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ГЕОЛОГИЯ НЕФТИ И ГАЗА
OIL AND GAS GEOLOGY

Часть 1
Part 1

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В пособии излагаются основы общей геологии, структурной геологии, геологии нефти и газа, геохимии.

Пособие рассчитано на специалистов Республики Ирак, обучающихся в Пермском государственном техническом университете по дополнительной образовательной программе профессиональной переподготовки специалистов «Руководитель нефтегазового производства».

General geology, structural geology, oil and gas geology and geochemistry.

The textbook is destined for the Iraq Republic specialists studying on the extra educational program of professional retraining «Oil and gas production manager» at Perm State Technical University.

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Course of lectures in
GENERAL GEOLOGY

Lecture 1

INTRODUCTION

Geology is one of the most important natural sciences, which studies the structure, composition, origin, and development of the Earth. It studies various processes and phenomena that were manifested in the past and are manifested and running now on our planet. The main objective of the General Geology courses is to study the outer stone layer of the planet (the Earth crust) and the external and internal layers of the Earth, which interact with it.

The range of geosciences which study various problems in more details includes:

Geochemistry: the science studying distribution and the processes of migration of chemical elements in the Earth crust and the Earth as a whole;

Crystallography studying the internal structure and forms of crystals;

Mineralogy studying the composition, properties, conditions of formation, and regularities of the spread of minerals;

Petrography studying rocks of the igneous and metamorphic origin;

Lithology (sedimentology) studying sedimentary rocks;

Geomorphology studying the today structure and the origins of the surface terrain of the Earth;

Geotectonics studying the development and structure of the Earth crust;

Structural geology studying modes of occurrence of the rocks;

Historic geology studying general regularities and the consequence of formation of the Earth crust;

Stratigraphy studying the consequence of formation and occurrence of stratified (bedded) formations;

Paleontology studying the development of the organic world in the past geologic periods; and

Geophysics studying the deep structure of the Earth, and the physical phenomena and processes taking place in its various layers.

Applied geosciences are: studies of mineral deposits;
Hydrogeology; and
Engineering geology

National economic importance of geology is that it ensures various industries of the economy with mineral resources, provides engineering geologic substantiation of constructing various civil and industrial objects, solves problems of potable and technical water supplies. Geology is especially important for mining and industry.

Currently, mineral deposits in near-surface areas of the Earth crust have been already identified and are developed intensely. Hence, the main task of applied geology is now to study deeper zones of the Earth crust and predict new mineral deposits that do not reach the daylight surface.

The problem of integrated usage of mineral deposits is very acute.

Intensification of mining practices leads to significant industry concentration and transfer of huge masses of rocks to the surface. This causes great disturbances of natural balances established in millions of years and can lead to dangerous consequences. That is why another challenge of modern times that geologists and miners face now is the problem of protection and rational usage of mineral deposits as a most important link in the general problem of environmental protection.

Structure of the Universe and the Solar System

The Earth is a tiny component of one whole world which is called the Universe or cosmos. The Universe is infinite in space and time. In the Universe, matter is distributed unevenly and is represented by stars, planets, dust, meteorites, comets, and gases. That part of the Universe, which is accessible for investigation is called the Metagalaxy. It includes over a billion of star clusters, or galaxies.

Our galaxy includes about 150 billion stars. It looks like a wide whitish stripe called the Milky Way. Our galaxy belongs to the spiral galaxy type. In its central part, the so-called galactic nucleus is situated, which consists of big and small stars. The whole star system revolves around this nucleus with the period of revolution (at the level of the Sun) equal to 200–250 million years.

The Sun is the star closest to the Earth. The distance between us and the Sun is 149.6 million km, and is taken as a conventional unit of measuring distances in space: astronomical unit.

The Sun is orbited by a swarm of smaller, cold cosmic bodies: planets, their satellites, asteroids, comets, and meteorites. Together with the Sun, these bodies form the uniform solar system.

The solar system consists of nine planets, 42 satellites, at least 50 thousand asteroids, an uncountable number of meteorites, and hundreds of comets.

The Sun takes upon itself 99.86 % of the entire mass of the system. The Sun is an average-size star being a plasma globe. About 70 chemical elements have been found in its contents. The main of those elements are hydrogen and helium. The average temperature of the external layers of the Sun is about 5600 °C. Thermal energy of the Sun is caused by fusion processes of hydrogen being transformed into helium.

Orbits of the planets are situated in one plane which coincides with the equatorial plane of the Sun. Relative to the Sun, the order of the planets is as follows: Mercury, Venus, the Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto.

Between the orbits of Mars and Jupiter, the asteroid swarm is situated. In terms of their location, mass, density, and other parameters, the planets of the solar system are divided into terrestrial, or earth-type (internal) and external planets (giant planets). The farthest of the external planets, Pluto, has the mass twice as small as that of the Earth).

The planet closest to the Sun is Mercury. Its terrain is very similar to that of the Moon. Vast plains are covered here with craters of various sizes. Weak magnetic field (1 % of the Earth's), very rare atmosphere (helium and other gases). The temperature, on the side turned to the Sun, is up to 420 °C.

Venus. Its surface is hidden from observations with a powerful atmosphere. It contains up to 97 % of gaseous carbon dioxide. The bottom layers of the atmosphere are heated up to 475 °C. Air density is 65 times greater than that at the surface of the Earth. Rock density, 2.8 g/cm^3 corresponds to the density of lunar basalts. In the terrain structure, craters 35–160 km in diameter have been found.

The Earth (its structure will be considered in full detail in the nex lectures).

Around the Earth, its natural satellite, the Moon, rotates along an elliptical orbit (average distance, 384400 km). It is four times smaller than the Earth, and is turned towards the Earth permanently with one hemisphere. Its average density is 3.34 g/cm^3, and the diameter is 3474 km. Eighty-five percent of its surface is covered with mountains, the rest is comprised of so-called "seas". The surface of the Moon is covered with craters up to hundreds of kilometers in diameter.

Along with impact craters, there are craters of the volcanic origin in the moon.

In lunar rocks, oxides of silicon, titanium, aluminum, and magnesium have been found. There is no pure iron, nor other minerals containing water and carbon dioxide here.

The size of Mars is twice as small as that of the Earth. The distance between its orbit and the orbit of the Earth is approximately 78 million km. Two satellites orbit Mars: Deimos (16 km) and Phobos (27 km). Each of them is a stone rock covered with small craters.

The elements found in Martian soil are Fe, Si, Ca, Al, and Fi.

On even areas of Mars, cracks, canyons, and river valleys are observed. River valleys have a well-branching system of subsidiaries. The riverbeds are dry. Some scientists think that now all the water on Mars is concentrated in polar caps, other suggest that it may be buried under alluvial drifts. The general opinion is that the Martian climate has changed drastical.

Craters of the impact and volcanic origin are also found on Mars. The unique feature here is Nix Olympica, a huge volcanic cone 500 km and diameter and over 20 km high.

The magnetic field of Mars is 500 times weaker than the Earth's. The atmosphere is very rare and consists of oxygen, nitrogen, argon, insignificant amounts of moisture, ozone, and carbon oxide. During the day, air temperature reaches +25 °, by night it drops to –70 °C. No signs of organic life have been found so far.

The size of Jupiter exceeds the size of the Earth by more than 11 times. Its mass constitutes 70 % of the total mass of the planets. It is surrounded with a heavy atmosphere consisting of methane, ammonia, molecular hydrogen, and other gases. The temperature of the upper layers of the atmosphere is 140 °C, and that of the interior of the planet, 15–20 thousand degrees. It has a strong magnetic field and a powerful radiation belt. 13 satellites orbit Jupiter. The larges of them are Ganymede, Callisto, Io, and Europa. By their sizes, they compare well with Mars and Mercury. Io and Ganymede are surrounded by atmospheres consisting of methane, ammonia, water, and nitrogen. Active volcanoes have been found on Io.

Saturn is surrounded with a dense meteoric ring. The heavy atmosphere of Saturn consists of ammonia and methane. It has a high-power magnetic field. Eleven Saturnian satellites have been discovered.

The diameter of Uranus is 51400 km. Its heavy atmosphere consists of methane. There are five satellites.

Neptune is four times larger than the Earth. Its atmosphere is the same as on Uranus. 2 satellites.

Pluto was discovered in 1930. Its atmosphere, supposedly, consists of neon. Methane ice has been found on Pluto. There is one satellite. The diameter of Pluto is 5800 km.

Small Bodies of the Solar System

Between the orbits of Mars and Jupiter, the belt of asteroids (minor planets) is situated. There are hundreds of thousands of them. Their diameters are up to 955 km. The plane of their orbit is close to that of the Earth. Some of them, e.g. like Icarus, have elongated elliptical orbits. Asteroids are scattered materials which have not formed a separate planetary body due to some reason.

Comets are the most peculiar bodies in the solar system. They move along strongly elongated elliptical orbits coming close to the Sun and going far from it, beyond the orbit of Pluto. The mass of comets is insignificant. They consist of methane, ammonia, hydrogen, traces of water ice, hydrogen cyanide, and methyl cyanide. In comet nuclei, fragments of rock materials are present.

Meteorites are small-size solid bodies. About 7 % of found meteorites consist of iron-nickel alloy, the rest are stone. The largest of found meteorites having fallen in the South-West of Africa weighed 59 tons. Judging by discovered meteorite holes (explosion structures, or astroblemes) which sometimes have huge dimensions, much larger bodies, probably, asteroids fell on the Earth in the past.

Lecture 2

STRUCTURE OF THE TERRESTRIAL GLOBE

Shape and size of the Earth. The shape or form of the Earth is understood as the shape of its solid body formed by the surface of its continents and the bottom of its oceans. The shape of the planet is determined by its rotation, the ratio of the attraction and centrifugal forces, the density of its substance, and the distribution of the substance within the Earth body.

A simplified shape of the Earth is close to an ellipsoid of revolution (spheroid). Its polar radius is 6356.8 km, and the equatorial, 6378.2 km.

Detailed measurements showed that the Earth has a more complicated shape which was termed a geoid. At any point of the geoid, the vector of gravity is perpendicular to its surface which can be obtained by mentally continuing the surface of the World Ocean under the continents. This very surface serves as the base when counting values of elevation in topography. The geoid and the spheroid do not coincide. The deviations of the surfaces reaches $\pm$160 m. From the recent, most accurate measurements, the Earth is pear-shaped three-axis ellipsoid. The South Pole is 242 m closer to the Equator that the North Pole.

The mass of the Earth is 5.977×10^{21} tons, its volume is 1.083 billion km^3, its area is 510 million km^2, and its average density is 5.517 t/cm^3.

Surface of the Earth. The actual surface of the Earth's solid body has a more complicated shape than the geoid.

71 % of its surface is covered with water, 29 % is dry land. Continents divide the World Ocean into four oceans: Pacific, Atlantic, Indian, and Arctic. Dry land is formed by six continents: Eurasian, North American, South American, African, Australian, and Antarctic.

The highest mark on dry land is 8884 m (mount Everest in the Himalayas), the lowest mark, 11022 m, is at the bottom of the Mariana Trench, in the Pacific Ocean.

Average elevation of the continents is 875 m.

Average depth of the ocean is 3800 m.

Outer and Inner Concentric Shells of the Earth

One of the most characteristic features of the terrestrial globe is its inhomogeneity.

It consists of concentric shells which are subdivided into outer and inner concnetric shells. Outer concentric shells are the atmosphere, hydrosphere, and biosphere, and inner concentirc shells are the Earth crust, the Earth mantle, and the Earth core.

External geospheres (layers) of the Earth penetrate each other and interact with each other and the Earth core continuously playing in important part in formation and development of the Earth.

Atmosphere is the gaseous air envelope of the Earth. It is subdivided into three horizons: troposphere, stratosphere, and ionosphere.

Over the Equator, the troposphere is approximately 17 km high. It contains up to 80 % of the whole mass of the air. At the top boundary, its temperatures falls down to 85 °C.

The stratosphere spreads up to the heights of 50–55 km. Here, the air is rarefied and heated with sun beams up to –10 +10 °C. The ozone layer up to 25–30 km thick is situated within the stratosphere and absorbs a greater part of the ultraviolet radiation of the Sun.

The ionosphere consists of rarefied air, which ionized under the effect of ultraviolet radiation and is capable of conducting electric currents. Its top boundary lies at the height of 1300 km. In its turn, the ionosphere is subdivided into three layers: mesosphere (25–30 km thick, t °C up to –90 °C), thermosphere, where t° increases to 1000–2000 °C at the height of 400 km, and exosphere, with t° about +2000 °C.

The main components of the atmosphere are nitrogen, oxygen, argon, and carbon dioxide. An important component of the atmosphere is atmospheric moisture which influences geologic processes greatly. Air masses of the atmosphere are in constant motion as affected by inhomogeneous heating of the Earth surface. The physical condition of the atmosphere is winds. Its temperature, pressure, and humidity determine the weather. A long-standing regime of the weather is called climate. Climates can be: hymid, i.e. wet, with moderate or high temperatures (tropical zones and the areas adjacent to them); arid, the dry and hot climate of deserts and steppes; and nival, the wet and cold climate of polar and high-altitude regions.

Hydrosphere. The top boundary of the hydrosphere is determined by the level of the surface of open water reservoirs. The bottom boundary is rather indefinite and corresponds, probably, to the temperature of +374 °C, at which water is gasified. Three main types of natural waters are distinguished in the hydrosphere: They are oceanosphere (waters of seas and oceans), continental waters, and glaciers. Subterranean waters, which are concentrated in the Earth crust but are tightly connected with the hydrosphere waters, take an intermediate position. The amount of oceanic water is estimated as 1370 million km^3, of continental water 0.5 million km^3, and subterranean water, 196 million km^3.

Hydrospheric waters are mineralized in a varying degree. Ocean water contains about 35 g of salts in 1 liter (3.5 %). Its salt content is constant. The main part is played by cathions Na^+, Mg^{2+}, Ca^{2+}, K^+, and Sr^{2+} and anions Cl^-, SO_4^{2-}, HCO_3^-, Br^-, CO_3^{2-}, and F^-. Along with ions, ocean water contains dissolved natural gases: nitrogen, oxygen, carbon dioxide, and hydrogen sulfide. The concentration of these gases varies depending on the physiographic conditions.

A major part of continental waters is formed by atmospheric precipitation characterized by minimal mineralization.

The waters of the hydrosphere are in constant circulation. One can distinguish between atmospheric oceanic, lithogenous, biogenous, and production circulations.

The moisture of the hydrosphere, along with the substances dissolved in it, takes an active part in chemical reactions running in the hydrosphere and in its interactions with the atmosphere, the Earth crust, and the biosphere. That is why the hydrosphere, like the atmosphere, is a factor of acrogenous geologic processes.

The biosphere encompasses the whole space of the upper horizons of the Earth, where organic life exists. It includes all the hydrosphere, the upper portion of the lithosphere, and the lower portion of the atmosphere.

In terms of the active influence on the environment, the living matter of the Earth occupies the first place.

By the feeding method and the relationships with the environment, living organisms can be autotrophic, i.e. consuming inorganic nutrients, and heterotrophic, feeding on other organisms and their remains. The majority of living organisms are aerobic, i.e. they live in media containing air. A minor part, mainly microorganisms, is anaerobic, living in oxygen-free media.

The basis for the living matter is carbon, and also oxygen, hydrogen, and nytrogen.

The main mass of the living matter is concentrated in green plants that collect the energy of sun beams and build complex compounds in their organisms (the process of photosynthesis). Photosynthesis is an oxidation-reduction reaction, CO_2+H_2O–CH_2O+O_2. This process generates 266 billion tons of free oxygen. The biomass of the World Ocean is the main generator of free oxygen in the atmosphere.

When living organisms die, the process, which is reverse to photosynthesis, takes place: decomposition of organic matter. The both processes are in equilibrium, therefore the total biomass amount on the Earth is a constant value.

Inner geospheres. Three layers, are distinguished in the solid body of the Earth: outer, the Earth crust; intermediate, the Earth mantle; and central, the Earth core.

The Earth crust is a most important object of geologic studies. The thickness of the Earth crust is from 7 km under oceans to 70 km on the continents, under mountain structures. Three layers are distinguished in the Earth crust: sedimentary cover, granite layer, and basalt layer.

The sedimentary cover is formed by sedimentary and igneous rocks which have not undergone any metamorphism or significant tectonic deformations. The thickness of the sedimentary cover ranges from 0 m to 20–25 km. The average density of the rocks is 2.45 g/cm^3. The wave propagation velocity (Vp) depends on the material constitution of the rocks and ranges from 1.8 to 5.0 km/s, and even more.

The granite layer is formed by metamorphic and igneous rocks, which are generally similar to granites by their composition and properties. The density of this layer is 2.6–2.8 g/cm^3. The average value of the wave propagation velocity is 6 km/s. The layer thickness is 5–40 km on continents. In ocean basins and, partially, in seas, the granite layer is absent. The bottom boundary of the granite layer is the seismic Conrad discontinuity.

The basalt layer consists of denser igneous rocks with the properties similar to basalts. Their average density is 2.9 g/cm^3, and the seismic wave propagation velocity is 6–7.6 km/s. The average thickness within the continents is about 20 km.

The thickness of the Earth crust in the ocean is 5–12 km, and on the continents, 30–70 km (mountainous regions). In 1910, Yugoslavian geophysicist Mohorovičić identified the boundary between the Earth crust and the mantle (referred to as the Moho, or M-boundary).

The mantle is an intermediate layer of the Earth. It can be traced down to the depth of 2900 km, where the Wiechert-Gutenberg boundary was identified. The density of the mantle substance grows with depth from 3.6 to 9.4 g/cm^3.

The mantle is inhomogeneous vertically and is subdivided into the upper mantle and lower mantle.

The upper mantle consists of a high-velocity layer 0–50 km thick; medium, lower-velocity layer about 100 km thick; and a homogenous layer about 250 km thick which spreads down to the depth of 400 km. The upper layer and the Earth crust overlying it are entirely solid and are called the lithosphere. The lower-velocity layer is called the asthenosphere, or plastic layer characterized by partial melting.

Transition layer and lower mantle.

In the transition layer, at depths of 400–800 km, there are several horizons, where the velocity of seismic waves grows sharply. This phenomenon is usually explained by recrystallization and formation of denser minerals.

The core of the Earth is subdivided into the outer core and inner core. By the character of seismic wave propagation, the outer core is liquid and is about 2200 km thick. Its average density is about 11 g/cm^3. The internal core is solid, its radius is 1250 km, its average density is 13 g/cm^3. The velocity of P-wave propagation is 11.1–11.3 km/s.

Lecture 3

GEOLOGIC PROCESSES AND THEIR ROLE IN FORMATION OF THE EARTH CRUST AND TERRAIN

1. General notions. Duration of geologic processes.

Geologic processes are caused by various forms and sources of energy. Some of them are associated with the forces acting within the Earth and are called the processes of inner dynamics, or endogenous. Another set of processes is manifested on the Earth surface and in the upper parts of the Earth crust, and is connected with the effect of the factors external to the crust. Such processes are called exogenous.

Endogenous processes include_various forms of matter motions which reflect the inner life of the Earth: magmatism, various tectonic motions, earthquakes, and metamorphism.

Magmatism is the whole set of geologic processes associated with the action of magma and its products. Magma is a high-temperature (800–1200 ° and more) melt of rocks occurring at individual regions of the mantle or the crust. From these sources, magma moves up towards the surface. In some cases, it is excreted to the surfaces and spreads over it. In other cases, it solidifies at some depth and forms co-called intrusive bodies. Regions of effusive and intrusive magmatism.

Tectonic motions of the Earth crust are rather diversified and are characterized by great complexity. They may be subdivided into vertical and horizontal motions.

Metamorphism includes various types of the changes in the rocks as affected by the temperatures and pressures, which disrupt the previous physico-chemical balance.

Exogenous processes are a set of many processes determined by the factors external to the Earth: the energy received from the Sun, the gravity, organic activity, etc. They are: 1) erosion (weathering): destruction of rocks affected by fluctuations of the temperature, water, oxygen, and gaseous carbon dioxide; 2) mechanical activity of winds, atmospheric precipitation, steaming waters on the surface, subterranean waters, and glaciers; 3) activities of oceans and lakes; 4) the processes running in swamps and permafrost zones.

The processes of erosion and the destructive action of other external factors lead to formation of great amounts of fragmentary materials and dissolved substances. These degradation products either move as affected by gravity, or get picked up by winds, streaming waters, and glaciers and drifted into lakes, seas, oceans, and other terrain depressions. The whole set of the process of rock destruction and drifting of the degraded materials are called the general name of denudation. It is most intense on the elevated areas of dry land.

The process of conglomeration of sediments is termed accumulation. The most important part in the course of geologic history was played by marine sediment accumulation. It results in large development of marine sedimentary rocks, and evidences repeated invasions of the sea into vast areas of modern continents.

Terrain-forming role of geologic processes.

The nowadays terrain is the result of complex interaction of endogenous and exogenous processes

I. EXOGENOUS PROCESSES

1. Erosion (weathering)

The near-surface area, in which an exogenous process affects the rocks and they undergo slow changes and are destroyed under the effect of fluctuations of the temperature, chemical action of water, oxygen, carbon dioxide, and organic substances excreted by plants and animals, is called a weathering zone.

Erosion (weathering) is an integrated complex process, in which two aspects are distinguished: physical (mechanical) and chemical (chemico-biological) erosion.

Physical weathering is decomposition of rocks and minerals into fragments without any changes in their chemical contents. Its simplest variety is thermal weathering caused by fluctuations of the temperature by day and by night, or in different seasons. Temperature changes lead to alternating expansion and constriction of the volume of rocks, which leads to formation of cracks and rock fragmentation.

Thermal weathering is especially intense in zones with dry climate, e.g. in deserts. In zones with cold climate, physical weathering is manifested as frost weathering, where the most important factor is the water penetrating into cracks. As if freezes, it expands in volume by almost 10 % and splits the rocks.

Physical weathering affects most strongly large-grained polymineral rocks…

Chemical weathering leads to transformation of the mineral composition of the rocks. In the majority of cases, its final products are clay minerals. Its main factors are free oxygen, gaseous carbon dioxide, organic substances, and water, and the main chemical reactions are oxidation, carbonatization, solution, hydrolysis, and hydration.

Oxidation is association of oxygen. Fast to oxidize are many sulfides (pyrite), some mica (biotite), $FeS_2+nO_2+mH_2O$ – $Fe_2O_3{\cdot}nH_2O$ (brown hematite, or limonite).

Carbonatization is the reaction, under which carbon dioxide takes bases off from minerals. The products of the reaction are carbonates.

Solution and hydrolysis happen when the joint effect of water, carbon dioxide, and organic acids takes place. The highest dissolvability is characteristic of salts of Na and K (salt rock and chloride of potassium, or sylvite), etc. In terms of dissolvability, chlorides are followed by sulfates (gypsum), then carbonate rocks………..

Feldspars are subject to intense hydrolysis and turn into kaolinite:

The common result of chemical weathering is beneficiating of primary rock substances with relatively light elements. Hydrogen, oxygen, and carbon are borrowed from the atmosphere, which leads to transformation of the chemical composition of the rocks. Chemical weathering (along with physical one) leads to formation of strongly loosen or water-soluble products, i.e. it transforms a substance into a more mobile phase, which assists the process of formation of sedimentary rocks in the reservoirs where they are deposited.

The part of the weathing zone, in which rocks and minerals undergo the strongest changes, but were not drifted into other regions, is called the residuum. It is formed by newly-formed rocks (elivium), which below pass over gradually to the unchanged initial mother beds or bed rocks.

In the upper part of the residuum, activity of plants and animals produce the soil. In the soil, the biologic circulation of the matter happens, which consists in the plants' recovering mineral and organic substances and giving them back when the plants die and decay.

II. GEOLOGIC ACTIVITY OF THE WIND

Geologic activities of the wind consists of the processes of deflation (blowouts), corrosion (grinding of rocks and their fragments by the sand suspended in the wind), transportation and accumulation (deposition). All the processes caused by wind activities are commonly called "eolian processes" (Eolus was the god of winds in Greek myths), and the sediments produced by wind accumulation are termed "eolian", too.

By their origin, the majority of eolian sands are the products of blowing the sediments of rivers, oceans, and lakes, as well as the sediments formed by the processes of physical erosion.

The following is characteristic of eolian sands: 1) relatively good rounding of the grains; 2) better sorting, compared to water sand formations; 3) small-grain composition (0.25–0.05 min); 4) domination of stable materials (quartz); 5) oblique, sometimes even cross bedding; 6) yellow color (or yellowish-brown, sometimes reddish).

Sand deposits form three main types of the terrain: 1) barchan type, characteristic mainly of tropical deserts; 2) semi-vegetated type (extra-tropical deserts); 3) dune type (off-desert).

Barchans are asymmetric crescentic forms characterized by sharp edges protruding forward, along the wind direction. The wind-facing slope is long and flat (10–15°), the downwind slope is steep (32–33°) and short. The height of barchans ranges from 1–2 m to 20–30 m and more. If the amount of sand is great, group barchans are most frequently developed in deserts, which form crosswind barchan chains. Barchans and barchan chains are moving forms of the desert terrain, they can move to tens of meters annually.

Dunes are asymmetric sand banks or elongated hills situated across the dominant wind direction. They are formed in off-desert areas on the coasts of oceans, lakes, and some large rivers, where denuded or rarely vegetated sand are well developed, and strong winds blow. If a dune is not held down by vegetation, it moves inland, and a new dune is formed in its earlier position. Thus, chains of parallel dunes are formed. The speed of their motion reaches 20 m per year. Dunes on sea coasts are 20–30 m high, sometimes they reach 100 m and more (the Atlantic coast of France).

The internal texture of dunes is characterized by oblique bedding with differently oriented thin straticula of large- and fine-grained sand in wedge-shaped and sagged strata reflecting the changes in the direction and speed of the wind.

On the surface of denuded sands, across the wind direction, eolian ripples are always formed. They look as low asymmetric bulges, 2–5 cm high, which extend parallel to each other.

Loess, or eolian soil, is unstratified, light-yellow material, which is easily ground by fingers and consists mainly of dust particles from 0.05 to 0.01 mm in diameter. It is characterized by systems of short vertical tubular pores (remnants of plant roots), high carbonate content, and capability of supporting steep walls in natural exposures. Loess formations are frequent in Middle Asia, China, America, and Ukraine. Their thickness ranges from several meters to several hundreds of meters (China).

Lecture 4

GEOLOGIC ACTIVITY OF STREAMING SURFACE WATERS

Streaming surface waters are dry-land waters flowing along the dry-land surface to lakes, seas, and oceans. Temporary torrents and permanent water streams are distinguished. They are fed by atmospheric precipitation, melt (snow and glacier) waters, and subterranean waters. Annually, only on the dry land of the continents about 100 thousand km^3 of water is precipitated in the form of rain and snow. Its major part evaporates and gets back to the atmosphere, and the minor part (about 40 %) gets involved in land runoffs or seeps into the soil.

Atmospheric precipitation on the land surface make geologic works, whichare expressed in rainwash and linear washout. In rainwash, water during rains washes loose rock fragments from flat slopes and shifts them towards the slope feet, where they are accumulated in the form of the deluvium.

Strong rains and melting snows produce water streams that flow down the slopes along linearly extended depressions. They erode these depressions and make them deeper: linear washout, or erosion happens.

One distinguishes between bottom, or deep erosion directed into the depth of the Earth, and lateral erosion that destroys the depression walls. Temporary torrents form ravines on flat lands and in mountainous regions, and permanent water streams (rivers) form river valleys. A ravine consists of: the beginning of the ravine (source, or head), the place where the ravine flows into a deeper depression (mouth), and side branches.

The profile of the ravine bottom is shaped like a curve called the longitudinal bed profile. In the case of long-term washout and stable erosion basis it is called the base level or profile of equilibrium. _At the ravine mouth, the washout depth is limited by the erosion base level. For ravines, it is some water reservoir.

As the longitudinal base level is worked out, the lateral erosion becomes dominant. The ravine becomes wider, and its slopes, gentler. In the long run, the ravine turns into a clough (an old, vegetated ravine).

Temporary mountain torrents. They run in dry mountain valleys in the periods of strong rains or glacier melting caused by sudden warming. In the period of the absence of water, great amounts of the products of physical weathering are accumulated in mountain valleys in the form of fragments of various dimensions: from silt particles to boulders several meters in diameter. During heavy showers or sudden melting of the mountain snows, short-living but powerful water torrents are formed in such valleys. They saturate the fragmentary masses with water, liquify them, and turn them into mud. 75 % of the whole mud mass is rock fragments, and only 25 % of the whole volume, water. Due to a steep inclination of the bottom, the mud masses start moving. This is how mud flows (sills) are formed. Their velocity is 10–15 km/h. Having reached the foot of the slopes, mud flows spread over, the fragmentary material they transport is deposited, and alluvial cones are formed. Depositions of mud flows are termed “proluvium”.

Rivers. Rivers are permanent water streams. Their geologic activity is very intense. Each river forms a river system, which includes, along with the main artery, numerous tributaries. River systems are separated by dividing ranges. The area that feeds water into a river with its subsidiaries is called the catchment basin, or drainage area.

Rivers are fed by atmospheric precipitation, melt waters and subterranean waters. For example, rivers in Middle Asia (e.g. Amu-Darya and Syr-Darya) are fed by the waters formed by melting mountain glaciers. Rivers in the Far East replenish their waters with rain waters (80 %) and melt waters (20 %). Rivers in the European part of Russia (Volga, Don, Dnieper, etc.) use subterranean waters, atmospheric precipitation, and melt waters as permanent feeding sources. Subterranean waters take part in feeding almost all the rivers to a different degree.

Each river begins with its head and ends with its mouth, i.e. the place where the river flows into another water artery or water basin. In terms of their structure, two types of river mouths are distinguished: deltas and estuaries. Deltas are characteristic of the rivers which bring a lot of destruction products in the form of sand or silt to the river mouth. The ocean floor at the point where the river flows into the ocean shallows fast and becomes dry land. During floods, water jets flush numerous branching arms. Examples of the delta are the mouths of the Volga and Lena. The area of the Lena’s delta is 45 000 km^2, the Volga’s 18 000, Mississippi 150 000 km^2. The rate of delta attacks on the ocean is measured by tens, and sometimes, even by hundreds meters a year. For example, the delta of Syr-Darya grows annually by 108 m, and that of the Volga, by 170 m. This is evidenced by surviving harbor structures. Due to the ocean’s being attacked by the delta of the Po River, the city is now 22.5 km from the sea.

An estuary is a funnel-shaped gulf formed by flooding and expansion of a river mouth. Estuaries are typical for the rivers, whose mouths are subject to the action of tidal waves, which carry the sediments transported by the rivers from dry land into the ocean depths. Tidal waves wash out the banks, widen and deepen the river bed. The Ob River has a mouth in the form of an estuary (the Gulf of Ob). In the process of their development, rivers form linearly extended depressions: river valleys.

In the transverse cross-section, valleys are asymmetric, which is explained by uneven erosion of the slopes. One reason for that is the Coriolis force (any body moving horizontally near the surface of the Earth, independently of the direction of the motion, deviates from the motion direction to the right in the Northern hemisphere, and to the left, in the Southern hemisphere, due to the rotation of the Earth from the West to the East). Thus, in the Northern hemisphere, right river banks are eroded, and in the Southern hemisphere, left ones.

In the process of development of the rivers, their straight stream channels become wandering, and then get straight again having moved to a new place.

The motion of a water stream along a winding channel from one bank to another gradually makes the channel even more winding and helps formation of winding bends, or meanders. Detached parts of stream channels turn into cut-off meanders, or cut-offs.

The flood plain is that part of the river valley which is flooded with water in the flood period. Old flood plains leave step-shaped ledges extended along the slopes. Such ledges are termed terraces.

In the transverse cross-section of the valley, the following elements are distinguished: terraces, the flood plain, and the stream channel.

The stream channel is the part of the valley filled with water permanently. Stream channels can be straight and winding, narrow and wide, shallow and deep.

The highest terrace is the oldest one. Terraces can be pedimental, erosive, and accumulative. Erosive terraces are formed by bed rocks. Accumulative are formed by alluviations. Terraces, in which the bottom part consists of bed rocks, and the top one, of alluviations, are called pedimental. When dry land is depressed, earlier formed terraces can be buried under a layer of sediments (buried terraces).

Valleys of lowland rivers usually are wide and shallow, and have the V-shaped form. In mountainous regions, they are deeply cut, have the V-shaped form, and look as chasms and canyons.

Three stages are distinguished in the development of rivers: youth, maturity, and old age. Young rivers have deeply cut stream channels, bottom erosion is predominant. Mature rivers are characterized by attenuation of bottom erosion and intensification of lateral one; stream channels become wide, affluent, flood plains develop. Old rivers have shallow channels, the current speed is low, meanders and cut-offs are observed in wide flood lands.

<u>Erosion works</u> of rivers start at the moment when a water stream is formed. The speed and depth of rock washout depends on the speed of the current, bottom inclination, and rock composition. The erosion works of lowland rivers are weaker.

Deepening of the bottom goes on until the longitudinal base level is formed.

Simultaneously with the deepening of river valleys, lateral erosion continues. In the case of repeated activation of bottom erosion caused by vertical motions of the Earth crust, erosion terraces are formed. Their number corresponds to the number of river rejuvenation stages.

<u>Transportation and deposition of sediments.</u> Rivers play a major part in redistribution of the matter on the Earth surface. They carry huge amounts of fragments from mountains to the lowlands, and then, into the ocean. A significant portion of the matter is transported in the dissolved state. Colloid solutions carry compounds of iron,

aluminum, manganese, silicon, and regular solutions, salts of sodium, potassium, calcium, magnesium, etc. Rivers of arid regions are richer in salts. Annually, rivers transport millions of tons of the matter in the dissolved state (chemical runoff), and the amount of fragmentary materials (solid runoff) is even more significant.

In the process of transportation, low-hardness minerals and rocks are ground into powder, harder rocks are rounded and acquire elliptical forms.

As the energy of the water stream decreases, first solid, and then fine particles start to be deposited on the bottom. The fragmentary material is sorted. Fragments are sorted not only by size, but also by density.

The sediments deposited by rivers are called alluvium. _They are accumulated on river beds, flood plains, in deltas and cut-offs, and build up terraces. The processes of accumulation of river sediments run at the old mature stage of river development and reaches their maximum in the old age of the rivers.

Streaming waters play a major part in changes and formation of the dry-land terrain, formation of sedimentary rocks and mineral deposits. Erosion activities of surface waters smoothes elevations gradually. Undulating lowlands, peneplains are formed in place of mountainous structures (Kazakhstan). The surface of dry land becomes lower annually on the lowlands too.

Lecture 5

UNDERGROUND WATER

The main mass of underground water is formed in the process of infiltration (seeping) of atmospheric precipitation and melt waters. A part of the water is formed by condensation of water vapors in rock pores and cracks. Some amount of water is contained in the form of inclusions in sedimentary rocks (residual water). Formation of underground waters is also contributed to by juvenile waters released in rock metamorphism and igneous waters. Down to the depth of 16 km, the crust contains about 4000 million km^3 of water, which is equal to one third of the volume of the World Ocean.

The chemical composition of subterranean waters is varied. By the dominant chemical components, subterranean waters are subdivided into four groups: hydrocarbonated, sulfate, chlorinated waters, and complex waters: chloride-carbonated, sulfate-hydrocarbonated, etc.

Formation of subterranean waters and the regime of their activities depend on water chemistry properties of rocks: water permeability and water capacity.

In terms of water permeability, rocks are subdivided into: well-permeable (coarse gravels, large-grained sands), permeable (sands, fissured rocks), weakly permeable (chalky clays, sandstone, sandy loams), very weakly permeable (clayey sandstones, clay loams), impermeable (water-resisting clays, solid rocks).

Water capacity is the capacity of rocks to contain and hold a certain amount of water. Three categories are singled out: water-storing (bog muck, clays, clay loams), weakly water-storing (chalky clays, loess, clayey sandstone, clayey sands), nonwater-storing (metamorphic, igneous, and dense sedimentary rocks including fissured ones). For example, 1 m^3 of clay can absorb and hold from 400 to 700 l of water, and quartz sand, only 0.08 l/m^3.

Subterranean water affected by gravity are in constant motion. They move from the catchment areas to discharge (or drain) areas: to river valleys, ravines, ocean water basins, and other terrain depressions, where they crop out in the from of springs or brooks.

In terms of occurrence, catchment, and motion, subterranean waters are subdivided into soil waters, leakage waters, subsoil waters, and interstratal waters.

Stratal waters fill permeable strata underlying water tables and, unlike the latter, they are underlaid and overlaid by impermeable rocks. Strata saturated with water are called water-bearing. Generally, they are artesian strata. The area of distribution of one or several artesian horizons is called an artesian basin. In an artesian basin, the catchment area, pressure area, and drainage (discharge) area are distinguished.

Depending on the water pressure, any point of an artesian basin is characterized by hydrostatic pressure and a piezometric level. A piezometric level is the level, which the pressure waters reach in a bore well, and hydrostatic pressure characterizes the height of the column between the piezometric level and the confining overlaying bed (Fig.).

Subterranean waters carry out a great destructive work consisting in dissolution and mechanical washout of rocks. It is associated with karst phenomena, suffosion, and soil slips.

Interstratal waters are subdivided into free waters and pressure waters. Free waters occur where the water-bearing horizon is well drained, and the incoming water is insufficient to provide complete saturation of the water-permeable stratum. Pressure (artesian) waters are formed due to complete saturation of a water-permeable horizon with water, when the horizon lies at a significant depth and is not drained by natural drainages (ravines and rivers). The greater is the difference between the catchment area and a given area of the water-bearing horizon, and the lower is its drainage in the discharge area, the more is the pressure arising in water-bearing strata.

By the character of the conditions, in which subterranean waters move, they are subdivided into pore waters, stratal waters, fissure waters, karst waters, fissure-vein waters, and mixed waters. Pore waters and stratal waters are characteristic of water-permeable rocks. In water-permeable igneous and metamorphic rocks, the water moves along systems of cracks or fissures. In the zones of tectonic disturbances, fissure and fissure-vein waters can descend to significant depths.

The destructive work of subterranean waters consists in their chemical interaction with rocks (dissolution, hydration, hydrolysis, oxidation, and desalination) and mechanical fragmentation and washout by moving flows.

The destroyed material is transported mainly as a chemically dissolved substance.

The processes of chemical rock decomposition under the effect of subterranean and surface waters are called karst processes. Haloid, sulfate, and carbonated rocks are most favorable for karst formation. Karsts are subdivided into closed and open ones.

An open karst is developed in soluble rocks cropping out to the daylight surface. A purely surface form of karst manifestation is shallow gulches and furrows that are termed kars. Larger and more complicated forms are dolines, or karst funnels.

A closed karst develops in soluble rocks laying at a certain depth. Vertical and inclined karst passages, wells, holes, and complicated systems of cavities, karst caves, are formed. They may be horizontal or inclined, consist of one elongated cavity, or of a branching labyrinth. They may serve as channels of subterranean rivers.

Subterranean waters can also destroy mechanically the rocks in clays, loams, and loess. This process is called suffusion. Various shapes of terrain subsidence over the water-bearing horizon emerge: suffosion sinks, funnels, wells, ravines, and saucers.

Chemical sediments are accumulated in subterranean water when fissures, voids, and cavities are filled due to metasomatic replacement of the enclosing rocks or when subterranean waters emerge to the daylight surface near the drainage point.

In large karst cavities, chemogenous sediments form peculiar flowing forms on the roofs of the cavities (stalactites) or their floors (stalagmites).

Of big practical importance are sediments of subterranean waters near ore deposits, especially sulfide ones. Subterranean waters can redeposit ores and form new aggregates, which are sometimes richer and more accessible for development.

At the point where subterranean waters saturated with carbonate substances crop out to the surface, calcareous tuffs (porous formations) can be formed. Formation of travertines (banded marbles; solid well-crystallized rocks) is associated with outcrops of thermal calcium-carbonated waters.

Geologic activities of seas and oceans depends on the configuartion of the ocean floor, mobility of the Earth crust, chemical composition and temperature of the water, motions of water masses, etc.

Several geomorphologic zones are singled out in the terrain of the floor of the World Ocean, and each of those zones is characterized by its own physico-chemical conditions of the processes of denudation and accumulation:

1. The coastal zone is subject to continuous or temporal effect of ocean waves.

2. The shelf rims all the continents and islands of the continental origin. Near gently sloping coasts, this zone exceeds sometimes 1000 km. Usually, the depth of the ocean bottom within the shelf does not exceed 200 m.

3. The continental slope is characterized by the inclined position of the bottom surface (at the angles from 3° to 15°) down to depths of 2000–3500 m. The foot of the continental slope is a gently dipping flat land passing over into the ocean floor.

4. The floor of the world ocean is situated at the depths from 3500 to 6000 m. Its surface configuration is rather complicated.

Sea and ocean waters are natural solutions, in which oxygen, hydrogen, chlorine, and sodium are predominant. In the salt mass, chlorides of Na and Mg are dominant. Carbonates, compounds of nitrogen, phosphorus, and silicon earth are digested by living organisms and used to build shells and skeletons. Various gases are contained in the dissolved state: from 5 cm^3/l near the Equator to 8 cm^3/l in high latitudes.

The temperature of the waters is determined by the climatic conditions and the depth.

The organic world is extremely rich here. In terms of their areals and travels, marine organisms are subdivided into benthonic, which live on the bottoms of ocean reservoirs (the organisms especially active in the shelf zone are sea grass, sponges, and crustaceous life forms); planktonic, which are transported by waves and currents passively (foraminifers, radiolaria, various sea weeds; and nektonic, which move actively in the aquatic environment.

The shelf supports up to 80 % of the entire biomass of the World Ocean. After living organisms die, masses of biogenic sediments are formed.

Ocean waves are in constant motion. Here, one distinguishes wind waves, tidal waves, and permanent ocean currents.

The destructive work of seas and oceans is expressed most intensely in the coastal and shelf zones. In the zones of continental slope and ocean floor, the destructive work is made due to deep-water currents.

Waves and coastal currents destroy rocks constituting the coasts and the costal line retreats inland. This work is called abrasion. Due to abrasion of the shores, an undercut or steep see cliff (abrasion ledge). To its foot, a gently dipping, leveled plot (abrasion terrace) is adjacent. The part of the abrasion terrace covered with water during storms and tides, and formed by fragmentary materials is called a beach.

Chemical decomposition of minerals and rocks (halmyrolysis) also occurs.

The accumulative work of seas and oceans is also most intense in the coastal and shelf zones.

In the coastal (littoral) zone, various sediments with high variability of the composition along short distances are formed.

In the shelf region, terrigenous sediments are represented by well-sorted and rounded gravel pebbles, sands, and silts. The sizes of fragments become smaller, as the distance from the shore grows.

The sediments of the continental slope are homogenous. Usually, they are blue, red, or green silts.

The most widely met sediments of the ocean floor are red oceanic clays accumulated at the rate of 0.5–1 mm per century.

Chemical sediments are rarely formed in the coastal zone. They are represented by oolite limes. In the shelf zone, these are carbonate sediments, bauxite nodules, and ferromanganesian nodules. Chemogenous sediments are not characteristic of the continental slope. Among chemical sediments, iron nodules are characteristic on the ocean floor. These nodules are rotund nodular deposits of colloidal clots of manganese and iron hydrogen oxides.

Biogenic sediments are most characteristic of the shelf zone, but are frequently met in the littoral zone. Bog muck is formed on swamped ocean coasts, especially in the subtropics. In the shelf zone, biogenic sediments are formed at the cost of dying organisms. Of special interest are corals, which build various structures, coral reefs.

In the places of mass mortality of living organisms, phosphate sediments are formed on the ocean bottom.

Lecture 6

GEOLOGIC ACTIVITY OF LAKES AND SWAMPS

Modern lakes takes about 1.8 % of the dry land area on the Earth surface. They are subdivided into endogenous, exogenous, and mixed-type lakes.

Endogenous lakes are formed by water filling depressions of the tectonic origin and craters of extinct volcanoes. Examples of endogenous lakes are Baikal, Teletskoye, big lakes in East Africa (Victoria, Tanganyika, Kiwu), volcanic lakes in the Kamchatka Peninsula, Sevan (dammed with lava flows).

Exogenous lakes are subdivided into glacier lakes, river lakes, cave-in lakes (as affected by subterranean waters), and dam lakes.

Mixed-type lakes were formed by a simultaneous action of endogenous and exogenous processes. For example, Lake Ladoga and Lake Onega are connected with the zone of a fault-type tectonic disturbance, but their present-day structure was determined by glacier processes. Some lakes are remnants of former sea basins: Caspian Sea, Aral Sea.

By their hydrological regime, lakes are divided into flowage (drainage) lakes and basinal (undrained) lakes.

By the chemical composition and degree of mineralization, lakes are divided into fresh-water and salt lakes.

Swamps are areas of the Earth surface with excessive watering of the top rock horizons and development of hydrophilous swamp vegetation. Currently, the total area occupied by swamps is assessed as 2 million km^2; of them , about 60 % are in the territory of Russia.

Swamps are frequently formed in the locations of lakes, on flood lands and in deltas of large rivers, in coastal depressions, on vast areas of permafrost development. By their origin, swamps are divided into intracontinental and marine. On flood lands and in deltas, so-called overflow lands and spring bogs are developed.

Denudation and Accumulation activity of Lakes and Swamps

Lakes, similar to marine water basins, destroy coastal cliffs and bottom areas, and scatter the fragmentary and dissolved materials. The motion of water masses is manifested in the form of waves and currents caused by the wind.

In the arid-climate lakes, mainly haloids, sulfates, and carbonates are deposited due to vaporation of solutions and concentration of the dissolved substance. Depending on the composition of the deposits, sulfate-, haloid-, and natron-type lakes are distinguished. In sulfate-type lakes, the first to set are chalkstones and dolomites. Then, interbeds and lentils of gypsum and anhydrite are formed. Haloid formations finalize the setting.

In haloid-type lakes (Elton, Baskunchak) porous sodium is deposited in arid seasons. In natron lakes (Mikhaylovskoye and Petukhovskoye in Kuluidinskaya steppe), sodium carbonates precipitate in colds seasons.

Big hymid-climate lakes are fresh-water and weakly mineralized. They accumulate mainly terrigenous materials. The products of chemical erosion are carried in by rivers in the form of colloid solutions. In shallow-water coastal areas, they coagulate and form ferriferous sediments, and in tropical and subtropical areas, clay-rich and ferriferous sediments. Deposits of chalk and chalky clays are formed by carbonates in calcium brought in by subterranean waters.

Peculiar sediment accumulations occur in ocean lagoons. In salinized lagoons, chemical deposits of gypsum, anhydride, mirabilite, and salt rocks are formed. In desalted ones, mainly terrigenous and biogenous deposits are developed.

In the reducing environment of swamps, chemical sediments can be formed: protoxidic compounds of iron and manganese (swamp ores).

Lakes and swamps accumulate great amounts of biogenous sediments. The source materials for their formation are lower plants and planktonic algae. When they die, they fall to the bottom, where they decay under the effect of bacteria in the conditions of almost complete absence of oxygen, and form organic silts. This liquid colloidal mass with the aggressive odor of hydrogen sulfide is called sapropel. As it accumulates, this mass consolidates and turns into so-called slimy sapropel. Sapropels and slimy sapropels are valuable organic fertilizers.

The main role in the composition of higher plants also forming organic sediments is played not by proteins or fats, but by hydrocarbons. In the upper layers of basins they are transformed into swamp muck (humus), and in the lower ones, into bog muck. Due to all these transformations, a lake turns into a swamp.

Diagenesis.

Under the effect of gravity and as more and more sediments accumulate in the lower parts of basins, loose deposits start interacting with each other, with porous waters and the environment, in which they accumulate. As a result, the substance of primary sediments is gradually transformed, and new structures which are stable towards changes in physico-chemical conditions are formed at the deposition location. Theses processes are called diagenesis, and newly formed structures, sedimentary rocks.

Water takes upon itself about 90 % immediately when a sediment is deposited, and the sediment is subject to chemical and mineralogical changes. In chemical transformations, a major part is played by the processes of solution of weakly stable minerals, haloids, as well as of their redeposition and formation of new mineral species. The substance is redistributed, and nodules of various compositions are formed.

The process of diagenesis includes:

1. Dehydration of the sediment due to squeezing of water out of lower layers under the weight of overlaying sediments. The minerals rich in water are dehydrated and recrystallized, and readily freely soluble components are removed from the sediment.

2. Case hardening is filling of the interstitial space with the substance which binds separate components of the sediment. Precipitation of the binding agent can occur simultaneously with formation of the sediment itself or at later stages of its

precipitation. Most frequently, the binding agents are silicon earth (quartz and opal), ferrous oxides, carbonates, phosphates, etc.

3. Solidification is constriction of the initial sediments under the pressure of the overlaying ones. Recrystallization happens, mainly, to homogeneous small-grain sediments consisting of freely soluble compounds. The character of solidification transformations is largely dependent on the composition of the initial sediment, mineral composition, shapes and dimensions of fragments, and on tectonic processes.

В результате уплотнения резко меняются физические параметры осадков за счет уменьшения пористости. Так пористость песков может уменьшиться с 40–60 % до 25–30 %, а ила от 90 % до 30–35 %.

Solidification leads to abrupt changes in physical parameters of sediments due to a decrease in porosity. For example, porosity of sands can reduce from 40–60 % to 25–30 %, and that of silts, from 90 % to 30–35 %.

In the long run, all the processes lead to the sediments' losing looseness and plasticity and transforming into solid petrified rocks. Sands turn into sandstones or clays, salt brine into salt rocks, fragments of carbonate shells and carbonated slits, into chalk stones.

Due to redistribution of the sedimentary substance in the process of diagenesis, mineral deposits are concentrated and occurrences of iron, magnesium, aluminum, sulfur, phosphorites, coals, etc. come into being.

Geologic Activity of Glaciers.

A glacier is a huge mass of moving natural ice. Glaciers are formed in the process of accumulation and further transformation of solid atmospheric precipitations. The preconditions for formation of glaciers are cold climate and solid atmospheric precipitations. In the conditions of cold climate, snow covers are gradually accumulated. The boundary, over which snow is accumulated and does not melt for a long time, is called the snow line or the snow boundary. Over this boundary, the snow is distributed unevenly. Under the pressure of overlaying snow layers, surface melting and refreezing, snow turns into grained ice, or firn. Diameters of ice grains range from 1 mm to 5 mm. The thickness of the ice layer ranges from 10 cm to 100 m and more. In the foundation of such a layer, under the effect of the pressure, the crystal grains merge with each other and form a solid layer. The region where the snow turns into ice is called the catchment area. The region where the glacier moves is called the drainage area. If the amount of melting ice is equal to the amount of the ice coming in from the catchment area, the boundaries of the glacier stay more or less stable, and the position of the glacier is regarded stable. If the boundaries of a glacier expand, the glacier advances, and if they retract, it retreats. Inhomogeneities of the terrain and changes in the velocity of glacier motion cause formation of fissures. The fissures are longitudinal, transverse, and diagonal. They appear when the velocity of the glacier motion is different in different intervals.

Types of glaciers.

1. Integumentary glaciers (ice sheets).

Thickness over four kilometers. They cover large areas (up to several million km^2), have the arching, shield-like form, high thickness, overlapping catchment and drainage areas, radial ice flows (from the center towards the edges of the continent). This type includes the glaciers of the Antarctic, Greenland, Novaya Zemlya, and Severnaya Zemlya. When they dip into the ocean, the edges of the glaciers split into vast ice fields up to 167 km long and more. They are called icebergs (ice mountains).

2. Mountain glaciers.

Mountain glaciers are smaller, their shape is various and frequently complicated. The area of large glaciers exceeds 1 thousand km^2. Depending on the shape and the regime, two main types of mountain glaciers are distinguished: cirque glaciers and valley glaciers.

Cirque glaciers are formed in bowl-like hollows on mountain sides. They have insignificant dimensions and small thicknesses. On steep mountain sides, glaciers overhang corniches. They are hanging glaciers. Periodically, they break away from the slope and fall down. Lumps of fallen ice merge and form a newly reborn glacier (Urals, Transbaikalia).

Valley glaciers spread over valleys of mountain rivers. They are “fed” by firn basins situated in bowls or mountain trenches. The richer the feeding, the longer is the glacier. Largest valley glaciers are found in the Pamir and Himalayas.

3. Intermediary glaciers

Intermediary glaciers are similar both to intergumentary and mountain glaciers. They are subdivided into glaciers of uplands (Scandinavia) and piedmont areas (Alaska).

Glaciers make large destructions. They cut cliffs and transport rock fragments frozen into the ice. The motion of glaciers is assisted by water, it serves as a lubricator. Under the weight of a glacier, terrain roughness smoothes up, and depressions are ploughed in loose rocks. Destructive works of glaciers are called exaration or glacial erosion. The size of destructions depends on the pressure exerted by the glacier on its bed. They are stronger, if fragments of hard rocks are sealed in the glacier foundation. These fragments scratch and polish hard rocks. One can determine the direction of glacier motions from the position of the “scars”. Smoothed rocks are called roche-moutonnee, and groups of such rocks but of a smaller size and alternating with depressions are called ice-dressed rocks.

A glacier transports fragments of geological materials (moraines). Moraines can be moving and immobile. Depending on the position of moraines in the body of the glacier, moving moraines are subdivided into surface, internal, and terminal moraines. A surface moraines is situated on the surface of a glacier. It can be lateral (situated along the glacier edges) and medial (formed between two adjacent glaciers). As the ice melts, the latter moves into the glacier and becomes internal. Internal moraines are formed also when the surface of a moraine crushes into a crack in the glacier. The fragments frozen into the glacier foundation constitute the bottom moraine. As they move, moraines are ground and pulverized, and the hardest of them get covered with cracks and turn into pebbles or clays.

As a glacier melts, a moving moraine constantly sinks into it and is deposited on the glacier bed. There, an immobile moraine is formed. Main and terminal moraines are distinguished.

Main moraine is merged bottom, medial, and internal moraines. They occur in the form of moraine ridges extended along the direction of the glacier motion. They consist of small-grained fragmentary materials (clays and pebbles).

Terminal moraine. Has a composition similar to the main moraine. The difference is that it is elongated along the glacier edge.

Another form of the glacier terrain is drumlins (shaped as oblong ovals). They are formed near obstacles in the path of the glacier, on which morainic deposits stop. Morainic deposits occur in mountain regions. In geologic cross-sections, morainic deposits from early geologic periods are represented by heavily solidified deposits, in which scarred boulders and smaller-size morainic materials are observed. (The thickness of an ancient moraine reaches 180 m). Unlike modern moraines, they are termed tillites (drift clays).

Another form of glacier deposits are fluvioglacial (water-glacial) sediments. They are formed with participation of glacial waters. Water flows comes to being when snow and ice melt. They wash small fragments out of the glacier body and transports them out of it. Deposits of glacial waters are represented by sorted, and frequently stratified clays, sands, gravels, and pebbles. Sediments of pre-glacier lakes are characterized by stratification caused by alternating thin layers of clays and small-grained sand. Each pair of such layers is deposited during a year. From their amount, one can judge about the age of deposits. Clays of this structure are called banded clays.

The traces of the most ancient glaciation were found first in North America. The age of these glacial deposits is about 2 billion years. They are represented by tillites and banded clays. The second, Proterozoic glaciation (1500 billion years ago) was found in Equador and South Africa, and also in Australia. At the end of the Proterozoic era, the third glaciation happened, Pre-Cambrian, or Scandinavian. There were 2 glaciations in the Paleozoic period. The first one happened about 600 million years ago. Glacial deposits of this age have been found in the territory of Morocco, Libya, Spain, and France. It began in the Ordovician, and ended in the Silurian period. The second, Gondwanian, embraced India, Africa, and South America. It started in the Carbonic period, at the end of the Permian period.

The reasons of glaciation are as follows:

1. Change in the inclination of the Earth's axis;
2. Deviation of the Earth from its orbit away from the Sun; and
3. Irregular thermal radiation of the Sun.

Glaciology is the science studying glaciers. Geologists use it to study the moraine materials in order to seek for mineral deposits.

Lecture 7

MODES OF OCCURRENCE OF IGNEOUS AND METAMORPHIC ROCKS

Effusive rocks

Effusive rocks can be found in geologic cross-sections among formations of all geologic periods, from the Archean to Quaternary. They can be observed in the form of ground-level and underwater effusions, as tuffs and tuffites being the products of volcanic emission. Pre-Cambrian effusive rocks have mainly undergone intense metamorphism and turned into various crystalline schists, porphyroids, etc.

Volcanic activity can be of two types: eruptions of the central type, when magma eruption and extrusion occurs through a channel, which has comparable dimensions in the transverse (horizontal) cross-section; and eruptions of the linear type, when magma is erupted through a channel, in the horizontal cross-section of which the length in one of the directions exceeds the width by tens and hundreds of times.

The mode of occurrence of effusive rocks is also largely dependent on the chemical composition of the erupted lava. Basic lavas are very fluid. As a result, before they solidify, they can cover vast areas on the Earth surface. By contrast, acid lavas are significantly less fluid, and do not propagate far from the volcanic orifice.

As a rule, in eruptions of the central type on continents, a volcanic cone is formed of eruption products, volcanic ash, bombs, etc.

Linear eruptions are most frequently associated with platforms. Usually, the lava content here is basic, hence even on insignificantly inclined terrains lava can sometimes cover extremely vast areas forming so-called trappean plateaus.

Underwater lava outflows occur in the conditions, which differ significantly from those on the continents. Such lavas are usually characterized by stable thickness along great distances, good sorting of piroclastic materials, and alternation with marine sedimentary rocks.

The age of effusive formations is determined from the age of the sedimentary rocks, in which they are confined.

Intrusive rocks

Intrusive rocks occur frequently in the Earth crust. The majority of ancient crystalline masses, which are currently denudated, consist primarily of intrusive rocks.Depending on their relationships with enclosing rocks, intrusive rocks are subdivided into concordant and discordant.

Main types of concordant intrusions are laccoliths, lopoliths, phacoliths, and sills.

Laccoliths are bodies whose shape resembles the cap of a mushroom, and the size (diameter) usually does not exceed 5 km. They are the result of penetration of significantly pressurized magma.

The overlaying strata are usually bended by the pressure, and occur in concordance with the laccolith body.

Laccoliths are usually formed at shallow depths (500–600 m) and, consequently, are frequently exposed due to erosion processes. Most often, they are composed of acid rocks. Such formations are common in the Crimea, the Caucasus, the Carpathians, and other regions.

Lopoliths are intrusive bowl-shaped bodies from hundreds of meters to hundreds of kilometers in diameter. This is a typical mode of occurrence of intrusions with basic, ultrabasic, and alkaline contents.

Phacoliths are intrusive bodies shaped as a saddle or a lens in plan and cross-section. Most frequently, they are formed in the curve sections of anticline folds, rarer, in syncline ones. The thickness of phacoliths can reach several hundreds (rarely, thousands) of meters.

Sills (intrusive sheets) are intrusions shaped as strata and occurring mainly in concordance with the bedding. Their thickness is from several centimeters to several hundreds of meters, and the areas they occupy exceed sometimes 1000 square km.

The rocks comprising sills can be from acid to basic ones (Siberian traps).

Main types of discordant intrusions are batholiths, diapirs, nekks, dikes, and lodes.

Batholiths are extremely large masses of intrusive granitoid rocks formed at significant depths. A batholith, when exposed, usually reveals its elliptical form. In the majority of cases, batholiths do not disrupt the harmony of the folding structure of the enclosing rocks, and often the produced impression is that a batholith is formed by their melting without any pressure exercised on them.

The surface of exposed batholiths exceeds 100 km and sometimes reaches several thousands of kilometers. In the deep, they go directly into magma. The problem of batholiths, especially of the space they occupy, has not been solved yet.

There are three opinions about this issue:

1. Ascension of a batholith (magma) causes destruction of the rood, which is further dissolved (assimilated) by the batholith, which had not solidified yet.

2. Magma penetrating the rocks expands its aureole by assimilating and remaking the enclosing rocks near the batholith contacts.

3. Penetrating into the Earth crust, magma raises it on vast territories without disrupting earlier structures and the level of metamorphism.

Along the mentioned viewpoints concerning the origin of batholiths, there is another one: such bodies are formed due to granitization of the enclosing rocks, i.e. complete reworking of their texture, structure, and mineral composition under the effect of active solutions fed in from depth sources.

Diapirs are hypabyssal intrusive bodies elongated in plan and cross-section and not exceeding several kilometers in size. Unlike laccoliths, they affect actively the enclosing rocks following cracks in the Earth core, and crush them.

Nekks are bodies that serve as the ways of magma penetration to the surface; they are vents of the volcanoes that once were active. In the transverse cross-section, they are rounded, elliptic, or irregular. Their diameter ranges from tens of meters to 1000–15000 m. The walls of nekks are steep. Sometimes, unclassified fragmentary material (explosive breccia) is observed along the walls. Famous kimberlitic pipes containing diamonds are nekks.

Dikes are discordant intrusions limited by parallel walls. Dikes are the result of magma's filling cracks in the Earth core. The thickness of dykes varies in a wide range, and their lengths can reach 100 and more kilometers.

Loads, unlike dikes, have less regular thickness and can be composed of various materials being the products of magma decomposition. Often loads contain valuable minerals.

The age of intrusions is determined from their relationships with the enclosing rocks (relative age). The absolute age is determined from radioactive minerals.

Interaction of intrusive bodies with the enclosing rocks can be manifested in their active action on such rocks (presence of an aureole of the contact thermal effect, contact metamorphism), which evidences later origination of the intrusion relative to the enclosing rock. Sometimes an intrusive mass can be eroded and overlaid with younger formations: hence, it is older than those new formations.

Analysis of these relationships makes it possible to restore the history of geologic development of the area.

In the Figure, granites tear through the deposits of Carbonic and Permian sediments and, at the same time, in the North-West part of the region they are overlaid by Jurassic and Cretacious sediments lying on the eroded surface of granits and Permian and Carbonic formations. In this case, one can say that the granits can be Upper Carbonic, Permian, or Triassic. However, it other sources provide the information that crustal folding, as well as the magmatic activity, occurred in this area only in the Permian period, and in the Trias the area was not subject to intense tectonic movements, it is most reasonable to suppose that the age of the granites is Permian. When determining the relative age of intercrossing intrusive bodies, it is necessary to trace their contacts attentively. The youngest body is that which breaks through other intrusions.

Metamorphic rocks

Metamorphic rocks are those initially sedimentary and magmatic rocks, which have undergone significant changes in their structure, texture, and mineral composition under the effect of high temperatures and pressures. These transformations can have both the local and the regional character. Local development of metamorphic rocks is usually a result of the effect of invasive magmatic rocks. Local metamorphism can be observed also in the zones of large-scale faults.

The rocks having undergone regional metamorphism are very abundant. All Pre-Cambrian rocks are metamorphized. The rocks having undergone regional metamorphism in the Paleozoic are widely developed, less developed are those metamorphized in the Mesozoic, and still less, in the Paleozoic.

Special features of the conditions, in which rocks are metamorphized, result in formation of foliation, i.e. planar arrangement of flaky materials. Foliations are frequently situated at an angle to stratification planes, similar to cleavage.

Depending on their initial nature, metamorphic rocks are studied either as sedimentary or igneous rocks. The rocks of initially sedimentary formation occur in the form of strata forming folded structures of various types. They form folded structures of different types. In them, marking horizons can be also distinguished, e.g. marble strata between mica schist or quartz rocks. One can identify stratigraphic relationships, unconformities, facies changes, faults, etc. Similar to sedimentary rocks, geologic maps and cross-sections are plotted.

Sometimes, zones of regional metamorphism may not coincide with the general line of rock bearing. In this case, it is very important to study the bearing of the strata in full detail. For example, the same stratum of initially clay composition can be represented, in the zone of high-temperature of metamorphism, by mica schist with garnets and disthens, and in a lower-temperature zones, by phyllites. In this case, the geologic map is supplemented with so-called metamorphism isogrades (an example: Mamsk).

Widely developed in metamorphic rocks are so-called zones of crush and mylonitization represented by the products of dynamic metamorphism, i.e. metamorphism of high pressures and relatively low temperatures. In such zones, rocks are subject to intensive cracking and mastication.

Folding morphology in metamorphic rocks is usually more complex compared with sedimentary series. Very frequently, isoclinal and flow folds are dominant here, boudinage of relatively hard strata and early lode formations is well-pronounced.

Maximal reworking or initially sedimentary and magmatic rocks occur in ultrametamorphic zones characterized by extremely high temperatures. Here, disappearance of the surfaces of primary stratification is frequently observed, and the series is granitized. In such areas, the rock mass becomes actually non-stratifiable. Series can be distinguished only on the basis of their mineralogic composition and the character of migmatites (laminary migmatites, shadow migmatites, gneissic granites).

In terms of the relative size of mineral grains, one distinguish equigranular structures (all the grains of the same mineral have equal dimension), inequigranular, or porphyraceous (in which individual large grains, porphyritic effusions, are enclosed in small-grained aggregates), and porphyritic (which differ from the porphyraceous in that porphyritic effusions here are set off against the background of the main adelogenic mass).

A texture is a set of the parameters of the rock structure, which are determined by the position of its components relative to each other and the way of space filling.

<u>Massive texture</u> is most widely spread. It is characterized by even and chaotic disposition of mineral grains in any part of the rock, without any kind of orientation.

Schlieren texture: individual areas in the rocks differ from each other in their composition and structure.

<u>Spherical</u> texture: minerals in the rock are situated as concentric layers around some centers.

In terms of space filling, dense, porous, and amygdaloid structures are distinguished.

Dense texture: grains sit densely, without free space or gaps between them.

Porous texture: hollows of the spherical or uneven shapes are present in the rock.

If the hollows are filled with secondary minerals, such texture is called amygdaloid.

ROCKS

Rocks are natural mineral aggregates of the more or less constant composition. In terms of their origin, rocks are divided into three large groups: igneous, sedimentary, and metamorphic.

Igneous rocks

Igneous rocks were formed as a result of solidification of the flaming mass erupted from the Earth interior in the form of lava on the surface (effusive rocks) or at a certain depth (intrusive rocks).

Igneous rocks consist of the minerals formed at high temperatures (700–1300°). The majority of igneous rocks is characterized by massive structures with even chaotic distribution of mineral grains. Structures formed by igneous rocks usually have sharp boundaries. They tear through enclosing rocks and frequently occur in discordance with them.

Igneous rocks are frequent in the Earth core. On the surface of the continents, they occupy 25 % of the total area, and in deep horizons of the Earth core, up to 90 %.

Chemical composition. Main chemical components of igneous rocks are the following nine elements: O, Si, Al, Fe, Mg, Ca, Na, K, and H. All igneous rocks contain SiO_2, therefore its content is the basis for their chemical classification. Rocks containing over 65 % of SiO_2 are acid; 52–64 % SiO_2, medium; 45–52 % of SiO_2, basic, and less than 45 % of SiO_2, ultrabasic.

The mineral composition of magma rocks depends on their chemical composition and formation conditions. Of the 2000 known minerals, only 30 occur frequently in igneous rocks. The main minerals are divided into two groups: color, or femic (rich in iron and magnesium), and light, or salic (rich in silicon and aluminum). Examples of color rock-forming minerals are olivine, pyroxene, amphibole, and biotite. Examples of light minerals are feldspars, quartz, and kephalin.

Structures and Textures of Igneous Rocks

Features of the internal structure of the rocks are conventionally described by two terms: structure and texture.

The structure is the set of the rock structure indicators that characterize the degree of its crystallization, absolute and relative dimensions of mineral grains, as well as the shape and interrelationship of the minerals constituting the rock.

By the crystallization degree, three types of rocks are distinguished: 1) holocrystalline (consisting entirely of crystal grains); 2) undercrystallized (consisting of crystals and volcanic glass); 3) glassy (consisting entirely of volcanic glass).

In terms of the absolute dimensions of mineral grains, rocks may be giant-grained (diameter of mineral grains over 50 mm), large-grained (5–50 mm), medium-grained (0,5–1 mm), and adelogenic (consisting entirely of microscopic crystals; they may be holocrystalline or contain volcanic glass, i.e. be undercrystallized).

Sedimentary rocks

Sedimentary rocks are formed of the sediments deposited mainly on the bottoms of water basins and on the surface of dry lands. Such rocks are deposited at comparatively low temperatures and pressures characteristic of these areas due to the products of decomposition of earlier rocks, products of organic life, and materials of the volcanic origin.

The process of formation of sedimentary rocks is subdivided into the following main stages:

1) erosion: mechanic or chemical destruction of earlier formed igneous, metamorphic, or sedimentary rocks;

2) transportation of erosion products by flowing waters, winds, and living organisms;

3) deposition (which can be temporary and occur repeatedly) and accumulation, the main feature of sediment formation, in which it acquires its main characteristic features: the size and shape of the particles that constitute it, its mineral and chemical composition, organic remnants enclosed in it, stratification, etc.

Sediments can be overlaid by other sediments, sink deep down, and gradually turn into sedimentary rocks. The processes of such transformation are called diagenesis.

Classification of sedimentary rocks

Sedimentary rocks are most frequently classified by their origin and the composition of their components into the following main groups: 1) igneous-fragmental; 2) fragmental; 3) clay; 4) biogenic-chemical; and 5) chemical.

Igneous-fragmental (piroclastic) rocks are the products of volcanis eruptions in the form of volcanic bombs, laccolith, volcanic sands, and fine particles of volcanic cinders. Any other sedimentary material, as well as organic remnants can be present in igneous-fragmental rocks as admixtures.

If the volcanic material constitutes over 90 % of the rock, such rock is called volcanic tuff. If it is 50–90 %, it is tuffite, and if it is less than 50 %, the rock is called according to its prevalent fraction.

Fragmental rocks consist of fragments of other, earlier formed rocks and are a characteristic product of mechanical erosion. Here, three parameters are of the special importance: 1) size of the fragments; 2) their shape; and 3) mineral composition.

The first two parameters show the distance and method of fragment transportation, the third one depends on which rocks were subject to destruction.

In fragmental rocks, one distinguishes between fragmental grains and the binding agent, which fixes these grains to form solid rocks. In terms of the size of the prevailing grains, sedimentary rocks are divided into three main classes: rudaceous, sandy, and aleuritic rocks.

Rudaceous rocks are subdivided additionally, by the form of the fragments, into angular, semi-rounded, and rounded.

By their mineral composition, sedimentary rocks are subdivided into monomictic (if they are constituted by one mineral predominantly, e.g. quartz sands) and polymictic (if the mineral composition is diversified).

The binding agent can be clayisch, chalky, ferrian, siliceous, or of a mixed type.

Clay rocks consist mainly of clay materials. The majority of the grains in them has diameters less than one hundredth of a millimeter.

These are the most frequent rock sediments. Their share in all the sedimentary rocks is about 40 %. Clay minerals are formed due to chemical decomposition of the minerals in source rocks. There is about 60 clay minerals. They are subdivided into three main groups: kaolinite group, montmorrilonite group, and hydromica group. By the degree of densification, they are subdivided into clays (multiplying in water) and argillites (non-multiplying).

Biogenic-chemical rocks are the rocks, in whose formation the matter of living beings participate.

There are rocks consisting almost entirely of organic products: fossil coals, some chalk stones, and other rocks. In other materials, there are only insignificant admixtures of the organic substance.

Chalk stones are rocks that consist of calcite by more than 50 %. By their origin, they may be organic, organogenic-chemical, chemical, and fragmental. The first two groups occur especially often.

<u>Rocks of the chemical origin.</u> The rocks of the chemical origin are gypsum rocks, halite rocks, sylvin rocks, ferrous rocks, glauconite rocks, phosphate rocks, etc.

<u>Metamorphic rocks</u>

The rocks of the igneous or sedimentary origin, which have undergone the effect of intense heat flows from the interior of the Earth, as well as the effect of the pressure or direct heat effect of magma and, consequently, having endured significant changes in the mineralogic composition and structure are called metamorphic rocks.

If a metamorphic rock originated from an initially igneous rock, it is called an orthorock.

Metamorphic rocks originating from sedimentary rocks are called pararocks.

Metamorphic rocks affected by tectonic forces are usually cleaved, i.e. they acquire the cleaved structure characterized by subparallel position of the scales of micaceous minerals. When metamorphic rocks are formed by immediate thermal effect of magma, the massive texture is formed.

Depending on the temperature and pressure, the following facies of metamorphism are distinguished: greenschist, amphibolite, and granulite. In the greenschist (low-temperature) facies, chlorine schists, phyllites, and part of quartzites and marbles are formed.

In the amphybolite facies, crystallized schists, gneiss, quartzites, and marbles are formed.

In the granulite facies, various magmatites and irestones are formed.

Marbles are recrystallized chalk stones and dolomites. The mode of occurrence is sheeted. They can be of different colors. They have a crystal-granular structure. By their structure and shine they resemble sugar. When polished, frequently show beautiful patterns.

<u>Quartzites</u> are solid confluent masses of quartz, with soapy luster and granular fractures. They occur in the form of strata and were formed from sand stones (primarily, quartz ones).

Phyllite is micromicous schist. Usually it is black or grey. Mica is not seen with a naked eye, but its numerous small scales make the luster of the rock silky.

Clay schist is shaly metamorphic clay rock, non-multiplying in water. A major part of its clay minerals as effected by metamorphism turned into various mica (microscopic scales).

Mica schist is a light, shiny with crystals of white mica (muscovite), sharply sheared rock. They differ from gneiss by containing no feldspar and were formed of sedimentary rocks.

Gneiss are crystalline, light-color schist rocks consisting of quartz, mica, and feldspar. Mica are often situated in ribbons.

Talcous schist is very soft, schistous, greasy to the touch rock, pale-green, consisting of talcum. It was formed by the changes in main igneous rocks.

Serpentinite is the rock that contains mainly serpentine and was formed by ultrabasic rocks (peridotites).

Minerals are natural chemical compositions or individual elements that are the products of various geologic processes, homogenous in their chemical composition and physical properties.

As of now, about 2000 minerals have been found in the Earth crust, and counting their varieties, about 4000.

Each mineral has its own set of certain properties characteristic of that mineral. Simplest properties used to identify minerals visually are called <u>diagnostic properties</u> or signs. They are: color, streak color, luster, hardness, cleavage, etc.

<u>Color of the minerals.</u> Three types of mineral coloring are distinguished:

Idiochromatic: caused by crystallo-chemical properties of the mineral itself. Most frequently, it is caused by chromophores (color-bearing elements) in the mineral content. Minerals with the idiochromatic nature of the coloring always have the same color.

Allochromatic coloring is connected with foreign mechanical admixtures fine-spread in the mineral. In this case, the color of the mineral is not constant.

Pseudochromatic, or false coloring is caused by optical effects, most frequently, by the interference of the reflected light.

One can often see bright iridescent films, which are called tarnish, on the oxidized surfaces of minerals (copper pyrite, erubescite, etc.).

The color of the streak, which a mineral makes on a matte porcelain plate, or the color of a powdered mineral can coincide with the own color of the mineral or differ from it. It is reasonable to determine the streak color for opaque and semi-transparent minerals with the hardness less than that of porcelain.

The mineral luster depends on the refraction and reflection indexes. There main types of the luster are as follows:

Glassy: resembling the shine of glass. It is characteristic for transparent and semitransparent minerals;

Brilliant: strong sparkling luster;

Submetallic: similar to the luster of a tarnished metal surface;

Metallic: resembles the luster on a smooth metal surface.

One distinguishes also dull (soapy), waxy, matte (weak), and pearly lusters.

Transparence. Minerals can be transparent, semitransparent, and opaque (non-transparent).

Hardness is the capacity of minerals to withstand an external mechanical effect of a harder body. In mineralogy, relative hardness is usually determined by scratching one mineral with another. For this, the Mohs scale of relative hardness is used, which includes the following minerals:

	Hardness
Talcum:	1
Gypsum:	2 (finger-nail)
Calcite:	3
Fluorite:	4
Apatite:	5 (glass)
Orthoclase (common feldspar):	6 (steel knife)
Quartz:	7
Topaz:	8
Corund:	9
Diamond:	10

Cleavage is the capacity of minerals to split or splinter along certain crystallographic directions using even planes, which are called cleavage planes. Cleavage can be:

1. Perfect. The mineral splits easily into separate plates or sheets. It is very hard to break it in another direction (micas, chlorites, talcum).

2. Good. The mineral splits easily along cleavage planes (calcite, galenite, halite).

3. Distinct (average). There are both cleavage planes and uneven breaks in arbitrary directions (feldspars, irestone).

4. Indistinct. Minerals split along arbitrary directions forming uneven breaking surfaces, cleavage planes are hard to find (apatite, nepheline).

5. Poor: no cleavage (magnetite, corund).

Break, or fracture: the type of the surface produced by splitting a mineral. It can be:

Shell-like (mountain crystal);

Splintery (gypsum, irestone);

Uneven, or irregular (nepheline); and

Earthy (brown hematite, kaolin).

For different minterals, density ranges from 600 to 27000 kg/m^3. In practice, for the purposes of fast identification, minerals are subdivided into “heavy” (density > 4000 kg/m^3, ore minerals), “average” (calcite, quartz, feldspars), and “light” (oils, tars, coals, gypsum, salts).

Magnetics is revealed by a mineral's effect on the magnetic hand of a compass (magnetite, pyrrhotine, platinum).

The reaction with the 5–10 % solution of hydrochloric acid accompanied with release of gaseous carbon dioxide is used to diagnose the minerals of the carbonate class. Calcite bubbles up demonstratively in a lump.

