz and plagioclase grains. The content of silt material varies from 12 to 25%. Phosphatized ostracod remains are also present. The rocks show parallel, wavy, and lenslike bedding.

Oil shales are brown to dark gray and largely developed in rocks of the Shasyshang and Shasangxia epochs (Lower and Middle Eocene). Dustlike pyrite aggregates, pyritized fragments of carbonate organisms, and plant detritus are dispersed in the rocks. Parallel bedding of these rocks is emphasized by the alternation of two types of laminae: laminae of the first type consist of clay material, while laminae of the second type contain fine grains of calcite and shell fragments. The laminae are 0.01–0.5 mm thick. Interlayers of coarse-grained clastic rocks are sporadic in oil shales.

Calcareous clays and mudstones were observed in Shasangxia deposits (Middle Eocene) as gray irregularly bedded and schistosed rocks. They include fine laminae (0.5–5 mm) and lenses of micro- and fine-grained calcite. Some laminae contain pyrite dissemination, phosphatized remnants, plant detritus, and ostracod shell fragments. Clastic admixture is commonly absent in these rocks.

Carbonate rocks are rather widespread in the Bohai Bay Basin. They occur in the Lower Paleozoic, Kungdyian (Paleocene), Shasy (Lower Eocene), and Shayi (Lower Oligocene) sequences. Their formation under different (frequently changing) conditions led to diversity of their types. As compared with terrigenous rocks, carbonate rocks are characterized by more intense diagenetic and catagenetic alterations, variability of reservoir properties and composition in both lateral and vertical directions.

Early Paleozoic carbonate rocks are exposed on the southern wall of the Dongying Depression (near the Binxian basement uplift). They are represented by slightly altered limestones, sedimentary dolomites, secondary metasomatic dolomites, and strongly altered limestones. The weakly altered Middle and Upper Cambrian limestones are composed of a thick thallus of algae with a large amount of ooids, gravel-sized carbonate detritus, and well-rounded and sorted trilobite fragments. The irregular development of carbonate matrix promoted the leaching and formation of epigenetic pores. Cambrian limestones have good reservoir properties. Therefore, they can enclose hydrocarbon pools.

Middle Ordovician limestones belong to detrital and biomorphic-detrital varieties. They include sand-sized fragments of trilobites, brachiopods, and echinoderms. Carbonate detritus is characterized by poor roundness and sorting, because it was probably accumulated under stagnant conditions and only periodically subjected to the influence of waves and currents. Caverns and fractures are common in the rocks.

The sedimentary dolomites include dolomite microcrystals, gypsum pseudocrystals, and granular algal structures. They were accumulated in the littoral and sublittoral zones of lagoon. The secondary dolomites are related to the metasomatic replacement of sedimentary limestones and dolomites with the participation of Mg-rich mud waters. Relicts of the primary detrital texture are preserved in the dolomites.

Paleogene carbonate rocks described in the Paleocene, Lower Eocene, and Upper Oligocene sections are lacustrine formations. The Lower Eocene deposits (Shasyshang sequence) are dominated by biohermal limestones, but the Upper Oligocene section (Shayi sequence) mainly comprises the oolitic, pelletal, algal, and biomorphic-detrital varieties. As is evident from Fig. 10, the oolitic limestones are largely composed of ooids (up to 95%). The concentric ooid shells are composed of ferruginous dolomite. Their matrix consists of micrite, which is also represented by ferruginous dolomite. Pores are represented by intergranular-corrosion and oolitic-corrosion types. In some places, they are filled with fibrous and microcrystalline dolomite or calcite. Pelletal and algal limestones are often observed together with the oolitic limestones.

Biomorphic and biomorphic-detrital limestones (Fig. 11) include elements of carbonate organisms and

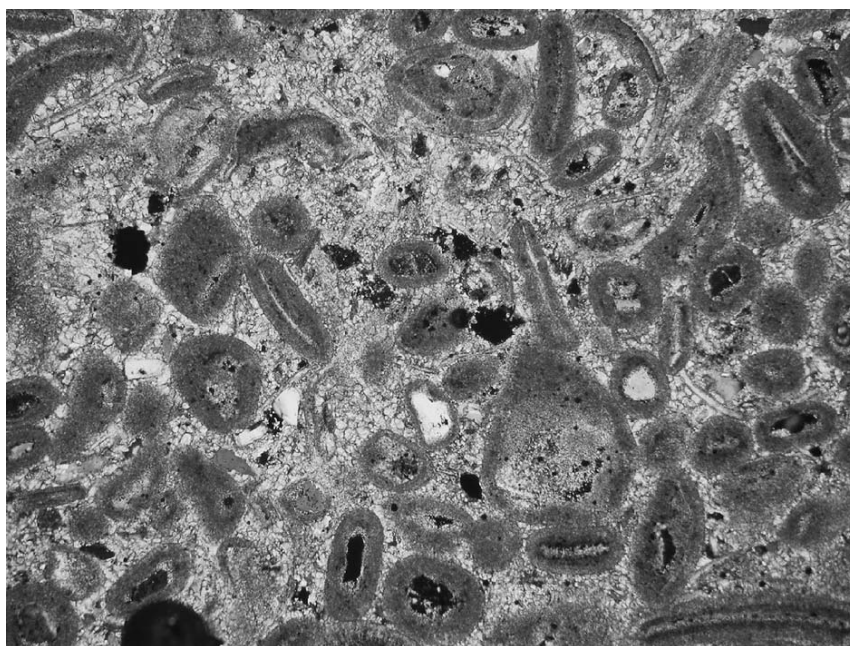


Fig. 10. Oolitic limestone (Es_1), Well Guang 18, depth 1765 m, northern slope of the Dongying Depression. Magn. 100.

their detritus (maximum content 95%). They are composed of shells and fragments of snails and ostracods. Walls and cores of the shells are composed of microcrystalline calcite, dolomite, or ferruginous dolomite. Fragments of phosphate material are rarely encountered.

Massive sandy marls are developed in Eocene deposits. They are characterized by a large content of carbonate detritus and micrite, which is irregularly dispersed in the clayey and sandy clastic material. Fine carbonaceous detritus oriented along the bedding is frequently observed in thin sections.

Evaporites (gypsum, anhydrite, and rock salt) are mainly developed as interlayers and packages in mudstones and sandstones of the Lower Eocene (Shasyshang sequence) deposits. They are most abundant in the central part of the basin. The thickness of rocks, which include gypsum and rock salt layers, reaches 600 m. The thickness of individual layers exceeds 10 m. Pebbles and clay interlayers are often present in these rocks. It should be noted that evaporites make up extended beds and serve as screens for fluids in the upper part of the Shasyshang sequence. In (Yuan Jing and Qin Ke, 2001), some varieties of evaporites are considered as possible sources for oil.

Gypsum and anhydrite have white, grayish, and grayish black colors. In well sections, they occur as banded, granular, and fine-crystalline rocks. In addition to anhydrite (often >90%), dolomite, clastic particles of sand and gravel sizes, and pyrite inclusions are found. The majority of anhydrites are products of metasomatic replacement. The rocks include intercrystalline pores that are communicated with each other.

