ISSN 2663-0419 (Online)
ISSN 2218-8754 (Print)

AZERBAIJAN NATIONAL ACADEMY OF SCIENCES

ANAS TRANSACTIONS

EARTH SCIENCES

www.journalesgia.com

2020
№2

Buraxılışına məsul: **Hafiz Abıyev**

Dizayn/Qrafika: **Kərim Nəbiyev**
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Veb-redaktor: **Tofiq Rəşidov**

Jurnal Azərbaycan MEA Geologiya və Geofizika İnstitutunda yığılmış və səhifələnmişdir

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Responsible for the issue: **Hafiz Abiyev**

Design/Graphycs: **Karim Nabiyev**
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Web-editor: **Tofig Rashidov**

This journal has been prepead at the Geology and Geophysics Institute of Azerbaijan National Academy of Sciences

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Ответственный за выпуск: **Хафиз Абиев**

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Веб-редактор: **Тофиг Рашидов**

Журнал набран и сверстан в Институте геологии и геофизики НАН Азербайджана

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Ünvan: AZ1001, Bakı şəhəri, İstiqlaliyyət küçəsi 30, “ANAS Transactions, Earth Sciences”

Address: “ANAS Transactions, Earth Sciences” 30, Istiglaliyyat str., Baku, Azerbaijan, AZ1001

Адрес: AZ1001, г. Баку, Истиглалият, 30. Редакция “ANAS Transactions, Earth Sciences”

* * *

İcraçı redaktorlar: **A.A.İsrafilova, C.S.Qurbanova**
Executive Editors: **A.A.Israfilova, J.S.Gurbanova**
Исполнителные редакторы: **А.А.Исрафилова**
Дж.С.Курбанова

ELM NƏŞRİYYATI

Formatı: 60x84 1/8. Həcmi: 11,25 ç.v.
Tirajı: 300 nüsxə

ANAS Transactions **Earth Sciences** **2 / 2020**

Geology and geophysics

http://www.journalesgia.com

PLATE TECTONICS AND EARTH EVOLUTION: A CONCEPTUAL REVIEW

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Keywords: *plate tectonic processes, main forces, thermodynamic models, role of density, models of deep structure, early Earth evolution*

Summary. Numerous attempts have been made to understand the rules of Earth's tectono-geodynamic processes over the past centuries. While no paradigm has offered comprehensive answers to all of the questions, the present review aims to acquaint readers with the modern state of developments in the tectonic insights of Earth's evolution. A number of very interesting and unique processes and features took place during the evolution of early Earth. Most of these, however, were largely erased over the course of Earth's ensuing evolution; some leaving only traces of their existence and remnant phenomena, especially those taking place in the Hadean and Early to Late Archean. Among such processes and features are: the planetary accretion of Earth, formation of unique rock complexes, initiation of the plate tectonics phenomenon, main forces driving plate tectonics, significant influence of thermal parameters, role of overpressure under different physical-geological environments, stratification of Earth's crust and lithosphere by density, and various other thermodynamic models. Nearly all of these remain enigmatic, due to considerable uncertainty in the timing and method of their evolution, and the ambiguity of their secondary processes and tectono- geophysical indicators. At the same time, these tectono-geodynamic processes and features are also interrelated, and the simultaneous fluctuation of myriad different factors plays a significant role in their formation. Some of these intricate questions are discussed in this paper. What is the role of the plate tectonics phenomenon and when did this process initiate on Earth? Especial attention is paid in the review to the sophisticated historical methods of understanding tectonic processes over the course of various generations of geoscientists. In the conducted analyses, certain physical data derived from other planets of the Solar System were utilized as well.

Introduction

It is evident that solidification of the magma-ocean and formation of the lithosphere were among the first steps necessary to initiate different tectonic processes on Earth (e.g., Pilchin and Eppelbaum, 2009). It is then essential to understand which tectonic processes operated during early Earth evolution. At a time with only partial solidification of the magma-ocean, any formed (or partly formed) solid blocks could undertake strictly vertical movements, as dictated by Newton's law of gravity and Archimedes' law of buoyancy. However, it would be premature to account such movements of solid blocks floating within the magma-ocean as tectonic processes. Only as the magma-ocean solidified, with the formation and thickening of the early lithosphere tectonic processes could finally commence. It is important to determine what types of tectonic processes were operational at the time: Were they caused mostly by vertical (isostatic) movements (one of the fixist models) or horizontal (one of the mobilistic models)? There are myriad differences between these two groups of models. Fixist models (e.g., contraction theory, theory of isostasy, gravitational differentiation, expanding Earth, pulsating Earth, geosynclinal theory, rifting, and diapir model) postulate an unchanged position of continents over the asthenosphere, emphasizing vertical movements and not permitting horizontal displacement by greater than tens of kilometers. In contrast, mobilist models (e.g., continental drift, seafloor spreading, plate tectonics) postulate immense (hundreds and thousands of kilometers) horizontal displacements of the lithosphere (including continents) over the asthenosphere, with subordinate vertical displacements.

The known fixist models explain tectonic evolution as a consecutive change of stages: pre-geosynclinal (formation of oceanic crust; basaltic layer); geosynclinal (formation of continental crust; granitic-metamorphic layer); and platform (transition from active regimes to quiet and stable ones) (e.g., Gnibidenko and Shashkin, 1970; Хаин, 1973; Белоусов, 1975). The geosynclinal theory stood as the primary tectonic methodology for over a hundred years (e.g., Хаин, Шейнман, 1960), before most scientists adopted the plate tectonics theory as the main tectonic model of Earth evolution. In recent times some scientists (for instance, private communications with V.E.Khain in 2010) consider it obsolete.

The geosyncline theory, the most comprehensive of the fixist models, was first introduced by

J.Hall in his meeting report in 1857 (Knopf, 1960, Knopoff, 1964) and his subsequent publication (Hall, 1859), to be further elaborated by Dana (Dana, 1873; Knopf, 1960, Knopoff, 1964). Additional improvements on this theory are attributed to such scientists as Daly (1912), Kober (1921), Stille (1924, 1940, 1944) and many others (Knopf, 1960, Knopoff, 1964). This theory helped explain many tectonic processes taking place on continents, but from the onset of the second half of the 20th century, a growing number of geological and geophysical data for oceanic regions raised new problems that it could not explain. This led to the introduction of a new model in a number of publications at the end of the 1960s and 1970s, plate tectonics, which took the geosynclinal theory's place as the foundational geotectonic model.

The following is under question: can the fixist models be used to explain the tectonic regime in the Hadean – Early Archean. We beleive that the answer is 'yes' – some fixist models can be applied to illustrate the tectonic evolution in the Hadean – Early Archean. This period of Earth's evolution was characterized by a regime of cooling (solidification of the magma-ocean, and formation and cooling of the lithosphere), which means that the contracting Earth theory (e.g., Алейников и др., 2001; Stacey and Davis, 2008) can at least partially be applied to tectonic evolution. At the same time during most of the Hadean – Early Archean, the upper mantle was hot and the asthenosphere likely not yet completely solidified. Logically, the early lithosphere would then have been floating atop the remnants of the magma-ocean in the cooling mantle, and the lithospheric temperature would have been comparatively high, with surface temperatures dropping to 500-600 K only at the very end of the Early Archean (Pilchin, 2011; Pilchin and Eppelbaum, 2012; Eppelbaum et al., 2014). This would mean that the lithosphere was likely dictated by vertical forces, which could be explained by the isostatic theory (Anderson, 2007; Stacey and Davis, 2008). However the geosynclinal theory could not be applied to tectonic evolution in the Hadean – Early Archean, even though regions of the early Earth were represented by ancient shields that were not tectonically active. The reason for this is the fact that the water-ocean only emerged at ~3.42-3.26 Ga, at the end of the Early Archean (Pilchin and Eppelbaum, 2012; Eppelbaum et al., 2014), which eliminates the possibility of oceanic crust formation (pre-geosynclinal stage) prior to that time. Moreover, the geosynclinal stage requires the collection of a thick sedimentary layer, while no significant amounts of sedimentary deposits are known in the Hadean and Early Archean before the start of the formation of Moodies Group, Barberton GSB, South Africa at about 3.26-3.259 Ga (Eppelbaum et al., 2014). This means that the geosyncline theory cannot be used for analysis of possible tectonic processes during early Earth evolution.

The plate tectonics theory is accepted at present by the absolute majority of geoscientists, it is important to analyze the geological-geophysical facts (evidence) which may help facilitate further evaluation of this theory.

What is the plate tectonics model?

Before delving into the plate tectonics model, let us briefly discuss what modeling means in science, and in geology in particular. Scientific modeling is the generation of a physical, conceptual or mathematical representation of a real phenomenon that is difficult to observe directly (Roger, 2015). While over the past decades modeling has become a powerful method of research, scientific models remain approximations of the objects and systems they represent, rather than their exact replicas (Roger, 2015). The aim of scientific modeling is to visualize certain events and processes for easier learning and better understanding. The purpose of modeling is generating new knowledge about the objects in question (Schwarz et al., 2009). Various (sometimes specific) types of modeling are utilized in different scientific disciplines (e.g., Cartwright, 1983; Hacking, 1983). A scientific model is usually based on certain empirical facts and observations related to events, phenomena and physical processes reflecting or representing the reality as closely as possible. A good model should focus on the key features to explain and predict the scientific phenomena (Schwarz et al., 2009). The main criteria for a model are: the ability to explain past observations better than other models, revealing new knowledge about the object of modeling, and making predictions for future observations (actual testing of the model). Models that are employed should be perpetually re- evaluated and revised (e.g., Schwarz et al., 2009). Geologic modeling (geomodeling) is usually related to representations of different parts of the Earth (layers, regions, areas, structures, blocks, slabs, domains, objects) based on geological and geophysical data and observations (it could be computerized, 1D, 2D or 3D) (e.g., Mallet, 2008).

One of the most complete reviews on the problems of modeling, collecting data and data interpretation (analysis) in geology is given by Naimark (Наймарк, 2006) on the basis of discussions between followers of the fixist and mobilist models in geotectonics. He states that one of the most urgent problems in geoscience is the correct modeling of different intricate geologic features and processes. Naimark (2006) asserts that since none of the models (fixist, mobilist, or any other concept) encapsulate our physical-geological reality, by definition they can neither entirely describe our reality, nor entirely disprove our understanding of it. He indicates that there are no clear facts that uniquely speak for themselves without the necessity for interpretation, which always relies on certain methodologies. This makes any modeling fundamentally subjective, because any model is developed by a researcher whose views on different matters could be vastly different from those of others. However, any real object could be represented by multiple different models in a fashion that is not arbitrary, but reflects real facts and observations. Interestingly, one of the authors of this paper previously realized this idea in exploration geophysics (Эппельбаум, 1987), where he suggested the application of a multi-model approach to these same subjects under study.

The notion of objectivity in geoscience means that something is independent of our individual awareness of reality (Абрамович, 1978). Ivin (Ивин,1986) states that any fact exists within the framework of a certain theoretical construction, and is therefore always theoretically loaded; that behind any fact there is always some reasoning. Frolov (Фролов, 2002) believes that objectively collected and correctly summarized facts will lead to a correct interpretation on their own. Yet we must ask: where does such criteria and correct summarizing of facts come from? Researchers themselves develop these over a framework of their experience, where they employ certain theoretical views (Наймарк, 2006). Verhoogen et al. (1970) also point out that while field observations are an important source of information in geology, they could only be fully interpreted by analytical methods. Naimark (Наймарк, 2006) notes that if any particular concept at present solves a great number of fundamental problems more effectively than alternative concepts, then it is a better reflection of reality than the others. Based on such inquiry, Naimark (Наймарк, 2006) came to the following conclusions:

(1) the direct purpose of a model is not reflecting reality absolutely fully and exactly (as that is impossible), but to be convenient for solving certain important problems effectively; (2) preference of specific scientific concept is justified only to the extent in which it is effective for the explanations, reconstructions and predictions of natural processes; (3) a model should include only those properties and relations that are necessary for solving a specific problem; and (4) the main purpose of any research is not to search for truth as such, but the development of models of reality based on which it would be possible to solve problems more effectively.

Unfortunately, many geologists believe that geology is too complex to follow the classical laws of physics (e.g., Thomas, 1932; Wilson, 1990), with some scientists going so far as to outright challenge physical laws as contradictory to geological processes (e.g., Petrini and Podladchikov, 2000; Dunlop, 2009). With respect to this, it should be stated that regardless of the given model chosen by a researcher in geology, the model still necessarily includes rocks and/or rock complexes. Rock complexes are characterized by their: position within geologic structures; dimensions (length, width, height); volume; incidence angle (slope angle); contacts with other rock complexes, water bodies, and/or atmosphere; and other properties. Certain rock complexes have categorical rock compositions, and each rock has certain mineral compositions. In turn, every mineral has a certain chemical composition, which is characterized by physical and chemical properties. There are characteristic features among the physical properties of any mineral: density, melting point, liquidus and solidus temperatures, hardness, volume thermal expansion, compressibility, tensile, shear and compressive strength limits, conditions of stability at temperature and pressure, and others. Among the most important chemical properties of any mineral are: reaction with oxygen; reaction with water; reaction with aggressive fluids formed within the Earth layers; transformations between rocks and minerals under certain conditions (e.g., transformation of ferrous iron oxides to ferric iron oxides, transformation of basalt to eclogite, metamorphic processes, and many others), and certain others. Whether or not all of these properties are discussed in a geological (geophysical) model, they are nevertheless always in effect and will always play a role under certain conditions. Any geologic process is dictated by certain physical and chemical properties, and it is wrong to say geology does not follow the proven laws of physics.

The plate tectonics model is based on two previous mobilist models: (a) Mantle convection, and (b) Seafloor spreading (or continental drift). Convection is a key component in the plate tectonics model, as seafloor spreading also depends on mantle convection.

Hopkins (1839, 1847) was the first to use mathematical analysis and mechanical principles to propose the possibility of convection below Earth's crust (Davies, 1999; Glen, 2005), even though he believed the solid crust was hundreds of miles thick. Fisher (1878, 1881) discussed a thin fluid layer just below the crust in the Earth's interior, proposing mantle convection as a tectonic agent, with flow rising beneath the oceans and descending under continents to explain mountain building (Davies, 1999; Glen, 2005). Ampferer (1906) was the first to introduce the hypothesis of understreaming currents in the mantle as the driving force for mountain building. He postulated that compression forces and the formation of nappes were generated by mass currents beneath mountain ranges. Ampferer (1906) also proposed the existence of downwelling mantle convection currents (Unterstromungen) causing orogenic folding and shearing. Joly (1909) offered an explanation to Ampferer's ideas, suggesting that radiogenic heat cyclically melted and solidified the subcrust to produce convection. Schwinner (1915, 1919) used Ampferer's ideas to develop a theory stating that convective heat transport produces currents in the Earth's interior. He modeled convection currents in a tectonosphere as crustal plates positioned atop convecting flows. Lord Rayleigh (1916) offered a correct theoretical interpretation of Bénard's (1900, 1901) experiments using thin liquid layers. The idea of mantle convection was introduced by Bull (1921) to explain continental drift (Herndon, 2010). Jeffreys (1927) came to the conclusion that the viscosity of the mantle would *not disallow* convection. Based on the above ideas, Holmes (1928a,b, 1929, 1930, 1931) introduced the model of a convection engine for seafloor spreading, which is generally implemented in the present plate tectonics model. His model is described in greater detail in Holmes (1944).

Theories related to the movement of continents were offered by a number of researchers starting from the 16th century (Romm, 1994). Ortelius (1596) was the first to propose the basic elements of the continental drift theory. Among other researchers to offer such theories, the following should be mentioned here: von Humboldt (1801), who can be considered one of the founders of Geothermics (Eppelbaum et al., 2014), proposed that the lands bordering the Atlantic Ocean had once been joined together (see Schmeling, 2004); and later Antonio Snider-Pellegrini (1859) proposed that the Americas were at one time connected to Europe and Africa. These problems were also discussed by Taylor in 1908 (as described in: Leviton et al., 1985 and Frank B. Taylor, 2015) and in Taylor (1910), who linked the formation of Earth's Tertiary fold-mountain belts to horizontal thrust movements directed inland from the ocean, invoking the notion of continental collision to explain the formation of certain mountain ranges (e.g., Frank B. Taylor, 2015). His model of the "horizontal sliding of continental crust-sheets" was subsequently published in greater detail (Taylor, 1930). However, the hypothesis that the continents once formed a single landmass called Pangaea, before breaking apart and drifting to their present locations was first presented by Wegener (1912). He also introduced the term '*continental drift*,' and a more complete version of the continental drift hypothesis was offered in Wegener (1929). The concept of '*seafloor spreading*' was introduced by Holmes (1931) (Meyerhoff and Meyerhoff, 1987), who also indicated that mantle convection is a mechanism for continental drift (seafloor spreading) and offered the first model for such convection (see Fig. 2 in Holmes, 1931). Hess in 1960 (Meyerhoff and Meyerhoff, 1987; Hey, 2011), Dietz (1961), and Hess (1962) offered a new vision for the concept of seafloor spreading, which was adopted later by the plate tectonics model. Hess (1962) proposed a model in which mantle convection carried the seafloor and continents away from seafloor spreading centers (mid-ocean ridges), toward trenches. According to the model offered by Dietz (1961), the lithosphere moves on top of the plastic asthenosphere with convection currents.