Dolomite, only as a powder.

Magnesite, only when heated.

Water solubility (taste) is characteristic of natural chlorides. Halite is salty, sylvin is bitter-salty.

A course of lectures in

STRUCTURAL GEOLOGY

Lecture 1

INTRODUCTION

Structural geology is a subdiscipline of geotectonics and has two primary tasks:

1) it studies the morphology, i.e. the exterior and size of structural forms (e.g. individual folds, faults, rock bodies) and their simplest combinations and interrelationships;

2) it reveals the mechanisms for the formation and sequence of evolution of these structural forms.

Structural geological studies are performed in the process of geological mapping.

Geologic maps

Geologic mapping (geologic survey) is a set of studies aimed at building the geologic maps and identifying the prospects of the territory under consideration in terms of mineral products.

A geologic map is a graphic representation of the geologic structure of this or that territory on the topographic basis. Legend, i.e. special conventional signs, color backgrounds, and various marks are used to show the age, composition, and mode of occurrence of geologic materials, as well as the nature of the boundaries between individual rock units. At the same time, a map should be structural, i.e. it should reflect the mode of occurrence and interrelationships of rock units within a given area not only on the surface, but in depth. Reading a map provides the opportunity to comprehend the structure of the whole bulk of deposits, to forecast the distribution and mode of occurrence of mineral products, and select the right search direction.

Geologic maps show mainly original, i.e. Pre-Quaternary rocks: sedimentary, ignious, or metamorphic formations. Quaternary-system deposits are shown only when their thickness exceeds 5 m.

Depending on their scale, geologic maps are subdivided into 4 groups:

1) Small-scale (general) maps, having a scale of 1:500 and smaller;
2) Average-scale maps, 1:200 000 – 1:100 000;
3) Large-scale maps, 1:50 000 – 1:2500; and
4) Detailed maps, 1:10 000 and more.

Average-scale, large-scale, and detailed geologic maps are supplemented with stratigraphic columns and cross-sections.

A stratigraphic column is a 2–4 cm wide column, in which the location and composition of all the rocks developed within the territory shown in the map are represented in the age (stratigraphic) sequence using conventional hatching. To the left of the column, the age of the rocks (system, series, stage, suite, etc.) and their indexes are shown. To the right, their thickness are given, and their composition and found fossils are described. The scale of the column may vary, but it is larger than the scale of the map.

Geologic cross-sections are vertical cross sections of the Earth crust from its surface to this or that depth. They are plotted along straight lines drawn across the whole map in such a way as to provide the fullest understanding of rock occurrence. The vertical and horizontal scales of cross-sections must correspond to the scale of the map. If the strata bedding is horizontal, or the scale of the map is too small, the vertical scale of the cross-section may be increased.

Coloring and symbols of the main stratigraphic subgroups
in geologic maps

Group	System	Color	Index
Cenozoic		yellow	KZ
	Quaternary	yellow-gray	Q
	Neogene	yellow	N
	Paleogene	orange-yellow	P
Mesozoic		green	MZ
	Cretaceous	green	K
	Jurassic	blue	J
	Triassic	purple	T
Paleozoic group		brown	PZ
	Permian	orange-brown	P
	Carboniferous	grey	C
	Devonian	brown	D
	Silurian	green-gray	S
	Ordovician	olive	O
	Cambrian	blue-green	C
Proterozoic group		pink	PR
Archaean group		purple-pink	AR

MODES OF OCCURRENCE OF SEDIMENTARY ROCKS

1. Strata and Stratification

The most characteristic feature of sedimentary rocks is their occurrence in the form of strata or layers.

A stratum or a layer is a geological body being a tabular formation of a comparatively thin thickness and significant dimensions, which is formed by a sedimentary rock, differs from the adjacent strata in some properties, and is limited by stratification planes.

For each stratum, its base, top, and thickness are distinguished.

The base is the most ancient part of the layer, and the top is its youngest part. The thickness, or depth of a stratum is the distance between its top and bottom. For inclined strata (see fig. 1), true (*a*-*c*), horizontal (*a*-*b*), and vertical (*a*-*d*) thicknesses are distinguished.

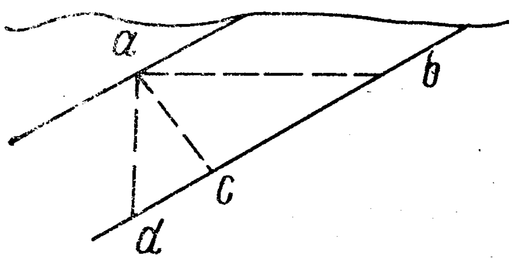

Fig. 1

Alternation of strata is called bedding. Bedding is occurrence of an inhomogeneity in the mass of sedimentary rocks, and it evidences the changes in the sedimentation conditions.

The main part of the sediments on the Earth surface is accumulated in ocean and continental water bodies or on coastal planes. The surface, on which rocks are accumulated in these conditions, is usually inclined at small angles (less than 1°). Therefore, the main part of sedimentary rocks is deposited almost horizontally. However, the initial occurrence of sedimentary rocks comparatively rarely stays the same. It is disrupted by later tectonic movements which can lead to significant inclinations of strata and formation of folds and faults.

In terms of the connection between individual beds, transgressive (*T*) and regressive (*P*) bedding is distinguished (fig. 2). The most frequent type of sedimentary rock occurrence is the transgressive bedding caused by formation of sediments in a downfold against the background of general long-term depression.

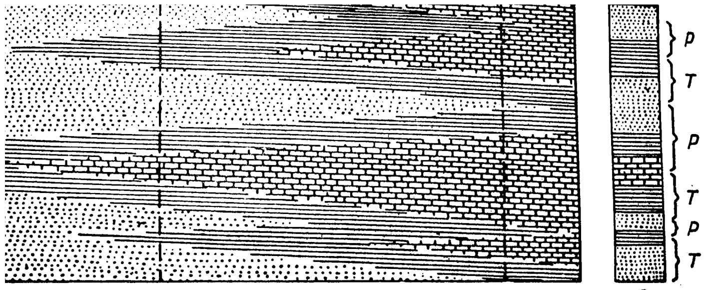

Fig. 2

A transgressive sediment series is characterized by an increase in the size of fragments of the terrigenous material from the top towards the base.

The regressive bedding type is manifested in a sequential contraction of the area of the sediment accumulation basin, and the absence of the ocean caused by upward movements of the Earth crust. A regressive sediment series is characterized by an increase in the size of fragments towards the top of the formation.

2. Forms of Stratification

When studying bedding, one should first pay attention to the shape and thickness of the layers.

The shape of the bedding reflects the character of the motion of the medium, in which the sediment was accumulated. Four main bedding forms are distinguished: regular, undulated, diagonal (cross), and lenticular (lens-shaped).

In case of parallel stratification, stratification planes, in terms of their structure, are close to plane surfaces. This type of stratification shows that the medium, in which the sediments were accumulated, was relatively stationary. Such conditions occur in lake and ocean basins below the level of wave effects. Here, the main role is played by the amount and dimensions of the sedimenting materials.

Undulated bedding has rolling wavelike bedding planes. It is formed when the directions of medium motions are interchanged or repeated periodically, e.g. in flood and ebb currents or turbulence in coastal or shallow-water zones of the ocean.

Cross bedding is the bedding with rectilinear or curvilinear bedding planes, with smaller-scale beddings situated at different angles to those planes within the layer. This bedding type is formed when the medium moves in one direction, e.g., in rivers, ocean currents, or air flows. Depending on the formation conditions, several varieties of cross bedding are distinguished:

1) stream cross bedding (fig. 3);
2) estuary cross bedding;
3) cross bedding of marine sediments;
4) shallow-water cross bedding;
5) aeolian (wind-laid) cross bedding (fig. 4).

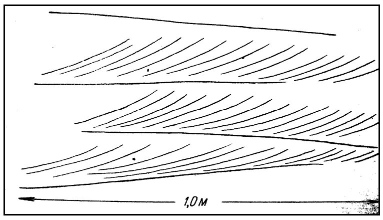

Fig. 3

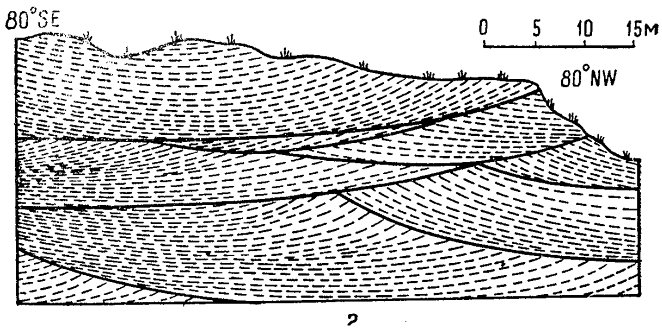

Fig. 4

Stream cross bedding has the same general inclination towards the direction of water motion. Deltal cross bedding, usually, has a larger scale, oblique straticules run smoothly into the layer base and disappear at the top, where coarser materials appear.

Cross bedding of marine sediments has large dimensions and gentle inclination. In shallow-water zones affected by waves, a peculiar, extremely fine, interlacing cross bedding is formed, which is aligned in various directions. Aeolian cross bedding is peculiar for its distinctive directivity. It can be oriented to different directions and has variable thickness.

Lenticular bedding is characterized by a great variety of shapes and variability of the thickness of individual layers. In this case, the layers is frequently pinched out completely, which leads to its decomposition into separate parts of lentils. Lenticular bedding is formed when a water or air medium moves fast and irregularly, e.g. in river streams. Not infrequently, it is associated with bottom irregularities.

The thickness of a layer reflects the intensity of the motions of the medium, in which the sediment is accumulated, and the amount of the material entering the sedimentation zone. Depending on the thickness, four bedding types are distinguished: large-scale, with the thickness of individual layers from tens of centimeters to several meters; small-scale, with the thickness of the layers measured in centimeters; fine, for which the layer thickness is measured in millimeters; and microbedding, which is visible under a microscope only.

3. Structure of Bedding Planes

Studying the features of the bedding-plane structure helps revealing the origin and conditions of occurrence of sedimentary masses.

Among these features are: fossil herbs, ripple marks, initial cracks, desiccation cracks, fossilized traces of various living organisms, rain-drop and ice-crystal impressions, etc.

Ripple marks look like more or less parallel, rectilinear or curvilinear striae and ridges, 5–2 cm high.

Desiccation cracks dissect the bedding plane into polygons. They develop in the layers formed by clay rocks, and are filled later by coarser-grained materials. Desiccation cracks are characteristic of fossil deserts, alluvial plains, and wide beaches.

Traces of animal life (bioglyphs) are impressions made by bottom-dwelling organisms.

Rain-drop and hail impressions, as well as traces of ice crystals evidence formation of the sediment in the conditions of a coastal strip. They look like rounded cavities, pimples, or notches.

Lecture 2

HORIZONTAL OCCURRENCE OF LAYERS

Horizontal layer occurrence is characterized by the general horizontal, or nearly horizontal position of bedding planes. Such masses are developed on the Russian and Siberian platforms, on the West Siberian plate and in other regions, where sedimentary rocks were not affected by significant tectonic movements after their formation.

In horizontal occurrences, absolute values of the inter-strata boundaries are approximately the same, therefore in geologic maps they either coincide with horizontal contour lines or are parallel to them. Each underlying stratum is older than the stratum overlying it. Ancient layers crop out to the ground surface in the lowest depression areas, and the youngest layers, in elevated ones. The true thickness, in case of a horizontal occurrence, is determined as the difference between the marks of the top and the base of the layer.

For horizontal occurrences, the most rational direction of a geologic cross-section will be the line passing through the lowest and highest points in the terrain. In this case, the main information for construction of a cross-section below the terrain level is yielded by drill wells.

STRATIGRAPHIC UNCONFORMITIES

If each overlying stratum or a stratum series lays on the underlying layers without depositional breaks, which reflects discontinuity of the deposition process, it is called conformity or regular bedding. If this sequence is disrupted, and for a more or less long-term period no deposition are formed (e.g. due to elevation of the bottom of a former basin above the sea level), unconformity is developed. Such unconformities are called stratigraphic.

Along different criteria, stratigraphic unconformities can be subdivided into several types.

Based on their angles, unconformities may be: parallel, angular (fig. 5), and geographic.

A parallel unconformity is signified by a break in the layers positioned in parallel.

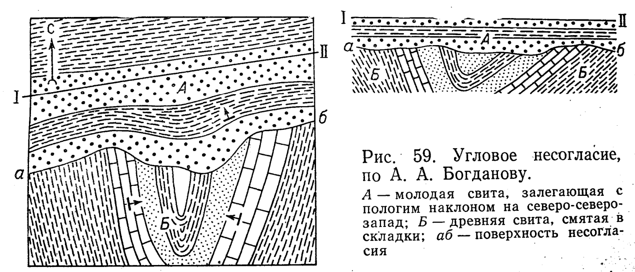

Рис. 59. Угловое несогласие, по А. А. Богданову.
А — молодая свита, залегающая с пологим наклоном на северо-северо-запад; *Б* — древняя свита, смятая в складки; *аб* — поверхность несогласия

Fig. 5

An angular unconformity is signified by a break between two stratum series with different inclination angles. Such unconformities are usually clearly reflected both in natural vertical cross-sections and in geologic maps. In the both cases, the surface of the unconformity separates unconformable suites, cuts different formations of the ancient suite at an angle, and runs more or less in parallel to the boundaries between individual formations of the younger suite. The value of the unconformity angle can vary in a wide range and change abruptly in different zones.

A geographic unconformity is an angular unconformity with an angle of less than 1^{o}. It can be identified only when studying vast territories.

From the viewpoint of distinctness of the unconformity surface, there may be obvious unconformities with distinct unconformity surfaces, and hidden unconformities, with undefined positions of unconformity surfaces.

In terms of the spread area, unconformities may be regional (spread over vast territories) and local.

INCLINED OCCURRENCE OF LAYERS

Inclined occurrence of strata is a result of tectonic dislocations. If the strata are inclined to one side at a constant angle, it is conventionally called a monoclinal structure. The inclination angle may range from several degrees to 90 degrees (vertical occurrence). If this angle exceeds 90 degrees, it is called overturned occurrence.

In case of an inclined occurrence, the direction and inclination angle of the strata are measured. Their position in space is characterized by occurrence elements: strike line, dip line, and dip angle (fig. 6).

The strike line (*a-a*) is the line of the surface crossing with the horizontal plane. An infinite number of strike lines may be drawn on the stratum surface: all of them will be horizontal and parallel to each other, and will differ only in their absolute marks.

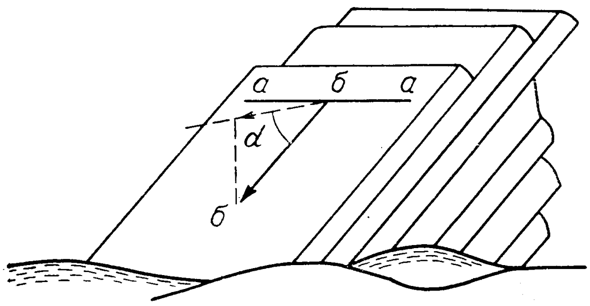

Fig. 6

The dip line (*b-b*) is the vector perpendicular to the strike line, lying on the stratum surface and directed towards the direction of its inclination.

The dip angle (α) is the angle between the dip line and its projection on the horizontal plane. Their position of the dip line in space is determined by the azimuth and angle of its inclination.

The azimuth of a given direction is the right vectorial angle contained by the northward direction of the true meridian and the given direction. Hence, the dip azimuth will be the right vectorial angle between the projection of the dip line on the horizontal plane and the northward direction of the meridian.

The strike line is horizontal, therefore it has two directions. To measure the elements of rock occurrence, a mining compass is used.

Lecture 3

STRUCTURE OF A BED OUTCROPPONG FROM OCCURRENCE ELEMENTS

The position of the top or base of a stratum on the surface, i.e. its geologic boundary depends on its dip angle and the terrain profile.

To show an inclined occurrence stratum on a map, a so-called horizontal equivalent is used. The horizontal equivalent is the projection of the interval of the stratum dip line, which is contained between two strike lines drawn on the base or the top of the stratum, on the horizontal plane.

The value of the horizontal equivalent is determined as follows.

The vertical cross-section is plotted along the direction of the stratum dip line to the scale of the map (fig. 7). In such a cross-section, stratum inclination angles (α) will correspond to the true dip angle. The line that shows the stratum (*M-H*) can be its top or base. We cross this stratum with several horizontal planes at equal intervals. The distance between the planes (*h*) is chosen depending on the cross-section of the contours on the topographic base. The value of the horizontal equivalent will be interval (*a*).

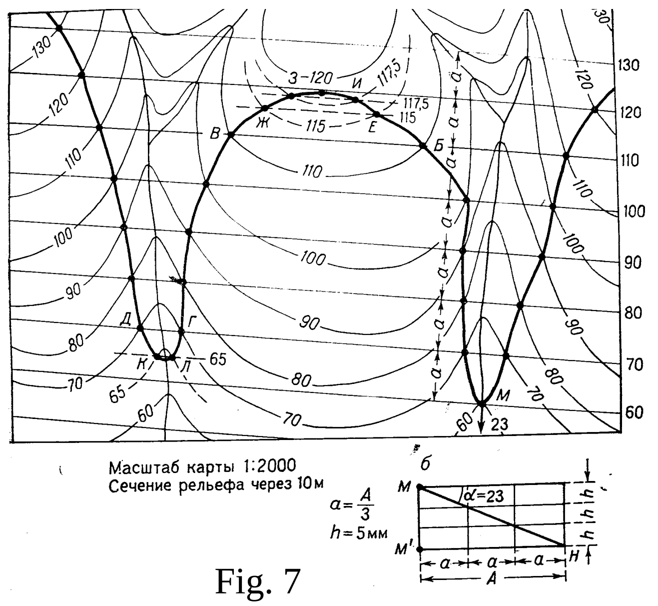

Fig. 7

On the topographic base, the dip line and the stratum strike line, which is perpendicular to the dip line, are drawn through point *M*, at which the occurrence elements have been measured. The strike line will have the absolute mark corresponding to the mark of the point of measuring the stratum occurrence elements. The strike line is broken into the intervals equal to the value of the horizontal equivalent, and a series of strike lines parallel to the line drawn through point *M* is drawn through the obtained points. The absolute marks for each of these strike line will be decreasing consequently in the direction of the stratum subsidence by the value of the cross-section of the terrain contours, and increasing by the same value, in the direction of the stratum rise. The next operation is to find all the points, at which strike lines cross the terrain contours with the corresponding terrain contours. These points are connected with a smooth curve that will correspond to the exposure of the geologic boundary registered at point *A*.

DETERMINATION OF OCCURRENCE ELEMENTS BASED ON A STRATUM OUTBREAK USING THE HORIZONTAL EQUIVALENT

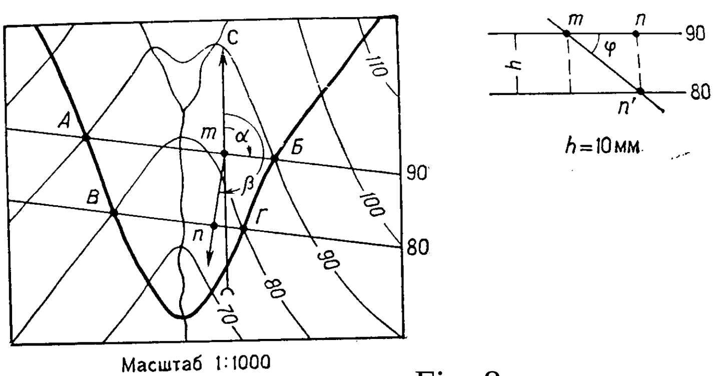

Fig. 8

By using horizontal equivalents, it is easy to solve the inverse problem to the previous one and determine stratum occurrence elements on the contoured map based on the stratum outbreak (fig. 8). To solve this problem, we should select two points (*A* and *B*) in the map, at which the stratum outbreak crosses the same terrain contour. These points are connected with a straight line that will be the strike line of the stratum, i.e. it is horizontal and lies on the surface of the stratum. The height of the strike line is equal to the mark of points *A* and *B*, i.e. 90 m. Then, two new points (*C* and *D*) are found, at which the line of the stratum outburst crosses the next underlying (or overlying) contour. They are also connected with a straight line which will be another strike line having the height equal to the mark of these points (80 m). Perpendicularly to the strike lines, the dip line is drawn, which will show the direction of stratum subsidence from the strike line with a greater mark towards the strike line with a smaller mark. After the strike and dip lines have been constructed, a protractor is used to measure their azimuths. To find the stratum dip angle on the scale of the map, the difference of elevations of the drawn strike lines is calculated. On one of them, this value is laid off from the crossing with the dip line (*m*-*n* interval), and the found poin is connected with the point, at which the dip line crosses the other contour. The obtained angle (φ) is the required dip angle.

STRATAL TRIANGLES

One can easily see one unique feature of the shape of the stratum outburst line in the map showing the stratum outburst (fig. 9: *a* – plan, *b* – cross-section).

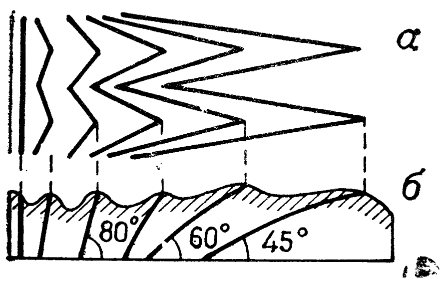

Fig. 9

It forms comparatively well-pronounced angles at the lowest and highest points of the terrain. The vertex of the angle situated at the lowest point of the terrain is directed down-dip, and that at the highest point, up-dip to the stratum. If we imagine that the arms of these angles are connected by straight lines, we will obtain triangles which are called stratal triangles. They make it possible to determine easily the direction of strata subsidence in those cases, when there are no terrain contours on the topographic base of the geologic map. Strata are inclined in the direction, where the vertex of the angle formed by the stratum outburst line is directed at the lowest terrain point (in the valley), and in the direction reverse to the direction of the angle vertex, at the highest point (at the divide). The value of the angle indicating the dip direction in stratal triangles may differ. It depends on the strata inclination and the form of the terrain. For vertical subsidence, the stratum outburst will look as a straight line. For steep occurrences, the angle will be broad, and as the stratum inclination decreases, it will become sharper. For the same stratum inclination, its outburst in a steep terrain will have a sharper angle compared to shallow terrains.

NORMAL AND OVERTURNED BEDDING

Two basically different types of stratum occurrences may exist when the strata are inclined: normal and overturned (Fig. 10). In case of the normal occurrence (*A*), the top of a stratum is higher than its base, and when the occurrence is overturned (*B*), the base is higher than the top. As the strata are turned, up to the moment when the angle of their inclination equals 90 degrees, their occurrence will be normal, i.e. their top will be situated hypsometrically over the base, and younger strata will be overlying older ones. When the angle becomes greater, the strata will be in an inverted (overturned) occurrence, and older strata will be overlying young ones.

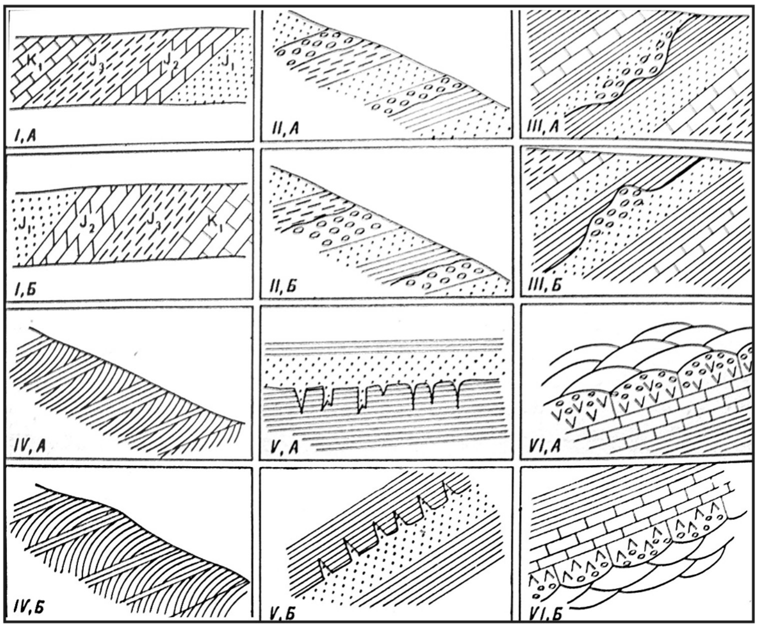

Fig. 10

When analyzing obliquely occurring strata, it is very important to identify the character of their occurrence. Underestimating the possibility of an overturned occurrence can lead to errors in determining the locations of the top and base of the stratigraphic horizon, in characterizing the stratigraphic sequence of the strata in the cross-section, in calculating the thicknesses, and in performing tectonic plotting. An overturned occurrence can be distinguished from a normal one by a set of characteristic indicators:

1) If the data about faunal characterization of the rocks are sufficient, an overturned occurrence can be easily identified by seeing that younger stratigraphic horizons are overlapped by older ones;

2) Frequently, the position of the top and the base can be found with a fair degree of confidence by observing the distribution of fragmentary materials in laminated series. In aquatic environment, sharp changes between undisturbed and moving conditions are manifested, in the cross-section, by accumulation of coarse sediments: sands or coarse gravels. If such sediments are deposed on the surface of a fine-grained sediment (clays or siltstone), traces of intraformational erosion appear at the interface between coarse-grained and fine-grained rocks.

3) In the stratum overlying the surface of an intraformational fault, one can frequently see lentils and irregular accumulations of large-grained rocks, e.g. conglomerations in sandstone rocks linked to washouts or pockets on the unconformity surface. If the occurrence is normal, lentils and accumulations of

large-grained materials are situated over the erosion surface, and if the occurrence is overturned, below it.

4) In some cases, the mode of occurrence can be indicated by cross bedding. Oblique layers are usually cut off sharply at the top and connect smoothly to the contact base.

5) Frequently, close studies of the contacts between the strata make it possible to discern penetration of the rocks from the overlying stratum into the underlying layer. Usually, the reason for this is the emergence of cracks in the underlying layer, which are caused by densification or desiccation of the sediment and into which the sediment of the overlying stratum drifts.

6) In solidified lavas, the hardened zone in the top is several times thicker than at the base. On the surface of lava flows, a special, pillow-type jointing form is developed. To determine the top and bottom surfaces of the spread of lava, one can accumulations of gas bubbles or vugs, which are sometimes filled with secondary minerals, near the top.

Lecture 4

FOLDED MODES OF STRATUM OCCURRENCE

1. Folds and Elements of Folds

Folds are undulating (or wave-like) bends in bedded formations, which are formed by plastic deformations of the rocks. An aggregation of folds is a folded structure (folding).

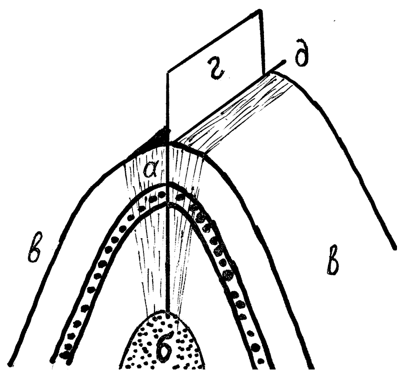

Fig. 11

Two main fold types are distinguished: anticline and syncline folds.

Anticline folds (anticlines) are the bends, in the centre of which the oldest, as compared to their edges, rocks are situated (fig. 11). In syncline folds (synclines), the central parts are composed of younger rocks as compared with the rocks composing their edges. The following elements are distinguished in the fold:

a) curve: the part of the fold at the point where the strata bend (cross-hatched in the Figure);

b) core: the oldest (in the anticline) or youngest (in the syncline) rocks;

c) limbs: parts of the fold adjacent to the hinge (in an anticline and a syncline adjacent to each other, one limb is common);

d) axial plane: the surface passing through the lines of bending of the strata that make up the fold;

e) hinge: the line of the axial plane’s crossing the top or base of each of the strata that make up the fold;

f) axis: the line of the axial plane’s crossing the terrain.

2. Morphological Classification of Folds

In terms of the ratio between fold limbs and the shape of the hinge, the classification is as follows:

a) Usual, or normal folds: limbs dip in opposite directions;

b) Isocline folds: limbs are parallel;

c) Fan-shaped folds: limbs resemble a fan, and the curve is rounded. The cores in the crestal zones can become squeezed.

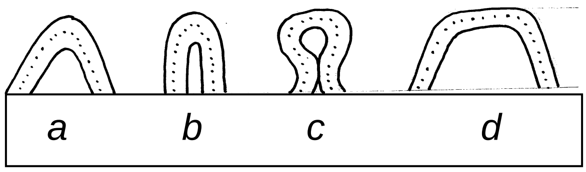

Fig. 12

d) Flat-topped, or box folds: the curve is wide and flat, and the limbs are steep (fig. 12).

In terms of the axial plane and limbs, folds can be:

a) Symmetrical, or upright: the axial plane is vertical, and the both limbs dip symmetrically;

b) Inclined: the axial plane is inclined, and the limbs are asymmetric;

c) Overturned: inclined folds, in which one limb is tucked under, and the strata in it are in an overturned occurrence;

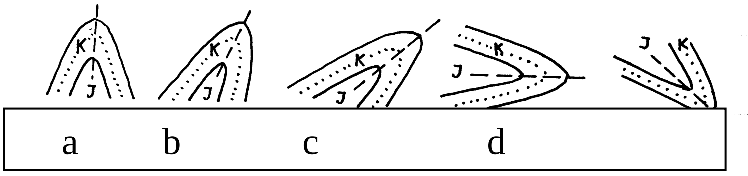

Fig. 13

d) Recumbent folds: the axial surface is situated horizontally;

e) Overfolds: the axial surface has gone beyond the horizontal position and acquired a backward inclination.

In these cases, anticline curves look as syncline ones (fig. 13).

Monoclines. Monoclines are a special type of fold forms. They are elbow bends in bedded formations (fig. 14). Usually, they are expressed by an oblique position of strata in a narrow area while their general occurrence is nearly horizontal. In vertical cross-sections, monoclines are characterized by:

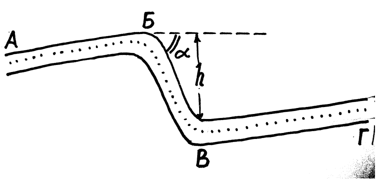

Fig.14

– upper limb (*AB*);
– lower limb (*CD*);
– joining limb (*BD*);
– the dip angle of the joining limb (α); and
– the vertical amplitude of the joining limb (*h*).

3. Representation of Folds in the Maps

Folds can be shown both in usual geologic maps, and in special structural maps. In geologic maps, the fold structure is shown by outbursts of the strata differing in their age and composition.

Structural maps are more frequently used to show the features of the morphology of deep-seated folds. They are plotted in isolines (bed contour lines) that show the surface of one separate layer.

Most frequently, structural maps are plotted in oil and coal geology basing on the data of drill wells.

The topographic map show all the wells, using which one can determine the position (absolute mark) of one and the same horizon of interest.

To do this, we should know the absolute mark of the well mouth (altitude) and the depth to that stratum. Their difference yields the required mark: 200 – 340 = –140.

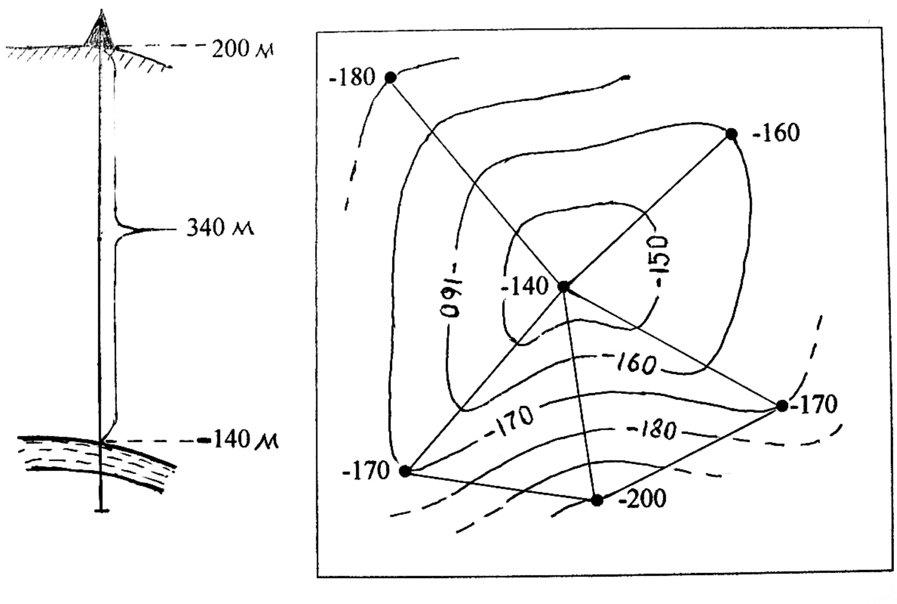

Fig. 15

After calculating of all altitude marks, wells are connected with straight lines, which comprise a network of triangles (fig. 15). Here, one should try to make the triangles equilateral, wherever possible. Selecting the vertical distance between stratal contours, the required marks are found on the sides of the triangles, and the equal marks are connected with smooth curves, which are stratal contours.

Lecture 5

MODES OF OCCURRENCE OF MAGMATIC AND METAMORPHIC ROCKS

1. Effusive Rocks

Effusive rocks can be found in geologic cross-sections among formations of all geologic periods, from Archean to Quaternary. They occur in the form of overland and underwater effusions as tuffs and tuffites produced by volcano ejections. Pre-Cambrian effusive rocks have mainly undergone active metamorphism and turned into various crystalline schists, porphyroids, etc.

Volcanic activity can be of two types: eruptions of the central type, when magma eruption and extrusion occurs through a channel, which has comparable dimensions in the transverse (horizontal) cross-section; and eruptions of the linear type, when magma is erupted through a channel, in the horizontal cross-section of which the length in one of the directions exceeds the width by tens and hundreds of times.

The mode of occurrence of effusive rocks is also largely dependent on the chemical composition of the erupted lava. Basic lavas are very fluid. As a result, before they solidify, they can cover vast areas on the Earth surface. By contrast, acid lavas are significantly less fluid, and do not propagate far from the volcanic orifice.

As a rule, in eruptions of the central type on continents, a volcanic cone is formed of eruption products, volcanic ash, bombs, etc.

Acid lavas can solidify before they reach the surface.

Linear-type eruptions are most frequently associated with platforms.

Usually, the lava content is basic, hence even on insignificantly inclined terrains lava can sometimes cover extremely vast areas forming so-called trappean plateaus (East Siberia).

Underwater lava outflows occur in the conditions, which differ significantly from those on the continents. Such lavas are usually characterized by stable areal thickness along great distances, good sorting of piroclastic materials, and alternation with marine sedimentary rocks.

The age of effusive formations is determined from the age of the sedimentary rocks, in which they are confined.

2. Intrusive Rocks

Intrusive rocks are wide-spread in the Earth crust. The majority of ancient crystalline core-areas outcropped at present consist mainly of intrusive rocks. Depending on their relationships with enclosing rocks, intrusive rocks are subdivided into concordant and discordant. Main types of concordant intrusions are laccoliths, lopoliths, phacoliths, and sills.

Laccoliths are bodies whose shape resembles the cap of a mushroom, and the size (diameter) usually does not exceed 5 km. They are produced by penetration of magma under a significant pressure, due to which the overlying strate are usually bended by the pressure, and occur in concordance with the laccolith body (fig. 16).

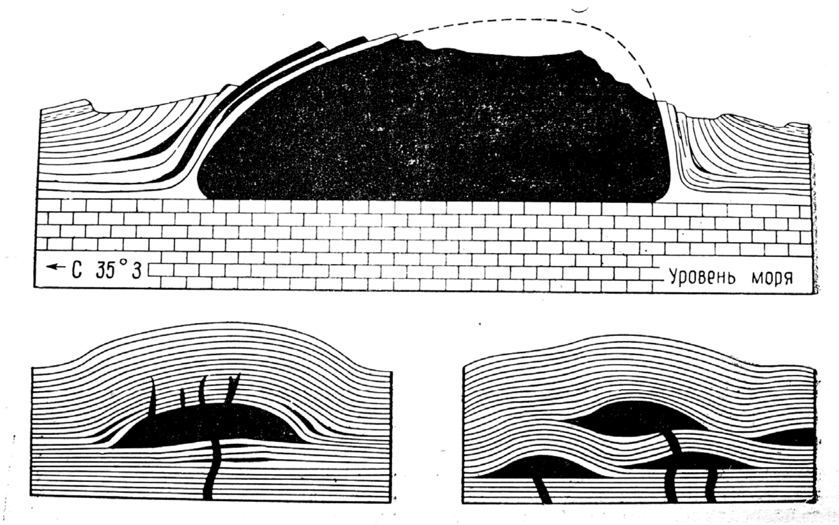

Fig. 16

Laccoliths are usually formed at shallow depths (500–600 m) and, consequently, are frequently exposed due to erosion processes. Most often, they are composed of acid rocks. Such formations are common in the Crimea, the Caucasus, the Carpathians, and other regions.

Lopoliths are intrusive bowl-shaped bodies from hundreds of meters to hundreds of kilometers in diameter. This is a typical mode of occurrence of intrusions with basic, ultrabasic, and alkaline contents.

Phacoliths are intrusive bodies shaped as a saddle or a lens in plan and cross-section. Most frequently, they are used in the curve sections of anticline folds (fig. 17). Thickness of phacoliths can reach several hundreds of meters.

Sills (or nappes) are intrusive sheaths. They are intrusions shaped as sheets and occurring mainly in concordance with the bedding (fig. 18). Their thickness is from several centimeters to several hundreds of meters, and the areas they occupy exceed sometimes 1000 square km.

The rocks comprising sills can be from acid to basic ones (Siberian traps).

Main types of discordant intrusions are batholiths, diapirs, nekks, dikes, and lodes.

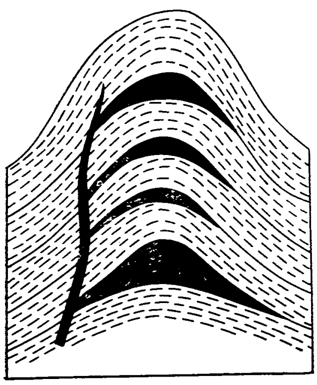

Fig. 17

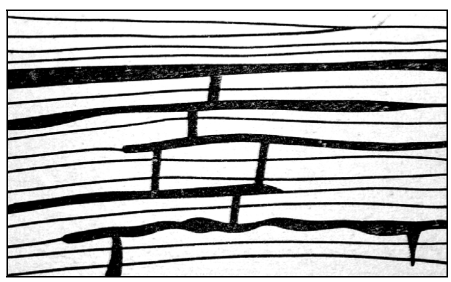

Fig. 18

Batholiths are extremely large masses of intrusive granitoid rocks formed at significant depths. Having uncovered a batholith, usually erosion processes reveal its elliptic shape. In the majority of cases, batholiths do not disrupt the harmony of the folding structure of the enclosing rocks, and often the produced impression is that a batholith is formed by their melting without any pressure exercised on them.

The surface of exposed batholiths is sometimes up to several thousands of sq. km. Up to recently, there has been the opinion that with depth, batholiths go directly into the magma. The problem of batholiths, especially of the space they occupy, has not been solved yet. The most substantiated of all different viewpoints is the opinion that such bodies are formed due to granitization of the enclosing rocks, i.e. complete reworking of their texture, structure, and mineral composition under the effect of active solutions fed in from depth sources.

Diapirs are hypabyssal intrusive bodies elongated in plan and cross-section and not exceeding several kilometers in size. Unlike laccoliths, they affect actively the enclosing rocks following cracks in the Earth crust, and crush them (fig. 19: *a* – plan, *b* – cross-section).

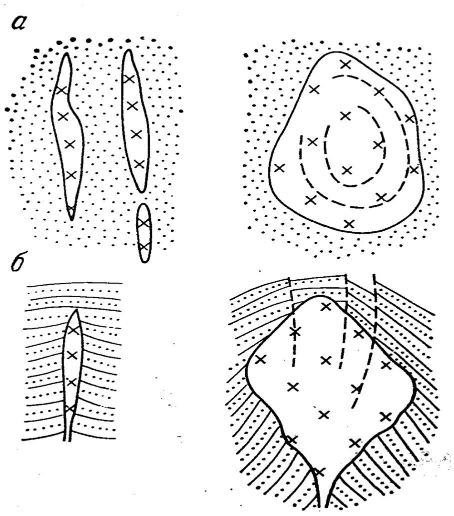

Fig. 19

Nekks are bodies that serve as the ways of magma penetration to the surface; they are vents of the volcanoes that once were active. In the transverse cross-section, they are rounded, elliptic, or irregular. Their diameter ranges from tens of meters to 1000–15000 m. The walls of nekks are steep. Sometimes, unclassified fragmentary material (explosive breccia) is observed along the walls. Famous kimberlitic pipes containing diamonds are nekks.

Dikes are discordant intrusions limited by parallel walls. Dikes are the result of magma's filling cracks in the Earth crust. The thickness of dykes varies in a wide range, and their lengths can reach 100 and more kilometers.

Loads, unlike dikes, have less regular thickness and can be composed of various materials being the products of magma decomposition. Often loads contain valuable minerals.

The age of intrusions is determined from their relationships with the enclosing rocks (relative age). The absolute age is determined from radioactive materials. Interaction of intrusive bodies with the enclosing rocks can be manifested in their active action on such rocks (presence of an aureole of the contact thermal effect, contact metamorphism), which evidences later origination of the intrusion relative to the enclosing rock. Sometimes an intrusive mass can be eroded and overlaid with younger formations: hence, it is older than those new formations. Analysis of these relationships makes it possible to restore the history of geologic development of the area (fig. 20).

In the Figure, granites tear through the deposits of Carbonic and Permian sediments and, at the same time, in the North-West part of the region they are overlaid by Jurassic and Cretaceous sediments lying on the eroded surface of granits and Permian and Carbonic formations. In this case, one can say that the granits, most probably, has the Triassic age. When determining the relative age of intercrossing intrusive bodies, it is necessary to trace their contacts attentively. The youngest body is that which breaks through other intrusions.

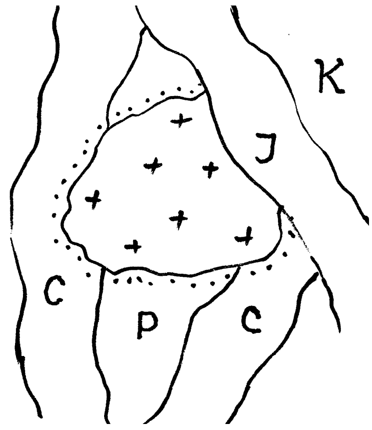

Fig. 20

3. Metamorphic Rocks

Metamorphic rocks are those initially sedimentary and magmatic rocks, which have undergone significant changes in their structure, texture, and mineral composition under the effect of high temperatures and pressures. These transformations can have both a local and a regional character. Local development of metamorphic rocks is usually a result of the effect of invasive magmatic rocks. Local metamorphisms can be observed also in the zones of large-scale faults.

The rocks having undergone regional metamorphism are very abundant. All Pre-Cambrian rocks are metamorphized. The rocks having undergone regional metamorphism in the Paleozoic are widely developed, less developed are those metamorphized in the Mesozoic, and still less, in the Paleozoic.

Special features of the conditions, in which rocks are metamorphized, result in formation of foliation, i.e. planar arrangement of flaky materials. Foliations are frequently situated at an angle to stratification planes, similar to cleavages.

Depending on their initial nature, metamorphic rocks are studied either as sedimentary or magmatic rocks. The rocks of initially sedimentary formation occur in the form of strata forming folded structures of various types. In them, marking horizons can be also distinguished, e.g. marble strata between mica schist or quartz rocks. One can identify stratigraphic relationships, unconformities, facies changes, faults, etc. Similar to sedimentary rocks, geologic maps and cross-sections are plotted.

Sometimes, zones of regional metamorphism may not coincide with the general line of rock bearing. In this case, it is very important to study the bearing of the strata. For example, the same stratum of initially clay composition can be represented, in the zone of high-temperature of metamorphism, by mica schist with garnets and disthens, and in a lower-temperature zones, by phyllites. In this case, the geologic map is supplemented with so-called metamorphism isogrades (an example: Mamsk crystalline strip and Bodaibo synclinorium).

Widely developed in metamorphic rocks are so-called zones of crush and mylonitization represented by the products of dynamic metamorphism, i.e. metamorphism of high pressures and relatively low temperatures. In such zones, rocks are subject to intensive cracking and mastication.

Folding morphology in metamorphic rocks is usually more complex compared with sedimentary series. Very frequently, isoclinal and flow folds are dominant here, boudinage of relatively hard strata and early lode formations is well-pronounced.

Maximal reworking or initially sedimentary and magmatic rocks occur in ultrametamorphic zones characterized by extremely high temperatures. Here, disappearance of the surfaces of primary stratification is frequently observed, and the series is granitized. In such series, the rock mass becomes actually non-stratifiable. Series can be distinguished only on the basis of their mineralogic composition and the character of migmatites (laminary migmatites, shadow migmatites, gneissic granites).

Lecture 6

DISJUNCTIVE DISLOCATION (FAULTS)

Faults in rocks are categorized as brittle deformations. They occur either simultaneously with formation of folds, or in after-folding periods. Two main groups of faults are distinguished:

1) faults with relative displacement of associated blocks; and

2) fractures, i.e. faults without displacement or with insignificant displacement.

The following main elements can be distinguished in faults with displacement (fig. 21):

a) dislocator surface, which can have different dip angels (α), from the vertical position to the horizontal one;

b) upper limb: the block situated over the dislocator surface;

c) lower limb: the block situated under the dislocator surface.

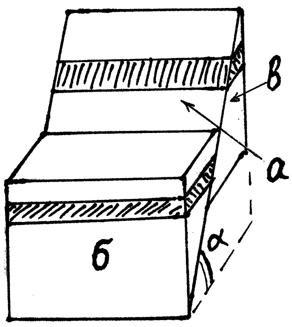

Fig. 21

If the position of the dislocator is vertical, only raised or lowered limbs are distinguished.

In geology practice, faults with displacements are subdivided into five main groups: downcasts, upcasts, shears, oversteps, and expansions, as well as various combinations of those groups (fig. 22).

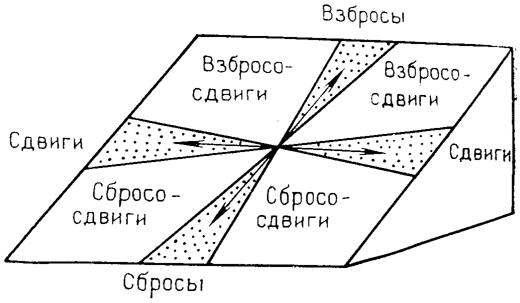

Fig. 22

The arrows on the lower limb shows the thrust direction of the upper limb.

A shift is a fault with displacement of the mass of the upper limb down-dip relative to the dislocator (fig. 23). When the position of the dislocator is vertical, relative vertical displacements of associated blocks are also conventionally called downcasts.

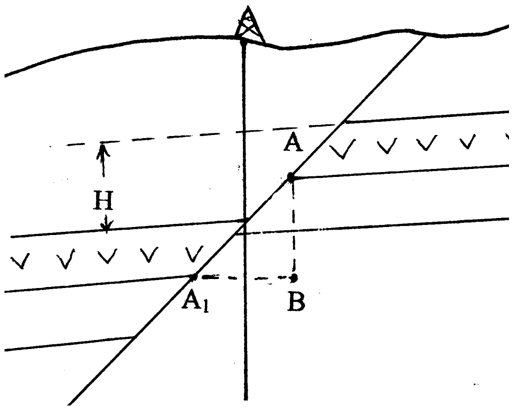

Fig. 23

The main elements of a shift are:
Amplitude of oblique displacement (A-A_1);
Amplitude of vertical displacement (A-B);
Amplitude of horizontal displacement (A_1-B); and
Amplitude of stratigraphic displacement (H).
Along the strike of the fault, its amplitude can change significantly, up to complete attenuation.

As a well crosses the downcast dislocator surface, the obtained cross-section, as a rule, is incomplete.

An overfault is a fault with displacement of the mass of the upper limb up-dip relative to the dislocator (*F*ig. 24).

The main elements of an upcast, similar to the downcast fault, are:

Amplitude of oblique displacement (A-A_1);
Amplitude of vertical displacement (A_1-B);
Amplitude of horizontal displacement (A-B); and
Amplitude of stratigraphic displacement (H).

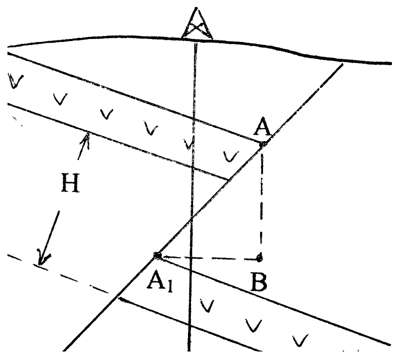

Fig 24

Along the strike of the fault, its amplitude also can change significantly, up to complete attenuation. Besides, steep dipping of the upcast fault flattens out with depth, and the entire fault structure is interpreted as an overstep.

When a well crosses the upcast dislocator surface, a part of strata in the obtained cross-section, unlike in a downcast, is repeated twice.

A shear is a fault with relative displacement of associated blocks in the horizontal direction.

In this case, the dislocator surface usually is inclined sharply. Left or right shears are distinguished, depending on the in-plan direction of relative displacement of the block opposite to the observer.

Fig. 25

An overstep is a fault with a flat-lying dislocator (fig. 25), under which the upper limb (allochthon) moves to significant distances (sometimes, to tens of kilometers) in the horizontal direction. The inclination angle of the overstep dislocator surface can change within a wide range. Usually, it is the steepest in front of the frontal part, and near the surface is frequently registered as an upcast.

Lecture 7

FRACTURING OF ROCKS AND METHODS OF STUDYING IT

Along with faults with displacements, faults without displacements or fractures are commonly observed both in folded and platform areas.

As a rule, strata of sedimentary and metamorphic rocks, as well as masses of magmatic rocks are fractured, i.e. carved with more or less extended cracks or fractures, which dissect the rock mass into a multitude of small-size blocks. According to definitions by V.V. Belousov (1952), V.E. Khain, and other authors, fractures should be understood as faults in rocks, in which there is either no displacement, or the displacement is insignificant.

Platform, regional, and local fractures are distinguished.

Studying fractures is of great interest for solving many theoretical and practical geologic issues (distribution of Earth crust tensions in tectonic deformations, mechanisms of various tectonic formations, engineering and geologic construction conditions, formation and destruction of deposit occurrences, etc.).

In recent years, oil geology has started intense studies of fractured reservoirs which frequently contain large oil deposits (e.g., Upper Cretaceous chalkstones in the North-East Caucasus, numerous deposit occurrences in Northern Africa, etc.).

Each fracture, as any planar structure, has occurrence elements: azimuth, dip angle, and strike.

Fractures are distinguished by the degree of exposure, dimensions, and other characteristic indicators.

In terms of exposure, fractures can be open, close, or hidden (unseen with the naked eye). Open fractures are partially or entirely made of calcite, quartz, or other minerals, which are frequently of practical interest as commercial deposits.

Groups of subparallel fractures having similar occurrence elements are conventionally called families of fractures.

Intercrossing families of fracture form so-called jointing, i.e. ability of the rocks to disintegrate into blocks having a well-defined form. For example, parallelepiped jointing is determined by three families of fractures breaking the rocks into separates pieces resembling parallelepipeds. For qualitative estimations of fracturing, the notions of specific fracturing, fracturing intensity, and fracturing density (number of fractures per square meter of the analyzed cross-section) have been introduced.

Geometric Classification of Fractures

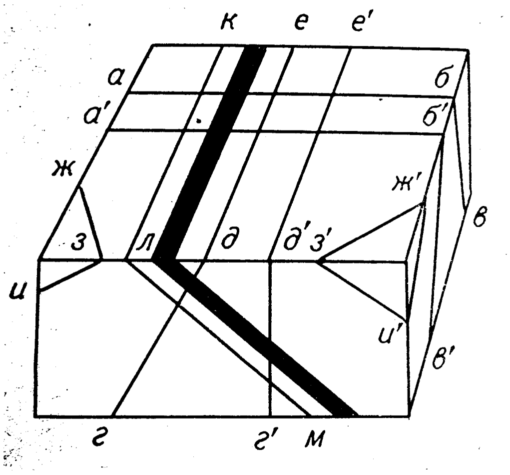

Fig. 26

Geometric classification of fractures is based on the features of their orientation relative to the bedding of sedimentary and metamorphic rocks (). Fractures can be concordant (*lkj*), longitudinal (*def*), transverse (*abc*), or slanted (*ghi*). According to the fracture inclination angle, fractures can be vertical (80–90°), steeply dipping (45°– 80°), slightly dipping (10°–45°), and horizontal (0–10°).

Genetic Classification of Fractures

In terms of their origin, fracture may be subdivided into two classes: non-tectonic and tectonic fractures.

Non-tectonic fractures are caused by internal forces arising in rocks as they cool down, desiccate, etc. Such fractures are called initial, or primary. They include, specifically, fractures in effusive rocks which, e.g. in basalts form unique prismatic jointing.

In sedimentary rocks, initial fractures can be polygonal fracturing in silt sediments produced as a result of dryouts of shallow-water basins in summertime. They are situated perpendicularly to the stratification, and develop usually individually in each layer, without crossing bedding surfaces.

Primary fractures formed in the process of sediment diagenesis, develop individually in the strata with different lithologic composition (fig. 27).

The distance between the fractures dissecting a stratum depends on the thickness and hardness of the stratum: the greater are the thickness and hardness, the greater is the distance between the fractures.

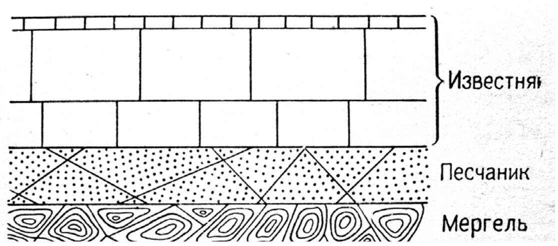

Fig. 27

Fractures of the tectonic origin (fig. 28) can be subdivided into three main subgroups: shear fractures (*a*), tearing fractures (*b*), and squashing fractures (*c*).

Shear fractures (*a*) are situated at angles of 30–60° to the direction of the effecting force *C*. Tearing fractures (*b*) arise in the plane of the vector of the applied force. Usually, they are open, hollow (or filled with some mineral) fractures with

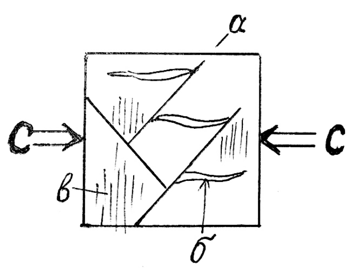

Fig. 28

uneven walls, frequently lens-shaped.

Formation of squashing fractures is connected with plastic flowing of hard rocks. Such fractures are formed in the plane perpendicular to the direction of the applied force.

They are comparatively rectilinear, pressed tightly, and broken-in. Formation of folded structures is also accompanied by formation of various families of fractures, whose orientation and type depend both on the regional plan of applied tectonic forces and on specific peculiarities of the fold. Most frequently, fracturing affects curve parts of formations (fig. 29).

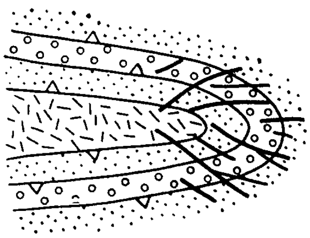

Fig. 29

A special place among tectonic fracturing is occupied by cleavages (fig. 30), i.e. systems of densely situated fracturing surfaces that are oriented regularly relative to the folded structure (independently of the changing bedding orientation). Cleavages are observed exclusively in folded zones of the geosynclinals origin.

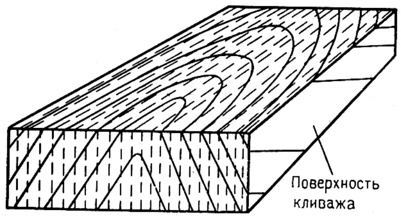

Fig. 30

<u>Methods used to Study Fracturing</u>

The basis for studying regular connections of fracturing with various tectonic forms, faults, etc. is usually massive measurements of fractures and their statistic processing. Here, it should be taken into consideration that fractures are vastly different in terms of geologic formations of their origination, mechanic conditions and time of their development. Therefore, before starting statistic generalizations, fractures must be analyzed from the viewpoint of singling out their different genetic groups. Without this analysis, statistic generalizations can lead to confusion between dissimilar fractures, and not to explanation of regularities in fracture distribution.

Observations of rock fracturing have different objectives. They are performed to:

1) reveal the physical status of the rocks, e.g. for excavation of building stones;

2) identify intensity and spatial orientation of the fractures, which can influence significantly the collecting properties of rocks in oil geology;

3) to determine the character and directions of displacements of rock blocks affected by various dislocators;

4) to reveal folded structures and its spatial orientation if it cannot be done by tracing its individual horizons (e.g. in monotonous rocks), etc.

Fracturing studies run in three consequent stages:

1. measurements of spatial orientation and description of peculiarities of the fractures;

2. processing of the obtained data (development of fracture diagrams); and
3. interpretation of the obtained data.

Since even in two adjacent exposures, fractures can differ significantly in the character and orientation of their families, it is reasonable to group the data obtained by measuring the elements of their occurrence over small areas, within which the directions of main fracture families are retained.

The choice of the boundaries of an area, for which a unified diagram is developed, is a very responsible matter. None of the mechanical systems of area distributions (e.g. a square, triangle, or another grid) is acceptable. Each area must be structurally homogenous.

For example, within a folded structure, diagrams should be plotted separately for individual limbs, curves, and periclines (independently of the structure dimensions).

Near a fault, diagrams must be plotted separately for each block. The area of such blocks can vary in the range from several tens to several hundreds of square meters and more (for less-scale works). In each area, from 100 to 200 measurements should be made.

The areas must be positioned positively against the terrain in the map and, wherever possible, against folded and fractured structures.

Due to inevitable influence of the physico-mechanical properties of rocks on fracturing development, fractures should be measured separately in the rocks with different lithologic-petrographic composition.

It is feasible to measure separately rectilinear fractures, empty fractures, fractures with torn and tortuous walls, fractures filled by carbonaceous, quartziferous, or other mineral substances, fractures with mirrors and shift hatches on the walls. In the latter case, the elements of shift hatches are also measured.

Wherever possible, the frequency of fracture development in certain families is characterized. Usually, the development frequency is determined as the number of fractures per running meter in the direction perpendicular to the fracture strike.

Significant help in identifying and studying fracture tectonics can be provided by aerial photographs, in which (if the scale is sufficiently large) well-developed systems are registered. This makes it possible to compare various fracture families and reveal their relative relevance and occurrence.

Similar requirements are imposed when studying fracturing of deep strata. Here, detailed descriptions are based on well core samples, and orientations are measured from a directed core or photologging.

<u>Observational Data Processing</u>

A simplest way to process measurement data is to construct rose-diagrams of fractures. However, this method does not yield sufficient information and does not make it possible to reflect accurate spatial configuration of individual systems or families, in order to perform integrated kinematical and dynamic analyses and restore the tension fields, in which these tectonic deformations occurred.

The best tool for these purposes is the Wolf grid. Some kinematical tasks can be solved also by using the polar Schmidt grid.

Lecture 8

MAIN STRUCTURAL ELEMENTS OF THE EARTH CRUST

The crust of the Earth is the top sial of the planet and is a component of the lithosphere. It is characterized by horizontal inohomogeneity of its petrographic composition and different thickness under oceans (5–10 km) and on continents (from 20 km on platforms to 70 km in mountainous areas). Based on this, the Earth crust is subdivided into the continental and oceanic crust.

Thus, continents and oceans are the largest structural components of the Earth crust. They are different not only in their structure, but sharp distinctions in their individual evolution.

Oceans cover 71 % of the Earth surface, whereas the continents are responsible for 29 % only. However, the Earth crust of the continental type is not limited by the coast lines, but goes below the sea level to the depths of 200 m and deeper.

The continental crust is iaracterized by the tree-compo- nt structure (fig. 31):

1) sedimentary cover,

2) granite layer, and

3) basalt layer.

The structure of the oceanic ust is two-component.

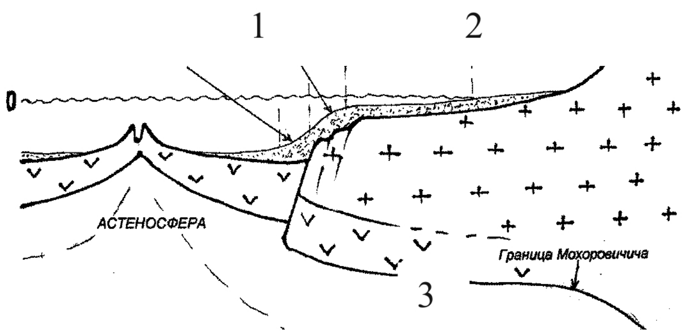

Fig. 31

The following features are stinguished in the contemporary ucture of the continents:

1) platforms, within which there are shields (areas, where the crystalline foundation crops out to the surface and is void of the sedimentary cover) and plates (areas, where the folded foundation is hidden under the cover of undisturbed sedimentary rocks: anticlises and syneclises);

2) folded areas represented by mountain ridges of different ages;

3) Submontane troughs, which are usually extended along the folded areas and characterized by a think sedimentary cover and weakly pronounced bedding (Suburals trough); and

4) Avlakogenes, graben-like, linearly extended depressions with higher mobility, which frequently cross platforms to the length of thousands of kilometers (Dnieper-Don avlakogene).

the Earth crust of the continental type situated below the sea level on the periphery of all continents has the width from several tens of kilometers (the Northern and Atlantic coasts of Africa) up to many hundreds of kilometers (seas of the Arctic basin). It is a transitional zone between continents and oceans and is currently the object of close studies and the search for various mineral deposits, primarily, oil and gas.

Underwater margins of the continents are the zones of intense sediment accumulation ensured by the products of erosion of the continents. Here, the thickness of sediments is frequently over 10 km. Usually, continental margins are subdivided into three structural elements: continental terrace (shelf), continental slope, and continental apron.

The shelf is a continuation of coastal plains and is the point of ocean transgressions and regressions, which change the contours of continents continuously. Here, the average angle of the shelf's sloping towards the ocean does not exceed several minutes, the average depth is about 130 m, but sometimes the depth here reaches 600 m.

Epicontinental seas, such as the North Sea, Baltic Sea, Barents Sea, etc. are nothing else but the continental shelf.

The continental slope is a sufficiently steep bluff, which ends the continental shelf. Its crest is situated at the depths from 50 to 800 m. The angle of dipping towards the ocean is from 4° to 45°. Due to this, rather steep, dipping the continental slope is frequently dissected by numerous deep canyons, along which vast masses of loose sedimentary materials, which accumulate on the shelf, slide down and form gigantic deep-water alluvial cones. The most vivid examples are the cones in the canyons that continue the beds of such rivers as the Ganges and the Indus.

At a depth of 3000–3500 m, the continental slope is continued by the continental apron, which connects the slope with the oceanic deep-water basin. This is also a very important zone, where a great amount of loose sediments of terrigenic and pelagic character are deposed. The continental apron is distinguished clearly only in those regions, where the continental margin is well developed.

The ocean bed is represented by the Earth crust of the oceanic type, i.e. the crust without the granite layer. Here one can distinguish deep-water basins, the depth in which ranges from 3 to 6 km, and mountain ridges. The terrain of the ocean bed reflects the peculiarities of its geologic development. Deep-water basins are stable zones not subject to active tectonic movements. Here, we observe deposition of sediments with very fine grain, mainly deep-water clays. The rate of sediment accumulation is very slow.

Mountain ridges are situated mainly in the central parts of the oceans (Atlantic ocean) and sometime stretch to tens of thousands of kilometers. These are tectonically active zones characterized by intense underwater magmatism of basic composition. Frequently, individual sections of such ridges go over water and form islands and archipelagos (Iceland).

Deep-Seated Faults

Large-scale disjunctive dislocations that play a great part in formation and development of the Earth crust were called ‘deep faults’ by A.V. Peyve (1945). They are characterized by long durations of development and great depths of occurrence, determine the appearance of magmatic rocks and metalliferous deposits, and are boundaries between sharply different structural formations. The lifetime of many deep faults is from the Proterozoic to our time (the Karatau zone in Tien Shan, Jalair-Naiman zone in...) Usually, continental margins are subdivided into three structural elements: continental terrace (shelf), continental slope, and continental apron. The shelf is a continuation of coastal plains and Central Kazakhstan).

According to N.S. Shatsky, deep faults not only dissect the lithosphere, but penetrate deep into the Earth mantle.

Deep fractures can differ in their kinematic characteristic, i.e. they can be accompanied by displacements of the downcast, upcast, overstep, and shear types and their combinations, as well as by expansions.

In terms of the displacement character, V.E. Khain (1960, 1963) suggests distinguishing between deep downcasts (faults confining the Eastern African zone and the Rhine graben), deep upcasts and oversteps (faults along the boundaries of mountainous formations with submontane and intermontane troughs), and deep shears (San Andreas, the Talasso-Fergana fault).

In terms of penetration, faults are subdivided into superdeep (700–300 km), deep (300 km and up to the base of the Earth crust), and carpet faults.

According to many scientists, deep faults delineate the entire architectural plan, the whole framework of the surface terrain. In terms of their geomorphologic character, the following faults can be distinguished:

1) faults that determine the contours of coastal lines separating oceans from continents (shores of Africa, India, South America).

2) faults that predetermine positions of straits and deep gulfs,

3) faults passing along the boundaries of mountainous formations with submontain regions and lowgrounds (the South Atlas fault);

4) faults determining boundaries of intermontane valleys (Baikal, Rhine, Red Sea);

5) faults within mountainous formations;

6) faults accompanied by chains of active and dead volcanoes.

Deep faults in oceans include: deep faults in the region of the continental slope and deep faults on the bottom of the ocean basins (deep faults of median ridges and deep-water troughs).

Lecture 9

CONTOUR MAP PLOTTING

A contour map is a graphic representation of the mode of occurrence of some geologic surface (top or base of a statum, surface of an unconformity of a tectonic fault, etc.) in the form of isohypses, i.e. lines of equal absolute marks. Isohypses plotted on a surface having a specific position in the stratigraphic cross-section are called stratographic isohypses, or stratoisohypses. Similar to the contour lines, or isobars reflecting the terrain character, stratographic isohypses represent the lines of crossing of the top or base of a stratum as imaginary horizontal planes equidistant from each other. The difference between those planes is called the cross-section of stratographic isohypses. The value of this cross-section is usually taken depending on the strata dip angle, on the amount of the initial data, and on the specific tasks. Generally, the steeper the strata dip angles are, the larger should be the value of the cross-section. This value should be constant in one and the same map.

A stratographic isohypse of a stratum shows its strike. The direction perpendicular to the strike and going towards lesser absolute marks of stratographic isohypses shows the dipping of the stratum. Density of stratographic isohypses on the contour map reflects the value of the stratum dip angle. The denser is the positions of stratogrpaphic isohypses to each other, the greater is the dip angle. Its value can be determined by two methods: the graphic method and the method of calculations. In oil-prospecting geology, two methods of contour map plotting is generally used: the method of triangles and the method of profiles. Frequently, it is necessary to plot a contour map from a base surface exposed by single wells only. In this case, if there are certain data available, the so-called convergence method is used.

1. Method of Triangles

To plot a contour map for the top (or base) of some key horizon basing on the drill well data, it is necessary to plot the top of all wells on the plan (topographic base) and calculate the absolute marks of the required surface. If there is no crookedness in the borehole, the mark of the key horizon is determined as the algebraic difference between the altitudes and the depth to this horizon. For example, if the key horizon is situated at a depth of 800 m in a well with an altitude of 1000 m, the elevation of the key horizon over the sea level is 1000–800 = 200 (meters). If the depth is 1300 m, and the altitude is 1000 m, the absolute mark will be negative and equal to 1000–1300 = –300 (meters).

This method is used to determine the absolute marks of the key horizon for all the wells in the area under consideration, and the obtained values are plotted on the plan at the corresponding points.

In the absence of preliminary geologic and geophysical data on the character of the analyzed structure as a whole, before going over to breaking the area down into a system of triangles, it is necessary to analyze the character of variation of the value of absolute marks on the surface of the key horizon, along which the contour map will be plotted. The objective of this analysis is to identify the position of the roof part of the formation. If its nature is elongated (a brachystructure or a linear fold), a line should be drawn with a pencil along the strike of the assumed roof. This line should not be crossed by the sides of the triangles, otherwise, when interpolating altitude marks between two points situated on opposite limbs of the structure, its actual morhology will be inevitably, and seriously, distorted.

After calculating of all absolute marks of the key horizon surface for all the wells and identifying the position of the structure roof, all the points are connected by straight lines forming a network of triangles. Here, one should try to make the triangles equilateral, wherever possible.

Having chosen the cross-section of stratographic isohypses, we pass over to interpolating altitude marks on each of the lines connecting the tops of the neighboring wells. Altitude marks between the wells are interpreted such as to ensure that the marks of intermediate points are multiples of the chosen cross-section. The obtained similar marks are connected consecutively with smooth lines, stratographic isohypses.

When plotting contour maps, it should be kept in mind that stratographic isohypses, similar to terrain contours, can never have the so-called “triple points”, and a bend of the surface can not be reflected by one isoline in the map. Altitude marks of the stratoisohypses are signed in line breaks so as to make the "head" of each figure face the isohypse with a larger absolute mark.

It should be noted that by now, all operations of plotting contour maps manually in scientific and scientific organization have already been replaced by computerized plotting almost entirely.

2. Method of Geologic Profiles

This method is used to reflect structures complicated by faults, and in the case of the linear character of the structures, drilled by transverse profiles, the distances between which exceed significantly the distances between the wells. In this case, the altitude marks of the key horizon are interpolated along the lines of each profile only. After that, equal absolute marks are connected from profile to profile, and reflect, finally, the morphology of the formation.

3. Convergence Method

After plotting the contour map of the top or base of some key horizon, it frequently becomes necessary to identify the structure of the underlying key horizon exposed in the same area by only single (at least three) wells only. To do this, first the map of the thicknesses of the intermediate rock mass is developed. The lines of equal true thicknesses are called isopachytes, and the lines of equal vertical thicknesses, isochors. For insignificant rock dip angles (not exceeding

10°), the difference between the true and vertical thicknesses is insignificant, hence one can use vertical thicknesses for map plotting without significant errors.

To plot isochors, the points of the wells exposing the lower key horizon are connected with straight lines. On the sides of the obtained triangles, the value of the thickness of the intermediate pack is found at the intervals corresponding to the intervals between stratographic isohypses of the upper key horizon. For example, if the cross-section of stratographic isohypses is 5 meters, then the isochors should be drawn at the same distance, 5 m. The points with the same thickness values are connected either with straight lines, or with smooth curves, depending on the specific situation.

The thickness map plotted in the described way is placed on the contour map of the upper key horizon, and the mark of the surface of the lower horizon is determined as the algebraic difference between the values of the stratographic isohypse and the isochor at each point where the isochors cross the stratographic isohypses. For example, if the absolute mark of a stratographic isohypse is 200 m, and the value of the isochor is 150 m, the absolute mark of the lower key horizon will be – 200 m – 150 m = – 350 m. Having used this method to calculate the altitude values at each point, we connect the same marks with smooth point, which will be stratographic isohypses for the lower horizon.

4. Plotting of Geologic Profiles

A geologic profile (cross-section) is a graphic representation of the structure of the Earth interior in some selected vertical cross-section. It is a visual representation of the features of the formation under configuration, the character of changes in the lithologic composition and thickness of different horizons, positions of producing horizons in the cross-section, conditions of their satiation with oil, gas, water, etc.

Depending on the geologic objectives, either a general cross-section may be developed, which shows the entire cross-section of the rocks exposed by wells, or a detailed cross-section showing the detailed structure of only that part of the cross-section that contains producing horizons.

Profiles can be transverse (built across the strike of a strata or a folded formation extended in a certain direction) and longitudinal (along the strike of a strata or along the axial line of the formation). Plotting of diagonal profiles is used less frequently.

Development of a General Geologic Profile

When developing a general geologic profile, usually the horizontal and vertical scales are the same, to avoid artificial distortions in the dip angles and thicknesses of the strata.

Independently of the orientation of the profile, the westward bearing should be on its left, and the eastward, on its right. In case of transverse arrangement, the left-hand side of the profile is usually directed towards the South, and the right-hand side, towards the North.

Drawing of a profile should be started with drawing a straight horizontal line corresponding to the zeroth absolute mark. In the left-hand side part of the drawing, the vertical-scale rule is shown. On the horizontal line, at some distance from the scale rule, the distance between the wells situated on the profile line in the map is shown to the assumed horizontal scale. Vertical lines representing boreholes of the wells are drawn through these points. On these lines, the values of the altitudes of well tops are laid off to the corresponding vertical scale, and these points are connected with a smooth line showing the character of the surface terrain in the cross-section of this profile. At the depth corresponding to the position of the bottom hole of each well, the line ends with a short transverse dash.

The position of all subsections of the cross-section is marked along the boreholes basing on the calculated values of the absolute marks for the top and the base. Then, from well to well, the boundaries of stratographic and lithologic subsection are traced and connected with smooth lines.

On its right-hand side, a geologic profile is accompanied with a stratographic column showing the age of the exposed formations. The depths of stratographic units in the column should match the depths, at which they are observed in the right-most well. If any changes in the sequence of strata occurrences, sharp variations in their thickness, or their dropouts from the cross-section are observed in well cross-sections, it evidences that there are faults or stratographic unconformities. Then, the entire profile should be analyzed thoroughly, before its final version is drawn.

Detailed Geologic Profiles

When developing detailed geologic profiles for studying the features of the geologic structure of producing horizons, the vertical scale of the cross-section can be made several times greater relative to the horizontal one. Detailed geologic profiles are developed in order to show separation of producing strata into individual interlayers and reflect the character of their facies variation and features of oil-and-gas saturation.

Course of lectures in

OIL AND GAS GEOLOGY AND GEOCHEMISTRY

INTRODUCTION

Oil and Gas (Petroleum) Geology is an applied science that studies geological processes, in particular:

1) Formation of hydrocarbons in the Earth's crust;
2) Migration and accumulation of hydrocarbons in reservoir beds;
3) Formation of oil and gas deposits and their further redistribution and collapses; and
4) Patterns of location of deposits in horizontal and vertical sense.

The Russian word "Neft" (Oil) and the word "Naphtha" are originated from the Arabic word "Naphata" that means "erupt".
In 1859, E.L. Drake, an American businessman, drilled the **first** well in Pennsylvania, USA. The depth of this well was 21 m. The flow rate of the well was 4.8 tons per day. This is the official date of birth of Oil Industry.

The **first** well in Russia of 70 m depth was drilled by Nikolskiy in the Kuban area in 1864. The flow rate of this well was 36 tons per day.
The **first oil field** in Perm Region was discovered in the Verkhne-Chusovaya area in 1928.
The bases for oil and gas production were created in Kazakhstan, Central Asia, Ukraine and Belorussia.
Beginning in 1970–80, the main oil and gas production region of Russia has become Western Siberia.

Lecture 1

CAUSTOBIOLITHS

Oil and Gas in the Caustobiolith Series

Fossil fuels of the petroleum series, to which oil and its derivatives belong, as well as combustion gases, are termed Caustobioliths.
The etymology of the word Caustobiolith is as follows: "caustos" means combustible, "lithos" means stone and "bios" means life, i.e. combustible stone of organic origin. The author of the term "**Caustobiolith"** is G. Potogne, a German scientist (1908).

Caustobioliths appeared due to conversing of organic matter originated from remains of life forms. In general, the sequence of such conversion is as follows:

1. Conversion of organic matter in the Earth's crust or on the beds of water bodies.
2. Accumulation of died off organisms.
3. Immersion in the entrails of the Earth and enriching of organic matter with carbon.

All fossil fuels (Caustobioliths) are subdivided into:

1) Caustobioliths of asphaltic or **petroleum series** – petroleum asphalts. They include oil, combustible hydrocarbon gases, asphalts, fossil wax (ozocerite) and other;

2) Caustobioliths of **coal** or humic series**.** They include syngenetic rocks and minerals (peat, coal, anthracite and other);

3) **Liptobiolites**. Some phytogenous organolites (fossil resin, wax, ember and other).

The inherent difference of elements of petroleum and coal series is the carbon/hydrogen ratio C/H, which is equal to 5,5–11,5 in oil, and 9,4–45 in fossil fuels of the coal series.

PHYSICOCHEMICAL PROPERTIES OF OIL

<u>Oil</u> is a viscous liquid of, most commonly, dark-brown color. Sometimes it is colorless and greasy by feel. It consists of a blend of various hydrocarbon compounds. In nature, oil can be of various consistencies that ranged from liquid to sticky, resinous oil.

Oil Composition

1) Carbon (C) – 82–87 %,
2) Hydrogen (H) – 11–14 %,
3) Oxygen (O) – 0,2–0,7 %, (sometimes up to 4 %),
4) Nitrogen (N) – 0,1–0,3 %, (sometimes up to 2 %),
5) Sulfur (S) – 0,09–0,5 %, (sometimes up to 2 %).