Rock salt usually occurs together with gypsum and anhydrite. The rocks contain an insignificant admixture of clayey material, pyrite inclusions, and lazurite. Their color can vary from gray to brown. Lenses of dolomite and clays are often found in beds of rock salt.

LITHOFACIES COMPLEXES OF PALEOGENE ROCKS

Analysis of seismic and well log data, as well as results of the study of cores and petrographic-geochemical features of Paleogene and Neogene rocks in different sectors of the Dongying Depression allowed us to distinguish five principal lithofacies complexes and related sedimentation settings: proluvial fans, fan deltas (fanlike deltas), river deltas, foreshore sand bars and storm bars, and, finally, deep-water fans consisting of turbidites and other sediments of gravitational genesis.

Proluvial fans were formed near the exit of mountainous rivers to the plain, where the velocity of river streams sharply decreased, resulting in the deposition of the major and coarsest part of clastic material. Proluvial sediments were accumulated at the margin of sedimentation basins at the boundary with mountain ranges. In Paleogene sections of the Bohai Bay Basin, they were first described in the Liaohe Depression by Yan Huo (1990). Their area and thickness were determined on the basis of movements along large boundary faults. Proluvial fans were developed mostly during regression stages of the lake evolution.

Proluvial fan deposits occur as a huge lens expanding upward. However, they frequently form bodies of

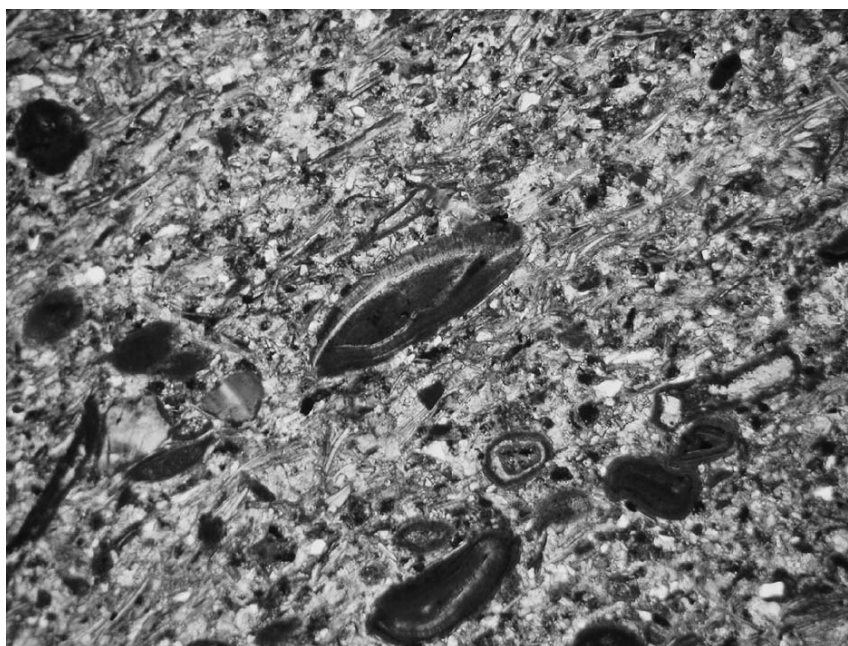


Fig. 11. Biomorphic-detrital limestone (Es_1), Well Ning 9, depth 1678 m, northern slope of the Dongying Depression. Magn. 50.

the sheet type with a thickness of more than 300 m. The distal part of such proluvial fan penetrates deep into the offshore plain. The section of these rocks can be divided into cyclites. In the piedmont (proximal) part of the fan, one can observe a gradual decrease in the grain size of material from the bottom to top of the cyclites. This pattern is characteristic of branched streams. The section is dominated by coarse-grained (poorly sorted and weakly rounded) rocks with interlayers of red or patchy silty clays. The sandstones are composed of rock fragments (28–45%), feldspars (25–26%), and quartz (25–32%).

In contrast, the grain size of the material increases upward the section in each cyclite in the distal part of the fan (Yan Huo, 1990). In silty clays, gravel and sand are accompanied by carbonatized plant remnants, pellets, and carbonate concretions. The red-colored clays are devoid of any fossils, whereas the gray clays sometimes contain shells of ostracods and gastropods. Massive structure is characteristic of debris flows with oblique and parallel bedding. Ripple marks are rare, whereas cut-and-fill structures are widespread.

In the Dongying Depression, sediments of proluvial fans occur in the Shaer (Late Eocene) deposits in the northeastern (Zhenzyia-Vanchuan) and southern sectors. They are represented by gray or variegated conglomerates, gritstones, and coarse-grained sandstones with interlayers of variegated clayey rocks. The conglomerates have a complex composition, and the maximum diameter of clasts can reach several tens of centimeters. The gravel- and sand-sized grains are poorly rounded and sorted. Bedding is obscure. Cut-and-fill structures are evident in some places. When moving

away from the mountain area, grains and fragments in the sediments get smaller, and clays play a more significant role.

Figure 12a shows the grain size distribution in sandstones from proluvial fans. It is clearly seen that the content of particles gradually increases from fraction 1.5 mm to fraction 0.5 mm and decreases in fine-grained fractions. The silt fractions show a uniform distribution of particles.

Fan deltas are formed when a part of the proluvial fan subsides to the lake filled with terrigenous material transported by debris, mud, and branched water flows. They are usually formed during the tectonic activation in provenances. The principal characteristics of sediments accumulated in fan deltas are very close to those of proluvial fans. In both cases, deposits of branched channels alternating with the load of debris flows are present in the section. The material in sandy conglomerates is poorly sorted. It contains a large amount of weakly rounded angular rock fragments.

Rocks of debris flows, which supplied material at the late stage of the fan delta evolution, are characterized by massive structure. Accumulation of large rock fragments and U-shaped layering are common at the bottom of beds. Ripple marks are present in deposits of the frontal part of fan delta. Water flows from mountainous valleys were loaded with clastic material. They ran into lake waters and preserved some resource of energy. Therefore, distributary channel systems were also developed in the frontal zone.