The subduction process plays a pivotal role in the plate tectonics model. Ampferer and Hammer (1911) introduced the term "Verschluckungs-Zone" (literally, the swallowing-up zone: White et al. (1970)). André Amstutz (1951) was the first to introduce the word '*subduction*' to replace the earlier term, in relation to the development of tectonic nappes in the Swiss Alps, and this was the term later recommended by White et al. (1970) for use in the plate tectonics model.

In 1967 and 1968 several papers (McKenzie and Parker, 1967; Morgan, 1968; Le Pichon, 1968; Isacks et al., 1968) offered a model which laid the groundwork of plate tectonics (Cox, 1973; McKenzie, 1977; Stewart, 1990). The model assumed that the earth's surface was composed of a set of rigid plates that were separated from each other by boundaries of different types, and that new seafloor was formed at ridge axes and destroyed in trenches (Stewart, 1990; Hey, 2011). Unfortunately, the model was offered as a package of highly generalized postulates, requirements, and assumptions, primarily of kinematic significance; yet it is still represented in this form with minor additions to this day:

(1) The Earth's surface consists of a number of rigid plates (e.g., Morgan, 1968) that move relative to one another. The rigidity of lithospheric plates is one of the fundamental tenets of plate tectonics (e.g., Solomon et al., 1975). These plates move at velocities of 1-10 cm per year (Richter, 1973).

(2) Main tectonic processes take place at plate boundaries, of which three types exist (e.g., Stewart, 1990; Meissner, 2002): (1) transform boundaries, (2) divergent boundaries (constructive; seafloor spreading centers), and (3) convergent boundaries (destructive; subduction).

(3) Transform faults (or boundaries), introduced by Wilson (1965), neither create nor destroy lithosphere; their relative motion is predominantly horizontal. These are the most important type of faults for plate tectonics (Hey, 2011).

(4) Mantle convection with large convection cells is the main cause of plate motion (e.g., Chapple and Tullis, 1977; Anderson, 1989). Convection currents are the driving force of Earth’s tectonic system (e.g., Holmes, 1931, 1944).

(5) Under long sustained loads, the Earth's mantle behaves as a viscous fluid which will convect if heated from below or within, or cooled from above (Anderson, 1989).

(6) Thermal convection (as a whole) in some form is the only source of sufficient energy for tectonic processes (e.g., McKenzie, 1969). The energy for convection is provided by the decay of radioactive isotopes of uranium, thorium and potassium, as well as the cooling and crystallization of Earth (Anderson, 1989).

(7) Mantle convection could mean: whole-mantle convection with the dimensions of major lithospheric plates in the order of 10^3 to 10^4 km (e.g., Anderson, 1989); small-scale convection (vertical scale convection of 500 and 1000 km) (e.g., Solomatov, 2004); stratified convection (e.g., Gutenberg et al., 1951; Jordan et al., 1989); within very weak upper mantle or asthenosphere (e.g., Elsasser, 1971); and plate-sized convection cells, or convection cell size as wide as the layer is thick (Bercovici et al., 2000).

(8) Mantle convection is caused by radiogenic heat produced by the radioactive decay of isotopes in the crust and mantle, and the primordial heat remaining from the formation of Earth (e.g., Turcotte and Schubert, 2002). This role of radiogenic heat in generating of mantle convection is greatly emphasized (e.g., Schubert et al., 1980; Davies, 1980, 2011; Turcotte and Schubert, 1982; Lyubetskaya and Korenaga, 2007; Lee, 2014).

(9) Mantle convection is a fundamental mechanism for the loss of primordial and radiogenic heat (e.g., Bercovici, 2011).

(10) Seafloor spreading (Dietz, 1961; Hess, 1962) is related to mid-ocean ridges and the creation of oceanic crust and upper mantle within them. Formation of new oceanic crust/lithosphere within mid-ocean ridges requires the destruction of lithosphere (its consumption) in subduction zones (for instance, within trenches and island arcs) (e.g., McKenzie, 1969).

(11) Subduction commonly involves convergence and underthrusting of adjacent lithospheric plates, but may also involve downfolding within a single plate (White et al., 1970). Initiation of subduction is a vital phase of the plate tectonic cycle (Gurnis et al., 2004), because it is the method of consumption and re-working of oceanic lithosphere formed in spreading centers. The lithosphere is consumed asymmetrically by island arcs (e.g., McKenzie, 1969). The subduction process requires dense rigid plates (e.g., Anderson, 2007). It is also viewed as a method of cooling Earth’s interiors (e.g., Stern, 2007) and delivering water to deep levels within the mantle.

(12) The subducting slab is colder than the mantle (Elsasser, 1969; McKenzie, 1969; Chapple and Tullis, 1977; Bina et al., 2001; Wessel and Müller, 2009; Kirdyashkin and Kirdyashkin, 2014) and must be denser than mantle rocks. The cooling subducting lithosphere is heavier than the underlying mantle and therefore drags the attached plate (Elsasser, 1967; Cruciani et al., 2005). The oceanic lithosphere is isostatically sinking away from the mid-ocean ridge as it cools and densifies (Wilson, 1993). Slab buoyancy provides the primary driving force for subduction (e.g., Forsyth and Uyeda, 1975; Chapple and Tullis 1977). Plate tectonics is driven by negative buoyancy of the outer shell (Richardson, 1992; Anderson, 2001). This negative buoyancy of the slab is proportional to the age of the oceanic lithosphere (Cruciani et al., 2005). Buoyant slab material entering the subduction system steepens the slab angle and reduces the velocity of the trench (Royden and Husson, 2009). The negative buoyancy of a subducting oceanic slab provides a peak subduction rate of 5 cm per year (Mahatsente and Ranalli, 2004).

(13) The sinking slab must be brittle enough to produce earthquakes by fracturing, and sufficiently undeformable to maintain its shape at a depth of 600 km (Sykes, 1966). The concept of rigid plates with deformations primarily concentrated near plate boundaries provides a comprehensive understanding of the global distribution of earthquakes (Isacks et al., 1968). The motion of a slab is well known from the location of deep earthquakes (Sykes, 1966). Earthquakes are restricted to those regions of the mantle which are colder than a certain temperature (e.g., McKenzie, 1969). There is an apparent relationship between the depths of the deepest earthquakes and the temperature distribution within the sinking lithosphere (e.g., McKenzie, 1969). Plate tectonics has related seafloor spreading to the focal mechanisms of earthquakes (e.g., McKenzie, 1969). The relative motion between plates may be determined from these focal mechanisms (McKenzie and Parker 1967; Isacks et al., 1968).

(14) Plate boundary and plate body forces are responsible for the initiation of plate movements. These primary forces are: basal drag, ridge push, slab pull, trench suction, and collisional resistance (e.g., Richardson, 1992).

(15) Plate tectonics is a far-from-equilibrium self-organized system (Anderson, 2001, 2002, 2007; Stern, 2007).

(16) Plate tectonics is a late-stage method for cooling off the interior (e.g., Anderson, 2007).

Peculiarities of plate tectonic processes are described in: McKenzie and Parker (1967), Le Pichon (1968), Morgan (1968), McKenzie (1969), Cox (1973), McKenzie (1977), Cox and Hart (1986), Turcotte and Schubert (1982, 2002), Anderson (1989, 2001, 2002, 2007), Kearey et al. (2009), Wessel and Müller (2009), Kirdyashkin and Kirdyashkin (2014).

Hey (2011) notes that a key step in building the plate tectonics model was Wilson's (1965) conclusion that the deformation of Earth's crust is concentrated in narrow mobile belts that are interconnected in a global network. Hey (2011) calls this introduction of transform faults and other ideas presented in Wilson (1965) as the first qualitative model of plate tectonics. McKenzie (1969, p. 2) also believed that "Wilson stated the basic assumptions of plate theory, but made no further use of them."

Among other mobilist models related to plate tectonics here should be mentioned: the Wilson cycle, formation and breakup of supercontinents, and the Benioff zone (Benioff, 1949, 1954).

Wilson (1966) offered a tectonic model now known as the "Wilson cycle" (e.g., Whitmeyer et al., 2007; Burke, 2011). According to this model, overall tectonic evolution follows alternating cycles of oceanic opening and closing (e.g., Atlantic Ocean). Wilson (1965) identified six specific stages within each cycle (e.g., Jacobs et al., 1973): 1) embryonic (uplifts); 2) young (spreading); 3) mature (spreading); 4) declining (shrinking); 5) terminal (shrinking and uplifts); 6) relic scar or geosuture (shrinking and uplift). Silver (2007, p. 30) characterized this model as follows: "This alternating ocean opening and closing, continental breakup and continental collision – now termed the Wilson Cycle – is arguably the single most important principle in continental evolution, providing an elegant explanation for the semi-periodic creation of mountain chains throughout Earth's history." Subsequent researchers proposed a nine-stage model of the Wilson cycle (e.g., Whitmeyer et al., 2007) containing the following stages: A) stable craton; B) hot spot/rifting; C) early divergent margin; D) full divergent margin; E) volcanic arc mountain building; F) island arc/continent collision; G) cordilleran mountain building; H) continent-continent mountain building; I) stable continental craton. This model was also used to propose a series of supercontinents assembled and broken up during Earth's evolution (e.g., Santosh et al., 2009; Nance and Morphy, 2013; Pastor-Galán et al., 2018).

Corresponding to the Wilson Cycle (1965), the most ancient oceanic crust is usually restricted to the Middle Jurassic (175-180 Ma); with some investigators indicating a maximum age limit dating to the end of the Jurassic (~200 Ma) (e.g., Cogné et al., 2006; Хаин, 2001; Хаин, Короновский, 2007). This is because the Wilson Cycle requires periodic reworking of the oceanic crust in subduction processes, consuming the older oceanic lithosphere. However, a comparatively recent study in the Eastern Mediterranean on the basis of combined magnetic-paleomagnetic-gravity-seismic and tectonic-structural-petrological-radiometric analyses has revealed the Kiama paleomagnetic hyperzone of inverse polarity (Figure 1) (Eppelbaum et al., 2014; Eppelbaum, 2015; Eppelbaum and Katz, 2015a,b). This zone covers a period between 293-242 Ma (47 million years) within the Permian epoch and its discovery contradicts the Wilson Cycle, which assumes that age of the most ancient oceanic crust should not exist beyond 180-200 Ma. It is necessary to note that the theoretical possibility of the presence of more ancient oceanic crust (230-270 Ma) in the Mediterranean Sea was displayed earlier in Müller et al. (2008) and Stern and Scholl (2010). However, practically identifying this large block of ancient oceanic crust, the Kiama paleomagnetic hyperzone necessitates further correction of the Wilson Cycle.

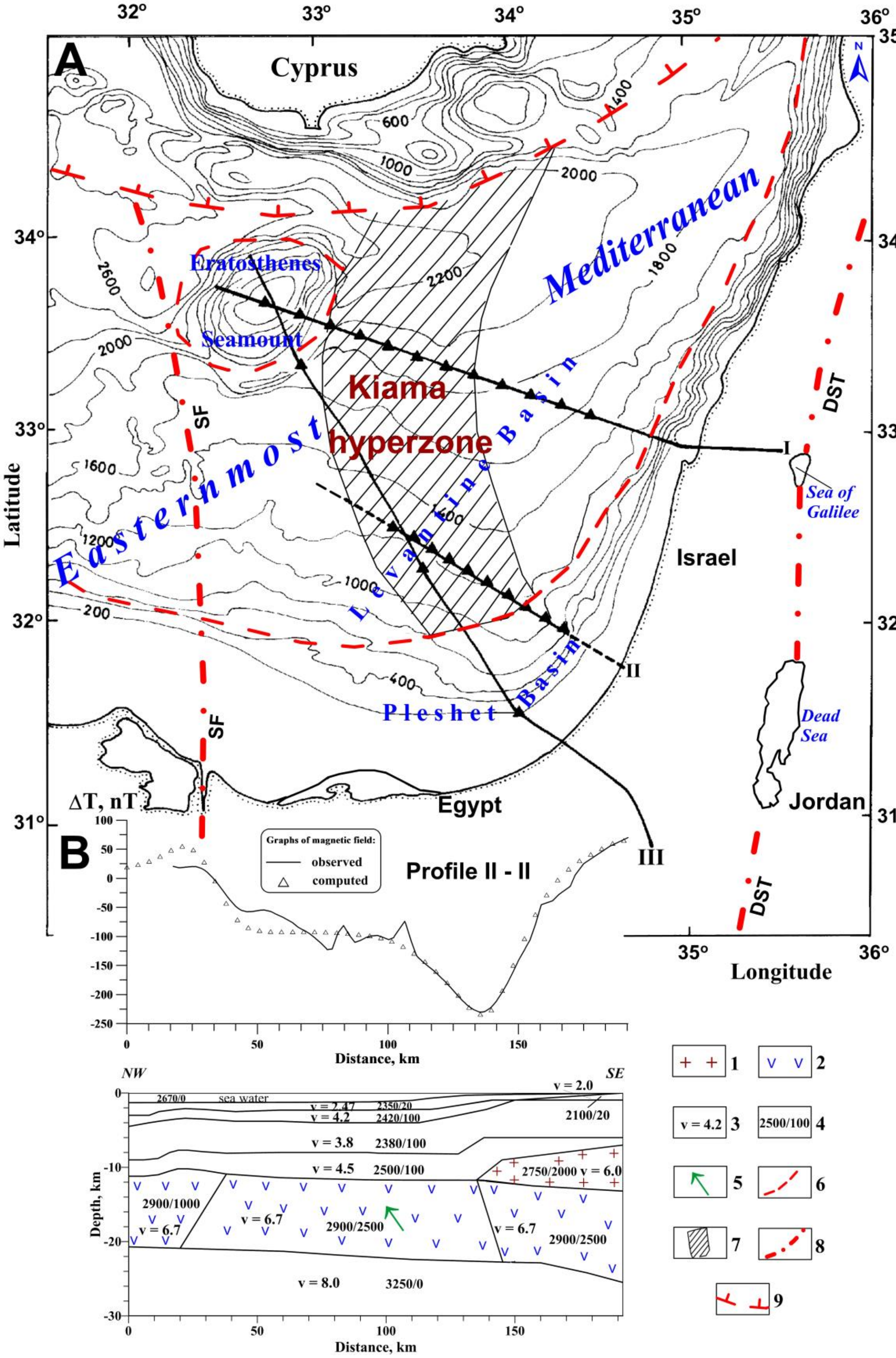

Fig. 1. A: Location of seismic-gravity-magnetic profiles placed on the bathymetric map, B: Results of 3D magnetic field modeling along profile II – II (similar results were received for profiles I – I and III – III). 1 – granitic layer, 2 – basaltic layer, 3 – seismic velocity, km/s, 4 – physical properties (numerator, density, kg/m^3, denominator, magnetization, mA/m), 5 – direction of the magnetization vector other than the geomagnetic field inclination of the region, 6 – boundary discovered between the continental and oceanic crust within the Sinai plate, 7 – delineated contour of the Kiama paleomagnetic zone, 8 – interplate deep faults of the Eastern Mediterranean: SF, Sinai Fault and DST, Dead Sea Transform, 9 – deep fault separating the Alpine Belt and oceanic depression of the Easternmost Mediterranean (after Eppelbaum and Katz (2015a), with modifications).

A number of supercontinents have been proposed to exist on Earth at different time periods (e.g., Zhao et al., 2002, 2004 and references therein): Vaalbara (between ~3.6 and ~2.8 Ga); Ur (at ~3 Ga); Kenorland (between ~2.7 and ~2.1 Ga); Columbia (between ~1.8 and ~1.5 Ga); Rodinia (between ~1.25 Ga and ~750 Ma) and Pannotia (at ~600 Ma). Fragments of the breakup of the supercontinent Pannotia are believed to have ultimately collided and formed the supercontinent Pangaea, which in turn broke up during the opening of the Atlantic Ocean and closing of the Greater Tethys between ~203-125 Ma (e.g., Keppie, 2015) to form Laurasia and Gondwanaland.