Sometimes it also contains heteroelements: phosphorus, vanadium, nickel, iron, aluminum and other.

So, as we have already mentioned above, the base of oil is **hydrocarbons (HC).**

It was established that oil contains three main HC groups:

1. Methane or Paraffin Hydrocarbons.
2. Naphtenic Hydrocarbons.
3. Aromatic Hydrocarbons.

Paraffin (Methane) Hydrocarbons

General formula is $C_nH_{2n+2.}$

$C\ H_4$
C_2H_6 – gaseous HC
C_3H_8
C_4H_{10}

C_5H_{12}
C_6H_{14}
C_7H_{16} – liquid HC
C_8H_{18}
C_9H_{20}
$C_{10}H_{22}$
…….
$C_{16}H_{34}$

$C_{17}H_{36}$ and higher – solid paraffins.

Naphtenic Hydrocarbons (Naphthenes)

General formula is $C_nH_{2n.}$

These hydrocarbons are characterized by cyclic structure. They consist of several CH_2 groups chained in a closed system. These are naphthenes – cyclopentane and cyclohexane (fig. 1, 2) which include five or six CH_2-groups.

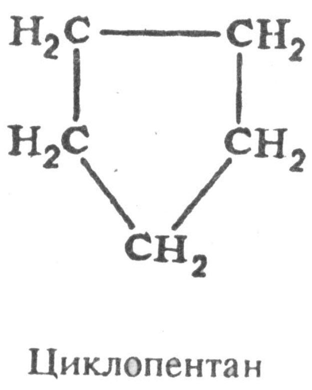

Fig. 1

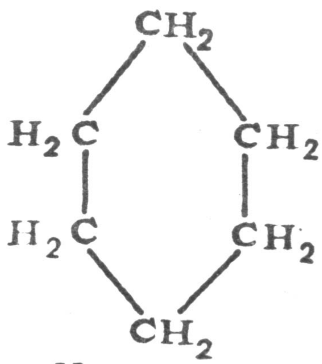

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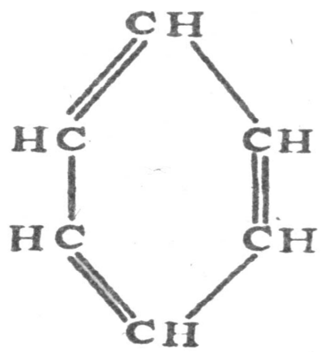
Fig. 2

Aromatic Hydrocarbons (Aromatics)

General formula is C_nH_{2n-6}.
These hydrocarbons have a cyclic structure, but atoms of carbon are linked with each other by double and ordinary bonds.
The fundamental substance is **benzene** (fig. 3).



Бензол

Fig. 3

Hydrocarbon type content of oil is important because ability of oil to migrate and form of accumulations depends on chemical and physical properties of oil. Some parameters are used for design and engineering of oil field development systems, oil pipeline transportation systems and so on. Regularities of changing in oil composition and physical properties in horizontal and vertical sense within a field make it possible to solve many issues of geological development of the given area.

In addition to the above listed three HC groups, oil can contain non-hydrocarbon components, i.e. in addition to C and H, oil can contain oxygen, nitrogen, sulfur and metals, all of which are termed as asphaltic resinous components of oil.

Resins are viscous semi-liquid substances which contain oxygen, nitrogen, sulfur and metals soluble in organic solvents. The molecular weight is ranged from 600 to 2000.

Asphaltenes are solid matters insoluble in low-molecular alkanes which contain HC structures with heteroelements. The molecular weight of asphaltenes is ranged from 1500 to 10 000.
The chemical nature of these components has not yet completely studied. It is established that the heavier oil, the more resins and asphaltenes it contains.

By resin content, oil is classified as follows:
1) Low-resin crude oil (resin content is to 10 %),
2) Resinous crude (Tarry) oil (10–20 %), and
3) Highly resinous crude oil (20–40 %).

By sulfur content, oil is classified as follows:
1) Sweet crude oil (sulfur content is to 0,5 %),
2) Sulfur-bearing crude oil (0,5–2 %), and
3) Sour crude oil (over 2 %).

By paraffin content:
1) Low-paraffin crude oil (paraffin content is less than 1 %),
2) Paraffin crude oil (1–2 %), and
3) Highly paraffinic crude oil (более 2 %).

PHYSICAL PROPERTIES OF OIL

1. Oil Density – amount of substance in a volume unit (weight/volume ratio).
Unit of measurement: kg/m^3 and g/cm^3.
In practice, **relative density** is used, which is ratio of oil density at temperature – 20 °C to water density at temperature 4 °C. The density changes in the range 0,73–1,04 g/cm^3.
Usually, oil density is less than 1 and is ranged from 0,82 up to 0,92 g/cm^3.
By density, oil is classified as follows:
1) Light oil (density is to 0,81 g/cm^3),
2) Medium oil (0,81–0,87 g/cm^3),
3) Heavy oil (0,87–0,90 g/cm^3),
4) Very heavy oil (0,90–1,04 g/cm^3).

Under reservoir conditions, oil density is less than that in surface, as under reservoir conditions oil contains soluble gases (up to 650 m^3 of gas can be dissolved in 1 m^3 of oil).
Oil density depends on asphaltic resinous components content of oil.

2. Oil Viscosity is a property of liquid to resist mutual movement of its particles due to force applied to liquid.
Viscosity parameter is of great importance:
a) for determining the nature and size of migration; and
b) for oil pool development and oil production.

There are dynamic, cinematic and relative viscosities.

Dynamic Viscosity is a force of resistance to movement of liquid layer of 1 cm^2 with speed 1 cm/s. Units of measurement are Poise (p, or g/cm.s; and in the SI System Pascal per second (Pa.s) – this is resistance of liquid during movement of two layers in relation to each other, area of each layer is 1 m^2 and each layer is at a 1 m distance from each other, speed is 1m/s under applied force 1 N.
The dynamic viscosity of water is 1 mPA.s.
Based on the dynamic viscosity, the values of rational well flow rates are calculated.

Kinematic Viscosity is a ratio of liquid dynamic viscosity to its density. Units of measurements are Stokes (St=cm^2/s =10^{-4} m^2/s); and m^2/s in the SI System.
Kinematic viscosity data are used in process designs.

Relative Viscosity is a ratio of oil viscosity to water viscosity at the same temperature.

Instrument for viscosity measuring is termed **viscosimeter**.

Oil viscosity is widely ranged depending on its properties: from 0,1 to 10 mPa.s.

<u>Conclusions:</u>

1. The heavier oil, the less movable it is.
2. Oil viscosity increases together with increasing asphaltic resinous components content of oil.
3. Viscosity is reduced if temperature is increased.
4. Viscosity is increased if pressure is increased.
5. The group of Naphtenic HC is characterized by higher viscosity than Aromatic and Paraffin (Methane) HC groups.

The above properties (density and viscosity) are determined in laboratory using surface samples.

3. Gas Saturation (Gas-Oil Ratio) of oil is determined by volume of gas dissolved in oil under reservoir conditions. Unit of measurement is m^3/m^3 (the range is 30–500).
Gas saturation is determined by using subsurface samples which are taken in the bottom-hole area by subsurface samplers.

4. Optical Activity of Oil.
Oil is capable to rotate the polarization plane of light ray. In the majority of cases, oil rotates the light ray polarization plane to the right direction, but left direction rotations were also identified. It is established that the more recent oil, the larger turn angle of the polarized ray.

5. Luminescence is glow under external radiation. This is an integral property of all oil and natural oil products.

6. Electrical Conductivity.

Oil is a dielectric material, i.e. non-conductor of electric current.
Oil has high electrical resistivity ($10^{10} – 10^{14}$ Ohm.m).

7. Boiling Point of Hydrocarbons.

Boiling point of hydrocarbon depends on the structure of the given hydrocarbon. The more carbon atoms are in the molecular, the higher boiling point.
The boiling points of Naphtenic and Aromatic HC, atoms of carbon of which are linked in cycles (rings) are higher than the boiling point of Paraffin (Methane) HC.
Natural oil contains components that boil out at the wide range of temperatures from **30 ° up to 600 °C.**

a) the first stage of distillation temperature up to 350° (gasoline and kerosene); and
b) the second stage temperature over 350° (fuel oil).

8. Temperature of solidification and melting of various oils is different.
Temperature of oil solidification depends on the composition of the given oil. The more solid paraffin it contains, the higher temperature of solidification. Resinous substances produce opposite impact – the higher their content, the lower temperature of solidification.

PHYSICOCHEMICAL PEOPERTIES OF GASES

Hydrocarbon gases constantly accompany oil. In nature, pure gas pools can occur, but no pure oil pools can exist.
In the Earth's crust gas can be in the following forms:

1. in free state (gases of gas caps).
2. in dissolved state (gases dissolved in oil and water).
3. in solid state (at particular temperatures and pressure gas molecules forms hydrates by penetrating the crystal lattice of water).
4. in pores of rocks.
5. in gas flows (volcanic and tectonic).

Natural gas is a blend of saturates: methane, ethane, propane and butane. The share of methane always dominates: (CH_4) – 98 %. Other gases can be contained in small volumes.

There pure and associated gases.

Pure (dry) gases are mainly presented by methane (98 %) and small number of its homologues.

Associated (fat) gases are gases dissolved in oil. They differ from dry gases by high content of ethane, propane and butane (up to 50 %).

PHYSICAL PROPERTIES OF GASES

1. Gas Density is weight of 1 m ^{3} of gas at temperature 0° and under pressure 0,1 MPa (760 mm of mercury). Gas density depends on pressure and temperature.

Relative density by air is commonly used (dimensionless value – ratio of gas density to air density; under normal conditions the air density is 1,293 kg/m^3). Density of gases ranges within 0,55–1 g/cm^3.

2. Gas Viscosity is internal friction of gas occurred during gas movement. Gas viscosity is very low 1.10^{-5} Pa.sec. Such low gas viscosity provides high flows in fractures and pores.

3. Gas Solubility is one of the most important properties of gases. Gas solubility in oil under pressure not higher than 5 MPa is governed by **Henry law**, i.e. amount of dissolved gas is directly proportional to pressure and gas solubility factor.

$$V_i = k_i P.$$

Under higher pressure, gas solubility depends on a number of factors: temperature, chemical composition, mineralization and other. Solubility of hydrocarbon gases in oil is 10 times higher than solubility in water. Solubility of fat gas in oil is higher than that of dry gas. Gas solubility in light oil is higher than that in heavy oil.

4. Formation Gas Volume Factor is ratio of gas volume under reservoir conditions to the volume of the same gas under standard conditions ($T = 0°$ и $P = 0{,}1$ MPa).

$$B_g = V_{fgv} / V_{stg}$$

Volume of gas in formation is 100 times less than that under standard conditions as one of the properties of gas is supercompressibility.

GAS CONDENSATE

Gas Condensate. Not only gas has the property of dissolving in oil, but also oil has the property of dissolving in gas. Oil dissolves in gas under particular conditions, namely:

1) Gas volume is higher than oil volume;
2) Pressure is 20–25 MPa; and
3) Temperature is 90–95 °C.

Under these conditions liquid HC begin dissolving in gas, and this blend is passes into gas mixture. Such phenomenon is termed **retrograde evaporation.** If reservoir pressure is decreased (for instance, during development), condensate evolves from this mixture in the form of liquid HC. Composition of condensate: C_5,H_{12}(pentane) and higher. This phenomenon is termed **retrograde condensation.** Gas Condensate is a liquid part of gas condensate accumulations. Gas condensates are termed clear oil because it does not contain any asphaltic resinous substances. Density of gas condensate ranges within 0,65–0,71 g/cm^3.

GAS-HYDRATE

Gas-hydrate. The major part of gases and water form crystalline hydrate (solid matter). Such substances are termed Gas-hydrates and formed at low temperature, high pressure and at small depths. Their appearance bears a resemblance to spongy ice or snow. Deposits of such type were discovered in the permafrost areas of Western and Eastern Siberia and in water areas of the northern seas.

To date, the problem of gas-hydrate utilization has not yet sufficiently solved. All issues of gas-hydrate production come to creating in formation such conditions under which gas-hydrates would be decomposed into gas and water.

For this purpose, it is necessary to:

1) Reduce reservoir pressure;
2) Increase temperature; and
3) Add special reagents.

Lecture 2

HYPOTHESES OF OIL AND GAS ORIGIN

Oil and gas origin became a subject of studying before oil industry appearing. Clarification of oil and gas genesis is not only of theoretical importance, but also of significant practical importance.

There is no consensus of opinion on oil and gas genesis. Theory of organic origin of oil is conventional, but there are hypotheses of inorganic oil genesis.

HYPOTHESES OF OIL AND GAS INORGANIC ORIGIN

1. In 1886, **D.I. Mendeleyev** created a **carbid hypothesis** of oil and gas origin that was the first hypothesis of inorganic origin of oil and gas.

Fundamental Provisions

a**)** oil seeps testifies that the place of oil generation is located deeply in the mantle, and oil moves upward; and

b) chemical reaction resulting in formation of carbon and hydrogen compounds;

$$2FeC + 3H_2O \rightarrow Fe_2O_3 + C_2H_6$$

Hydrocarbons in gaseous state flow up to the upper cold zones of the Earth in which they are condensed and accumulated in fractures, voids and pores, thus, forming deposits.

Objections against this hypothesis

a) existence of molten mass of carbon metals has not proved;

b**)** no water migration ways in the molten rock mass deep in the Earth;

c**)** hydrocarbons obtained as a result of this interaction in the laboratory show no **optical activity,** which is a property of natural oil; and

d**)** this hypothesis provides no explanation of existence of oils of various compositions.

2. In 1892, **V.D. Sokolov** put forward a **cosmic hypothesis** of oil and gas origin**.**

The reason for proposing such hypothesis was the fact that hydrocarbons were found in meteorites.

According to this hypothesis, hydrocarbons were contained in the gaseous mantle of Earth when Earth was in fire and liquid state. As Earth cooled, these hydrocarbons were absorbed by being cooled substrate, and, at last, condensed in the upper, the coolest strata – in the Earth's crust.

Refutation

Based on the present-day concepts the Earth was formed due to concentrating cosmic **cold gaseous-dust matter.** It is quite clear that under such conditions oil would have been evaporated and burned.

3. In 1966, **N.A. Kudryavtsev** proposed on **a volcanic hypothesis** of oil and gas origin.

According to this hypothesis, hydrocarbons and their radicals are formed in the magma deep-earth chambers in which high pressure and temperature dominate. Then, due to enriching with hydrogen of deep-earth origin, more complicated HC are formed, and they migrate to the sedimentary mantle of Earth.

I.M. Gubkin proved **groundlessness** of this hypothesis**.**

– there is not any mechanism of interaction of HC formation;

– there are no oil accumulations in the central parts of undersurface structures, in which igneous activity was most active; and

– there is still a question how HC penetrate to the upper strata.

OIL AND GAS ORGANIC ORIGIN THEORY

The beginning of the purposeful development of idea of organic origin of oil was laid more than two hundred years ago by M.V. Lomonosov. I.M. Gubkin, B.I. Vernadsky and N.D. Zelinsky greatly contributed to the development of this theory.

BASIC ARGUMENTS FOR ORGANIC HYPOTHESIS

1. All plants and living organisms in the Earth comprise carbon and hydrogen, i.e. in Earth there is sufficient organic material that fully provides oil and gas accumulating.
2. **Porphyrines** (derivatives of chlorophyll) were found in many oils. They make blood red, and plants green. Presence of porphyrines in oils testifies that temperature of these oils did not exceed 200 °C, because this is the temperature at which oil begin collapsing.

3. All living organism contain nitrogen. And all oils contain nitrogen.

4. All biological substances and all oils are **optically active.**

DISPERSED ORGANIC MATTER IN THE EARTH CRUST

All defenders of the organic theory consider Dispersed Organic Matter (DOM) to be original product for oil generation. There are several types of the DOM.

1. **Sapropelic DOM** – plankton decomposition products, which had been accumulating in the marine mud in deoxidizing or low deoxidizing conditions. Sapropelic DOM is an original product for oil generation.

2. Humic DOM are plant body decomposition products without oxygen. Humic DOM is an original product for gaseous HC.

3. DOM of mixed type – sapropelic-humic or humic-sapropelic DOM.

DOM has been accumulated since the time of the spring of life in Earth, i.e. 3–3,5 billion years ago.

The process of conversion of DOM in oil and gas is gradual and **multi-staged**. Stages of petroleum generation in lithosphere are as follows :

1. Accumulation of original source DOM in sedimentary deposits.
2. Petroleum hydrocarbons are formed during conversion of DOM.
3. Movement of petroleum hydrocarbons from source rocks to reservoir rocks.
4. Migration of HC along reservoir bed.
5. Accumulation of oil and gas under favorable conditions (structures, lithology and other).
6. Oil and gas pool formation.
7. Redistribution and collapse of oil and gas pools.

DOM CONVERSION STAGES

LITHOGENESIS is a process of formation and alteration of sedimentary rocks. Lithogenesis is phased as follows:

1. **Sedimentogenesis** – accumulating, migrating and final sedimentation of organic components.
2. **Diagenesis** – conversion of sediment in sedimentary rock.
3. **Epigenesis** – alteration of sedimentary rocks in the process of immersion before their converting in metamorphic rock.
4. **Katagenesis** – processes of alteration of some components of sedimentary rock (minerals and fluids) during Epigenesis.
5. **Hypergenesis** – breaking of rocks under rising.

SOURCE ROCK INTERVALS AND REGIONAL PLAYS

Oil is originated in the so termed **source rock intervals** (SRI). Source rock intervals are carbonate-clay rocks enriched with dispersed organic matters which were accumulated in the areas of long depression under low deoxidizing and deoxidizing conditions.

Not always deposits which contain organic matters can generate oil and gas, and that is why there are **potential** and **generating** source rock intervals.
Under discussion is a question at what stage of lithogenesis SRI potentially becomes oil generating SRI. According to the scientists, it is katagenesis during which dispersed organic matters are converted in oil. It is not a gradual process, it has clearly expressed maximums which are termed – **main stage of oil generation** and **main stage of gas generation** (fig. 4).

Oil and Gas Generation Activity in Sedimentary Rocks.

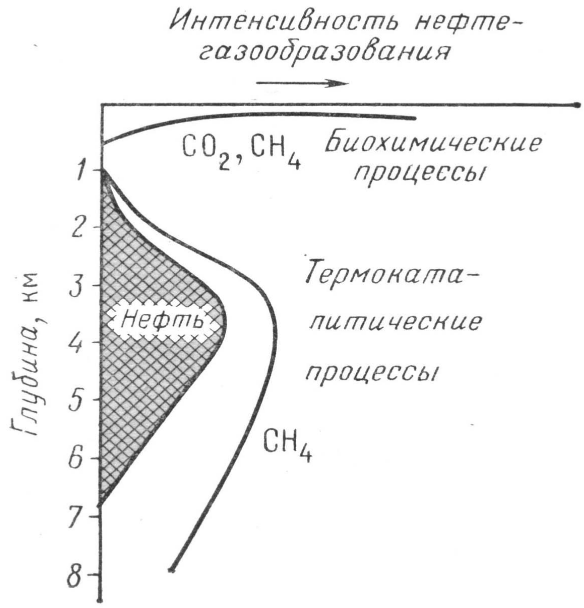


Fig. 4

Lecture 3

ROCKS AS OIL AND GAS RESERVOIRS

Reservoir Rock

Rocks which have the property of containing oil, gas and water, and release them under development are termed **reservoirs**.
The majority of the reservoir rocks are of sedimentary origin. Both **terrigenous** rocks (sand, sand stone rock and siltstone or aleurolite) and **carbonate** rocks (limestone, dolomite and chalk) can be oil and gas reservoirs.
By pore space type, all oil and gas reservoirs are subdivided into three groups:

1. Porous (granular) reservoirs. They are typical for detrital rocks.
2. Fractured (fissured) reservoirs. They are typical for all rocks.

3. Cavernous reservoirs. They are typical for carbonate rocks.

It should be noted that very often the combined types of reservoirs occur.
Ability of rock to be a reservoir is specified by the given reservoir properties: reservoir **porosity and permeability**.

Porosity

Porosity of rock is the property of the rock that lies in presence of voids in it (pores, caverns, micro- and macrofissures).
There are **total, effective, hydrocarbon-saturated and sealed** porosities.

Total porosity is a volume of all pores in the rock. The total porosity factor is ratio of the volume of all pores to the total volume of the rock.

Effective porosity is a volume of interconnecting pores, caverns and fissures. The effective porosity factor is equal to ratio of the volume of effective pores to the volume of specimen rock.

Hydrocarbon-saturated porosity is a volume of those pores and channels connecting these pores through which fluid can flow under development. The hydrocarbon-saturated porosity factor is equal to the volume of pores, through which oil, gas and water flow is possible at a particular temperature, pressure gradients to the volume of the specimen rock.

Sealed porosity means a volume of isolated pores that are not connected with other voids.
Porosity is measured in percent. Value of the rock porosity factor can reach 40 %. The most common values are:

$K_п$ = 17–24 %.

By size all voids or pores are subdivided into:

1. **Hypercapillary** pores (more than 0,5 mm). Fluid moves under hydraulics laws (oil and gas flow under gravitational force).

2. **Capillary** pores (0,5–0,0002 mm). Flow of liquid is complicated due to molecular cohesive force.

3. **Hypercapillary** pores **(**less than 0,0002 mm). Water percolation through such pores is impossible. The process of **diffusion** can take place **–** this is a self-movement of substance at the molecular level towards decreasing concentration. Hypercapillar pores are typical for argillaceous rock.

By origin pores can be:

1. Primary (syngenetic) pores. They are formed during formation of rock and changed in size and form during compacting and cementing.
2. Secondary (epigenetic) pores. They are formed during secondary processes (dissolution, weathering, crystallization and recrystallization).

Permeability

Permeability is the property of rocks to be permeated by liquid and gas under pressure difference. The unit of permeability is taken 1 mcm^2 (1 $mcm^2 \cong$ 1 Darcy) – this is permeability under which 1 cm^2 of liquid with viscosity 0,001 Pa s. passes through the cross section of 1 cm^2 area at pressure difference 0,1 MPa.

Very often rocks with fair high porosity (for instance, clays, whose porosity is up to 40 %) practically are not permeable. That is why they cannot release oil and gas contained in their pores. So, for assessing **practical** significance of reservoirs, it is necessary to have porosity and permeability data.
There are the following types of permeability: **absolute** permeability**, effective (**permeability **to phase)** permeability and **relative** permeability.

1. Absolute permeability is permeability measured when fluid was passing through rock under full saturation of pores of the rock with this fluid.

2. Effective permeability is permeability determined for any fluid in the presence another fluid in the rock.

3. Relative permeability is determined by ratio of the effective permeability to the absolute permeability. It is expressed by dimensionless value that is less than 1.
Reservoir permeability can be also expressed by reservoir fluid loss coefficient.

$$K_{пр}=Q\mu\, L \,/\, F\, \Delta P,$$

Q – liquid flow rate; μ – dynamic viscosity; L – length of specimen;
F – cross sectional area; and ΔP – pressure difference.

Dimension of values in the International System of Units is 1 mcm^2 = 1 D

Permeability of reservoir rocks depends on:

1. packing density and relative position of grains;
2. extent of grain size distribution, cementing and reservoir-scale fractures; and
3. interconnection of pores, caverns and fractures.

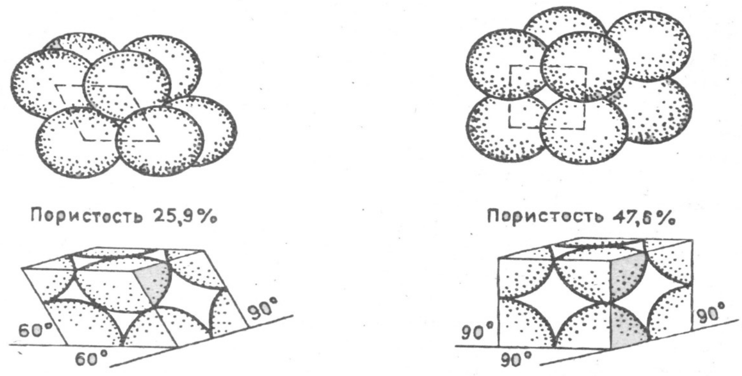


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Fig. 5

CLASSIFICATION OF RESERVOIR ROCKS

1. By permeability coefficient value the reservoir rocks are subdivided into 5 classes:

I – very high permeable, over 1 mcm^2;
II – high permeable – 0,1–1 mcm^2;
III – medium permeable – 0,01–0,1 mcm ^{2};
IV – low permeable – 0,001–0, 01 mcm^2; and
V – impermeable, less than 0, 001 mcm^2.

From the point of oil accumulation and oil recovery, the reservoirs of the first three classes are of practical interest, and the first four classes for gases.

2. Classification based on the **effective porosity value** was developed by P.P. Avdusin and M.A. Tsvetkova. According to them, there are five classes.

A – over 20 %;
B – 15–20 %;
C – 10–15 %;
D – 5–10 %;
F – less than 5 %.

The reservoirs of the first four classes are of practical interest.

DETERMINATION OF RESERVOIR PROPERTIES OF ROCKS

The reservoir properties of rocks (porosity and permeability) can be determined by:

1. in laboratories using samples from wells (core) or samples of natural deposits. There are special units for analysis of dense and loose rocks;
2. using field data (rates of production wells); and
3. using integrated well log survey data.

Thus, porosity factor, oil- and gas saturation factors are determined. These factors are used for calculating the HC reserves. Permeability coefficient required for design of field development is also determined.

CHANGE OF RESERVOIR PROPERTIES AT VARIOUS DEPTHS

Since it is necessary to conduct deep development, at present, of special attention is study of regularities of changes reservoir properties of rocks at depths over 5 000 m.
As the depth of occurrence of reservoir rocks increases, their density is also increased under geostatic pressure, and, subsequently, **porosity is decreased and permeability is worsened**. However, at some intervals of depths, the reservoir properties are retained, and sometimes are even **improved**.

1. In response to tectonic stresses, the reservoir properties of **carbonate rocks** are improved due to creating the <u>secondary porosity</u> (dissolved carbonaceous cement, fracturing and so on).

Fissuring of carbonate deposits occurs at fault-angle structures and during hydraulic fracturing.

2. The secondary porosity **in terrigeneous rocks** at large depths appears due to leaching or dissolving carbonaceous – argillaceous cement under action of hot water saturated with carbon dioxide.

Thus, decrease of reservoir storage capacity at large depths in compensated by fracturing and secondary pores and caverns.

CAP ROCK (SEALS) (IMPERMEABLE BED).

When determining conditions of oil and gas accumulation conditions, it is necessary also to determine that in addition to the reservoir rocks, gas-oil impermeable cap rocks (seals) presented by clays, argillites and **evaporites** (salts, plaster-stones and anhydrates) play an important role in forming and maintaining the natural reservoirs.
Clayey silt and clayey limestone and other can also serve as cap.
The screening capacity of caps is impacted by occurrence (length), thickness, composition, homogeneity tectonic deformation, depth of occurrence and other. For instance, property of clay cap rocks is worsened, and screening capacities of salt cap rocks are improved (plastic property of salts at large depths is high).

E.A. Bakirov proposed the below classification of impermeable beds.

1. **<u>Regional</u>** impermeable beds**.** These are impermeable rock masses occurred within the entire territory of petroleum province (Western Siberia petroleum province).
2. **<u>Subregional</u>** impermeable beds. These are impermeable rock masses which are confined to with petroleum regions (Turonian clays in Western Siberia petroleum province).

3. **<u>Zonal</u>** impermeable beds. These are impermeable rock masses, occurrence of which is restricted by petroleum accumulation zone (Kungurian deposits in the Caspian depression).

4. **<u>Local</u>** impermeable beds. These are impermeable rock masses which seal a local structure (Maikopian clays of the Zhuravskoye field).

By lithological composition, cap rocks are subdivided into:

1. **homogeneous cap rocks,** which consist of rock of one lithological composition (clayey); and
2. **heterogeneous cap rocks**, which consist of rocks of various lithological composition (clayey-salt).

Lecture 4

<u>NATURAL RESERVOIRS AND TRAPS</u>

Natural reservoirs and traps are intimately connected notions as trap is a part of reservoir.

<u>Natural reservoir</u> is a natural oil and gas container inside which circulation of fluids is possible. Fluid is oil, gas and water in rocks. Morphology of natural reservoir depends on the ratio of horizontal and vertical senses of the reservoir to the low permeable rocks that contained them.

There are three main types of the natural reservoirs**: formation reservoirs, massive reservoirs and lithologically screened reservoirs.**

FORMATION RESERVOIR

Formation reservoir is a complex of permeable reservoir rocks bounded by impermeable rocks at the top and bottom.

The formation reservoirs are characterized by the following:

1. They occur in terrigeneous and carbonate rocks.
2. They are well persistent in lithology and thickness within large areas of petroleum (oil-and-gas bearing) regions.
3. The reservoir rocks are characterized by small thickness (up to several tens of meters).

а *б*

Fig. 6

MASSIVE RESERVOIR

Formation reservoir is a complex of permeable reservoir rocks bounded, unlike the formation reservoirs, by impermeable rocks only at the top.
The massive reservoirs are characterized by the following:
1. They are very thick (several hundreds of meters).
2. In terms of lithology they are subdivided into:
– **homogeneous – massive reservoirs.** They occur in carbonate deposits (limestone and dolomites); and
– **heterogeneous – massive reservoirs.** They are formed by carbonate and terrigeneous rocks.

LITHOLOGICALLY SCREENED RESERVOIR

Permeable screened reservoir rocks surrounded on all sides (locked) by low permeable rocks relate to the lithologically screened reservoirs. For instance, sand packages – lenses.

Very often reservoirs can be related both to the formation reservoirs and to the massive reservoirs. Such reservoirs (formation-massive) within particular part of the section have properties of the formation reservoirs, though they are massive as a whole, i.e. are an **unified hydrodynamic system,** in consequence of which WOC and GOC are at one the same hypsometric point. Thickness of oil and gas accumulation is fair large in such reservoirs.

NATURAL OIL AND GAS TRAPS

Trap is a part of the natural reservoir. It is characterized by conditions that promote generating and retaining oil and gas accumulations (pools).
Oil and gas are lighter than water, and they move in water both vertically and horizontally until they reach impermeable rocks. The basic principles of migration are pressure difference and gravitational floating up of oil and gas in water.
The role of trap can be played by:

1. dome parts of positive structures;
2. stratigraphic unconformity areas;
3. lithologic thinning-out areas.
4. porosity and permeability local change areas; and
5. tectonically screened parts of structures.

Based on the reasons that cause forming traps, there are the following types of traps:

1. **Structural Traps** (anticline traps).
2. **Stratigraphic Traps.**
3. **Lithologically Screened Traps**.

STRUCTURAL TRAPS

The below types of structural traps are of commercial significance:

1. Dome traps and
2. Tectonically screened traps.

Dome Traps

Hydrocarbons arrive at trap by migrating in reservoirs along bed rise or perpendicular to their stratum on tectonic deformation, i.e. domes of anticline structures, in which they form commercial accumulation of oil and gas.
Often the dome traps are termed <u>anticline traps</u>, and all the rest traps – <u>non-anticline traps.</u>

Tectonically Screened Traps

Such traps occur in folded regions and domed salt areas.

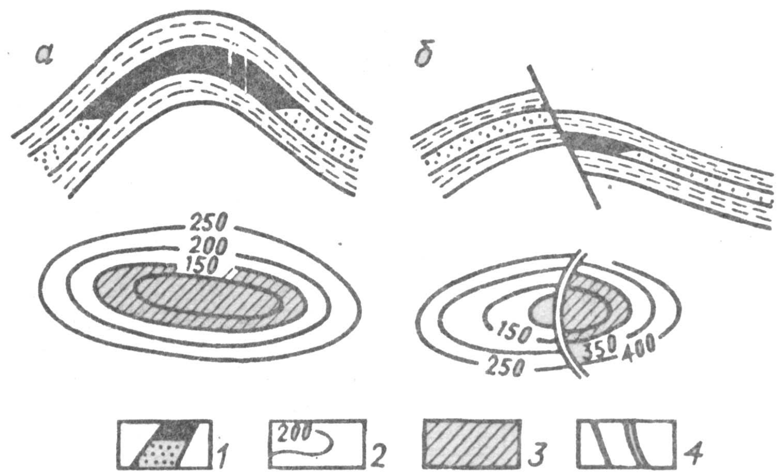

Fig. 7

STRATIGRAPHIC TRAPS

The below structures can be termed as stratigraphic traps:

1. Reef masses in which oil and gas are accumulated in porous limestones overlapped by low permeable rocks (plaster-rocks, anhydrites and other).

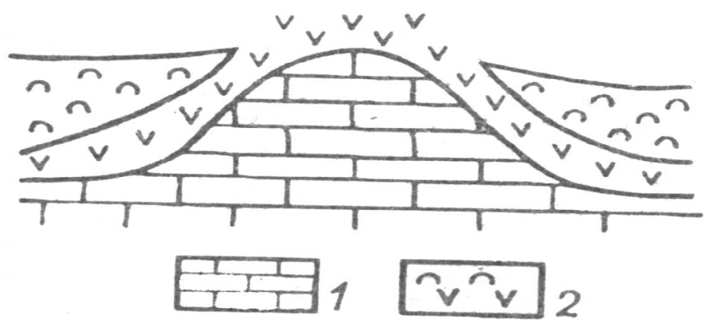

Fig. 8

2. Stratigraphic traps are formed at overlap of head parts of reservoir rocks undermined by impermeable rocks. The surface that separates these strata from the earlier formed strata is termed the **surface of stratigraphic unconformity.**

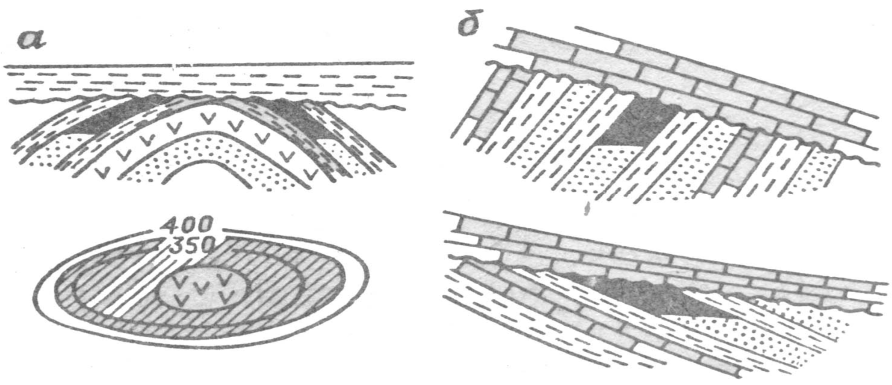

Fig. 9

LITHOLOGICALLY SCREENED TRAPS

Lithologically screened traps are formed due to:

1. lithologic variation in reservoir rocks;
2. pinching out sands and sandstone along bed rise;
3. reservoir porosity and permeability changing; and
4. rock-scale fracturing.

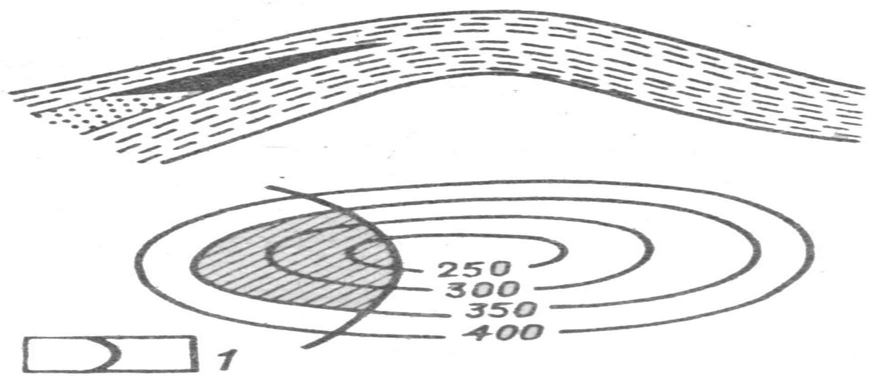

Fig. 10

Traps can be combined or complex, i.e. their formation is caused by various factors.

Lecture 5

<u>OIL AND GAS MIGRATION</u>

Migration of oil and gas is all their movements in the Earth's crust. The main factors of oil and gas migration are gravity, pressure gradients, temperature and concentration of hydrocarbons.

Role and impact force of the above listed factors depend on the particular properties of geological space and duration of their impact. There are primary and secondary migration:

1. **Primary** migration is a process of hydrocarbon migration from source rocks to reservoir rocks.
2. **Secondary** migration is migration of hydrocarbons in reservoir rocks, disjunctive dislocation, fractures, stratigraphic unconformity surfaces and so on (fig. 11).

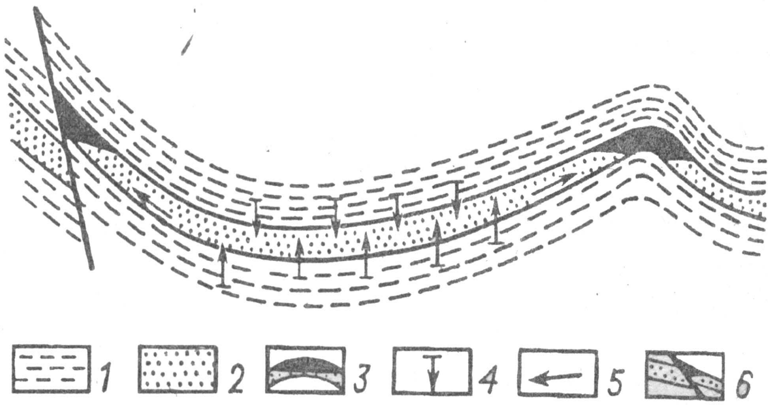

Fig. 11

The basic property of geologic environment that provides oil and gas migration is heterogeneity of porosity, permeability and structural-tectonic conditions. Migration conditions depends on lithological and tectonic conditions which affect the ways of oil and gas migration and places of accumulation.

Migration takes place in the proper least flow coefficient sense, i.e. in direction of the bed rise in its top part through the rocks with highest permeability up to tectonic or lithologic screen. Such migration is termed **secondary (**intrastratal**)** migration.

Inter-reservoir (interstratal) migration is a migration of oil and gas along disjunctive dislocations or stratigraphic unconformities (discordances).

OIL AND GAS FIELDS

Oil and gas field consists of one or more oil and gas pools within bounded area which are genetically interconnected and originated due to common geological factors. Notions the "field" and the "pool" are interconnected. As it is well known there single play and multiplay fields. In the first case the field and pool are synonyms.

Fields differ in fluid content and composition.

In 1961, I.A. Eremeenko said that "tectonic characteristics of this or that structural element that controls forming of field, first of all, depends on with what large geostructural elements of the Earth's crust the formation of the given element is associated". Based on the above, there are two basic classes of fields:

1. **Folded region fields**; and
2. **Platform fields.**

By amount of oil reserves (mln tons) and gas (bln m^3), the fields are subdivided into small (size) – less than 10 mln tons of oil or less than 10 bln m^3 of gas, medium (size) – 10–30 mln tons of oil or 10–30 bln m^3 of gas, large (size) – 30–300 mln tons of oil or 30–500 bln m^3 of gas, unique – more than 300 mln tons of oil or more than 500 bln m^3 of gas [3].

Lecture 6

OIL AND GAS ACCUMULATIONS

FORMATION OF OIL AND GAS ACCUMULATIONS

The fundamental processes of oil and gas accumulations are interconnected processes of migration, differentiation and accumulation of hydrocarbons. Filling up traps, fluid phase and composition of hydrocarbons depend on these processes. According to A.A. Bakirov, there are primary reservoirs which are within the source rocks, and secondary reservoirs which are beyond the source rocks. Consequently, intrastratal (lateral) migration plays the key role in forming of primary reservoirs, and interstratal (vertical) secondary reservoirs.

In nature, accumulations are formed due to combining of various types of migration. Accumulations can be formed stepwise by combined horizontal and vertical migration.

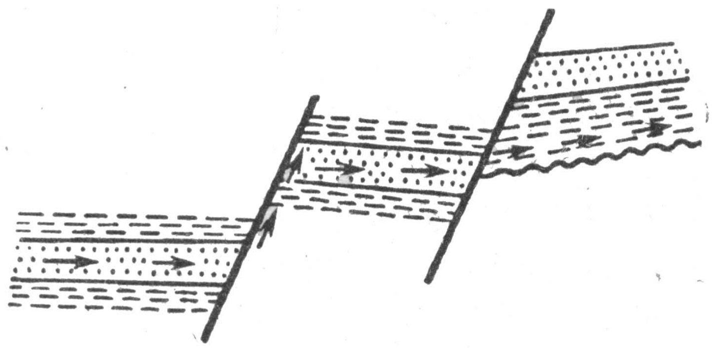

Fig. 12

One of the main, though presumably not all-pervading, explanation of peculiarities of trap filling is the principle of differential trapping of oil and gas that was put forward by S.P. Maksimov, V.P. Savchenko and V. Gasso. It is based on the capability of gas to migrate faster than oil, replace and displace oil from the overfilled trap, i.e. gas accumulations are replaced with gas-and-oil and oil accumulations as hypsometric points of traps are risen.

Oil and gas accumulations are located according to the principle of differential trapping only in case if HC migrate in a **free state in the form of oil and gas currents.**

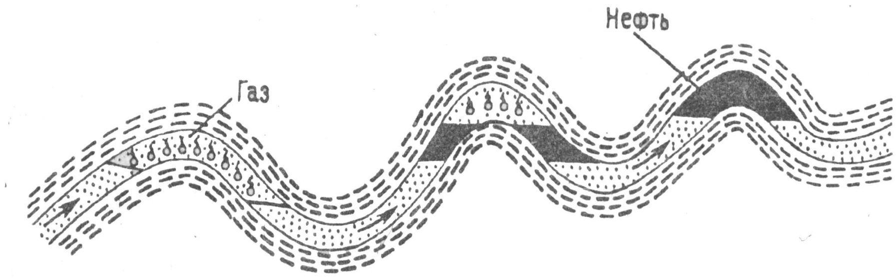

Fig. 13

A completely different type of situation occurs if HC migrate in a **dissolved state.** If hydrocarbons migrate in dissolved state along regional bed rise, pressure and temperature decrease promotes transforming oil and gas in a free state. As solubility of liquid HC is lower than that of gaseous HC, first, oil transforms from the dissolved state, and fills the first hypsometrically lowest trap. In further, as dissolved HC migrate upward along bed rise, gaseous HC are evolved together with liquid HC, and that is why oil and gas are accumulated in the next traps, and higher – only gas. Such differentiation of HC takes place under the principle of gravity segregation of fluids.

Upon a whole, type of accumulation, its fluid state and HC composition depend on features of regional geological structure and development. Despite the great theoretical interest and practical significance, time and duration of formation of oil and gas accumulations are ones of the most discussible issues of Oil and Gas (Petroleum) Geology.

Some scientists consider that oil accumulations are formed directly after depositing of reservoir rocks. According to other scientists, there is a long time period between these processes. And there are scientists who believe that oil and gas accumulations have been formed in relatively recent geological age.

Moreover, sometimes oil and gas formation is related to the particular stages of geological evolution. In this connection, we can note that time of formation of oil and gas accumulations depends on geological features and history of evolution of particular regions, which greatly differ for each of them.

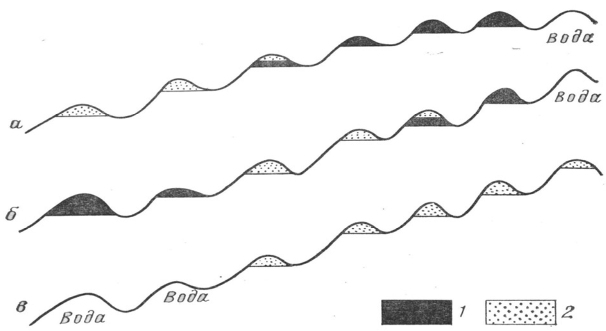

Fig. 14

CLASSIFICATION OF OIL AND GAS POOLS

Pool is a natural local accumulation of oil and gas that occupies a part (trap) of natural reservoir. If pool development us economically feasible, it is termed as commercial pool.
It is necessary to consider that pools differ in fluid content and composition (pure oil, pure gas and combined pools, i.e. two fluids: oil pool with gas cap and gas pool with oil fringe (leg), and gas condensate pools).
There are simple and complex (sandwich-type, multi-cap and other) pools.

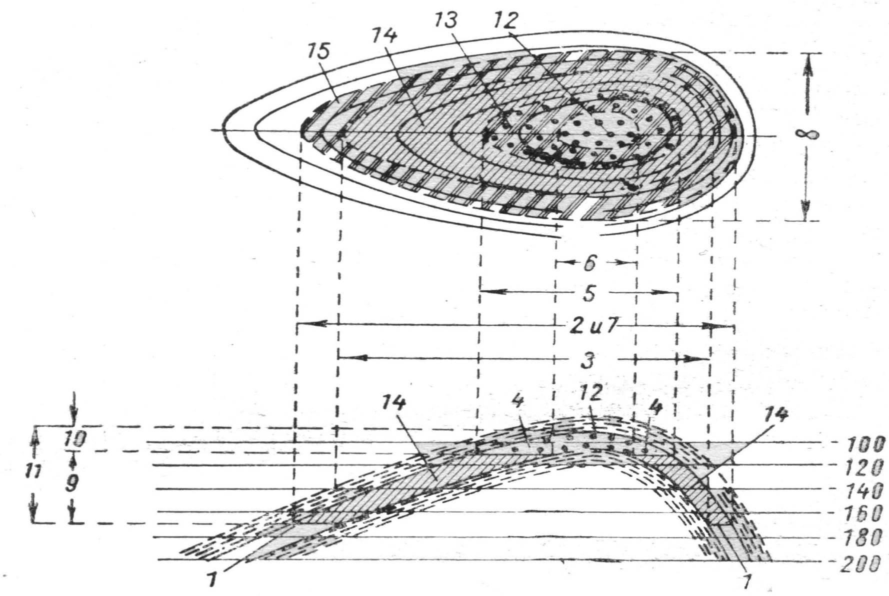

Fig. 15

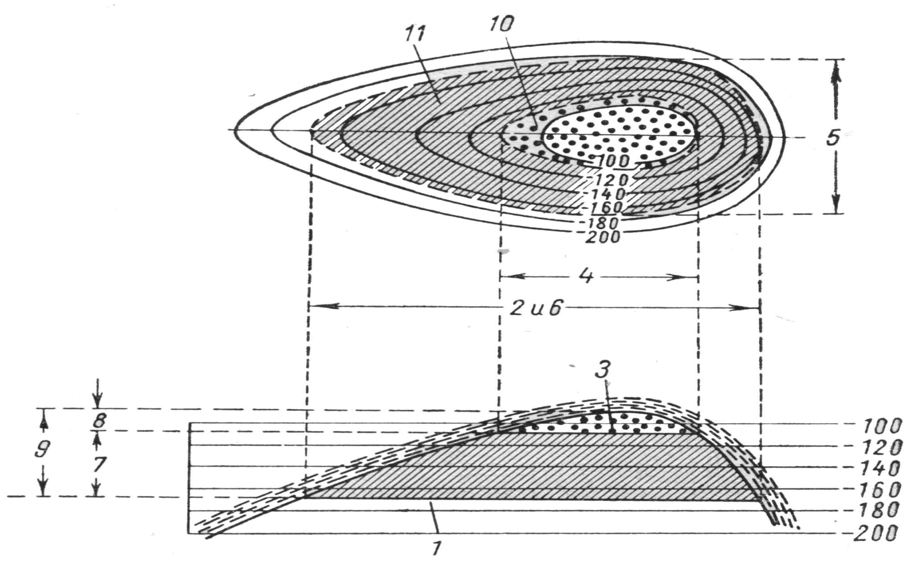

Fig. 16

It is advisable to take a classification proposed by A.A. Bakirov (1960), who by developing I.M. Gubkin concepts, identified four main classes of local oil and gas pools: **structural pool, lithological pool, reef pool and stratigraphic pool.**
When studying this section, it is necessary to get knowledge sufficient for identifying genetic type of pool, determining by geological documentation and diagrammatic lay-out such elements of pool as height, length, width and area of pool, vertical closure of trap, water-oil contact (WOC), gas-oil contact (GOC), gas-water contact (GWC), outer and inner oil pool (gas pool) outlines and so on.

Classification of Oil and Gas Pools

Классификация залежей нефти и газа (по А. А. Бакирову)		
Класс	Группа	Подгруппа
Структурные	Залежи антиклинальных структур	Сводовые Тектонически экранированные Приконтактные Висячие
	Залежи моноклиналей	Экранированные разрывными нарушениями Связанные с флексурными образованиями Связанные со структурными носами
	Залежи синклинальных структур	
Рифогенные	Связанные с рифовыми массивами	
Литологические	Литологически экранированные	Приуроченные к участкам выклинивания коллекторов Приуроченные к участкам замещения проницаемых пород непроницаемыми Экранированные асфальтом или битумом
	Литологически ограниченные	Приуроченные к песчаным образованиям русел палеорек (шнурковые или рукавообразные) Приуроченные к прибрежно-песчаным валоподобным образованиям ископаемых баров Линзовидные (Гнездовидные)
Страти-графические	Залежи в коллекторах срезанных эрозией и перекрытых непроницаемыми породами	Связанные со стратиграфическими несогласиями на тектонических структурах Связанные со стратиграфическими несогласиями, приуроченными к эродированной поверхности погребенных останцев палеорельефа или выступов кристаллического фундамента

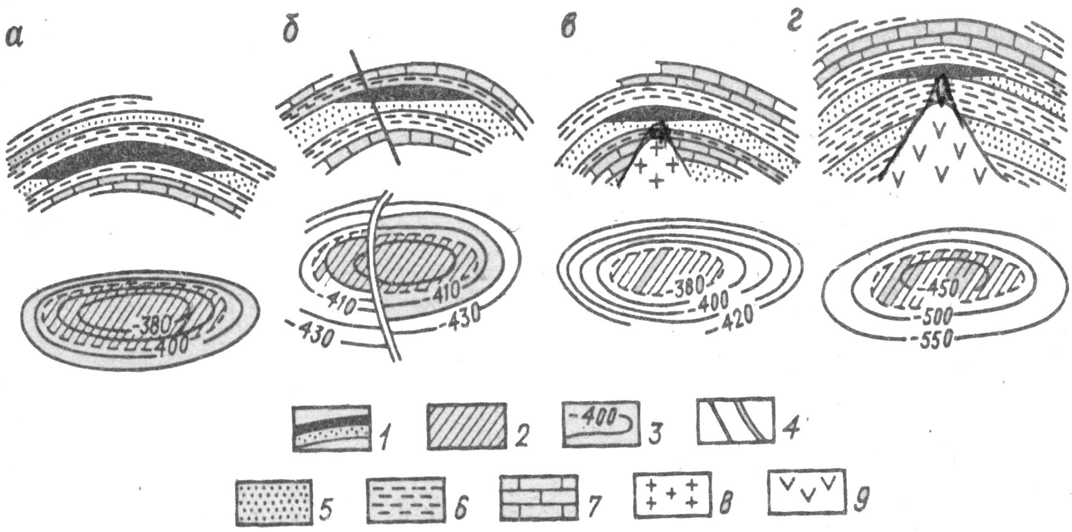
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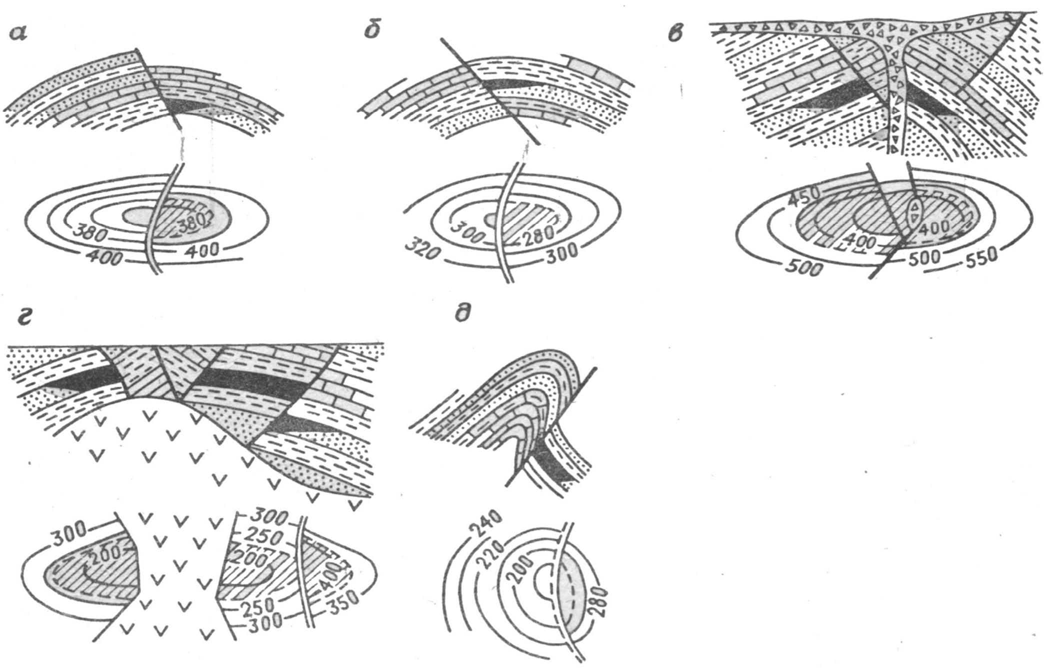
Fig. 17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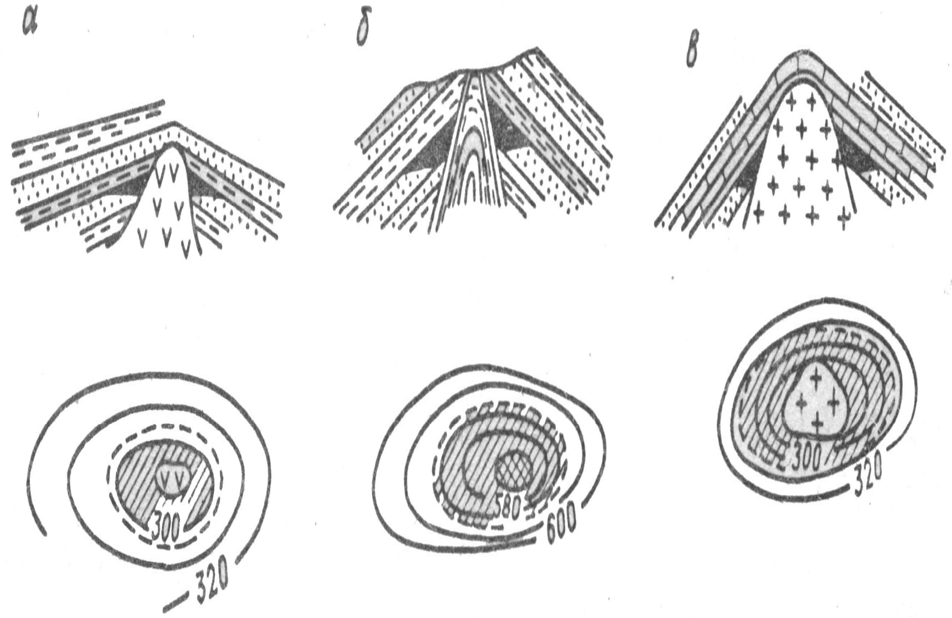
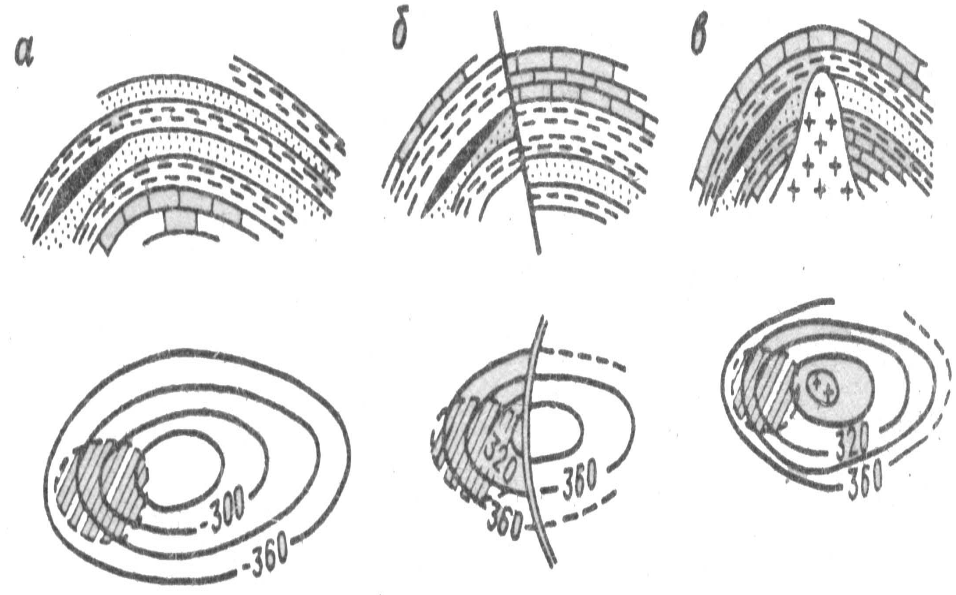


Fig. 19



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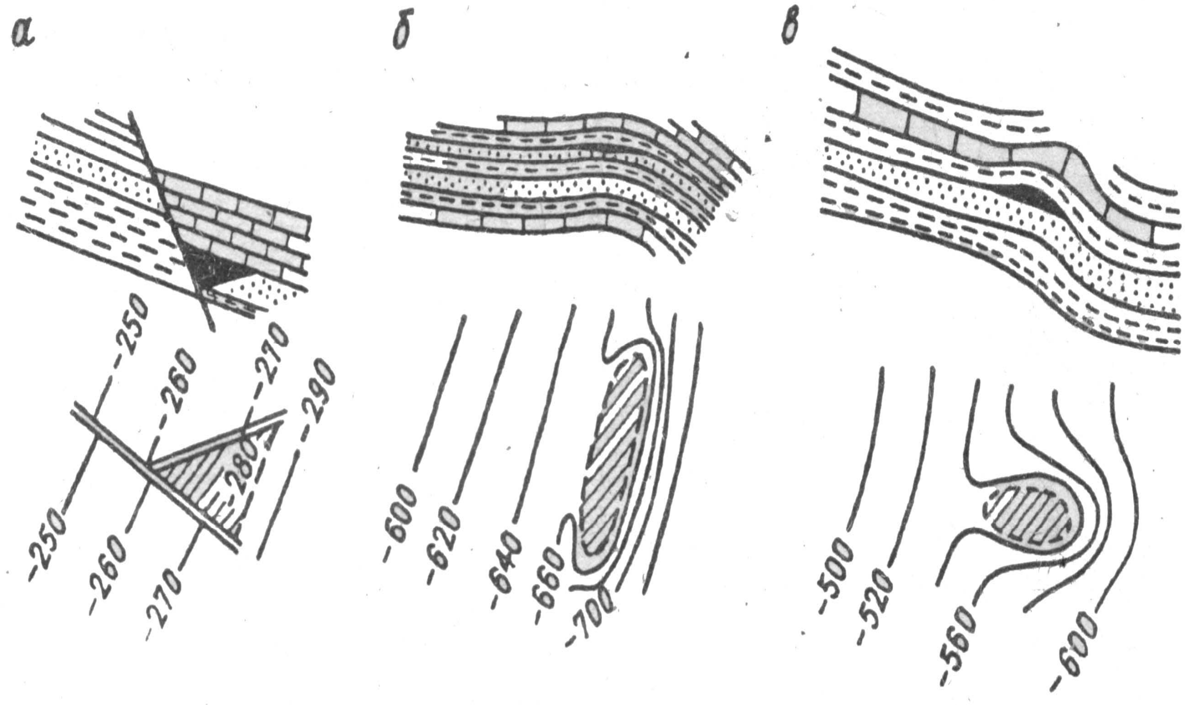
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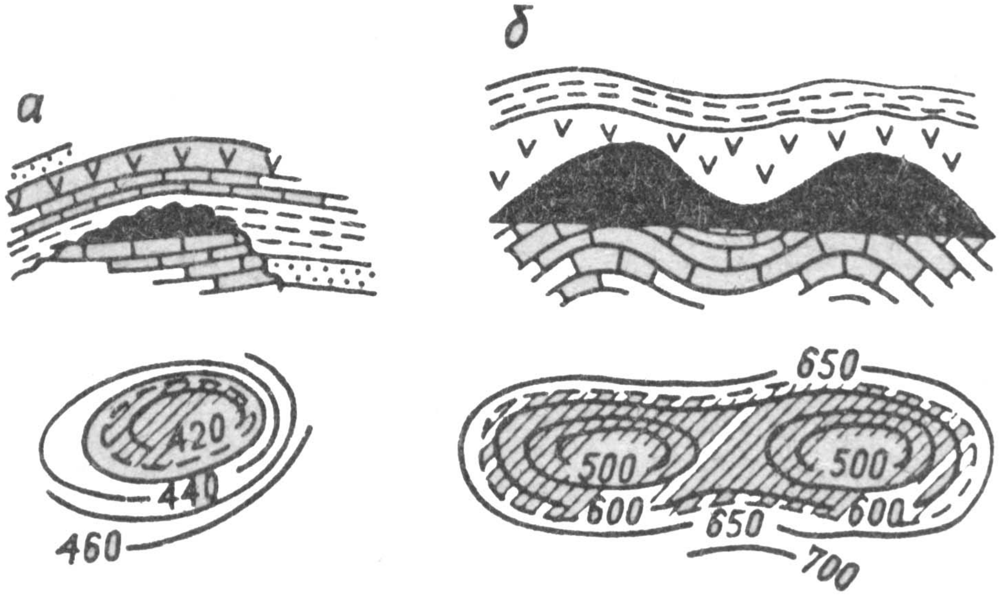
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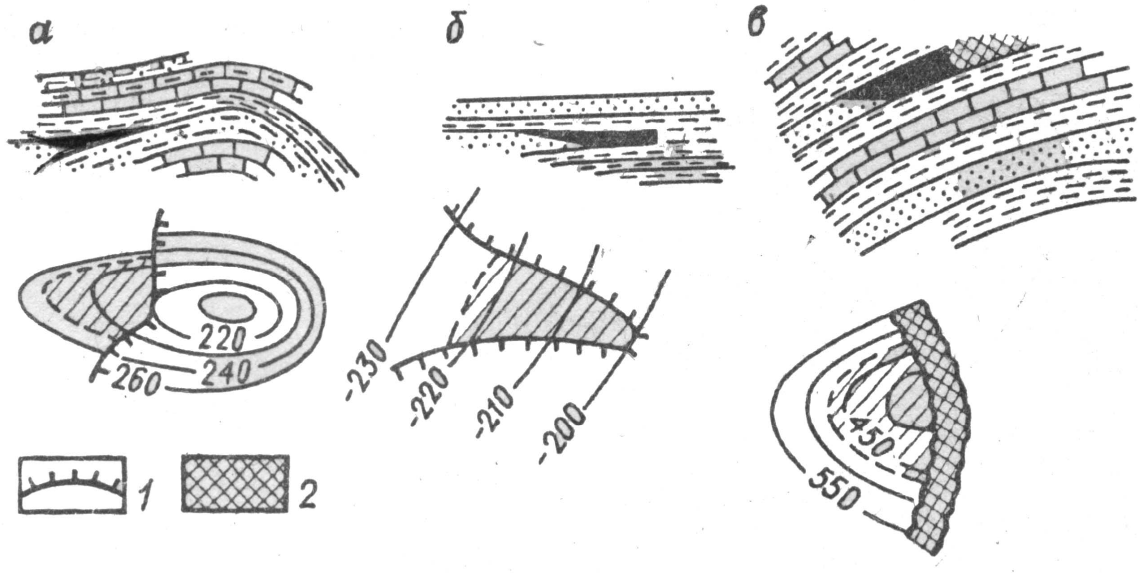

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Fig. 23

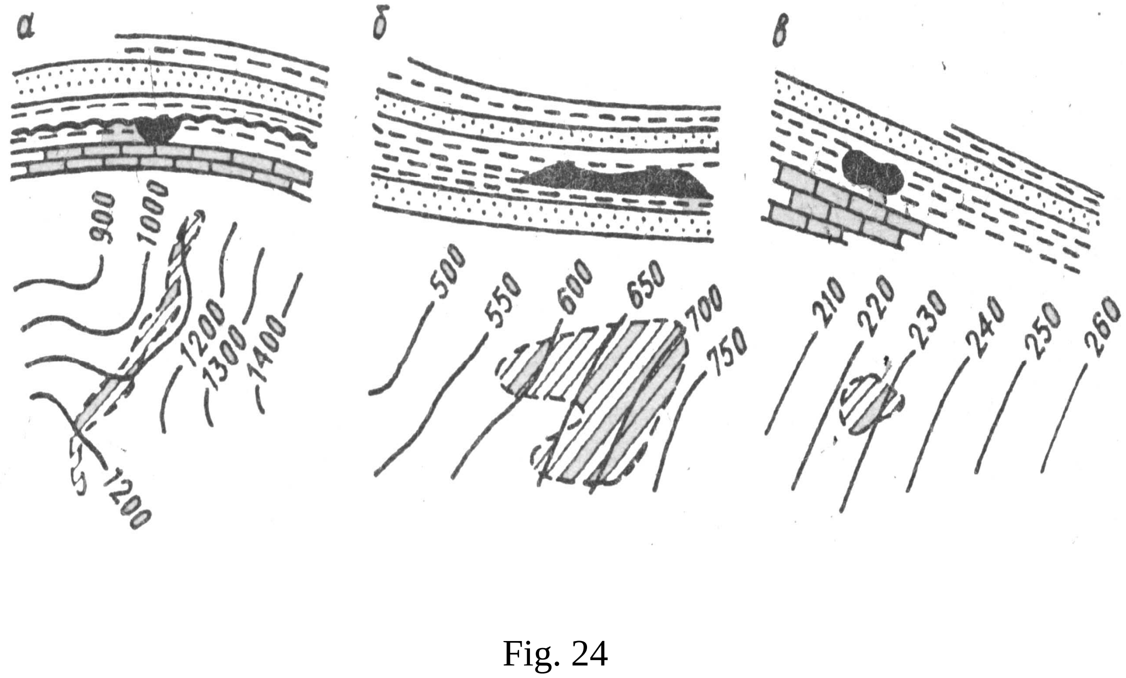

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Fig. 24

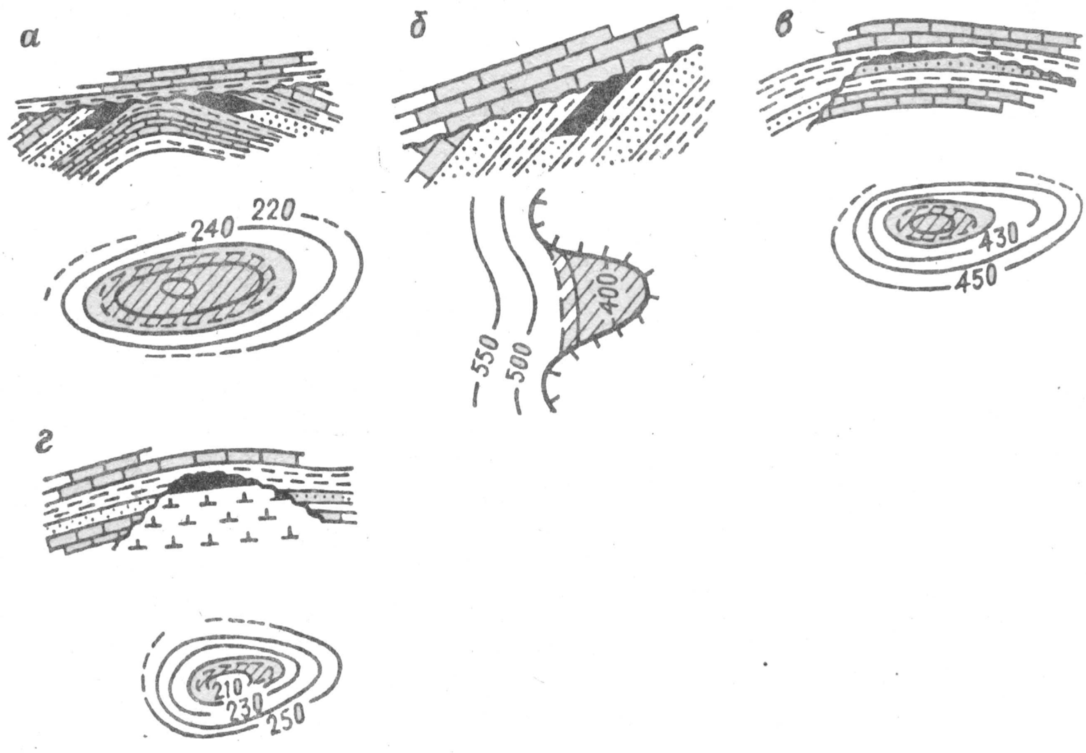

Fig. 25

OIL AND GAS POOL COLLAPSE AND REDISTRIBUTION

Collapse and redistribution of oil and gas accumulations is practically caused by the same processes that cause forming of oil and gas accumulations.
The main processes include tectonic, physical, chemical, biochemical, hydrodynamic, hydrologic and hydraulic processes.

The tectonic factor manifests itself in differential adjustment movement that promote to trap opening, trap collapsing due to disjunctive dislocating, complicating field structure due to appearing salt and clay diapirism, introducing igneous intrusions and so on.
During rising tectonic movements, when pools are taken out from depth, the pools that are occurring near the surface can be erosion damaged. Nature and extent of such manifestation of tectonic factor depends on tectonic setting of fields.

Extent of manifestation of chemical and biochemical factors is determined by temperature and pressure changing, which, to a great extent, depends on the depth of pool occurrence. In a number of cases, the reason of pool collapse is hydraulic factor (washing out of oil and gas by underground water).
Collapse of oil and gas traps results in various shows of oil, gas and pitch mineral, and sulfur deposits.

CONCLUSION

Integral study of geological and geochemical aspects of petroleum geology at the present-day science development level should be the basis for the future researches. For studying actual problems of petroleum geology, great emphasis should be laid on natural process modeling that should be maximally closed to the natural conditions, as well on applying the advanced geochemical methods considering developments and gains of the related branches aimed at developing direct methods of hydrocarbon accumulations.

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OIL AND GAS GEOLOGY

Часть 1

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OIL AND GAS GEOLOGY

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Излагаются основы нефтегазопромысловой геологии, поиска и разведки нефтяных и газовых месторождений, геофизических исследований скважин.

Рассчитано на специалистов Республики Ирак, обучающихся в Пермском государственном техническом университете по дополнительной образовательной программе профессиональной переподготовки специалистов «Руководитель нефтегазового производства».

Petroleum field geology introduction. Search for and exploration of oil and gas fields. Geophysical well surveying (logging).

The textbook is destined for the Iraq Republic specialists studying on the extra educational program of professional retraining «Oil and gas production manager» at Perm State Technical University.

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Course of lectures on

PETROLEUM FIELD GEOLOGY INTRODUCTION

Petroleum Field Geology studies geological structures of oil and gas reservoirs, properties of oil-and-gas bearing formations, and formation saturating liquids and gases, for designing the improved systems of hydrocarbon pool development that is aimed at maximizing oil and gas extraction.

Petroleum field geology is the geology of extracting oil and gas providing geologic substantiation for rational development and control of hydrocarbon deposits.

After an oil-and-gas reservoir has been discovered and recoverable resources calculated, the most important issues are those of selecting a rational system of developing, extracting, and regulating the process of oil and gas withdrawal. These issues are the subjects studied by petroleum field geology.

Its practical tasks are associated with solving of the issues of studying and generalizing geological and geophysical data about the structure of oil and gas reservoirs, estimation of hydrocarbon reserves, and maximization of the formation oil recovery rate.

The subjects studied by this discipline are as follows:

- natural conditions existing in the strata of oil and gas deposits, methods of studying and representing them;
- geological structure of deposits, properties of fluids, and parameters of reservoir beds;
- methods of determining hydrocarbon resources in productive strata;
- thermobaric conditions existing in the strata of oil and gas fields;
- methods of geological-withdrawal control and regulation of development of oil and gas deposits.

Topic 1.
Permeability and Porosity of Reservoir Beds

Oil and gas fill porous spaces of rocks. A rock capable of holding fluids and gases and carry them in the presence of pressure differences is called a **reservoir bed**.

Porosity is the parameter of a reservoir bed represented by intergranular pores and expressed in fractions of unity or as a percentage. Porosity of a rock means that the rock contains pores which are filled with solid materials. Total (open) porosity and rock matrix porosity are distinguished. **Total** porosity includes absolutely all pores of the rock, both isolated and open ones, and communicating with each other and the surface of a sample. Porosity formed by communicating pores is called **open**.

If all cement is removed from a terrigenous rock without disrupting the positions of the mineral grains in it, we obtain the "pure matrix" of the rock, which is formed by mineral grains with porous space between them. This space is called porosity of the rock matrix. Quantitatively, rock porosity is characterized by the porosity factor. The total (or absolute) porosity factor, K_p, is the ratio of the total volume V_{por} of the pores in a rock sample to its visible volume V_{sam}:

$$K_p = V_{por}/V_{sam} = (V_{sam} - V_{grain})/V_{sam} = 1 - V_{grain}/V_{sam},$$

where V_{grain} is the total volume of grains. The porosity factor is measured in fractions of unity or as a percentage of the rock volume.

In terms of their size, pore channels of oil and gas reservoirs are conditionally subdivided into three groups: 1) hypercapillary, 2–0.5 mm; 2) capillary, 0.5–0.0002 mm; and 3) subcapillary, less than 0.0002 mm in diameter.

In large (hypercapillary) channels and pores, oil, gas, and water run freely, and in capillary channels, under a considerable effect of capillary forces. In natural conditions, fluids actually cannot run in subcapillary channels.

The open porosity factor, K_{po}, is the ratio of the total volume V_{po} of the open communicating pores to the visible volume V_{sam} of the sample:

$$K_{po} = V_{po}/V_{sam}.$$

To determine the matrix porosity factor K_{pm}, it should be taken into account that the grain volume V_{grain} includes not only the volume of fragmentary particles, but also the volume V_c of cement, which can consist of clay and carbonate materials. Then,

$K_{pm} = V_{pm}/V_{sam} = (V_{sam} - V_{grain} - V_c)/V_{sam}$. Reservoir porosity ranges from 5 % to 30 %. Usually, it is from 10 % to 20 %. Carbonate rocks have lower porosity than terrigenous.

Permeability is the ability of a rock to transmit fluids and gases (in the presence of pressure differences). Fluids move over pore channels following the Darcy law, where the permeability ratio k_{perm} is

$$k_{perm} = \frac{Q \cdot \mu \cdot \Delta L}{F \cdot \Delta P};$$

here Q is the flow rate of the fluid in cm^3/s, μ is fluid viscosity in formation conditions in mPa s, ΔL is the length of the sample, through which the fluid is delivered (in cm), F is the area of the transverse cross section of the sample in cm^2, and ΔP is the pressure difference in MPa. The unit of permeability is 1 μm^2. The following permeability types are distinguished: absolute, phase (effective), and relative.

Table 1

Permeability classification of reservoirs (according to G.I. Teodorovich)

Class	Assessment	Value
1	Excellent permeability	> 1 μm^2
2	Good permeability	0.10–1 μm^2
3	Moderate permeability	0.1–0.01 μm^2
4	Weak permeability	0.01 > 0.001 μm^2
5	Zero permeability	< 0.001 μm^2

Only reservoirs of the 1st, 2nd, and 3rd classes are relevant for commercial development.

Absolute, **efficient(phase)**, and **relative** permeability of rocks is distinguished. Absolute permeability characterizes physical properties of the rocks. It is determined by the laboratory methods based on modeling of the filtration process in a cylindrical sample of the rock, in which the pore space has been preliminarily purified of moisture, salts, residual oil, tars, etc. Efficient or phase permeability means the permeability of a porous medium for a given fluid or gas in the presence of another fluid or gas in the pores. The less viscous fluid will have greater mobility. When the viscosity is the same, but the content of the fluids is different, the prevailing component will be more mobile. For any media saturating a rock, efficient permeability is always less than the absolute permeability, and depends on oil, gas, and water saturation of the rock.

When water appears, efficient permeability of oil becomes even lower. **Relative** permeability equals to the ratio of the efficient permeability to the absolute one. Efficient and relative permeability for a complex fluid as a whole and, especially, for each of the phases are significantly lower than the total permeability. In the process of deposit development, the efficient (and, consequently, relative) permeability changes continuously: at the beginning of the development, when pure oil moves along the pores, the efficient permeability of the rock is the greatest and close to the absolute value. Further, as the stratum pressure falls below the critical value and gas starts to escape in bubbles, the efficient oil permeability starts decreasing. The more is the stratum permeability, the higher is the productive capacity and the oil recovery rate of the strata.