Unlike the river deltas, fan deltas do not form a wide deltaic plain. In the Liaohe Sag, the lacustrine fan deltas are usually represented by a narrow belt of gravelly sed-

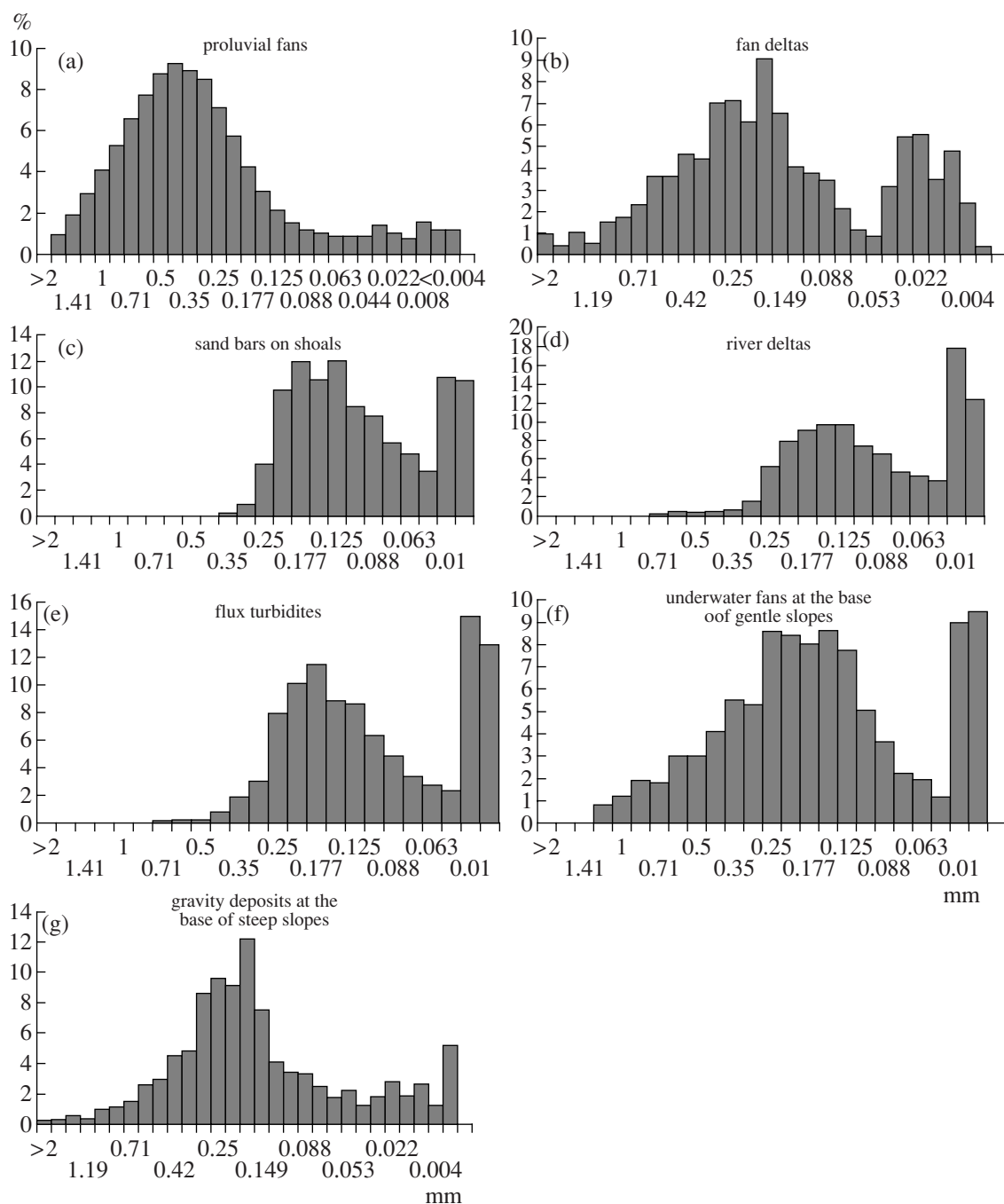


Fig. 12. Bar charts of grain size composition of sandstones in lithofacies complexes of different types.

iments that alternate with red clays and siltstones containing coalified plant remnants. The prodelta and frontal parts of the delta always contain ostracod and gastropod shells and fish fragments. Thinning of material from bottom to top is observed in individual beds of sandstones (Yan Huo, 1990).

In the Paleogene, fan deltas were developed both within the northern and southern slopes of the Dongying Depression. Deposits of this type were described in

sections of wells Tung 40, Cao 32, and Shan 25. Deposits of fan deltas are characterized by significant thickness and great extent in the longitudinal direction. In the cross sections, they pinchout over a short distance and show sharp facies changes. Terrigenous material in fan delta deposits within the steep wall of the basin is poorly sorted and slightly rounded. Sediments of debris flows play here a great role. Massive and U-shaped oblique bedding structures prevail. Ripple marks and cross-bedding are absent. At the same time, sediments

accumulated on the gentle slope of the basin are characterized by a finer composition and relatively high degree of maturity. The load of debris flows is negligible or absent at all. The delta plain area is significantly wider than that of fan deltas near the steep wall. Underwater channels bounded by levees are developed in their frontal part.

As mentioned above, the fan delta can be divided into the above-water zone located above the coastal plain, its underwater component, and delta front. The first zone is similar to the proximal part of proluvial fans. This area is dominated by variegated sandy conglomerates, gritstones, and sandstones with interlayers of grayish and brownish red clayey rocks, coaly shales, and coals. The underwater zone is composed of deposits of numerous short channels separated by bands of interchannel sediments and mouth bars (gray and grayish green gravelly sandstones, sandstones, siltstones, and clayey rocks). Figure 12b shows the bar chart of grain size composition of sandstones, which are typical of this part of the ancient fan delta. One can clearly see two maxima of particle concentrations. The first peak includes mainly fine sand fractions (0.3–0.15 mm) and shows the highest content of particles with a size of 0.175–0.15 mm. The second peak includes fine silt fractions (0.05–0.01 mm). Particles with a size of 0.05–0.07 mm are rare. The fine silt material obviously plays the role of cement.

The frontal part of the fan delta is dominated by gray siltstones along with clayey and silty-clayey rocks.

Sand bars in shoals make different sand complexes in the coastal zone and on the lake shoal: spits, along-shore bars, and storm bars. Deposits of this type are widespread on the southern, gentle flank of the Dongying Depression. They are particularly common in Middle and Upper Eocene (Shasyshang and Shasan epochs and Shaer epoch in some places) sequences. These sedimentary deposits include siltstones and fine-grained sandstones with interlayers of gritstones and gravelly (poorly sorted) sandstones. The base of many bars contains fine-grained rocks, which are replaced upsection by coarser varieties. Relatively fine-grained varieties appear again at the top.

Sandstones in these bars are mainly composed of materials of the fine sand (0.1–0.25 mm) and fine silt (0.04–0.01 mm) sizes. The content of particles of other fractions is very low. It is evident that the clastic material underwent multiple reworking by waves and is distinguished by rather high sorting. Particles of the fine silt and pelite sizes serve as the cement.

River deltas are not universally developed in the Dongying Depression. In general, they were formed at its eastern periphery, where the shoreline gradually prograded toward the lake center during certain stages of the geological evolution. Deltaic sandy bodies were found at different levels of the Paleogene section. The most typical bodies were formed in Late Eocene (Shasanshang–Shaerxia sequences), when the deltas

were formed not only in the eastern sector, but also in the western and southern sectors of the basin.

The deltaic deposits contain sediments of the coastal delta plain, frontal delta, and prodelta facies. Deltaic sediments in the Dongying Depression are represented by medium- to fine-grained sandstones, gray and light gray siltstones, grayish green to violet-red clayey rocks, and coaly shales and coals. The coastal delta plain also contains gravelly sands. The fine-grained rocks often grade upsection into the coarser varieties. The color variation of the clayey rocks reflects the change of geochemical conditions from the oxidizing environment in the coastal plain to the reducing (anaerobic) one in the frontal part of the delta and prodelta, which prograded toward the center of lacustrine basin. Sandstones accumulated in the frontal part of river deltas are distinguished by well sorting. The sand-sized particles are mainly confined to interval 0.25–0.1 mm, and their content diminishes in coarse silt fractions. The second peak is related to fine silt and coarse pelite fractions (Fig. 12d). In general, the distribution of particles is very similar with that in sediments of accumulative bars at the lacustrine shoal. However, this facies is characterized by a lower size of particles playing the role of cement in the sandstones.