Benioff (1949) introduced a method for determining planes of seismicity along a particular fault. Such planes applied to plate tectonics were named Benioff zones (or Wadati-Benioff zones) (e.g., Condie, 1987; Hasegawa and Takagi, 1987; Zhao et al., 1997). Condie (1987) especially indicates that in terms of plate tectonics, the Benioff zone is the site of plate consumption and often referred to as a subduction zone. This assumption allows hypocenters and the distributions of deep earthquakes to be used in tracing subduction zones.

Main forces operating in plate tectonics processes

Classical mechanics, also known as Newtonian mechanics, is composed of three main segments: kinematics (describing the motion of material points, objects and systems of objects without consideration to the causes of motion); dynamics (describing the motion of objects under the influence of forces); and statics (describing bodies at rest and forces in equilibrium). Since moving plates have limited velocities, their movement must satisfy the corresponding laws of classical mechanics (Pilchin, 2016b). However, from this point of view, most of the earliest publications on plate tectonics (e.g., McKenzie and Parker, 1967; Morgan, 1968 and many others) were only concerned with the kinematics of plate motion, rather than the causes of their movement (e.g., Stewart, 1990). Unfortunately, the authors of most subsequent articles were also generally more concerned with the kinematic part of plate motion, rather than its dynamics. This brings us to today, where the dynamics of plate motion are still greatly underdeveloped. Pratt (2000, p. 342) states that “There is no consensus on the thickness of the ‘plates’ and no certainty as to the forces responsible for their supposed movement.” This can be clearly seen from the forces postulated to operate in plate tectonics, as they are described in the most general form with very little or no detail, and seldom actually used in discussing plate movements.

Alvarez (1990) also notes that even though the plate tectonics model has been nearly universally accepted, researchers still do not understand the driving mechanisms in anything other than the most general terms. In plate tectonics, where dynamics is the fundamental element, as the motion of a plate results from forces perpetually applied to it, it is absolutely crucial for the precise forces to be explained in detail. In the early years of developing the plate tectonics model, McKenzie (1969, p. 3) wrote that: “The major remaining problem in plate theory is the driving mechanism.”

It has been yet another quarter century since Wilson (1993) noted how earth scientists have debated the nature of the forces which drive the lithospheric plates for more than a quarter of a century. “Plate tectonics offers no explanation for the forces that drive plates” (Frankel, 2012; Introduction, p. XXI). Lyttleton and Bondi (1992; p. 195) state that “A further difficulty with the plate-tectonic hypothesis is the absence of even a notional causative force for the plate movements” and “the absence of an identifiable driving force and a quantitative analysis of the source of the alleged motions remains, in our view, the biggest gap in the plate tectonics theory.” The forces that were once postulated with no satisfactory explanation therefore remain unchanged from the time of their conception until now (e.g., Kirdyashkin and Kirdyashkin, 2014), because most publications still define these forces as they were in the very beginning, lacking any viable detail. Frankel (2012; Introduction, p. XXI) gives his full support to this situation, stating: “Ironically, it is remarkable that plate tectonics was accepted almost immediately even though it is a kinematic not a dynamic theory. Once accepted, the lack of mechanism was no longer a difficulty but an advantage, freeing the discussion of the relentless and unnecessary burden it had carried for so long.” Bercovici (2003, p. 108) also points out that there has been little to no change in vision of the plate tectonics model: “Many students of geology are taught how mantle convection drives plate tectonics in much the same way that Arthur Holmes envisioned it 70 years ago, i.e. convective ‘wheels’ driving the tectonic ‘conveyor belt.’” However, as they say, the devil is always in the details.

There are a number of traditional driving forces that were postulated for plate tectonics, which include: slab pull, ridge push, basal drag, trench suction, and collisional resistance (e.g., Forsyth and Uyeda, 1975; Richardson, 1992; Wilson, 1993). These forces are generally treated as either plate boundary or plate body forces. For example, ridge push is considered both: a body force caused by cooling and thickening of the oceanic lithosphere with age (e.g., McKenzie, 1969; Richardson, 1992);

and a boundary force caused by the 'gravity wedging' effect (Bott, 1993).

Slab pull forces are believed to originate from the negative buoyancy of the cold subducting lithosphere (e.g., Chapple and Tullis, 1977), and is considered a boundary force (e.g., Wilson, 1993). In slab pull, it is assumed that the slab is mechanically attached to the subducting plate, and its weight will pull on the subducting plate, drawing it toward the subduction zone (e.g., Conrad and Lithgow-Bertelloni, 2002). Slab pull is usually considered one of the dominant acting forces, and may account for roughly half of the total driving force exerted in plate movement (Anderson, 2007).

Basal drag (or basal shear traction) is associated with the interface between the upper mantle and the lithosphere and is caused by mantle convection (Wilson, 1993).

Trench suction forces are usually observed in the overriding plate at subduction zones as a net trenchward pull (Forsyth and Uyeda, 1975; Chase, 1978). In the slab suction mechanism, it is usually assumed that slabs are detached from their surface plates and sink within the upper mantle (e.g., Conrad and Lithgow-Bertelloni, 2002).

Collisional resistance force directly opposes the slab pull force (e.g., Richardson, 1992). This occurs because the mantle resists subduction to some extent due to friction and when continental plates collide (e.g., Cloetingh and Wortel, 1986). Such forces are considered to be only locally significant (e.g., Cloetingh and Wortel, 1986).

There is no consensus among researchers about the importance of one main force compared to the others (e.g., Wilson, 1993), and in the case of the basal drag force even any indication of it operating at all is uncertain (e.g., Richardson, 1983; Anderson, 2007).

Some researchers consider basal drag as a passive force, either driving or resisting plate motion, but not dominating it (e.g., Chapple and Tullis, 1977; Richardson, 1992), while drag due to classical Rayleigh-Bénard convection in the upper mantle is not an adequate driving force (Richter, 1973; Solomon et al., 1975). However, Chapple and Tullis (1977) state that motion of lithospheric plates is a manifestation of convection, while other researchers believe that mantle forces related to large convection cells dominate the driving forces (e.g., Jacoby, 1980). Ziegler (1993) also believes that the basal drag (shear-traction) force exerted by the convecting asthenosphere on the base of the lithosphere plays an important and sometimes even dominant role as a plate-moving mechanism.

Ziegler (1992) states that in the Western Hemisphere frictional forces exerted on the base of the lithosphere by the slowly convecting sub-lithospheric upper mantle play a key role as the driving mechanism of plate movements, and such forces as slab-pull and ridge-push can be considered secondary. At the same time, in a formula for determining plate velocity Carlson (1981) marks basal drag force as negative (opposing plate movement). Forsyth and Uyeda (1975) also indicate that drag on the bottom of plates resists motion, and would be stronger under continents than under oceans. Richardson (1983) questions whether the drag force is negative or positive as well. Bercovici (2003, p. 108) openly accuses some researchers (e.g., Jurdy and Stefanick, 1991; Anderson, 2001) of stepping back from the main postulates of the plate tectonics model, stating that: "… there are several fundamental aspects of it that are misleading at best; in particular, it portrays the plates and convection as separate entities, with convection currents prying open mid-ocean ridges and dragging down subducting slabs. The other limit of plate models disregard convection, referring instead to pre-existing plates moved by forces such as slab pull and ridge push … that are somehow unrelated to the convective energy source that fuels these forces …". If mantle convection with large convection cells is the main cause of plate motion (e.g., Chapple and Tullis, 1977; Anderson, 1989), and convection currents are the driving force behind the Earth's tectonic system (e.g., Holmes, 1931, 1944), how could it be that the drag force generated by mantle convection would not be the most significant force?

Certain researchers presume that plate motions are mostly dictated by ridge push and subduction pull forces (e.g., Dewey, 1988; Anderson et al., 1992; Lithgow-Bertelloni and Richards, 1995; Anderson, 2001; Buiter et al., 2001; Conrad and Lithgow-Bertelloni, 2002). Cruciani et al. (2005, p. 298) states that: "During the last years has become quite popular the idea that the slab pull is primarily driving plate tectonics." Bott (1993, p. 949) comes to the conclusion that "It has been tacitly assumed by the author that the plates are essentially driven by edge forces such as ridge push and subduction pull, rather than by underside frictional drag exerted by mantle convection."

Chapple and Tullis (1977) consider the ridge push force as very minor. They believe in the importance of the different forces acting on plates, due to the fact that each of them has an unknown sign and magnitude. Wilson (1993) states that the relative importance of the different forces involved may vary both in the space and time, and they may either reinforce or counterbalance each other depending upon the tectonic setting.

Forsyth and Uyeda (1975) suggest that the forces exerted on a downgoing slab dictate the velocity of attached oceanic plates, being an order of magnitude stronger than any other force, and causing any oceanic plates attached to substantial amounts of downgoing slabs to move with 'terminal velocity.' They assert that at such velocity, the gravitational body force pulling the slab downward would be nearly balanced with the resistance acting upon the slab, regardless of other features of the trailing plate.

However, some researchers also emphasize the importance of resisting forces. Buiter et al. (2001) showed that plates are largely driven by slab pull and ridge push forces, which are counteracted by resistive forces (e.g., plate contact resistance and viscous resistance). Forces resisting drag beneath continents and net pull toward trenches on upper plates are small but significant (Chapple and Tullis, 1977). Tectonic resistive forces are considered equal and opposite in sign to the force exerted on the subducting plate, and therefore do not contribute greatly to the net driving force of plate motion (Meijer and Wortel, 1992). Wilson (1993) asserts that plate tectonic resistive forces are exerted on the overriding plate in a subduction zone at the interface with the descending slab.

Other researchers believe that plate tectonics is a far-from-equilibrium self-organized system (Anderson, 2001, 2002, 2007; Stern, 2007). Bird (1998, p. 115) states that "… it became natural to regard plates of lithosphere as driving themselves and, incidentally, stirring the rest of the mantle." Hamilton (2002) further believes that upper mantle convection is a product, not a cause, of plate motion.

At the same time, many researchers have consistently pointed out the persistent problems in understanding the processes driving lithospheric plates. In the 1970s, Forsyth and Uyeda (1975, p. 164) noted how "…rather little is known about the driving mechanisms of plate tectonics, although various types of forces have been suggested." In the 1980s, Alvarez (1982) wrote that "the driving mechanism of plate tectonics remains elusive." In the 1990s, Wilson (1993) stated that the processes which drive the lithospheric plates were still not fully understood, and Kerr (1995) indicated that the next central unsolved mystery was: What drives plates in the first place? Bokelmann (2002, p. 1027) stated that "Although the concept of plates moving on Earth's surface is universally accepted, it is less clear which forces cause that motion," while Schellart (2004) pointed to the considerable debate about the driving forces of tectonic plates and their relative contribution. More recently, Van Andel (2015) specified that: "… the lithospheric plates move across Earth's surface, driven by forces as yet not fully understood …"

Some scientists have also suggested that plate tectonics may be triggered by the effect of tidal variations across many hundreds of millions of years (influence of the Moon and Sun's gravity) (Riguzzi et al., 2010; Eppelbaum and Isakov, 2015). However, there is currently no theoretical or practical methodology for testing this hypothesis.

Certain researchers (e.g., Skobelin et al. (1990); Хаин, (2001)) indicate that the plate tectonics model cannot account for intraplate (platform) magmatism (e.g., traps, platobasalts, kimberlites) and metallogeny. From this point of view, the discovery of a giant quasi-ring counterclockwise-rotating structure in the Earth's mantle centered below the Cyprus Island holds significant importance (Eppelbaum et al., 2020; Eppelbaum and Katz, 2020). This deep structure helps explain the linear nature of continental magmatism, which had not been previously given sufficient tectonic-geophysical justification.

As a rule, any net force different from zero must create acceleration in the direction of the net force. At the same time, terminal velocity is achieved only when the forces of friction are overcome by the other forces applied to the plate. Consequently, a subducting plate must either move with acceleration or not move at all.

All of the abovementioned illustrates how there is no clear definition of the forces operating in plate tectonics and plate movement. In none of the cases the role of different forces is made clear, and in many it is not yet understood. In over fifty years since introducing the plate tectonics model, the question "What are the forces that drive plate movement?" still remains unanswered, and the answer is long overdue.

Did plate tectonics operate in the Hadean and Early Archean?

Determining when plate tectonics began on Earth is among the most important and enigmatic problems in modern day geology. However, here it is most important to learn whether plate tectonics operated during the early Earth evolution (mostly the Hadean – Early Archean).

Based on an analysis of the detrital zircons from Jack Hills (Western Australia), Harrison et al. (2005) concluded that a continental crust with volume similar in magnitude to the present day crust had formed by 4.4 to 4.5 Ga, and was rapidly recycled into the mantle. Many recent investigations established the geochemistry of Hadean zircons from the Jack Hills (Yilgarn Craton, Western Australia) (ranging from ca. 4.4 to 3.0 Ga), showing that their Hf isotope compositions suggest dominant sourcing from the ancient felsic crust (Bell, 2013). Nebel et al. (2014) also indicate that previous researches from Jack Hills contain detrital zircon grains with ages as old as 4.37 Ga which are rare remnants of the Hadean (4.5-4.0 Ga) terrestrial crust, and only a small proportion of detrital zircons shows the Hadean age spectra. On top of this, younger overgrowth rims on all 'Hadean' grains indicate multiple recycling events. Their elemental and isotope budget and mineral inclusions were utilized in postulating the presence of an evolved water-rich Hadean crust. The use of these zircons for proposing that plate tectonics operated in the Hadean is in many cases self-evident (e.g., Maruyama et al., 2016). Really, if we accept that these zircons are remnants from a continental crust that somehow disappeared sometime in the Hadean, it is easy to surmise that the Hadean crust was simply recycled into the mantle over the course of plate tectonic processes. These zircons found in the Jack Hills area (Yilgarn Craton of Western Australia) are held as evidence of the presence of a continental crust and oceans at the time of their formation, with the oldest being nearly 4.4 Ga based on its $\delta^{18}O$ values (Peck et al., 2001; Wilde et al., 2001).

Analysis presented in (Wilde et al., 2001) demonstrates that this oldest zircon is zoned with respect to rare earth elements and oxygen isotope ratios ($\delta^{18}O$ values vary from 7.4‰ to 5.0‰), and that some data point to its growth from a granitic melt. However, it is not the isotope $\delta^{18}O$, but some very specific rocks which can be formed only within oceanic environments (e.g., carbonates, evaporites, the presence of oceanic crust fragments (ophiolites, peridotite layer)) that characterize the presence of a water ocean, yet none of these rocks are known for this period. This then places doubts on the existence of a water ocean in the Hadean (e.g., Pilchin and Eppelbaum, 2009; Eppelbaum et al., 2014). Different scientists have come to conclusions that Earth's oceans were formed as early as: by ~4.5 Ga (Condie, 1989), in the Hadean (Morse and Mackenzie, 1998), at ~4.4 Ga (Peck et al., 2001; Wilde et al., 2001; Valley et al., 2002; Liu, 2004), ~4.3 Ga (Lowe, 1994; Mojzsis et al., 2003), by 4.2 Ga (Sleep et al., 2001; Mojzsis et al., 2003), by 3.85 Ga (Nutman et al., 1997), by 3.8 Ga (Lambert, 1982; Nisbet and Sleep, 2001), by 3.6 Ga (Grotzinger and Kasting, 1993), ~3.5 Ga (Knauth and Lowe, 2003; Nunn, 1998).

Contrastingly, Pilchin and Eppelbaum (2012) have shown that the oldest zircon of up to 4.4 Ga found in the Jack Hills area does not prove that oceans were necessarily present at the time of its formation, as there could have been numerous other causes for the elevation of $\delta^{18}O$ values in this zircon. A number of facts will be found to contradict the presumption that $\delta^{18}O$ values within the zoned zircon of 4.4 Ga (from the Jack Hills area) indicate the existence of oceans prior to about 4.4 Ga. Since the zircon was grown from a granitic melt, its $\delta^{18}O$ content should not be compared with the standard mantle $\delta^{18}O$ content, especially as granitic melts are not usually formed in the mantle. Data of Peck et al. (2001) and Wilde et al. (2001) show that zircons from the Jack Hills area are characterized by $\delta^{18}O$ values of about: 7.4‰ at 4.353 Ga, 5.7‰ at 4.15 Ga, 7.2‰ at 4.13 Ga, 6.8‰ at 4.01 Ga, and 6.3‰ at 3.6-3.3 Ga, which would suggest that oceans existed at some periods, but not in other periods of the Hadean-Archean. The strong relationship between $\delta^{18}O$ values and the formation temperature of quartz (SiO_2) should indicate that there were drastically fluctuating temperatures during the Hadean-Archean.