Oil, gas, and water saturation of reservoirs

Initially, the strata saturated with oil, gas, and water were filled with stratal waters. Then, in the migration process, oil and gas, as substances with lower densities, forced the waters out and move to elevated stratum zones, i.e. the traps were filled in accordance with the principle of “differentiated entrapping” following the gravity law (the gas takes the highest position in the trap, then the oil, and at the bottom, the water). In reality, the position of fluids in a stratum are more complicated. Along with the gravity, the distribution of fluids is affected by capillary forces hindering clear density stratification of hydrocarbons into phases. Due to this, the water is not forced out completely from the porous space of reservoirs as oil migrates. The rest of the water is called residual, bound, or relict water. In order to determine the volume of the pores occupied by oil, it is necessary to know the amount of the bound water contained in a stratum. This value is determined by using the **water saturation factor**. The value of the water saturation factor yields the **oil saturation factor**, i.e. the ratio of the volume of oil in open pores and the volume of the pores. Depending on the percentage content of the residual water, reservoirs can be hydrophilic (water-wetted) or hydrophobic (water-repellant). Along with the oil, the porous space always contains bound water. Water contents in a strata is determined by using the oil saturation factor β, which means the ratio of the volume V_o of the oil contained in the stratum pores and the entire volume (V_p) of all the pores of the oil-bearing stratum:

$$\beta = \frac{V_o}{V_p}.$$

With the water saturation factor, K_w, i.e. the ratio of the volume of bound water to the volume of the porous space, known, the value of the oil saturation factor β can be determined as

$$\beta = 1 - K_w.$$

The content of bound water in oil-bearing strata ranges from 6 % to 70 %. In sands and sand rocks there may be film water, which is a water film on the surface of mineral grains, which is constrained by molecular forces of coherence between the rock and the water. Bound water usually contains more salts than ocean water.

In order to determine the volume of the pores occupied by oil, it is necessary to know the amount of the bound water contained in this volume. The oil penetrating into a core sample does not change the content of the bound water in it.

Studies showed that as the permeability of rocks grows, water saturation of strata decreases.

The lower boundaries of the parameters used to categorize strata under a certain category of reservoir rocks are called **conditions**. **Conditions** are the minimal values of porosity and permeability, at which a rock is capable of containing and delivering oil.

In this case, the main rock criterion is their productivity determined by the specific productivity factor q:

$$q = \frac{Q}{H\Delta p},$$

where Q is the daily yield of the well in tons per day, H is the efficient stratum thickness in meters, and Δp is the pressure difference in MPa. The results of laboratory sample studies are used to determine the values of open porosity (m_1) and permeability (K_{perm}). Then, the graphs of the interdependence of permeability and the specific productivity factor for individual wells are plotted (fig. 1). Based on the data about the limits of the value of the specific productivity factor, at which the development will be cost-efficient (e.g. about 0.05 (tons per day) / (MPa^{-1} m)), the graph is used to determine the corresponding permeability value (from the graph, about $15\times10^{-15}\text{m}^2$).

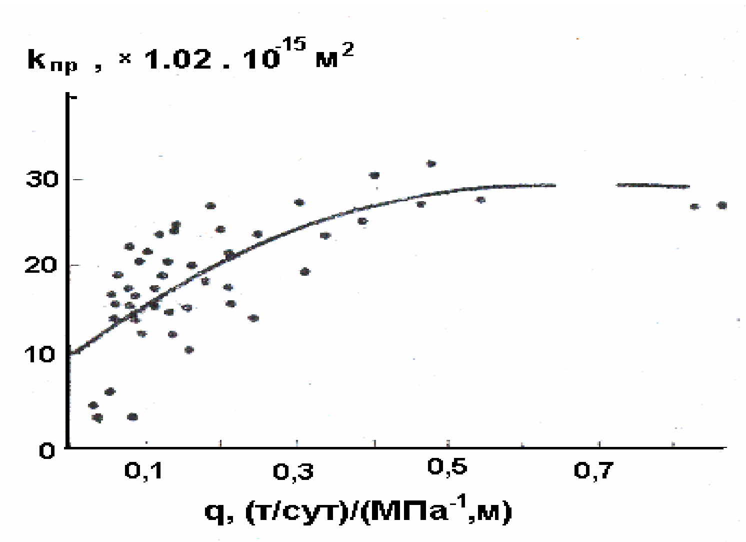


Fig. 1. Relationship between permeability K_{perm}
and specific productivity factor q

Finally, the curves of the interrelation between the open porosity and permeability are plotted for the same wells (fig. 2), and the required conditional value of the open porosity is found for the obtained permeability value ($15\times10^{-15}m^2$).

The assessment of the lower conditional values of porosity and permeability for oil-bearing stratal reservoirs, at which the reservoir retains filtration properties and is capable of delivering oil is of great importance for calculation of oil resources, and for designing and analysis of the field development.

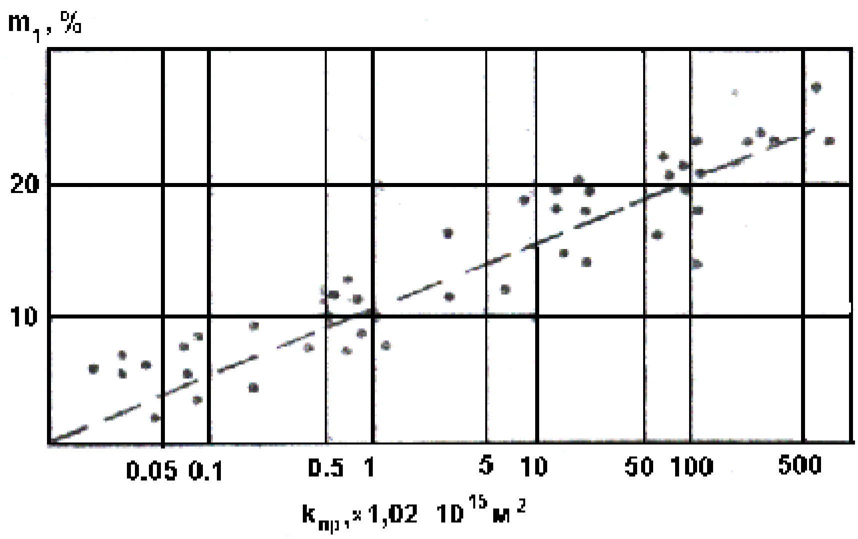


Fig. 2. Relationship between porosity m_1 and permeability K_{perm}

Topic 2.

Accumulation Occurrence Mode

Oil and gas reservoirs cannot be prospected and developed without clear and precise information about their properties, conditions of occurrence in the Earth crust, and regularities of their spatial arrangement.

Formation of an oil or gas reservoir requires three preconditions:

1. **Reservoir rocks:** a porous permeable rock capable of absorbing and delivering oil, gas, and water, e.g. sand rocks and chalk stones.

2. **Natural reservoir:** a natural container of oil, gas, and water, whose shape is determined by the relationships between the reservoir rocks and the enclosing low-permeability.

A natural reservoir is a reservoir bed bounded by impermeable rocks.

3. **Trap**: a part of the natural reservoir, in which an accumulation of oil and gas can be formed or has been already formed.

A hydrocarbon pool is a natural accumulation of oil, gas, and gas condensate in a trap formed by the reservoir rock under a cover of impermeable rocks.

A **formation pool** is an accumulation of oil and gas in a reservoir bed bounded by impermeable rocks at its roof and bottom.

A trap for oil and gas is created by bending of stratum roofs. In terms of the trap character, formation dome pools and formation screened pools are distinguished.

Formation dome pools are pools in anticline structures. In practice, they are met most frequently. The trap in a formation dome pool is formed by a bending in the overlaying cover.

Figure 3 shows the scheme of formation dome pool. The line of crossing of the oil-water contact (OWC) surface with the roof of the stratum is called the **external oil-water contact.** The line of crossing of the oil-water contact (OWC) surface with the bottom of the stratum is called the **internal oil-water contact.**

Tectonic screening is associated with a fault, along which the reservoir bed is "cut off". The fault is impermeable.

Stratigraphic screening is associated with an unconformable occurrence of one deposit complex over another. It is formed when reservoir beds exposed by erosion are overlaid with impermeable rocks of another age. There are cases when a reservoir bed is bounded by cut-out surfaces both from above, and from below.

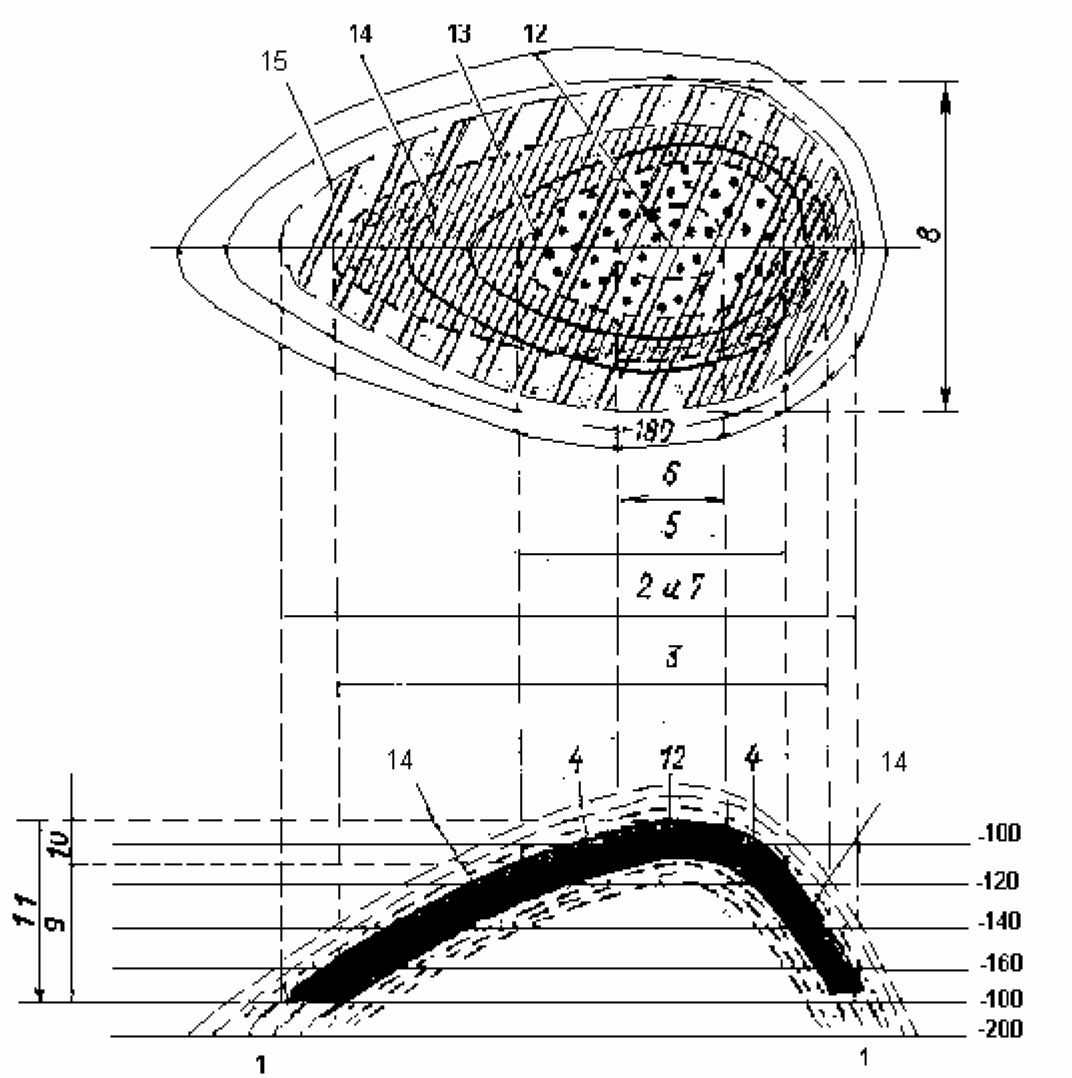


Fig. 3. Formation Dome Pool (according to N.A. Eremenko):
1 – bottom of the oil deposit (surface of the oil-water contact); oil-drainage boundary: *2* – external; *3* – internal; *4* – surface of the gas-oil contact; gas-oil contact; *5* – external (gas cap contour), *6* – internal; *7*, *8*, *9* – length, width, and height of the oil pool, respectively; *10* – height of the gas cap; *11* – total height of the oil-gas pool; parts of the pool: *12* – gas; *13* – gas-oil; *14* – oil; *15* – oil-water

One of the largest oil fields of the world, East Texas in USA with recoverable reserves of 810 million tons of oil, is confined to the structural nose on the Eastern arm of the Sabin swell (fig. 4).

Crossing of two unconformity surfaces caused attenuation of permeable sand rocks at Woodbine (Upper Cretaceous).

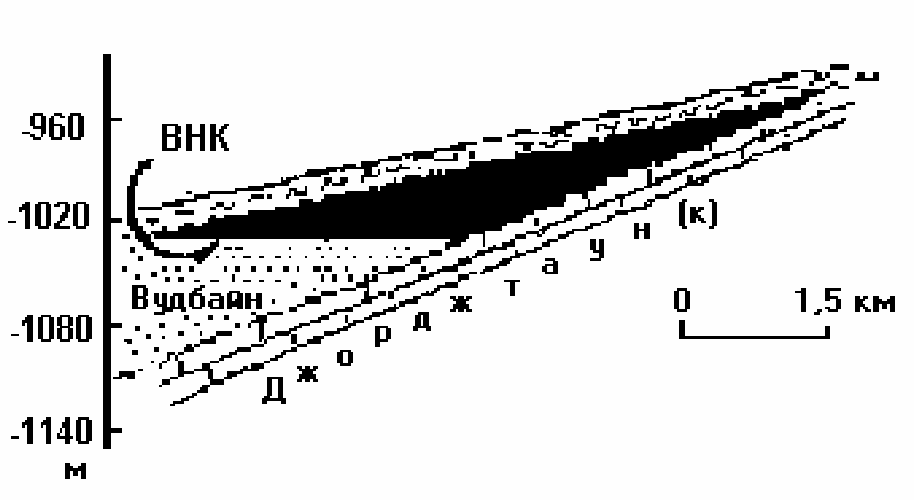


Fig. 4. Stratigraphically Screened Pool

(Cross section of the East Texas field)

Lithologically screened pools are formed mainly when the thickness of a reservoir bed contracts upstructure on the slopes of regional upheavals almost up to its complete disappearance or as a results of deterioration of reservoir properties of the stratum: porosity and permeability (fig. 5).

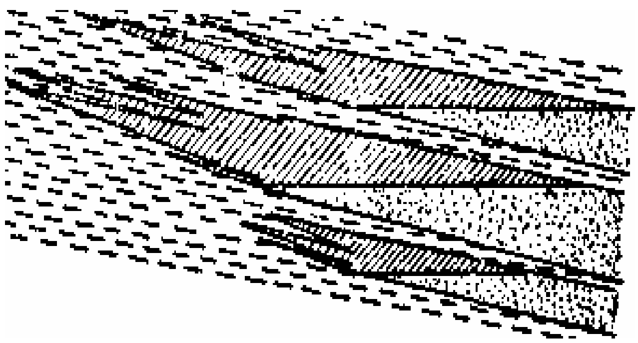


Fig. 5. Formation Lithologically Screened Pools

Massive Pools. Massive pools are represented as massive thicknesses consisting of many permeable strata which are not separated from each other with poorly permeable rocks.

Massive pools are associated with massive reservoirs. The shape of the reservoir surface is important for formation of massive pools. Oil and gas saturate the massive pool in the uplifting part. The shape of the trap is determined by the shape of the roof bending. Massive pools are formed most frequently on noses of carbonate rocks.

The oil-water contact cuts the whole body of a massive pool irrespective to the composition and stratigraphic category of an inhomogeneous reservoir bed.
Groups of massive pools are associated with structural noses, erosion scarps, and biogenic upwells.
Structural noses are anticlines, swells, and dome folds.

Erosion scarps are connected with residual outcrops of the ancient terrain. For example, a formation of chalk stones and dolomites was washed out and covered with clays. In the erosion process, a scarp was formed, and when it was buried, an oil deposit appeared.

Biogenic upwells are reefs, which are prevalent in the Perm region and are associated with the Kamsko-Kinelsky trough system. Inhomogeneous distribution of porous and permeable zones in the massive are characteristic of massive pools. Figure 6 shows a reef massive.

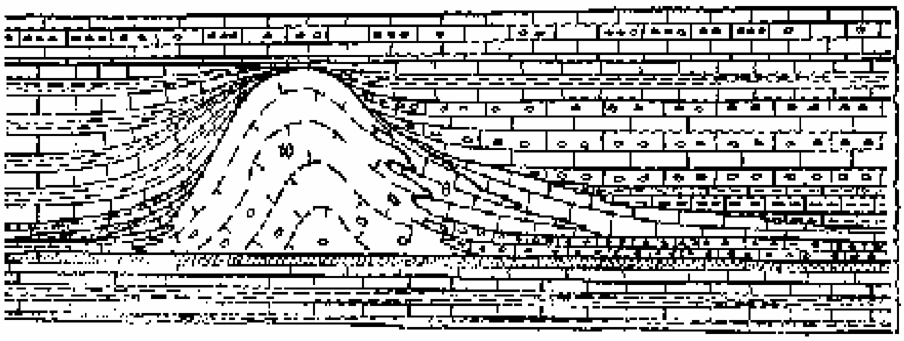


Fig. 6. Massive Reef Pool

Oil-water contact (OWC) is a boundary that separates oil and water in a stratum. It is a zone with a certain thickness, which contains oil and free water. As the distance to the clear-water surface becomes shorter, the oil contents in the stratum decreases gradually. That part of a reservoir, within which the transition from pure oil to pure water is observed, is called the transition zone.

In sand rocks with high permeability and good grain separation, the thickness of the transition zone does not exceed 0.3 m. In sand rocks with inhomogeneous lithologic composition and poor grain separation, it may reach 8 m.

According to the geophysical research based on studying variations of the specific resistance during transitions from the oil-saturated part of the stratum to the water-saturated one, as the oil-water contact such a boundary of the transition zone should be selected, at which the specific resistance is equal to the critical one, 10 Ohm/m. The critical resistance means the minimum specific resistance of the stratum, at which the water-free inflow of the oil is produced.

The oil-water contact is not always horizontal, it is frequently inclined. It depends on the size and position of the catchment area, character of the reservoir permeability, and the dynamics of the subterranean waters' motion. Displacement of oil and gas deposits (and non-horizontal positions of the oil-water and gas-water contacts) is mainly associated with the motion of stratal waters. The gas-oil contact (GOC) is determined as the boundary of the 100 % content of free gas and 100 % dissolution of gas in oil. In this case, there is a transition zone between oil and gas. The oil-gas contact is a boundary in a mixture of hydrocarbons with similary physical properties, therefore determining it is even more complicated than determining OWC.

Precise determination of the contacts is required to plot isopachous maps of efficient oil-saturated formations when calculating oil resources. To obtain precise information about the position of the oil-water contact, a set of studies is performed:

1. A well test is performed: in this case, the oil-water contact should be within the interval between the lowest position of the shooting holes for the perforation yielding 100 % of oil, and the highest position of the shooting holes yielding 100 % of water; a fast increase of the water amount in the well after it has been commissioned can indicate that the well is within the oil-water zone.
2. A core sample is studied: the presence of oil and water in it, and their mutual position should be determined.
3. Electric and radioactive well logging is performed; the results of these measurements prove to be very useful in OWC determination.

To determine GOC, one can also map isolines of the gas factors by wells; the isoline corresponding to the 100 % gas extraction is found by interpolation and extrapolation, it is taken as the gas-water contact and, basing on this, the gas-oil contact is found.

Topic 3.
Thermobaric Conditions in Natural Reservoirs.
Formation Pressure and Temperature

The difference in the pressures at the bottom hole and in the stratum is the force which moves oil and gas along the stratum to the well. The values of formation pressures at different points of the deposit are not the same, they change in time and space. To calculate the resources of oil and gas, and plan and control their development, the following types of pressures are studied:

1. Formation pressure: the pressure at some point of the stratum, which has not been affected by depression cones of the adjacent operated wells.
2. Initial formation pressure measured at the first well which exposed that stratum, before the fluid was extracted from it;
3. Current static formation pressure: static bottom hole pressure measured as of a certain date in the well, after the relative static equilibrium has stabilized in it;
4. Dynamic formation pressure: the bottom hole pressure of an operating well;
5. Dynamic formation pressure: the pressure in the developed stratum or at the bottom hole of the operating well in the conditions of no static equilibrium.

The pressures measured in killed wells, in which the relative static equilibrium has stabilized, are conditionally called static formation pressures, and the pressures measured in operated walls, are called dynamic formation (bottom-hole) pressures.
Knowing the value of the formation temperature is required to study the properties of formation oil, gas, and water, to design and analyze formation development, to determine the formation occurrence mode, dynamics of formation water flows, to reveal the conditions of accumulation formation, to study the thermal field of the Earth crust, etc.

Temperatures in wells are measured with special thermometers.
In operated wells, temperatures are measured after the pump has been pulled out. These measurements prove to be reliable for the interval of the occurrence depth of the productive formation. To obtain reliable temperature data in other stratum intervals, the well should be filled with mud fluid and leave for a long time (sometimes, up to 20 days).
Physical properties of oil (viscosity, gas trapping capability, etc.) change as the temperature changes. Hence, oil ability to move along the formation changes too; therefore, the data about formation temperatures are always necessary.

Topic 4.

General Notions of Reserves and Their Classification (Commercial, Non-Commercial, Initial, and Current Reserves) Main Development Parameters. Reservoir Recovery. Oil Recovery Factor. Development Stages

Reserves of oil, gas, or condensate are their amounts contained in reservoir rocks within the studied portion of the geological space. Accordingly, one can talk about the reserves of individual layers, formations, blocks, accumulations, and fields. The procedure of calculating the amount of hydrocarbons is called estimation of reserves. The object, in which the reserves are calculated, is called the reserve estimation target. Ranking of reserves under this or that category is done in accordance with reliability of determining them, which depends on geological conditions and the volume of the information about the reserve estimation target.

When estimating commercial reserves of oil, dissolved gas, condensate, and the components contained in them, recoverable reserves are calculated and registered, i.e. that portion of commercial reserves, which can be recovered by using today oil and gas recovery techniques and technologies efficiently. One distinguishes also the initial and current (residual) reserves of oil, gas, and condensate. The initial commercial (initial recoverable) reserves of hydrocarbons are the reserves of accumulation or field before the beginning of development. Current (residual) commercial (and, correspondingly, current recoverable) reserves of hydrocarbons are the reserves that constitute, as of a certain date, the difference between the initial reserves and the cumulative production. The residual reserves serve as the basis for taking measures to regulate the development and further development of deposits, as well as to increase the final recovery of oil, gas, and condensate.

When using the volume method of oil reserve calculation, the basic assumption is that the oil is deposited in the stratum pores whose volume can be determined granted that the geometric dimensions of the oil-bearing stratum and porosity of the rocks that build up the stratum are known.

To calculate oil reserves, the following formula is used:

$$Q = Fhm\beta\eta\rho\theta,$$

where Q is the recoverable oil reserves in tons, F is the area of oil bearing capacity in square meters, h is the oil-saturated thickness of the stratum in meters, m is the open-porosity factor of oil-containing rocks, β is the oil saturation factor of the stratum (saturation factor), η is the oil recovery factor, ρ is the surface density of the oil in tons per cubic meter, and θ is the conversion factor that takes oil shrinkage into account: $\theta = 1/b$ (where b is the formation oil volume factor).

The formula for calculation of gas reserves using the volume method is as follows:

$$V = Fhmf\,(P_{\alpha} - P_f\alpha_f)\,\beta_g\eta_g,$$

where V is the recoverable (commercial) gas reserves as of the calculation date in cubic meters; F is the area within the productive gas-water contact in square meters, h is the thickness of the porous portion of the gas-bearing stratum in meters, β_g is the gas-saturation factor with account for the content of bound water, η_g is the gas recovery factor, m is the open-porosity factor, P is the average absolute pressure in the gas deposit as of the calculation date in MPa and P_f is the average residual absolute pressure (final) in the deposit after extraction of the commercial reserves of the gas and achievement of the absolute pressure equal to 0.1 MPa at the bottom hole,

$$P_f = P_{atm} e^{1293 \cdot 10^{-9 \cdot H\rho_g}},$$

α and α_f are the corrections for deviations of hydrocarbon gases from Boyle's law for the pressures P and P_f, respectively, and f is the correction for the temperature to reduce the gas volume to the standard temperature:

$$f = \frac{T + t_{sT}}{T + t_{st}}$$

(t_{sT} = 20ºC, T = 273ºC).

The formation pressure in gas wells is determined from the data about the pressures at the well bottom holes (when they are shut down temporarily) with account for the force of gravity of the gas column:

$$P_f = P_m e^{1293 \cdot 10^{-9 \cdot H\rho_g}},$$

where P_m is the manometric pressure on the mouth of the shut well as of the calculation date in MPa, e is the base of natural logarithms equal to 2.71, H is the depth of the roof of the gas-bearing stratum in meters, and ρ_g is the gas density with respect to air.

The residual pressure in the deposit (P_f) is determined granted that the pressure on the well mouth is P = 0.1 MPa (after extraction of commercial gas reserves) using the following formula:

$$P = P_m e^{1293 \cdot 10^{-9 \cdot H \rho_g}} .$$

Usually, depending on the depth of occurrence and the composition of the gas, the value P_f ranges from 0.1 to 0.3 MPa. It is evident that for the water-driven regime, the account for the residual pressure P_f in the stratum is unreasonable. In this case, P_f in the formula is assumed to be zero ($P_f = 0$). The oil-water contact, average thickness of the porous part of the stratum, and the average porosity factor are determined in the same way, as when calculating oil reserves using the volume method.

When determining the deviation of the natural gas from Boyle's law, one should introduce the compressibility correction z depending on the gas content, pressure, and temperature. The correction equals to $\alpha = \dfrac{1}{z}$, where $z = \dfrac{P\,V}{R\,T}$ is the gas compressibility factor (here, P is the gas pressure, V is the gas volume, R is the universal gas constant, and T is the absolute temperature). Numerical values of the compressibility factor for different conditions are determined in laboratory. Wherever necessary, approximate values of the compressibility factor are obtained from experimental curves or graphs.

To determine the gas saturation factor β_g, one can use the graph which makes it possible to determine this value with account for the content of bound water. Such a graph is used in tentative calculations, if there are no laboratory data about gas saturation.

The question about substantiation of the gas recovery factor is complicated, since the data may be insufficient. It has been stated that:

a) for the fields with gas reserves over 1.5–2.0 billion m^3, the gas recovery factor ranges from 0.9 to 0.99 (of the initial reserves calculated with the account for the residual pressure of 0.1 MPa);

b) for the fields with less reserves, the gas recovery factor ranges from 0.66 to 0.8;

c) when gas is forced out of loose sands by water, the residual gas saturation is about 16 %; for strong sands it ranges from 25 % to 50 %; and

d) field data obtained by studying the sample taken from the water-cut part of the gas-bearing area yield the residual gas saturation ranging from 16.7 % to 21.8 %.

Calculation of Oil-Dissolved Gas Resources

The data required for the use of this method are: *P*, average stratal oil-deposit pressure calculated from the isobaric map as of the calculation date in MPa; Q_1, residual recoverable oil resources as of the calculation date in tons; g_r, the average gas factor as of the calculation date in cubic meters per ton, *g*, gas solubility in oil calculated from the graph as of the calculation date (at the pressure *P*) in cubic meters per ton. Then, gas reserves *V* (m^3) will equal to:

$$\text{at } g_r > g,\ V = Q_1 g,$$

$$\text{at } g_r < g,\ V = Q_1 g_r.$$

Since that part of the oil which is unrecovered after the pressure decreased will be still making the gas, then in the dissolved gas mode and in the gas cap mode, the account is taken for those amounts of the gas, which can be obtained additionally from the oil which is left underground. Then, the formula for calculating the reserves of the oil-dissolved gas will have the following form:

$$V_0 = Q_0 r_0 - Q_{rec} b_0 P_f \alpha_f f - Q_{rec}(b_0 - b) P_f \alpha_f f - Q_{unrec} z_f ,$$

where V_0 is the recovered reserves of the oil-dissolved gas under standard conditions (in m^3), Q_0 is the commercial oil reserve under standard conditions (in m^3), Q_{rec} is the recoverable oil reserves under standard conditions (in m^3), Q_{unrec} is the unrecoverable oil reserves under standard conditions (in m^3), b_0 is the formation oil volume factor as of the initial development date at the pressure P_0, *b* is the formation oil volume factor as of the final development date at the residual pressure P_f, g_0 is the average weighted initial gas factor measured at the sample trap at 0.1 MPa (in m^3/m^3), g_f is the residual amount of the oil-dissolved gas at the residual pressure P_f (in m^3/m^3), P_f is the residual pressure in the formation (in MPa), α_f is the correction for the gas compressibility factor for the pressure P_f, and *f* is the temperature correction.

To simplify the calculation, it is usually assumed that

$$P_f = 1 \text{ MPa}.$$

Oil Recovery

The oil recovery coefficient η is the value showing which part of the initial commercial oil reserves is recovered or can be recovered as the deposit is developed up to the profitability limit.

$$\eta = Q_{out}/Q_{res},$$

where Q_{out} is the total oil output in tons, and Q_{res} is the initial commercial reserves in tons.

The oil recovery factor η depends on the lithological properties of the reservoir, oil properties, the rate and system of development, production method, etc.

Depending on the drive, the value of the oil recovery factor is assumed to be as follows:

- for the efficient water drive	0.65–0.8
- for the elastic water drive	0.5–0.7
- for the efficient gas cap drive	0.4–0.6
- for the inefficient gas cap drive	up to 0.4
- for the internal gas drive	0.2–0.4
- for the gravity drive	0.1–0.2.

Main Indicators of the Development Status

1. Total fluid output, tons;
2. Total oil output, tons;
3. Average formation pressure, MPa;
4. Current oil output, tons;
5. Current water output, tons;
6. Gas factor, m^3/ton;
7. Percentage of water content relative to the total fluid, %;
8. Number of operated wells; and
9. Average daily oil output per well, tons.

The total fluid output is the cumulative fluid recovery as of a certain date since the start of the object development.

The total oil output is the cumulative oil recovery from an object as of a certain date since the start of the object development.

The field gas factor *G* is the amount of the recovered gas (in m^3) in 1 m^3 (ton) of degassed oil. There are the initial gas factor determined from the data for the first month of operation, the current gas factor determined for any intermediate time period, and the average gas factor determined for a period since the development start up to some date.

The bubble point pressure is the pressure, at which the gas starts to pass from the oil-dissolved state into the free state.

Development Stages

The 1st stage is the stage of development of the production facility, which is characterized by the growth of the annual oil production; at this stage, the main well stock (or its major part) is drilled and commissioned, and the designed system of stratum treatment is utilized.

The 2nd stage is the stage of preservation of the maximum achieved annual oil output, which is traditionally called the maximum output level or the maximum production rate; at this stage, the rest wells from the main stock are drilled and commissioned, the system of stratum treatment is developed further, and the plan of geological and technical measures for the development process regulation is fulfilled;

The 3rd stage is the stage, at which the oil output decreases, since the major part of the reserves has been already extracted; at this stage, in order to decelerate the rate of the production decrease, the stratum treatment system is developed further by drilling additional wells for water pumping, standby wells are drilled, isolation works in the wells are underway, forced drainage of water-cut wells is started along with other measures aimed at controlling the development process; and

The 4th stage finalizes the development period; it is characterized by a further decrease of oil output at slow development rates; at this stage, the same works of regulating the development process, as at the 3rd stage, are performed

The schedule for development of each production zone shows the boundaries between development stages.

Oil production. The 1st stage is characterized by the rate of the oil production increase, which determines its duration. The duration of the 1st stage can be reduced by increasing the production capacity and improving the organization of the works of drilling and constructing organizations. The duration of the 1st stage is from 1 to 8 years.

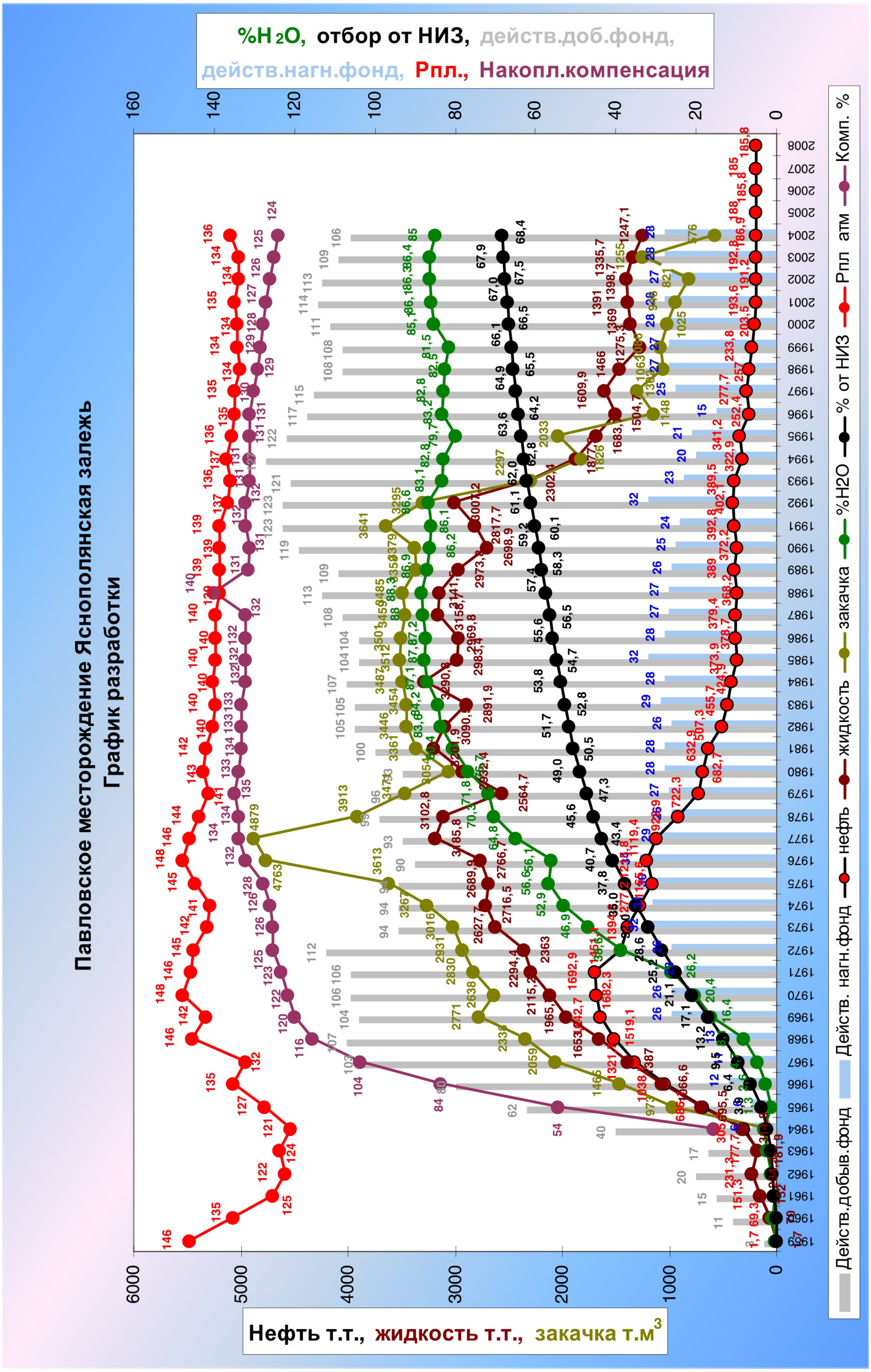


Fig. 7. Production Zone Development Schedule

The 2nd stage is characterized by the maximum recovery rate for the developed production zone. The duration of the 2nd stage is from 8 to 10 years. The shortest durations are characteristic of:

high-productivity, small-size deposits, for which a high rate of oil production is achieved;

deposits with higher values of oil viscosities, for which the maximum recovery rate cannot be maintained due to progressing well drowning.

The share of the extracted reserves recovered by the end of the 2nd stage, i.e. by the beginning of a drop in oil production, is largely determined by oil viscosity. At low values (less than 5 MPa.s) it is about 50 %, at higher values, about 35 %. The following should be emphasized for these approximate data:

1) to prevent declining of the oil production at oil facilities, it is necessary to undertake a large-scale complex of geological and technological measures to perfect and regulate the development system;

2) if by the end of the 2nd stage, 65–70 % of recoverable reserves have been extracted without much effort, it usually indicates that the actual recoverable reserves of the facility are greater than the calculated ones; an early decline of the production that happens despite active measures taken to regulate the development may indicate that calculated reserves were overestimated or the designed technological solutions for the facility development are insufficient.

The difficult stage is the 3rd stage of the development, at which the oil production declines inevitably due to depletion of a major part of the reserves. The water content of the products which is growing at this stage complicates the process of oil extraction from the strata.

The scope of measures taken to regulate the development and aimed at slowing down the production decline and reducing extraction of associated water, which does not displace water from the strata already, grows sharply.

Topic 5.

Oil and Gas Field Development Regulation in Various Geological and Physical Conditions

Main Objectives of Development Regulation. Regulation of the development of oil and gas fields is understood as the control of the process of hydrocarbon extraction using a complex of various technological and technical measures. The essence of the regulation is changing purposefully the direction and velocity of filtration of formation fluids, and in establishment of favorable conditions for reserve drainage.

A developed field is a complex dynamic system changing with time continuously. As the reserves are withdrawn, the conditions of their extraction change at individual sections and in the entirety of the field. Purely oil zones of the stratum are decreasing along with the oil-saturated massive, the well stock and its status undergo some changes. It requires reviewing the technological decisions made earlier constantly, redistributing the volumes of extraction and injection of the working agent between the wells and field areas, taking measures to engage the undeveloped zones and identified bypassed oil. Primarily, the regulation should be used to ensure oil production at the developed facility. Another important objective of development regulation is achievement of the designed oil extraction factor for the field under consideration. When selecting the measures of oil recovery regulation, one should proceed from the task of ensuring the maximum level of reserve extraction from the underground.

The third objective of the regulation is the comprehensive upgrading of economic indicators by using the stock of drilled wells to the maximum, minimizing the costs of injecting the displacement agent, and reducing the withdrawal of the associated water without damaging oil output.

Many methods and ways are used to solve specific tasks of supervising the development process. These methods and ways can be categorized into two big groups:

regulation through drilled wells without changing the adopted development system significantly; and

regulation by changing or upgrading the development system (drilling of new wells, drawing of new cut-off lines, changing the injection pressure and the operation system).

Main measures taken to regulate the development include:

establishment of the optimal regime for producing and injection wells;

optimal completion and changes in the perforation intervals;

treatment of the bottom hole zone; and

application of multiple zone injection and multiple zone development, in the case of the multipay structure of the production zone.

Establishment of the optimal regime for producing and injection wells. For each well, the norms are set for the daily oil output, number of work days, bottom hole pressure and surface pressure, water content and gas factor, with account for the location of the well. For injection wells, the cyclic operation regime is established, i.e. it has the number of work days and the number of idle days.

Optimal completion and changes in the perforation intervals. To prolong the water-free period of operation of the wells situated within the oil-water zone, perforation intervals are situated at some distance from the OWC surface (4–5 m). When the underlaying facility gets flooded, the overlaying facility is perforated and operated. In contour (boundary) injection wells, the stratum is perforated along the entire efficient thickness.

Treatment of the bottom-hole zone. Producing strata are completed by flushing of the bottom hole with the clay fluid. Despite the mud cake formed on the well wall, due to the effect of the pressure difference, the bottom hole zone is mudded with the filtrate of the drill fluid. In the process of well completion and at the initial stage of well operation, part of the drill fluid filtrate and clay fragments is washed away from the stratum, and the bottom-hole zone is purified partially. The poorer are the collecting properties of reservoirs, the greater is deterioration of such properties when they are opened up by drilling, and the more difficult it is to restore the natural productivity of the well. In multipay production zones, which are constituted by interbed strata differing significantly in their permeability, only the strata with the best properties start working as the well is developed, and less permeable strata stay undeveloped and do not take part in the operations. After the end of drilling, if it is necessary to improve well productivity, the bottom hole zone should be treated using such methods as treatment with acids and surface-active agents, hydraulic fracturing of the formation, hydraulic jet perforation, etc. In the further process of well development, the procedures of treating the bottom-hole zone in order to improve or restore the well productivity can be repeated continually.

Application of multiple zone injection and multiple zone development, in the case of the multipay structure of the production zone. Application of special equipment ensures independent regulation of the development of strata with different permeability. This equipment makes it possible to use a packer in order to disengage two strata (or two groups of strata) in the well bore, and withdraw (or inject) matter from each of the strata through their own tubing string, or for one, through the tubing, and for the other, outside of the tubes.

PRACTICAL TRAINING

Topic 1. Structural mapping the roof and bottom of the productive formation. Mapping of efficient masses and efficient oil-saturated masses.

Structural mapping

One of the most wide-spread methods of studying oil and gas fields is the method of structural mapping the roof (or sometimes, the bottom) of the oil-and-gas bearing reservoir bed. This method was adopted in the geological practice to search for and prospect oil and gas fields.

A structural map is a graphic representation of some underground stratigraphic surface on a horizontal plane using stratigraphic isohypses, or simply isohypses. Isohypses are the lines representing equal absolute depths of the mapped horizon. Marks of isohypses below the sea level have the negative sign. Absolute marks of the depths of the stratum roof occurrence are calculated from the data about drilled wells, and from logging diagrams. Structural maps can be of very different scales: from large-scale, detailed maps used for oil fields (1:5000, 1:10000, 1:25000) to small-scale maps for large territories (1:200000, 1:500000, etc.). The scale of the map is chosen depending on the purpose of the studies. A structural map reflects the geologic structure, morphology, dimensions, and the depth of occurrence of the mapped horizon. Along with the scale, the isohypse cross section is selected, i.e. the intervals between isohypses, which are equal in heights. The isohypse cross-section should be less than an element of the field structure, which we would like to see reflected in the structural map. For example, if the amplitude of small domes is 15 m, the cross-section of isohypses should be 10 m, to ensure that they are not “missed” in mapping. Isohypses show the strike of the stratum.

On curvilinear intervals of isohypse bendings, at any point the strike of the stratum is directed tangentially to this point, and the dip, perpendicularly to it (from lesser values of absolute marks to greater ones). As the stratum dip angles decrease, isohypses diverge and, on the contrary, as the dip angles increase, they converge.

Two methods of plotting structural maps are used in the oil-field practice:
1) the method of triangles, for the cases of weakly deformed flat structures, and

2) the method of profiles, for the cases of strongly deformed structures. To plot a structural map over the roof of an oil-bearing stratum, absolute marks of the stratum roof in all wells are calculated. Well locations are plotted on the topographic base according to their coordinates. Judging from Fig. 8, the number of wells is 15. The following is shown next to the well: the number of the well in the numerator, and the absolute mark of the stratum roof in the denominator. The essence of the method of triangles used to map structural maps is that the wells are connected with straight lines such as to obtain a system of triangles.

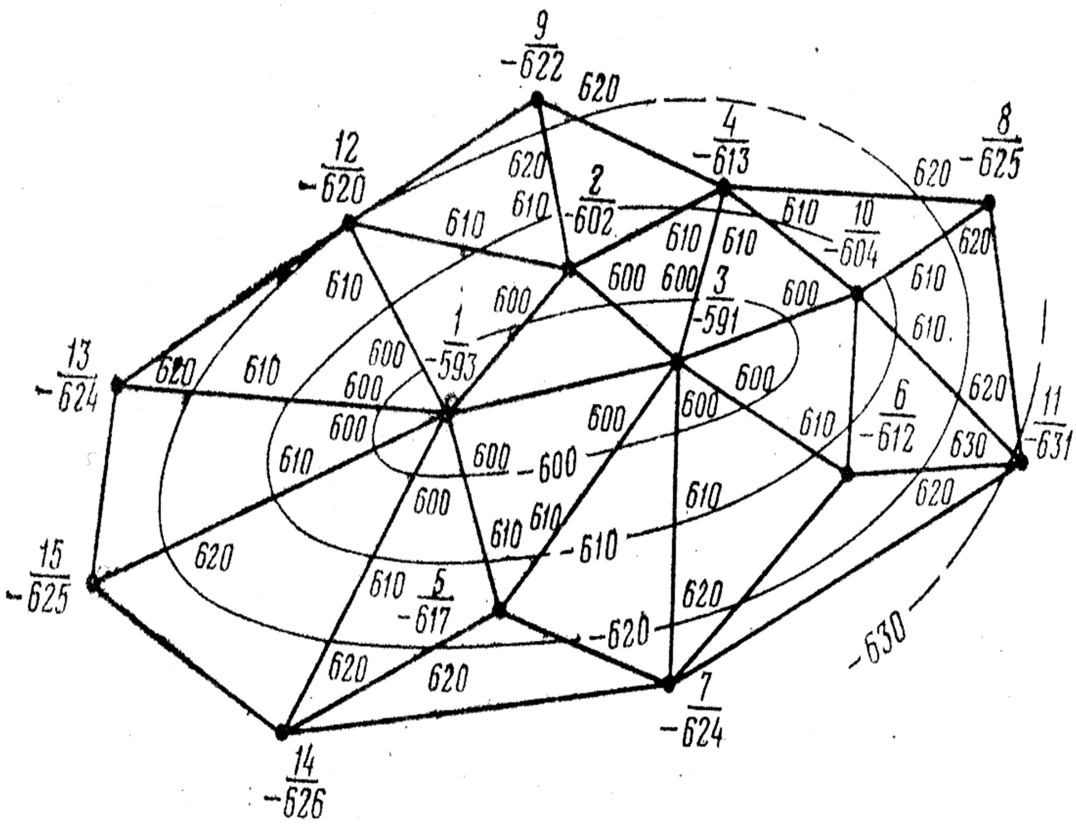


Fig. 8. Plotting of the structural map using the method of triangles
The number of the well in the numerator; the absolute mark of the stratum roof (bottom) in the denominator

Then, interpolation between the wells is performed with account for the isohypse cross-section equal to 10 m. If the absolute mark of the roof of the oil-bearing stratum is –593 m in well 1, and –625 m in well 15, the depths are interpolated between such wells in such a way as to find the points with isohypse marks, which are multiple of the selected cross-section: – 600 m – 610 m – 620 m. Then, the homonymous marks are connected with smooth lines, and finally obtain the structural map shown in fig. 8.

When the values of absolute marks are interpolated between two adjacent wells, it is assumed that their variation follows the linear law. For example, the difference of absolute stratum roof marks between wells 15 and 1 equals to 625 – 593 = 32 m. The distance between these wells in the map is 32 mm. Dividing these 32 mm into 32 equal shares, each of which corresponds to 1 m of the depth of occurrence of the stratum roof, we obtain 1 mm. From well 1 with the absolute mark of –593 m, 7 mm fall short of the isohypse with the mark of –600 m towards well 15. Then, as we advance towards well 15, isohypse –610 will occur in 10 mm, then isohypse –620 mm, in another 10 mm, etc. For small inclination angles, it is frequently assumed to equal to 10 m. After interpolation, homonymous points are connected with smooth lines (isohypses). The aggregation of these lines generates the structural map. After the isohypse with the notation corresponding to the external OWC contour is plotted on the structural map, the map plotting is done (fig. 9).

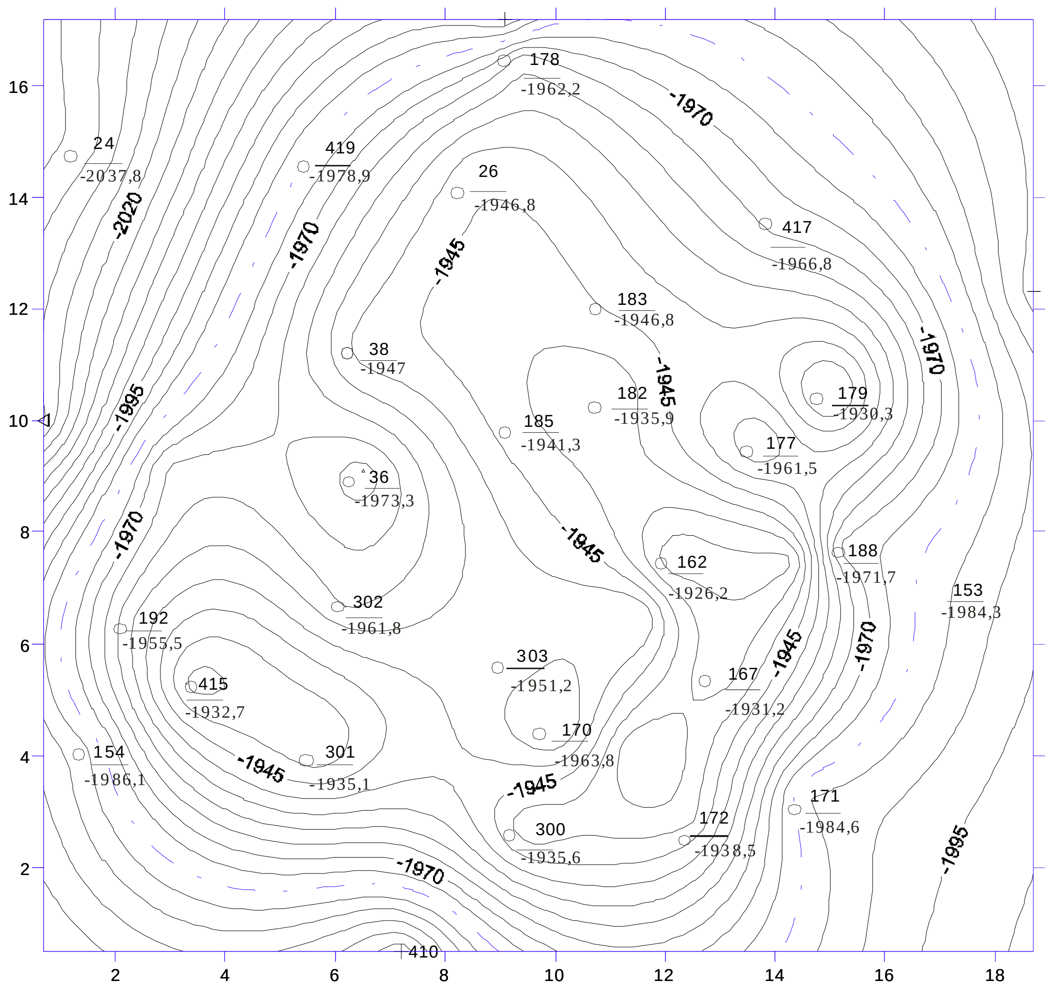


Fig. 9. The structural map of the roof of the productive stratum

The map is plotted along the bottom of the productive stratum with plotting of the internal OWC contour in a similar way (fig. 11).

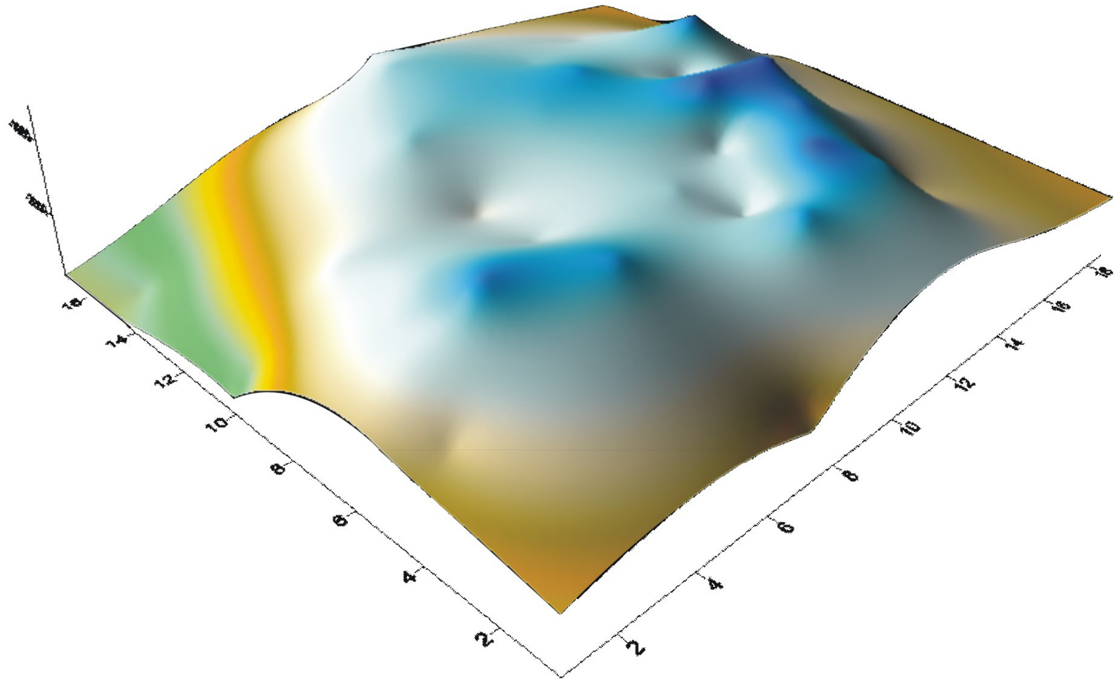
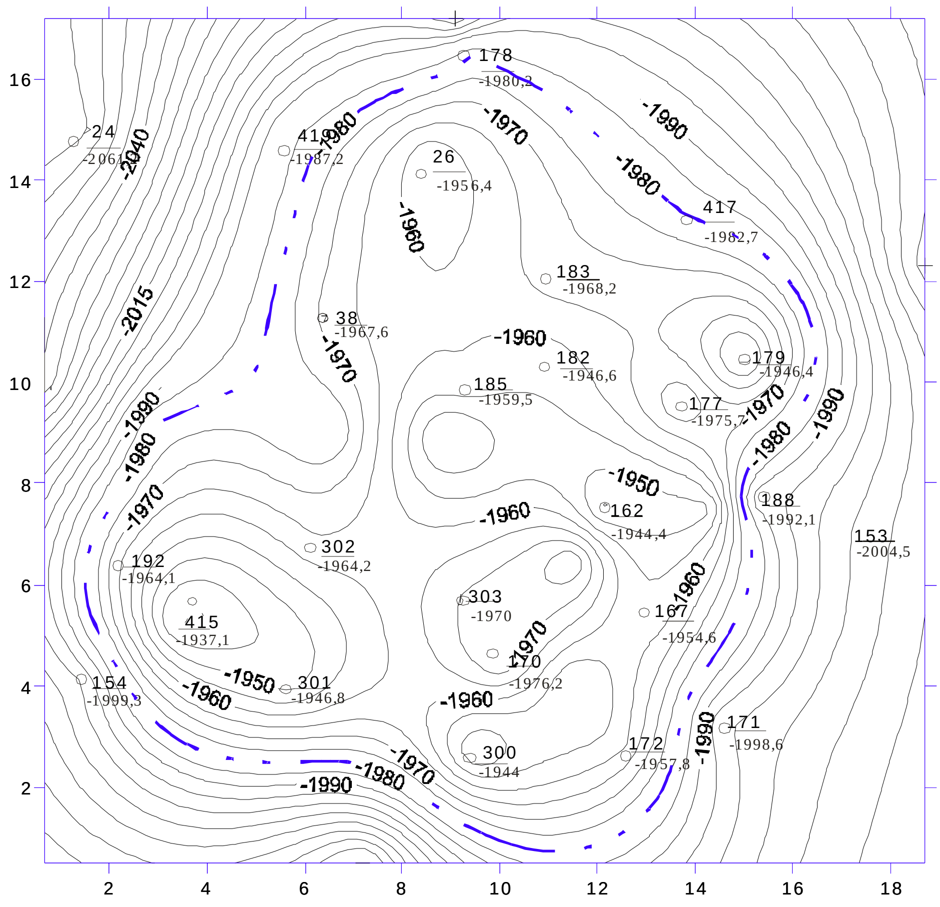


Fig. 10. The surface of the roof of the productive stratum



To plot the **map of effective thicknesses**, values of effective thicknesses are written out into the denominator for each wells, respectively. To do this, the values of thicknesses are interpolated. The cross-section of isopachytes is assumed to equal to 1 or 2 m, sometimes 3–4 m. Then, external and internal oil-water contacts are copied to the map of effective thicknesses from the structural maps of the roof (bottom). This map has prevalence when the flooding system (out-contour, near-contour, contour one) is designed (fig. 12.)

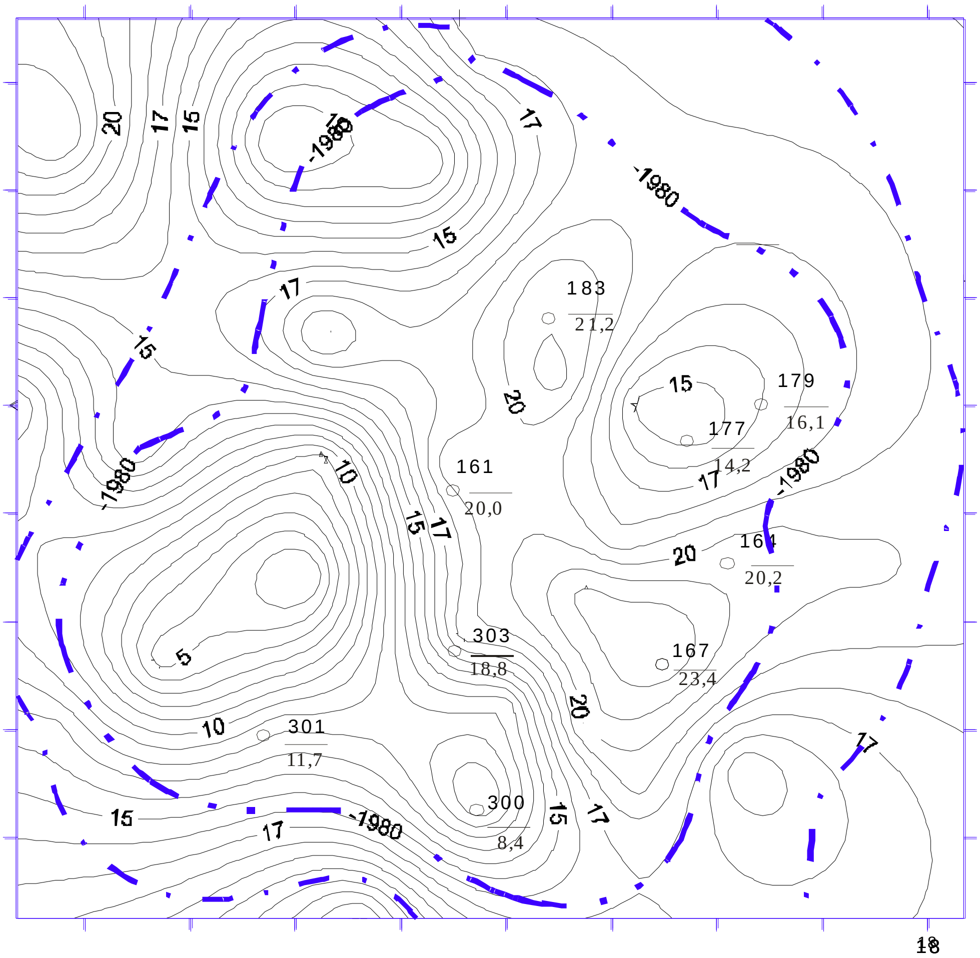


Fig. 12. Map of effective thicknesses

To plot the **map of effective oil-saturated thicknesses**, point with the locations of well bottom holes are plotted on the plane table (well number in the numerator, and value of effective oil-saturated thicknesses, in the denominator) (fig. 13). The external oil-water contact is copied on the map from the structural map of the roof of the productive stratum. The external oil-water contour is shown by the isopachyte corresponding to 0. After that, the values of effective oil-saturated thicknesses are interpolated with account for the zeroth isopachyte. The cross-section of isopachytes is assumed to equal to 1 or 2 m, sometimes 3–4 m.

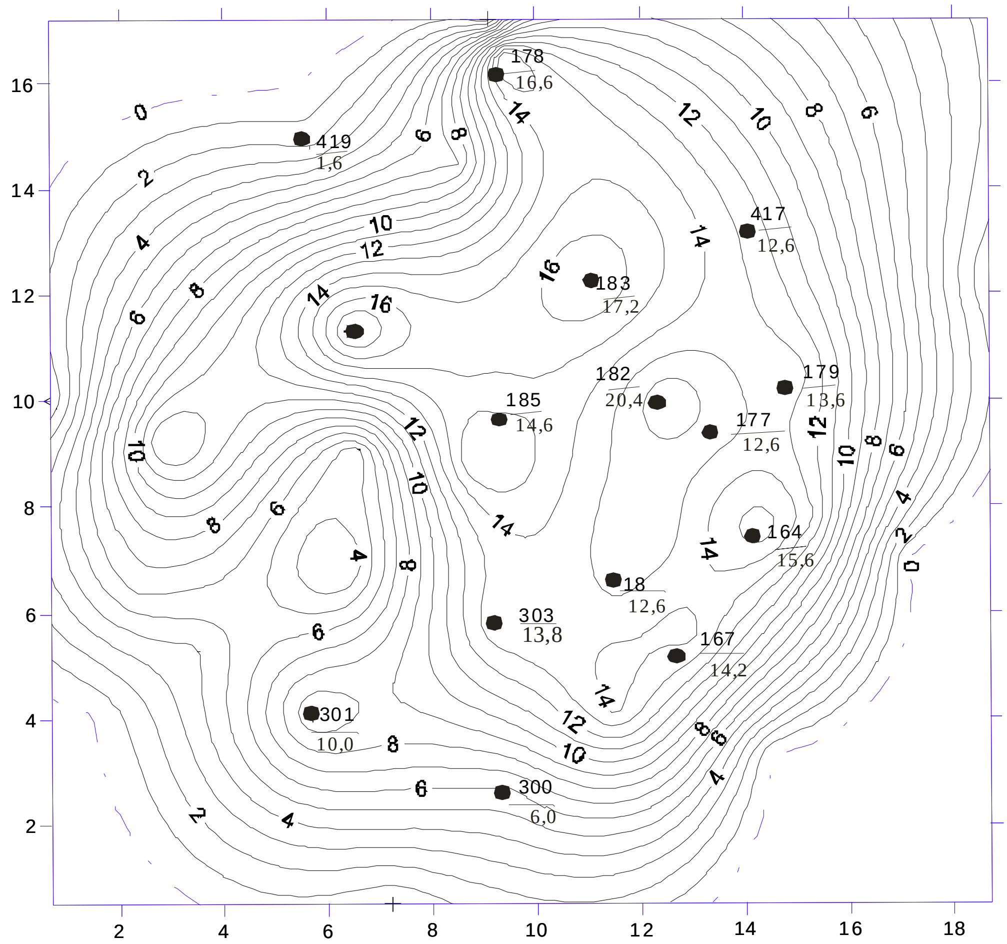


Fig. 13. Map of effective oil-saturated thicknesses

Topic 2. Logging of the Geologic Profile of the Oil (Gas) Field

Generally, the geological profile shows the structure of the upper part of the Earth crust in the vertical cross-section within the accessibility zone of deep-hole drilling. The geologic profile for an oil or gas field is developed basing on the materials from drilled wells. It represents visually the structure of oil deposits, variations in the lithology of reservoir beds and their thicknesses, the relationships between various reference horizons, which is important for tectonic studies. In the practice of oil and gas exploration, geological profile can be oriented in different directions to study the details of the structure of different oil (gas) field areas (in the transverse or longitudinal directions relative to the field structure).

When designing a geological profile, the vertical and horizontal scales must be equal. However, in the conditions of flat platform elevations, the vertical scale is most frequently increased, in order to reflect the structure of oil and gas deposits and other structural elements with more details. Enlargement of the vertical scale relative to the horizontal one must not exceed 10:1 to exclude aberrations in the modes of stratum occurrences. Geological profiles are logged in a certain order, by points of compass: At the upper left of the profile, write W (west), at the upper right E (east), and from left to right: south-north, south-west-north-east, north-west-south-east.

Geological profiles are logged in the following order:

1. The line of the sea level is drawn, and the graphic vertical scale is shown on the left (it may be shown on the both sides).

2. At the sea level line, the locations of the wells in the profile is shown in accordance with the selected scale.

3. Through these points, the vertical lines of well bores are drawn: connecting the altitude marks yields the schematic surface terrain towards the geological profile (altitude - elevation of the well mouth from the sea level).

4. When logging the geological profile, the absolute marks of the depths of stratum occurrence depths and stratigraphic horizons are calculated for the whole wells from logs. The depth of the stratum roof depth is determined from the log, let it be 4200 m. The altitude of the rotary drilling table, i.e. the height of the well mouth relative to the sea level, e.g. +202 m is subtracted. Then, the correction for the hole curvature is subtracted; let us assumet that at the depth of 4200 m, according to the dipmeter log, it is 4.8 m. The absolute mark is 4200 m – (202 m + 4,8 m) = –3993.2 m. Then, it is written down and read: “the roof of the stratum is tapped at the absolute mark minus 3993.2 m”.

5. Absolute marks of the strata and horizons are shown in the profile, then the well logs are correlated, and homonymous surfaces of the strata and horizons are connected with smooth lines.

Fig. 14 shows the geological profile logged from the data of well drilling. As seen from the Figure, the correlation of the well logs and analysis of the sequence of strata occurrence in them shows that the normal occurrence of rocks is disrupted in wells 2 and 3. In well 2, strata of water-bearing sand, dolomite, and clay fall out of the log. Immediately under the chalk stone, a stratum of bituminous shale occurs only in the log of this well. Thus, the anomalous point in well 2 is situated at the contact between the chalk stone and the bituminous shale, at the depth of –50 m.

In well 3, the anomalous factor is the overlaying of the stratum of bituminous shale, which has a clipped thickness in this log, immediately on the chalky clay stratum. Strata of clayey shale and oil-bearing sand fall out from the log of this well. Thus, the anomalous point in the log of well 3 is situated at the contact between the strata of bituminous shale and chalky clay, at the absolute depth of –600 m. The line that connects the identified abnormal points is the trace of profile planes' crossing the surface of the fracture, in this case, a fault.

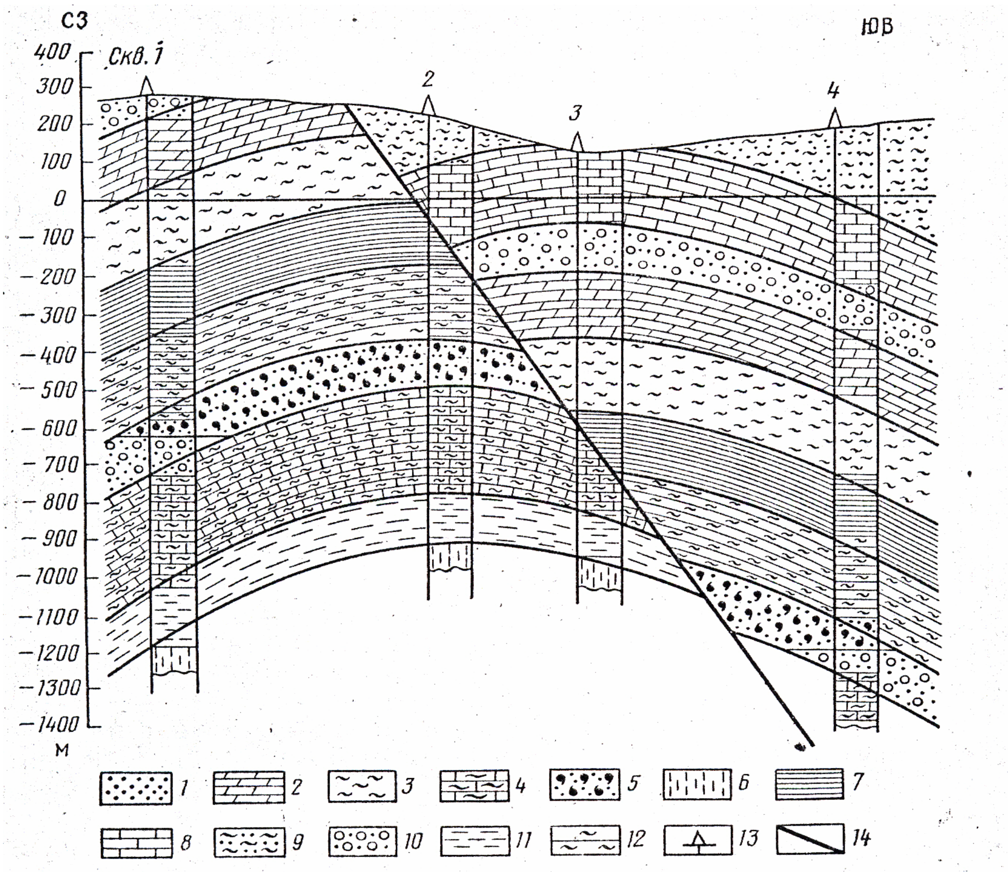


Fig. 14. Geological Profile by Wells:

1 – sand, *2* – dolomite, *3* – clay, *4* – chalky clay, *5* – oil-bearing sand, *6* – gypsum, *7* – bituminous shale, *8* – chalk stone, *9* – clayey sand, *10* – water-bearing sand, *11* – strong clayey sandstone, *12* – clayey shale, *13* – well mouth, *14* – trace of profile planes' crossing the surface of the fracture.

The geological profile shows the detailed cross-section of the lithology of reservoir beds, facies changes from well to well, presence of clay bands among sand stones, etc. If the geologic profile has been logged to study the tectonics and the structure of the field, the lithology is shown schematically, but greater attention is given to the character of relationships between reference horizons of the log, their locations and absolute marks are shown with greater accuracy, etc. As well logs are correlated layer-by-layer using electrical logging diagrams and radioactive logging, one can identify falling out of individual layers or, on the contrary, their repetition, which is associated, in the first case, with a fault, and in the second case, with a reversed fault. Geological profiles are used also to plot structural maps over the roof of a productive oil-and-gas bearing horizon or any other subterranean horizon.

Topic 3. Substantiation of the Position of the Oil-Water Contact (OWC)

The oil-water contact (OWC) is the boundary layer, which separates oil and water in a stratum, and is a zone of varying thickness, which contains oil and free water. As the distance to clear water becomes shorter, the oil contents in the stratum decreases. In natural conditions, there is no ideal OWC surface, but there is a transitional zone between the deposit parts saturated with different fluids. In highly porous, well sorted, sandy reservoir beds, the thickness of the transitional zone is 1–3 m. In complicated (inhomogeneous) reservoirs, these values range from 10 to 30 m. In this case, the greater the difference between fluid densities, the less the transitional zone. Depending on the geological properties, natural mode of occurrence, as well as the development conditions, the shape of the OWC surface can be different: horizontal, concave, convex, convex-concave, inclined, etc.

Current OWC is the boundary in the developed productive formation, which separates the water-washed part of the formation, and the formation zone, which contains movable oil.

To determine the location of OWC in wells, the following set of studies is performed:

- core sampling and studying;
- collection of well logging data (electric and induction logging); and
- well testing data.

Reliable data about OWC positions can be obtained from the data of testing prospecting, exploratory, and operated wells. It is evident that if pure oil is obtained in well testing, the boundary between the water and the oil will be lower than the perforation interval, and if pure water is obtained, it is above the perforation interval.

The log positions of oil-saturated and water-saturated core samples pulled out of the well also indicates the position of the oil-water boundary.

In terrigenous strata that have good collecting properties, the boundary between oil and water is clearly seen in electric logging diagrams and in the graphs of induction logging.

According to the electric logging, the oil stratum is characterized by high resistivity (< 10 Ohm); the water stratum, by low (1–10 Ohm) resistance; and the transitional zone, by the resistance, which is somewhat higher compared to pure water, but much lower than that of pure oil

According to the data of the inductance logging, the oil part of the log is characterized by low values, and the water part, by high values.

To determine the OWC position, the **scheme of OWC substantiation** (fig. 15) is plotted from the data of geophysical studies and the results of well testing. The scheme is drawn on A4 sheets.

To determine the common height of the scheme, the value of the absolute height for the highest point of occurrence of the roof of the top permeable stratum and the value of the depth for the lowest point of occurrence of the bottom of the low permeable stratum are selected. The difference between those absolute marks determines the vertical size of the graph in meters (with account for the scale). The scale of absolute marks (vertical scale 1:400) is plotted on the map, and provisional lines show the axes of the wells with no account for the horizontal scale. The boundaries of the strata (roofs and bottoms) are plotted on the axis of each well, and the homonymous boundaries are connected with straight lines. Then, in each stratum, permeable alternations are singled out basing on the results of geophysical studies, and well testing shows the character of their saturation. Intervals of perforation and test results are shown to the right of the well bore axis.

If it is a multipay formation, the boundaries of all the formation plotted (roofs and bottoms), and the strata are indexed to the left of the depth scale.

Then, basing on the data of the studies set for each well, the absolute OWC mark for this or that stratum is found and traced consecutively from one well to another. Basing on the data for all the wells, the position of OWC across the entire field is determined.

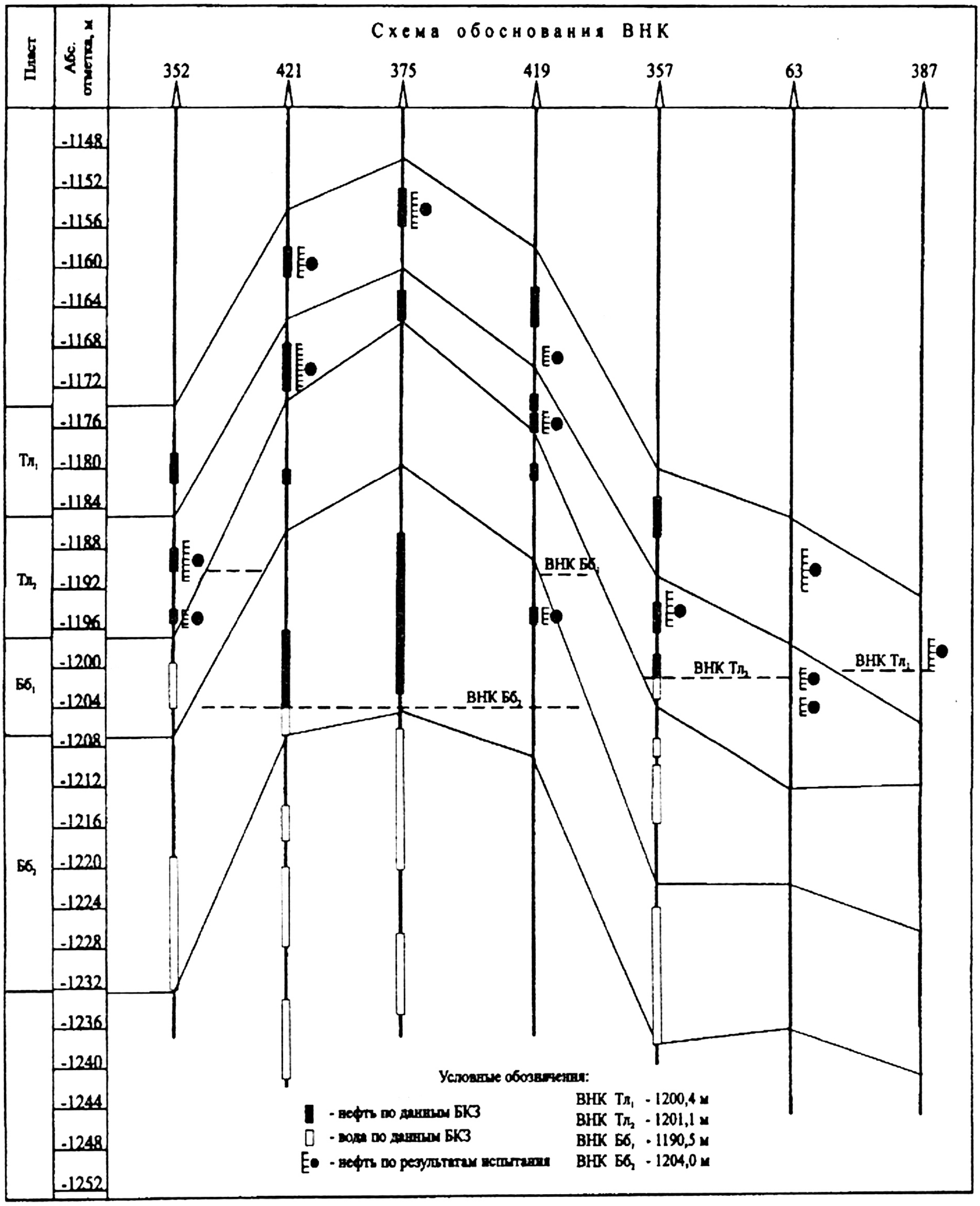


Fig. 15. Scheme of OWC Substantiation

Course of lectures in

SEARCH FOR AND EXPLORATION OF OIL AND GAS FIELDS

Subject 1. Fundamental Regularities of Oil and Gas Generation and Accumulation. Oil and Gas Accumulation Zones

Oil and Gas Prospecting and Exploration

Perm State Technical University

Chair of Oil and Gas Geology

Regularities of Oil and Gas Generation and Accumulation

1. Oil is generated and accumulated in sedimentary rocks.

Facts of evidence:

- 99,9% of the discovered HC reserves are confined to sedimentary rocks;
- O_2, N and S compounds in oil are of biogenic origin;
- Optical activity of oil;
- Paraffin and sulfur are decomposed in oil at t° > 250-300°, therefore, oil cannot be formed at large depth;
- Similarity of HC composition and isotopic compositions of oil and HC of one and the same stratigraphic unit;
- Presence of oil accumulations in sand lens of clay rocks; and
- Obtaining of petroleum hydrocarbons from organic matter in experimental conditions.