Deltas in the Dongying Depression were commonly formed by loads of small rivers, which transported clastic material from different provenances. After the advance of deltas to the edge of the lake shoal, the gentle slope of the lacustrine basin became the principal zone of sedimentation. Here, underwater canyons originated and high sedimentation rates predominated. The weak compaction of sediments favored the development of slumps and the origination of turbidity and other gravity flows. These processes fostered the formation of fans in the deepest part of the lacustrine basin and the gradual origination of turbidite and flux turbidite systems that were genetically related to the deltas and their sediments.

Underwater canyons are widespread within the gentle wall of riftogenic depressions. They are commonly oriented perpendicular to the strike of boundary faults that were active during fast riftogenic subsidence of the earth crust. Sandy deposits in the underwater canyons have an elongated shape. Their thickness gradually increases from the head of the canyon to its mouth. In the canyon cross sections, they are replaced by gray and brown clayey siltstones. In the sections, clayey siltstones intercalate with sandstones and conglomerates. Pebbles in their matrix are supplemented with materials of the pelite, silt, sand, and gravel sizes. These sediments contain abundant lacustrine ostracod shells and pyrite. Boundaries between the sandstones and clayey siltstones are always sharp. In some sections, sandstones alternate with conglomerates, gritstones, siltstones, clays, oil shales, and dolomitic marls. Moreover, traces of slumping are clearly visible (Yan Xuo, 1990).

Deep-water fans were formed near the mouth of underwater canyons in the central depression. They include gritstones and sandstones with fine-grained cement. Fragments and grains are poorly rounded and sorted. Rock fragments are mainly represented by granites, quartzites, basalts, siltstones, dolomitic marls, and coalified plant detritus (30–50 vol %). Feldspars account for 20–30 vol % (Fig. 2e). The contact between gritstone and sandstone beds, on the one hand, and silty clay beds, on the other hand, is sharp. The rocks are usually characterized by massive structures with graded bedding. Oblique bedding is subordinate. The dark gray mudstones and siltstones contain remnants of deep-water ostracods. Many beds of silty clays and siltstones lack faunal remains, because anoxic conditions predominated near the bottom and the water was saturated with hydrogen sulfide. The pyrite content in the rocks is very high (as much as 70% in some places). Sediments are more fine-grained downward the strike of fans. The thickness of gritstone and sandstone interlayers decreases, while the thickness of clays increases. Graded bedding is well manifested in the sediments.

The deep-water fans at the foot of gentle and steep slopes show significant differences in the composition and structure of sediments. In the clastic rocks in the fan of steep wall, massive structures prevail, graded bedding is rare, and prominent U-shaped oblique bedding is observed. Water flows along the steep slopes quickly delivered sediments to the burial site. Therefore, they are not sorted. In marginal parts of the fan, the coarse-grained sediments are abruptly replaced by deep-water silty clays. Gravitational sediments deposited on the gentle slope are sorted much better. Massive structures are atypical for them. Instead, graded bedding and ripple marks are widespread. The maturity degree of material is higher as compared with analogical deposits in the steep slope area, and its grain size changes from gravel to fine sand. The content of clay and silt particles does not exceed 20%. The underwater channels are universally bounded by levees. Migration and downcutting of these channels is expressed in the presence in the sequence of normal and reverse graded bedding in the sections.

In the fans in the lower part of the steep slope of the Dongying Depression, sediments were accumulated by grain flows rather than turbidity flows. Periods of high activity of floods and frequent earthquakes were marked by the displacement of sandy loads as slumps and underwater avalanches toward the depression center, resulting in the formation of small but thick deep-water fans at the base of slopes. They are widespread in Eocene deposits (Shasyshang, Shasanxia, and Shasanzhung sequences).

In sequences accumulated at the steep foothills, one can distinguish facies of the upper, middle, and lower parts of the deep-water fans. The upper (proximal) sector is composed of poorly sorted gritstones and sandy-gravelly rocks that are developed over a small area. The

middle (largest) sector is dominated by gravelly-sandy rocks and sandstone members with thin interlayers of clayey rocks. The grain size distribution of particles in the sandstones is shown in Fig. 12f. One can see the presence of gravel-sized particles and gradual increase of the content of particles 1.0–0.25 mm in size. Their maximum concentrations are recorded in fractions 0.117 and 0.2 mm. The silty material is distributed rather uniformly. The content of coarse-pelitic fractions in sediments is high. In terms of the grain size composition, these sandstones are almost identical to the sandstones of fan deltas and near-shore underwater fans, suggesting an evident link between them.

Deposits of the lower fan are usually represented by dark-colored clayey rocks containing thin interlayers of siltstones and fine-grained sandstones, which are characterized by poor or medium degree of sorting. In the direction from the slope to its foot, the coarse-grained sediments give way to fine-grained varieties with thin lamination and the amount of clayey rock interlayers simultaneously increases. Sections of fan deposits usually include a large number of small cyclites, in which the coarse-grained varieties grade into the fine-grained varieties and clays at the top.

Underwater fans in the lower part of the gentle slope usually extend over a long distance into the central depression. Gravity flows transported large masses of sediments, which contained the sand-sized material along with gravel and even pebble. Underwater fans of this type are mainly developed in deposits of the Middle and Upper Eocene (Shasan and Shaerxia epochs). They can be divided into the upper proximal, the middle principal, and the lower distal zones. Sandstones in these fans are marked by high filtration capacity. Their grain size composition is very close to that of the sandstones accumulated at the base of the steep underwater slope (Fig. 12). However, the former sandstones are characterized by the higher content of particles of sand (0.5–0.25 mm) and pelite fractions (0.005–0.1 mm).

In the Shasanxia Epoch, the main sediment depocenter was located in the eastern part of the depression (Guangli Sag). In Shasanzhung Epoch, this depocenter shifted to the west (Nyuzhuang zone), where a large gravity sediment complex was formed. Terrigenous material was delivered along underwater canyons located within the eastern underwater slope. During the later on (Shasanshang) epoch, the Lizing Sag, situated even further to the west, became the principal zone of sedimentation. This time was marked by the replacement of humid climate by arid one and the formation of the large Liangjyalou underwater fan. This zone accumulated terrigenous material delivered from the Lusi Uplift located at the southern periphery of the Dongying Depression. This fan occupied an area of 180 sq. km, and the thickness of accumulated sediments exceeded 100 m (Jin Qiang et al., 2005).