According to experimental data derived from zircons discovered in the Jack Hills area and the relationship between the $\delta^{18}O$ values and the temperature of quartz formation (Clayton et al., 1972; Spooner et al., 1974), the temperatures during the formation of those zircons were greater than 583-623 K. Based on the micro-inclusions of SiO_2 in zircons from the Jack Hills area, Wilde et al. (2001), Valley et al. (2006) and Harrison et al. (2006) came to the conclusion that the zircons formed from silica-saturated granitic or granitoid magma. However, silica-saturated magmas are known for the high $\delta^{18}O$ content in quartz (Mariano et al., 1990; Knight et al., 2000), which may have been a possible cause for the elevated $\delta^{18}O$ values of some grains of these zircons. Moreover, $\delta^{18}O$ values are higher for quartz formed at relatively higher temperatures (Mariano et al., 1990; Gallagher et al., 1992; Knight et al., 2000). Temperature estimations indicate that Jack Hills zircons ranging from 4.0 to 4.35 Ga yielded crystallization temperature peaks at 943 K and 983 K (Harrison and Watson, 2005), which would be favorable for the elevated $\delta^{18}O$ values in quartz and some zircons (Pilchin and Eppelbaum, 2009). Research also shows that $\delta^{18}O$ values are high for carbonates (Ducea and Saleeby, 2003; Sharp et al., 2003), CO_2 (Sharp et al., 2003), and sulfates (Bindeman et al., 2007). This means that the zircons of Jack Hills could have become enriched with $\delta^{18}O$ through contact with carbonate or sulfate rocks, or with CO_2 itself from the early Earth atmosphere (Pilchin and Eppelbaum, 2012). Elevated $\delta^{18}O$ values for barite from the Pilbara block of Western Australia (Richards et al., 2001) and Barberton Mountland of South Africa (Gutzmer et al., 2006) also point to the possible involvement of sulfates and SO_2 in the elevated $\delta^{18}O$ values of the zircons from the Jack Hills area of the Yilgarn Craton (Pilchin and Eppelbaum, 2009). Conversely, data of Fehlhaber and Bird (1991) have shown that some minerals in gabbros that have been in contact with supercritical water (which was widely present in the early Earth atmosphere (Pilchin and Eppelbaum, 2012; Eppelbaum et al., 2014)) actually have lowered values of $\delta^{18}O$.

Pilchin and Eppelbaum (2012) note that taking all of these details into account, it is more likely that the zircons from the Jack Hills area represent the first or one of the first attempts of Earth crust formation. The only thing certain about those zircons is the fact that after formation they were never again heated above ~1173 K, or their age records would have been completely erased. It is also clear that the presence of an ocean is not necessary to form a zoned zircon with $\delta^{18}O$ values in some grains a little bit higher than those of the average mantle (Pilchin and Eppelbaum, 2009, 2012). This also means that such zircons existing in a local isolated place (or even several places) likewise would not indicate the existence of plate tectonics in the Hadean. This is in agreement with results of other researches. For instance, Shirey et al. (2008) come to the conclusion that subduction was initiated by 3.9 Ga or at least by 3.5 Ga. They also dismiss the idea that Hadean zircons aged between 4.4 and 4.0 Ga were formed in continents, stating instead that they were most likely derived from a continent-absent, mafic to ultramafic protocrust that was remelted multiple times between 4.4 and 4.0 Ga.

Based on an investigation of the over 4-billion-year history of the Jack Hills zircons, Bell (2013) interprets the Hf isotope record as evidence of subduction-related recycling, mainly from the ancient Hadean crust at ca. 3.8-3.7 Ga. Nebel et al. (2014) also state that the Hadean detrital zircon grains from the Jack Hills area of the Narryer Terrane (Western Australia's Yilgarn Craton) were formed not within the granitic continental crust, but within the initially homogeneous thin mafic layer. They believe that late heavy bombardment (3.85-3.90 Ga) is related to the onset of Archean-style tectonics, likely associated with subduction activity and lasting until ~3 Ga, when modern style plate tectonics emerged. On the other hand, it was shown earlier (Pilchin and Eppelbaum, 2012; Eppelbaum et al., 2014) that formation of oceans on Earth only began at the end of the Early Archean, at ~3.42-3.26 Ga (most likely at ~3.26 Ga).

Among other researches pointing to the possibility of plate tectonics operating in the Hadean-Eoarchean, the following should be mentioned here. Based on analysis of the Hadean to Eoarchean, Turner et al. (2014) point to the possibility of subduction of Earth's crust and modern-day plate tectonics in the Hadean. De Wit (1998) presumes that the formation of oceanic lithosphere started from ~4.5 Ga, the hydrosphere was accumulated by about 4.0 Ga, and modern plate tectonics probably started between 4.2 and 4.0 Ga. Ernst (2009) argues that by ~4.3 Ga shallow seas were present, so surface temperatures had fallen well below the (1) ~1573 K, (2) ~1393 K, and (3) ~1223 K (temperatures which are much greater than those of the liquefaction of atmospheric water from the early Earth (Pilchin and Eppelbaum, 2012; Eppelbaum et al., 2014)) for low-pressure solidi of (1) peridotite, (2) basalt, and (3) granite, and he proposes there was growth of the oceanic and continental plates during 4.4-2.7 Ga.

Based on analysis of Hadean to Eoarchean rocks from Nuvvuagittuq Greenstone Belt (Canada), O'Neil and Carlson (2014) suggest that a process similar to subduction, if not subduction itself, was active as early as in the Hadean or Eoarchean. Sleep (2010) states that the Earth began hot after the moon-forming impact, and cooled to the point where liquid water was present within about 10 million years. He also believes that a warm 500 K, 100 bar CO_2 greenhouse persisted until subducted oceanic crust sequestered CO_2 into the mantle, mentioning as an example carbonate subduction by 4.26 Ga in India, and indicating that mantle-derived rocks, especially kimberlites and similar CO_2-rich magmas, preserve evidence of the subducted upper oceanic crust. Foley et al. (2014) argue that subduction was possible in the Hadean's Earth (referring to it as proto-subduction or proto-plate tectonics), and that this proto-subduction tectonics differed from modern plate tectonics. They state that at high mantle temperatures of ~2000 K, the mode of subduction switches to a "sluggish subduction" style. They also indicate that a number of models of post-magma-ocean mantle convection demonstrates that proto-plate tectonics likely initiated within ~100 My of the magma ocean's solidification. Arndt and Nisbet (2012) state that after the Moon-forming event occurred at ~4.5 Ga, the ocean/atmosphere system and uppermost few kilometers of the crust cooled within a few million years and, if early subduction were efficient, this could have taken as little as 10 million years, leaving a cold lifeless Earth, its oceans white with ice. They also suggest that from ~4.4 to 4.0 Ga, wide areas of the planet may have been covered in lava flows beneath a deep ice-covered ocean.

Many researchers believe that plate tectonics started in the Archean (Bercovici, 2003; Shervais, 2006) or even in the beginning of the Early Archean (probably from 3.8 Ga; Shervais, 2006). At the same time, the initiation of recognizable plate-tectonic processes occurred by 3.0 Ga (Shervais, 2006). Tatsumi et al. (2015) found mounting evidence that both ocean formation and plate tectonics operation took place in the Early Archean between

3.6-3.9 Ga. Nutman et al. (2002) report horizontal movements in the Isua supracrustal belt between 3.65-3.60 Ga, and propose that some form of plate tectonics was operational back then. Kröner and Layer (1992) state that rigid continental plates must have existed since at least 3.5 Ga. Based on paleomagnetic, geochemical and tectonostratigraphic data, Cawood et al. (2006) establish that plate tectonics have been active since at least 3.1 Ga. Condie and Kröner (2008) also state that modern plate tectonics were operational at least in some regions on Earth since 3.0 Ga, or even earlier, and that they became widespread since 2.7 Ga. Rapp et al. (2008) indicate the appearance of monzodiorites and trachyandesites of the sanukitoid suite in ~3.0-2.8 Ga, marking it the beginning of "modern-style" plate tectonic subduction. Calvert et al. (1995) discuss the following items: (1) start of plate tectonics at ~1.89 Ga in the Svecofennian orogen (Fennoscandian Shield); (2) inferred plate convergence, subduction and accretion in the Trans-Hudson orogen (Precambrian Canadian Shield and North American Craton) at ~1.91-1.79 Ga; and (3) combining seismic data with geochronology and structural mapping to identify the collision zone in the Superior Province of Canada (involving the Abitibi Subprovince and the Opatica belt), which represents a relict 2.69 Ga suture associated with subduction, thereby arguing this is a period of active plate tectonics.

Sizova et al. (2010) used numerical modeling to identify a first-order transition from a "no-subduction" tectonic regime (with upper-mantle temperatures >250 K higher than present), through a "pre-subduction" tectonic regime (upper-mantle temperatures 175-250 K higher than present), to the modern form of subduction (when upper mantle temperatures dropped below 175-160 K higher than present). These results suggest that the transition to the modern plate tectonic regime may have occurred during the Mesoarchean-Neoarchean period (~3.2-2.5 Ga). Grove and Parman (2004) distinguish that the decline in the abundance of komatiites from the Archean to the Phanerozoic is evidence of secular cooling of the mantle (up to 773 K between 3.5 Ga and today). In another model they show hydrous melting at shallow mantle depths in a subduction environment within the Archean mantle to produce komatiites at only slightly hotter temperatures than at present (~373 K), indicating that subduction operated in the Archean.

Some researchers point out that the hotter mantle (~200 K hotter, e.g., Hamilton, 1998, 2007b; ~175–250 K hotter, e.g., Sizova et al., 2010) during early periods of Earth's evolution (such as the Archean) would produce a thick and buoyant crust that could pose a problem for subductability of the oceanic lithosphere (e.g., Hamilton, 1998, 2007b; Korenaga, 2008). Hamilton (2007b) shows that mantle temperatures are likely to have been hotter than at present by about 300 K at 3.5 Ga, 200 K at 2.5 Ga, and 120 K at 2.0 Ga; with a secular cooling of the upper mantle by 75 K-100 K per Ga (Anderson, 2007; Hamilton, 2007a,b). Korenaga (2008) believes that such high mantle temperatures could present a problem for the emergence of plate tectonics prior to the Proterozoic.

Hamilton (2007a,b) shows that plate tectonic processes did not operate in the Archean, with some elements of plate tectonics beginning at ~2.1 Ga, though they were quite distinct from the modern form, which began to operate only from Neoproterozoic or very early Paleozoic period. He links initiation of the present form of plate tectonics with the formation of ophiolites and ultra-high pressure rocks. Sharkov and Bogatikov (2001) also indicate that the onset of plate tectonics on Earth took place at 2.2-2.0 Ga.

Hamilton (2011) shows that Archean, Paleoproterozoic and Mesoproterozoic rocks, assemblages and structures greatly differ from each other and from modern ones; he indicates a lack of evidence for subduction and seafloor spreading in rocks of Mesoproterozoic age and older, while they are widespread in Phanerozoic terrains. He states that subduction began at ~850 Ma, while fully modern plate-tectonic processes only started in the Ordovician. Stern (2005, 2007, 2008) argues that criteria for the operation of plate tectonics includes ophiolites, blueschists, and ultra-high-pressure metamorphic belts, all of which predominantly appear after ~1 Ga, which is the reason why modern style plate tectonics began at this time or later in the Neoproterozoic. Ophiolites are very rare before ~1 Ga, and they manifest two modes of lithospheric motion expected from subduction tectonics: seafloor spreading and obduction. However, if the appearance of UHP rocks was explained as processes only taking place at great depths in subduction zones (Ernst, 1971), then the absence of these rocks prior to ~620 Ma (Stern, 2005) would put in the question the existence of the subduction process at earlier time periods. On the other hand, obduction is the most well-known process of plate tectonics (e.g., Pilchin, 2015), and always includes the presence of serpentinized peridotites and ophiolites.

The process of obduction with a model of the following evolution of region is thoroughly discussed in Pilchin and Eppelbaum (2002) and two simplified models for obduction on continental margin (1), and parts of ocean plate onto itself (2) are presented in Figures 2 and 3, respectively.

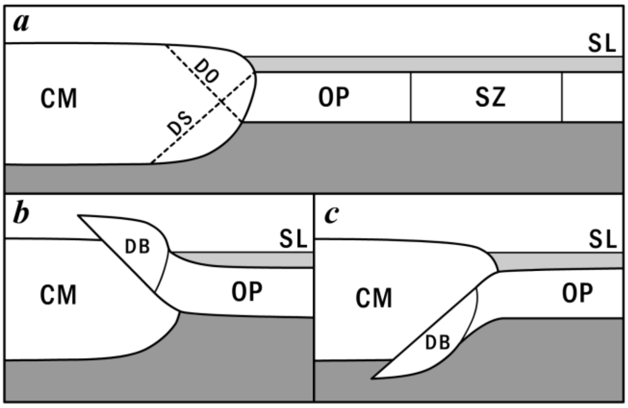

Fig. 2. Simplified diagram of tectonic activity of an oceanic plate near the continental margin caused by serpentinization within its peridotite layer: *a*) initial push of activated oceanic plate against the continental margin; *b*) formation of decollement and start of the obduction process; *c*) formation of the decollement and start of the subduction process. CM – continental margin; OP – oceanic plate; SZ – zone of serpentinization of peridotite layer of oceanic plate; SL – sea level; DO – possible position of decollement for starting the obduction process; DS – possible position of decollement for starting the subduction process; DB – detached block of continental margin.

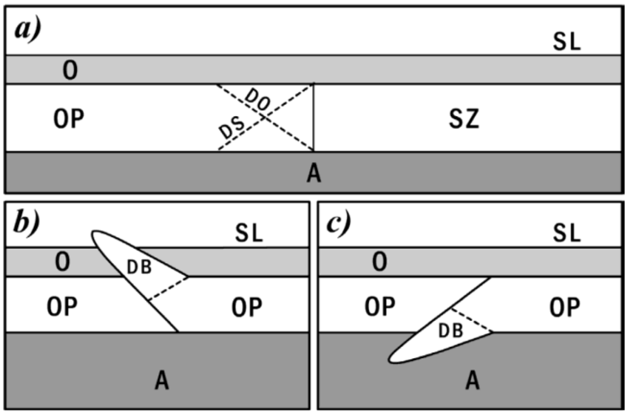

Fig. 3. Simplified diagram of tectonic activity of an oceanic plate in the oceanic areas caused by serpentinization within its peridotite layer. The designations are the same that in Fig. 2.

The aforementioned means that the absolute majority of ophiolites appearing only after ~1 Ga also creates problems explaining obduction processes at earlier time periods. Certain other researchers also note the scarcity of complete ophiolites before 1 Ga (Condie and Kröner, 2008). Additionally, it is important to mention that blueschists (usually having age ≤800 Ma (Stern, 2005), ≤1 Ga (Condie and Kröner, 2008)) are always associated with ophiolites and serpentinite-containing thrusts (e.g., Pilchin, 2005), which is the main reason why they were chosen as one of the markers of the onset of plate tectonics. Stern (2005) indicates that plate tectonics could not have begun until the Earth cooled sufficiently. Davies (1992) shows that the corresponding cooling of the crust and upper mantle necessary for the onset of plate tectonics took place sometime between 0.9-1.4 Ga. He also notes that plate tectonics could have operated at earlier times, but more slowly.

The problem of plate tectonics emerging on Earth was thoroughly discussed at the Geological Society of America Penrose Conference in Lander, Wyoming, USA (June, 2006), where among others researchers came to the conclusion that "Earth is the only planet with plate tectonics, and it is controversial why and when this began. Some argue that plate tectonics already operated in Archean time, whereas others argue for a much later beginning… Demonstrating that plate tectonics operated at any given time requires evidence for subduction and independent plate motion and rotation. Understanding when and why plate tectonics began is one of the most important unresolved problems in understanding Earth…" (Stern, 2007; pp. 578-579). Reporting the discussions from this conference, Witze (2006) states that the 65 attendees came up with 18 different definitions of plate tectonics, with the majority voting that plate tectonics started between 3 billion and 4 billion years ago. Most researchers at this conference agreed on three components required for plate tectonics (Witze, 2006): (1) there must be rigid plates at the surface of the Earth; (2) those plates must move apart through ocean spreading with new crust being made where the sea floor pulls apart, and (3) the plates must dive on occasion beneath each other in subduction zones.