Regularities of Oil and Gas Generation and Accumulation

2. Oil and gas are generated and accumulated at all geological epochs, and are of periodic nature and connected with the cycles of lithogenesis;
3. Oil and gas generation and accumulation processes were of regional nature;
4. Organic matters can be transformed in Hydrocarbons only in aqueous medium with anaerobic geochemical environment against the background of relatively substantial downwarping of the sedimentation basin;
5. Organic matter is transformed in hydrocarbons, at first, under the action of microorganisms and ferments, and then, temperature and pressure;
6. Composition and properties of oil depend on parent organic matter and features of oil occurrence environment; and
7. Oil migrates from source rocks to reservoirs, and accumulates in traps.
8. Oil and gas fields are united in the zones of oil and gas accumulation. Zones are united in the regions, and regions are united in provinces;
9. Within platform areas the oil-and-gas bearing regions are confined to intraplatform and fore deeps, to arched and linear uplifts, and avlakogenes; and to submontane and intermontane troughs, and median mass - in folded areas;
10. Several types of accumulations can occur within one field; and
11. Necessity of impermeable trap and favorable paleo-conditions for trap conservation.

Oil and Gas Accumulation Zones

Definition:

- Oil and Gas Accumulation Zone is a group of oil and gas fields which is similar in their geological structures, and confined to the unified group of allied traps.

Classification

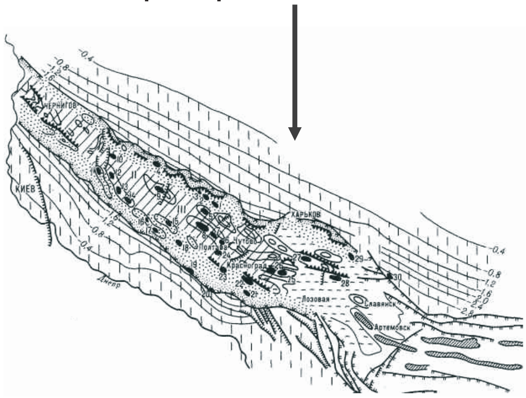
Oil and gas accumulation zones are subdivided into 5 classes:

- Structural class;
- Reef class;
- Lithologic class;
- Stratigraphic class; and
- Lithologic-and-stratigraphic class.

Structural Class Zones

Formation of the Structural zones is attributable to:

1. Elongated dumped positive structures

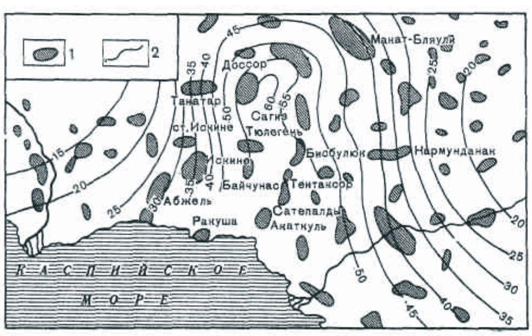


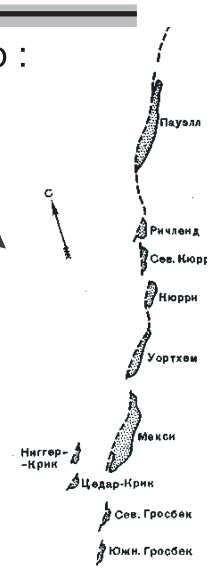
Structural Class Zones

Formation of the Structural zones is attributable to :

2. Regional disjunctive dislocations

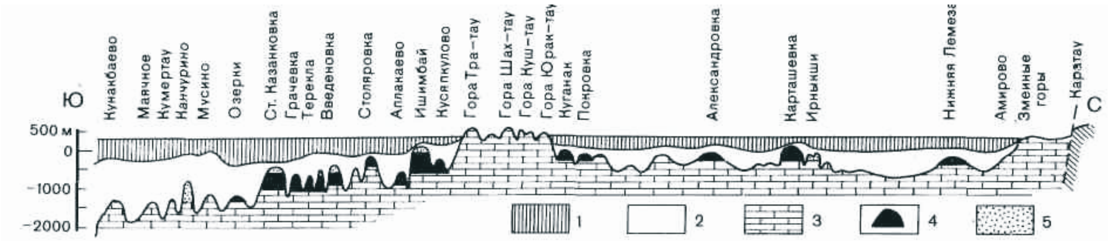
3. Salt dome zones





Reef Class Zones

- Fields are connected with atoll reefs and barrier reef

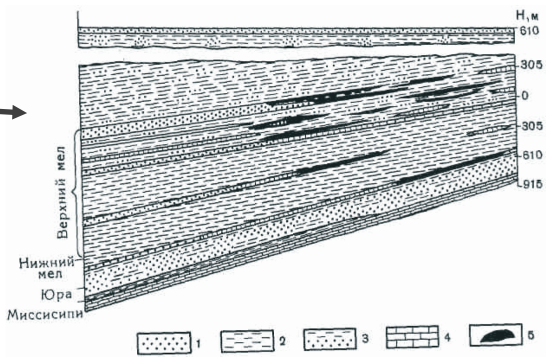


Lithologic Class Zones

Formation of the Lithologic zones is attributa

1. Regional change of lithological compositic

2. Up-dip pinching-out of reservoirs

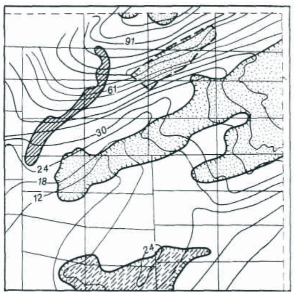


Lithologic Class Zones

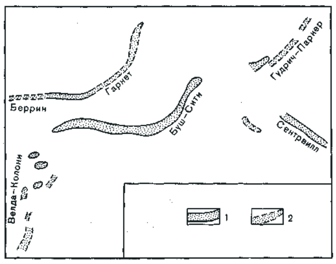
Formation of the Lithologic zones is attributable to :

3. Concealed sand formations along coastal beds of ancient seas:

- Confined to sand bars



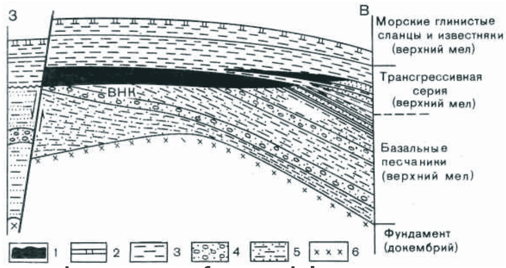
- confined to paleochannels of rivers



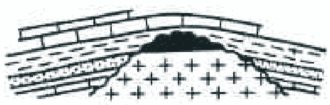
Stratigraphic Class Zones

Formation of the Stratigraphic zones is attributable to overlapping of separate lithologic-and-stratigraphic complexes with posterior impermeable rocks:

1. Zones confined to the areas of regional stratigraphic unconformities



2. Zones confined to areas of igneous rocks unconformable occurred among sedimentary rocks



Classification of Oil and Gas Fields

Respectively, oil and gas fields are subdivided into the same classes as zones:

- Structural;
- Reef;
- Lithologic; and
- Stratigraphic.

Subject 2. Phases of Oil and Gas Prospecting

Oil and Gas Prospecting and Exploration
Perm State Technical University
Chair of Oil and Gas Geology

Principles of Phasing Oil and Gas Prospecting

- Continuous study of earth interior aimed at field discovering and preparing for development is phased and staged schematically.
- The main objectives of phasing are to solve gradually various tasks at different levels, to assess efficiency and quality of work at each stage and to plan further work.

Regional Survey Phase

Phase	Stage	Survey Targets	Main Tasks and Objectives	Final Evaluation of Resources
Regional Survey	Oil and gas occurrence forecast	Sedimentary basins and their areas	1. Identify lithologic-stratigraphic units, structural basins, stages and structure-facies zones; determine nature of the main phases of geological development; and determine tectonic zoning. 2. Identify oil and gas promising zones (reservoirs) and zones of potential oil and gas accumulation; and determine oil-and-gas geological zones. 3. Make qualitative and quantitative assessment of oil and gas bearing prospects and quantitative assessment of oil and gas occurrence perspectives by categories. 4. Select the main trends and priority targets for further research.	Forecast resources D_2 and partially D_1
	Estimation of oil and gas accumulation zones	Oil and gas promising zones and oil and gas accumulation zones	1. Identify subregional and zonal structural relations among various oil-and-gas promising zones and lithologic-stratigraphic zones, general regularities of reservoir rock properties and impermeable beds, and alteration of their properties. 2. Specify oil-and-gas and geological zones. 3. Quantitative assessment of oil and gas bearing prospects. 4. Select zones and set a priority of prospecting operations.	Forecast resources D_1 and partially D_2

Prospecting Phase

Phase	Stage	Survey Targets	Main Tasks and Objectives	Final Evaluation of Resources
Prospecting	Identification of prospecting drilling targets	Identified and potential oil-bearing zones	1. Identify occurrence conditions and other geological and geophysical properties of oil and gas bearing and oil and gas promising zones. 2. Identify promising traps. 3. Make quantitative assessment of the forecast localized resources. 4. Select targets for detailing work.	Forecast localized resources $D_{1л}$
	Preparation of targets for prospecting drilling	Identified traps	1. Detail the identified promising traps what makes it possible to forecast three-dimensional position of pools. 2. Make quantitative assessment of prospects within the targets prepared for prospecting drilling. 3. Select targets and set priorities of prospecting drilling	Prospective resources C_3
	Prospecting and evaluation of fields (pools)	Identified traps, discovered fields (pool)	1. Identify reservoirs and covers in oil-and-gas bearing horizons and prospective horizons and determine their geological and geophysical properties (parameters). 2. Single out and test oil-and-gas promising formations and horizons; obtain commercial inflows of oil and gas; and determine fluid properties and permeability and porosity characteristics. 3. Discover field and put the reserves in the state balance of reserves. 4. Select prospecting and exploratory targets. 5. Determine basic characteristics of the fields (pools). 6. Estimate field (pool) reserves. 7. Select exploration targets.	Inferred reserves C_2 and probable reserves C_1.

Exploration Phase

Phase	Stage	Survey Targets	Main Tasks and Objectives	Final Evaluation of Resources
Exploration	Exploration and test production	Commercial fields (pools)	1. Specify geological structure and estimate reserves of pools. 2. Test production for obtaining data and parameters for reservoir management planning. 3. Transfer C_2 reserves to C_1 reserves.	Explored reserves C_1 and partially prospected C_2

Subject 3. Oil and Gas Prospecting. Regional Survey Phase.

Oil and Gas Prospecting and Exploration

Perm State Technical University

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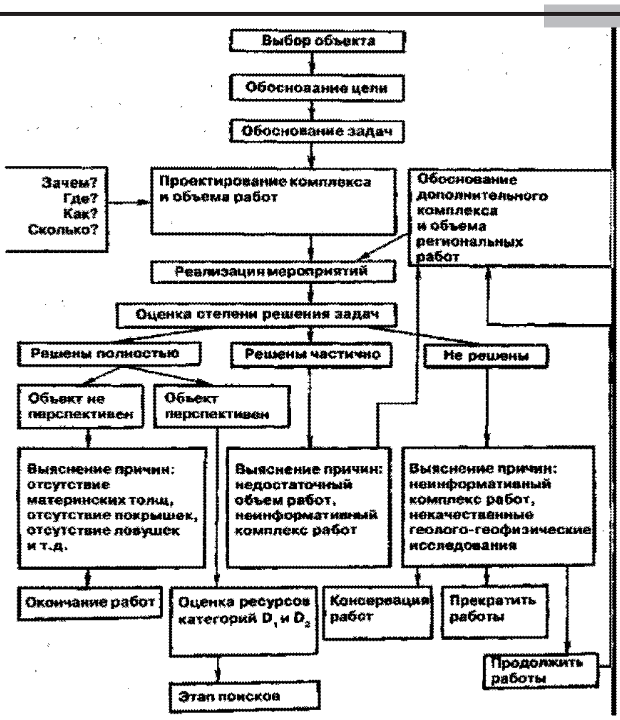
Regional Survey Tasks

The tasks depends on the level of knowledge about regions to be surveyed. Schematically all regions are subdivided into:

- <u>New</u> frontier regions
- <u>Old</u> oil and gas producing regions

Sequence of Solving Tasks at the Regional Survey Phase



New Frontier Regions

Survey targets:

- First of all, <u>basement</u> structure, because:
  - Basement depth of occurrence makes it possible to determine thickness of sedimentary rock mass.
  - Basement structure reflects the structure of the sedimentary cover.
  - Basement structure makes it possible to identify the buried structures of the lower tectonic stages of the sedimentary cover.

The basement is studied by geophysical surveys.

- Second, <u>sedimentary rock mass</u>, its age, composition, thickness, structural staging and oil-and-gas content. This task is solved by drilling key and stratigraphic wells, and by studying natural bed outcrops.

Old Oil and Gas Producing Regions

The tasks are solved by drilling key and stratigraphic wells and detailed seismic survey:

- Development at large depths.
- Identification of new structural members, stages and oil-and-gas accumulation zones.
- Prospecting more complicated pools.

Scope of regional survey within the old oil and gas producing regions is significantly less, but, at the same time, it is more detailed.

Typical Regional Survey

In Russia, the regional survey operations include the below given operations:

- Airborne study, photo survey and space survey;
- Geological and structural-geomorphologic surveys;
- Geophysical surveys: magnetic survey, gravitational prospecting, geoelectric survey and seismic survey;
- Geochemical survey;
- Hydrogeologic survey;
- Drilling key and stratigraphic wells in seismic markers; and
- Special scientific studies.

Regional Survey Result

Regional Survey is resulted in Geological Model of the surveyed area that includes:

- Set of maps based on the results of all types of surveys;
- Set of well logs, correlation profiles and interim sections;
- Estimation of resources and map of oil-and-gas occurrence with distribution of resources density and identification of the priority areas for prospecting.
- Calculation of potential economic effect, i.e. supposed growth of HC reserves and volume production for the nearest years.

Forecast of Oil and Gas Occurrence

The task of the Regional Survey Phase should be to forecast oil and gas occurrence within the large areas. The forecast is made for three items:

- Individual forecast of distribution of oil and gas accumulations.
- Forecast of large fields.
- Oil and gas occurrence prospects.

Individual Forecast of Distribution of Oil and Gas Accumulations

As a rule, oil-and-gas bearing basins are characterized by clear zoning of oil and gas pools. It depends on genetic, historical - geological, and structural factors.

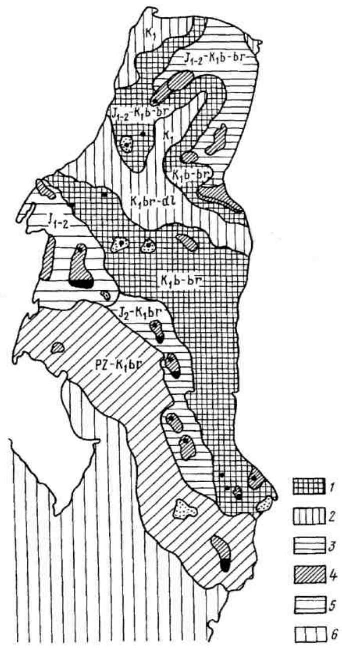
Commercial **gas content** has been discovered in zones characterized by:

- Large thickness of the sedimentary cover (> 8 - 10 km);
- High geothermal gradient;
- Stagnant expelled conditions of water drive systems;
- Gas-saturated formation water;
- Presence of regionally persistent thick gas-proof rock masses – clay or salt-bearing rock masses.

Forecast of Distribution of Oil and Gas Pools

Yamal Peninsula Oil and Gas Occurrence Prospects.

Areas: 1 —oil prospecting zone of high interest (pre-depression zone); *2* — oil prospecting zone of interest (synclinal zone); *3* — oil prospecting zone of low interest (anticline zone); *4* — oil and gas condensate prospecting zones of interest (within the boundaries of anticline structures); 5 — gas condensate prospecting zones of interest ; *6* — liquid HC prospecting zones of no interest



Forecast of Large Fields

Today, oil and gas are mainly produced at <u>major and giant</u> fields. That is why it is necessary to foresee probability of major discoveries in forecasting.

Giant Field Formation Factors:

- Vast sizes of oil and gas bearing basin, large thickness of the sedimentary cover and high geothermal gradient;
- Presence of interstratified source rocks, reservoir beds and regionally persistent impermeable beds in the sedimentary cover;
- Presence of large and hard traps in the regional migration paths.

Conclusion

Integrated application of the principles, which are used for each trend, makes it possible to forecast more precise oil and gas occurrence of the area to be surveyed.

Regional Survey Principles

In Russia, four basic principles are used for regional surveying:

- Making-up the geological model of the region;
- Applying various surveying methods;
- Integrating survey data integrating; and
- Applying principle “from the general to the special”

Principle 1: Making-up the Geological Map of the Region.

Regional surveys of new targets are planned in advance based on the developed geological model of the given region. This model is of hypothetical nature and shall not contradict to available accumulated geological data.

Principle 2: Application of various surveying methods.

Various survey techniques should be used for geological structure study, as accuracy of obtained data is different due to heterogeneity of geological structure of each of them:

- Near-surface tectonic contours are surveyed by a set of methods: geological, structural and geological, and remote sensing surveys, and structural drilling.
- Structure of various stages of the sedimentary cover is studied by seismic survey and deep drilling.
- If there are fair thick rock masses within the contour and they are characterized by high electric resistivity (limestone, anhydrites and salts) geoelectrical prospecting should be used.

Principle 2: Application of various surveying methods.

- Gravity survey is used for studying salt dome structures and buried compact carbonate rocks.
- Basement surface is studied by seismic survey. Electric survey, magnetic survey and gravity survey provide less accurate data.

Set of methods should be determined based on the set tasks and particular geological conditions. Survey methods should be used in such a way as to provide new data and not to duplicate other methods.

Principle 3: Data Integration.

- Rational scheme foresees making mandatory regional seismic and electrical survey lines through the points of key and stratigraphic well drilling, what makes it possible to apply reliable regional geological data obtaining for particular point to substantial area.
- Locating wells to geophysical lines makes it possible to use more accurate physical parameters of the drilled-in section (elastic wave propagation velocity, density, electrical resistance) for specifying geophysical data.

Principle 4: "From the General to the Special" Principle.

- At the first stage, general tectonic profile, geological section of the area, regional impermeable beds and potential play zones are studied. Geochemical and hydrological parameters, oil-and-gas occurrence signs and degree of accessibility are determined.
- At the second stage, potential zones of oil and gas accumulations, and probable types of fields are determined by drilling.

Conclusion

Application of the above principles makes it possible to reduce time and costs for developing the area under survey.

Topic 4. Play Identification Phase

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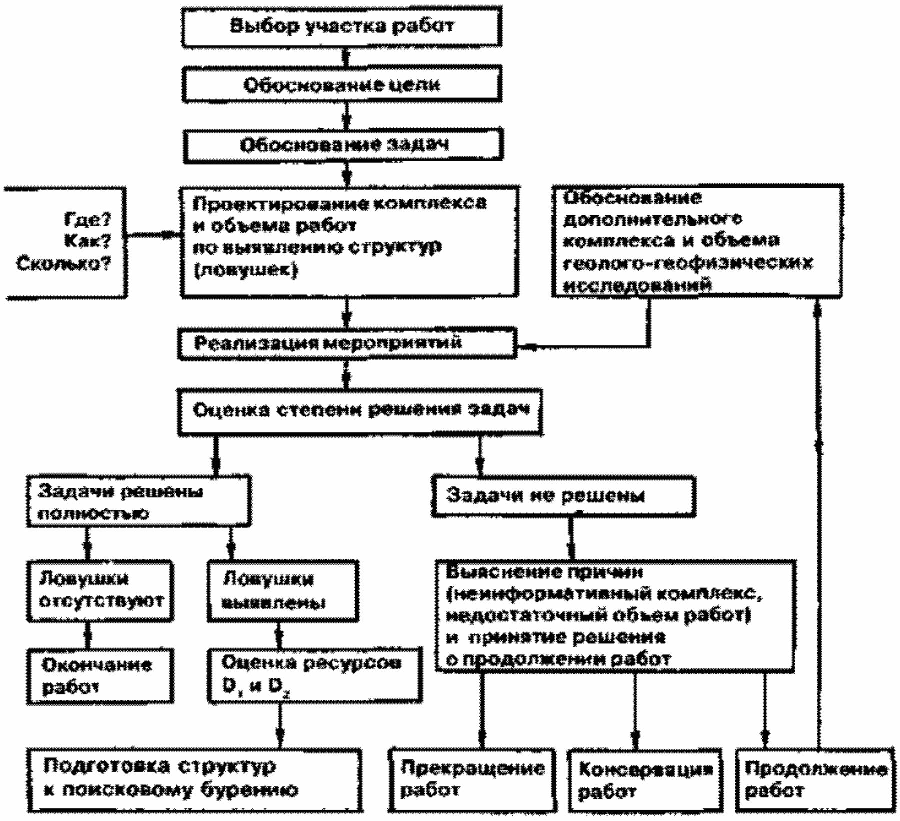
Identified Structure

- Identified structure is an objective interval, which is an anticline crest of strata, obtained as a result of geophysical (seismic, gravity, electric and magnetic), geological and geochemical survey, or as a result of structural drilling.

Identification Phase Objectives

- <u>The main and final objective of the identification phase</u> is to create an accurate and reliable model of local structure and prepare it for prospecting drilling.
- Model is a representation of potential types of traps and pools within the given area, their position in section, sizes, phase state and HC content (oil, gas and gas condensate).
- Models are created **<u>by analogy</u>** with the fields discovered within the region under survey or in the regions with similar geological structure.

Play Identification Procedure



Play Identification Methods: Remote Surveys

- They are based on photographing the earth surface from a plane or from satellite. The content of the methods is geological decoding of photos reflecting the terrain structure.
- Airborne methods are used for studying soil, vegetation, field and water resources, dry land terrain and sea surface. Oil and gas accumulations are more frequently confined to anticline folds that can be identified using the terrain photos. That is why the airborne methods are used for studying the structural members of I, II and III order. The airborne methods can be applied if direct signs of marine oil and gas occurrence are identified. Oil and gas bearing areas of seabed display themselves on the sea surface as oil stains which are not carried away with sea current. Gas bearing areas can display themselves with white foam (like boiling water).
- Satellite methods are more scaled and operational. The existing terrain has been formed due to the recent tectonic motions and can be a sign of growth of local positive structures. That is why the landscape reflected at photos can indicate the areal extent of the positive structures, which are possible associated with the buried structures.

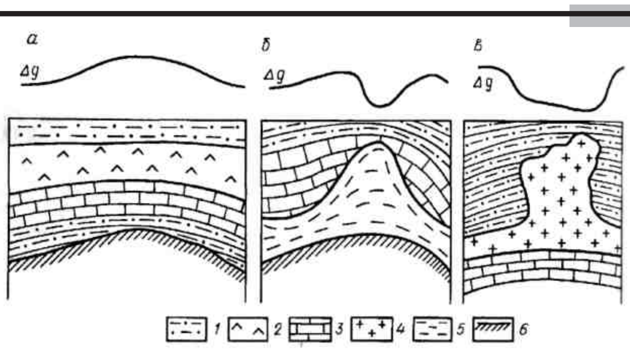
Play Identification Methods: Structural-Geological and Geomorphologic Surveys

- Application of these methods for identifying structures is based on the fact that in many areas the large structural members are still developing from the basement to the recent time. That is why they are fixed in the existing terrain.
- They are most effective for surveying within the basement oil-and-gas bearing provinces which can be characterized by frequently occurred through structures.
- Surveys are accompanied with geological and geomorphic mapping. Map scales are 1:100 000 and 1:50 000.

Play Identification Methods: Geophysical Methods. Gravity Survey

- This method is based on studying the gravitational abnormalities on the earth surface.
- Identification of the structural zones on the basis of gravity survey data is associated with density heterogeneities of rocks.
- Abnormal gravitational field is formed under impact of sectioning of rocks of different density if such rocks from large bodies. The higher contrasting the configuration of density of separating, the higher intensity of abnormality.

Play Identification Methods: Geophysical Methods. Gravity Survey



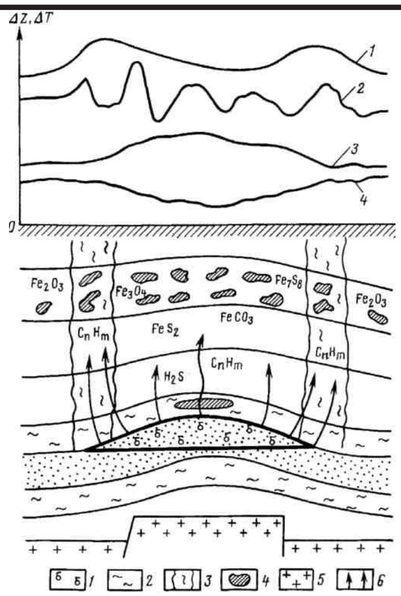
Application of Gravity Survey for Local Structure Search

а – direct reflection of the structure by local abnormality; inverse reflection of the structure by local abnormality; *б* — minimum gravity above the local structure with upswell of clay rock masses in dome, *в* — minimum gravity above salt dome; *1* — sand-clay deposits; *2* — gypsum-anhydrate rock masses; *3* — carbonate rocks; *4* — salts; *5* — clays; *6* — bottom of the sedimentary cover

Play Identification Methods: Geophysical Methods. Magnetic Survey

- This method is based on studying abnormalities of magnetic field, which are caused by difference of magnetic properties of rocks. Only rocks of crystal basement have magnetic properties. Sedimentary rock masses does not contain magnetized rocks. So, magnetic survey is used for studying the inner structure of the basement and its reflection in the sedimentary rock mass, as location and nature of the structural forms of the sedimentary cover depend on the basement.
- Gravity survey, unlike magnetic survey, reflects also the inner structure of the sedimentary cover.
- One more difference from gravity survey is higher compartmentalization and contrast. Rocks are more differentiated by magnetization than by density. That is why the geomagnetic field on the platforms provides more complete and accurate data than gravitational field.
- Geomagnetic abnormalities within the geosyncline zones and edge depressions are highly smooth, and the magnetic field is uniform.

Play Identification Methods: Geophysical Methods. Magnetic Survey



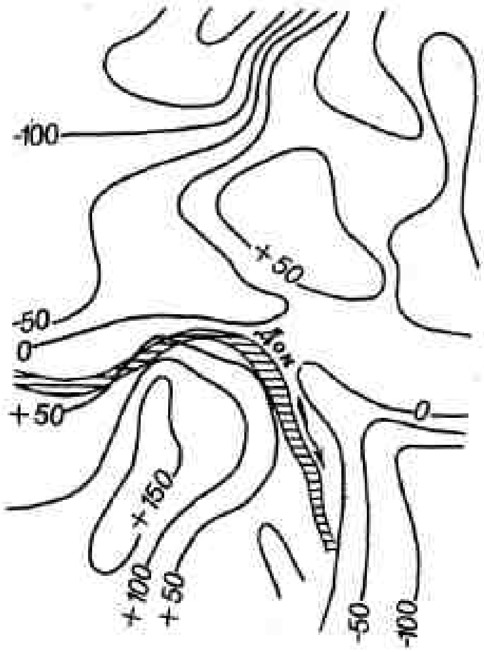
Geomagnetic Model of Oil-and-Gas Field:

Geological plays: *1* — oil-and-gas pool; *2* — underlying and overlapping covers; 3 — zones of near-vertical heterogeneities; *4* — secondary causative magnetic bodies; *5* — basement; *6* — hydrocarbon migration paths. Abnormalities of the magnetic field caused by the secondary causative magnetic sources: *1* — double-humped; *2* — fluctuating; *3* — positive; 4 — negative

Play Identification Methods: Geophysical Methods. Electric Survey

- This method makes it possible to determine distribution of rocks of different electrical conductivity within the earth's crust.
- The method is applied for determining the basement occurrence depths and total thickness of sedimentary rock masses. It is also used for identifying and mapping local positive structures of the low conducting basement horizons or salt rock masses.
- The higher electrical conductivity and homogeneity of rock masses overlapping the basement or salt rock mass, and more contrasting structures, the more effective identification of structures.

Play Identification Methods: Geophysical Methods. Electric Survey

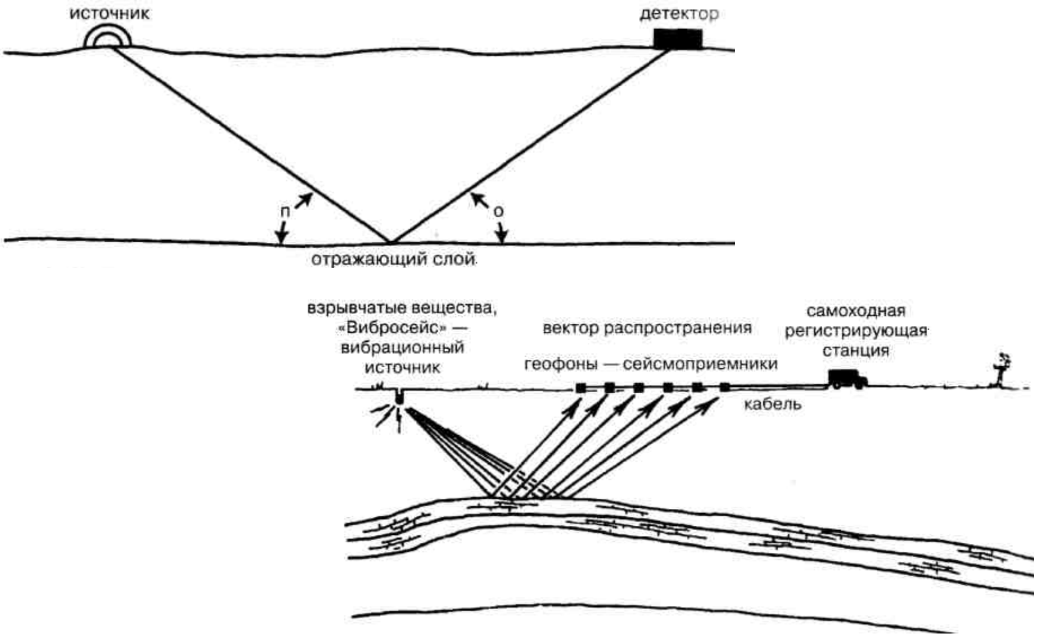


Structural map of Carbonic limestone according to VES survey

Play Identification Methods: Geophysical Methods. Seismic Survey

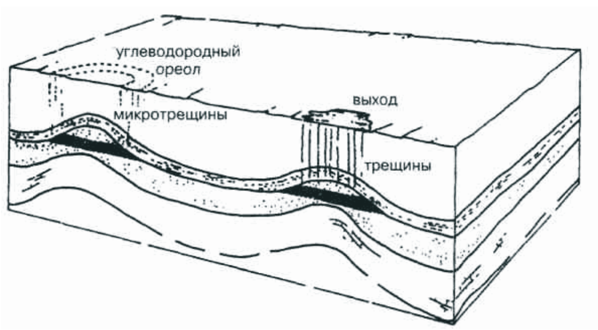
- Seismic survey is universally applied and it is the main surveying method for structure identification and further structure preparation.
- Seismic survey techniques are based on using acoustic energy penetrating the ground. Sonic impulse passes through the rocks, reflects from them and comes back to the surface, where its reading is fixed. Acoustic sound velocity varies and depends on density inhomogeneity of rocks.
- Based on the seismic survey data the structure of rock occurrence and location of oil and gas traps are determined.
- Seismic survey data are expressed in the form of reflection-time sections and reflection time (isochronic) maps. The structural maps of the reflecting horizons are made-up based on the reflection time (isochronic) maps. Accuracy of mapping depends on accuracy of subsurface velocity distribution interpretation.

Play Identification Methods: Geophysical Methods. Seismic Survey



Play Identification Methods: Geochemical Methods

- It is fair easy to identify the presence of petroleum trap by HC traces in soil and water. Major part of petroleum reservoirs are flow through reservoirs, which causes formation of oil seeps which can be observed with the naked eye. But in some cases the trap are more impermeable and that is why there are only petroleum micro–seeps in the form of hydrocarbon halos on the surface.



- Gas, gas biochemical, bitumen-fluorescence surveys are used as geochemical surveying methods.

Play Identification Methods: Geochemical Methods. Gas Survey

- Gas survey is based on the gaseous HC scattering from oil and gas accumulation to the upper rock mass, up to the daylight surface.
- Gaseous HC are scattered through disturbances (fracture porosity), rock fractures (effusion) and directly through the rocks and water (diffusion).
- Gas survey includes rock sampling with further degassing in structural or blast holes during seismic operations.
- HC concentration is not high (<0,01 %). Concentration values are plotted on the map. And the areas characterized by abnormal high values are potential fields.

Play Identification Methods: Geochemical Methods. Gas Biochemical Survey

- Gas Biochemical survey is conducted in underground water and non-deep wells. The survey target is salt and gas composition of underground water of the upper water-bearing strata. It is assumed that geochemical abnormalities occur due to penetrating deep high-pressure water to the upper horizons.
- The basic search criteria are as follows:

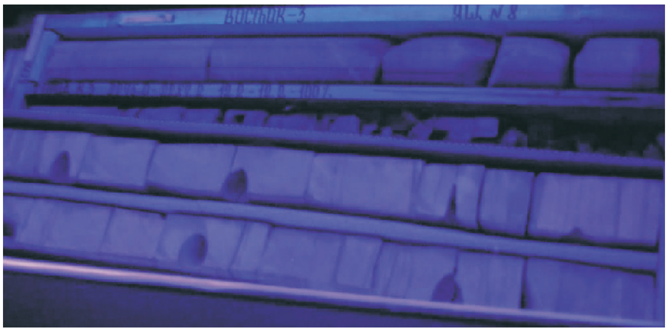
  1) Increase of heavy HC share in the dome of the structure;

  2) Presence of bacteria and microbial flora; and

  3) Increase of underground water salt concentrations within the abnormal zones.

Play Identification Methods: Geochemical Methods. Bitumen - Fluorescence Survey

- Bitumen – Fluorescence survey is used for studying bitumen or light HC that penetrate into the upper rock masses from pool.
- Bitumen are characterized by fluorescence under UV-rays radiation of rocks. The higher fluorescence, the higher bitumen concentration. Abnormal zones indicating the presence of pool in depth are identified on the basis of fluorescence intensity alteration.



Play Identification Methods:
Geothermal Survey Methods

■ Rate of temperature rise depends on rock conductivity and thermal flow density. Thermal conductivity of rocks is increased as rock density and degree of saturation with fluid is increased.

■ Temperature alterations are studied in wells and temperature logs are obtained. Based on the temperature logs, geothermal stage (number of meters, on which it is necessary to drill deeper for changing temperature on 10 degrees) and geothermal gradient (temperature rise under deepening on 100 m). Geothermal maps are made-up based on these data.

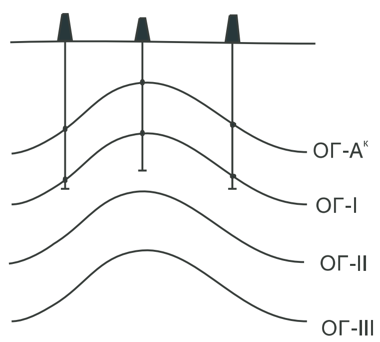
■ Abnormalities are observed above the basement highs and anticline structures. Geothermal gradients on domes are higher that those on the wings. Positive geothermal abnormalities above domes can be caused by uplift of more thermal conducting rocks, including water-saturated rocks in the nucleus.

■ Petroleum regions are characterized by geothermal abnormalities above oil fields regardless to the type of the structure. By comparing empty and petroleum structures it was determined that temperature of productive structures is higher on 5-10 °C and over.

Play Identification Methods :
Structural Drilling

■ Structures are identified by drilling non-deep structural wells on the upper reference horizon. It is assumed that the structure, which is identified in the near-surface plans, can be also traced at depth.

■ In order to identify the structure, it is sufficient to identify the crest of anticline by drilling several structural wells.



Topic 5. Phase of Structure Preparation for Deep Drilling

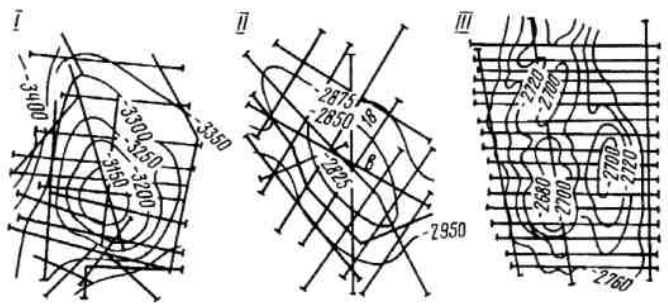
Oil and Gas Prospecting and Exploration

Perm State Technical University

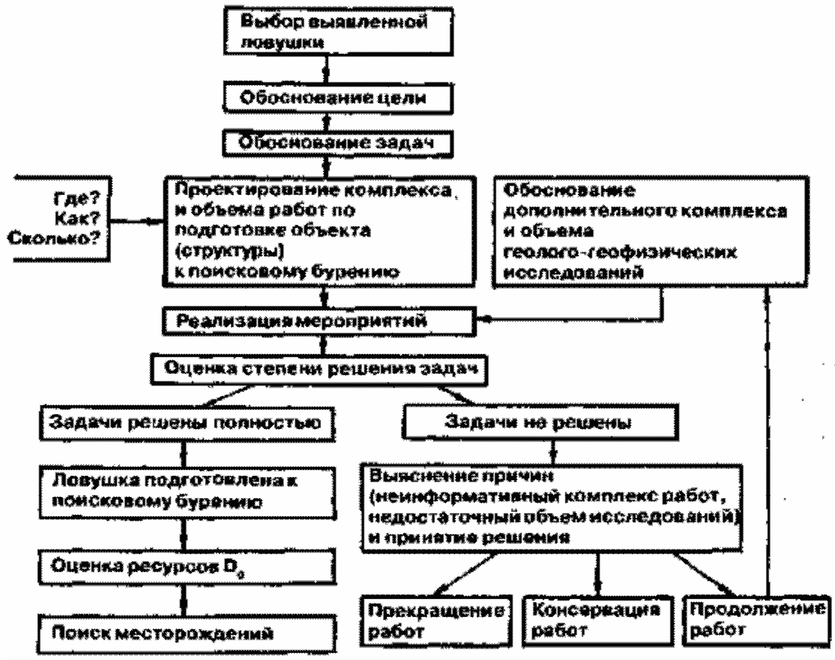
Chair of Oil and Gas Geology

Structure Preparation Phase

- The objective of the structure preparation is to transfer the identified structure to the prepared structure status.
- The prepared structure is a play mapped by seismic survey, or structural drilling, or by combining these two methods.
- To transfer the identified structure to the prepared structure, it is necessary to make-up conditioning contour maps that make it possible to select prospecting drilling sites, to determine the basic parameters of potential trap structure (size, amplitude (vertical closure) and structural features).



Play Prospecting Drilling Preparation Procedure



Structure Preparation Phase

In Russia, two basic methods of structure preparation are used:

- Seismic operations (90%)
- Structural drilling (10%)

Effectiveness of seismic operations and structural drilling differs for various tectonic zones.

The objective of prospecting operations is to determine regularities and areas that are most suitable for prospecting by this or that method.

Seismic Methods of Structure Preparation

In order to prepare plays for deep drilling, it is necessary to perform detailed seismic surveys:

- Surface seismic survey using common depth point (CDP) method;
- Offset vertical seismic profiling;
- Deep seismic shooting;
- Direct geophysical surveying methods which are based on identifying abnormalities of “pool” type;
- 3D seismic survey that makes it possible to obtain three-dimensional maps of the earth interior. This method provides more accurate data and details than 2D seismic. 3D seismic costs are high due to equipment and computer data processing expenses. However, nowadays, 3D seismic is used more frequently than 2D seismic, because it cuts drilling costs by reducing the number of dry wells.

Seismic Methods of Structure Preparation

Advantages of Seismic Survey:

- Transmission distance. Seismic survey makes it possible to map the structure of reference reflecting horizons at depth range from 5 km to 10 km with accuracy of 1-2% from the depth of occurrence;
- Regional operational efficiency. Structure of vast promising areas were studied in many regions; and
- Relative low cost of operations. However, nowadays, implementation of new technologies leads to substantial appreciation of seismic operations.

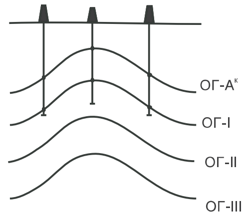
Seismic Methods of Structure Preparation

Disadvantages of Seismic Survey:

- Strict requirements and standardization of field operation procedures causes incompliance of procedures with complexity of seismic conditions;
- Insufficient application of multiplex surveying systems, and this complicates mapping of small structures;
- Accuracy of mapping is low in complicated seismic conditions (diapir, salt stocks and abundance of tectonic dislocations);
- Complexity of seismic operations in broken ground, in agricultural areas, in human settlements and protection zones; and
- Insufficient technique of velocity determination, as a result of which alteration of formation velocities caused by reefs, salts and karsts, is not taken into consideration. That is why underlying bed data are often inaccurate.

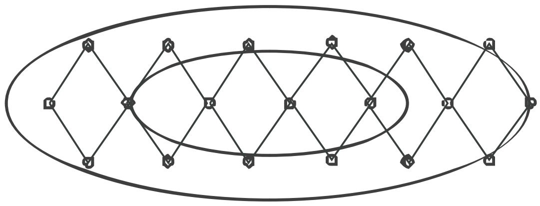
Structure Preparation by Structural Drilling

- Structural drilling is used in areas, in which seismic surveying is inefficient.
- Structural drilling for preparing structures is carried out by locating several non-deep wells up to the upper marking horizons. Wells are drilled on such reference horizons that are in parallel bedding with the expected pay horizons.
- To provide accuracy of mapping and determining inheritance of structural plans in the upper part of section, it is recommended to map using two marking horizons.



Structure Preparation by Structural Drilling

- Diamond-shaped pattern is used for placement of wells.
- Depth of structural wells is 600 – 800 m, and in some cases it is 2000 m.
- Technical capabilities to drill to such depth make it possible to use structural drilling in areas, within which the given portion of section is productive. In such cases, structural drilling plays a role of prospecting drilling, or structural-prospecting drilling.



Structure Preparation by Structural Drilling

Advantages of Structural Drilling:

- High accuracy of marking surface mapping – 1 m.
- It is used for prospecting small structures of through nature.
- It is used for prospecting pools at small depths (structural – prospecting drilling).
- Structural drilling can be used in adverse conditions for seismic operations.
- Structure preparation takes a short period of time.

Structure Preparation by Structural Drilling

Disadvantages of Structural Drilling:

- Disadvantages are caused by geological structure features – alteration as structural plane becomes deeper.
- Application range is limited by depth.
- Comparatively high cost of structure preparation.

Conclusion

Efficiency of deep drilling is based on quality of structure preparation.

Topic 6. Phase of Oil and Gas Field Prospecting, Exploration and Estimation

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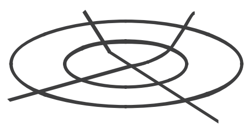
Phase of Oil and Gas Field Prospecting, Explo ation and Estimation

- The main objective of this phase is to discover and estimate a field.
- Survey target is a prepared structure.
- For prospecting and exploration phase this stage is final. The phase is completed with estimating reserves by C_1 и C_2 categories.

Selection of Priority of Prospecting Targets

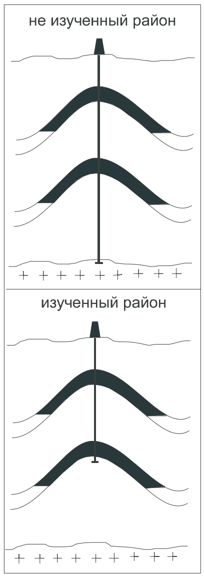
- The priority should be given to positive structures with largest amplitude, size and resources.
- For providing accuracy of the dome portion mapping, a necessary condition is availability, for at least, of two crossing seismic profiles which are the nearest ones to the dome of the structure.



- The priority should be given to the positive structures that are accurately mapped on the basis of several reflecting horizons and reliability of which makes it possible to select optimal prospecting and exploratory well sites.

Prospecting Well Depth

The depth of the projected well depends on the objectives of prospecting drilling. It should be sufficient to penetrate the dome of the structure for identifying the commercial oil-and-gas content of the entire section, and studying the geological structure of the projected area.



■ In frontier areas, it is recommended to drill the first prospecting well to the basement with drilling-in the entire sedimentary cover.

■ In explored areas, it is necessary to drill-in only all oil prospects.

■ Design well depth depends on the basement occurrence depth, or bottom of the lowest prospect, and considering drilling technique.

Prospecting Drilling Results

Prospecting drilling is deemed to be completed if:

- Commercial inflow is obtained;
- Non-commercial HC accumulation are identified; and
- Negative results were obtained.

Commercial Inflow Is Obtained

- Rate of commercial inflow is and economic notion. It is determined by geological and economical conditions for each particular region.
- Based on the prospecting operation results, C_1 - 20 % and C_2 - 80 % oil and gas reserves are discovered, and further prospect evaluation surveying or exploration should be conducted.

Non-Commercial HC Reserves Are Discovered

- In such case, conducting further operations is economically unadvisable.
- The discovered field should be classified as out of balance field.

Negative Results of Prospecting Drilling

Negative results mean water inflow or no inflow at all (closed boundary).

Reasons of negative results can be as follows:

- Absence of structure or incompliance of the structural plans;
- Small size of play and its complicated structure (well missed and is beyond the trap outline);
- Adverse geological conditions for accumulation and preservation; and
- Preparation of positive structures for drilling is of poor quality.

In such cases it is necessary to analyze the results and make a decision whether to continue operations or not. If lack of prospects within the area is evident, the prospecting drilling should be completed in the drilled-in portion of the sediment section, and "having no prospects" report should be prepared.

Number of Prospecting Wells

- Well drilling is the most expensive work among the all types of prospecting operations. That is why it is necessary to determine the optimal number of prospecting wells.
- Location and number of prospecting wells should be determined considering the type of trap and its size, accuracy of preparation, complexity of geological structure of the earth interior and amount of oil and gas resources.
- To date, four methods for determining number of prospecting and exploratory wells have been suggested:
  - Depending on the depth and cost of well, and resources;
  - Depending on area and thickness of effective oil-bearing formation;
  - Depending on the length and height of fold; and
  - **Depending on the expected C_1 and C_2 reserves, and costs.**

Number of prospecting wells should be established in the prospect evaluation survey project so that two main tasks are solved:

- Field discovery and
- Field estimation (determination of pool size, i.e. identification of OWC).

For substantiating prospecting well sites it is necessary to use two methods:

- Selection of **"priority" well sites** and
- Selection of **"pitch of prospecting drilling"** .

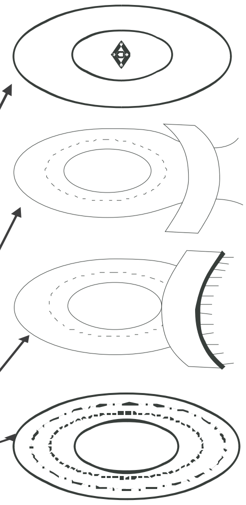
These methods are used for estimation the scale of the discovered field or pool. They make it possible to minimize the scope of work, to reduce exploration time and obtain substantial economic effect.

Selection of “Priority" Well Sites

These are well sites, drilling well in which will make it possible to prove presence of HC accumulations, and evaluate the scale of the field.

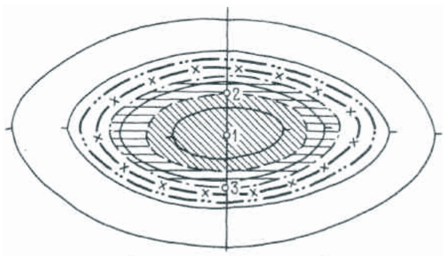
The “priority" well sites for various types of traps are:

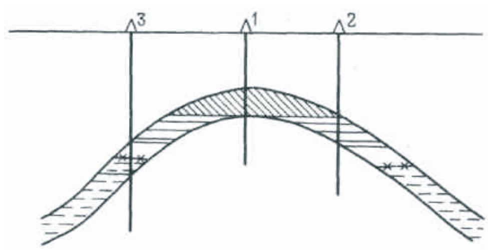
- Dome parts of the structure;
- Areas of least expressed structure closure, due to which the pool is preserved, and which express its potential height;
- Areas adjacent to the screening zones; and
- Fluid contact zones.



“Pitch of Prospecting Drilling"

- Well location under this method is aimed at gradual surveying of the pool, and makes it possible to avoid missing the oil-water contact at the minimal risk of dry wells.
- According to this method, the first well is prospecting well, the next wells are prospecting – exploratory and exploration wells. Such well location makes it possible to identify OWC in the dome pools.
- For massive pool OWC resolution 1 well is required.
- **Prospecting well 1** drills-in the entire thickness *h* of the formation in the dome. It means that the pool is present in the pre-dome part and is bounded by the surface of the pool occurrence. The proved surface line horizontally passes through the lowest point, at which oil is discovered.
- **Well 2** should be located on the profile in crosspoint of the pool occurrence proved surface line and top of the formation. It provides data of the pool in space between the proved surfaces identified in wells 1 and 2.
- The next wells should be located similar until OWC is identified.





Conclusion

Correct selection of the optimal number of prospecting wells and prospecting well sites makes it possible to save time and funds.

Topic 7. Prospecting and Exploratory Well Patterns

Oil and Gas Prospecting and Exploration
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Chair of Oil and Gas Geology

Prospecting and Exploratory Well Patterns

- **Well pattern** is a set of rules of well location, including priority of drilling prospecting and exploratory wells, which consider the planned location of earlier accepted well sites and accumulated data on the drilling target parameters spatial distribution.
- Location of prospecting and exploratory wells should form a pattern, which is further added with production wells. As a result, the uniform integrated field development system is created.

Prospecting and Exploratory Well Patterns

There are several well patterns that depends on type of trap, and are used considering “priority well sites", “pitch of prospecting drilling" and priority of drilling:

- **Profile method;**
- **“Critical direction” method;**
- **Location on multi-domed structures;**
- **“Principal” direction method;**
- **Location on tectonically disturbed structures;**
- **Prospecting and exploration in reef traps; and**
- **Well location on non-anticline traps.**

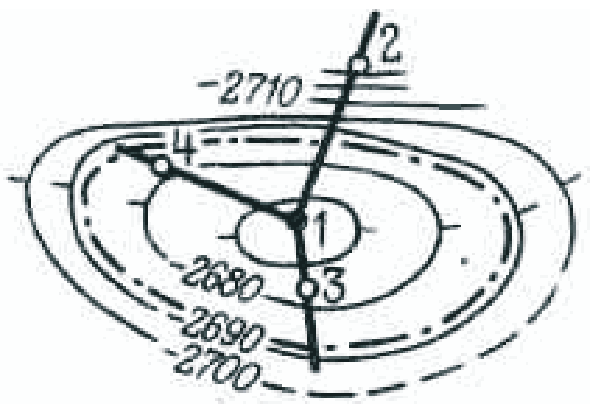
Profile Method

This method can be subdivided into:

- Radial profile method and
- Longitudinal profile method.

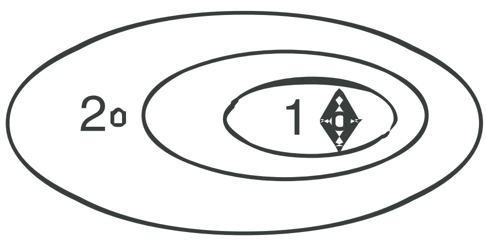
Radial Profile Method

- This method is used for dome-shaped folds.
- The first well is drilled in the dome, and the next wells are drilled on profiles of the triradial system considering “pitch of prospecting drilling” at various hypsometric marks.



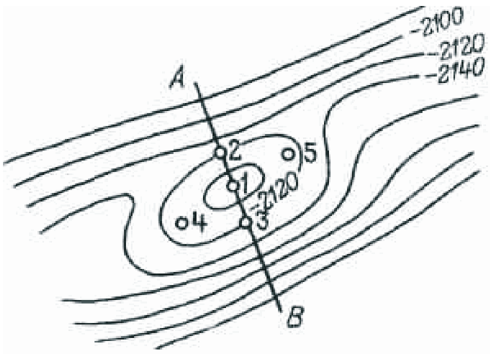
Longitudinal Profile Method

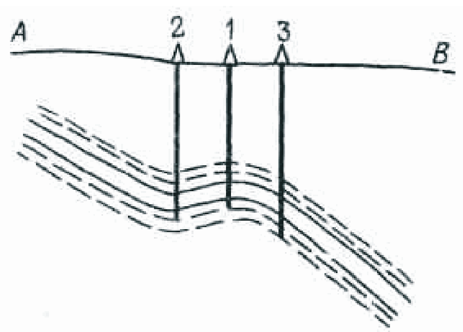
- This method is used for brachyanticline folds.
- The first well is drilled on the dome, and the second well is drilled on the flatter pericline.



“Critical Direction” Method

- This method is used on low-relief, ambiguously mapped structures.
- Two prospecting wells – one well in the area of supposed dome, and the second well within the zone of the poor expressed trap closure.

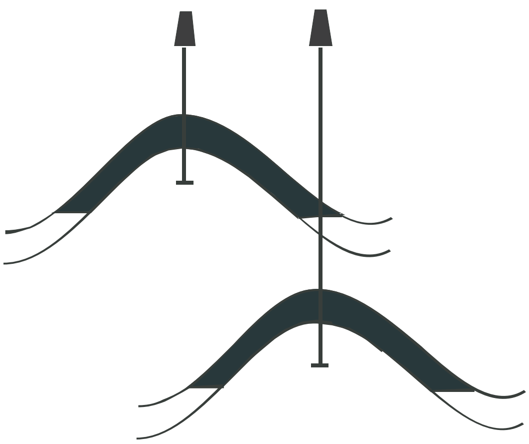




“Principal” Direction Method

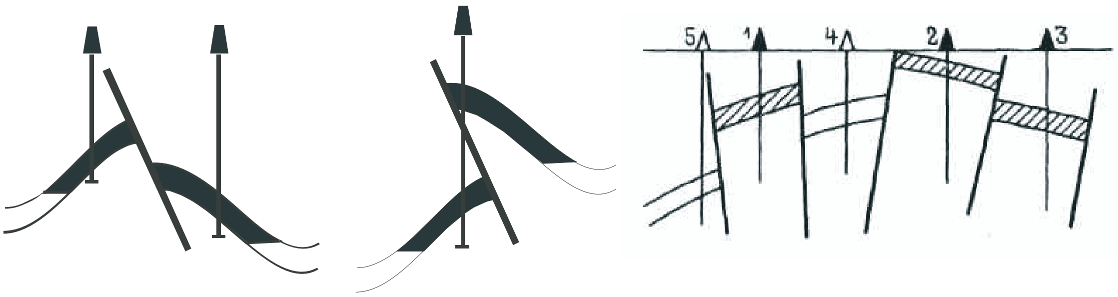
This method is applied as follows:

- The first well is drilled on the dome of the main structure, and
- The second well is drilled to the direction of the dome shift (preferably to the oil outline of the main structure).



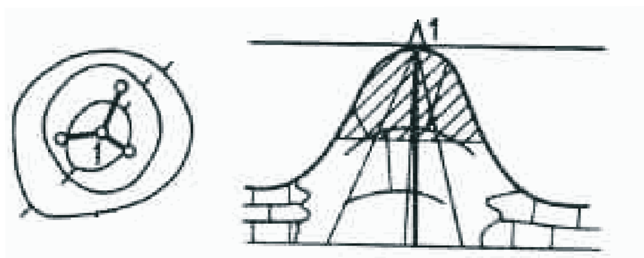
Location of Wells on Tectonically Disturbed Structures

- If the structure is complicated with downthrow, two independent wells should be drilled, one well on the upthrown block and one well on the downthrown block.
- If the structure is complicated with upthrow – one well in the zone of intercrossing of upper block and lower block.
- On the tectonically disturbed structure - single wells on the most upthrown and large blocks.



Prospecting and Exploration Drilling in Reef Traps

- Prospecting and exploration depend on the morphology of the reef body, its interrelations with adjacent facies and rock distribution – reservoirs and caps.
- In such traps reserves are concentrated in the central part, as 75 % of the entire trap volume falls to the axial region, and reservoirs are concentrated near the axis.
- One more feature, on which the method of prospecting work depends, is small sizes of pools.
- **Survey method – multilateral well drilling.**



Location of Wells on Non-Anticline Traps

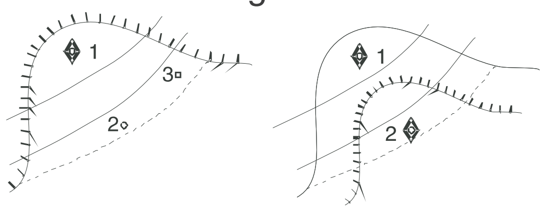
To this type of trap relate:

- Lithologically screened pools;
- Shoestring pools; and
- Clinoform (wedgeout) pools.

Lithologically Screened Pools

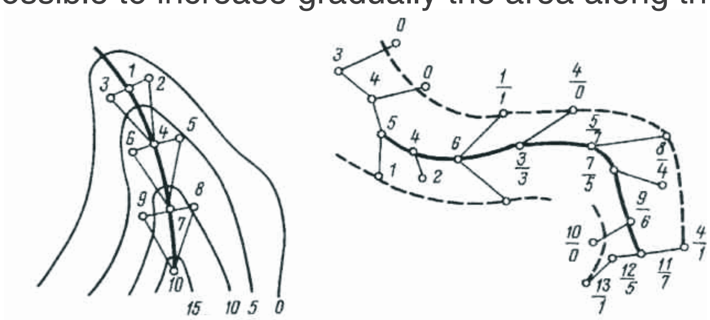
Purposeful search for such traps is conducted by drilling short profiles (2 – 3 wells) across the strike:

- The first prospecting well is located near the supposed screen. A distance from the screen should be set based on minimal amount of reserves, which is feasible to develop in the given region.
- If well 1 is productive, wells 2 and 3 should be located down-dip along the strike and aside for identifying maximal pool size and OWC. If well 1 is dry, well 2 should be located downward along the strike.



Shoestring Pools

- “Wedge method” is used for exploration of shoestring pools.
- The first prospecting well should be located in the area, within which presence of pool is expected.
- If oil pool is identified, prospecting wells 2 and 3 should be located perpendicular to the assumed axis position, to the sides from the well 1, for specifying the pool axis position and its boundaries.
- Then, considering the above data, well 4 should be drilled down-dip on the pool axis. And so on. Such system makes it possible to increase gradually the area along the axis.



Topic 8. Exploration and Test Production Phase

Oil and Gas Prospecting and Exploration

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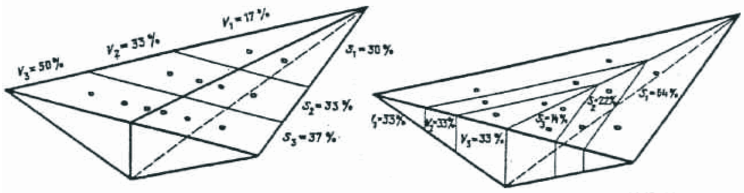
Exploration and Test Production Phase

- The main objective is to study and specify field characteristics for developing reservoir management plan;
- In modern practice, stages of field prospecting, estimation and exploration are often combined because of small sizes of many structures. Consequently, the objectives of prospecting stage and exploration stage are combined; and
- Well planning is based on the principle of uniformity.

Uniformity Principle

- Analyzing reservoir uniformly by volume and not by area is more rational. Especially, this concerns massive and lithological reservoirs.
- It is recommended to split reservoir into blocks equal by volume. Such splitting is aimed at well pattern infilling within the zone of maximum effective thickness of oil-and-gas bearing reservoir, i.e in places of concentration of largest reserves. As a result, each exploration well explores the equal volume of the oil-and-gas bearing reservoir.
- Such system is aimed at detailed analyzing the most valuable part of t reservoir that contains the main HC reserves.



Uniformity Principle

- <u>On massive pools,</u> uniform location of well would lead to over-exploration of marginal zones, the share of reserves of which is low.
- <u>Non-anticline pools</u> can be characterized by thinning and worsening reservoir properties in marginal direction, what causes reducing the amount of reserves in this portion of pool. So, it is possible to avoid drilling inefficient wells near the pinch-out line.

Uniformity Principle

Uniformity in volume of well pattern is also rational for production.

Location of production wells in the centers of zones of equal volumes provides:

- **Increasing well work period;**
- **Increasing well cumulative production;**
- **Reducing the length of in-field pipelines.**

Exploration of Multipay Fields

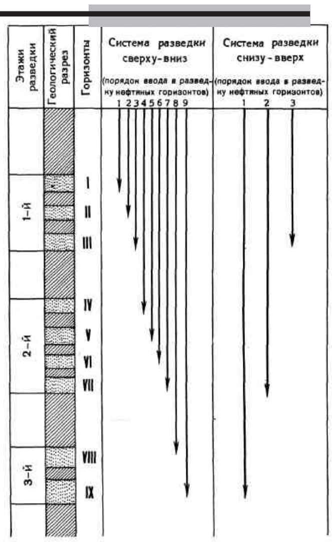
- In comparison with single-pay fields, the multipay fields can be characterized by higher concentration of reserves within the same areas. Majority of the multipay fields can be also characterized by combining reservoirs of different productivity in section of the pool.
- There are **exploration levels** in section of the field.

Exploration Levels

- Exploration level is a part of the field section which consists of several oil-bearing or gas-bearing horizons combined for exploration by independent well pattern.
- Exploration Levels should be selected in the field if commercial pools are discovered. Such exploration leveling promotes accelerated exploration and pool development.

Selection of exploration levels depends on:

- <u>Geological factors;</u>
- <u>Specifications; and</u>
- <u>Economic assessment.</u>



Geological Factors

- Thickness of pay zones;
- Number of oil and gas formations, horizons and pools;
- Presence of thick intermediate dead rocks;
- Type of reservoir;
- Type of pool;
- Position of main key beds in section; and
- Amount of reserves and well productivity.

Specifications

Specifications shall provide:

- Well design differences; and
- Differences in hole making technologies.

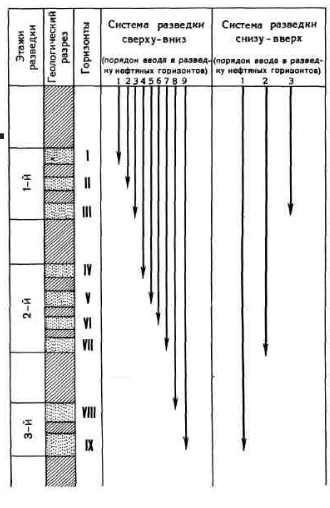
Economic Assessment

- Priority of exploration and bringing into development of one or two strata which are most prolific and easiest for development.
- Necessary condition for combining the group of formations in exploration level is presence of highly productive pool in the given part of the section, i.e. key bed of production zone.
- “Key bed" is an oil-and-gas bearing horizon, within the exploration level, with largest reserves and of highest commercial significance.
- Singling out the key bed makes it possible to explore, first of all, the thickest formations, to increment C_1 reserves and accelerate bringing of pools into development.
- The rest reservoirs of the exploration level should be developed following the key bed.
- One well pattern can explore several highly productive reservoirs.

Multipay Field Exploration Systems

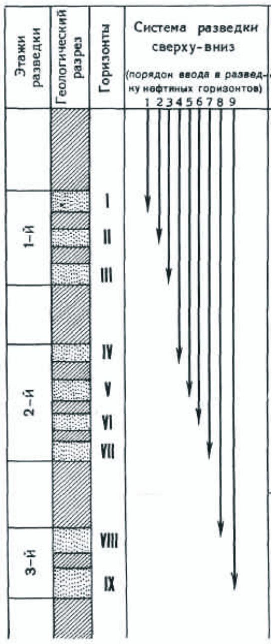
As a rule, practically, two multipay field exploration systems are used:

- **From top to bottom and**
- **From bottom to top.**



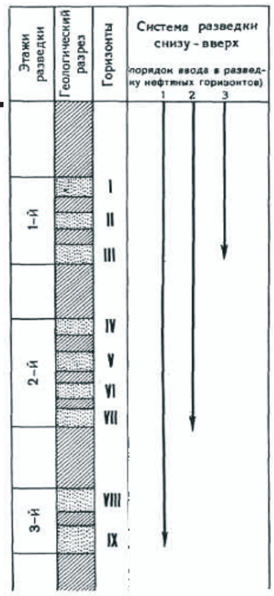
“From Top to Bottom” System

- This system specifies gradual exploration of underlying exploration levels after exploration of overlying exploration level.
- According this system, the overlying bed id drilled out with production wells after exploration. Then, exploration wells are sunk on the second bed, and the first bed is brought into development. Then, exploration wells are sunk on the third bed and so on.
- Application of this system should be substantiated by economic feasibility.



“From Bottom to Top” System

- This system specifies exploration of the entire sedimentary rock mass or its major part. According to the system, the overlying bed should be gradually explored after exploration of the underlying bed.
- Advantage of this system is possible return of the well to upper bed testing.



Exploration System

- All the systems are considered as design systems, and are applied only at the initial stage of exploration.
- Initial well pattern continuously undergoes great changes in regard to drilling each next exploration well.
- That is why it is necessary to substantiate economic feasibility and each well site at the final stage of exploration.

Application of exploration systems depends on:

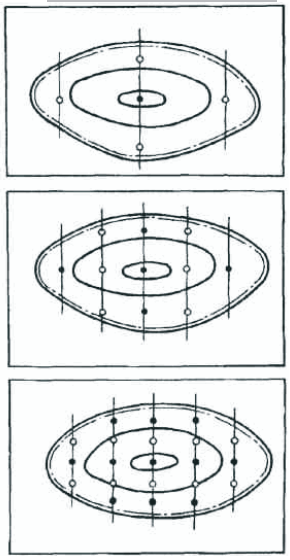
- Drilling priority:

1. *Infilling system; and*
2. *Creeping system.*

- Trap morphology:

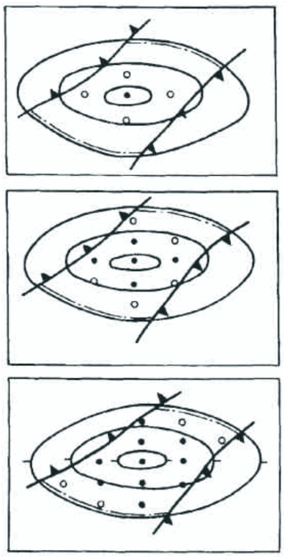
1. *Profile system;*
2. *Ring system; and*
3. *Triangle system.*

Infilling System



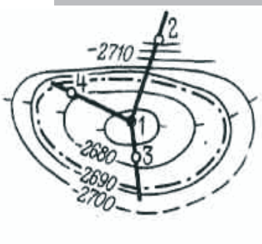
- This system specifies drilling out the entire area of the field using wide well spacing pattern at the initial stage. At the next stages the well pattern is infilled.
- The system is used for exploration **sheet** and **massive** pools.
- **Advantages:** ideally , it is preferable as it provides high rates of the field producing area increment. It makes possible to determine time of exploration completion, and adjust exploration process.
- **Disadvantages:** great number of perimeter wells can be drilled, especially on the structures with complicate configuration of oil pool outline.

Creeping System

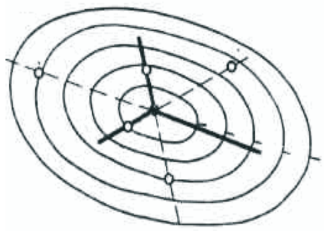


- This system is characterized by gradual extension of drilling area with design well pattern spacing without further well pattern infilling. Profiles are located according to the design well spacing in direction from the explored areas to unexplored ones.
- The system is used for exploration of pools **of all types, especially for exploration of non-anticline structures.**
- **Advantages:** the system is more economically rational (cost effective) - minimal number of perimeter and dead wells.
- **Disadvantages:** exploration time is significantly increased, because each next well is located depending on the drilling results of the previous well. Picture of the entire pool as a whole can be obtained only after completion of exploration. Application of the system affects effectiveness of planning and routine control.

Profile System of Exploration

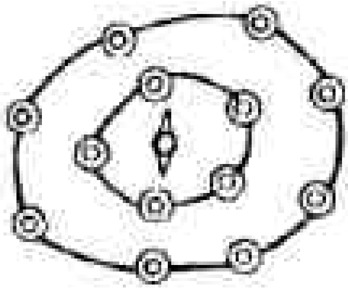


- This system is used for exploration of pools of all types.
- Well profile is located transverse to the strike or in direction of maximal alteration of target parameters.
- By drilling sequence, it can be **“infilling"** and **“creeping".**



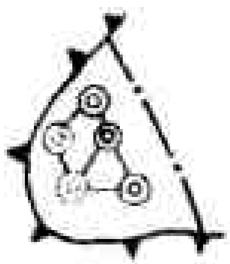
Ring System of Exploration

- This system is used for exploration of large field with isometric form.
- It is not recommended for lithologically, stratigraphically and tectonically screened pools.
- The ring system specifies well drilling in series rings in direction from the center of the filed to the margin.
- By drilling sequence, it can be **“infilling"** and **“creeping".**



Triangle System of Exploration

- This system is mainly used for exploration of lithologically screened pools. By sequence of drilling, it is “**creeping"** system.
- The system specifies location of each new well in the corner of a equilateral triangle, and wells with commercial inflows of oil or gas are located in two other corners of this triangle.
- **Advantages:** even exploration of the entire pool.
- **Disadvantage:** each new well is located depending on the obtaining positive drilling results from neighboring well. Exploration and delineation of the entire pool takes much time.



Topic 9. Well Logging while Well Drilling

Oil and Gas Prospecting and Exploration

Perm State Technical University

Chair of Oil and Gas Geology

Well Logging While Well Drilling

Purpose:

- Identify oil content of the section;
- Estimate reserves; and
- Develop reservoir management plan.

Set of surveys include:

- Core and mud sampling;
- Well logging;
- Open hole testing;
- Drill stem testing; and
- Laboratory tests of core, mud, oil, gas and water.

Core and Mud Sampling

Core data serves for determining lithological structure, rock ages, specifying stratigraphic boundaries within oil-and-gas bearing interval, reservoir properties and fluid content.

Scope of core sampling depends on well purpose and geological features of structure under survey.

- Key wells – 100% core sampling.
- Stratigraphic wells - core sampling is 20 % of total meterage.
- Prospecting wells - 10-12 %.
- Exploration wells - 4-8 %.
- Production wells – not in all wells, only for detailed reservoir surveying.
- For all wells, 5 m core sampling in bottom-hole zone is mandatory.

Types of core description:

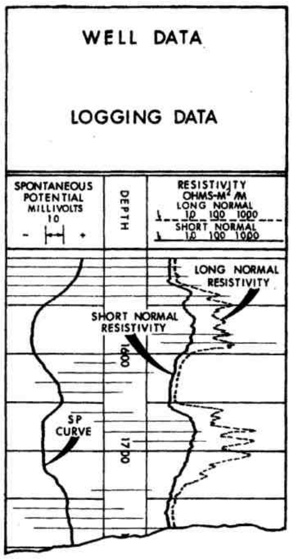
- <u>Prompt description</u> is carried-out at the rig directly after core removal from core barrel.
- <u>Macro description</u> is carried-out in core storage or laboratory.
- <u>Micro description</u> is carried-out by analyzing thin sections using petrographic (polarizing) microscope. Stratigraphic control is carried-out using key fauna.

Well Logging

Geophysical well surveying (GIS) is aimed at:

- Lithologic and stratigraphic layering of geological section;
- Identifying marker beds;
- Determining depth of occurrence and thickness of formations;
- Selecting core sampling intervals in the new wells;
- Correlating well sections;
- Identifying oil and gas reservoirs, studying features of their horizontal distribution, evaluating their nature and fluid content and determining reservoir properties;
- Selecting perforation intervals;
- Integrated interpreting GIS data for estimation of oil and gas reserves and reservoir management plan development. It includes mapping reservoir characteristics – effective thickness, heterogeneity, porosity, permeability and other; and
- Identifying phase contacts.

Well Logging



Well Logging shall be planned in all oil and gas well construction projects, and performed by special geophysical companies.

Well logging should be carried-out in two scales:

- For the entire well bore - Scale 1cm:500m.
- Detailed well logging within oil-and-gas bearing rock masses - Scale 1cm:200m.

Well Testing

Objective:

- Recovery of formation fluids and gases from potentially productive formations, and subsequent determination of their quality and quantity.

Tasks:

- For each reservoir, determine oil, gas, condensate and water daily production rates under various operation conditions, formation and bottom-hole pressure, and formation temperature; and
- Deep oil, gas and condensate sampling.

- **Potential pay bed testing while drilling (drill stem test)** is a work package for obtaining **qualitative** characteristic of fluid content of penetrated section.
- Formation testing should be performed in key, stratigraphic, prospecting and exploration wells, and, in some cases, in structural wells.
- Testing targets should be selected based on set of geological and geophysical data obtained for the well to be tested and for other wells within the area and the region.
- For obtaining formation productivity data while drilling, wireline (repeat) formation tester and drill stem testers are used. Wireline tester is also used for formation fluid sampling.

Well Testing

- **Potential pay bed testing in production string** is a work package in well aimed at obtaining **quantitative** parameters of formation fluid inflow in well.
- Perforation is used for pay zone testing through the cased hole.
- For perforation of strings in conditions of continuous cementing, bullet, projective gun, hydraulic jet and cumulative perforators are used**.** Shot density depends on the reservoir nature, filter capacity and formation productivity:
  - 4 – 6 shots for well-permeated uncompacted formations; and
  - 20-40-60 shots per 1 m of perforation interval for heterogeneous formations.
- Formations are tested in well from bottom to top. Cement plug is placed after each test that caused inflow.
- Thickness of perforation interval should be from 5-10 up to 30 m.
- Testing intervals while drilling and in production string should be determined by geological department based on the existing well section.
- Deep oil, gas, water and condensate samples should be taken during test.

Laboratory Analysis

Laboratory analysis includes analysis of core and formation fluid samples.

Core sample analysis includes granulometric (grain-size) and mineralogical analysis, paleontological and petrophysical analyses, description of thin sections, and determination of physical parameters of formations.

Oil samples are used for determining:

- Fractional and group composition;
- Content of silica-gel resins, asphaltene, paraffin and sulfur;
- Gravity in formation and surface conditions;
- Bubble point pressure;
- Gas solubility in oil; and
- Elastic constants.

Formation water analysis shall include:

- Complete chemical composition, including valuable associated components, iodine, boron, bromine, lithium and other elements;
- Volume and composition of water-dissolved gas;
- Water resistivity;
- Composition of water-dissolved organic matter;
- Combined (interstratial) water.

Scope of rock and oil properties analysis to be set by geological department of the contractor.

Course of Lectures on

GEOPHYSICAL WELL SURVEYING (LOGGING)

INTRODUCTION

Geophysical Well Survey (GIS) basing on the modern physical rock exploration techniques is used for studying the geological structure of subsurface resources by well log, identifying and evaluating hydrocarbon reserves and obtaining data of the technical state of wells during field development.

Recently, new geophysical well logging techniques have been developed. At present, the state-of-the-art geophysical equipment is universally implemented, and it makes it possible to carry-out integrated processing and interpretation of field geophysical survey data using electronic data processing machines and personnel computers by advanced software techniques.

In-depth field geophysical survey data processing obtained while well drilling and operation makes it possible to solve a wide range of geophysical tasks. Considerable part of information about the deposits crossed by wells is obtained by interpretation of geophysical logging data which are used together with lithological and paleontological sample rock data and well testing data for creating lithological and stratigraphical descriptions of well logs, characterizing each penetrated formation, building up structural correlations and so on. Thus, geophysical logging data is a very important source of information about geological structure of oil and gas fields.

Well drilling in oil and gas industry is conducted not only for hydrocarbon field prospecting and exploration nut also for their development. Geophysical well surveying is conducted for the purpose of geological survey of wells, their technical state and monitoring the conditions of field development. A complex of geophysical well surveys in well is Geophysics.

Surveying of geological section of well is aimed at determining a sequence of occurrence of rock beds, their lithological and petrographic properties, evaluating presence and quantitative content of minerals in place. Study of geological section of well is possible by using core sampling. However, core samples from the required interval can be taken not always (incomplete core recovery), and rock properties and saturating liquid properties are significantly changed during core sampling and recovery, and that is why core and mud analysis data does not provide a comprehensive idea about geological section of well.

At the same time, some physicochemical properties of rocks (electric conductivity, electrochemical activity, radioactivity, temperature conductivity, elasticity and other can be studied directly in well under conditions of their natural occurrence by conducting in well special geophysical surveys. Such geophysical surveys, which partially or completely replace core sampling, are termed Logging. The results are shown in the form of diagram of alteration of physical properties of rocks along wells – well logs. Depending on the properties of rocks to be studied, the following types of logging can be used: electrical logging, radioactive logging, thermal logging, acoustic logging and other.

Logging data make it possible to obtain a geological description of well log. Logging data are initial data for studying the geological structure of the entire field and the region in whole, as well as for calculating reserves and designing the rational system of oil and gas field development. At present, geophysical data are the basic data, and they are used for evaluating reservoir characteristics of rocks and degree of oil, gas or water saturation.

Technical state of wells is monitored at all phases of well existence: drilling, перед pre-commissioning and during operation. When drilling, borehole deviation is determined by inclinometer, well diameter – by caliper, points of liquid entry from formation and lost returns are determined by resistivity meter and electric thermometer. Before putting of well on production, integrity of string and cementing quality is tested. For production wells, their technical state testing includes detecting leaks of cement sheath, failures of cement bond with string and rock which caused occurring of annular liquid circulation.