Complexes of flux turbidite deposits. It is known that when the thickness of sand load accumulated in the

frontal part of the delta near the underwater slope reaches the critical value, the sediments become unstable because of the insufficient compaction and high content of pore fluids. Therefore, they are subjected to gravity sliding, which is initiated by many factors, such as movements along faults, earthquakes, and catastrophic floods. Huge masses of sediments in the form of slumps and grain flows start to move downward the slope. Turbidity currents, which are frequently provoked in this process, transport sedimentary material to the deep-water basin, resulting in the formation of sedimentary complexes, which can include deposits related to both slumping and turbidity. They can be located at the extension of not only river deltas, but also fan deltas or accumulative bars in the outer part of the lacustrine shoal.

In the Dongying Depression, such deposits are widespread. They are characterized by multistage structure and appreciable thickness. They occur frequently as lenses in thick hemipelagic clayey rocks. For example, large flux turbidite bodies were formed in the Nyjuang Depression in front of the ancient river delta in the Shasan Depression (Middle and Late Eocene). Alternation of siltstones and fine-grained sandstones is typical of sections in the proximal part of this fan. The central zone usually includes thick packages of fine-grained (more rarely, medium-grained) sandstones, while siltstones and silty clays predominate along the outer margin of the sandy bodies. The grain size distribution of particles in the flux turbidite sandstones is very similar to that in the sandstones of delta complexes and bars in the shoals (Fig. 12e). This fact indicates that the material of flux turbidites was delivered from the river delta and is not genetically related to the sandstones of fan deltas that delivered the material to deep-water fans at the foothills of both gentle and steep underwater slopes.

The lenslike sandy bodies of flux turbidites at the river delta front are one of the principal types of reservoirs that enclose oil and gas pools in the Dongying Depression.

PALEOGEOGRAPHY OF THE DONGYING DEPRESSION AT DIFFERENT STAGES OF ITS EVOLUTION IN THE PALEOGENE

Analysis of the distribution of genetically different sedimentary deposits over the area and in sections of the Dongying Depression shows that quite definite lithofacies types of deposits got priority during the origination and development of this lacustrine basin. At the first stage of rift evolution in the Paleocene, the depression represented a lake that began to deepen rapidly in early Eocene. The deep-water depression existed here for a long time. It was gradually filled with sediments and transformed into an alluvial delta plain in the Oligocene. Many Paleogene sections of the Dongying Depression are characterized by cyclic pattern. The largest cycles of sedimentation are clearly correlated

with the principal tectonic events in this region, variations in water level of the paleolake, and climatic fluctuations.

Discordances and hiatuses in sedimentation revealed in the Paleogene rocks can serve as indicators of active tectonic movements along faults. The main discordances are observed at the boundaries between the Kundian, Shasy, Shasan–Shaerxia, and Shaershang–Dongying sequences that reflect the largest stages of the Paleogene history of the Dongying Depression.

The **Kundian Epoch** (Paleocene–Early Eocene, Ek). In the Paleocene, active subsidence began in the study region and the Kundian Formation was formed. Its lower part is composed of variegated (mainly red-colored) graywackes, which are replaced upsection by clayey rocks and gypsum. Rocks of the Kundian Formation overlie Mesozoic deposits with a sharp angular discordance. In terms of genesis, they are represented by alluvial, proluvial fan, and lacustrine shoal sediments accumulated under conditions of arid climate. The maximum thickness of this complex (10.5–14.6 Ma) reaches 2000 m. The formation can be divided into two (Kunxia and Kungshang) sequences separated by a hiatus probably related to a fall of the lake water level. Both sequences are characterized by an asymmetric structure: they are significantly thicker within the western and northern flanks of the basin in comparison with the eastern and southern ones. Discordances are observed at margins of the base and top of the Kunxia and Kungshang sequences, but they are concordant in the central sector.

The **Shasy Epoch** (Early Eocene–beginning of the Middle Eocene, Es₄). Sediments of the Shasy Formation accumulated during the activation of rifting. They discordantly overlie both Mesozoic and Paleocene Kundian rocks. Active movements along faults promoted a large-scale renovation of the topography and wide distribution of fan deltas. Predominantly coarse-grained sediments were accumulated in many parts of the basin during ~8 Ma. In the eastern and southern parts of the basin mainly occupied by lagoons, sections of the Shasyxia sequence (first half of the Shasy Epoch) are composed of gray, dark gray, and brown limestones and dolomites or mudstones with interlayers of limestones, sandstones, and oil shales. The climate became more arid in the second half of the Early Eocene (Shasyshang Epoch). This was accompanied by the accumulation of evaporites, rock salt, and gypsum (Fig. 13). In the central part of the lacustrine basin marked by the greatest subsidence of the Earth's crust, the evaporites are up to 400 and even 600 m thick in some places.

The end of the **Shasyshang Epoch** (beginning of the Middle Eocene, Es₄²) was characterized by intensification of rifting, increase in volumes of water delivered to the lake, and appreciable expansion of the lake area. Relatively deep-water conditions were established in its central and northern sectors. The tectonic activa-

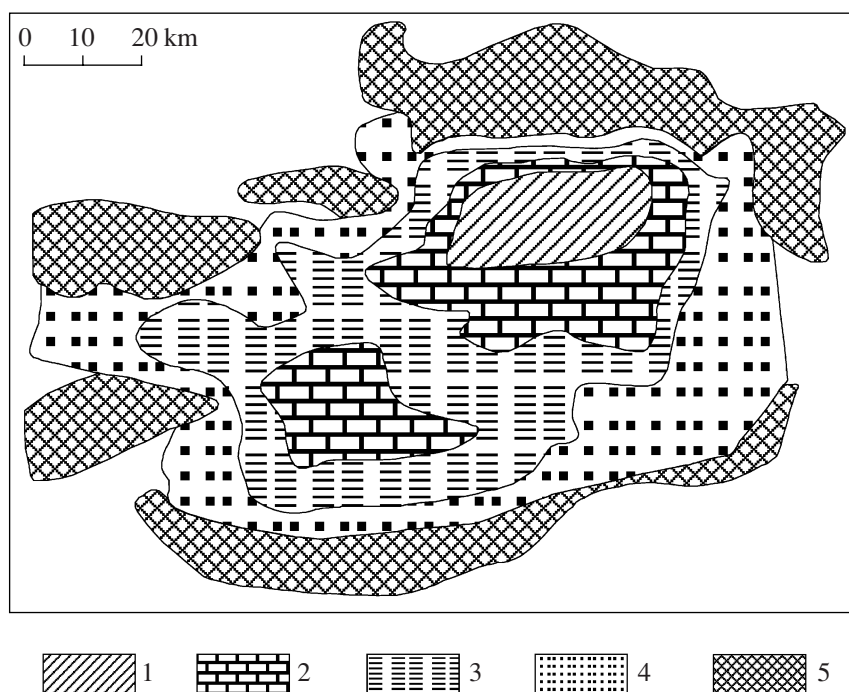


Fig. 13. Fields of different types of Lower Eocene (Shashang Epoch) deposits in the Dongying Depression (after Zhu Guangyou et al., 2004). (1) Evaporites; (2) carbonate rocks; (3) clayey rocks; (4) sandstones; (5) uplifts and rises of the basement.

tion fostered the replacement of carbonate rocks in the peripheral parts of the basin by sandstones and gritstones, which were universally gradually replaced by finer sediments (dark gray clays and oil shales) at the transition to the central areas. The presence of a large amount of pyrite dissemination in beds of these rocks, which are considered as oil source rocks, indicates that water circulation in the basin was rather restricted and reducing conditions dominated at the lake bottom. Judging from the composition of faunal remnants, the sediments were deposited in arid climate (Yuan Jing and Qin Ke, 2001).