At the same time, researchers accepted subduction as a diagnostic factor for plate tectonics. However, the word "rigid" means "unbending," which as it was shown above could be a problem for the initiation of subduction. A rigid plate also means that it must be able to transfer applied force (pressure) to its other parts without altering its shape. This would require the plate to contain an elastic layer (elastic lithosphere) of significant thickness for the plate to operate as a single unit. The plate therefore could not be brittle, because it would then simply break apart before accomplishing the processes required for plate tectonics. We know that any typical lithospheric plate is composed of an upper brittle layer (with temperatures <~573 K), an intermediate elastic lithosphere (with temperatures between 573 K and 873 K), and a lower more plastic part of the lithosphere (with temperatures >~873 K). It is indeed the elastic lithosphere that holds the plate together and provides necessary support for its operation as a single unit, so naturally a plate will be stronger when its elastic part is thicker. At the same time, a colder plate would have a thinner lower (plastic) part, which would also make the plate much stronger. This clearly indicates that thermodynamic conditions (primarily temperature conditions) of the surface and within the lithosphere are key parameters to the characteristics of lithospheric plates and their formation.

Let us take a look at the thermodynamic conditions of Earth's surface, and conditions of formation of the earliest lithosphere during the early Earth evolution. It was shown earlier (e.g., Pilchin and Eppelbaum, 2009; Eppelbaum et al., 2014; Pilchin, 2015) that after accretion of the Earth and other planets, the Moon and terrestrial planets were covered with a magma-ocean, which for Earth was ~1000 km deep. This means that formation of the early Earth lithosphere, as well as that of any other planet, first began with solidification of the magma-ocean, and was strongly dependent on the rate of cooling of its surface and upper layers as it solidified (e.g., Pilchin and Eppelbaum, 2012). Formation of the early lithosphere in the Earth first began with the solidification of a forsterite layer at a depth of 70-100 km in Archean cratons within the magma-ocean (Pilchin, 2011; Pilchin and Eppelbaum, 2012).

The following features are among the best markers of the surface temperature conditions of early Earth: (1) drop of temperatures below 1173 K in the Hadean-Eoarchean during formation of zircons in the Jack Hills area (Yilgarn Craton, Western Australia); (2) formation of first Algoma-type banded iron formations (BIFs) as early as 3.85 Ga in Greenland (Klein, 2005) and 3.5 Ga in Australia (Klein, 2005), indicating a drop of surface temperatures below 843 K; (3) temperatures dropping to ~600 K at the time of the start of water-ocean formation at ~3.42-3.26 Ga in Barberton GSB (South Africa) (Pilchin and Eppelbaum, 2012; Eppelbaum et al., 2014).

These temperature values clearly show that: formation of a brittle layer of lithosphere was not possible in the Hadean – Early Archean; no elastic layer of lithosphere could have been formed during the Hadean; the thin elastic lithosphere in the Early Archean began directly from the surface and had no contact with the convecting mantle. All this clearly demonstrates that the formation of strong rigid plates was not possible in the Hadean – Early Archean. It also means that plate tectonics did not operate on Earth during the Hadean – Early Archean. Analysis of conditions of the formation of granulites during different periods of the Archean and Early Proterozoic (Eppelbaum et al., 2014) reveals the following average temperatures:

This data indicates that crustal temperatures were relatively high at depths of the lower crust during the Early Archean – Early Proterozoic, and that the effective elastic thickness (*Te*) of the continental lithosphere within Archean cratons during these periods of granulites formation was below 9-12 km, with a total thickness of the young lithosphere of ~100 km (e.g., Pilchin and Eppelbaum, 2012). Such high temperatures and such low effective elastic lithospheric thickness would force it to lose some or even most of its strength and rigidity, and consequently such lithospheric plates would not be able to participate in plate tectonic processes at this period (Pilchin and Eppelbaum, 2012). This is in agreement with data of Artyushkov et al. (2000) on the loss of lithospheric rigidity in areas with high temperatures and low effective elastic thickness.

Table 1

Averaged relationship between the age, temperature and depth of Earth's crustal blocks

Age	Temperature, K	Depth, km
Early and Middle Archean	1059	30.3
Late Archean	1127	30.0
Early Palaeoproterozoic	1040	23
Late Palaeoproterozoic	1087	28.4

At the same time, for subduction to take place, crustal rocks must first be converted to dense eclogite to form the negative buoyancy force required (Pilchin, 2015). Analysis of the thermodynamic conditions of the formation of eclogites indicates that they were formed at average depths of ~64 km (within the subcontinental lithospheric mantle) with average temperatures of 856 K and an average geothermal gradient of 9.1 K/km. This means that for the formation of eclogites through a basalt-eclogite phase transformation or other process involving the presence of crustal rocks, those rocks must first somehow be delivered to a depth of ~64 km (e.g., Pilchin, 2015). It should also be stated that eclogites formed during the solidification of basaltic magma within magma chambers or magmatic channels would not form layers, especially not dense homogeneous layers, but rather eclogite pockets. It is also evident that the average temperature expected for eclogite formation at depths of ~64 km is much lower than temperatures at shallower depths defined by conditions of granulite formation during the Early Archean – Early Proterozoic. Table 2 displays an analysis of thermodynamic conditions of the formation of eclogites at different temperatures (low, intermediate, and high temperatures).

Table 2

Thermodynamic conditions for the formation of eclogites with different origins
(after Pilchin (2011), with modifications)

Eclogites Formed at Temperatures K, (*n*)	Average *T*, K	Average *P*, GPa	Average *P/T* *, MPa/K	Average Depth of Lithostatic Pressure, km	Average Geothermal Gradient (K/km)
$T < 843$ ($n = 279$)	762	1.51	3.10	50	9.8
$843 < T < 993$ ($n = 216$)	910	2.13	3.34	70	9.1
$T > 993$ ($n = 61$)	1075.3	2.77	3.46	90	8.7

*Average *P/T* values were calculated as the average of the *P/T* ratios

If we compare temperatures of the formation of eclogites (Table 2) with those of the formation of granulites at different periods of the Early Archean – Early Proterozoic (Pilchin and Eppelbaum, 2012; Eppelbaum et al., 2014), it becomes clear that only high temperature eclogites (if any) could have been formed at depths greater than 30 km; and the average depths of high-temperature eclogite formation are ~90 km. This means that crustal protoliths for the formation of eclogites during the Early Archean – Early Proterozoic would have to be delivered to an average depth of ~90 km rather than ~64 km. This makes the problem even more complicated, because of the immensely gigantic force that would be required to push a plate/slab downwards to such an extent. Moreover, even though all kimberlites within cratonic areas of southern Africa contain eclogite (Gurney et al., 1991), it nonetheless remains a rare type of xenolith in most localities (Gurney et al., 1991; Pearson et al., 2003). Schulze (1989) concluded that the amount of eclogite in the upper 200 km of the subcontinental upper mantle is perhaps less than 1% by volume. Carlson et al. (2005) show that in general, high-velocity bodies consistent with large masses of eclogite are not observed in the continental mantle, and that at present eclogite appears to be a relatively minor component of the continental lithospheric mantle. At the same time, eclogites of Hadean – Early Archean age are completely unknown. All of the above means that during the Archean eclogite content within the subcontinental lithospheric mantle ranged from very low to negligible and could not play a significant role in generating conditions with negative buoyancy, and therefore the conventional subduction process was not possible.

Another problem that appeared with the onset of plate tectonics and subduction during early Earth evolution is related to the fact that the iron content of magmatic rocks in the Archean was the lowest, increasing towards the present time (Pilchin and Eppelbaum, 2008, 2009). Careful examination of magmatic rocks during most of Earth's evolution shows that mafic magmas in significant amounts only began to appear in continents from the Late Archean (Pilchin and Eppelbaum, 2008). The content of FeO (as total iron content) in mafic magmatic rocks in continents was <10-11% in the Archean, 11.5-13.7% in the Proterozoic-Mesozoic and 12.25-14% in the Tertiary (Pilchin and Eppelbaum, 2012). Additionally, the FeO-content of oceanic magmas is significantly lower, at about 8.3-9.1% for mid-ocean ridge basalts, 8.5-9.7% for island arc basalts, 10.2% for ocean floor basalts and 10.6-12.6% for oceanic intraplate volcanism. While this means that continental rocks were less dense in the Archean, the low iron content in oceanic rocks also creates a density problem for the oceanic lithosphere, which would have been even more buoyant than continental rocks. This is a fundamental obstacle to the start of the subduction process for which negative buoyancy is crucial.

On other hand, the fact that water-ocean formation began only at the end of the Early Archean (at ~ 3.26 Ga; Pilchin and Eppelbaum, 2012; Eppelbaum et al., 2014) means that during the Hadean – Early Archean, the oceanic lithosphere as we know did not exist, rendering the present form of plate tectonics impossible during these time periods. It also means that formation of the oceanic lithosphere started around the boundary between the Early and Middle Archean. It is difficult to pinpoint when the first oceanic lithosphere emerged on Earth, but we know that formation of obduction processes and the appearance of remnants of an oceanic peridotite layer on the surface started only in the Early Proterozoic (e.g., Pilchin, 2016b). In other words, formation of the oceanic lithosphere and the start of plate tectonic processes in the Earth took place a long time after the Early Archean.

To reiterate, the high surface temperatures, a mostly plastic lithosphere, the presence of magma layers at shallow depths, absence of a water-ocean and oceanic lithosphere, absence of eclogites, absence of serpentinites and many other mentioned above reasons made it impossible for plate tectonics to operate on Earth in Hadean – Early Archean.

Let us take a look at the possibility of plate tectonics operating on other planets of the Solar System during their early evolution. It is generally accepted that the Earth is the only known planet with subduction zones and plate tectonics (e.g., Stevenson, 1994; Stern, 2005, 2008). At the same time, some researchers believe that some form of plate tectonics could have occurred in the history of Mars and Venus (Sleep, 1994; Schubert et al., 2001; Fowler and O'Brien, 1996; Turcotte et al., 1999; Solomatov, 2004).

Dohm et al. (2015) hypothesize plate tectonics on Mars to have terminated sometime prior to the ~4.0 Ga Hellas impact events, which is referred to as the Mars plate-tectonic-basement hypothesis and includes the Claritas subduction zone region. The data points to a Hadean-age-equivalent phase of plate tectonism on Mars.

Pilchin (2016a) has shown that the region of Venus's accretion within the solar nebula was relatively hot (750-850K), and that the planet was most likely able to collect more heat energy during accretion than Earth or Mars. Venus was under heavy bombardment during its early evolution, as any other planet, and received much more heat energy from the Sun than Earth or Mars, making it likely that Venus never had a surface temperature lower than it currently does (~740K). This means that the Venusian surface never cooled below the temperature of water-ocean formation, and subsequently never had an oceanic lithosphere. It would also mean that its lithosphere never formed an elastic layer thicker than a few kilometers, which always ran from the surface. The plastic and molten rocks at shallow depths would not permit any plate to descend under such thermal conditions (Pilchin, 2015). It is of course too early to talk about plate tectonics on Venus, as it does not yet have thick elastic plates, nor has it yet cooled sufficiently to form rigid plates. However, the impossibility of a water-ocean forming, not to mention an oceanic lithosphere, and the impossibility for the serpentinization process to take place makes Earth-type plate tectonics on Venus simply unimaginable in its future.

In the case of Mars, many researchers believe that a water-ocean has existed on the planet at some period (e.g., Carr, 1996; Clifford and Parker, 2001), with different researches proposing various sizes for it. Such an ocean may have contained a significant amount of water, estimated at a global equivalent layer (GEL) of ~500-1000 m in the Late Hesperian – Early Amazonian (Carr, 1996), and alternatively at a total GEL of ~550-1400 m (Clifford and Parker, 2001). This means that the formation of an oceanic crust/lithosphere was possible in the past. This is in agreement with recent discoveries of serpentine on the Martian surface (e.g., Ehlmann et al., 2010) in mélange terrains of the Claritas Rise and the Nili Fossae, several southern highlands impact craters, and the regional olivine-rich stratigraphic unit near the Isidis basin. This evidence of the presence of serpentine is very important in analyzing the possibility of the existence of a Martian water-ocean, as well as that of plate tectonics having operated on the planet in its past, since on Earth the formation of serpentine is invariably associated with the serpentinization process. That the presence of serpentine on Mars is uncommon (e.g., Ehlmann et al., 2010) means that serpentinization took place at some depth, and that the process was of a limited scale, preventing the evolution of thrust systems. The fact that serpentine is found in association with mélange terrains at the Claritas Rise and the Nili Fossae is unequivocal evidence that the serpentinization process did in fact take place on Mars, as the formation of mélanges is also typical for the serpentinization process on Earth (e.g., Pilchin, 2005). However, the presence of significant amounts of olivine on Mars (e.g., Ehlmann et al., 2010) indicates that serpentinization was not widely spread across the planet. It also suggests either a quick cooling of the planet's crust to below about 473-523 K, or a lack of water within the crust in contact with olivine. Ehlmann et al. (2010) come to the conclusion that serpentine-bearing materials appear to be restricted to Noachian-aged rocks in the Nili-Fossae olivine-carbonate-serpentine unit. Since it is clear that water was present on Mars in significant quantities, it is then likely that the temperature at some depths within the crust dropped below 473-523 K by the end of the Noachian. In which case, most of the crust would have been much colder than is required to form the elastic portion of the lithosphere, and it is possible that plates were then too thick to initiate plate tectonics. Moreover, the absence of SO_2 from the present Martian atmosphere (e.g., Catling, 2004) indicates the lack of any significant volcanic activity for a long period of time. The abovementioned shows that Mars does not have the energy required for plate tectonics at this time, and its ensuing cooling hinders any expectations for plate tectonic processes in the planet's future.

Lastly, to briefly mention conditions on our nearest terrestrial neighbor. The presence of a 52-km-thick (Taylor and McLennan, 2009) buoyant anorthosite crust on the Moon and a lack of energy sources indicate that plate tectonics was not possible there in the past, and nor will it take place there in the future. The enigmatic event proposed to have taken place on the Moon between 3.4-3.9 billion years ago (Pechersky and Eppelbaum, 2018) requires further study for possible connection with plate tectonic processes.

Conclusions

The review given here does not at all exhaust such a complex topic as the assessment of the mutual influence of plate tectonics and Earth evolution. It is multicomponent and intricately prolonged (over hundreds of millions of years). Due to the lack of sufficient space in the journal, some key processes of Earth's development preceding the start of plate tectonics were overlooked such as: 'Formation, evolution, and solidification of the magma-ocean', 'Problems relating to the Earth's primordial crust', 'Formation of overpressure', 'Eclogite problems' and others. Nevertheless, the authors hope that this study will contribute to a deeper understanding of these complex processes that have shaped the modern face of the Earth.

Dedication

Dr. Arkady Pilchin (1951-2016) was passionate about passing his understanding, unique perspectives, and methods of inquiry to future generations of geoscientists. His seminal contributions to different branches of Geophysics and Earth and Planetary Sciences continue to shine in our field of study.

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ТЕКТОНИКА ПЛИТ И ЭВОЛЮЦИЯ ЗЕМЛИ: КОНЦЕПТУАЛЬНЫЙ ОБЗОР

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Резюме. На протяжении последних столетий предпринимались многочисленные попытки осознать закономерности тектоно-геодинамических процессов, происходящих на Земле. Хотя ни одна парадигма не дала исчерпывающих ответов на все вопросы, настоящий обзор призван познакомить читателей с современным состоянием развития тектонических представлений об эволюции Земли. Надо отметить, что эволюция ранней Земли характеризовалась рядом уникальных процессов, характеризующихся неконвенциональными параметрами. Однако физико-химико-геологические параметры большинства из них были в значительной степени утрачены (стерты) в ходе последующей эволюции Земли; некоторые процессы оставили лишь слабые следы своего существования и некоторые остаточные эффекты (особенно те, что имели место в катерхее и раннем-позднем архее). Среди таких процессов можно отметить планетарную аккрецию Земли, образование ряда уникальных горных комплексов, инициирование процесса тектоники плит, появление основных сил, движущих тектонику плит, значительное влияние тепловых параметров, роль избыточного давления в различных физико-геологических условиях, стратификацию земной коры и литосферы по плотности и ряд других термодинамических процессов. Почти все они остаются недостаточно исследованными ввиду значительной неопределенности в сроках и способах их эволюции, а также неоднозначности их вторичных показателей и тектоногеофизических характеристик. В то же время многие тектоно-геодинамические процессы и параметры были и остаются взаимосвязанными, и одновременное изменение множества различных факторов играло существенную роль в их воздействии на геологическую среду. Некоторые из этих сложных вопросов обсуждаются в данной статье. Например, какова роль феномена тектоники плит и когда на Земле начался этот процесс? Особое внимание в обзоре уделено непростым методам анализа природы тектонических процессов, применяемым учеными-геологами на протяжении многих поколений. В проведенном обзоре также использовались некоторые физические параметры, полученные на других планетах Солнечной системы.