Geophysical well surveying also includes: perforating-explosive operations, wireline test, sidewall coring, perforation of casing strings for penetrating formation and torpedoing relate, торпедирование.

Depending on condition of formation and areal extent, rocks have their own structural and textural signs. They are characterized by a particular set of physical properties: porosity, permeability, density, clay content, flexibility and other. Science that studies physical properties of rocks and determining numerical interconnection of various parameters is termed Petrophysics. All the above mentioned physical parameters are determined based on data, such as true resistivity, natural and induced radioactivity, wave propagation velocity and other, obtained by well logging techniques.

Geophysical well surveying methods are subdivided into electrical (laterologging (BCZ), spontaneous potential (SP), lateral logging (BC), micro laterolog (MBC), micrologging sonde (MZ) and induction logging (IL); radiactive (gamma-ray logging (GC), neutron gamma-ray logging (NGL) and other); acoustic (acoustic logging (AL), magnetic, thermal logging and other.

1. WELL LOG DATA INTERPRETATION

1.1. General Information

Oil and gas field prospecting, exploration and development are conducted based on the enormous material data obtained by well drilling and surveying. This material serves as basis for detecting oil-and-gas bearing horizons, and makes it possible to obtain data of geological structure of bowels of the earth. The main data on rock deposits penetrated by well are obtained due to well logging data interpretation for each well. Joint processing of well logging data and materials obtained by lithological and paleontological study of rock samples (coring) is the basis for characterizing each strata in the column of the well under survey, its physical properties, thickness, boundaries with neighboring strata, location in the geological section of well and so on.

Types of rocks identified based on the well logging data are aligned with classification of these rocks that had been earlier determined on the basis of physical and chemical properties of the rocks. For this purpose, geophysical characteristics obtained by interpretation of well logs are combined with petrographic characteristics obtained by studying rock samples taken during well drilling from particular depths in the form of core or mud, or sample taken by sidewall coring. Then, as sufficient experience is achieved, rocks can be petrographically and stratigraphically classified only on the basis well logging data.

Well logging data is the basic material for making-up of borehole geological section and for comparing (correlation) logs of several wells. In oil and gas industry, all wells are surveyed using this or that well logging: exploratory wells, prospecting wells, production wells and other. Well logging data is widely used for geological mapping and field seismic surveying. In many cases, borehole geological sections of wells made-up based on well logging data are the only source of information about bed sequence and composition and properties of their forming rocks. Detailed study of well logs makes it possible to obtain data of facies variation, thickness variation of each particular bed or bank, bed occurrence conditions, stratigraphic identification of deposits and so on.

Geological interpretation of well logging data processing results is used for solving two main tasks: 1) detailed study of intervals of borehole section which con-

tain minerals (oil and gas); and 2) study of general geological structure of oil and gas fields.
For solving the first task, not only oil-and-gas bearing formations and horizons are studied, but also all rocks with high reservoir properties. For this purpose, it is necessary to determine thickness of formation, extent and nature of their saturation with oil, gas and water, water-oil contact (WOC) and gas-liquid contact (GLC).

For solving the second task, based on the well logging data the well penetrated deposits are stratified, and well logs are compared, facies variation of deposits and depositional history are studied, sedimentary rock mass structure and occurrence conditions are also studied.
Based on the well logging data interpretation results, various maps and profiles are made-up. They characterize geological structure of this or that field under surveying.

The main well logging methods for borehole section study are data of electric logging, radioactive logging and caliper log measurements. This data is the basis to which data of lithological, paleontological and other studies obtained by core and mud analysis are aligned. It should be noted that logging provides more accurate measurement of depths than that during drilling, and that is why it is necessary to use well logs for depth determining.

1.2. Lithological Layering of Geological Well Sections

The most significant document of Geological Services that provides characteristic of well is considered to be lithologic-and-stratigraphic column that contains data of formation boundaries and their thickness, lithological composition and stratigraphic nature of rocks which form the reservoirs, presence of reservoir beds and nature of their saturation.

For studying lithological composition, the majority of the existing well logging methods are used in various combinations. The optimal well logging should be selected based on the particular geological conditions of section. It is connected with the fact that each well logging method provides different effectiveness in "recognizing" this or that lithological type of rock (see table 1). Classification of sedimentary rocks is based on the difference of their physical and chemical properties. Well section study using the well logging data is also based on the difference in physical properties of rocks, which, however, should not be equaled to the physical parameters of rocks. These are particular “geophysical” parameters: true resistivity (resistivity logging), natural radioactivity (gamma-ray logging) and so on. For geological interpretation of well logging data, of the basic importance are not their absolute values of geophysical parameters but their ratios. Let us discuss the methodology of layering using the most typical sections – terrigenous and carbonate section – as illustration.

Terrigenous section. Lithological layering of the section on the basis of well logging data is carried-out in two phases: at first, rocks are divided into reservoirs and non-reservoirs, and then, particular lithological varieties are determined among reservoirs and non-reservoirs. Based on the storage and deliverability properties, the reservoirs are subdivided into low, medium and high ones, and non-reservoirs are subdivided into clayey and all other country rocks. On the basis of well logging data only group of clay rocks can be identified without error (clays, argillites and clay shale). All these rocks are characterized by increasing of well diameter in comparison with nominal one, low true resistivity, and the highest spontaneous potential and gamma-ray logging readings, and low readings of neutron gamma-ray logging and micrologging sondes. For at least, there are two classes of non-reservoirs with different clay content and porosity among non-reservoirs.

The first class includes sandstones and siltstones which are characterized by lower porosity and higher clay content if compared to worse reservoirs; they are marked with high readings in lateral logging lateral logging sounding, laterologging and micrologging sondes, low values of Δt at acoustic logging, high readings at neutron gamma-ray logging, intermediate values at spontaneous potential and gamma-ray logging, but closer to the readings for the worse reservoirs.

The second class includes clay rocks that contain sand, silt or carbonate materials, for which the well logging readings typical for clays, are also typical. There is some difference in low increase of true resistivity if compared to resistivity of pure clay, in presence of insignificant abnormalities of spontaneous potential in relation to the pure clay line, and insignificant reduction of radioactivity if compared to pure clays at gamma-ray log (figures 1 and 2 and table 1).

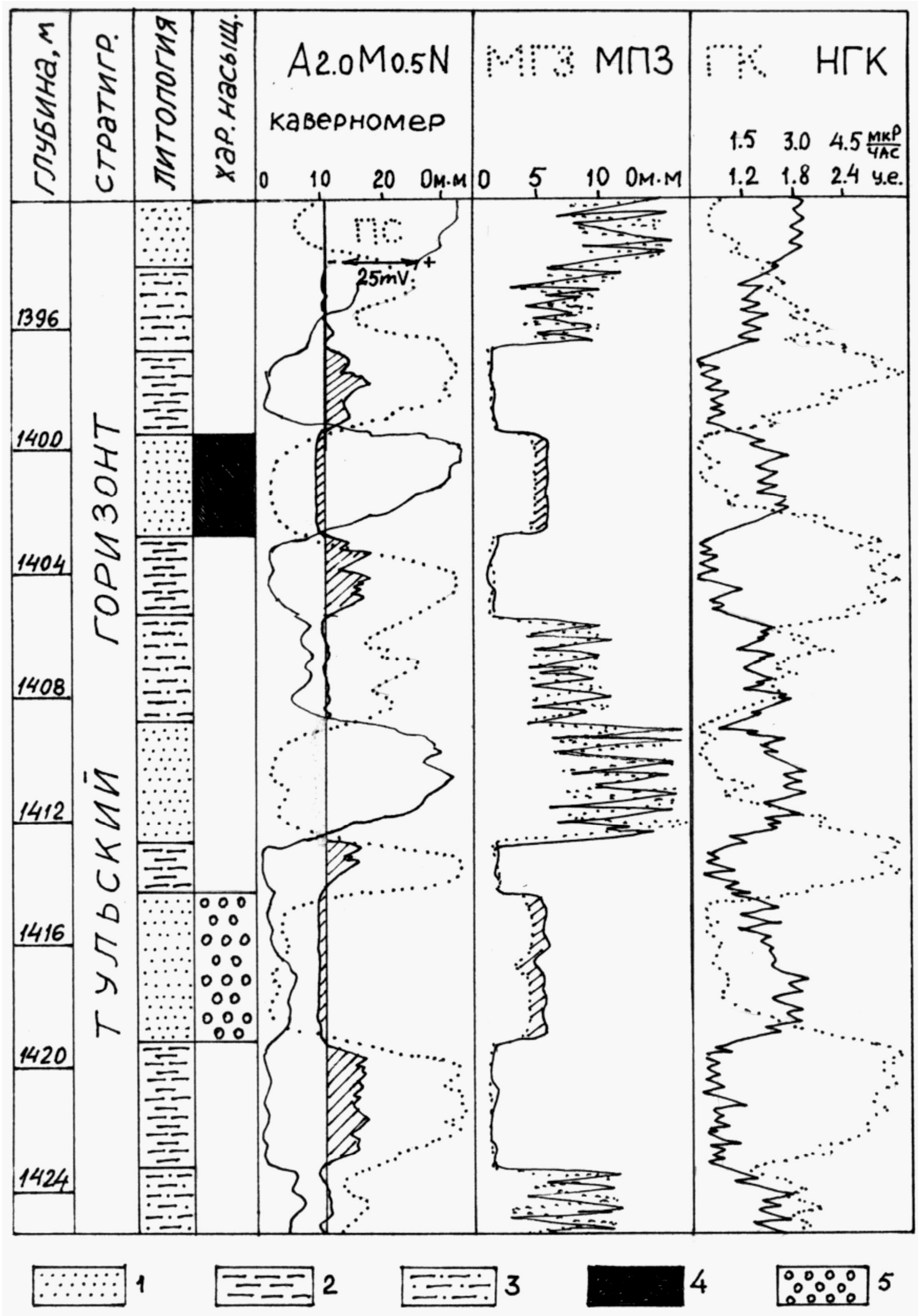


Fig. 1. Lithological Layering of Terrigenous Section
and Identifying Reservoirs based on Well Logging Data:
1 – sandstone, *2* – siltstone, *3* – argillite, *4* – oil-saturated reservoir,
5 – water-saturated reservoir. Shaded portions: caliper log curve – signs of reservoir (decrease of well diameter) and clay rocks (increase of well diameter); micrologging curve – signs of reservoir

Table 1

Characteristic of Lithological Composition of Rocks based on Well Logging Data

Rock	Spontaneous potential	Gamma-ray logging	Neutron gamma logging	Well diameter	Micrologging sonde	True resistivity (resistivity logging)
Clays	High readings. The higher dispersion of clay, the higher potential	High readings	The lowest readings, and minimal ones under high washout	As a rule, increase of well diameter. Some beds of plastic clays in points of diameter reduction	The lowest readings of microsondes. No increment between micro-potential sonde and micro-gradient sonde	Low readings which are close to the readings of drilling mud resistivity
Argillites, Clay Shale	The same as for clay or higher	The same as for clay	Low readings (especially if well diameter is increased) and medium readings.	Various cases. Most often – increase of well diameter	Readings are not typical	Readings are higher than those for clay. At highly compacted varieties the resistance is increased as density increases
Clays contained sand, silt and carbonate material	Presence of insignificant negative abnormalities of spontaneous potential versus pure clay line	Insignificant decrease of radioactivity if compared to pure clay	Low and medium readings	Increase of well diameter	Readings are higher than those for clay	Insignificant increase of resistance if compared to that of pure clay
Porous sandstone	Minimal readings	Low readings that increases with increasing clay material content	Low readings	Well diameter reduction. Nominal diameter in case of mineralized drill mud	Low readings with positive increment between micro-potential sonde and micro-gradient sonde	Mainly low and medium. In oil-bearing formations – low. High range of alteration.
Clayey sandstone	Intermediate readings	Medium readings, sometimes high readings	Higher readings than those for porous sandstone	Various cases. , caliper log curve is often not direct	Readings are higher than those for reservoirs, no increment	-“-
Dense sandstone	Readings range from minimal to maximal	Low readings	High readings (medium and high readings)	Nominal well diameter	High readings: ratio between readings of micro-potential sonde and micro-gradient sonde is indefinite	High readings
Siltstone	Minimum. In some cases with lower amplitude of deviation than that in pure sandstone	Low and medium readings	Usually low readings as those for porous sandstones	Well diameter reduction in case of porosity variety and frequent alteration of well diameter in other cases	Not high readings, there is an increment in porous variety	Resistance is the same as that of porous sandstone or little bit higher
Limestone, dense dolomite	Low readings of spontaneous potential	Minimal readings	Very low readings	Most often nominal well diameter	High readings, highly variable and not direct	Very high readings, especially for dense and silicified limestone
Limestone, clay marl	High readings (the same as for clay)	Medium readings, the higher reading, the higher clay material content	Low and medium readings	Nominal well diameter or increase of well diameter	-“-	From 10 mm and higher, but less than for dense varieties
Porous limestone	Low readings	Low readings	Low readings	Clay coating	Positive increments in micro-potential sonde and micro-gradient sonde , and lateral logging sounding and laterologging	From one to hundreds of ohmmeters

Non-reservoirs can occur in the terrigenous section. They are usually formed by sandstones and siltstones with carbonaceous cement and compact limestone. Such rocks are, as a rule, marked with low readings in spontaneous potential and gamma-ray logging curves – the same as those of reservoirs; but, at the same time, they are characterized by high readings in neutron gamma-ray logging and microsonde logs, and minimal values $\Delta\ t$ in acoustic logging curve.

Carbonate section. For carbonate section layering on the basis of well logging data, at first, intergranular reservoirs are identified, and at the rest part of the section, lithological layering with identifying complex reservoirs is carried-out. Clay is as easily identified in well logging as in the terrigenous section. Chalky clay is identified by high values of resistivity logging. They are higher than those of clays but lower than those of limestone and dolomite (fig. 2).
In neutron gamma-ray logging, chalky clays are marked with intermediate readings, and with nominal well diameter readings in caliper log curve.

Poor-porous limestone and dolomite are divided by deliverability into classes of non-reservoirs and cavernous fractured reservoirs, and into classes of limestone, dolomite and intermediate lithological varieties by mineral composition of matrix. The first task can be solved using standard logs and special well logging. The second task can be solved using the integrated interpretation of thermal-decay-time logging, measurement while drilling and acoustic logging data. Maximal value of resistivity are typical for compact carbonate rocks; porous and permeable varieties – lower values of resistivity. Natural radioactivity in pure lime stone and dolomites is minimal and increases with increasing clay content in these rocks. This dependence is so evident, that using gamma-ray logging it is possible to determine degree of clay content of carbonate rocks.

Readings of neutron gamma-ray logging against compact rocks are maximal, and significantly lowered in high-porous and cavernous rocks. Clay carbonate rocks are also marked with low values of neutron gamma-ray logging readings. They can be differed from porous rocks by comparing neutron gamma-ray logging data with gamma-ray logging and spontaneous potential data, at which clay rocks are clearly reflected. Well diameter in compact carbonates corresponds to the nominal diameter, and in clayey varieties and (very rare) in cavernous rocks d_{crd} is increased, and clay coating is formed against porous rocks.

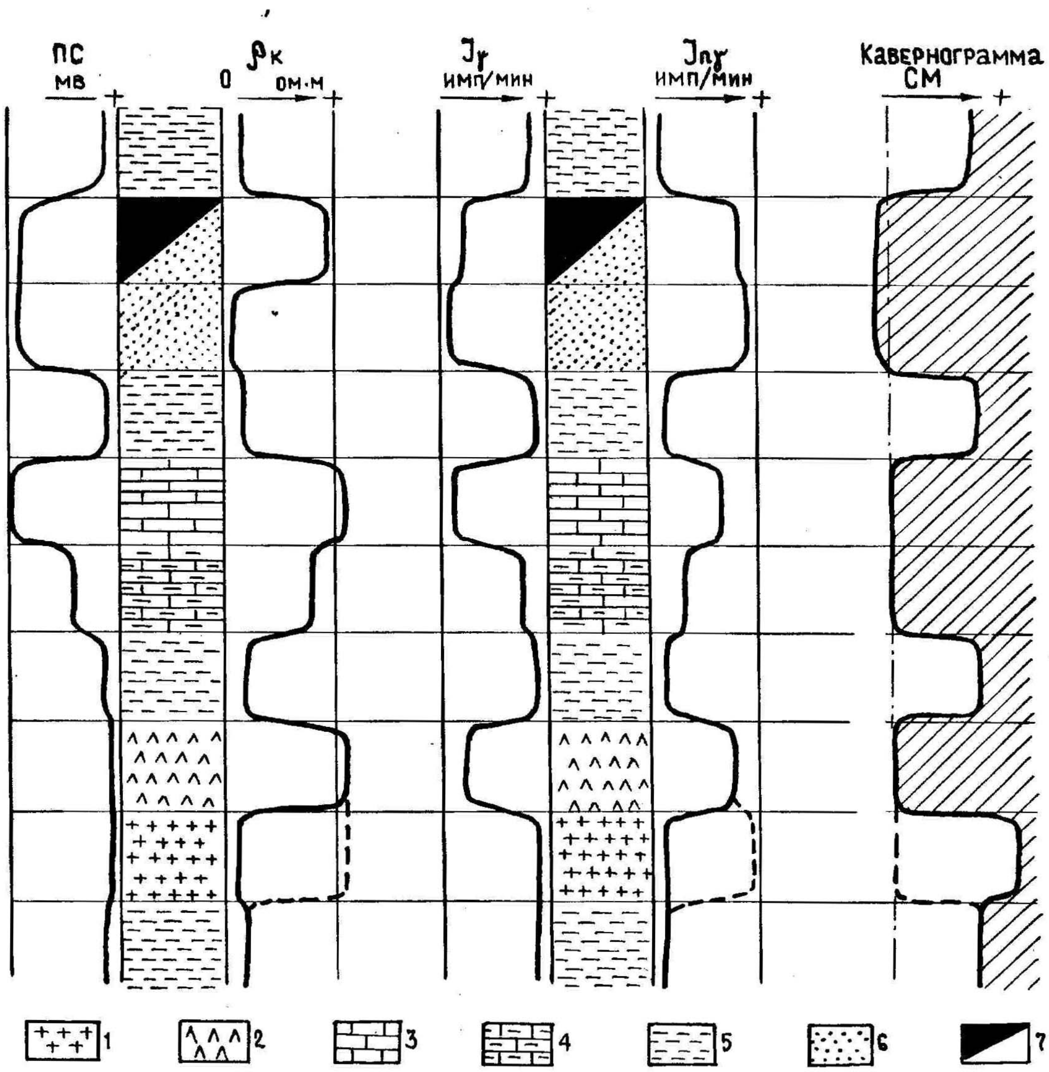


Fig. 2. Characteristic of Various Rocks using Well Logging Curve Configuration:
1 – salt; *2* – anhydrite; *3* – limestone or compact dolomite;
4 – limestone or clay dolomite; *5* – clay rock; *6* – sandstone;
7 – oil-saturated reservoir

1.3. Geologic-Geophysical Profiling of One Well and Cross-Borehole Correlation

The main tasks to be solved by geologic-geophysical profiling of each well are to dissect the drilled rocks in separate layers (beds) and to determine their lithological composition and stratigraphic implication. In doing so, a separate layer (or bed) is considered the part of well section which is formed by homogeneous rocks, and that is why it is characterized in well logging curve by, more or less, constant values of geophysical parameters. Boundaries between neighboring layers are determined by well logging and mark them in points of

sudden change of properties. Resolution of almost all well logging methods is such that based on well logging data it is possible to determine with confidence the beds with thickness less than 1 m, and by applying the special well logging methods it is possible to identify beds with thickness of 10-15 cm only.
Determination of the lithological composition of the identified formations is based on the core and drilling mud data processing results.
The basis of stratigraphic layering is paleontological data. The boundaries of stratigraphic unit should be tied with the points of the most sudden change of lithological composition as actually stratigraphic layering is based on lithologic feature.

For **cross-borehole correlation** on the basis of well logging data, it is assumed that on the same bed in sections of various wells is identically reflected in well logs and characterized by very similar configuration of curves of section areas. Similarity of configuration of compared parts of well logs is the most important and convincing sign of the bed identity in sections of a number of wells. Especially close similarity can be observed in thick key beds which greatly differ from the neighboring rocks in physical parameters within the entire area under survey.
Such marker beds can be, for instance, carbonate mass of compact dolomites and dolomite limestone of Sakmarian stage, Vereian clay masses, impermeable limestone of Sargaev and Kyn horizons.

It is better to begin correlating of the neighboring well section from identifying one or several marker beds clearly shown in well logs of all well sections under analysis. After comparing well sections in a first approximation, the detailed correlation should be started. The objective of comparison is to identify the same beds, banks and horizons which were identified earlier in the first well. Formations, beds and banks are traced by similar configurations in well logs. For identifying the basic regularities of the section and eliminating local inhomogeneities fixed in the log curves, it is advisable to make-up integral well logs.

For this purpose, the section of the surveyed well is split in unequal intervals, each of which is a part of the well logging curve. These intervals incorporate points in the well logging curve with close readings of this or that geophysical parameter. Such approach makes it possible to solve a task of stratification of well section using the marker beds of various classes identified in the integral well logs, by which it possible to determine the depths of seismic reflectors, intervals of water-bearing and water-resisting rocks and so on. The detailed layering of well sections makes it possible to stratify uniformly the penetrated deposits, make o point of the identified section units and observe, at the same time, all alterations of their thickness and lithologic variation. It should be noted that sometimes correlation of some sections of wells can be made even by logs of one geophysical parameter.

Correlation data can be provided in drawing that is termed correlation profiling. (fig. 3). To make comparison of section easier, one of the beds in the upper part of the being compared complex of deposits is taken as horizontal plane that is indicate in the drawing with horizontal line (line of comparison).

The sections of all wells are leveled by this bed, which makes all changes in thickness of underlying rock mass easily noticeable. Boundaries of the beds of the same age identified in different wells are connected with direct lines. To simplify reading of the correlation profiling, the lithological composition of the section is usually indicated in one of the columns of a well. When making correlation profiling, it is very important to select reference bed (horizon) by which all sections of wells to be correlated are compared.
If the correlation profiling reflects not only lithological composition data of rocks and their age, but also well logging records are provided, such drawing is termed Columnar Geological-Geophysical Section (see fig. 37).

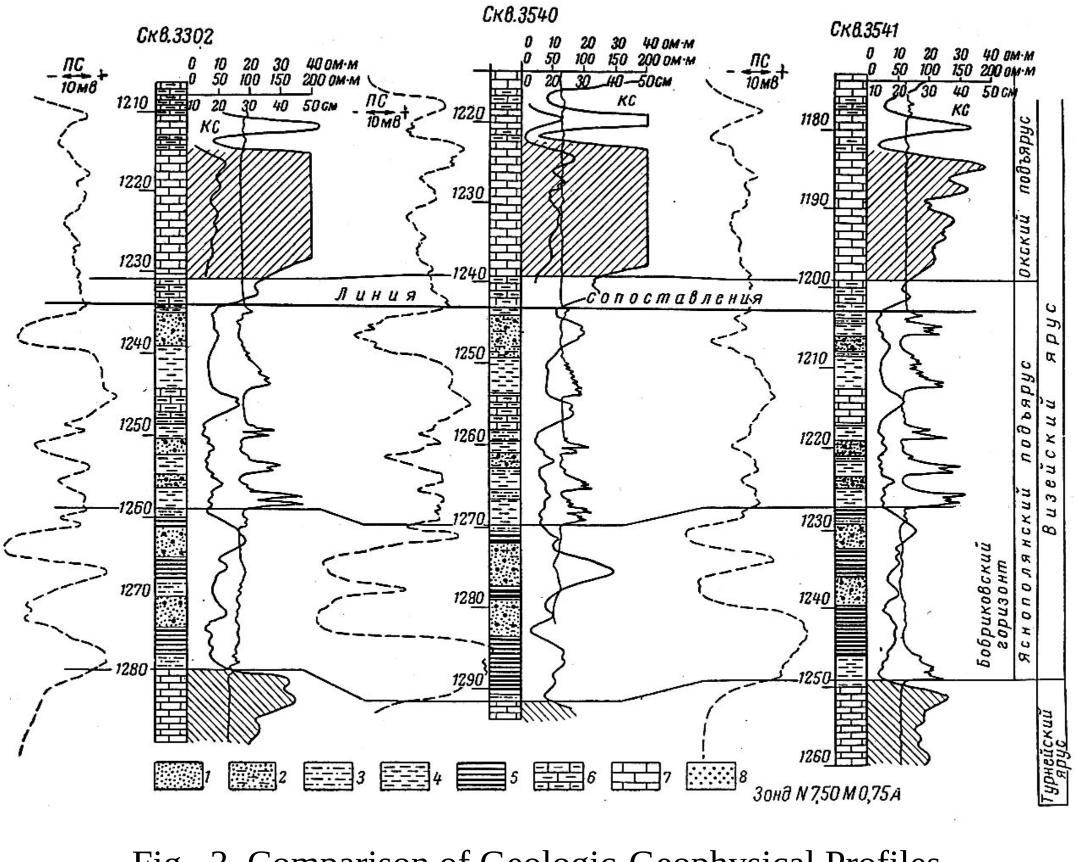


Fig. 3. Comparison of Geologic-Geophysical Profiles
of Terrigenous Rock Mass:
1 – sandstone; *2* – clay sandstone; *3* – siltstone; *4* – argillite;
5 – argillite with coal seams; *6* – clay limestone; *7* – limestone; *8* – oil content

Comparison of deposits of the same age by well logging data of several exploration areas is termed Interregional Correlation, which makes it possible to evaluate their prospects in terms of content and volume of hydrocarbons, and other parameters.

1.4. Operational and Consolidated Interpretation of Well Logging Data

Operational interpretation. Operational interpretation of well logging data means preparing conclusions on presence of hydrocarbon filled layers with indicating their basic parameters (thickness, porosity and oil-and-gas saturation factors) and recommendations on testing, and issuing it to Geological departments of drilling organizations. Operational interpretation shall be carried-out at all phases of exploration and operation of oil and gas fields, including first well drilling, when no reliable information about the being explored geological profiles are available, and no particular relationships of geophysical parameters and reservoir properties have been yet identified. That is why, unlike to the results of consolidated interpretation, the characteristics of reservoirs to be determined are of qualitative and semi-quantitative nature: for instance, general, but not effective thicknesses of reservoirs, is provided, predictive estimate of their saturation, but not oil-and-gas saturation factors, is given.

Operational interpretation is phased as follows:

– log data quality control;

– layering of sections, determining boundaries of layers and their relevant geophysical parameters (A_{sp}, ρ_r, Δt, $\Delta I\ \gamma$, $\Delta I_{n\gamma}$, and other) adjusted considering measurement conditions impact. At the first phase, specific resistance is determined $\rho_{пв}$, $\rho_{пп}$, $\rho_{зп}$, $\rho_{п}$;

– identifying the reservoirs and determining their thicknesses; and

– predictive estimating of saturation nature (oil, gas and water) of pay formations.

The above mentioned can be more simple solved in terrigenous section. By similarity of geophysical characteristics, granular carbonate reservoirs are adjacent to them. To identify and evaluate reservoirs formed by several minerals, or which have a complex structure of pore volume, special research procedures are used. Operational interpretation of well logging data begins with layering of the explored sections to separate layers that differ by geophysical parameters, and with determining their boundaries. Then, against the being interpreted beds, measured apparent values of geophysical parameters are calculated and are adjusted considering impact on measurement conditions. Further, at the phases of geological interpretation, their geological characteristics are determined based on the data set of physical properties: lithological composition, effective thicknesses, porosity and oil-and-gas saturation factors.

Layering of sections should be carried-out at the qualitative level: intervals are identified in particular beds, against which considerable variation of geophysical parameters takes place if compared to enclosing rocks. Considering various reasons of variation of these parameters (variation of lithological composition, porosity, permeability and rock saturation nature), sections are layered by using the entire set of geophysical data. In case of small change of one or several geophysical parameters within one layer, this bed is subdivided into interlayers.

The boundaries of layers and interlayers are determined by representative points in curves of each type of well logging. For layers of large thickness, when it exceeds the length of measurement sondes, the boundaries of some layers correspond to:

– sudden transition in micro-logging sonde and multisonde laterolog curves from high readings to low ones and vice versa;

– points in the curves of spontaneous potential, induction logging and Δt, the reading of which are equal to the mean value of readings against the middle of layers and enclosing rocks;

– points in the curves of radioactive types of logging (gamma-ray logging, neutron gamma-ray logging, gamma-gamma logging and other) corresponding to the beginning of steep rise at the transition (upward movement) to the bed with high readings and beginning of sudden fall at the transition to the bed with low readings. The boundaries of beads of small thickness are determined only by micro-logging sonde and multisonde laterolog curves.

True resistivity is determined by using electric methods (laterologging, lateral logging, induction logging, micro lateral logging and other).

The true values of geophysical parameters such as $A_{\text{пс}}$, $\Delta I\gamma$, $\Delta I_{n\gamma}$, and Δt are determined by calculating the measured values of these parameters against the beds under interpretation and further adjustment by well diameter, clay coating thickness, formation liquid properties, enclosing rocks and delayed action of measurement circuits.

Then, lithilogical layering of well sections and identifying reservoirs is conducted under the above rules.

Porosity values are determined by data of various loggings (electric logging, acoustic logging, neutron logging and gamma-gamma logging) in accordance with the rules described in Section 8.3. Clay content is, mainly, determined by curves of spontaneous potential and gamma-ray logging.

The reservoirs, which were identified in the section, are subdivided into productive reservoirs (oil-bearing, oil and gas bearing and gas-bearing formations) and non-productive reservoirs (water-bearing), i.e. formation content is determined. Well logging data provides only predictive estimate of formation content, and based on which the formation are recommended to test. The true evaluation of formation content is obtained by formation testing. Operational interpretation also determines the transition zone and position of gas-liquid contacts (GWC, GOC and WOC).

Operational interpretation of well logging data for sections with complex reservoirs differs from the above described operational interpretation only in data processing related to their geological interpretation.

Consolidated interpretation and calculation of oil and gas reserves. Consolidated interpretation is carried-out for particular productive formations at the final stage of oil and gas field exploration. In includes generalizing all geological, geophysical and test data obtained for the productive formations.

The objective of the consolidated interpretation is to determine comprehensive data for calculating oil and gas reserves of the field and preparing field development program. In order to calculate oil reserves in formation, it is necessary to know the below parameters:

– area $S_н$ of oil-saturated portion of reservoir;

– effective thickness h_{ef} of oil-saturated reservoir on each well and its mean value $h_{ef.m}$;

– porosity K_p and its mean value $K_{p.m}$ within the boundaries of the effective thickness;

– oil saturation K_o and its mean value $K_{o.m}$;

– density σ_o of oil under standard conditions (pressure 0.1 MPa and temperature 273 °K);

– formation volume factor B_o, which is equal to ratio of oil volume in formation and standard conditions;

– probable value of oil recovery factor β_o from the formation and its mean value $\beta_{o.m}$. Oil recovery factor depends on many factors (reservoir recovery determined by remainder of $K_i - K_{ir}$ initial and residual oil saturation, coverage of formation with production wells and reservoir throughput rates), that is why the probable value is used in calculating based on the experience in development of similar reservoirs.

Using the above parameters, in-place oil reserves are determined

$$Q_{\text{in-place}} = (\sigma_o / B_o)\cdot(S_o \cdot h_{\text{ef.m}} \cdot K_{\text{p.m}} \cdot K_{\text{o.m}})$$

and recoverable reserves

$$Q_{\text{recov.}} = (\sigma_o / B_o)\cdot(S_o \cdot h_{\text{ef.m}} \cdot K_{\text{p.m}} \cdot K_{\text{n.m}} \cdot \beta_o)\ .$$

In-place oil reserves are calculated by formula

$$V_{\text{in-place}} = S_g \cdot h_{\text{ef.m}} \cdot K_{\text{p.m}} \cdot K_{\text{g.m}} \cdot \alpha_t\,(PZ_g - P_c \cdot Z_{\text{g.c}}),$$

where S_g is gas-bearing portion of the reservoir; $h_{\text{ef.m}}$, $K_{\text{p.m}}$, and $K_{\text{g.m}}$ are mean values of effective thickness, porosity and gas-saturation of reservoir within the gas-bearing portion; α_t=293/T is adjustment for reducing gas volume from the formation temperature T (в °K) to temperature 293 °K; P and P_f – formation pressure at the initial and final periods of development; and Z_g и $Z_{\text{g.c}}$ are gas compressibility factors at the initial and final period of development.

Recoverable reserves are determined by multiplying in-place reserves and gas recovery factor β_g that is ranged from 0.8 to 0.99 depending on the lithological composition and structure of the reservoir pores, and formation. Gas recovery factor is maximal in high porous and highly permeable formations; and it is increased if formation pressure is increased.

The majority of parameters required for calculating reserves is determined using geophysical data (h_{ef}, K_p, K_o, and K_g) or by well logging data and test data (position of contacts between fluids, structural mapping for determining S_o and S_g). The rest parameters (σ_o, B_o, P, P_c, Z_g, and $Z_{\text{g.c}}$) are determined by well testing and laboratory analysis of oil and gas samples.

Values of h_{ef}, K_p, and K_{og} and positions of gas-liquid contacts are determined by using the same procedures as were used earlier for operational interpretation. The only difference is in degree of substantiation of the parameters to be determined. Unlike operational interpretation, during which it is allowed using approximate relationships between the reservoir parameters and their geophysical characteristics, for consolidated interpretation each parameter must be proved by core analysis, formation testing and special studies performed in relation to the given reservoir.

2. INTEGRAL INTERPRETATION OF WELL LOGGING DATA

2.1. General Information about Integral Interpretation of Well Logging Data

On the basis of the complex, i.e. qualitative and quantitative, well logging data interpretation the following tasks at the oil and gas field prospecting, exploration and development phases are solved: discovery and delineation of filed, field geological structure study, identification and exploration of reservoirs in pay zones, determination of the main parameters of reservoirs required for reserves calculation and field development program preparing, and oil and gas filed development monitoring.

The integrated interpretation is preceded by qualitative processing and quantitative interpretation with determining geophysical parameters using particular logging records.

The integrated interpretation of well logging data for each individual well is phased as follows:

1) lithological layering of well section with preparing a preliminary lithological column;

2) identifying reservoirs, evaluating reservoir content with preparing recommendations on testing the zones of interest;

3) determining effective thickness of productive reservoirs and water-oil and gas-liquid contacts; and

4) determining porosity / oil saturation factors.

The general geological data about the job area, data obtained during drilling, drill-stem test and wireline test data, rock sample data taken during drilling and side-wall coring gun are used for solving the above tasks.

Correlation of well sections by geophysical data; mapping on the basis of the correlation: structural maps, isopachous maps, oil and gas content maps per each development target; and detailed mapping of reservoir properties variation for development target, should be carried-out for calculating reserves.

2.2. Identification of Oil-and-Gas Bearing Reservoirs and Determination of The Reservoir Effective Thickness and Fluid Content

Identification of reservoirs and determination of their parameters is performed after lithological layering of well section.

Reservoir rocks are capable to enclose oil and gas and deliver it during development. They are the main targets of well logging during prospecting, exploration and production well drilling. The reservoirs are characterized by composition of mineral rock matrix (lithological composition), storage (porosity) and deliverability (permeability) properties and pore space morphology. In natural conditions, sand, siltstone and carbonate deposits most commonly serves as reservoir.

Identification of the productive reservoir consists of two operations: direct identification of reservoir with determining its boundaries and evaluating fluid content. Identification of reservoirs using well logs is promoted by a number of objective features, the main of which are: drilling mud filtrate penetration in permeable formation and presence of typical readings in various geophysical curves. In the general case, reservoirs are identified in section using geological-geophysical surveys of well sections, including coring and field study of well drive mechanism. Let us discuss the features of reservoir identification for various lithologic complexes.

Identification of sandstone-clay reservoirs. Sand and siltstone (poorly cemented clean) reservoirs are most reliably identified in the terrigenous section using combination of spontaneous potential, gamma-ray logging curve and caliper log curves.

Against clean reservoirs the following is observed: the highest deviation SP (spontaneous potential) curve from the clay line; minimal activity in the gamma-ray logging curve and formation of clay coating, and reduction of well diameter in the caliper log curve.

For lithological identification of poor-porous sandstone-siltstone rocks and poorly cemented reservoirs, additional logging is conducted, the most effective of which are micrologging (ML), neutron gamma-ray logging (NGL), gamma-gamma logging (GGL) and acoustic logging (AL).

Presence of argillaceous material in rock (in the form of inclusions, interlayers or dispersed within the formation) affect its resistivity, amplitude of SP (spontaneous potential) curve deviation, readings of gamma-ray logging, neutron gamma-ray logging, acoustic logging and other well logging methods. That is why it is customary to identify the sand reservoirs contained considerable amount of argillaceous material as separate group – clay reservoirs.

Amplitude of SP (spontaneous potential) curve in clay reservoirs in much less than that against clean sand formations. In some cases, a clay reservoir can be characterized by interbedding of sand and silt and clay interlayers. If thickness of interstratified interlayers reaches one-two well diameters, then, in addition to the SP amplitude decreasing, local minimums and maximums against some layers are reduced. Clay reservoirs, especially with high relative clay content, are not always identified with confidence in the well logs.

Identification of carbonate reservoirs. Depending on the structure of the pore space and permeability conditions, carbonate reservoirs can be conditionally subdivided into two types: granular (with intergranular porosity) reservoirs and fractured reservoirs (fractured, cavernous and combined).

Geophysical characteristic of the granular carbonate reservoirs is the same as geophysical characteristic of sand reservoirs. In this case, reservoirs can be identified by layering the section in clay and clean rocks and identifying highly porous varieties (fig. 4).
Generally, layering of carbonate section, which is presented by thin interlaying of compact and porous varieties, is complicated. The most reliable data, as it is for terrigenous section) can be obtained by micrologging.

Fractured and cavernous-fractured reservoirs are widely occurred among carbonate rocks. In the logging curves they does not have clearly expressed characteristics, and identifying them in well section by conventional well logging is rather difficult.

Only in some areas the fractured rocks can be identified by frequent distinguishing features in well logging curves. They can be identified by readings of micrologging of particular fractures and irregularities of caliper log curve. Under favorable conditions (clean and non-gas-bearing rocks) presence of fractured reservoirs can be detected by comparing and quantitative analysis of electric logging data, neutron logging and core analysis data. Fractured reservoirs can be also identified by acoustic amplitude logging data, method of combining normalized laterologging curve and neutron gamma-ray logging curve, and double mud method. The typical features of fractured-cavernous reservoir are intensive absorbing drilling mud and sudden increase of penetration rate while drilling.

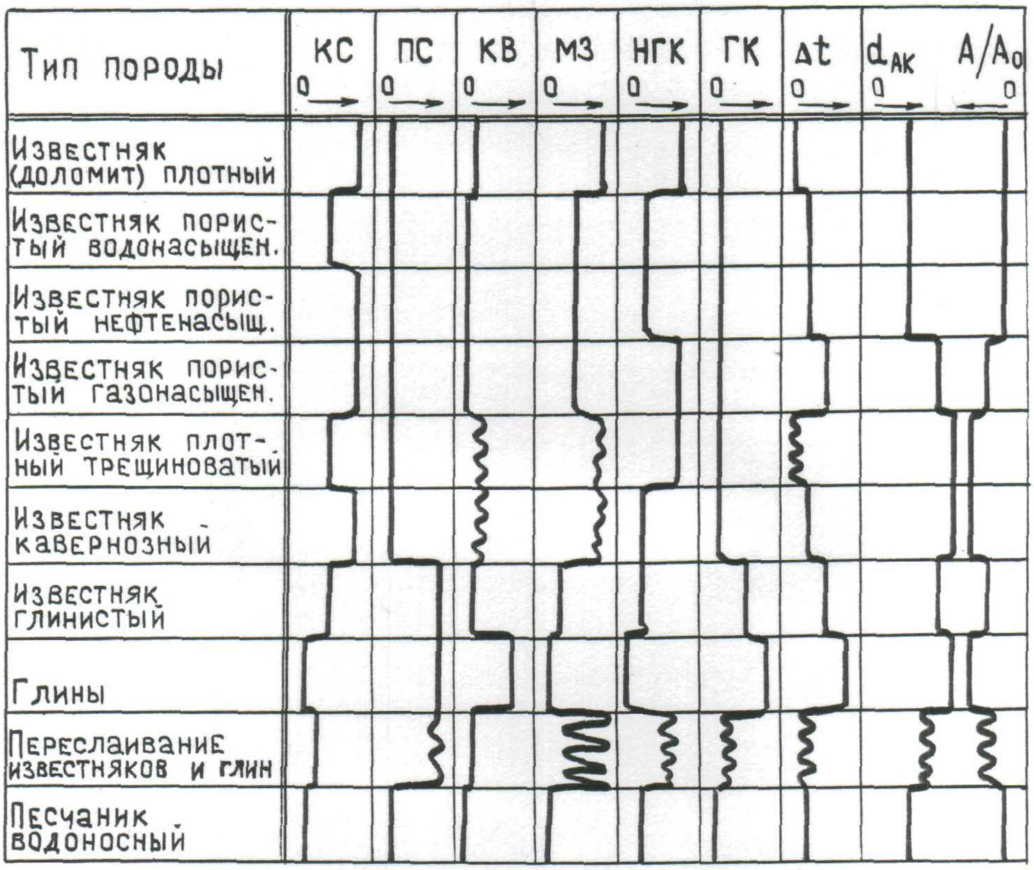


Fig. 4. Diagrammatic View of Logging Curves against
Carbonate Rock Series

Reservoir fluid content evaluation. For evaluating reservoir fluid content, the reservoirs are subdivided into productive reservoirs, from which commercial inflow of oil and gas is obtained during test, and water-bearing reservoirs, which extract only pure water, water with oil film or gas features. It is decided whether it is advisable to run tubing in open hole and test commercial oil-and-gas bearing targets.

The base for evaluating reservoir fluid content is determination of rock resistivity ρ_r in its invariant part and comparison of the obtained ρ_r data, calculated values of saturation parameter P_{fc} with critical values of ρ_r* и $P_н$*, which characterize for the reservoirs the boundary between commercially productive and non-commercial reservoirs. In the simplest case, resistivity of water-bearing horizons is low, and resistivity of oil-bearing horizons is high. Reliable determination of ρ_r using lateral logging sounding records is possible only for fair thick and homogenous targets. If there are compact highly resistant interlayers in the reservoir rock, it is necessary to determine ρ_r by ρ_{ef} using induction logs, and shielded probes. The favorable condition for determining ρ_r is presence of not deep penetration of drilling mud into formation.

When comparing the normalized by porosity resistivity curves of shielded probes or acoustic logging with neutron gamma-ray logging or Δt (acoustic logging), productive reservoirs are identified by increase of ρ_{ef} readings in the curve if compared to the base porosity under coincidence of the being comparable curves in water-bearing reservoirs and compact rocks.
For the major part of the productive reservoirs it is typical that sonde readings with medium and large radius of logging are lowering in the repeated measurement curves. By logging-testing-logging method, the productive reservoir can be identified by considerable increase of ρ_{ef} readings in the shielded probe or induction logging curves recorded after testing in the given interval (fig. 5).

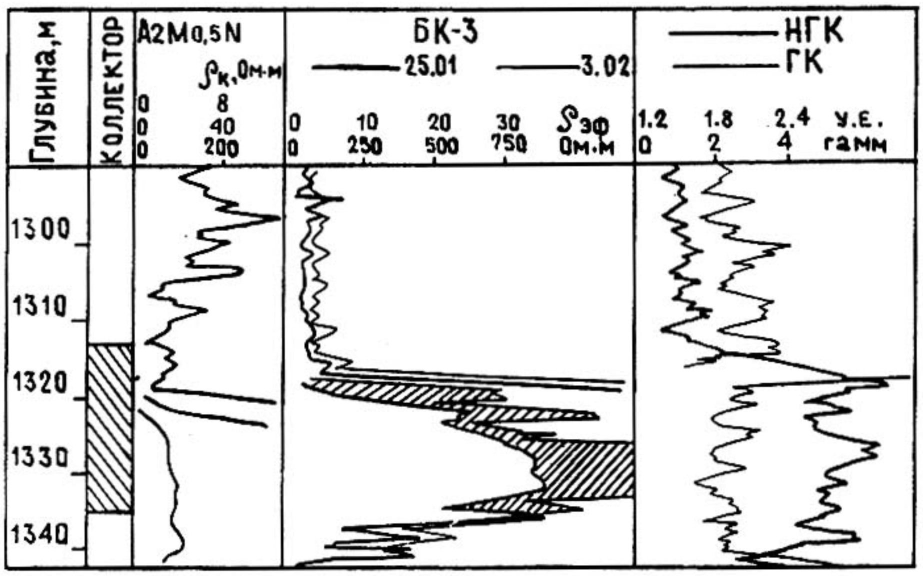


Fig. 5. Identification of Reservoir in Carbonate Rock by
Logging-Testing-Logging Method

Very promising are cased well survey by neutron logging and low frequency acoustic logging aimed at identifying the productive reservoirs based on the surveying of the reservoir penetration zone layering.
If determining the fluid content of particular reservoirs in well section by well logs fails, then direct methods (gasometry, drill-stem test and wireline test) are used for determining the reservoir productivity.
Determination of the effective thickness of productive reservoirs. Value of h_{ef} in homogenous reservoir bed is determined as thickness of this bed whose boundaries have been identified using well logs on the basis of the above rules.
For determining h_{ef} in heterogeneous reservoir bed that contains non-reservoir interlayers, it is necessary to exclude thickness of such non-reservoir interlayers from the total thickness. Non-reservoirs are identified using micrologging data considering the entire well logs.

2.3. Identification of Water-Oil and Gas-Liquid Contacts

If the reservoir bed is saturated with oil or gas only in the top part, which can be observed in water-oil zone of "water floating" oil accumulation, the position of water-oil contact (WOC) for oil-bearing reservoir and gas-liquid contact (GLC) for gas-bearing reservoir can be identified by electric logging data. Oil-water contact is not sharp in the natural rocks. Transition from the oil-and-gas bearing portion to the water-bearing portion of formation is gradual in some interval that is termed Transition Zone. The thickness of the transition zone, depending on the geological nature of the bed and physico-chemical properties of oil and formation water, ranges from one to tens of meters; the higher permeability of the formation and the less difference in oil and water density, the lower, under the other similar conditions, the transition zone thickness (Fig. 6).

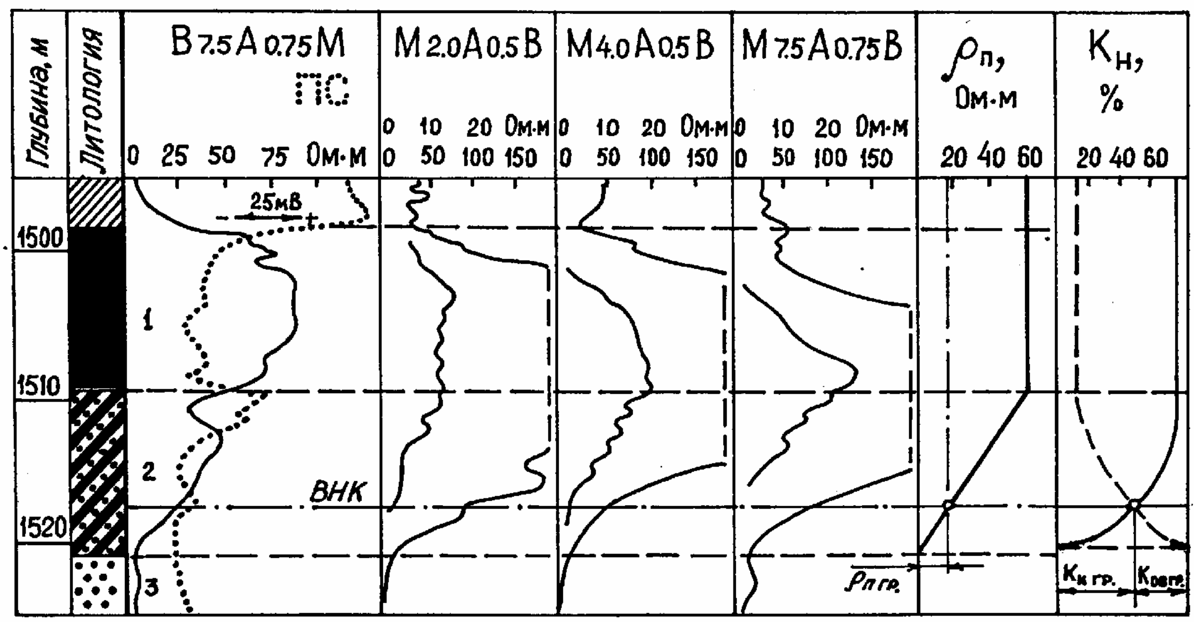


Fig. 6. Identification of WOC
under the Presence of Irreducible Oil Saturation Zone (*1*),
Transition Zone (*2*) and Water-Bearing Reservoir (*3*)

For reference WOC (GLC) is taken a level of the transition zone at which its resistivity corresponds to the critical resistivity. For the majority of fields, this level corresponds to the point located 1–1.5 m above the bottom boundary of the transition zone.

2.4. Determination of Reservoir Porosity and Oil Saturation by Well Logging Data

Determination of porosity of terrigenous rocks. Nowadays, the porosity factor K_p is mainly determined using the below geophysical parameters:

– resistivity;
– invasion zone resistivity;
– absolute values of SP (spontaneous potential) abnormality;
– relative values of SP abnormality (A_{sp}), and
– gamma-ray logging readings.

In some cases, porosity can be determined by elastic wave propagation velocity (acoustic logging), by density gamma-ray logging, by neutron density (thermal neutron-neutron logging), by readings of artificial electromagnetic field (по показаниям искусственного электромагнитного поля (nuclear magnetism logging) and other, as these well logging methods are usually conducted in single wells of the fields under survey.

Application of the first two methods is constrained as relationship between porosity parameter P_p (relative resistivity) and porosity factor K_p are obtained by experimental surveying in terrigenous deposits with high clay material content. Value P_p greatly depends on mineralization of formation water, which causes considerable errors in determining K_p .
Out of two methods of K_p determination using the spontaneous potential curves, the preference should be given to the method of relative abnormalities of spontaneous potential (SP) (A_{sp}), because when the method of absolute values of SP is used, it is impossible to prevent inaccuracy in establishing the curve scale of the SP absolute values and in drilling mud resistivity measuring.

Determination of porosity using gamma-ray logging is based on the correlation between the porosity of terrigenous rocks and clay content $K_p=f(C_{cl})$ on the one hand, and clay content and natural radioactivity of rocks $\Delta I\gamma = f(C_{cl})$ on the other hand. In Perm Prikamye we widely use the method of determination of K_p by gamma-ray logging readings, which we are going to discuss below in detail.

Determination of K_p using gamma-ray logging. To avoid impact of neutron source in the neutron gamma-ray logging channel, design features of measuring instrumentation, as well as background and well conditions on gamma-ray logging readings , the relative value of gamma-activity of reservoir beds (double gamma-ray index $\Delta J\gamma$) is used. Compact lime stone of Tournai stage with minimal values of gamma-ray logging ($J_{\gamma\ min}$) and Tula stage with maximal values gamma-ray logging ($J_{\gamma\ max}$) are used as marker bed (fig. 7).

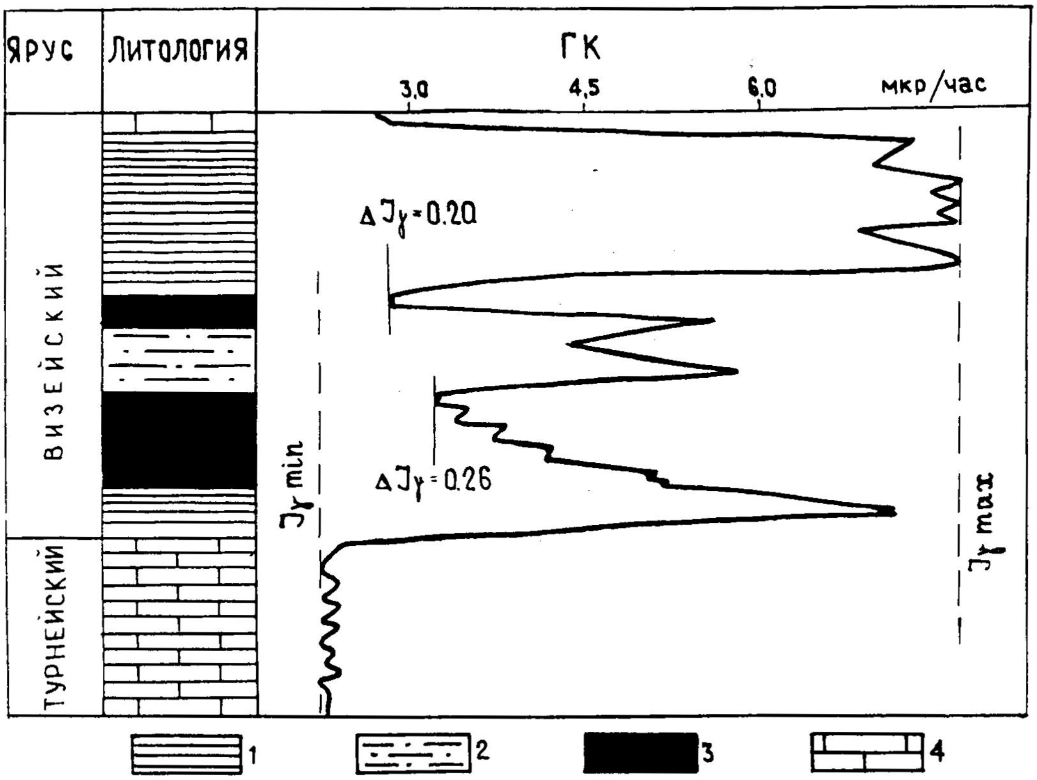


Fig.7. Calculation of ΔJγ at Gamma-Ray Log:
1 – clay, *2* – siltstone, *3* – reservoir, *4* – limestone

Parameter $\Delta J\gamma$ is determined by formula:

$$\Delta J\gamma = \frac{(J_{\gamma\ пл} - J_{\gamma\ min}) \pm \delta J\gamma}{J_{\gamma\ max} - J_{\gamma\ min}},$$

where $J_{\gamma\ bed}$, $J_{\gamma\ max}$, $J_{\gamma\ min}$ are values of the natural radiation intensity according to gamma-ray logging, respectively, against reservoir bed, clay, and compact limestone; $\delta J\gamma$ is adjustment that considers changes of the recorded gamma-radiation intensity depending on the instrument movement speed V, time constant of an integrated cell Δt and bed thickness h. The adjustments are added for beds of small thickness by formula $h \geq 4Vt / 3600$.

For determining K_p by gamma-ray logging for particular field, relationship $\Delta J\gamma = f(K_p)$ is used.

Determination of carbonate rock porosity. Porosity of reservoir beds in carbonate deposits mostly often is determined by neutron gamma-ray logging records using two marker horizons in thermal-decay-time logging curve of volumetric water content *W*. In the first case, neutron gamma-ray logging data against compact carbonate rocks (impermeable limestone and dolomites) with intensity $J_{n\gamma\ \mathrm{dense}}$ is taken as marker horizon, for instance, against limestones of Bashkir and Tournai stages, and readings of neutron gamma-ray logging against clay rocks with intensity $J_{n\gamma\ \mathrm{clay}}$, for instance, against clay rocks of Vereian and Tula horizons. As a rule, porosity is determined for permeable interlayers ($J_{n\gamma\ \mathrm{bed}}$ readings) of $h = 1$ m, for which it is not required to add drift adjustments for calculating gamma-ray index $\Delta J_{n\gamma}$. In principle, for beds of small thickness ($h \le 3V/3600$) it is possible to add shift adjustment.

$\Delta J_{n\gamma}$ is determined by formula:

$$\Delta J_{n\gamma} = (J_{n\gamma\ \mathrm{bed}} - J_{n\gamma\ \mathrm{clay}})/(J_{n\gamma\ \mathrm{dense}} - J_{n\gamma\ \mathrm{clay}}).$$

All these parameters are adjusted for clay content using gamma-ray logging curve:

$$J_{n\gamma\ \mathrm{bed}} = J_{n\gamma\ \mathrm{bed}} - k\, J_{\gamma\ \mathrm{bed}};\ J_{n\gamma\ \mathrm{dense}} = J_{n\gamma\ \max} - k\, J_{\gamma\ \min};\ J_{n\gamma\ \mathrm{clay}} = J_{n\gamma\ \min} - k\, J_{\gamma\ \max},$$

where $J_{n\gamma\ \mathrm{bed}}$ and $J_{\gamma\ \mathrm{bed}}$ are current readings of neutron gamma-ray logging and gamma-ray logging against the being interpreted reservoir bed, $J_{n\gamma\ \max}$ are maximal readings of neutron gamma-ray logging against dense rocks; $J_{n\gamma\ \min}$ are minimal readings of neutron gamma-ray logging against clays; $J_{\gamma\ \max}$ are maximal readings of gamma-ray logging against clays; $J_{\gamma\ \min}$ are minimal readings of gamma-ray logging against rocks, and *k* is instrumental factor.

If radiologging equipment with tube counters (BC) $k = 0{,}625$, with scintillation counters $k = 0{,}3$ (DRST-1equipment) or $k = 0{,}2$ (DRST-3 equipment) is used,

The complete formula for $\Delta J_{n\gamma}$ determination (with adjustments) is as follows:

$$\Delta J_{n\gamma} = \frac{(J_{n\gamma\ \text{пл}} - kJ_{\gamma\ \text{пл}}) - (J_{n\gamma\ \min} - kJ_{\gamma\ \max})}{(J_{n\gamma\ \max} - kJ_{\gamma\ \min}) - (J_{n\gamma\ \min} - kJ_{\gamma\ \max})}.$$

All values of $J_{n\gamma}$ and J_{γ} are converted into count per minute according to conversion factor given for each well. For operational calculation of $\Delta J_{n\gamma}$ by the above formula, the $J_{\gamma\ \mathrm{bed}}$ readings are usually replaced with the background values $J_{\gamma\ \min}$. For determining K_{p} using neutron gamma-ray logging, relationship $\Delta J_{n\gamma} = f(K_{\text{п}})$ created for the given field is used.

For determining K_p using thermal-decay-time logging records, the instructional guidelines on determination of porosity by radiologging data obtained by RKS-3 equipment should be observed. In doing so, water-content curve *W* but not thermal-decay-time logging curve should be interpreted.

Determination of reservoir oil saturation. Determination of oil saturation factor K_o by well logging data both for terrigenous reservoir beds and for carbonate reservoir beds, most commonly is performed using electric logging data as follows:
Value of porosity parameter is determined using value of porosity of oil-saturated interlayer by $P_p = f(K_p)$ relationship obtained in oil stratum physics laboratory from coring data (fig. 8). The, using the known value of resistivity of formation water ρ_w resistivity of interlayer ρ_{wil} is calculated provided that it is 100% saturated with water.: $\rho_w = P_p \cdot \rho_p$, where ρ_w is resistivity of formation water that is equal to 0.045 ohm·m for the Perm Prikamye.

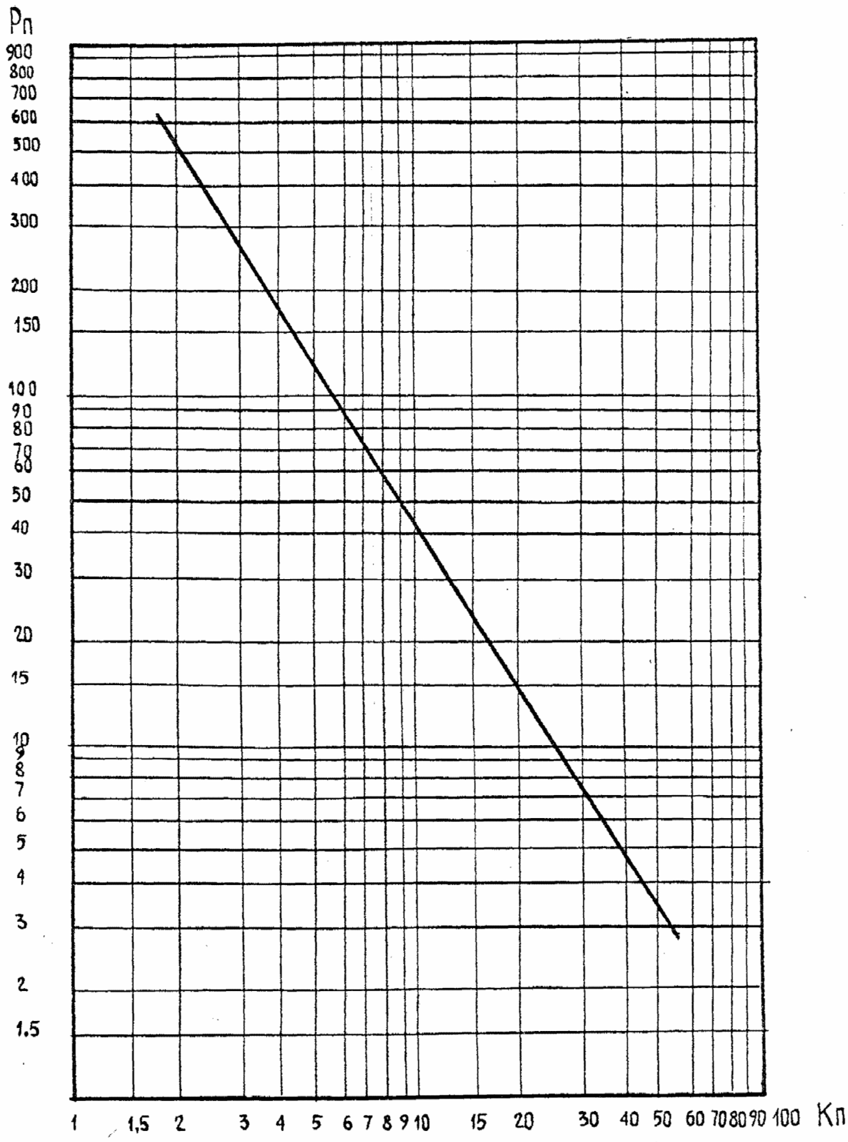


Fig. 8. $P_p = f(K_p)$ Relationship

Based on resistivity of oil-saturated interlayer ρ_{oil} (determined by laterologging or lateral logging resistivity curves) and calculated value of ρ_{fw} , parameter of the given interlayer saturation is calculated: $P_o = \rho_{fo} / \rho_{fw}$.
Using $P_o = f(K_{ow})$ obtained in oil stratum physics laboratory (fig. 9), oil saturation factor $K_o = 1–K_{ow}$ of permeable bed is calculated.

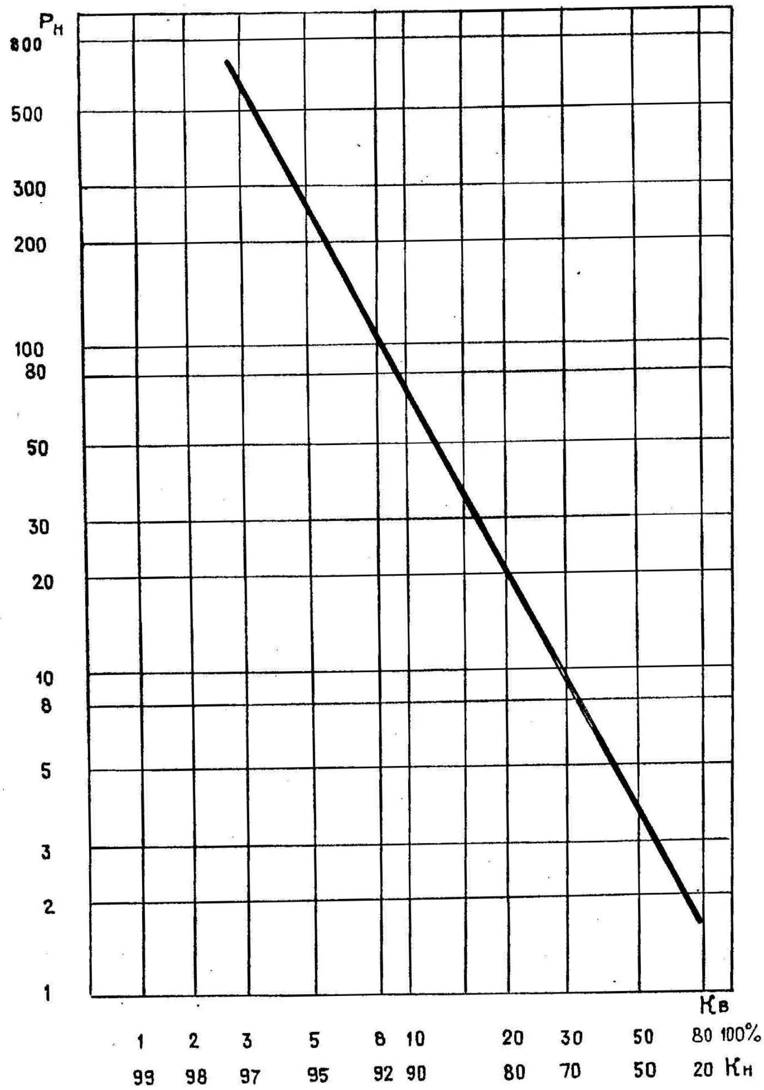


Fig. 9. $P_o = f(K_{ow})$ Relationship

Scope of data obtained due to well logging is highly labor and time consumptive. To accelerate well logging data interpretation and increase accuracy of data processing, data processing machines, personal computers and other auxiliary devices are widely used nowadays. Of the most significant is automatic well logging data processing for calculating oil and gas reserves, and immediate issuing of interpretation results at the phase of oil field development.

CONCLUSION

Geophysical well surveying (GIS) is carried-out in the majority of wells, and is an integral part of exploration, drilling and production operations performed during prospecting, exploration and development of oil and gas fields. In order to obtain comprehensive information about geological structure of subsurface resources, the integrated interpretation of well logging data shall cover sections of all wells and each of wells from wellhead to bottom-hole.

This document provides a description of high importance of well logging data for solving many geological tasks, and, in particular, in lithologic-stratigraphic layering of well sections and crosswell correlation using petrophysical and field geological data. Geophysical methods are also very effective for reservoir modeling, quantitative assessment of productive reservoir parameters and obtaining petrophysical functions for calculating hydrocarbon reserves, and for monitoring of accumulation conditions while development and technical state of wells.

Interpretation of well logging data is a creative process, depth of which depends on scope of available actual data of the geological target under surveying. The detailed analysis of the results of well logging data processing makes it possible to find out lithofacies changeability of deposits, conditions of sedimentation and formation of positive structures. Implementation of data processing machines and personal computers makes it possible to use automatic well logging data processing systems.

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Part 2

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OIL AND GAS GEOLOGY

Часть 3
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В пособии излагаются основы полевой геофизики, а также использование вероятностных оценок при экономическом обосновании инвестиционных проектов поисковых работ на нефть и газ.

Пособие рассчитано на специалистов Республики Ирак, обучающихся в Пермском государственном техническом университете по дополнительной образовательной программе профессиональной переподготовки специалистов «Руководитель нефтегазового производства».

Field geophysics. Probabilistic estimates used to substantiate investments in hydrocarbon exploration.

The textbook is destined for the Iraq Republic specialists studying on the extra educational program of professional retraining «Oil and gas production manager» at Perm State Technical University.

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Course of lectures in

FIELD GEOPHYSICS*

Topic 1. General Information about Field Geophysics

1.1. The Place of Geophysics in the System of Geosciences. Field Geophysics: the Object and Subject of the Research, Tasks and Objectives

Geophysics is the science studying physical phenomena on the Earth. Geophysics is subdivided into different directions. One of them is the lithosphere geophysics. It is subdivided into general and applied geophysics. The latter includes field geophysics. Field geophysics uses available methods of physical research to study the structure of the Earth interior (down to the depths of about a hundred kilometers). The object of field geophysics is the sources (rocks in the conditions of natural occurrences) of the geophysical fields under consideration, and the subject of the science is the geophysical fields measured instrumentally. The theory of field geophysics has the physico-mathematical basis and is based on solving forward and inverse geophysical problems.

A forward problem is determination of the elements of the studied subject from the known location and geometric and physical parameters of the studied object. It has the single and only solution. An inverse problem is determination of the parameters elements of the studied object from the known (measured) elements of the subject of the investigation. An inverse problem has many solutions. When interpreting the results of processing geophysical measurements, researchers use mathematical simulations, cutting-edge mathematical achievements, and the highest computer automation level. The methodology and equipment of field geophysics is based on using physico-technical measurement means. The measurements are made in air, on the ground, and in water basins. The highest requirements are set for the geophysical equipment. The topogeodetic support to the works is based on using of the positioning receivers operating simultaneously with the satellites of the GPS (USA) and GLONASS (Russia) systems. Application of modern equipment implies a huge volume of numerical data to be processed with the use of modern software means. The objectives of field geophysics are to develop and improve the measurement methodologies, theories of processing and interpreting the data of the geophysical methods used to study geological profiles in the process of solving practical tasks.

The main task of field geophysics is to prospect and explore mineral deposits. Along with that, it solves the problems of engineering geology, hydrogeology,

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glaciology, general geology, ecology, etc. As the equipment, field work methodology, and mathematical software are updated, their list widens continuously. The methods of field geophysics are used as advance and supporting works in prospecting and exploring mineral deposits at virtually all stages in the process of geological studies of the Earth interior (fig. 1.1).

No.	**Phase, scale**	**No.**	**Phase; scale**
I	Regional, 1:1000000–1:200000	1	Oil and gas occurrence forecast; 1:1000000–1:500000
		2	Oil and gas accumulation zone estimation; 1:200000
II	Prospecting, 1:50000-10000	3	Target (play) identification and preparation for prospecting drilling; 1:50000
		4	Field (pool) search; 1:10000
III	Exploration	5	Field (pool) estimation
		6	Preparation of fields (pools) for development

Fig. 1.1. Stages of the Earth interior utilization in oil and gas works

1.2. Physical fields, properties and parameters of the Earth rocks

The principal possibility to use the methods of field geophysics is based on differentiation of physical properties of the rocks, which are expressed in peculiarities of spatial distribution of geophysical fields, which are subdivided into natural and artificial. Each physical field is determined by its parameters (fig. 1.2).

Geophysical fields and their parameters depend on physical properties of the rocks and their spatial distribution. Physical properties of the rocks may change both within narrow limits (density σ) and within very wide limits (electric resistivity ρ). In practice, there are situations when one rock may be characterized by different values of physical properties, and when different rocks may be characterized by the same physical properties. This leads to ambiguity of solutions for inverse geophysical problems.

Physical field	**Parameter**	**Rock property**
Gravitational	Acceleration of gravity (g) and second derivatives of the potential (W_{zx}, W_{zy}, W_{xy}, W_{Δ})	Density (σ)
Magnetic	Full field vector (T), its elements (X, Y, Z, H, D and I)	Magnetic susceptibility (χ) and permeability (μ), remnant magnetization (J_r)
Electromagnetic	Vectors of the magnetic (H) and electric (E) components	Electric resistivity (ρ), polarizability (η), electrochemical activity (a), electric (ε) and magnetic (μ) permeability
Seismic	Amplitude (A), time (t), and velocity (V) of elastic waves	Density (σ), velocity (V), Poisson's ratio (v), Young's modulus of elasticity (E), Lame's elastic moduli (λ and μ)
Thermal	Distribution of temperatures (T) and the heat flow (q)	Heat conductivity factor (λ_T), heat absorption capacity (c), density (σ), thermal diffusivity (a)
Nuclear	Radiation intensity (I)	Radioactivity of radioactive nuclides and their density

Fig. 1.2. Physical fields and properties of rocks

1.3. Classification and general characteristics of geophysical methods

There are various applied (targeted) classifications of the field geophysics' methods. Taking into account stages and phases of geological studies of the Earth interior. e.g. in oil and field prospecting (fig. 1.1), they are subdivided into regional, prospecting, and exploration geophysics. In terms of the mineral, one distinguishes between oil-and-gas, metallic, non-metallic, and coal geophysics categorized under exploration geophysics. Sometimes, regional and oil-and-gas geophysics are combined as structural geophysics. One of the classifications widely used in field geophysics is shown in fig. 1.3).

Type of physical field	Name of the geophysical method
Gravitational	Gravimetric prospecting
Geomagnetic	Geomagnetic prospecting
Electromagnetic	Electromagnetic prospecting
Seismic	Seismic prospecting
Thermal	Geothermal prospecting
Radioactive	Radioactive prospecting

Fig. 1.3. Classification of geophysical methods by the type of the physical field

Siesmic survey is the most expensive (about 80 % of the total volume of the assigned funds) and the main method of oil-and-gas prospecting.

1.4. Principles of integration of geophysical methods

Geologic efficiency of each individual geophysical method is comparatively low. The necessity to integrate individual methods when solving practical tasks is mainly caused by theoretical incorrectness of solving inverse geophysical problems. To reduce this incorrectness, various ways are used: application of independent methods, use of the data obtained from parametric wells, improvement of the data reading accuracy, computer data processing, and method integration. Practice has shown the necessity of approaching the studies of the Earth interior systematically, which means necessity of intra-method and inter-method geophysical integration. The objective here is to select an integrated complex of the methods capable of providing an unambiguous solution for a set geologic problem within the required accuracy limits. In practice, various types of geophysical complexes are used: typical, rational, and technological ones.

The methodology of selecting the complexes must take into account the general rules for the works: selection of rational methods; proceeding from the general to the specific, from smaller scales to larger ones, from studying large areas to prospecting promising zones, from fast and less accurate methods to detailed developments; repetition of surveys using more accurate equipment and denser observation networks; advancing towards integrated computer processing of all the materials; proceeding from the qualitative geologic interpretation of the materials to the quantitative interpretation using petrophysical data. The main notions of the system approach to geophysical studies of the Earth interior can be reduced to the following principles: correlability, superposition, and physico-geological modeling.

Topic 2. Gravimetric Prospecting

Gravimetric prospecting is a geophysical method of studying the geologic profile for solution of geologic prospecting tasks, which is based on analyzing the gravitational field.

2.1. Gravitational field of the Earth, its elements and measurement methods

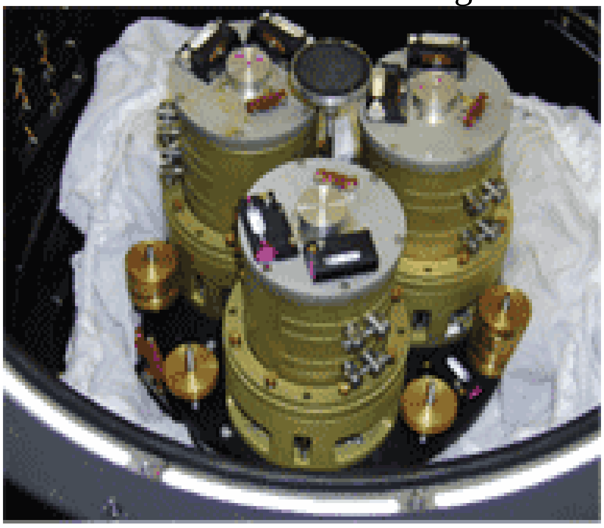
At each point, the gravitational field is characterized by the value of the acceleration of gravity g (m/s^2), which depends mainly on rock density σ (kg/m^3), and elevation H (m) of the observation point over the sea level. The force of gravity F_G is the resultant of two forces: the force of attraction F_{attr} and the centrifugal force F_c. In the SGS system, the unit of g is Gal equal to 1 cm/s^2. The gravimetic prospecting theory is based on Newton's law of gravitation: $F_{attr} = G\ mM/r^2$, where $G = 66.73 \cdot 10^{-12}$ m^3/kg·s^2, M and m are attracting and attracted masses, respectively, and r is the radius vector between their centers. At $m = 1$, the value of g is equal numerically to the intensity of the field: $GM/r^2 \approx g$. In practice, the centrifugal force F_c is neglected due to the insignificance of its influence. Therefore, the term "gravity" is traditionally used instead of the term "acceleration of gravity", for brevity. Measurements of gravity g can be absolute and relative. The methods of measuring g are subdivided into dynamic and static ones. In terms of the physical phenomenon used in the measurements, the dynamic methods are subdivided into pendulum, ballistic, and filament (string) ones.

2.2. Measured increments, normal values, reductions, and anomalies of the gravity. Abnormal rock density

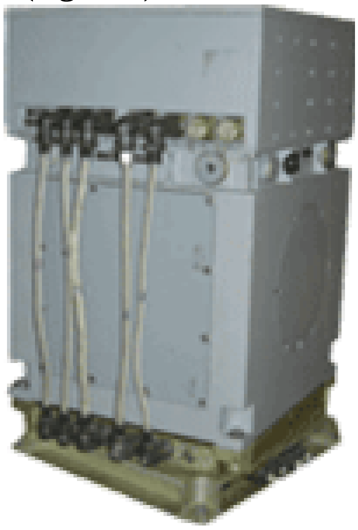
Observed gravity increments Δg_{obs} relate to the physical surface of the Earth, and the normal values γ_0, to the surface of the model approximating the shape of the Earth (geoid). Abnormal gravity values Δg are determined as the difference between them with allowance for the necessary reductions (corrections) aimed at matching the points of measurements Δg_{obs} and calculations γ_0 in space. Bouguer anomaly Δg_B is calculated by the formula $\Delta g_B = \Delta g_{NBL} + \frac{\partial \gamma_0}{\partial z} H - 2\pi G \sigma H + \delta g_{terr} - \gamma_0$. The second, third, and fourth terms of the right-hand part of the equation are corrections for the influence of the height H, of the rock layer between those points, and the relief of the terrain δg_{terr}. Following the instruction, anomalies Δg_B must be used when solving geoprospecting problems. Density σ of the majority of the rock-forming minerals ranges from 2.5 to 3.2 g/cm^3. Methods of determining rock density are subdivided into laboratory, well, and field methods. When solving inverse problems, a factor significant for gravimetic prospecting is abnormal density $\Delta\sigma$, i.e. the difference in the densities of the studied object and the medium that encloses it.