Sediments of proluvial fans were accumulated at the northern margin of the lake, whereas fan deltas were formed in the remaining shoal area and near provenances of the clastic material. They incorporate small sandy bodies that are particularly numerous on the gentle slope of the basin. Sediments of river deltas accumulated mainly in the eastern (Guanli zone) and western (Gaocynge zone) areas of the basin. They did not advance far beyond the shore zone. Individual bioherms continued to grow in the shoal zone beyond the riverine and fan-shaped deltas. However, deep-water zones were characterized by the formation of underwater fans of different types, which included both turbidites and other gravity flow deposits.

Sandstones accumulated during the Shasy Epoch are predominantly represented by quartz-feldspar graywackes. The greywacke arkoses were concentrated in accumulative bodies, such as spits, bars, and offshore barriers within the underwater shore slope.

The Shasanxia–Shasanzhong Epoch (Middle and Late Eocene, E_{s3}). Large-scale subsidences of the Earth's crust, which continued in the first half of the Middle Eocene, were not compensated by sedimentation. This period was characterized by a wide range of sedimentation settings. Rock sections of this age include sediments of fan and river deltas, as well as different underwater fans.

The lowermost (Shasanxia) complex corresponds to the period of drastic subsidence of the Earth's crust and formation of the deep-water lacustrine basin. Rocks of this age formed under conditions of hot humid climate, overlie the Shasy rocks with a regional discordance. Silty and carbonate clays, mudstones, oil shales, and turbidite sandstones predominate in these sections. The content of B in the oil shales is $(75-104) \times 10^{-6}$, which corresponds to the salinity of 2.0–15.5%.

The location of fan deltas and shallow-water fans in the northern sector of the lake was governed by a system of deep faults, along which individual blocks of the Earth's crust subsided. Sediments of small river deltas and flux turbidite complexes located at the extension of the deltas were accumulated in the eastern part of the basin (Guanli zone). Sedimentation of clays and oil shales continued in the deep-water depression. They were intruded by lenses of turbidites and gravity deposits of other types from deep-water fans at the foot of underwater slopes (Fig. 14).

The overlying Shasanzhong (Late Eocene) rocks overlie the Shasanxia rocks concordantly or discordantly in different areas. This epoch was marked by the

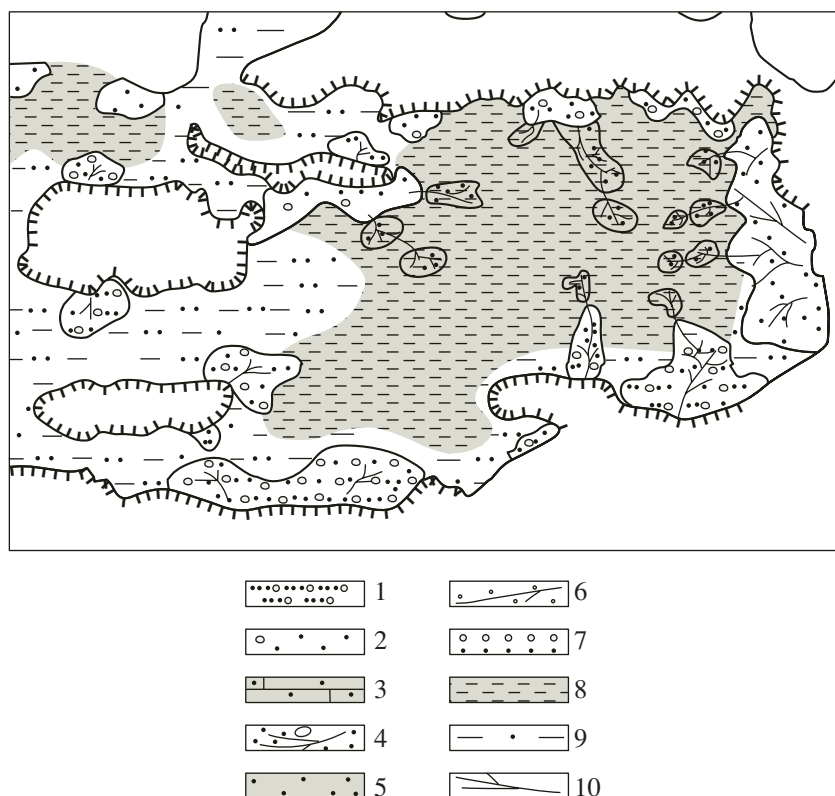


Fig. 14. Lithofacies types of deposits in the Dongying Depression for the Shasangxia Epoch (the first half of the Middle Eocene). Modified after (Li Pilong, 2004). (1–7) Deposits: (1) proluvial fans, (2) coastal underwater fans, (3) sand bars on shoals, (4) fan deltas, (5) complexes of gravity deposits (deep-water fans: debris flows, turbidites, and flux turbidites); (6) river deltas, (7) hemipelagic genesis; (8–10) geomorphology of the lake: (8) deep-water depression, (9) lacustrine shoals, (10) underwater canyons.

maximal depth of the lake and maximal distribution of fine-grained sediments (Fig. 15). They alternate with varved and lenslike interlayers of sandstones and siltstones. The rocks show different deformations (sand dikes, slump bodies, and structures typical of turbidites). All these features testify to high sedimentation rate under deep-water conditions (Zhy Guangyou et al., 2004).

Although sedimentation environments at that time were inherited from the preceding epoch, the domains of individual sedimentary complexes appreciably changed. The area of the lake increased, and the coastal shoal became much wider. In the northern sector, where the distribution of different lithofacies complexes were governed by faults of the Chengnan system, sediments of small proluvial and deep-water fans were accumulated. The deep-water fans were frequently situated at the extension of proluvial fans. Fan deltas were spread mainly on shoals near the southern gentle slope of the basin.

River deltas continued to develop simultaneously in the east (Guangli zone). Slumps and turbidites complexes were formed at their extension in the central depression. The thickness of deltaic deposits increased as compared with the previous epoch. A large deep-water fan (175 sq. km in area) appeared in the Lindzia-

lou zone (southeastern sector of the Dongying Depression). The sedimentary section in this fan is one of the major oil-containing complexes in the Dongying Depression (Qian, 1994). According to (Jin Qiang et al., 2005), the fan includes underwater channels of different orders: large underwater valleys, their distributaries, distal channels, and sandy bodies of the lobe type at the estuaries of creeks.

The underwater Liandzialou fan is mainly composed of gray gravelly sandstones, coarse- and fine-grained sandstones, and siltstones, including lenses and beds of dark gray and black clays. The thickness of fan deposits varies from 40 to 110 m. The median grain size diminishes from the south to north, i.e., from the proximal to distal parts of the fan. Large channels are usually filled with gravelly sandstones with good reservoir properties (porosity up to 20%, permeability >1 D).