Ключевые слова: *тектоника плит, основные движущие силы, термодинамические модели, роль плотности, модели глубинного строения, ранняя эволюция Земли*

PLİTƏLƏR TEKTONİKASI VƏ YERİN TƏKAMÜLÜ: KONSEPTUAL İCMAL

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Xülasə. Son yüzilliklər ərzində Yerdə baş verən tektonik-geodinamik proseslərin qanunauyğunluğunun dərk edilməsinə çoxsaylı cəhdlərlə təşəbbüs göstərilmişdir. Hərçənd heç bir paradiqma bütün məsələlərə tam cavab verməmişdir, bu icmal Yerin təkamülünə dair tektonik təsəvvürlərin inkişafının müasir vəziyyəti ilə oxucuları tanış etməyə çağırışdır. Qeyd etmək lazımdır ki, ilkin Yerin təkamülü qeyri-konvensional parametrlərlə səciyyələnən bir sıra unikal proseslərlə xarakterizə edilir. Lakin onların əksəriyyətinin fiziki-kimyəvi-geoloji parametrləri Yerin sonraki təkamülünün gedişində mühüm dərəcədə itirilmişdir (silinmişdir); bəzi proseslər özlərinin mövcüdluğunun yalnız zəif izlərini və qalıq effektlərini (xüsusilə Katerxeydə və İlkin-Gec Arxeydə baş verənlər) saxlamışlar. Belə proseslər içərisində Yerin planetar akkresiyası, bir sıra dağ komplekslərinin əmələ gəlməsi, plitələr tektonikası prosesinin öyrənilməsinə təşəbbüs, plitələr tektonikasını hərəkətə gətirən əsas qüvvələrin təzahürü, istilik parametrlərinin mühüm təsiri, müxtəlif fiziki-geoloji şəraitdə artıq təzyiqin rolu, yer qabığı və litosferin sıxlığa görə stratifikasiyası və bir sıra digər termodinamik prosesləri qeyd etmək olar. Onların, demək olar ki, hamısı təkamülünün müddətlərində və üsullarındakı mühüm qeyri-müəyyənliyə, həmçinin onların ikincidərəcəli göstəricilərinin və tektonik-geofiziki xarakteristikaların qeyri-birmənalılığına görə, kifayət dərəcədə tədqiq edilməmişdir. Eyni zamanda bir çox tektonik-geodinamik proseslər və parametrlər qarşılıqlı əlaqədə olmuşlar və olurlar, və çoxsaylı müxtəlif faktorların eyni vaxtda dəyişilməsi onların geoloji mühitə təsirində mühüm rol oynamışdır. Bu mürəkkəb məsələlərdən bəziləri hazırki məqalədə müzakirə olunur. Məsələn, plitələr tektonikası fenomeninin rolu necədir və Yerdə bu proses nə vaxt başlamışdır? Bir çox nəsillər ərzində alim-geoloqlar tərəfindən tətbiq edilən tektonik proseslərin təbiətinin analizinin sadə olmayan metodlarına icmalda əsas diqqət yetirilmişdir. Aparılmış icmalda Günəş sisteminin digər planetlərində alınmış bəzi fiziki parametrlərdən də istifadə edilmişdir.

Açar sözlər: *plitələr tektonikasi, əsas hərəkətverici qüvvələr, termodinamik modellər, sıxlığın rolu, dərinlik quruluşunun modelləri, ilkin Yerin təkamülü*

ANAS Transactions Earth Sciences 2 / 2020

Geology and geophysics

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DIVISION OF THE GEOLOGICAL SECTION INTO HOMOGENEOUS DRILLABILITY INTERVALS BASED ON THE RESULTS OF MODELING THE PROPERTIES OF ROCKS IN THE DRILLING PROCESS

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Keywords: *complex information, geological section, rock, bit, complications, classification, decision-making, uncertainty, fuzzy logic*

Summary. Improving the efficiency and quality of well drilling largely depends on improving the quality of information received. The quality of decisions made during drilling also substantially depends on the quality of information. Widely used in recent years in world practice, mud logging in the process of drilling allows us to solve a number of problems in the drilling process, when information about the section of the well being drilled is missing or is available in a limited amount. The application of the results of the complex of geological, geophysical and technological research allows us to study more deeply the section and thereby improve the quality of decisions.

The article discusses ways to improve the quality of information and obtain more extensive information about the drilled rock, which allows us to divide the section into homogeneous intervals. For this purpose, an approach known from fuzzy logic was applied to find the appropriate criterion for each of the indicators under consideration, and then their average harmonic value was calculated. The relationship between the mean harmonic value and the depth serves to define the boundaries between the intervals. The above algorithm was used for calculations for four wells in the Bahar field, and the results were clearly demonstrated using figures.

1. Introduction

The efficiency and quality of well drilling largely depends on the quality of the information received. The quality of decisions made during the drilling process also substantially depends on the quality of information. The low quality of the information received is one of the reasons for making erroneous decisions, which in turn leads to complications, accidents and in general to a decrease in the technical and economic indicators of well drilling. The aforementioned as well as the experience of drilling wells and numerous studies indicate the need to use appropriate methods of data processing and information analysis.

In recent years a large number of studies have accumulated on the process of interaction of a rock-cutting tool with a rock, in which methods and tools for determining the physical-mechanical properties and abrasiveness of rocks are proposed. These include experimental studies, studies based on the analysis of geological and geophysical information, as well as based on classification methods. In general, an analysis of the work performed shows that it is now possible to increase the level of decisions made by using complex geological, geophysical and technological information which forms the basis of technological decisions. Information of this nature can be obtained in various ways but to obtain and use such information it is also necessary to use modern methods of data processing and information analysis. In this regard the proposed article is devoted to improving the efficiency of using the information obtained in the process of drilling wells in order to improve the quality of decisions.

2. The value of integrated information in modeling the properties of rocks and the process of drilling wells

Gained in recent years in world practice widespread use of mud logging in the drilling process allows us to solve a number of problems in the drilling process, when information about the section of the well being drilled is missing or is available in a limited amount. The application of the results of mud logging in combination with well logging allows a deeper study of the section and thereby improves the quality of decisions.

As noted in (Ракитин, 2015), well logging-drilling (LWD) is the most interesting and rapidly developing area in the field of logging. When drilling onshore as a rule there are quite a lot of exploratory wells, which allow you to build a fairly reliable geological model. Production drilling at old fields is mainly of a clarifying nature. When drilling at sea and developing new fields with horizontal shafts, the role of LWD and solving geo-navigation problems is much more complicated. In addition, LWD is increasingly used in exploratory wells. This is due to the following circumstances:

1) obtaining technological data directly from the bottom provides an opportunity not only to reduce accident rate while drilling in new areas but also suggests the possibility of developing new directions of LWD;

2) the use of gamma-ray logging (GL) and electrolytic logging (EL) data during drilling allows not only to determine the most accurate coring intervals but also to develop a technique for repeated EL measurements at a higher level;

3) the most reliable data on flow rates can be obtained during tests from the offshoot with horizontal ending in promising collectors.

The limiting factor in the use of LWD on shelf exploratory wells is the high cost of using foreign equipment. LWD is most widely used in the construction of production wells. The article (Делия, Ракитин, 2014) presents prediction of development tendencies of mud logging and well logging on experience of well drilling at the example of "LUKOIL-Nizhnevolzhskneft" LLC in the north of the Caspian Sea.

3. Methods of investigation

When analyzing geological and technological information on well drilling in particular and data related to measurements in general, one has to deal with errors, uncertainty and unstable correlations between the studied parameters. Such difficulties are inherent in technical, technological, geological and geophysical studies due to the difficulties associated with the creation and use of more accurate instruments for measuring drilling performance, formation characteristics, especially with a complex geological structure, operational parameters, etc. It becomes very difficult to conduct a comparative analysis between values of the same parameter measured in different ways.

For instance, when analyzing the operation of the bits it is advisable to divide the section into homogeneous intervals and consider the patterns of changes in drilling performance within them. For these purposes various classification methods have been proposed. One of the simple methods that allows this operation to be performed is the method of D.A. Rodionov, known from geology, which was applied in drilling (Efendiyev et al., 1991). According to this method the massif over the entire depth is first assumed to be homogeneous, and then the Rodionov criterion for each interval is calculated according to the expression (1) proposed by the author:

$$V(r_0^2) = \frac{n-1}{n(n-K)K} \sum_{j=1}^{m} \frac{\left[(n-K)\sum_{j=1}^{k} \chi_{ij} - K\sum_{i=k+1}^{n} \chi_{ij}\right]^2}{\sum_{i=1}^{n} \chi_{ij}^2 - \frac{1}{n}\left(\sum_{i=1}^{n} \chi_{ij}\right)^2} \quad (1)$$

According to the analysis of (Родионов, 1968), the values of the Rodionov criterion are distributed obeying the law of χ^2 Pearson. Therefore, the program provides a comparison of each calculated value with a table one for a given level of significance within each interval. The intervals corresponding to the excess of the calculated value of the criterion over the tabular value χ^2 of Pearson are the boundary between two homogeneous packs that are heterogeneous with each other.

Many theoretical models have been developed to predict or correlate specific physical properties of porous rock. Most theoretical models are built on simplified physical concepts: what are the properties of an ideal porous media. However, in comparison with real rocks, these models are always oversimplified. Most of these models are capable of "forward modeling" or predicting rock properties with one or more arbitrary parameters. However, as is typical in earth science, models cannot be inverted from measurements to predict uniquely real rock and pore-fluid properties. Many efforts have been made and will continue to be made to build porous rock models but progress is very limited. Some of the most fundamental questions are still unanswered.

(Taylor et al., 2015) modeled reservoir quality evolution using the forward diagenetic model Touchstone, which simulates porosity loss due to compaction and quartz cementation. Quantitative petrographic analyses and burial history data were used to calibrate Touchstone model parameters. The results were applied to deeper prospects for pre-drill prediction of porosity and permeability. There was also an attempt to model the dynamic moduli of porous rocks saturated with viscous fluid at seismic frequencies on core scale based on the strain-stress method, aiming to provide a complement to real core measurements in lab (Wang et al., 2016). First the authors build 2D geometrical models containing the pore structure information of porous rocks based on the digital images (such as thin section, SEM, CT, etc.) of real rocks. Then they assume that the rock frames are linearly elastic and use the standard Maxwell's spring-dash pot model to describe the viscoelastic properties of pore fluids. Boundary conditions are set according to the stress-strain method; and the displacement field is calculated using the finite element method (FEM). They numerically test the effects of pore structure on the viscoelastic properties of saturated rocks. The preliminary results indicate that the pore structure parameters, such as porosity, aspect ratio (AR), and pore size affect the rock frame stiffness and results in different viscoelastic behavior of the saturated rocks.

The paper (Wawrzyniak-Guz, 2019) presents an application of rock physics templates constructed with the use of the granular effective medium theory and the shale model to estimate the elastic properties of the Silurian and Ordovician shale formations from the Baltic Basic, Poland. The author uses available logging data from three nearby wells and their petrophysical interpretation to distinguish various lithological types and to determine average matrix mineral composition of each lithology group, essential in further rock physics modelling. Anisotropy estimation and investigation of the relation between various petrophysical parameters precede the rock physics modelling. The paper includes also the proposition of the final rock physics template constructed for the Silurian and the Ordovician formation from the Baltic Basin that can contribute to a better understanding of the elastic properties of the lower Paleozoic shale plays in Poland.

To date fuzzy logic has also been successfully applied in the assessment and use of reservoir characteristics. Even in the past researchers in the field of natural sciences noticed that many, at first glance, random events are accompanied by certain laws. Later these regularities, or distributions, were closely approximated by continuous curves called "normal distribution curves of errors" and assigned to the laws of probability (Brown et al., 2000; Cuddy, Glover, 2002). In general analysis shows that the solution of problems of modeling technological processes is significantly hampered by the presence of uncertainty associated with the use of random and fuzzy quantities. Random variables convey the fact that the studied quantities can take different values with different probabilities. Fuzzy quantities convey approximation in determining the values of these quantities themselves. In addition, fuzzy values may be preferable in case of insufficient statistical data and related information necessary for more reliable estimates. Such estimates of the mechanical properties of rocks can be made according to their physical properties, estimated using well logging using probabilistic-statistical methods and the theory of fuzzy sets. The study of the considered dependencies made it possible to develop a reasonable design scheme for assessing the characteristics of the geological section.

4. Information analysis and results of investigations

The optimal decision-making when drilling wells requires an analysis of objectively existing, identified as a result of studies during the drilling process, qualitative and quantitative relationships of various geological and technological factors affecting the performance of this process, research and identification of the relationships between geological, geophysical, mechanical and technological characteristics of the section. Such regularities make it possible to further study the geological section, evaluate those geological characteristics that have not been previously evaluated, and also improve the accuracy of previously estimated characteristics and thereby ensure the development of a system for calculating the characteristics of the geological section (Джанзаков и др., 2019; Дюсенов, 2008; Efendiyev et al., 2017).

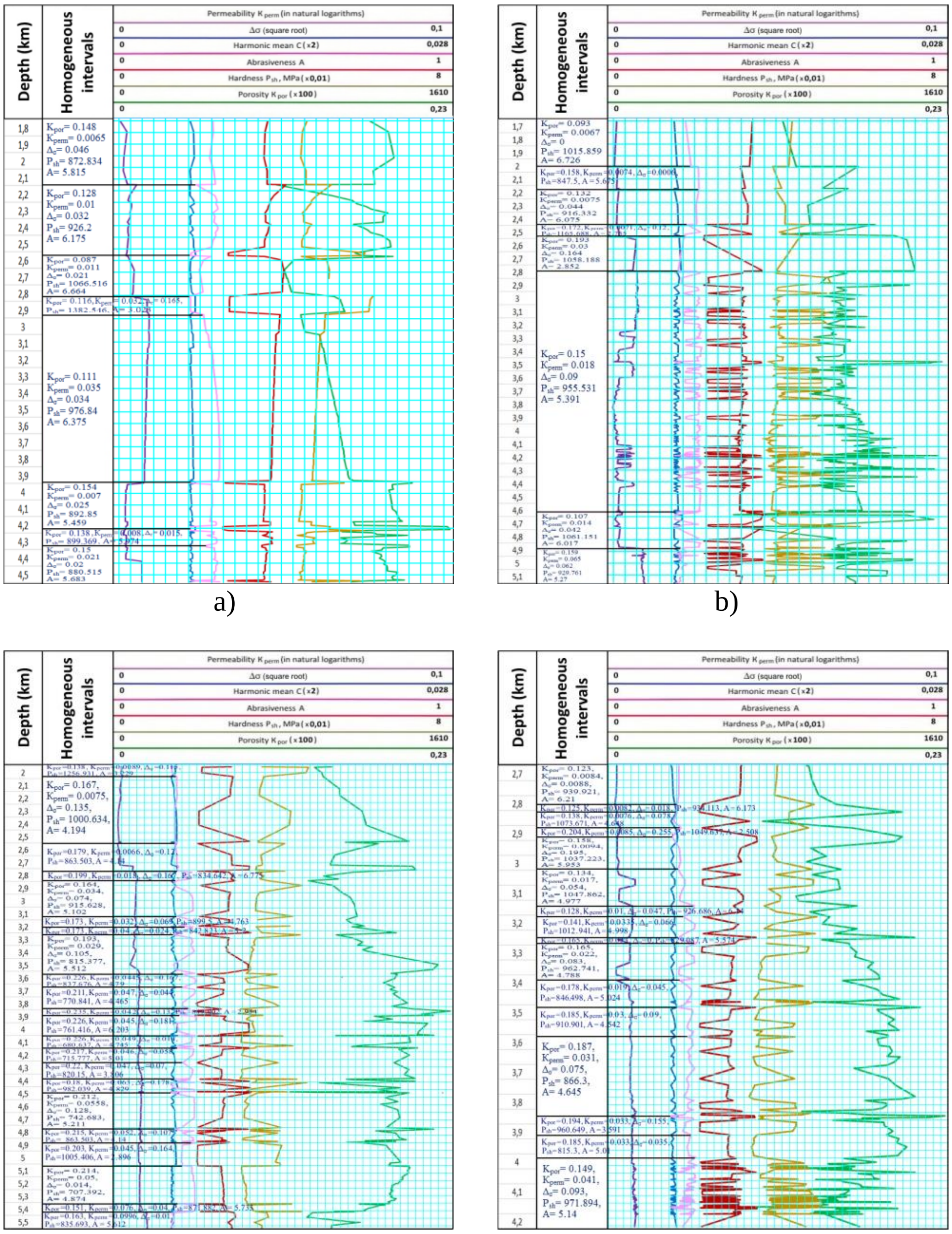
It should be noted that in the practical use of well drilling results, it is required to take into account the presence of noise. In this regard it becomes necessary to study some random processes against the background of others (pulsed interference). One of the most effective methods is the automatic selection method, which was used in (Мирзаджанзаде и др., 1973; Агаев, 1989) to estimate the useful signal in the operating parameters. The program that we used includes noise filtering when processing the d-exponent, and a change in the statistics L allows one to judge whether the system under consideration is homogeneous, i.e. from the value of L calculated for the indicator of drilling, it is possible to determine homogeneous intervals (Efendiyev et al., 2019; Эфендиев и др., 2019).