2.3. Equipment Used for Gravimetric Prospecting

For air-borne measurements (air-borne gravimetric prospecting), Russian developers have created a set of air-borne gravimetric equipment (fig. 2.1).



a



b

Fig. 2.1. Airborne gravimeters: 3 string gravimeters Graviton M (a) and AGK-1M (b) (State Scientific and Manufacturing Enterprise "Aerogeofizika")

The error of measuring gravity with these devices is 0.2–0.3 mGal. Experiments onboard IL-14 and AN-30 airplanes made it possible to measure fields with accuracy up to ±6.00 mGal. Experiments using helicopters yielded the accuracy of about ±1.00 mGal. In marine works, modern Russian equipment is also used (fig. 2.2).

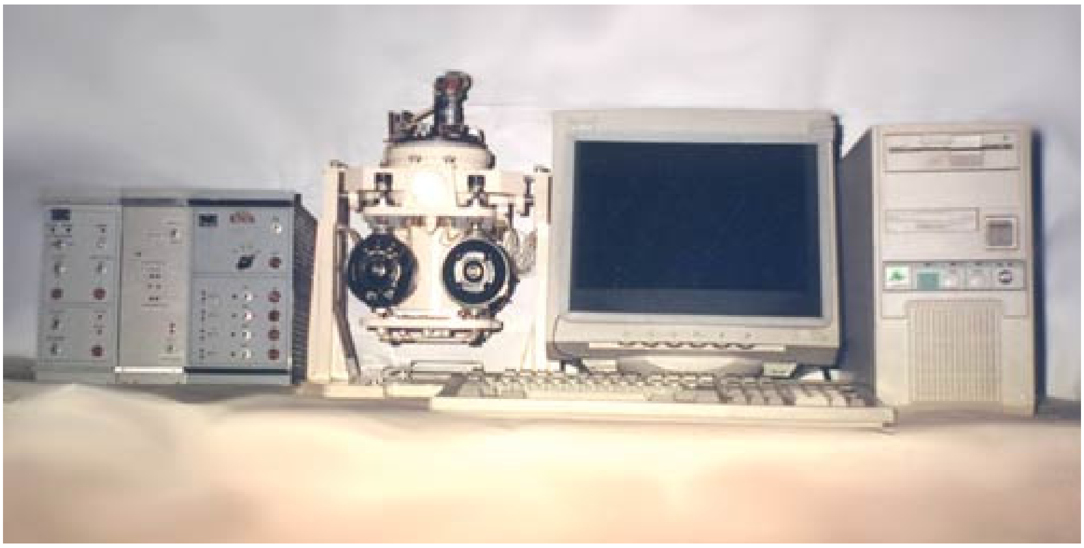
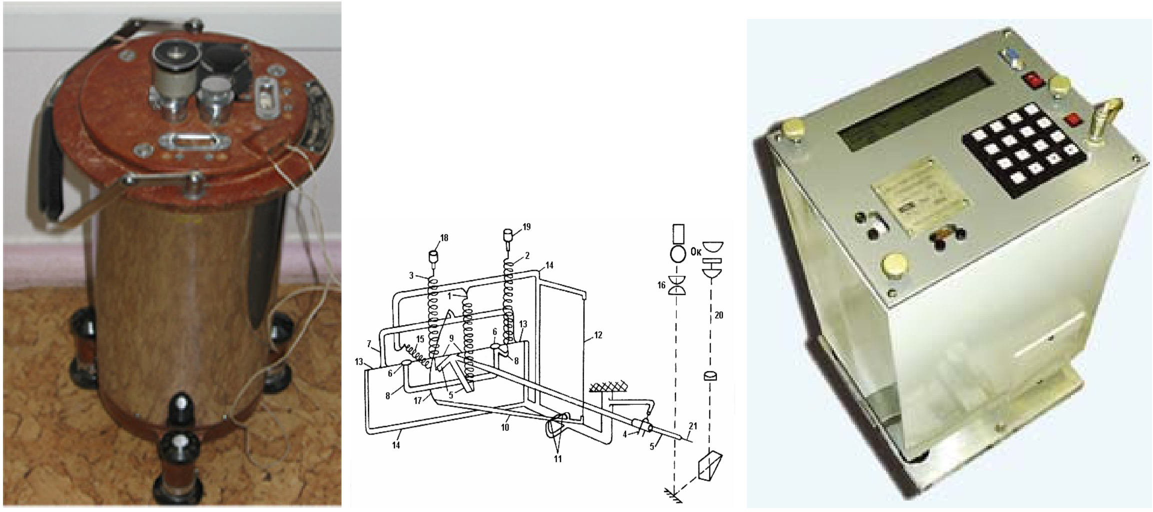


Fig. 2.2. Marine onboard gravimetric complex GMN-KM (OJSC "Neftekip")

Remotely operated ocean floor gravimeters have also been developed. The gravimeters used abroad are mainly of two types: GS-12 and GSS-3 produced by Askania (Germany) or those produced by LaCoste-Romberg (USA). They have

approximately the same measurement accuracy: 0.50–1.50 *mGal*.
In modern ground-based gravimetric practice, relative measurements of Δg are performed using mechanical spring gravimeters (static gravimeters), in which the equilibrium position of the “test mass” is observed, which is affected by the force of gravity and the reference elastic force of springs (fig. 2.3).



a b c

Fig. 2.3. External view and diagram (b) of the elastic quartz systems GNU-KV and GNU-KVK (c) (OJSC “Neftekip”)

Their measurement accuracy is centesimals of *mGals*, and, when used with the gravimeter CG-5 AutoGrav “Scintrex” (Canada), millesimals of mGals. This helps using gravimetric prospecting to search for oil and gas.

2.4. Gravimetric Surveys. Data Processing, Interpretation and Representation

A gravimetric survey is a combination of gravimetric observations of Δg and determination of their coordinates. The ground-based survey is the most wide-spread in terms of the volume of the gravimetric works. The conditions required according to the instruction about field in-gravimetric works are: a) establishment of the field network of reference points of the 3rd class; and b) correlation of the 3rd-class reference networks to the points of the state reference networks of the 1st or 2nd class. When establishing field reference networks, measurement methods and methodologies providing higher accuracy are used. The obtained data are processed, catalogued, and further, interpreted.
Quality interpretation starts with mapping of isonamaly curves, i.e. the lines of equal value of Δg (fig. 2.4).

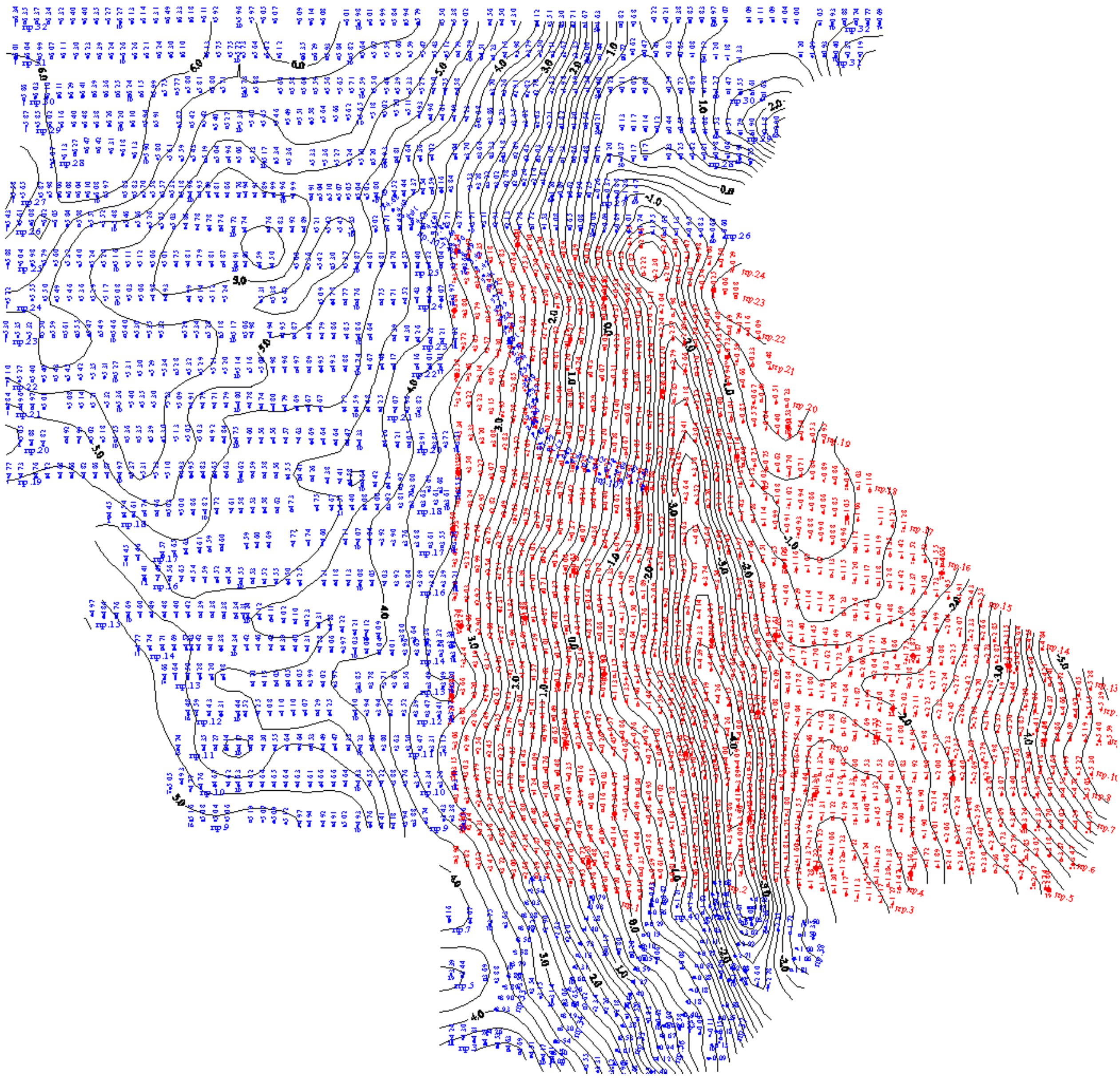


Fig. 2.4. Map of gravity anomalies M 1:50000.
Compartment of a deposit of potassium salts (GI, Ural Div. of RAS)

Maps can be plotted for various transformations of the field, e.g. for horizontal gravity derivatives or cutoffs of the transformants of the initial field (fig. 2.5). At this stage, the shape of the anomalies, their strikes and amplitudes are revealed. With account for the a priori information, the connection between gravity anomalies with the geologic structure is found. Regional anomalies are identified, which are associated with the structure of the Earth core, regional formations, and tectonic zones. Subtracting the regional background from the observed field, one obtains local anomalies Δg (fig. 2.6).

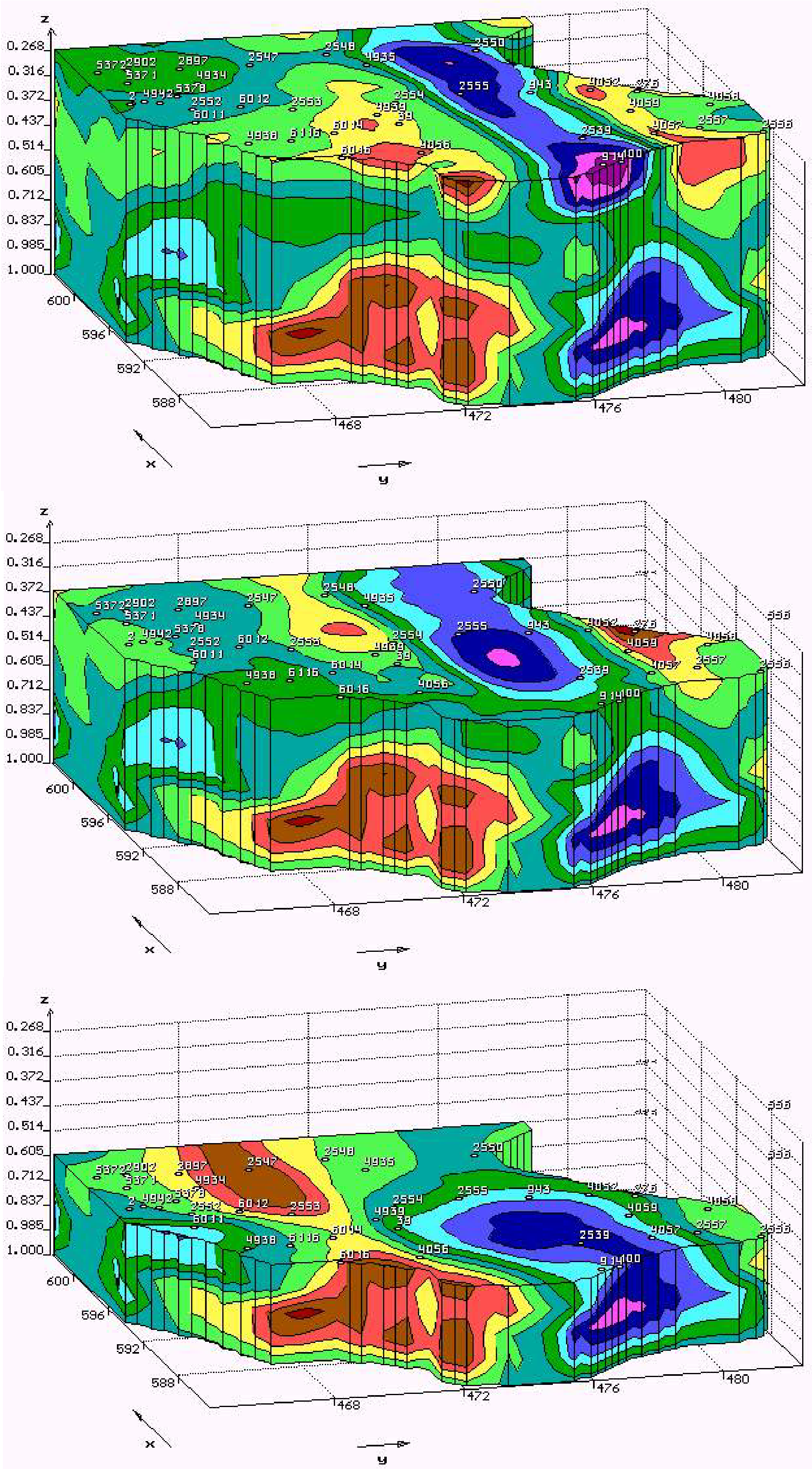


Fig. 2.5. Horizontal sections of the 3D field diagram
(transformation of the initial gravity field) (GI, Ural Div. of RAS)

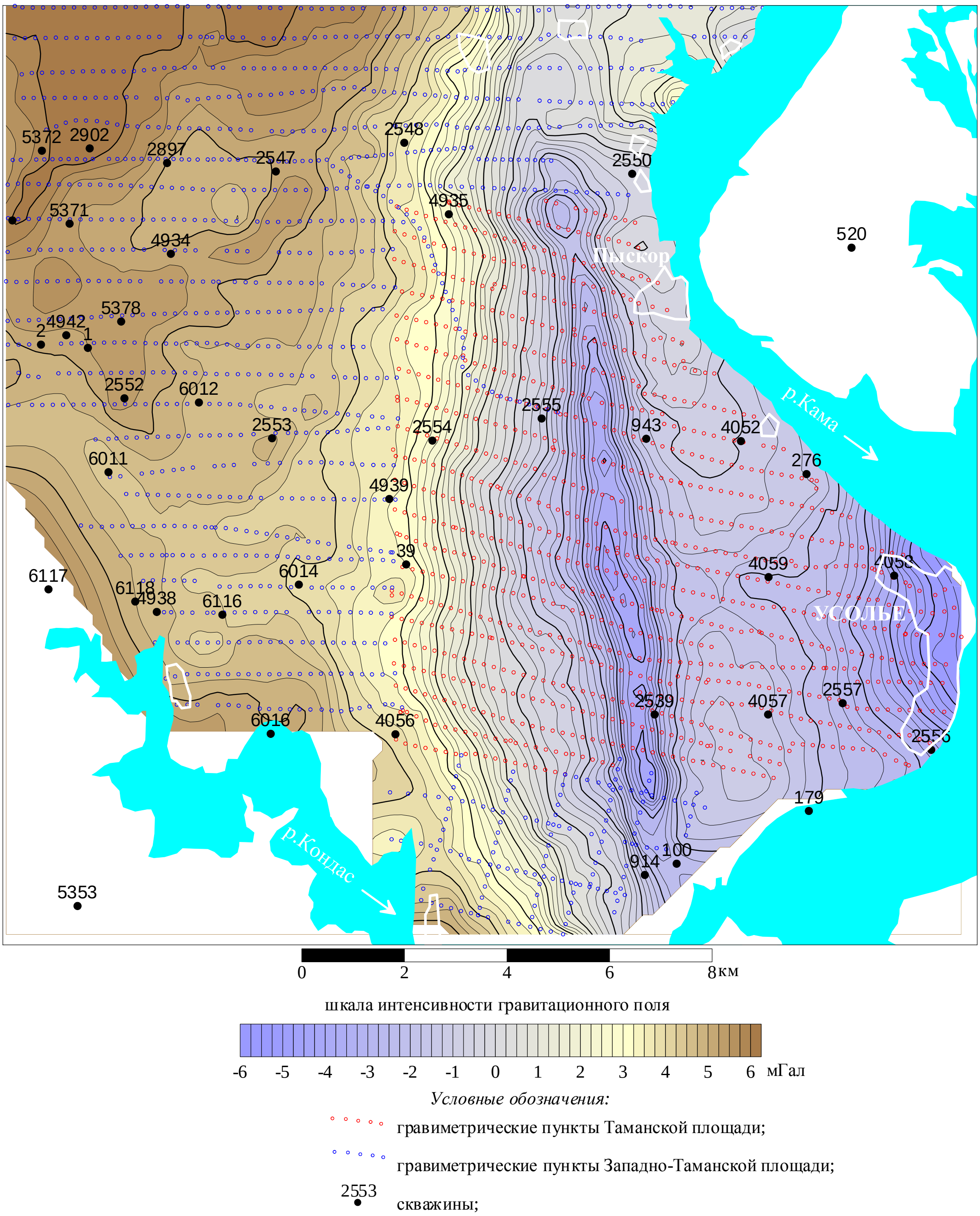


Fig. 2.6. Local gravity field (from the data of GI, Ural Div. of RAS)

Analyzing the maps and graphs of Δg with allowance for other methods, we form our judgment about the location, size, and shape of the studied objects, and choose the appropriate models to approximate them. In order to obtain the maximum possible information about the abnormal field, and then, quantitative data about abnormal objects (depth of occurrence, dimensions, abnormal density), an <u>interpretation (calculation) profile</u> is selected.

<u>Quantitative interpretation</u> starts after the graph of Δg_B has been plotted along the calculation profile (fig. 2.7).

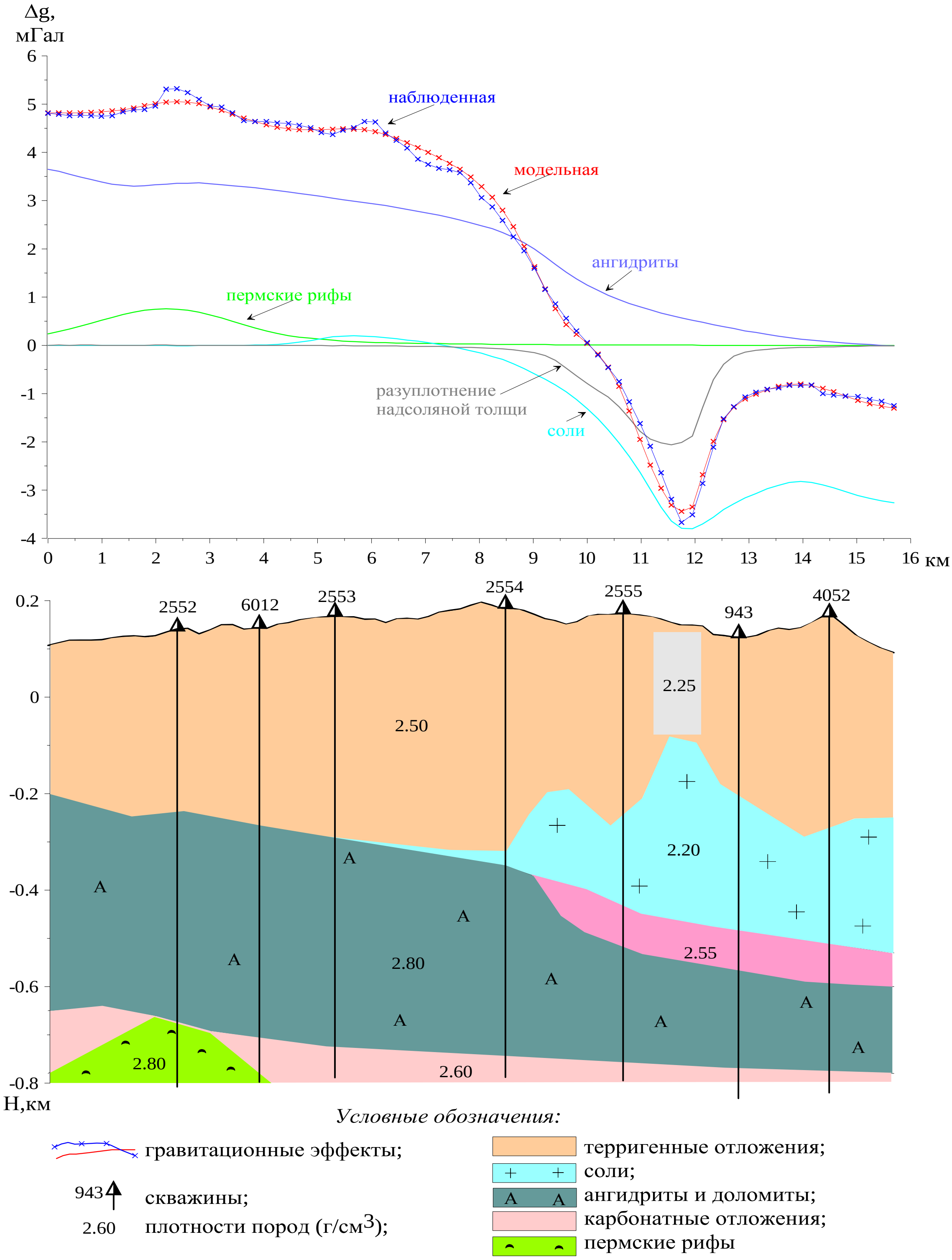
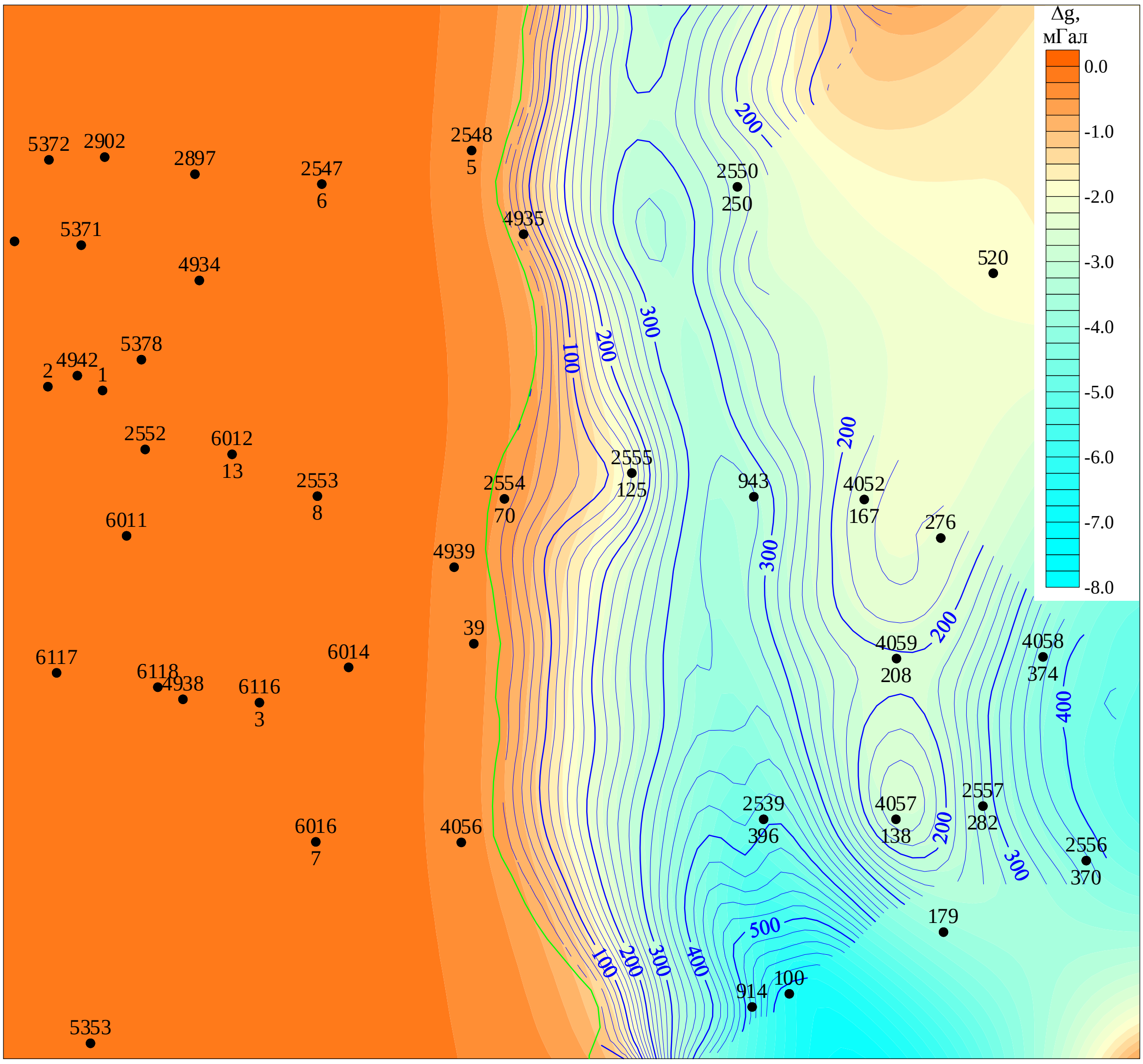


Fig. 2.7. Results of the two-dimensional gravitational modeling (from the data of GI, Ural Div. of RAS)

Selection of the modeling class is finalized, and the type of the model is selected, whose force of attraction will be used to approximate the local anomaly. After that, we start solving the inverse gravimetric prospecting problem. Then, the results of geophysical interpretation are interpreted from the geologic viewpoint, with account for the entire bulk of geological and geophysical data (fig. 2.8).



Условные обозначения:

6016 номера скважин
7 мощность соле́й;
100 изолинии мощности солей;
зона выклинивания солей;
гравитационный эффект толщи солей

Fig. 2.8. Thickness of the salts and gravity effect of the salt mass
(from the data of GI, Ural Div. of RAS)

Practice has shown that gravimetric prospecting is efficient when applied in prospecting and exploring oil and gas fields.

Topic 3. Magnetic Prospecting

Magnetic prospecting is a geophysical method of studying the geologic profile when solving geoprospecting problems, which is based on studies of the geomagnetic field. In many issues of the theory, field work methodology, and interpretation of the obtained materials, magnetic prospecting is similar to gravimetric prospecting. The both methods are based on studying anomalies of natural fields. The most intense magnetic anomalies are produced by magnetite iron ores. Magnetic prospecting started being used extensively in prospecting and exploring oil and gas fields after the equipment and methodology for magnetic measurements in motion have been developed, specifically, air-based and marine magnetic surveys. Currently, magnetic surveys combined with other geophysical methods is used widely to study the structure of large oil-and-gas bearing regions and to search for the deposits of various ores and other minerals.

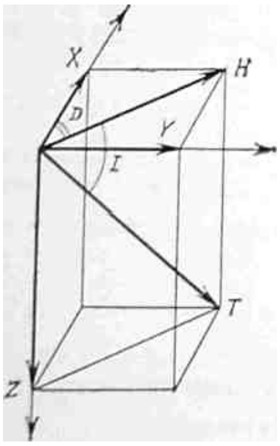
3.1. Gravitational Field of the Earth, Its Elements and Measurement Methods

In the general case, the magnetic field of the Earth is non-stationary (fig. 3.1).

Type of variations	**Intensity, nT**
Centennial	up to 100
Annual	up to 30
Daily	10 through 60
Magnetic storms	

Fig. 3.1. Variations of the magnetic field of the Earth

The portion of the field generated by the source located within the Earth is assumed to be constant. The magnetic field can be studied using the laws of electromagnetism or regarding magnetic anomalies as the result of studying the interaction of "magnetic masses" (a fictional notion). Magnetic poles are represented as agglomerations of magnetic masses, which are equivalent and opposite in sign. The force of the interaction between magnetic point masses is determined by the Coulomb law, which takes media properties into account, specifically: magnetization intensity J, magnetic susceptibility χ (matter ability to get magnetized) and permeability μ_a. In gravimetric prospecting, the magnetic field is characterized by magnetic inductance B (T). Under the effect of the external magnetic field of the Earth $B_{ext} = \mu_0$ T, the internal magnetic field $B_{int} = \mu_0$ J appears in rocks, where μ_0, μ_a, and $\mu = \mu_a/\mu_0$ are absolute magnetic permeability of the vacuum , the medium, and the relative magnetic permeability, respectively, and T is the full vector of the field intensity. Their superposition (sum) is measured with magnetometers. Taking into account that $\chi = J/T$, and in the medium $B = \mu_0\mu$ T, the value of B is equal to $\mu_0 T + \chi T$. In practice, magnetometers are either in air or in water during measurements. In the SI and SGS systems, $\mu = 1$ and $\chi = 0$ for air and water, virtually. Hence, $B = \mu_0 T$. It means that the force characteristic of the magnetic field can be expressed both in V and T, and in T and A/m. The elements, which also characterize the magnetic field and are measured with specially developed devices, are shown in fig. 3.2.



$$X = H \cdot \cos D$$

$$Y = H \cdot \sin D$$

$$T = \sqrt{Z^2 + H^2}$$

$$\mathrm{tg}\, Y = Z / H$$

Fig. 3.2. Elements of the magnetic field. *H*, *X*, *Y*, and *Z* are horizontal, northern, eastern, and vertical components of the vector *T*; *D* and *I* are magnetic declination and inclination, respectively

3.2. Normal and Abnormal Magnetic Fields of the Earth, Magnetic Properties of the Rocks

The measured values of the total vector T can be decomposed into the following components: $T = T_0 + T_1 + T_2 + T_3$, where T_0 is the field of the homogeneously magnetized globe of the Earth, T_1 is the continental anomaly, T_2 is the regional anomaly, and T_3 is the local magnetic anomaly. The normal field is $T_n = T_0 + T_1$, and the abnormal one is $T_A = T - T_n = T_2 + T_3$ and is of prospecting interest. In Russia, T_n is determined using normal-field maps calculated for the epochs multiple of five years (starting from 1925). Rocks have different magnetic properties (χ, I_n, and μ), and are subdivided into diamagnetics ($\chi < 1$ and $\mu < 1$) and ferromagnetics ($\chi >> 1$ and $\mu >> I$). Magnetic properties of rocks depend on the percentage content of ferromagnetic minerals. Igneous and metamorphic rocks are magnetic, and sedimentary rocks, are weakly magnetic. By analogy with abnormal density $\Delta\sigma$, the factor significant for magnetic prospecting is the abnormal magnetic susceptibility $\Delta\chi = \chi_{obj} - \chi_0$ where χ_0 is the magnetic susceptibility of the rocks enclosing the studied object with the susceptibility χ_{obj}. Favorable conditions for performance of magnetometric works are mainly the difference of the magnetic properties of the rocks in the profile, and the presence of subvertical separating boundaries.

3.3. Methods and Equipment for Measuring the Geomagnetic Field

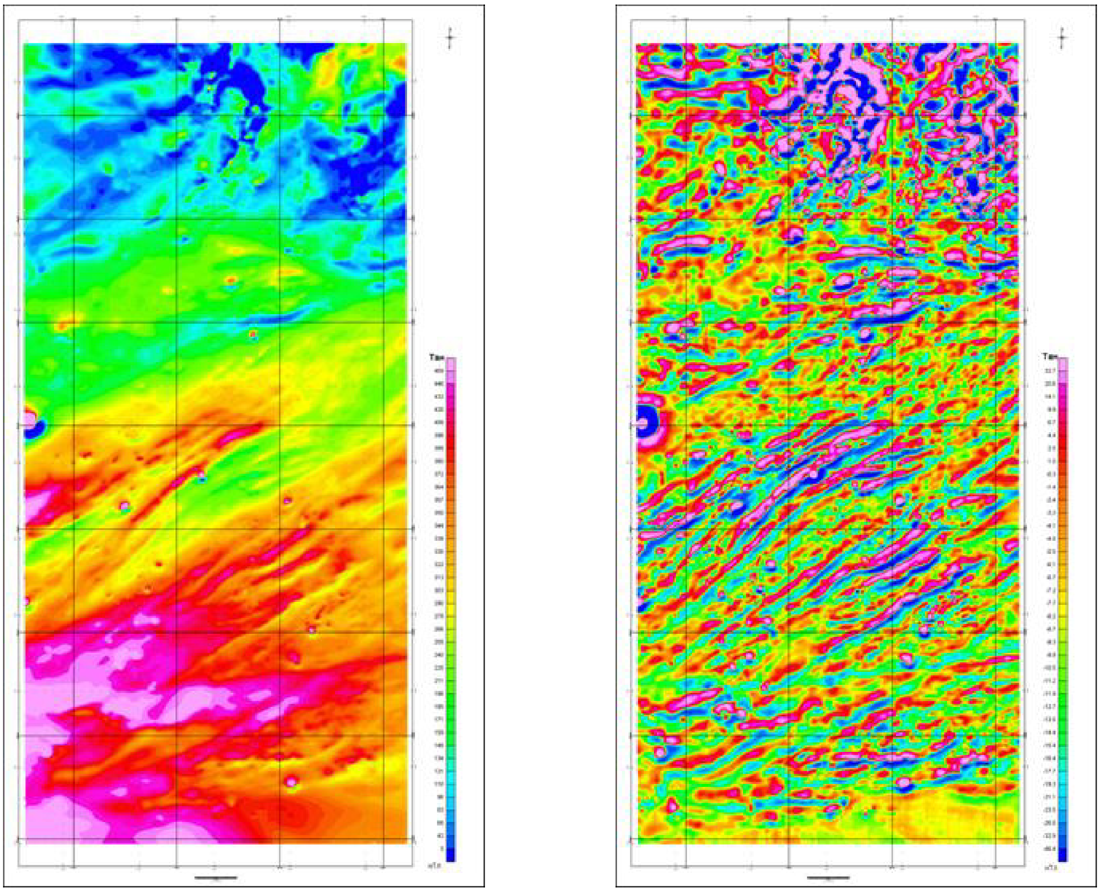
Magnetometer measurements can be absolute and relative. The devices are subdivided according to the type of measured magnetic values. Modern devices registering full values of $B(T)$ or its increment $\Delta B(\Delta T)$ are called magnetometers. By the operation conditions, magnetometers are also categorized as gravimeters. By the principle of operation of the measuring converter, magnetometers can be of the optico-mechanical, ferro-probe, proton, and quantum type. Currently, quantum and proton magnetometers are used mainly, which make it possible to perform absolute measurements of T and ΔT with high precision, $\pm(1\text{–}2)\ nT$ and $\pm(0.1\text{–}1)\ nT$, respectively.

3.4. Types of Magnetic Surveys, Methodology of Field Works, General Issues of Processing and Interpreting Magnetic Survey Data

When performing magnetic surveys, measurements of daily variations of the magnetic field are mandatory. As in gravimetric prospecting, various technological complexes are used. New-generation magnetometers used for air-borne magnetic prospecting, e.g. "AeroMaster-100", and stationary recording magnetometers are up-to-date digital devices that do not require special adjustment operations. Devices are towed on a rope. Flights are performed at the velocity of 100–200 km/h at the height of 50–200 m. As in gravimetric prospecting, first a network of reference routes is established. Favorable survey conditions are low field gradients, and high rock differentiation in magnetic properties.

Automotive magnetic surveys are used in steppe and semi-arid regions. A device is towed on a rope about 6 m long. The field ΔT is registered at stated intervals automatically using meters, e.g. proton or quantum ones. Measurement errors cannot exceed 3–5 nT. The survey results are used to develop correlation schemes of the graphs and the isodine map ΔT, which serve as the basis for interpretation and geologic analysis of the obtained data.
In water reservoirs, geomagnetic studies are performed with the use of floating craft. Almost two thirds of the Earth surface are covered with water, therefore potential opportunities of such studies are great. Naval proton (MPM-4, AMP-3) and quantum (KM-2M, KM-3) magnetometers are used. The measurements are performed following the system of parallel profiles (traverses) for areal surveys and, less frequently, along individual routes. To eliminate the interference, sensors are towed behind the craft at the distance of 2–3 board lines. The values of T or ΔT are measured. For detailed works, the measurement error is 0.4 nT, and for reconnaissance, first tens of nT. In terms of the technology, ground magnetic prospecting is very similar to gravimetric prospecting. Mainly, it is performed using proton devices (MMP-203 or MMP-303). In practice, other types of magnetic surveys are performed: micro-magnetic, subterranean, in-well, and paleomagnetic.

Magnetic survey data processing yields abnormal values of ΔT, which are exemplified in fig. 3.3).



1 2

Fig. 3.3. Abnormal magnetic field (1) and its residual component (2)
(GNPP “Aerogeophisika” data)

The theory for interpretation of magnetic survey data is based on solving forward and inverse magnetometric problems. When interpreting the magnetic prospecting data, the studied object is regarded as a homogeneously magnetized body. The theory considers solutions for bodies having simple geometric shapes. Their magnetic fields are used to model abnormal fields, which, in its turn, makes it possible to asses the parameters of anomaly-forming objects, as in gravimetric prospecting. By subtracting their effect from local anomalies, the residual magnetic fields are obtained. As a supplementary method, magnetic prospecting is used in oil-and-gas exploration. As an example, fig. 3.4 shows the results of processing the magnetometric data, which made it possible to localize a hydrocarbon deposit.

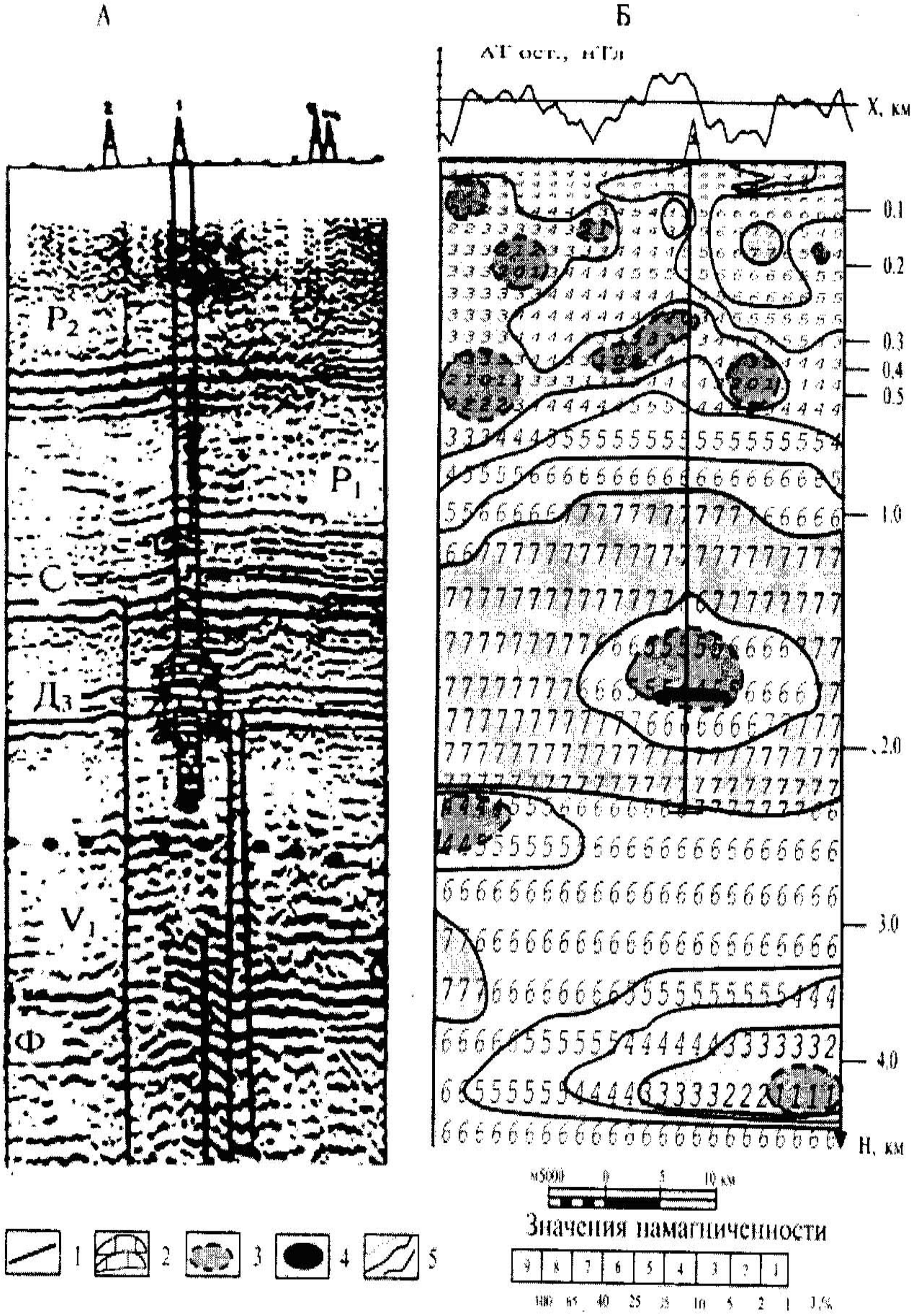


Fig. 3.4. Application of magnetic prospecting to study an oil field: *A* – temporal cross-section, *B* – cross-section by isolines of the relative parameter of the magnetic field; 4 – hydrocarbon deposit; 5 – *J* isolines (according to V.G. Mavrichev)

Topic 4. Geoelectric Prospecting

Geoelectric prospecting is a geophysical method of studying the geological profile when solving geoprospecting problems, which is based on studying natural and artificial alternating (ac) and constant (dc) electromagnetic fields.

4.1. Types and Methods of Excitation of Electromagnetic Fields Studied by Geolectric Prospecting

In geoelectric prospecting, the field is excited artificially, e.g. by passing the ac electric current through grounded feeding electrodes *A* and *B* (galvanic method) or through an electric wire laid on the ground as a loop or a contour (induction method). They also use linear electrodes in the form of naked non-insulated wires laid on the ground and connected to a power supply. The distribution of the joint electromagnetic field in a medium follows the complicated laws of electrodynamics and is described by Maxwell's equations.

4.2. Electromagnetic Properties of Rocks and the Fields Studied by Geoelectric Prospecting

Currently, there are over 50 different methods and their modifications in geoelectric prospecting. This is associated with five electric properties of rocks and six types of the fields studied by geoelectric prospecting (fig. 1.2). Electrical resistivity ρ (Ohm m) of the rocks changes in a very wide range and depends on a great number of factors (humidity, fracturing, temperature, etc.). Rock polarizibilty η (rock ability to produce the secondary electric field ΔU_{sec} under the effect of the primary field ΔU_{pr}) is determined by the formula $\eta=(\Delta U_{sec}/\Delta U_{pr})\cdot 100$ %. It depends mainly on the contact area of electron and ion conductors in the rock, as well as on other factors. As a rule, dielectric ε and magnetic μ permeability are studied by the high-frequency (thousands of kHz) methods, for example, by geologic radar. Electrochemical activity *a* (mV) is the ability of the rocks to generate electric fields due to the oxidation-reduction (redox) reactions. The fields studied by geoelectric prospecting include the constant field (excited with dc sources), natural electric field (generated by redox reactions and filtration and adsorption-diffusion processes in the ground), field caused by polarization (generated when the electromagnetic field is passed through a rock), harmonically varying field (one that has its intensity, current density, and other parameters changing sinusoidally or cosinusoidally, unstabilized field (the field of transitional processes that arise in the ground as the current strength in the source changes step-wise), and the magnetotelluric (MT) field (the field of natural variations of the electromagnetic field components).

4.3. Classification of Geoelectric Prospecting Methods

Depending on the survey principle, modifications of geoelectric prospecting are subdivided into three main methods, each of which includes two groups of methods: those of direct (dc) and alternating (ac) currents. Electromagnetic probing is a way to study geologic cross-sections vertically, which is based on measuring field elements at one point while increasing the depth of electric current penetration by changing the parameters of the electrometric setup (dimensions of the feeding line *AB*, field frequency, etc.). Electromagnetic profiling is a way to study geologic cross-sections along the profile at the same depth of electric current penetration while the parameters of the electrometric setup stay the same. The methods of in-well geoelectric prospecting fall under a separate area of well logging. Modifications of geoelectric prospecting methods are denoted by the first letters of their titles. To study the cross-section at a set depth, more efficient modifications of geoelectric prospecting methods are selected. In most cases, the main studied parameter is the parameter ρ. Sometimes, electric boundaries in the cross-section coincide with the stratigraphic ones, and are sued to correlate the geophysical and geological results. In the general case, these boundaries do not coincide.

4.4. General Notions of the Theory, Geometric Factor of the Electrometric Setup, Survey Depth

The basis for studying the fields from individual ground conductors is Ohm's law. In geoelectric prospecting, the horizontally-layered model of the medium is used widely. Different types of cross-sections (profiles) are distinguished by the number of layers and the ratio of ρ in them. For example, the three-layer profile consists of two layers with limited thicknesses H_1 and H_2 underlaid by a layer with the infinite thickness H_3. For three-layer profiles, there may be four types of ρ ratios: type *A* ($\rho_1 < \rho_2 < \rho_3,$), type *H* ($\rho_1 > \rho_2 < \rho_3$), type *K* ($\rho_1 < \rho_2 > \rho_3$), and type *Q* ($\rho_1 > \rho_2 > \rho_3$). Theoretical probing curves are calculated for known ratios of the model, which are used further to solve inverse problems by the trial-and-error method. Multi-layer media consist of an aggregation of the curves representing three-layer profiles. For a simple, symmetric, four-electrode setup (fig. 4.1).

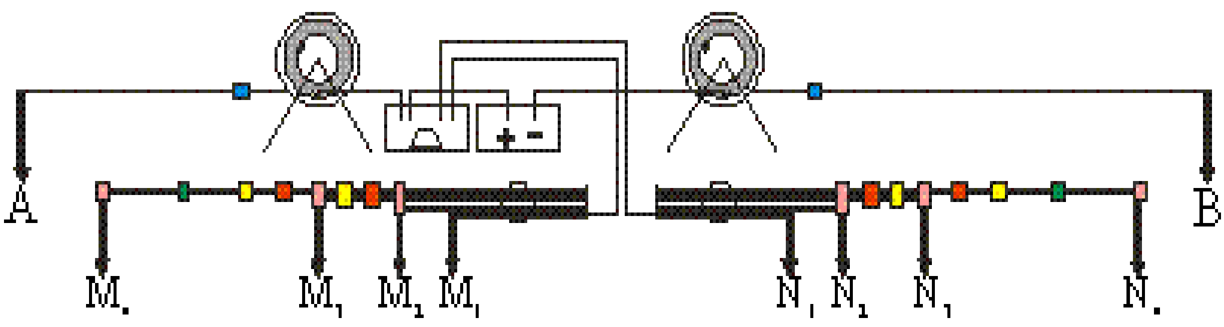


Fig. 4.1. Symmetric four-electrode setup. *ABMN* – ground connectors. *AB* – feeding line, *MN* – receiving line

Effective (apparent) resistance ρ_a is calculated using the formula $\rho_a = k\Delta U/I$, where k is the geometric factor of the setup, ΔU is the difference of the potentials in the receiving line MN, and I is the current in the feeding line AB. The depth of geoelectric prospecting depends on the efficient depth h_{eff} of current penetration into the ground. For a homogeneous medium, h_{eff} is 1/4 of the length AB. In an inhomogeneous medium, h_{eff} ranges from 1/4 to 1/10 of the length AB. When using the alternating current, the depth of electric current penetration depends on the wavelength or frequency of the field. In the case of short waves or high frequencies, currents are concentrated near the Earth surface (skin effect). As the wavelength grows, the depth of current penetration increases. At the reception points, the electric-field intensity E or the potential difference ΔU is registered by means of receiving lines MN, and the magnetic-field intensity H or magnetic inductance B is registered by means of induction frames or loops. They are used to calculated the efficient parameter. Most often, it is rock resistance.

4.5. Equipment and Power Sources Used for Geoelectric Prospecting

Electrometric equipment is subdivided into three groups: the first is portable and is used to study dc and low-frequency fields (fig. 4.2)

a *b* *c*

Fig. 4.2. "Era" equipment (*a*) and ANCh rectifier (*b*) and meter (*c*)

The second group is also portable and used to study ac electric fields. The third group comprises electrometric stations which could be borne by vehicles, for example, an automobile (fig. 4.3).

A separate group is borehole equipment. Power supplies used to feed the equipment and excite artificial electromagnetic fields are dry cells, accumulators, various dc and ac generators. Electrodes of feeding lines AB are made of steel, and those of receiving lines MN, of copper and brass.

a *b*

Fig. 4.3. Automotive vehicles used in electrometric works: *a* – ERS SGS-TEM ("Picket"); *b* – generator group ("Irkutskgeofizika")

To reduce transfer resistance, feeding electrodes A and B can be made as a group of 2 up to 100 pieces. In the probing process, to increase the potential difference in the receiving line, they pass from the small MN line to a greater one (fig. 4.1).

4.6. General Issues of Processing, Interpretation, and Geologic Analysis of Electrometric Data

Maxwell's equations make it possible to determine the main characteristics of the electromagnetic field in each point of space and at each moment of time, if we know the sources of the field, current density, and charge density as functions of coordinates and time. As other methods of field geophysics, the geoelectric prospecting theory is based on solving forward and inverse problems, which, when aggregated, comprise the physico-mathematical support to the methods of geophysical interpretation of the geoelectric prospecting results. Determination of the elements of the electromagnetic field in space for a preset model of the medium for the known geometric parameters of the medium and disposition of the field sources is called a forward problem. A reverse problem is to determine the parameters of the geoelectric cross-section from instrumentally measured elements of the electromagnetic field. The materials of probing obtained on dry land, on the sea, in air and underground, are processed in the same way. The results of the measurement are usually represented as the graphs plotting the dependence of efficient resistance ρ on the effective distances or frequency (length) of the wave of the feeding lines (fig. 4.4).

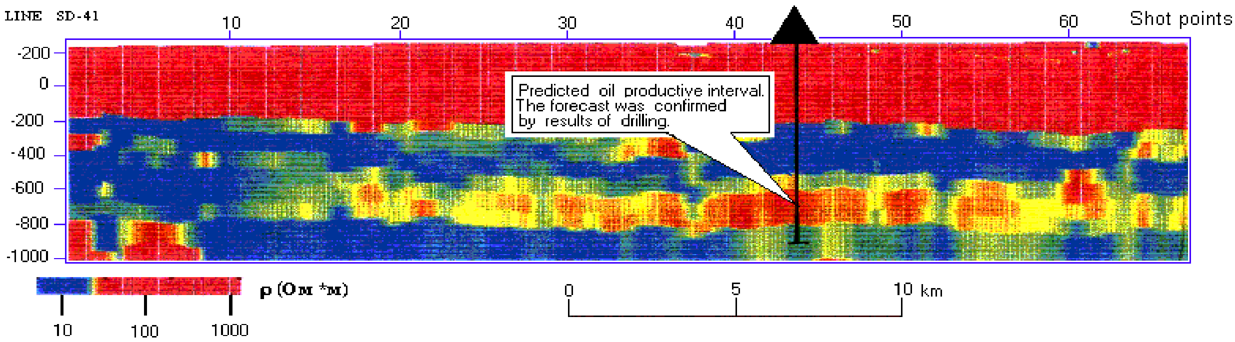


Fig. 4.4. Results of the near-field transient electromagnetic sounding in Australia ("Kazangeofizika")

Explanation of the obtained data relates to their interpretation. High-quality interpretation reveals peculiar features of efficient parameters, which can be used to differentiate rocks in the cross-section. At the stage of qualitative interpretation, qualitative characteristics of the cross-section are determined: layer thicknesses H, their resistance ρ, and occurrence depth h of individual horizons. At the recent stage, interpretation is performed using special computer software. The essence of interpretation is searching for parameters of a horizontally layered or inhomogeneous medium aiming at calculating the probing curve which would coincide with the interpreted curve to a preset accuracy degree. The final stage is to perform comprehensive explanation of the data of geophysical interpretation and correlate them with the geologic structure of the cross-section while employing all the *a priori* geologic and geophysic data in order to reduce incorrectness of solving the set problems. Finally, geoelectric cross-sections (fig. 4.5) and structural maps (fig. 4.6) are developed. Fig. 4.7 shows an example of using geoelectric prospecting for oil deposit surveying.

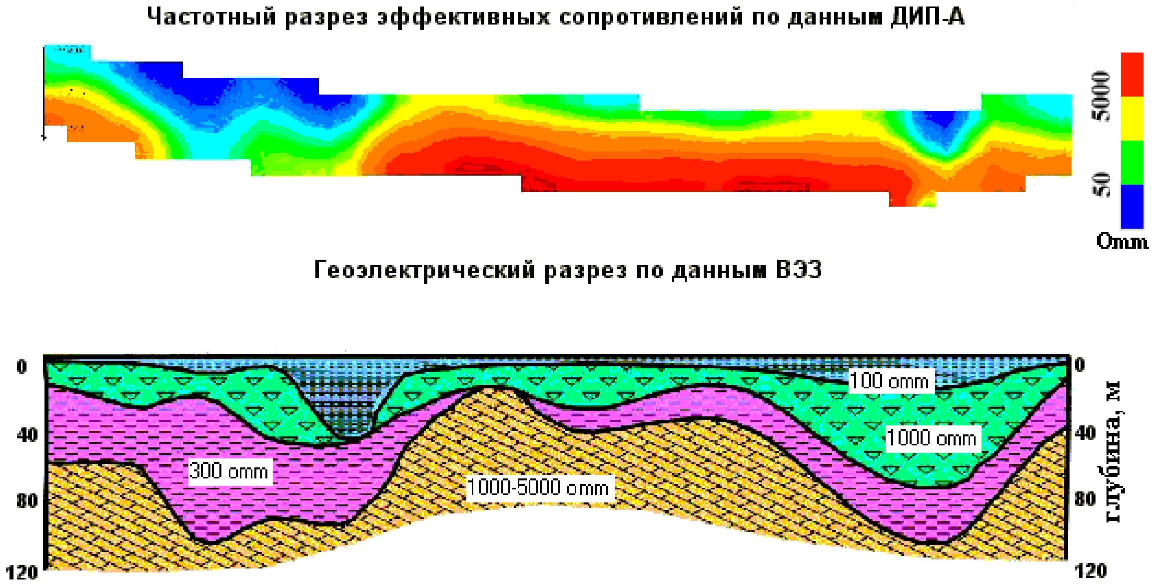


Fig. 4.5. Geoelectric cross-section according to VES data
(OJSC "Irkutskgeofizika")

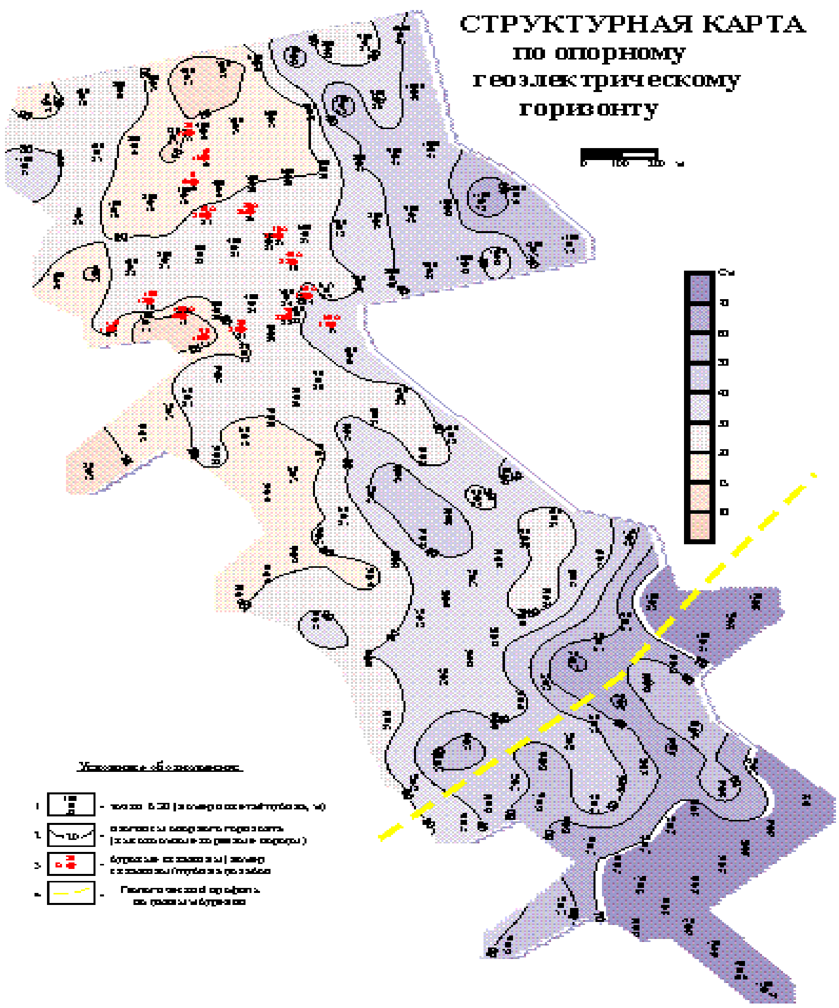
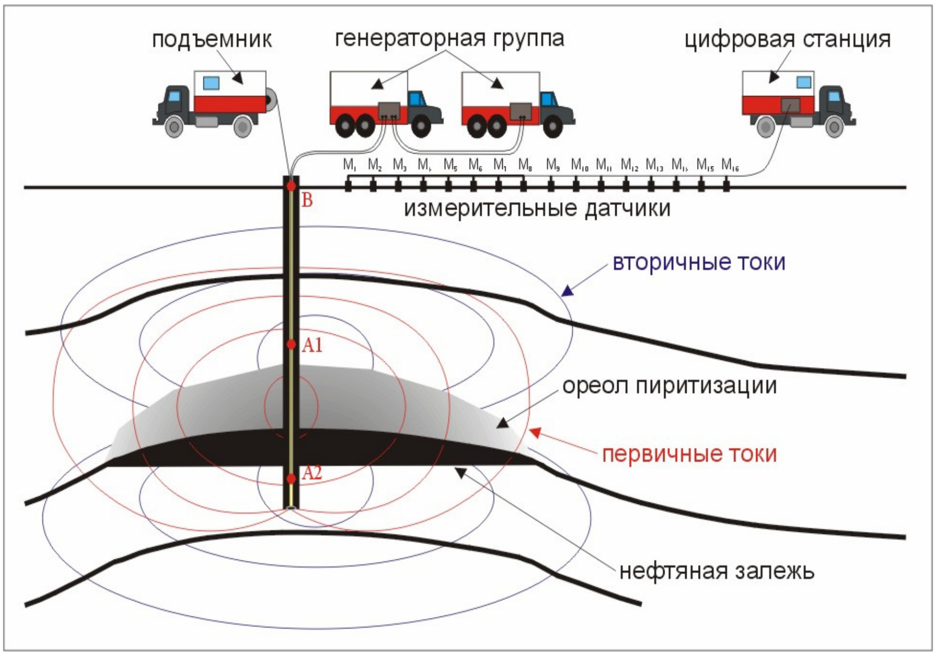
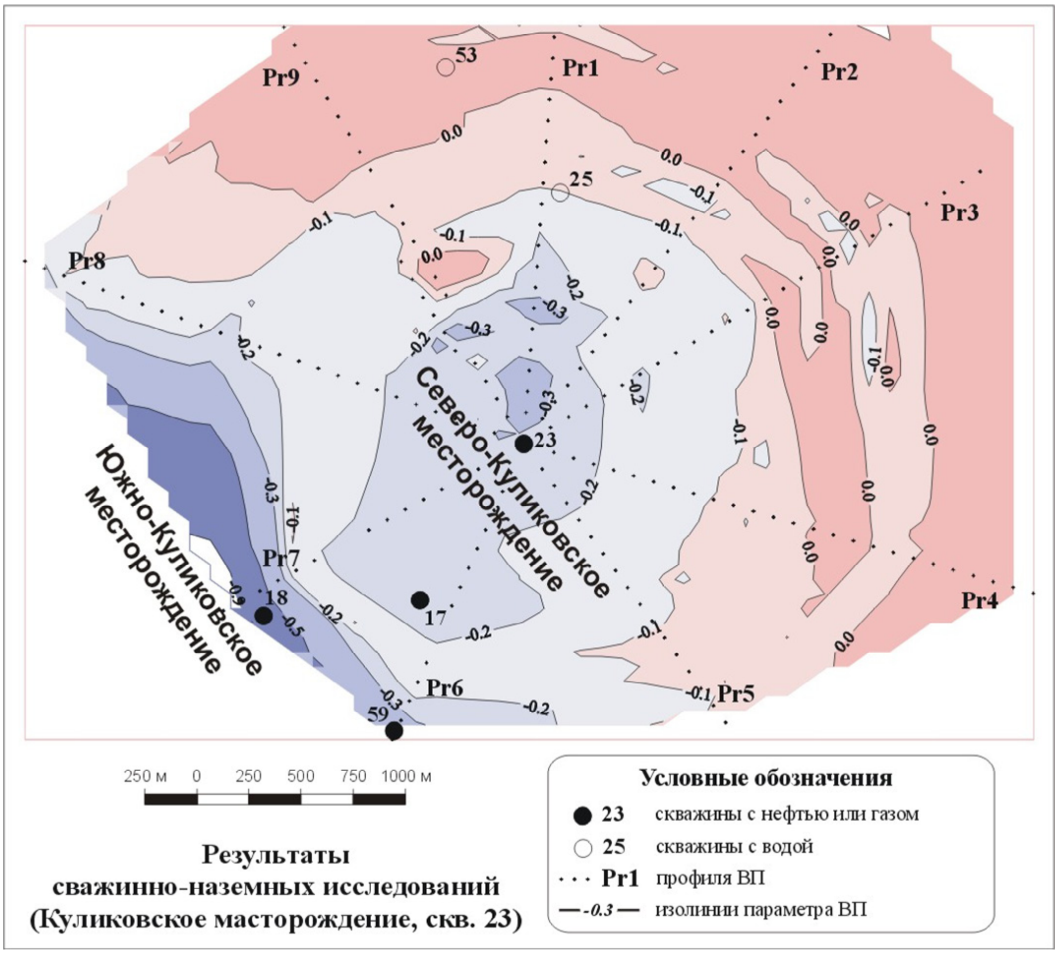


Fig. 4.6. Structural map developed along the geoelectric reference horizon
(OJSC "Irkutskgeofizika")



a



b

Fig. 4.7. Study of the deposit using the induced-polarization method:
a – scheme of the setup; *b* – delineation of pyritization zones

Topic 5. Seismic Prospecting

5.1. Basics and Tasks of Seismic Prospecting at Various Prospecting Stages

Seismic prospecting is a geophysical method of studying the geological profile when solving geoprospecting problems, which is based on studying propagation of artificially excited elastic (seismic) waves. Seismic prospecting is a leading method of solving structural geologic problems, especially when prospecting and exploring oil and gas fields. Seismic characteristics are used to determine the composition, structure, sedimentation conditions, type of the changes having affected the deposits, the age and history of the area evolution. When searching for oil and gas, this approach is the basis for the direct search method.

5.2. Technology of Field Works, Survey Systems and Equipment

Seismic prospecting includes a complex of ground-based and borehole methods used to study the geologic structure of the Earth core. To excite elastic waves, explosive and non-explosive sources of oscillations are used. Elastic waves are excited by the explosive method by means of exploding an explosive charge (most frequently, trinitrotoluol) of a certain mass (usually 1 to 10 kg) placed in a specially bored well down to 15–20 m deep (fig. 5.1). In marine studies, elastic waves are excited by pneumatic radiators which excite elastic pulses by discharging the air compressed under high pressures into the water instantaneously.

In ground-based oil- and gas-prospecting seismic works, seismic vibrators are widely used (fig. 5.2). External view (*a*) and basic scheme (*b*) of the vibration excitation source, special electrodynamic setups which are mounted on self-propelled chassis and radiate a long train (sweep) of harmonic actions of a smoothly varying frequency.

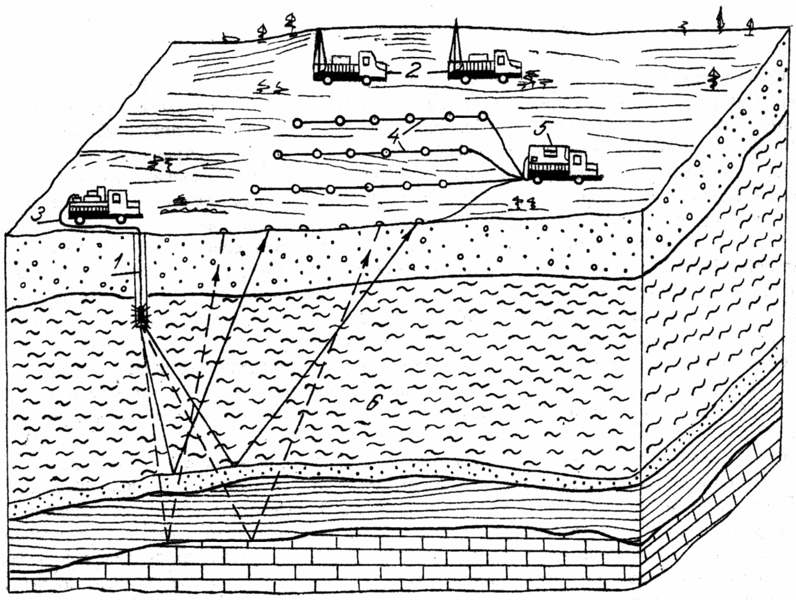
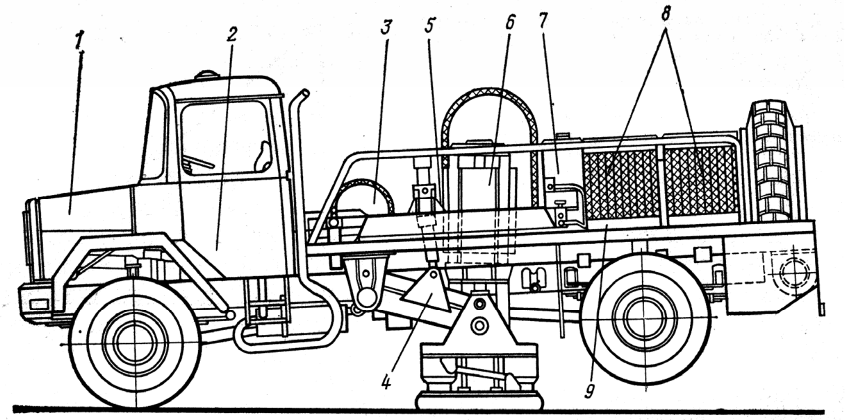


Fig. 5.1. Scheme of ground-based seismometric works:
1 – explosive well with an explosive charge; *2* – rock drills;
3 – explosion site station; *4* – seismic cables with seismic receivers;
5 – seismic station; *6* – geologic cross-section; *7* – trajectory of seismic waves

a



b

Fig. 5.2. External view (*a*) and basic scheme (*b*)
of the vibration excitation source

In the general case, two independent types of seismic waves are initiated by excitation: longitudinal and transverse ones. Longitudinal waves (P-waves) associated with deformations of the rock volumes are characterized by motions of the medium particles parallel to the direction of wave propagation and higher velocities: they are the first to reach any observation point running from the source. The transverse waves (S-waves), in which the motions of the rock particles and the wave propagation direction are mutually perpendicular are caused by shear deformations and do not propagate in liquid and gaseous media.

Elastic waves caused by explosions or mechanical actions propagate away from the oscillation source following the laws of geometric optics and penetrate the thickness of the Earth core to great depths. In the process of their propagation, elastic waves undergo the process of reflection and refraction at the boundaries of the discontinuities caused by changes in elastic properties of rocks (fig. 5.3).

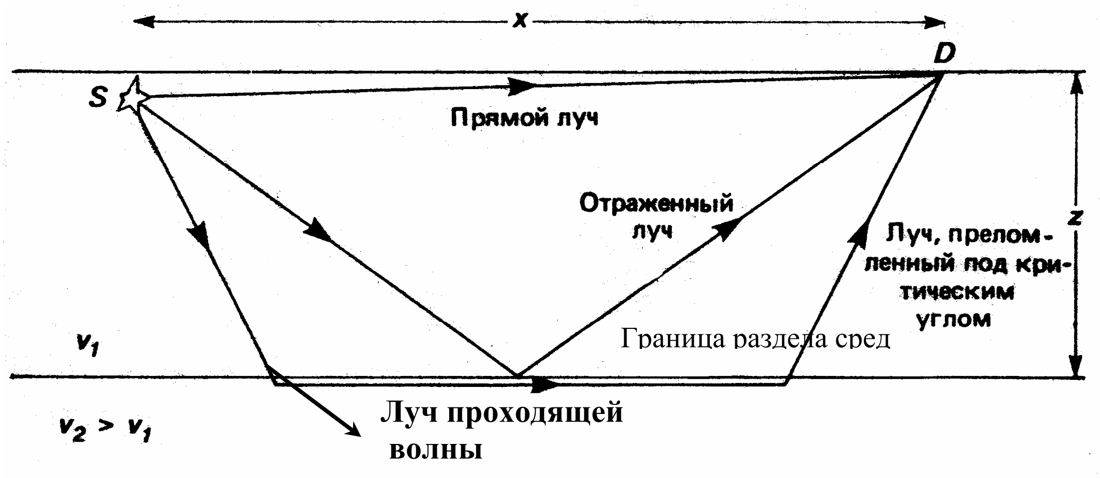


Fig. 5.3. Trajectory of propagation of seismic waves of various classed for the two-layer medium model: *S* – excitation source; *D* – seismic receiver; *z* – layer thickness; V_1 and V_2 – velocities of seismic waves in the overlying and underlying thickness, respectively

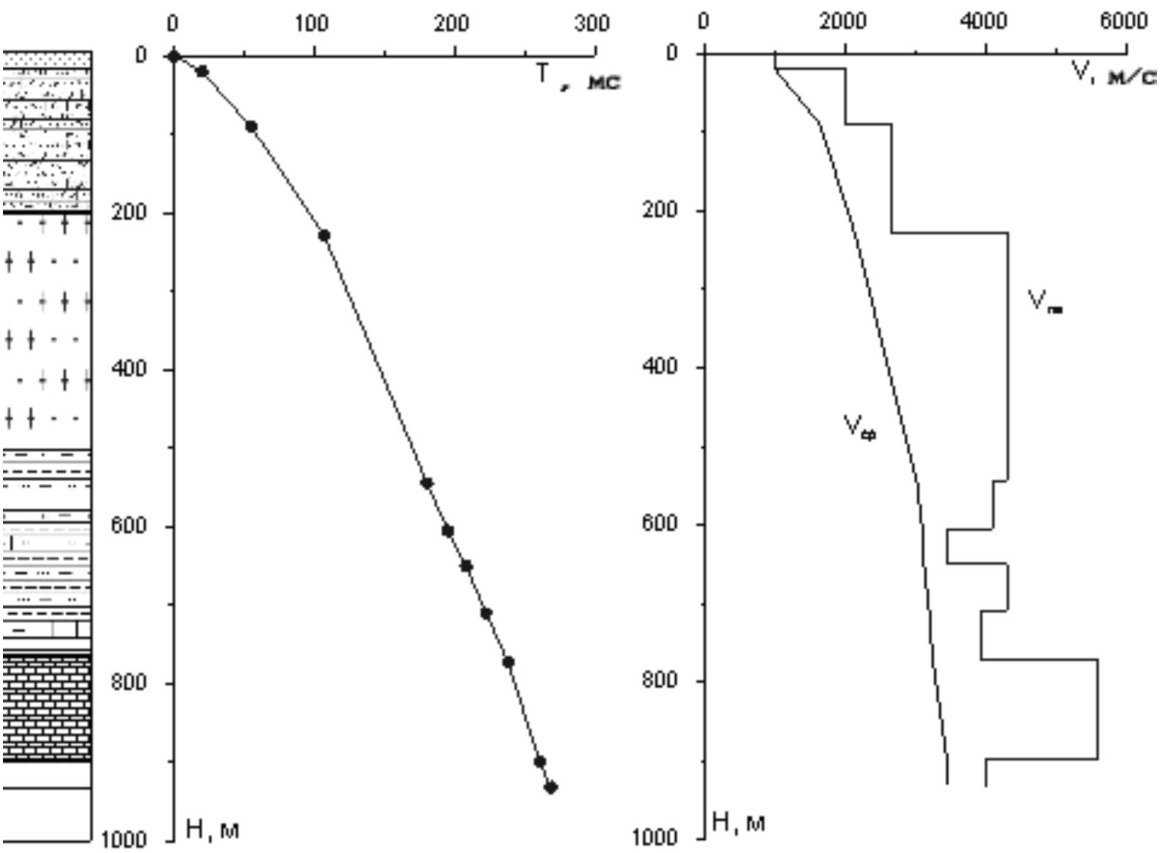
This leads to the fact that a part of the seismic energy returns to the Earth surface, where it causes comparatively weak oscillations which are registered by special equipment. Due to this, three main methods are subdivided in seismic prospecting: the method of reflected waves (reflection method), method of refracted waves (seismic refraction method), and method of transmitted waves (transmitted wave method). The reflection method is based on studying the peculiarities of propagation of elastic waves reflected from the boundary between two geologic layers different in their physical properties. Measuring the time of an elastic wave's passing from the source to several observation points on the Earth surface, one can gain the information about the spatial position of the reflecting boundary (occurrence depth, dip angle, etc.) and some properties of the medium overlying the reflecting boundary in the process of processing these data.

The refraction method is based on registration of seismic waves passing the greater part of their path through the cross-section nearly horizontally, along the roofs of layers, which are characterized by higher velocities as compared to overlaying ones. The main advantages of the refraction method is a wide range of survey depths (from first meters down to 10–15 km) and the possibility to determine the wave velocity in the thickness underlying the refractive horizon. However, it is characterized by coarser detailization of the cross-section and low accuracy of studying low-amplitude structural uplifts as compared with the reflection method.

5.3. General Information about Borehole Seismic

The transmitted wave method or borehole seismic prospecting combines a group of methods, in which elastic waves are received or excited (or both) at internal points of the medium: in wells (boreholes) or mine openings. The most widely used methods among seismic borehole ones are seismic well logging and vertical seismic profiling (VSP).

Seismic well logging is based on registration of transmitted waves' times of arrival along the borehole. it is used to study the velocity structure of the geologic cross-section (fig. 5.4).



a *b* *c*

Fig. 5.4. Processing of the seismic well logging data:
a – lithological column, *b* – vertical time curve,
c – graphs of layer velocity V_l and average velocity V_{av}

In vertical seismic profiling (VSP), unlike in seismic well logging, seismic waves are registered at internal medium points for a long time, which ensures a detailed analysis of the wave field and the dynamic of the process of seismic wave propagation in the geologic cross-section.

The method, which is most widely used in the practice of oil and gas prospecting works, is the seismic reflection method in its up-to-date modification: the common-depth-point (CDP) method. As a rule, seismometric works are performed along separate lines: seismometric profiles (fig. 5.1). Excitation points, at which elastic waves are excited consecutively, are situated along the profile at given intervals. Seismic cables (wire bundles) are also laid on the profile and connected to seismic receivers of elastic oscillations, which are put evenly, at the intervals of 20 to 100 m between them. When performing seismometric works by the CDP method, the interval between excitation sources is chosen comparable with the interval between seismic receivers, which ensures multiple registration of reflections from the same point on the reflecting boundary for different distances between excitation and reception points (fig. 5.5).