The sandy bodies (thickness 26.5 m) are composed of graded sandstone laminas (thickness 15–30 cm), which are characteristic of A and B intervals of the turbidite cyclite. Sandstones in the middle part of the fan are more massive and oblique-bedded, whereas sandstones in the distal fan are wavy-bedded.

Sandstones of underwater channels are characterized by the presence of large pebbles and gravel fragments. Plant detritus is abundant in finer varieties.

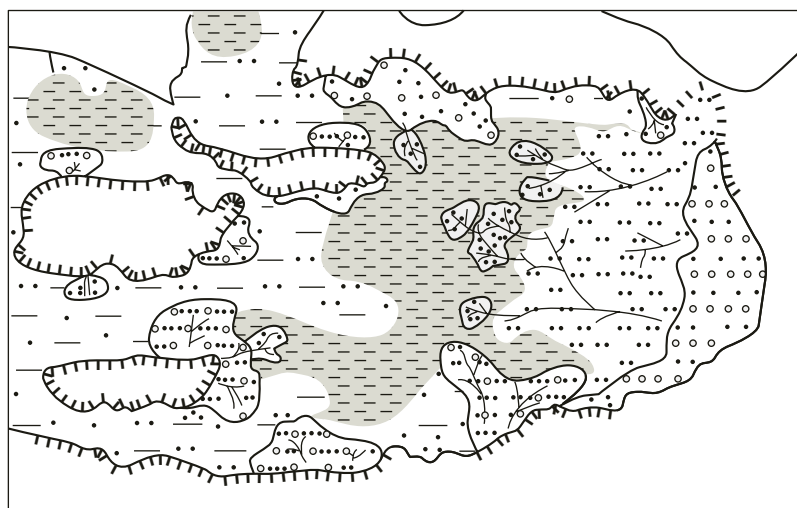


Fig. 15. Lithofacies types of deposits in the Dongying Depression for the Shasanzhung Epoch (the second half of the Middle Eocene). Modified after (Li Pulong, 2004). See legend in Fig. 14.

Slump structures and convolute bedding are widespread.

Specific features of the grain size distribution of particles in sandstones on the southern gentle wall of the Dongying Depression (Fig. 12) indicates that clastic material was delivered to the underwater Liandzialou fan from deposits of fan deltas previously formed within shoals. Indeed, bar charts of the grain size distribution of particles in sandstones from the sections of fan deltas and deep-water channels at the foot of the same wall are identical in many respects.

The other large underwater fan was formed at the eastern periphery of the central depression. This fan is characterized by lenslike sandy bodies in underwater canyons and large channels at their extension. The underwater canyons connected this channel with a river delta that occupied the major part of the littoral zone in the Guangli area. The grain size distribution of particles in deltaic deposits and flux turbidites is practically identical (Fig. 12), testifying to the genetic link between them.

It should be noted that clastic material accumulated in this epoch in deltas, deep-water channels, fan deltas, and other zones was marked by a higher degree of maturity in comparison with the previous epochs. In the Middle Eocene sections, quartz-feldspar graywackes are rare, but feldspar-quartz graywackes and arkoses prevail. This feature is probably related to the delivery of material from distal provenances and its considerable reworking in the process of transportation from the littoral zone to canyons and underwater channels of fans.

At the beginning of the Shasanzhung Epoch, climate became more and more humid, and the larger volumes of water and sedimentary material were transported to the lake. This situation led to the development of river deltas, their progradation toward the lake center, and

decrease of lake water salinity. The delivery of terrigenous clastic material and clayey suspension was not compensated by the subsidence any more.

The **Shasanshang-Shaerxia Epoch** (Late Eocene, Es_3^3 – Es_2^1). This epoch was marked by the gradual attenuation of rifting during the decrease in precipitation. Deposits of this age overlie the Shasanzhung rocks with regional discordance in some zones and concordance in others. In the lower part of the section (Shasanshang sequence), one can see an alternation of gray and dark gray clayey rocks and siltstones with interlayers of sandstones, gravelly sandstones, oil shales, or rare coaly shales. Owing to reduction of the volume of coarse terrigenous clastic material delivered to the lake, siltstones and clayey siltstones dominate in the section.

The upper part of the section includes an alternation of gray and green clayey rocks, sandstones, and gravelly sandstones with interlayers of carbonaceous-clayey rocks. Violet-red clay horizons appear at the top of the section. The input of large volumes of water led to the decrease of salinity in the lake. The thickness of dark gray clays and clayey siltstones deposited at that time reaches 500 m.

The eastern and western areas of the basin were occupied by river deltas inherited from the Shasanzhung Epoch (the Guanli delta in the east and the Gaocing delta in the southwest). Reduction of the lake area was accompanied by their rapid progradation toward the lake center (Fig. 16). At the end of the epoch, the deltas occupied almost one-half of the Dongying Depression area.

The final part of the Eocene (Shaerxia Epoch) was marked by even greater reduction of area and depth of the lake. This was accompanied by the filling of the central depression with sediments. River deltas were

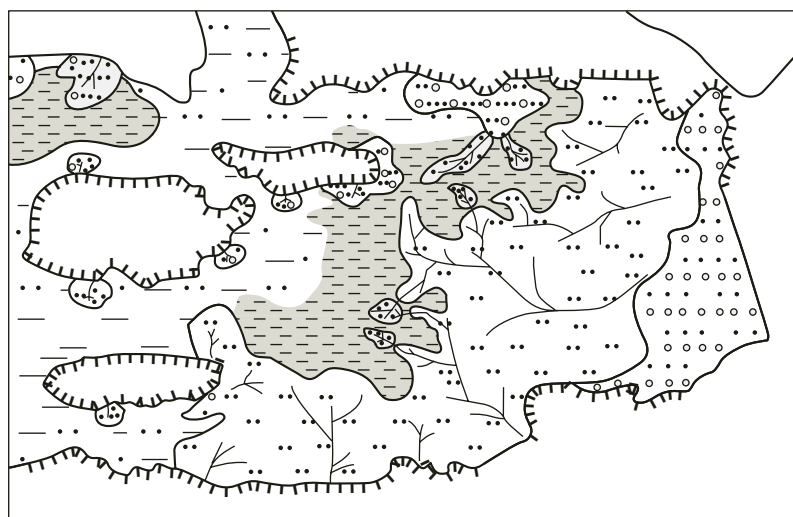


Fig. 16. Lithofacies types of deposits for the Shasanshan Epoch (Late Eocene). Modified after (Li Pilong, 2004). See legend in Fig. 14.

prograding to the basin center from both eastern and western sides. Deltaic deposits occupied its greater part at that time. Small fan deltas continued to form only near the Binxiang Uplift. Sandy sediments of this time again include graywackes, testifying to the contraction of transportation pathways for clastic particles and their rapid burial in deltas, fan deltas, and proluvial fans.

Figure 17 shows the structure of Eocene sections in different sectors of the Dongying Depression.