In (Brown et al., 2000; Cuddy and Glover, 2002) according to the measured rock characteristics (hardness is taken in our examples) which can be estimated from core studies, mud logging or well logging, the fuzzy possibility $F(x_f)$ is determined. The process is repeated for another parameter, for example, porosity, y. This step allows us to obtain $F(y_f)$, a fuzzy possibility that the measured porosity y belongs to the lithotype f. This process is repeated for other features characterizing the given rock, then for each lithotype of the rocks to get $F(z_f)$. At this stage we have five fuzzy probabilities ($F(x_f)$, $F(y_f)$, $F(z_f)$ ....) which are based on fuzzy possibilities available for different rock characteristics (x, y, z ...). They indicate that lithotype f is most likely. The indicated fuzzy possibilities are then harmoniously averaged (2) to obtain the aggregate fuzzy possibility:

$$C_f = \frac{5}{\frac{1}{F(K_{por.})}+\frac{1}{F(K_{perm.})}+\frac{1}{F(P_{Sh})}+\frac{1}{F(A)}+\frac{1}{F(\Delta_\sigma)}} \quad (2)$$

This process is repeated for each lithotype *f*. The lithotype associated with the highest C_f is taken as the most probable for a given set of features. This approach was used in our work because it makes the lithological forecast more reliable.

In this article, the noted theoretical prerequisites are considered on the example of forecasting the lithology of the rocks of a section of one of the wells drilled in Azerbaijan by a set of attributes (hardness P_{sh}, abrasiveness A, lithology indicator Δ_σ, porosity K_{por}, permeability K_{perm}) obtained as a result of geological, geophysical and technological studies during well drilling. An analysis of the distribution showed (Fig. 1) that for each of the listed attributes, with the exception of permeability, it obeys the normal law (permeability obeys the lognormal law, therefore their logarithms are taken as its values). In all homogeneous intervals, the weighted average values of each of the five parameters are given: porosity, permeability, lithology index, hardness, abrasiveness.



c) d)

Fig. The results of the analysis of information on drilling wells in the Bahar fields:
a) well 8, b) well 40, c) well 9, d) well 72

The figure clearly traces the boundaries of lithological differences of rocks, identified using the harmonic average of five indicators of rock properties which correlates well with each of the noted characteristics. The results obtained make it possible to enlarge homogeneous packs of rocks, to combine data on the development of bits within these packs, providing a sufficient amount of information about the work of the bits and, as one of the results, to begin to build a model of penetration rate for this rock. Weighted average values of rock characteristics for individual rock differences are shown in the figure. It should be noted that, depending on the problem to be solved, when breaking the section into homogeneous packs, other rock characteristics can also be used. In this case we considered indicators of those rock properties that are necessary for solving well drilling problems.

5. Conclusions

As studies have shown, the main purpose of monitoring the drilling process using complex information is the timely warning of emergency situations, improving the performance of bits, and, in general, optimizing the drilling process. During the implementation of any stage carried out at the drilling site, all parameters are recorded and processed in real time. The time of each operation is fixed and used at the next stage when constructing the corresponding dependencies.

Thus, the development of modern technical means and technologies for information support of the well drilling process and their widespread adoption can improve the quality of the information received and requires its appropriate analysis. The operational information obtained during the drilling process is of great importance, as we have already noted, when drilling wells, especially in poorly studied regions with difficult mining and geological and environmental conditions. At the same time, as can be seen from the figure, it is possible to conduct a comparative analysis of changes in rock properties and rate of penetration, to identify homogeneous intervals for rock properties and for drillability in general, in order to trace the intervals of possible complications, etc.

Depending on the problem to be solved, when separating a geological section into homogeneous packs using the proposed algorithm, other rock characteristics can also be used. In this case in connection with the formulation of the main problem we considered the indicators of those rock properties that are necessary when solving problems of drilling wells, in particular, decision-making when choosing bits and operating parameters of drilling.

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РАЗДЕЛЕНИЕ ГЕОЛОГИЧЕСКОГО РАЗРЕЗА НА ОДНОРОДНЫЕ ПО БУРИМОСТИ ИНТЕРВАЛЫ НА ОСНОВЕ РЕЗУЛЬТАТОВ МОДЕЛИРОВАНИЯ СВОЙСТВ ГОРНЫХ ПОРОД В ПРОЦЕССЕ БУРЕНИЯ

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Резюме. Повышение эффективности и качества бурения скважин во многом зависит от повышения качества получаемой информации. Качество решений, принимаемых в процессе бурения, также существенно зависит от качества информации. Широко используемые в последние годы в мировой практике геолого-технологические исследования в процессе бурения скважин позволяют решить ряд проблем в этом процессе, когда информация о разрезе пробуренной скважины отсутствует или доступна в ограниченном количестве. Применение результатов комплекса геолого-геофизических и технологических исследований позволяет более глубоко изучить данный вопрос и тем самым повысить качество принимаемых решений. Статья посвящена анализу и роли информации, получаемой при бурении, оценке ее качества и методов, способствующих повышению качества информации при принятии решений на различных этапах бурения. Рассмотрены методы обработки данных и анализа информации, показано, как использовать сложную геологическую, геофизическую и технологическую информацию, объяснена целесообразность использования различных методов, известных из математической статистики и теории нечетких множеств. В статье рассмотрены пути повышения качества информации и получения более обширных сведений о пробуренной породе, что позволяет разделить разрез на однородные интервалы. С этой целью применялся известный из нечеткой логики подход по нахождению соответствующего критерия для каждого из рассматриваемых показателей, а затем было подсчитано их среднее гармоническое значение. Зависимость между средним гармоническим значением и глубиной служит для определения границ между интервалами. Вышеотмеченный алгоритм был использован для расчетов по четырем скважинам на месторождении Бахар, а результаты были наглядно продемонстрированы с помощью рисунков.

Ключевые слова: *комплексная информация, геологический разрез, порода, долота, осложнения, классификация, принятие решений, неопределенность, нечеткая логика*

QUYU QAZILMASI ZAMANI SÜXURLARIN MODELLƏŞDİRİLMƏSİ NƏTİCƏLƏRİNƏ ƏSASƏN GEOLOJİ KƏSİLİŞİN BİRCİNS İNTERVALLARA BÖLÜNMƏSİ

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Xülasə. Quyu qazılmasının effektivliyi və keyfiyyəti əldə edilən informasiyanın keyfiyyətindən asılıdır. Qazma zamanı qəbul edilən qərarların da keyfiyyəti informasiyanın keyfiyyətindən asılıdır. Son zamanlar dünya təcrübəsində geniş istifadə olunan geoloji-texnoloji tədqiqatlar qazma zamanı informasiya çatışmazlığı şəraitində bir çox problemlərin həllini həyata keçirməyə imkan yaradır. Bununla əlaqədar təqdim olunan məqalə qazma zamanı kəsiliş haqqında əldə edilən informasiyanın keyfiyyətinin artırılması, qazılan süxurlar haqqında dahageniş məlumatın əldə edilməsi, bunun əsasında kəsilişin bircins intervallara ayrılmasına həsr olunur. İlkin məlumat kimi burada son zamanlar geniş tətbiqini tapmış geoloji-texnoloji tədqiqat sistemlərindən alınmış informasiyadan istifadə olunmuşdur.Bura kəsilişin litologiyası, süxurların məsaməliliyi, bərkliyi və digər xassə göstəriciləri haqqında məlumat daxildir. Əldə edilmiş məlumatın ilkin emalı, onun təhlili adətən ənənəvi statistik üsulların tətbiqi ilə həyata keçirilir. Lakin onu qeyd etmək lazımdır ki, bir çox hallarda qeyd olunmuş üsullar kifayət deyil. Burada mövcud qeyri-müəyyənlik üzündən qərarların qəbulu çətinləşir. Buna görə son zamanlar qeyri-səlis çoxluqlar nəzəriyyəsinə əsaslanan üsullardan geniş istifadə olunur. Qeyd olunmuş məsələ qeyri səlis məntiq əsasında hər baxılan amil üzrə müvafiq meyarın hesablanması, bütün bunların arasında orta harmonik qiymətin təyini vasitəsilə həll olunur. Belə ki, həmin orta harmonik qiymətin dərinlikdən asılılıq əyrisindəki sıçrayışlara uyğun dərinlik bir süxur ilə digər süxurun sərhədi kimi qəbul olunur. Qeyd olunmuş alqoritm üzrə Bahar yatağında qazılmış quyuların timsalında hesablamalar və müvafiq süxur bölgüsü aparılmışdır. Təklif olunmuş yanaşma ilə aparılmış bölgü vasitəsi ilə formalaşmış bircins intervallar üzrə qazma baltalarının iş göstəriciləri təhlil olunaraq onların işinin modelləşdirilməsi və qərarların qəbul edilməsi üzrə mərhələləri həyata keçirmək olar.

Açar sözlər: *kompleks informasiya, geoloji kəsiliş, süxur, balta, mürəkkəbləşmə, təsnifat, qərarların qəbulu, qeyri müəyyənlik, qeyri səlis məntiq*

ANAS Transactions **Earth Sciences** **2 / 2020**

Geology and geophysics

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SINGLE-STATION POLARIZATION ANALYSIS ACCORDING TO THE ZAGATALA EARTHQUAKE ON MAY 7, 2012

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Keywords: *polarization of shear SH and SV waves, Lissajous figures, incident angle and azimuth of the seismic waves*

Summary. The article presents an analysis of the parameters of split shear waves from a surface (h = 8 km) earthquake that occurred within the Great Caucasus in Zagatala region on May 7, 2012 with ml = 5.6. Spatial analysis of waveforms is carried out using 3-component digital signal recordings. For selected sections of the 3-component recording in the DIMAS program, a three-dimensional graph of the particle motion path and the projection of the motion path on the NE, NZ, EZ planes is constructed. The birefringence effect, i.e. the shear wave is split into two (S_1 and S_2), each of which has its own polarization and speed for broadband three-component records (HHE, HHN, HHZ) of one seismic station ZKT. This made it possible to study small-scale strains for a better understanding of the dynamic processes and properties chances of the medium with depth. At the same time, the dependence of the parameters of split S waves on the direction of propagation and spatial heterogeneity of the physical properties of the medium requires a more detailed analysis of the data in space and time. It was established that the fast and slow S-waves are well distinguished in the wave field, their polarization vectors are mutually orthogonal. Subsequent waves have much smaller amplitudes, and their azimuths are close to the azimuth of the slow wave S_2. The delay time between the first and second phases of the shear wave for the ZKT station is 3 seconds with the orientation of the polarization vectors along the azimuths 140º and 70º.

Introduction

The polarization properties of seismic wavefields recorded by triaxial (three-component) stations can be exploited for event detection, seismic direction finding, and wavefield filtering. Development of the method of shear and converted waves, creation of the basics of multi-wave seismic exploration make it possible to obtain more complete information about the medium, including anisotropy.As is known, according to the registration of longitudinal waves, it is not always possible to distinguish easily effects associated with heterogeneity and anisotropy of elastic properties, and a very detailed observation system is required for reliable detection of anisotropy. From the data of multicomponent observations, one can obtain both kinematic and dynamic characteristics of all types of waves associated with the anisotropy of the medium. Of the dynamic characteristics, the polarization parameters of transverse and converted waves are most important for determining anisotropy. In an anisotropic medium, two shear waves with different polarization and different velocities can propagate along an arbitrary direction. One of them is called fast (S1), and the other – slow (S2). When an anisotropic S-wave layer with arbitrary polarization is incident on the boundary, S-waves split, which is a sign of the presence of anisotropy, i.e., birefringence. Polarization analysis of shear and converted waves makes it possible to separate the waves S1 and S2 in the case of their interference and to determine their polarization parameters associated with the characteristics of the anisotropic medium (Гальперин, 1977).

For the first time the idea of the widespread use of wave polarization to increase the effectiveness of seismic and seismological studies was put forward in the 1950s by G.A. Gamburtsov. He proposed and developed a new type of wave correlation — azimuthal phase correlation, based on tracking the phases of seismic waves as a function of orientation in space of the component oscillations at a constant position of the observation points. The development of these studies led to the creation of the azimuthal method of seismic observations (Гальперин, 1977).

Methods have been developed for processing azimuthal seismograms and determining the polarization parameters of seismic waves. This approach to the study of anisotropy of shear waves has recently been used by professor at the University of Missouri E.Sandwoll in his studies.

Thus, the purpose of this article was to determine the direction of particle displacement of the medium and the parameters of elliptically polarized vibrations, to evaluate the accuracy of determining the direction of the particle motion vector, and to identify split shear waves using the Zagatala earthquake which occurred on May 7, 2012 with ml = 5.6.

Polarization

Wave polarization is a characteristic of shear waves that describes the behavior of a vector of an oscillating quantity in a plane perpendicular to the direction of wave propagation. Polarization cannot occur in a longitudinal wave, since the direction of oscillations in waves of this type always coincides with the direction of propagation. A transverse wave is characterized by two directions: the wave vector and the amplitude vector, which are always perpendicular to the wave vector up to the motion of space. The wave vector shows the direction of wave propagation, and the amplitude vector shows in which direction the oscillations occur. In three-dimensional space there is another degree of freedom – the possibility of rotation of the amplitude vector around the wave vector. The triple of vectors associated with each point of the biregular curve forms a Frenet frame (https://en.wikipedia.org/wiki/Polarization_waves).

There are three reasons for the polarization of waves: 1) asymmetric generation of waves in a disturbance source; 2) the anisotropy of the wave propagation medium; 3) refraction and reflection at the boundary of two media. Polarization is described by Lissajous figures (fig.1), and corresponds to the addition of transverse vibrations of equal frequency (with different phase shifts).

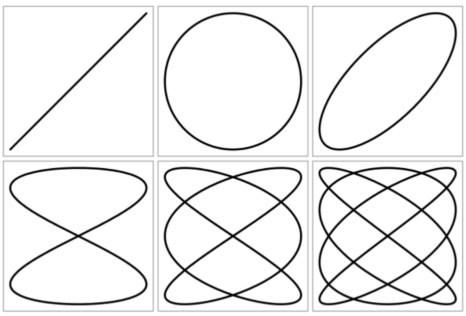


Fig. 1. The polarization described by the Lissajous figures

If the oscillation frequencies are equal, the Lissajous figures are an ellipse, the two extreme forms of which are a circle and a straight line segment. In the general case for harmonic waves, the end of the vector of an oscillating quantity describes an ellipse in the plane directed transverse to the direction of wave propagation: this is an elliptical polarization. Important particular cases are linear polarization, in which perturbation oscillations occur in one plane, in this case they speak of a "plane-polarized wave" and circular polarization, in which the end of the amplitude vector describes a circle in the plane of oscillation; circular polarization (like elliptical), depending on the direction of rotation of the vector, can be positive or right and negative or left (https://en.wikipedia.org/wiki/Polarization_waves).