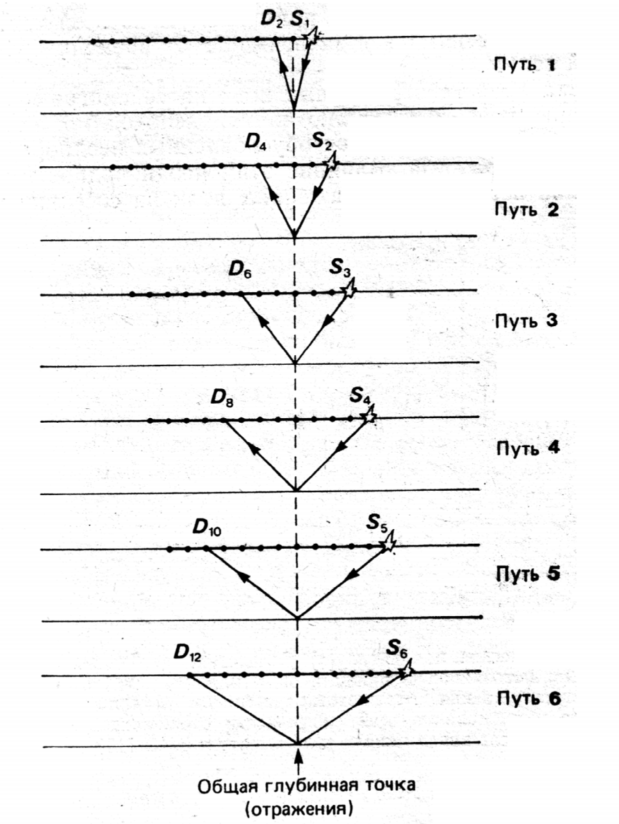


Fig. 5.5. Scheme of field observations
ensuring 6-fold CDP overlapping:
S – excitation sources; *D* – seismic receivers

5.4. Standard procedures for seismic data processing (2*D* – profile variant, 3*D* – areal variant)

Seismic receivers ensure registration even of minor shakes of the Earth surface, which are initiated by the source, and their conversion into electric signals. The most frequently used devices in ground-based seismic surveys are seismic receivers with electrodynamic converters (fig. 5.6) and in marine surveys, piezoelectric seismic receivers.

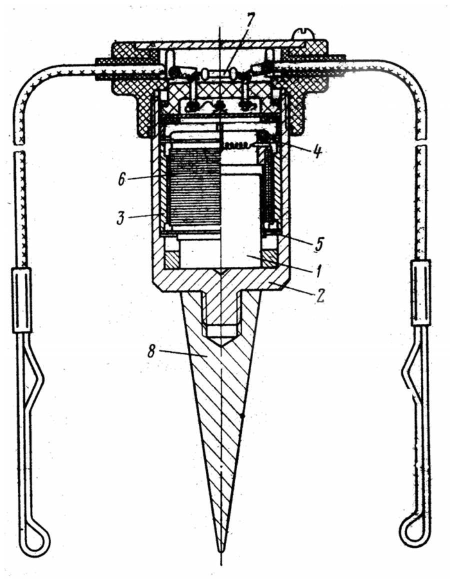


Fig. 5.6. Electrodynamic seismic receiver: *1* – permanent magnet, *2* – body of the seismic receiver, *3* – iron insert, *4* and *5* – springs, *6* – inert mass (electric coil), *7* – resistor, *8* – rod

Electric signal generated by the seismic receiver are transmitted via the seismic cable to the input of the special registering equipment: a seismic station usually mounted on an automobile (fig. 5.7).

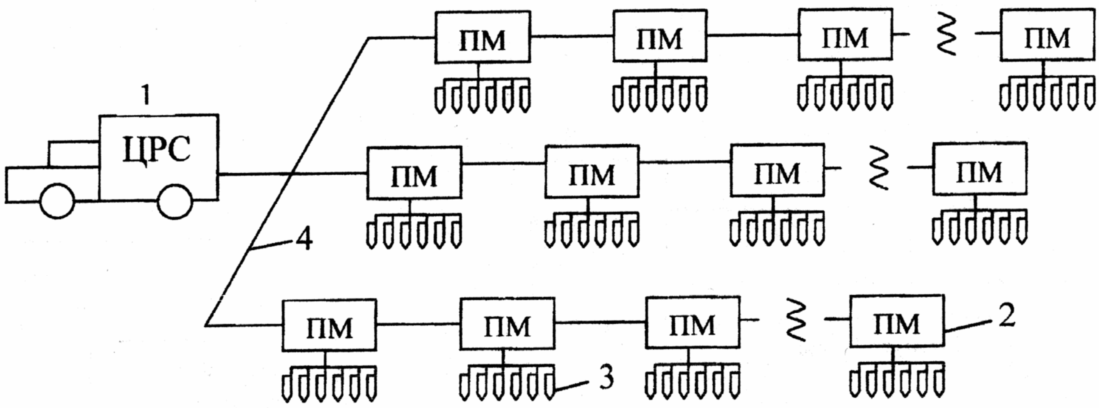


Fig. 5.7. Circuit of the registering telemetric seismic station: *1* – central registering station (CRS); *2* – field modules (FM); *3* – seismic receivers; *4* – telemetric communication channels

The signal received by the seismic station are amplified, filtered, and recorded on an permanent data carrier (magnetic tape or hard disk). Multi-channel digital stations are generally used to register seismic waves, since they ensure simultaneous registration of signals from several hundreds (thousands) of seismic receivers situated at various observation points.

The obtained seismic field records are traditionally called seismic records of the common excitation point (fig. 5.8).

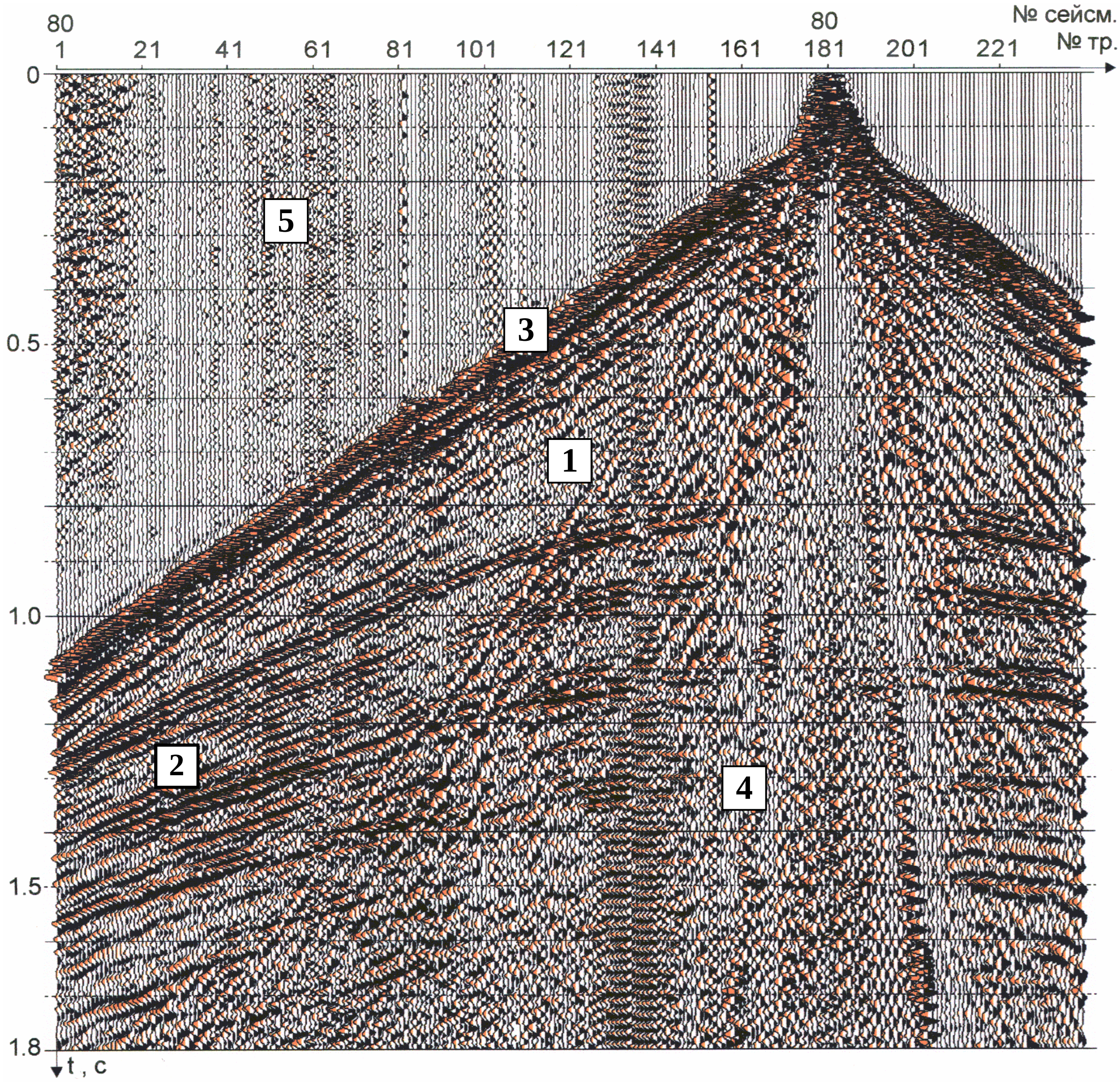


Fig. 5.8. Seismic field reflection-method record:
1 – direct wave; *2* – reflected waves; *3* – refracted waves; *4* – surface waves;
5 – irregular waves (noise)

Seismograms contain regular waves, whose energy change regularly from path to path. Characteristic features (maxima and minima) of the elastic waves singled out in the record form the lineups. Initial records are subject to computer processing along complex and branched graphs. Finally, the total temporal CDP cross-section (fig. 5.9).

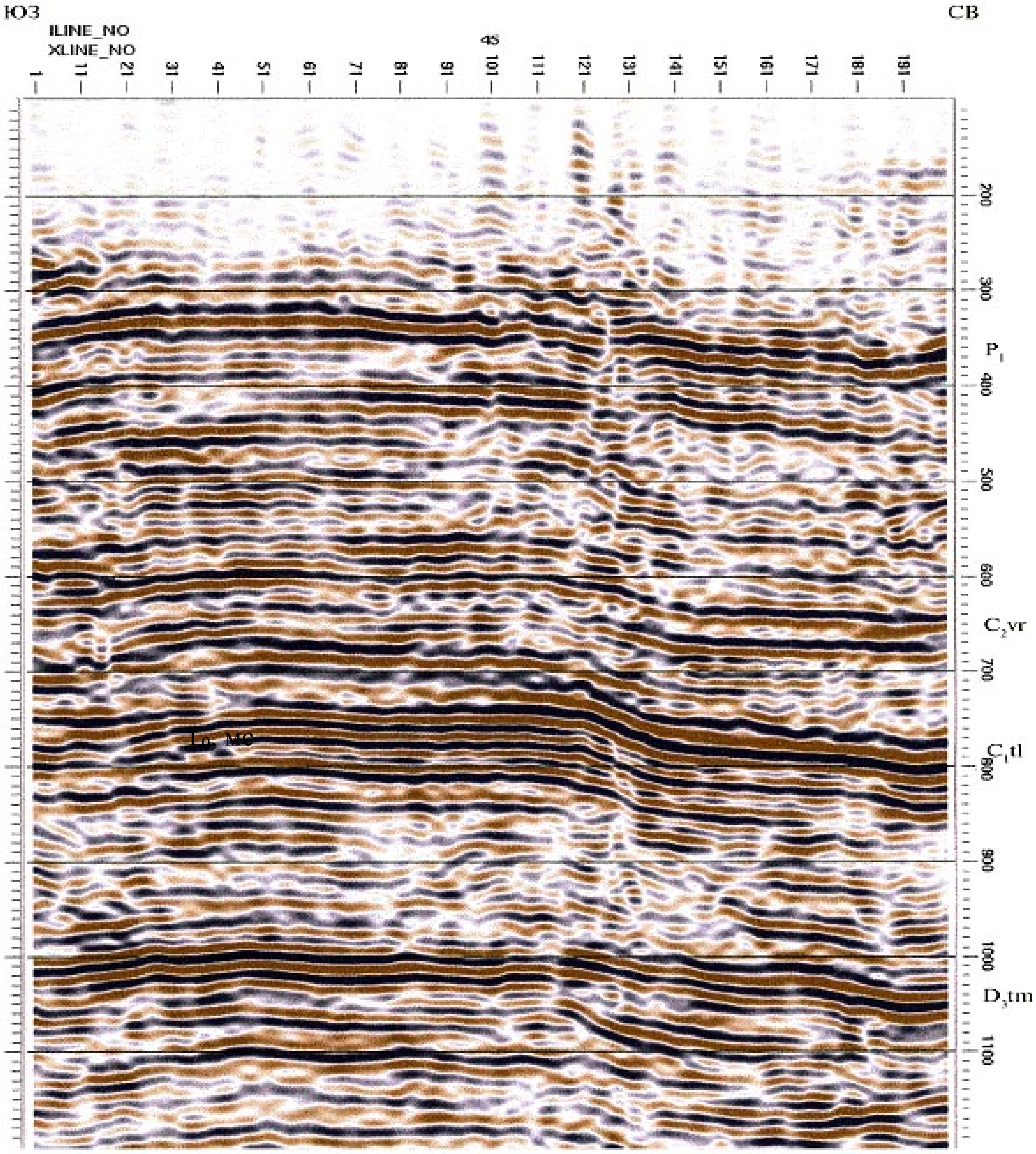


Fig. 5.9. Total temporal CDP cross-section

Currently, areal (3D) observation systems are widely used, in which seismic waves excited at one explosion point are registered simultaneously at several reception profiles (fig. 5.10). The results of processing areal CDP observations in the temporal seismic data cube (fig. 5.11).

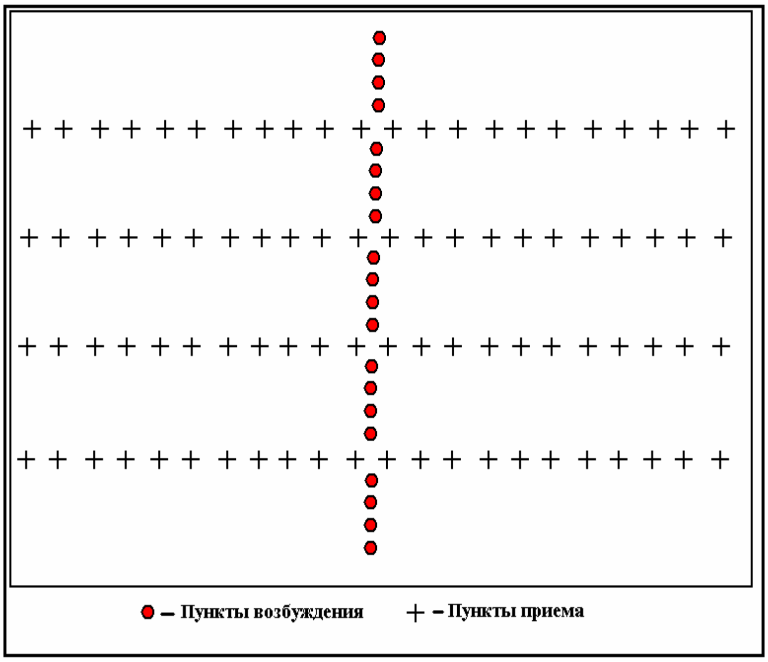


Fig. 5.10. Scheme of areal seismic observations

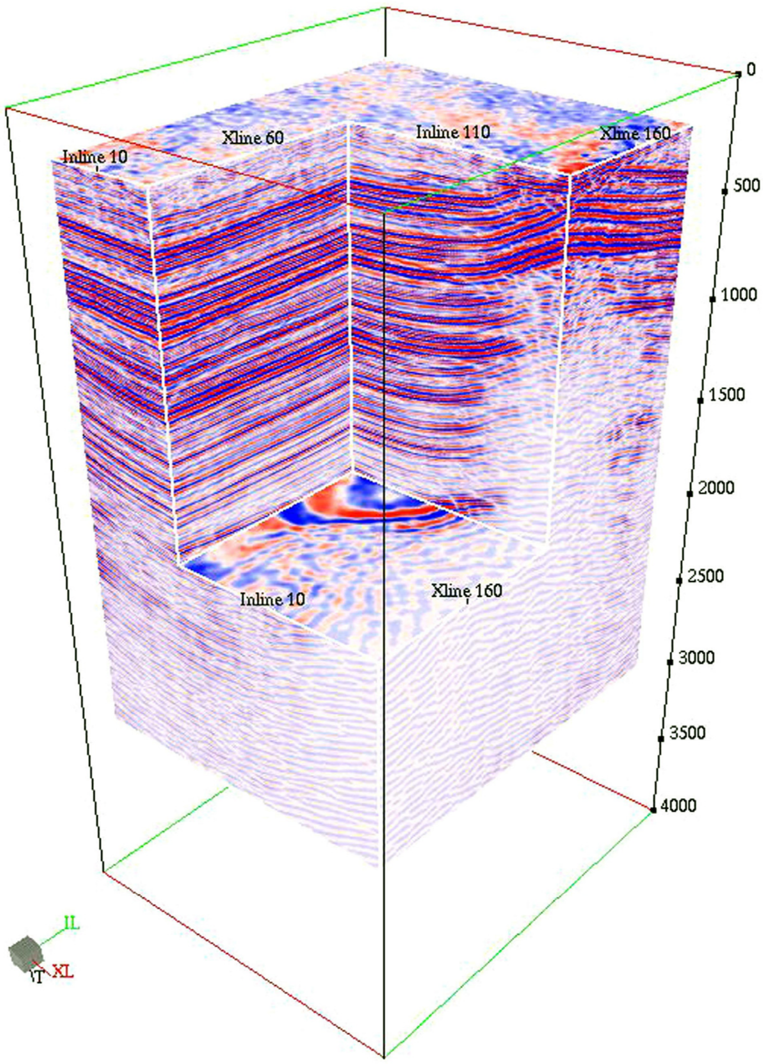


Fig. 5.11. Temporal seismic cube

5.5. Structural and Dynamic Interpretation

Analysis of temporal cross-sections and temporal cubes with allowance for the velocity structure of the cross-section (fig. 5.12).

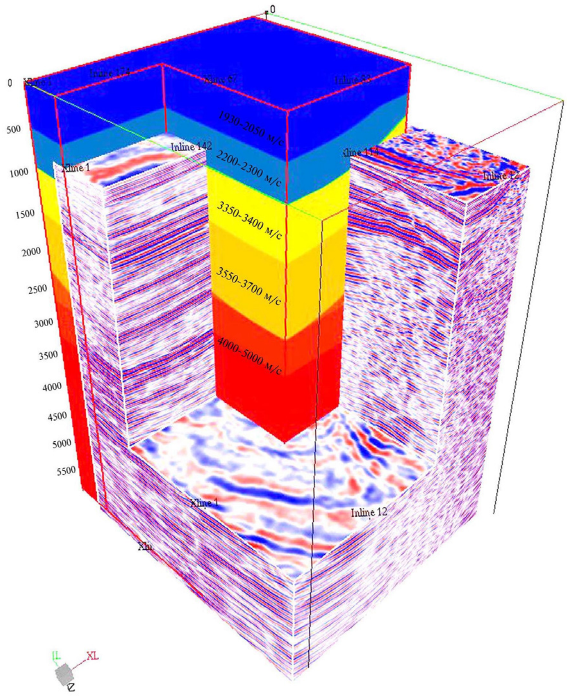


Fig. 5.12. Correlation of the temporal seismic cube with the depth-velocity medium model

It makes possible to determine the spatial position of seismic boundaries (fig. 5.13).

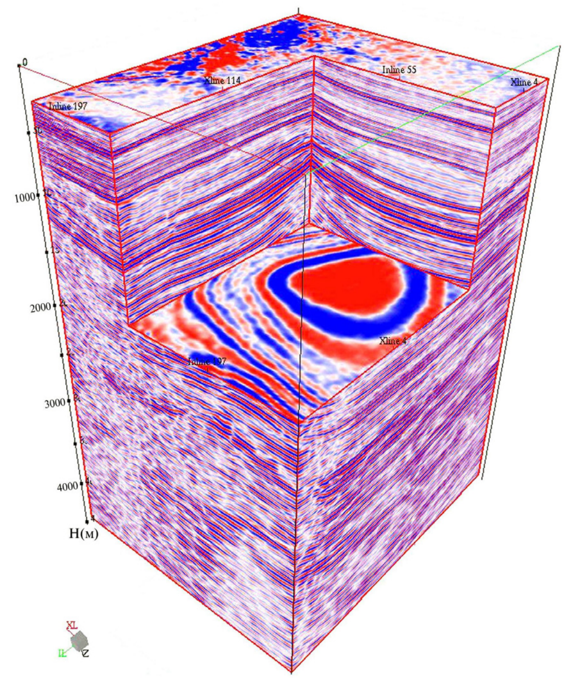


Fig. 5.13. Depth seismic cube

It also develops structural maps along the main reflecting horizons (fig. 5.14).

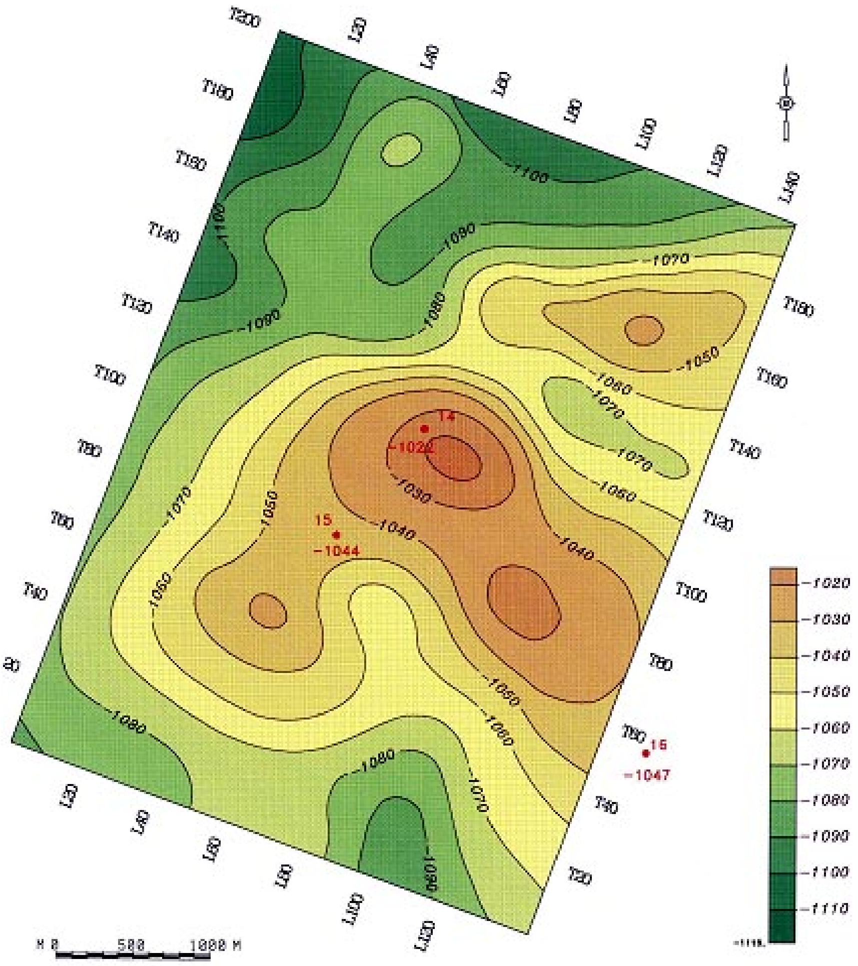


Fig. 5.14. Structural map plotted along the reflecting horizon

Since the rocks, which differs in their lithological and age composition, are different, as a rule, in the velocity of elastic-wave propagation, the sesmic boundaries, as a rule, has certain lithological-stratigraphic links in the cross-section. This regularity makes it possible to identify lithological and stratigraphic features of the studied cross-section basing on the seismic survey data.

5.6. Notion of the Engineering Field Model

The geological and engineering seismic survey model includes three interrelated elements: digital database, digital geological model, and digital hydrodynamic model. It is a mathematic representation of the development object and makes it possible to use up-to-date mathematical tools to obtain fast predictive assessments of various geologic engineering variants of solving production problems and to determine their economic efficiency.

In favorable geological and geophysical situations, one can predict physical properties of rocks basing on combined interpretation of the data of seismic observations and materials of geophysical borehole surveys (fig. 5.15).

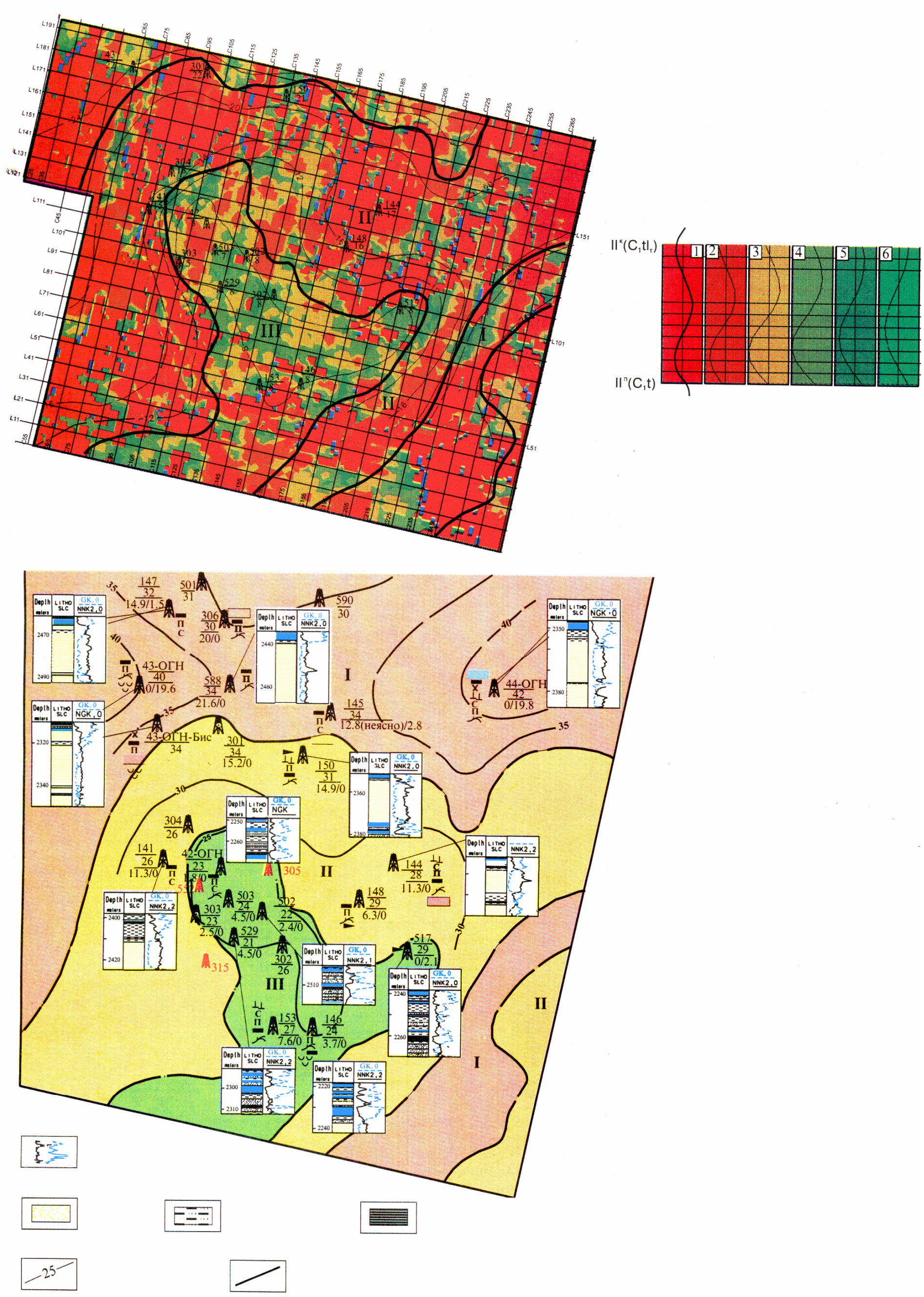


Fig. 5.15. Lithologic-and-facies scheme
of the Bobrikov horizon (Permian Cis-Kama region):
I – clay-sand sediments in the river bed (80–90 % of sandstones);
II – clay-silt-sandy sediments in the river bed (60–80 % of sandstones);
III – sand-silt-clay sediments in the flood land (25–35 % of sandstones)

Fig. 5.16 even reveals direct effects of hydrocarbon deposits (fig. 5.16).

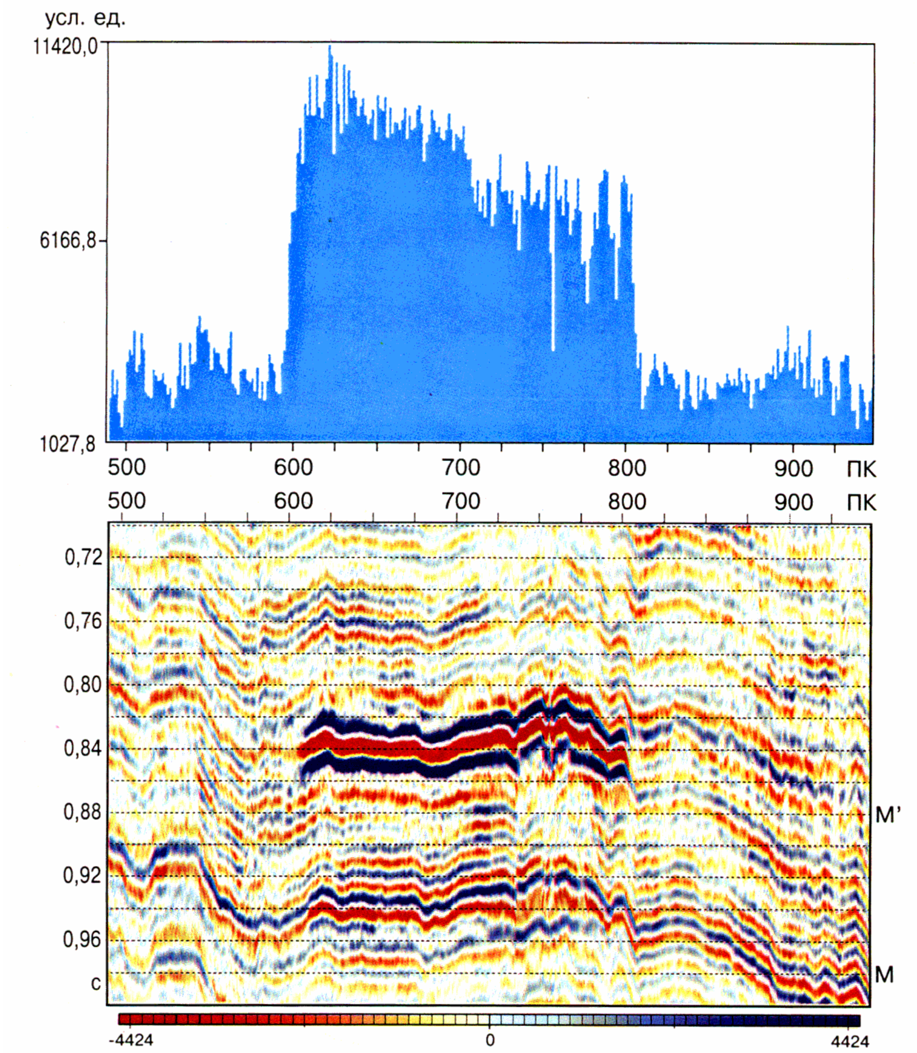


Fig. 5.16. “Bright-spot” anomaly over gas (Western Siberia)

Conclusion

The methods of field geophysics can be also categorized into the methods studying potential natural (gravimetric and magnetic prospecting) and wave natural and artificial (seismic and geoelectric prospecting) fields. In the recent decades, the sphere of the use of applied geophysics has been widening continuously. Considerable funds are spent on its application. It is used mainly to search for oil and gas fields, when the main search method is seismic prospecting. A considerable place is taken by searching for productive deposits of other minerals, e.g., iron ore. In this case, non-seismic method are used mainly. The area of application of geophysical methods when solving various applied tasks is continuously growing.

Course of lectures in

PROBABILISTIC ESTIMATES USED TO SUBSTANTIATE INVESTMENTS IN HYDROCARBON EXPLORATION*

Topic 1. Introduction. Basic definitions

The lectures address the issue of estimating geologic and economic efficiency of the explorations. Let us introduce a number of terms to be dealt with below.

Hydrocarbon deposit exploration means a scope of geologic work, stage I of which involves area-wide geophysical investigations, while the final stage of which includes deep well drilling. Area-wide investigations primarily mean seismic investigation techniques i.e. 2D detailed seismic survey. Seismic survey aims at finding anticline targets. Seismic investigations result in prepared oil or gas promising structures characterized in quality terms by quantities of prospective resources subsumed under category C_3 – RC_3. This stage still fails to establish commercial oil and gas bearing capacity of targets.

The next stage of the exploration consists in deep drilling (in Russia – 1,500–2,500 m) to discover new hydrocarbon deposits. A field could be considered discovered once the wells start yielding commercial inflows sufficient for the further development of the field with economic profitability. Deep drilling results provide a basis for governmental agencies to make the field reserves calculation required for evaluating reserves of commercial categories (category C_1 and upwards) – QC_1. Reserves of commercial categories (Russian classification) within the world classification serving as a benchmark for world exchange markets do roughly correspond to reserves of the PDP development areas category.

Deep well drilling is the most expensive exploration stage. Exploration efficiency is characterized by success ratio that is nothing but commercial oil field discovery probability - $P_{\text{усп}}$. Average world-wide exploration success ratio (the relationship between hydrocarbon deposits discoveries and total number of deep exploratory wells) is rather low accounting for no more than 30 %. Therefore, economic planning of exploration efficiency prior to deep drilling is one of the most significant optimization problems facing hydrocarbon deposits explorers.
Shown below are the following economic estimates meeting requirements of generally accepted world practice:

– net present value (NPV) – oil sales receipts plus depreciation charges minus development CAPEX;

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– productivity index (PI) – economic return on invested funds representing the relationship between total present cash flow and total discounted amount of CAPEX;
– payback period is a number of years (DPP) that should elapse to make initial negative accrued cash flow be fully set off by its further positive values;
– internal rate of return (IRR) is determined by the calculation of such variable discounting rate, given which total cash flow amount during an estimate-covered period is equal to zero.

Topic 2. Substantiation of need for using success ratios to evaluate prospects of local structures

At present, to make exploration-related investment projects capable of handling their major task i.e. profit maximization, their prospects are evaluated with due use of such geological-economic indicators as net present value (NPV), productivity index (PI), payback period etc. However, the procedure of calculating geological-economic indicators as applied in practice to planning oil and gas exploration would generally be similar to procedures applied for example in building industry. Given such an approach, the risk would only be assessed in terms of potential changes in price trends (amount of CAPEX or OPEX, price of finished product, currency exchange rate etc.).

Aspects of economic planning under conditions of uncertainty have been addressed in many studies. Risk assessment aims to evaluate (by some means or other) the influence of change in any background data on economic indicators of the project, and to determine whether such indicators are capable of assuming various values. The most common methods of risk assessment are point-estimation method, discrete probabilities method (probable outcomes tree) and distribution modeling (Monte-Carlo). Each of the above methods is based on the multi-choice calculation of NPV as a function of certain pre-set variables.

Point-estimation method proceeding from the assumption of a certain combination of values e.g. CAPEX and product prices obtains three NPV values, one of them is the basic one (M) with two others i.e. potential maximum (optimistic option O) and minimum (pessimistic option П). Three known values of NPV enable to evaluate the probability of its equality to a certain pre-set V. Probability that V =0 could be determined by the following equations:

$$P=A^2/B, \quad \text{if } M<V<O$$

or

$$P=1-(1-A)^2/(1-B), \quad \text{if } M>V>O,$$

where $A=(V-\Pi)/(O-\Pi)$ and $B=(M-\Pi)/(O-\Pi)$.

A weakness of the point-estimation method consists in a fairly rough estimate of distributing the analysis-covered quantities amongst three random values. Apart from this, such method handles resultant quantities of NPV that constitutes complicated functions of many variables, different values of which are not equally probable.

Discrete probabilities method directly uses original variables (product price etc.), various values of which are given credit for certain prior probabilities, while the probability of any combination of parameters (scenario) is determined by product of particular probabilities of initial events. A disadvantage of this method, for example in estimating product price variation influence of NPV, is postulated probabilities of initial values, as well as fixed and symmetric nature of probabilities distribution.

According to Monte-Carlo method, initial parameters are preset as continuous distribution functions considered standard for each of the values (normal, lognormal etc.). These distributions are used to perform computer-aided random sampling of values and each parameter's probabilities corresponding to them, and to divide them into scenarios in order to calculate final *NPV* for each of them. Special-purpose computer software may bring the number of such scenarios to several thousands. Obtained NPV values are used to plot histograms and cumulative probability charts (distribution curves), analysis of which enables to evaluate the most probable outcomes of the project implementation. Worth mentioning is the fact that Monte-Carlo method considers target parameters as independent quantities although in fact they are often interrelated.

Assessment of price risks alone is generally well-grounded to handle many geological tasks. For example, such approach could prove a success in evaluating development prospects of gold ore deposits. However, as concerns oil prospecting projects, the approach requires significant customization due to the complexity of reliably predicting the reserves in fields prior to penetrating them with deep wells.

As far as oil (gas) projects are concerned, it is required to realize that even the estimate of commercial category reserves yielding commercial inflow is characterized by significant errors and might widely range. The range of errors that could potentially take place in determining geological recoverable reserves could, as field development actual data show, quite frequently reach 60–80 % and even exceed these estimates.

Errors accompanying estimation of reserves depend not only on field available information, but on the extension of fields and complexity of their structure. Lower confirmability is peculiar to small fields. For example, according to reserves confirmability data in an area for a long period with respect to category C_1 reserves amounting to more than 10 M t, confirmability proved as high as 96.1 % and those less than 10 M t – merely 73.2 %. Therefore, such a sign as geological structure complexity (variation of oil-filled thickness and reservoir properties, average number of permeable intervals etc.) could, in evaluating confirmability of reserves, be considered subordinate to pool extension.

Risks arising out of potential losses due to the wrong determination of undiscovered reserves level would significantly complicate design efforts in oil and gas industry. If as generally accepted, for example, in machine building, about 85 % of its product prime cost would be determined at design stage, then even at the late stages of oil and gas field development, production costs value would widely vary depending on development plans. Apart from this, a peculiarity of oil and gas producing industry is markedly uneven territorial distribution of hydrocarbon fields and long distances to consumers of its products. Consequently, oil and gas projects are characterized by early growth of capital expenditures on infrastructure, environmental protection etc. As a result, if the cost of machines and equipment in general industry accounts for nearly 40 % of all assets' cost, their share in oil and gas producing industry is 16–18 %. At the same time, less than 70 % of all capital expenditures are used to drill new wells belonging to the passive part of fixed assets. Thus, the issue of making the estimate of reserves and especially resources in oil and gas industry reliable is one of the most relevant ones for investments planning.

Characterized by a greater extent of uncertainty than reserves of commercial categories are resources of oil fields, the forecast of which should precede deep drilling. A consequence of this is a higher degree of investment risks, which predetermines the necessity of probability-statistical approach to the estimate of exploration prospects. Enormous costs incurred in exploring hydrocarbon fields (as compared to other geological exploration tasks) could result not only in lost profit (project red ink position), but totally deprive the whole project implementation of positive investment inflows. Such risks having nothing to do with economic characteristics would generally be determined by geological and partly technological causes. Another significant feature of these risks is that given no further scopes of exploratory activities in areas of structures, geological risks in time could be assumed continuous.

Thus, should the estimate of oil and gas exploration project fail to entirely address the risks related to their potential negative result, economic estimates will significantly be distorted. Moreover, failure to take an entire account of exploration risks will have a more adverse effect on results of oil and gas exploration planning than for example the model simplification by assuming all price characteristics during the project implementation equal to values they had at the design stage. Subjective assessment or failure to entirely assess exploration risk could lead and would often lead to wrong conclusions at exploration planning stage.

Let us shortly dwell upon the scheme of evaluating efficiency of investment projects without regard for exploration risks. Calculated at Stage I are required scopes of geophysical and structural-parametric investigations used as a basis for evaluating the growth of prospective resource belonging to category C_3. Then, taking into account factor ($K_{пер}$) used to convert prospective resources into explored reserves and normally assumed as high as 0.40–0.70, expected reserves C_1 will be assessed in the following manner: $C_1 = K_{пер} \times C_3$. Based on the estimated reserves C_1 and well production rates expected in the region according to relevant regulations, the number of wells required for the target development will be calculated. All stages of the field development will involve approximate assessment of empty and producing wells. Thus, the above information provides a basis for calculating both costs and profits of the projects. Then, with appropriate discount factors put in, and geological-economic estimates *NPV*, *PI*, *PBP* calculated, the investment project will be estimated.

Such approach contains an error of principle as far as conversion of resources C_3 into reserves C_1 is concerned as it makes no allowance for potential exploration risks in various territories. According to exploration experience, a significant number of exploratory wells even despite of well thought-out decision making process would at any rate prove empty. Results of ignoring exploration risks could be illustrated by the following abstract example.

Let us assume that a certain area contains 10 targets prepared to deep drilling. Each of the targets has recoverable resources of category C_3–1 million tons. Let us assume that the ratio of converting resource of category C_3 into reserves of category C_1 is 0.70. This situation could be interpreted in two options. Option 1 consists in the reduction of reserves in each field to 0.7 million tons. According to option II that is closer to the truth, drilling should result in preparing 7 targets with reserves of 1 million tons in each. In such event, three drilled targets will prove non-productive. In both events, total recoverable reserves C_1 of the considered area are equal to 7 millions tons (10×0.7 or 7×1) i.e. the conditions C_1=0.7×C_3 is met (fig. 2.1).

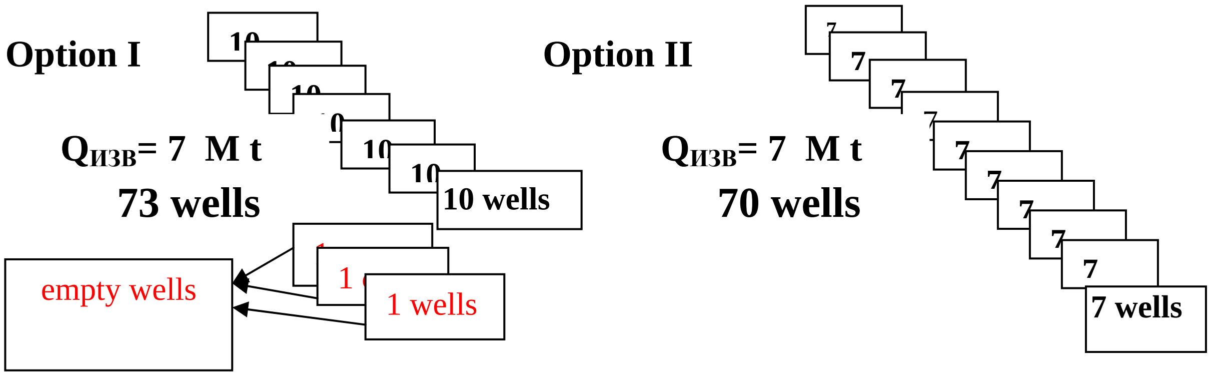

Fig. 2.1. Various schemes of converting prospective resources of category C_3 into reserves of category C_1

Let geological-economic conditions of the area be such that each well following a prospecting well (i.e. exploratory or production well) should be designed to develop reserves of 0.1 million tons. Thus, under Option I, each of 10 productive targets will be developed by means of 7 wells, while the whole area – by means of 70 wells. Under Option II, production targets of the area with total reserves of 7 million tons will also be developed by means of 70 wells. Apart from this, drilled under Option II will at least be 3 empty prospecting wells. As a result, under Option II as compared to Option I with the same growth of expected reserves and production rate, at least 3 excessive prospective wells will be drilled, and drilling efficiency (t/m) will accordingly be lower.

At first, prospecting wells are the most expensive ones. Worth mentioning is the fact that the major reduction of economic indicators such as drilling of excessive prospecting wells will take place at the initial stage that is particularly important (especially with due regard for introducing discount rates) for positive economic balance. For example, according to the example discussed above, with the potential for simultaneous commissioning of all 10 targets at stage I, only 7 targets will be used for production, which will reduce the expected production by 30 %. On an average, international experience indicates that success of drilling for oil has recently amounted to 30 %. Thus, actual number of empty wells will most likely be much higher than 30 % (3 of 10) with their number approximating to 70 %.

International experience of investigations related to modeling economic estimates of hydrocarbon exploration projects has been analyzed for a fairly long period. At the same time, application of methodical approaches widely differs as to oil deposits exploration projects and standard models of share markets, where selection criteria are restricted by 4 major parameters: time, difference between current and initial prices, rate of return and price fluctuation. Oil exploration would never bring immediate return on investments; expected revenues would normally be obtained 2–4 years later. Life cycle of huge discoveries projects is under 100 years, during which hydrocarbon prices would more than once change upwards and downwards. With regard for this, exploration projects viability criteria would be determined by technologies capable of reducing the projects costs and risks, but not those capable of keeping oil prices high.

The overwhelming majority of large oil companies try to invest their funds in large-scale and long-term exploration projects with huge promising reserves adequate to ensure steady production revenues for years to come. Accordingly, it is normally recommended to estimate project economics on the basis of pessimistic, the most likely and optimistic scenarios of exploration development taking mainly into account the expected discoveries of reserves. The latter would mainly undergo expert appraisal resulting in high subjectivity of decision-making process.

Absence of quantitative probability estimates of exploration success result in high subjectivity and failure to take an entire account at exploration risks designing stage. In early nineties, the majority of leading foreign oil companies acknowledged the fact that their salaried scientists were continuously overestimating expected reserves usually exaggerating them by 30–80 %. Many studies point out such an 'optimistic' deviation of predicted reserves. In particular, even with an allowance of using the latest technologies, deep-sea BP-Amoco's projects have demonstrated only 45 % of predicted reserves, while the Norwegian Sea exploration have proven merely 38 % of predicted reserves.

The major cause of overestimating the predicted reserves is failure to take into account geological risks of exploration and namely failure to make a proper allowance for their potential negative results. Risks of oil and gas explorations are primarily related to the potential absence of commercial oil and gas content, and therefore they should be primarily monitored by exploration success ratio ($P_{\text{усп}}$).

Topic 3. Probabilistic-statistical estimation of local structures exploration success ratio

Let us state the task and sequence of steps taken to probabilistic-statistical forecast of oil and gas content prospects in local structures prepared to deep drilling. At stage I, based on comparative investigation of fields and structures withdrawn from drilling with negative and positive results, it is required to choose an informative system of signs that allows for confidently classifying investigation targets judging by prospects of their commercial oil and gas content. On the basis of the obtained informative system, investigation and forecast targets will undergo probabilistic estimation of commercial hydrocarbon reserves discovery success ratio ($P_{\text{усп}}$).

The probabilistic estimation used to describe targets prepared to deep drilling $P_{\text{усп}}$ will enable to take into a more objective account the exploration risks during economic calculations of investment projects associated with them, which will make it possible to rank them in terms of implementation prospects. It is obvious that in predicting prospects of targets at pre-drilling stage, the potential for obtaining the initial totality of signs should be provided prior to deep drilling of structures. Apart from this, all indicators should be digitalized and reflect major components of hydrocarbon accumulations formation process.

The as-is accommodation of oil and gas accumulations in the earth is a result of many factors. Therefore, the forecast of prospects should be based on the account of a set of indicators. The problems of choosing an attribute space is one of the major issues encountered in handling prediction tasks. In accordance with principles of sedimentary-migration theory, it is ideally required to confirm the presence or absence of suitable conditions for bringing about and burial of the initial organic matter, its transformation into hydrocarbons of gas and petroleum series, migration into reservoir beds, subsequent secondary and intra-reservoir migration, accumulation in natural traps, preservation of resultant pools at subsequent stage of geological development.

Thus, probabilistic estimation of exploration success ratio is a function of probabilistic characteristics of generation, migration, accumulation and preservation, as well as confirmability of targets structure plans: $P_{усп} = f(P_{ген}, P_{мигр}, P_{акк}, P_{сохр}, P_{подт})$. Proper handling of this task needs a wide array of geological, geochemical, lithologic, hydrogeological and geophysical indicators. However, the majority of such indicators will remain unknown prior to drilling local structures. Apart from this, failure to determine the mass of these indicators leads to the incorrect application of probabilistic-statistical forecast methods.

Chosen indicators should reflect various features of local targets under investigation and geological conditions around them. Estimation of local structures oil and gas content prospects should rely upon the comprehensive use of indicators. On the other hand, the number of the indicators should not be too large. In this connection, prediction estimate within the limits of structures prepared to deep drilling should be mainly performed with the use of tectonic indicators.

Thus, the exploration success ratio $P_{усп}$ should be estimated for each individual local structure. Given a large number of drilled targets with positive and negative exploration results and information about geological properties of such targets, this task could be solved by probabilistic-statistical methods.

One of the recommended ways for solving this task could be the method of plotting probability curves. Initially it is required to plot distribution probability curves of these estimates $P_{усп}$ for each analyzed indicator of the learning sample. This will be based on the deep drilling-resulted information about classes, to which the structures belong. The above formulas will be used within each interval k of the indicators' values to calculate interval discrete values $P_{усп}(k)$, further averaging of which enables to transfer from the discrete values to plotting continuous probability curves. Considered as information-bearing in this case will be indicators, probability curves of which have regular distribution, and do not conflict with physical sense of the phenomenon under study.

An example of such a information-bearing curve from the indicator of structures' amplitude is shown in fig. 3.1. The probability curve appearance is indicative of the fact that over the whole range of the structures' amplitude, exploration prospects $P_{усп}(A)$ grow with the increase of the target dimensions.

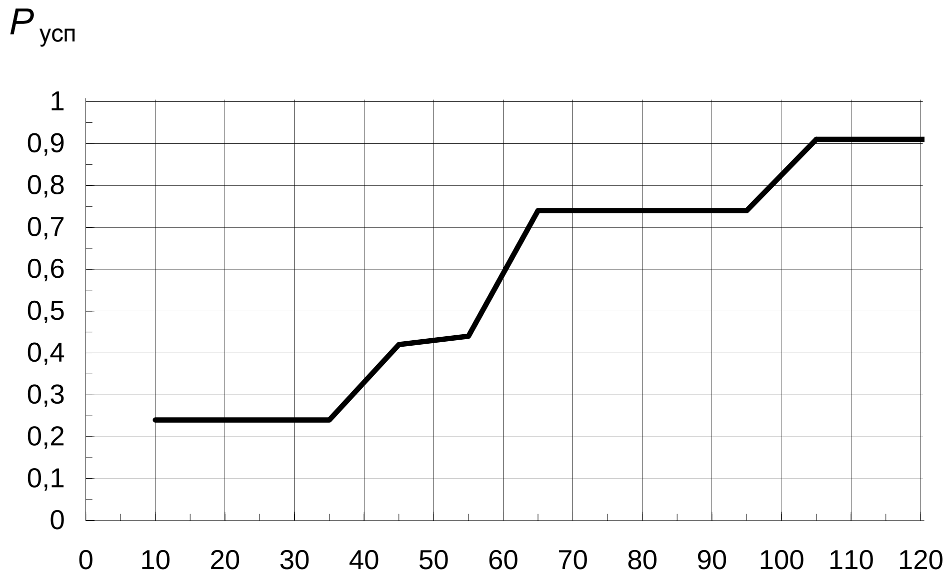

Fig. 3.1. Probability curve of exploration success ratio $P_{усп}$ depending on structures' amplitude

Thus, all information-bearing indicators could be characterized by appropriate probability curves. However, it is obvious that neither of any individual indicators could be used to reliably predict the prospects of local targets. Prediction efficiency could be significantly enhanced only in the event of the integrated use of information-bearing criteria. Should all indicators be independent on one another, their integrated influence on $P_{усп}$ could be provided with the use of statistical algorithms of independent events evaluation. However, the condition of the indicators' mutual independence would normally be never met in practice. Taking this into account, the evaluation of integrated influence of information-bearing indicators could be made more reliable with the use of the following approach.

Let us consider its implementation algorithm. Let the number of the learning sample targets be equal to i, and the number of indicators considered information-bearing ones be equal to j. At the same time, appropriate probability curves $P_{усп}$ (j) are plotted for each jth information-bearing indicator. Now, on the basis of probability curves, probabilistic estimation could be obtained for each ith target of the learning sample depending on the jth indicator's value $P_{усп}(i;j)$. A significant peculiarity of probabilistic characteristic $P_{усп}(i;j)$as distinct, for example, from the jth indicator's value that is its original value, consists in linearity of its distribution over probability scale from 0 to 1. Therefore, probabilistic estimations of $P_{усп}(i;j)$ could be made with the use of linear statistical estimates including linear multiple regression method.

This method aims at finding a certain function capable of giving a maximum reliable description to a certain phenomenon depending on a multitude of mutually independent (almost independent) indicators. Reliability measure of the sought function is multiple correlation coefficient R that reflects convergence of actually observed and predicted (with the use of the model) values. Mathematically this could be done by minimizing square of differences of predicted and observed values (residuals). A significant peculiarity of the method is nonbias of the predicted values relative to actually observed ones, i.e. equality of their average values.

Implementation of the method results in plotting the following linear multiple regression equation:

$$P_{\text{усп}} = \text{const} + a_1 P_{\text{усп}}(\Pi_1) + a_2 P_{\text{усп}}(\Pi_2) \dots + a_j P_{\text{усп}}(\Pi_j),$$

where $P_{\text{усп}}(\Pi_1)$, $P_{\text{усп}}(\Pi_2)$, $P_{\text{усп}}(\Pi_j)$ – probabilistic estimations of success ratio respectively from information-bearing indicators *1*, *2* and *j*;

a_1, a_2, a_j – regression equation coefficients;

const – absolute term of the regression equation.

Should there be no large amount of statistical information, values $P_{\text{усп}}$ could be assumed on the basis of expert opinion with an allowance for general data on geology of targets and its major properties. For example, larger targets must generally have greater prospects and values $P_{\text{усп}}$. The principal thing there is making probabilistic estimation $P_{\text{усп}}$ prior to deep drilling at a prospective target.

Topic 4. Probabilistic-statistical estimation of reserves increment under petroleum exploration projects

Apart from field discovery prediction estimate, one of the major components of exploration prospects forecast consists in the prediction of their reserves increment quantities. It is obvious that as there are factors making exploration results uncertain, such prediction tasks could only be handled in probabilistic-statistical manner. Thus, with $P_{\text{усп}}$ found, the next stage of this work consists in the probabilistic estimation of reserves increment ($P_{\text{зап}}$). In this case, on the basis of adjusted quantities of the expected reserves, economic planning should provide for the calculation of well stock, hydrocarbon production performance, operating and capital expenditures etc.

It is worth mentioning that as concerns the territories where «Tatneft» and «LUKOIL» operate (European part), oil reserves of commercial categories Q_{C1}, according to foreign audit, are in adequate conformity to proven reserves calculated as per SPE and WPC international classification. Therefore, in evaluating exploration projects in these territories, the reliable estimate of the categories' reserves could serve as a benchmark for investors including foreign ones.

Reserves of commercial categories Q_{C1} should be evaluated with due regard for quantities of the resources according to data of seismic survey R_{C3}. To do this, it is required to compare quantities Q_{C1} and R_{C3} in the already drilled wells.

It is obvious that equation $Q_{C1}= f(R_{C3})$ will differ in each territory. Fig. 4.1 shows an example of drawing such an equation $Q_{C1}= f(R_{C3})$ in practice. Learning sample comprised 98 discovered fields. The resultant functional relationship is in this case close to linear and could be described by the following function:

$$Q_{C1} = 1.1741R_{C3} - 0.0535$$

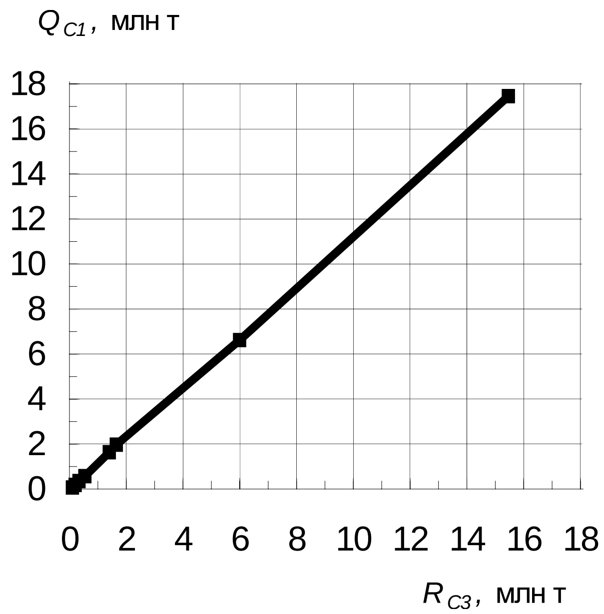

Fig. 4.1. Relationship between values of recoverable reserves (C_1) and prospective resources (C_3) for regions of south-eastern barrier reef BKB

Structures with resources under 0.4 *M t* reveal approximate correspondence of reserves to resources quantities, while structures with larger resources reveal excess of reserves over resources.

Thus, based on resources of the structures, prior to deep drilling, it is possible to predict the quantities of structures reserves, and use them as a benchmark for economic planning of exploration results.

Topic 5. Probabilistic-statistical substantiation of oil and gas exploration projects prospects

In practice, it is extremely important for investors to objectively compare a number of alternate investment projects to choose the most efficient ones. A similar problem of choosing a project to be implemented out of certain alternate ones is always facing governmental authorities. It is obvious that projects with negative values of MO (NPV) are inefficient and should not be implemented. Exception could only be made in the event of implementing projects essential for handling certain strategic goals. The best one among the projects with positive economic indicators will certainly be a project with the highest value of MO (NPV), the shortest payback period, the lowest investments etc.

However oil and gas exploration project would always widely differ in terms of investments required for their implementation. A project could appear highly fund-consuming, have long payback period, but its revenues following its implementation (NPV) could by times be higher than those of an alternate low-budget project with a lower payback period. In such an event, the available references suggest the following optional approach. All cash flows of a low-budget project (negative and positive ones) are multiplied by value (*n*) proportional to the relationship between costs of high-budget and low-budget projects.

Thus, a high-budget project is compared with a certain number (*n*) of low-budget projects. Such an approach seams to be rightful to a certain extent, but there are no much enterprises capable of investing their moneys into a large number of projects as efficient as a low-budget project under assessment. Occurring more often is the situation where an enterprise has a fixed amount suggested to be used. Quite logical in this case is the approach to choosing an optimum package of projects within the limits of the fixed amount. This could be done for example with the help of a probability tree, calculation and comparison of mathematical expectations of economic indicators MO(NPV), MO(DPP), MO(PI) of investment options under consideration.

As value NPV has additive property, its mathematical expectation value is calculated by summation of its probabilistic components. This justifies the following formula:

$$MO(NPV) = NPV3 + NPV2 + NPV1 \text{ or}$$

$$MO(NPV) = \boldsymbol{P}_{\textbf{негеол}} \times P_{\textbf{усп}} \times (\text{ПР} - Z_C - Z_Б - Z_Э)\ \boldsymbol{P}_{\textbf{негеол}} \times (1 - P_{\textbf{усп}}) \times (Z_C + Z_Б) - (1 - \boldsymbol{P}_{\textbf{негеол}}) \times Z_C$$

where ПР is product sales revenues;

$Z_С$, $Z_Б$, $Z_Э$ – costs incurred respectively on seismic survey, deep prospecting drilling and development drilling.

In territories where there are no non-geological risks, $NPV1$=0, and calculation formula will be essentially simplified:

$$MO(NPV)= P_{усп} \times (ПР–Z_C–Z_Б–Z_Э)–(1–P_{усп}) \times (Z_C+Z_Б).$$

Where $MO(NPV)<0$, the project is loss-making, while where $MO(NPV)>0$, it is profitable. The very moment of $MO(NPV)=0$ could be considered as mathematical expectation of time that should elapse to return investments into the project. At the same time, it is expected that the calculations could include discount coefficients to make allowance for the would-be inflation and capital price, economic risks etc. The higher the project's risk as estimated by the investor, the higher the project's profitability requirements imposed by it. The calculations would show this as the increase of discount rate i.e. risk adjustment (risk premium). Such a method is widely recommended in financial books and is frequently used in practical calculations. It could be expressed as probability tree (fig. 5.1).

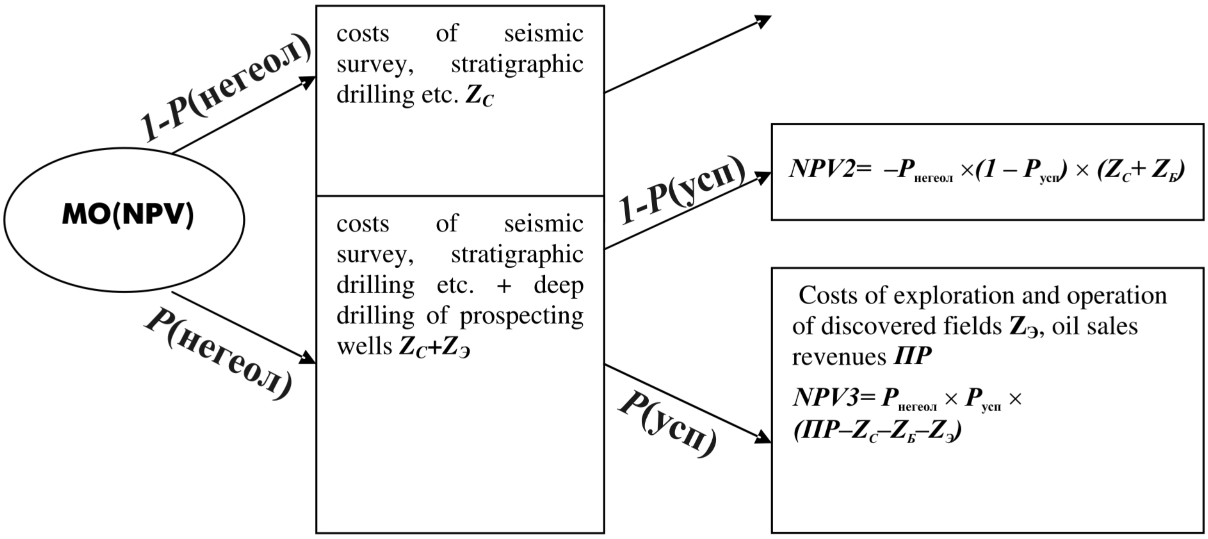

Fig. 5.1. Algorithm used to calculate mathematical expectation of *NPV* for exploration target to be drilled

Indicators $MO(NPV)$, $MO(DPP)$ only evaluate the most likely quantities of net present value and payback period of investment that will only be known on completion of the project. It is obvious that the extent of potential deviations from them in the course of planning unknown quantities will be primarily determined by prospecting success ratio i.e. probabilistic characteristic $P_{усп}$. The lower $P_{усп}$, the higher the risk of the project implementation, and therefore, the lower its efficiency given all other conditions equal. However, such conditions could be unequal. Quite frequent is the situation, where a project more efficient in terms of mathematical expectations *NPV*, *DPP* is characterized by higher risks. Thus, the comparison of project with various geological-economic conditions (primarily) prospecting-related risks could become a more complicated problem than the comparison of projects different in terms of costs.

According to the analysis of hydrocarbon prospecting investment project evaluation as-is status, their potential negative results are not adequately taken into account. At the same time, the estimate of probabilistic success ratio ($P_{\text{усп}}$) and quantity of reserves potential increments (C_1) for each specific local structure could enable to calculate probabilistic distribution of quantities of reserves total increments over all structures to be drilled within the prospecting project framework. Therefore, the next stage will consist in predicting prospecting projects implementation risks by comprehensive generalization of structures-related information.

The developed methodology was used at stage I on the basis of quantities of probabilistic estimates to calculate the potential for discovery of 0, 1, 2 … fields $P_n(m)$ due to deep drilling of n of forecast targets. In this case, where probabilistic-statistical estimate characterizes the prospects of specific local targets ($P_1, P_2, \ldots. P_n$), the probability picture could be obtained with the use of probability binomial distribution formula for generating function:

$$\varphi_n(z)=(P_1z+(1-P_1))(P_2z+(1-P_2))...(P_nz+(1-P_n)).$$

Occurrence probability of event $P_n(m)$ is equal to generating function expansion coefficient at z^m, that in turn could be calculated in the following manner:

$$P_n(m)=\Sigma\, P_{i1}...P_{im}(1-P_{im+1})\ldots(1-P_{in}),$$

where n is the number of targets to be prospected;

m – the number of prospecting successful outcomes, m = 0.1, …, n.

Let us consider the possibilities of the proposed approach using the practical example already referred to above. As an example of prospecting project, table 1 shows data related to prediction estimate of presently drilled structures as compared to actual drilling results. Analyzed for the project are prospects of deep drilling of 12 structures.

Table 1

Forecasting Oil Pay Zone Classification Results

Structure	Drilling results	$P_{усп}$	R_{C3}. *M t*	Q_{C1}. *M t*	Actual. *M t*
Target 1	negative	*0.52*	*0.195*	0.17	0.000
Target 2	negative	*0.44*	*0.275*	0.27	0.000
Target 3	field	*0.72*	*0.116*	0.08	0.184
Target 4	negative	*0.42*	*0.269*	0.26	0.000
Target 5	field	*0.48*	*0.365*	0.38	0.314
Target 6	field	*0.70*	*0.367*	0.38	0.043
Target 7	field	*0.76*	*0.177*	0.14	0.016
Target 8	field	*0.87*	*0.091*	0.07	0.142
Target 9	field	*0.50*	*0.753*	0.83	0.020
Target 10	field	*0.57*	*0.349*	0.36	0.046
Target 11	field	*0.61*	*0.217*	0.20	0.776
Target 12	field	*0.70*	*0.234*	0.22	0.130
Total:			***3.408***	***3.358***	***1.671***

At Stage I, binomial distribution of probabilities allows for calculating probabilistic distribution of potential number of discovered fields. The results are shown in fig. 5.2. In particular, it is obvious that according to this example, with 12 targets prospected, the most likely result will be discovery of 7–8 fields, the probability of which only accounts for 46 %.

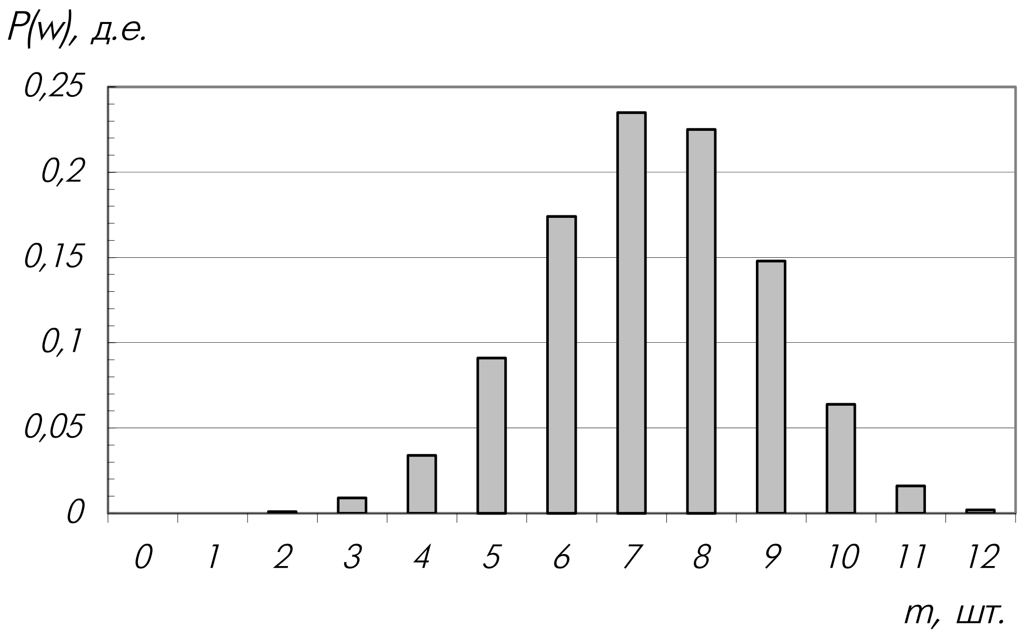

Fig. 5.2. Probabilistic distribution of the number of discovered fields for prospecting project

It is obvious that the number of discovered fields fails to fully determine geological efficiency of the prospecting project without regard for total increments C_1. The task of the transfer from the number of potential discoveries to potential increments could in the easiest case be handled by means of the proportional averaging of reserves increment by a single discovered field. In this case, we initially find total quantity of forecast reserves such as:

$$\sum_{1}^{n} Q_{C1} = Q_1 + Q_2 + Q_3 + \ldots + Q_n.$$

Then, in order to find the forecast increment following the discovery of fields *m*, the total increment is divided by *m*. For example, should the maximum forecast increment following the discovery of all 12 structures (m=12), as shown in the example, be $\sum Q_{C1}$ i.e. 3.358 (Table 1), the most likely estimation Q_{C1} following the discovery of 5 structures (m=5) will be:

$$Q_{C1}\,(m=5) = \sum Q_{C1}\,/(n - m) = 3.358/(12–5) = 0.480\ M\ t.$$

In our example, according to the forecast, the most likely result following drilling of 12 targets will be the discovery of 7–8 fields (46 %). Based on relationships $Q_{c1} = f(R_{C3})$, calculated for each specific local structure were potential increments of reserves as shown in table 1 (column Q_{C1}). Then, the proposed methodology for potential increment rates was used to calculate distribution densities *f(x)* and distribution functions *F(x)*. Based on the appearance of *F* (*x*) (cumulative curve), one can estimate the hydrocarbon increment values corresponding to various probabilities (fig. 5.3). For the present case, predicted with 90 % reliability (P_m) is reserves quantity more than 1.5 million tons, mathematic expectation *M(x)* accounts for 2.12 million tons (fig. 5.3).

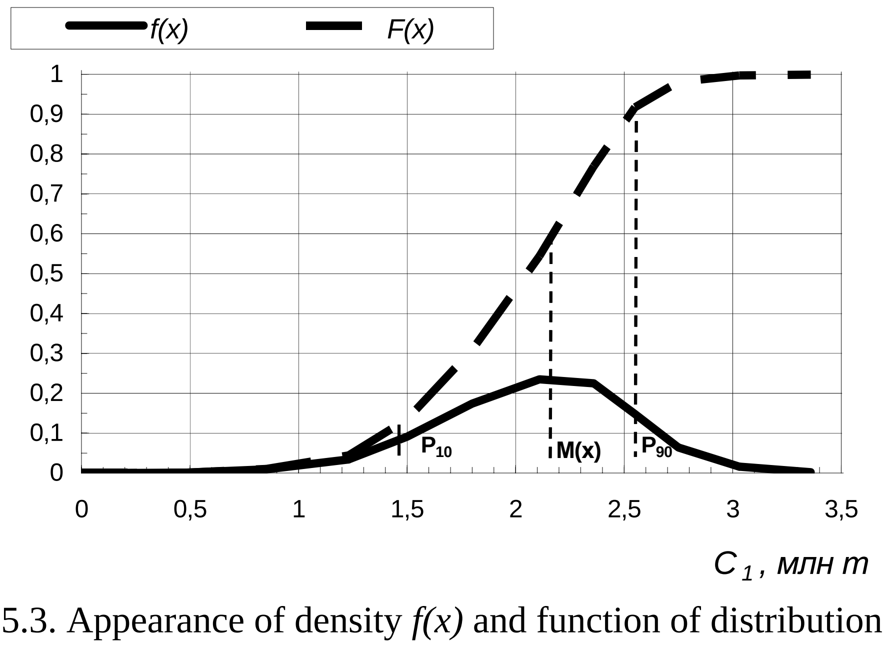

Fig. 5.3. Appearance of density *f(x)* and function of distribution *F(x)* of hydrocarbon reserves increments calculated by generating function formula (binomial distribution) for prospecting project

By present, all the forecast targets have already been drilled. The forecast was performed prior to drilling, and therefore, we are capable of comparing forecast results with actual data (right column from Table 1). 9 fields were actually discovered there including 2 with insignificant reserves of less than 20 thousand tons. Reserves increment in such region has actually proved as high as 1.671 million tons. In such case, forecast results could be considered quite satisfactory. A certain discrepancy between forecast quantities of increments and reserves assumed according to deep drilling data could be considered admissible for prospecting planning due to necessity of predicting a large number of unaccounted factors. For example, the reserves increment quantity assumed according to deep drilling data is a probabilistic observation per se. One can adduce a large number of examples showing that oil reserves in the course of field exploration and operation would be adjusted thus changing sometimes more than twice.

Thus, the probabilistic approach enables, with geological risks estimated, to make prospecting efficiency significantly higher. For estimating oil field prospecting projects, information about hydrocarbon reserves increments distribution should be a key factor.

Worth mentioning is the fact that its practical value concerns not only geological estimates, but could be used in economic calculations. On the basis of the probabilistic distribution of reserves increments by economic services for discovery options from *0, 1, …., n* fields and reserves increments corresponding to them, options of economic scenarios (*NPV*, payback period etc.) could be calculated. An example of calculating such scenarios is shown in table 2 and fig. 5.4. Through the comparison of economic calculations with the given scenario implementation probability, an investor is capable of numerically evaluating economic risks of various projects making a well-grounded choice of the top-priority ones amongst them.

Table 2

ECONOMIC PERFORMANCES

		P10	***P50***	***P90***
Oil production	*K t*	24 394.2	29 994.2	31 594.2
Total revenues	M RUR	113332.2	139327.7	146760.3
CAPEX	M RUR	9813.5	12084.2	13026.8
OPEX	M RUR	62269.7	76898.1	81222.6
Prime cost	*RUR/t*	2552.6	2563.7	2570.8
Transportation services	M RUR	5671.6	6973.6	7345.6

INVESTOR EFFICIENCY INDICATORS

Cumulative cash flow	M RUR	23965.4	29092.7	30484.4
NPV	M RUR	5440.2	6788.3	7153.9
DPP	years	10	10	10
IRR	%	28.2	29.6	29.4
PI	shares	2.08	2.13	2.10

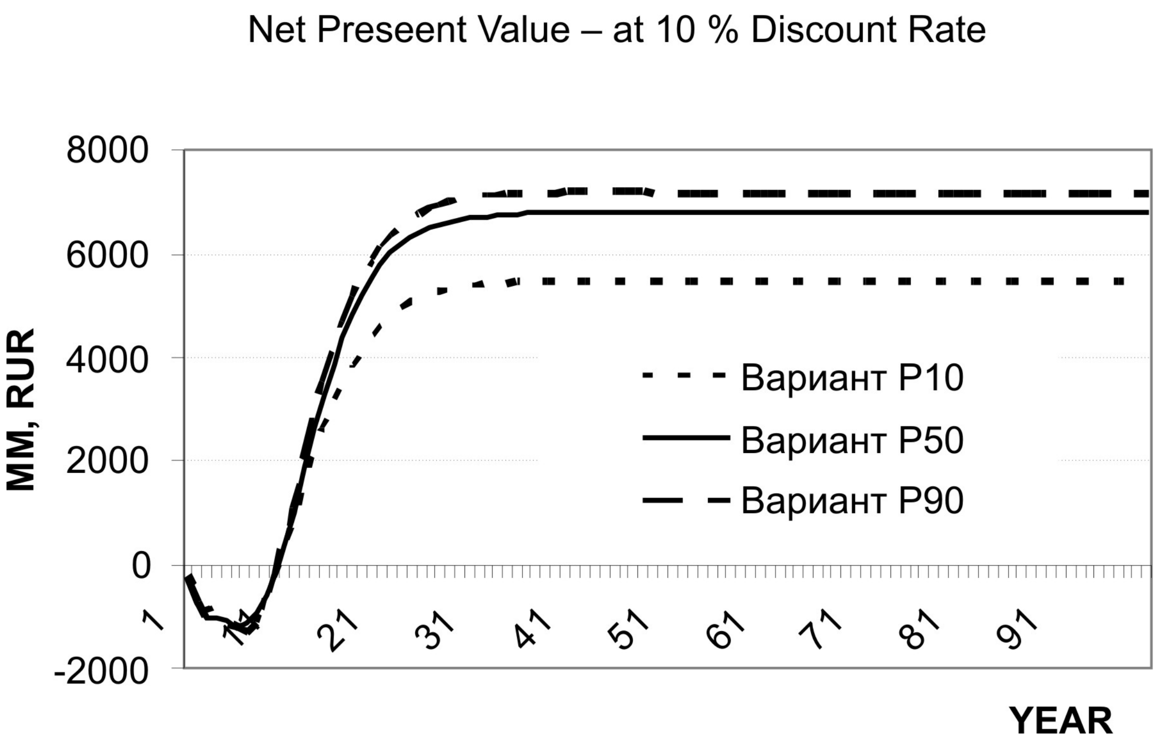

Fig. 5.4. Discount cash flow trends: the optimistic one – P90, the actual one – P50 and the pessimistic one – P10 for prospecting project development in time

At the same time, one should realize that even the most precise calculations may only give a quantitative estimate of the project prospects (riskiness). The matter of acceptability (or inacceptability) of a certain estimated risk fully rests on the investor who should handle it based on its own considerations. In this connection, deemed as the most acceptable is a scheme, using which an enterprise sets for itself certain limits of geological-economic indicators (payback period, return on investments etc.). At the same time, project, economic estimates of which fail with a great extent of probability to meet the statutory requirements, are evaluated as having low efficiency. Later on, the most efficient project out of the projects complying with the enterprise's standards should be chosen mainly on the basis of expert appraisal including geological risks of its implementation.

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