The **Shaershang–Dongying Epoch** (Early and Late Oligocene, Es_2^2 –Ed). Sediments of this epoch accumulated at the end of the Paleogene stage of the Dongying Depression evolution overlies the older rocks with traces of regional erosion. Despite the attenuation of tectonic activity, the earth crust continued to subside within the lake area, which was slightly larger as compared with the Shaerxia Epoch. During the first half of this epoch, sedimentation conditions were generally inherited from the previous epoch. The Shaershang section marked by several transgressions and regressions is composed of an alternation of gray, green, and violet-red clayey rocks with gray sandstones.

The Shai Epoch was characterized by significant aridization of climate and wide distribution of clays, oil shales, and carbonate rocks. The grain size in sediments gradually decreases and the sandstones are replaced by carbonate rocks upward the section. At the same time, the composition of sandstones becomes more diverse. They are represented by the typical graywackes, graywacke arkoses, and arkoses, suggesting tectonic activation within the uplifts around the Depression. This process led to the appearance of new provenances of clastic material and the washout of older (Eocene and possibly Mesozoic) terrigenous sediments.

Sediments of the Dongying Formation were mainly accumulated in the continental, shallow-water, littoral,

and sublittoral settings in the course of several transgressions and regressions. Alluvial sediments prevailed in this epoch.

FACTORS GOVERNING SEDIMENTARY PROCESSES IN THE PALEOGENE LAKE BASIN

Like in the other parts of the Bohai Bay Basin, tectonic and climatic conditions were the principal factors controlling sedimentary processes in the Dongying Depression. Their interaction was responsible for specific features of Paleogene sedimentary sections and the distribution of different lithofacies complexes in the peripheral and central sectors of the lake. The influence of factors varied with time. For example, the sedimentation rate and distribution of different lithofacies complexes in the Shasanxia and Shasanzhong epochs were mainly governed by tectonic processes. In contrast, the sediment composition was appreciably governed by climatic changes (namely, replacement of the humid climate by the arid one) at the final stages of rifting, when the tectonic activity gradually decreased (Shasanshang–Shaerxia and Shai epochs).

Let us note certain regularities in the development of sedimentation systems in the Dongying Depression. For example, in the first half of the Paleogene marked by active rifting, the sedimentation basin gradually deepened from a shallow lake to a deep-water basin. The starved subsidence regime was accompanied the appearance and distribution of diverse sedimentation systems, such as river deltas, deep-water fans, flux turbidite complexes (Shasy and Shasan epochs), which were absent at the Paleocene Stage (Kundian Formation). Attenuation of tectonic activity in the Late Eocene and Oligocene was accompanied by the gradual accumulation of sediments in the lake (primarily, the deep-water depression). Consequently, the deep-water

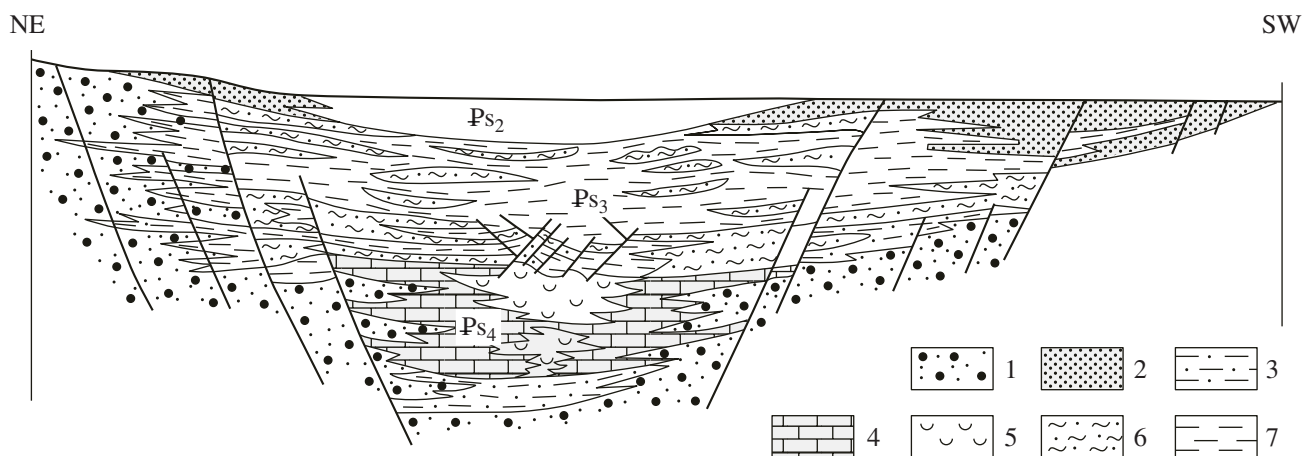


Fig. 17. Structure of Eocene deposits in the central and slope parts of the Dongying Depression. (1–7) Deposits: (1) fan deltas and proluvial fans, (2) river deltas, (3) accumulative sand deposits on the lake shoals, (4) carbonate buildups and brackish-water lagoons (limestones and dolomites), (5) halogenic lagoons (gypsums and rock salts), (6) deep-water fans (turbidites and flux turbidites), (7) hemipelagic sediments (clays and oil shales).

lake was transformed at the end of the Paleogene into a shallow-water basin, where primarily alluvial and deltaic sediments were accumulated.

Sedimentary processes were inherited over significant time intervals in different parts of the basin. For example, areas with short coastal shoal and steep underwater slope are dominated by proluvial fans, fan deltas, and deep-water fans. In contrast, areas with wide coastal shoal and gentle underwater slope are dominated by fan and river deltas, shallow-water coastal bars, and underwater fans with classic turbidites and flux turbidites.

The majority of Paleogene sections in the Dongying Depression are characterized by the cyclic pattern and presence of rocks with reservoir, oil-source, and screening properties owing to the combined influence of tectonic, climatic, and eustatic factors.

CONCLUSIONS

Analysis of data on the seismic survey, lithology of rocks, and well log allowed us to distinguish rocks of several lithofacies complexes formed in the Dongying Depression in the Paleogene: proluvial fans, fan deltas, sand bars at the shoals, river deltas, and deep-water fans composed of turbidites and flux turbidites.

The spatial distribution and role of these lithofacies complexes in different sectors of the Dongying Depression were governed by tectonic, geomorphologic, and subordinate climatic factors. Basin sectors adjacent to the paleouplifts are dominated by proluvial fans and fan deltas, while their extensions are represented by deep-water gravity complexes. Bar charts of the grain size distribution of particles in the deep-water sandstones accumulated within the northern and southern slopes of the Dongying Depression indicate the delivery of clastic material mainly from fan delta deposits.

Coastal lowlands were marked by the formation of alongshore sand bars, storm bars, and river deltas. Their front zone accumulated flux turbidite complexes, which filled underwater channels in deep-water fans with a different structure. Such channel systems extended deep into the central deep-water depression.

Specific features of the spatial distribution of various lithofacies complexes during different epochs of the Paleogene governed the distribution of various types of reservoirs. An important role was played by gravity- and turbidity-related lenslike sandy bodies in the deep-water fans formed in the front zone of rivers deltas and at the extension of fan deltas.

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