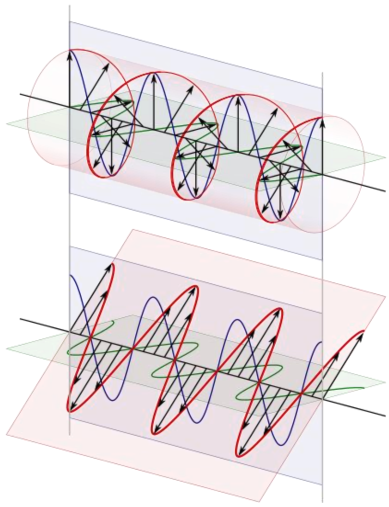


Fig. 2. The difference between circular and plane polarized waves

Particle motion

P and S waves are linearly polarized, with slight deviations in the inhomogeneous and partially anisotropic real Earth. Incontrast, surface waves may either be linearly polarized in the horizontal plane perpendicular to the direction of wave propagation (transverse polarization; T direction; e.g., Love waves) or elliptically polarized in the vertical plane oriented in the radial (R) direction of wave propagation. P-wave particle motion is dominatingly back and parallel to the seismic ray, whereas S-wave motion is perpendicular to the ray direction (Етирмишли, Казимов, 2007). Accordingly, a P-wave motion can be split into two main components, one vertical (Z) andone horizontal (R) component. S waves, on the other hand, may show purely transverse motion, oscillating in the horizontal plane (SH; i.e., pure T component) or motion in the vertical propagation plane, at right angles to the ray direction (SV), or in any other combination of SH and SV. In the latter case S-wave particle motion has Z, R and T components, with SV wave split into a Z and an R component.

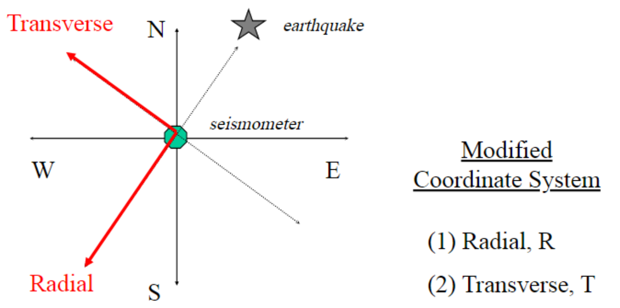


Fig. 3. Components of motion (rotation the horizontal components)

Thus, when 3-component records are available, the particle motion of seismic waves in space can be reconstructed and used for the identification of seismic wave types. However, usually the horizontal seismometers are oriented in geographic east (E) and north (N) direction. Then, first the back azimuth of the source has to be computed and then the horizontal components have to be rotated into the horizontal R direction and the perpendicular T direction, respectively. This axis rotation is easily performed when digital 3-component data and suitable analysis software are available. It may even be carried one step further by rotating the R component once more into the direction of the incident seismic ray (longitudinal L direction). The T component then remains unchanged but the Z component is rotated into the Q direction of the SV component. Such a ray-oriented co-ordinate system separates and plots P, SH and SV waves in 3 different components L, T and Q, respectively. These axes transformations are easily made given digital data from arbitrarily oriented orthogonal 3-component sensors such as the widely used triaxial sensors STS2.

Description of the DIMAS program

The DIMAS (Display, Interactive Manipulation and Analysis of Seismograms) program is designed for detailed processing and visual analysis of digital seismic signals from various acquisition systems (Дрознин, Дрознина, 2004; 2011). This program allows the user to both conduct complex processing and analysis of the seismic signal and evaluate the main parameters of earthquakes, meets the increased requirements of real-time operation on seismometric information collection systems. The “SAC” format is used as the water file. Traditional tool channel orientation:

Z-------Dip=-90, Azimuth=0
N-------Dip=0,   Azimuth=0
E-------Dip=0, Azimuth =90.

Spatial analysis of waveforms is carried out using 3-component digital signal recordings. For selected sections of a 3-component recording, a three-dimensional graph of the particle motion path and the projection of the motion path on the NE, NZ, EZ plane is constructed in the program. In this case, the effect of the volumetric trajectory is created by rotation using the function keys, and projections on the corresponding planes are obtained by turning the volumetric figure at the corresponding angles. The program provides for the study of the polarization characteristics of the signal (Горшкалев и др., 2011), as well as a graphic display of the azimuths and angles of exit of the axis of polarization of the seismic wave on the Wolfe grid for a given time interval. The direction of the largest axis gives the azimuth to the source. The statistical distribution of polarization vectors in space (polarization ellipsoid) is constructed in a time window based on the covariance method. The size of the time window is generally determined within the dominant period of the wave under study (Казимова, Казимов, 2011).

As mentioned above, studies were conducted on the example of one of the most powerful earthquakes in Azerbaijan over the past 10 years – the Zagatala earthquake on May 7, 2012 with ml=5.6. Broadband three-component records (HHE, HHN, HHZ) of one “ZKT” seismic station were selected (Fig. 4).

Fig. 5 shows azimuthal seismograms plotted in a horizontal plane with an azimuth step of 2º and a count from the north in the S-wave interval, the projection of particle motion in three-dimensional space, and seismograms of a three-component recording.

When shear waves pass through an anisotropic layer, a birefringence effect occurs, i.e. the transverse wave is split into two (S_1 and S_2), each of which has its own polarization and speed. The nonlinear polarization of the waves S is due to the superposition of several oscillations. In the case when the anisotropy is caused by directional fracture, the displacement vector of the wave S1 is parallel to the plane of the cracks, and by determining its polarization we are able to determine the direction of the cracks (Лунева, 2008, 2009).

Thus, for the estimation of wave parameters in the azimuthal seismograms, S_1 and S_2 phases and their following characteristics are distinguished: 1) the arrival time t_{S1}, t_{S2}; 2) the time interval Δt_{s12}, including both waves.

As can be seen in the figures, the fast and slow S-waves are well distinguished in the wave field, their polarization vectors are mutually orthogonal. Subsequent waves have much smaller amplitudes, and their azimuths are close to the azimuth of the slow wave S_2. The delay time between the first and second phase of the shear wave for the ZKT station is 3 seconds with the orientation of the polarization vectors along the azimuths 140º and 70º.

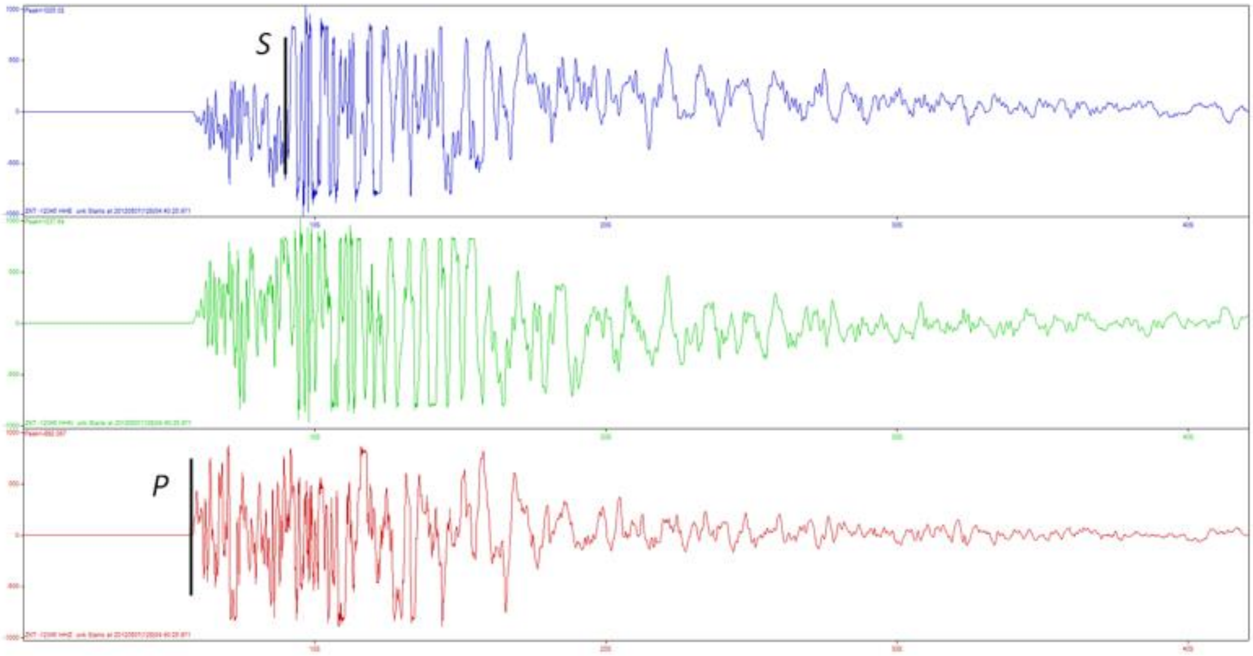


Fig. 4. Three-component recording of the Zagatala earthquake on May 7, 2012 at the "ZKT" station

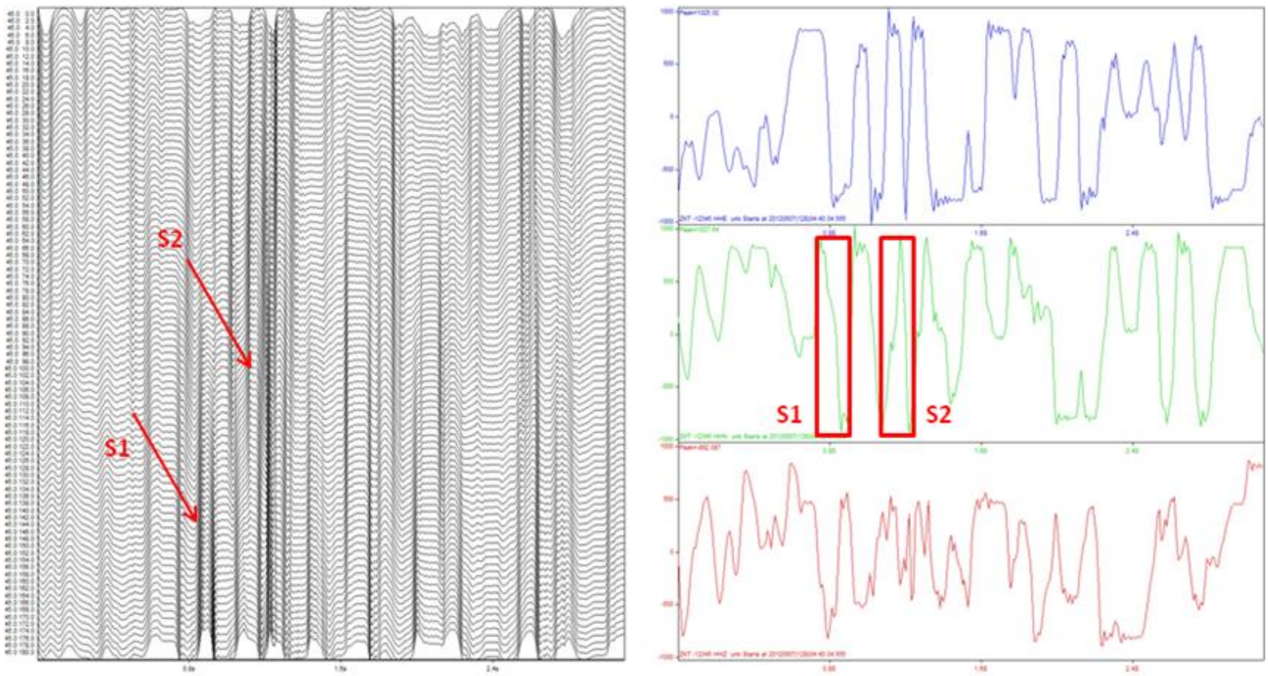
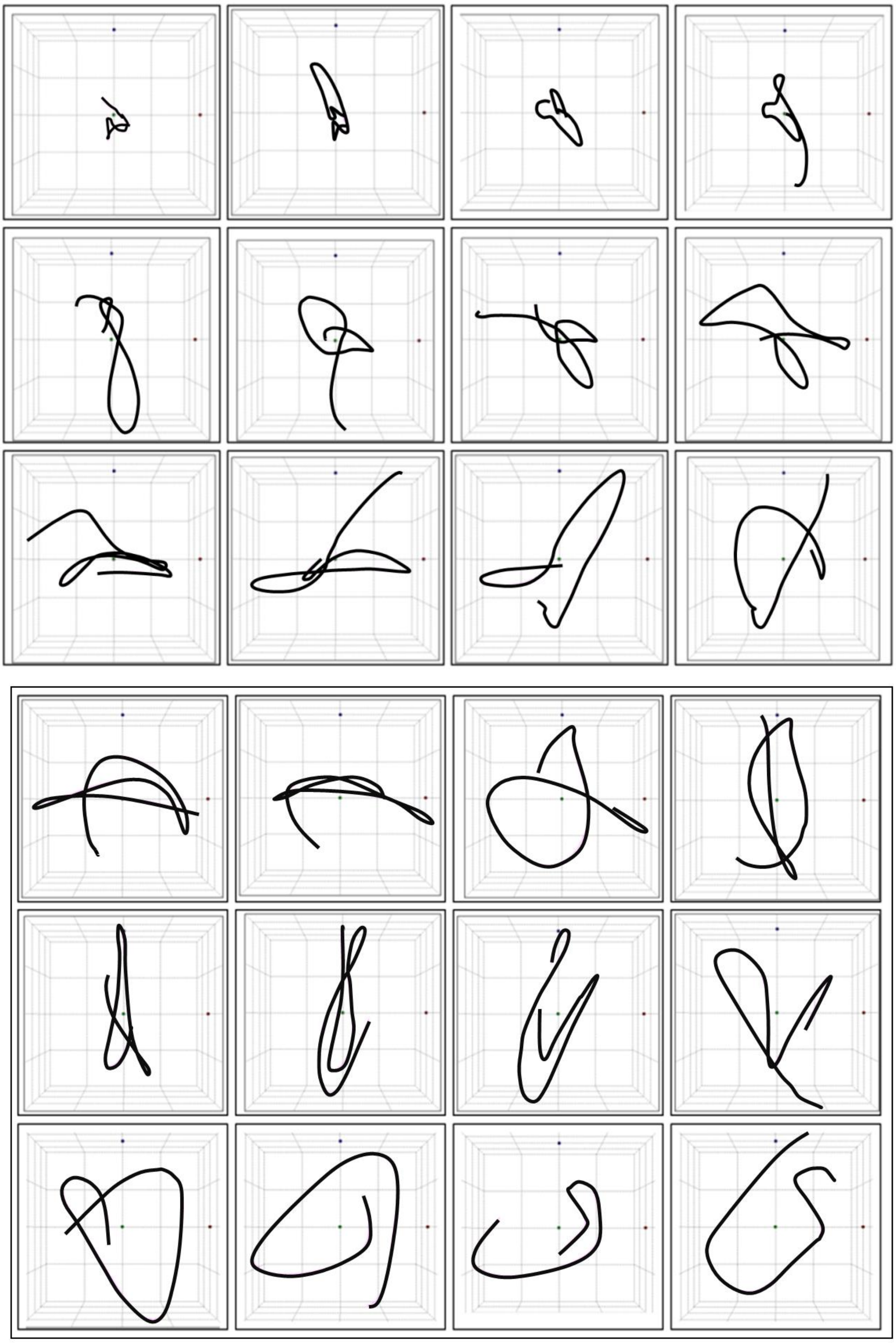


Fig. 5. An azimuthal seismogram plotted in a horizontal plane with an azimuth step of 2º and a reference from the north in the S-wave interval at the Guba (QUB) station. Fast (S1) and slow (S2) waves are indicated by arrows

34 shear intervals were identified on the shear wave seismogram and particle motion trajectories were constructed in three-dimensional space with a step of one second (Fig. 6). As can be seen in the figures on the 4th second, the trajectory of particle motion in three-dimensional space changes where wave S1 appears. At the 11th second, wave S2 appears, in which the oscillations are perpendicular to each other, i.e. they oscillate in different planes. This type of trajectory changes to elliptical one. Since the displacement vector of the wave S1 is parallel to the plane of the cracks, by determining its polarization we are able to determine the direction of the cracks. Only the initial part of the recording of waves S1 is less interference, because the interfering waves, as a rule, are offset in time relative to each other (Казымова,

Казымов, 2010, 2016). The shear wave splitting is maximum when the wave propagates parallel to the layering plane. At that moment, when the waves S1 and S2, propagating at different speeds, are displaced in time relative to each other and, interfering with each other, can form an oscillation polarized by the ellipse. The nature and parameters of the ellipse will vary depending on the conditions of the superposition of the waves. This phenomenon is clearly manifested at 25-30 time intervals where the elliptical polarization is oriented in the NE direction, and at 33-34 time intervals the oscillations polarized along the ellipse have the NW direction. At 35-36 time intervals polarization fluctuations take the form of a circle.



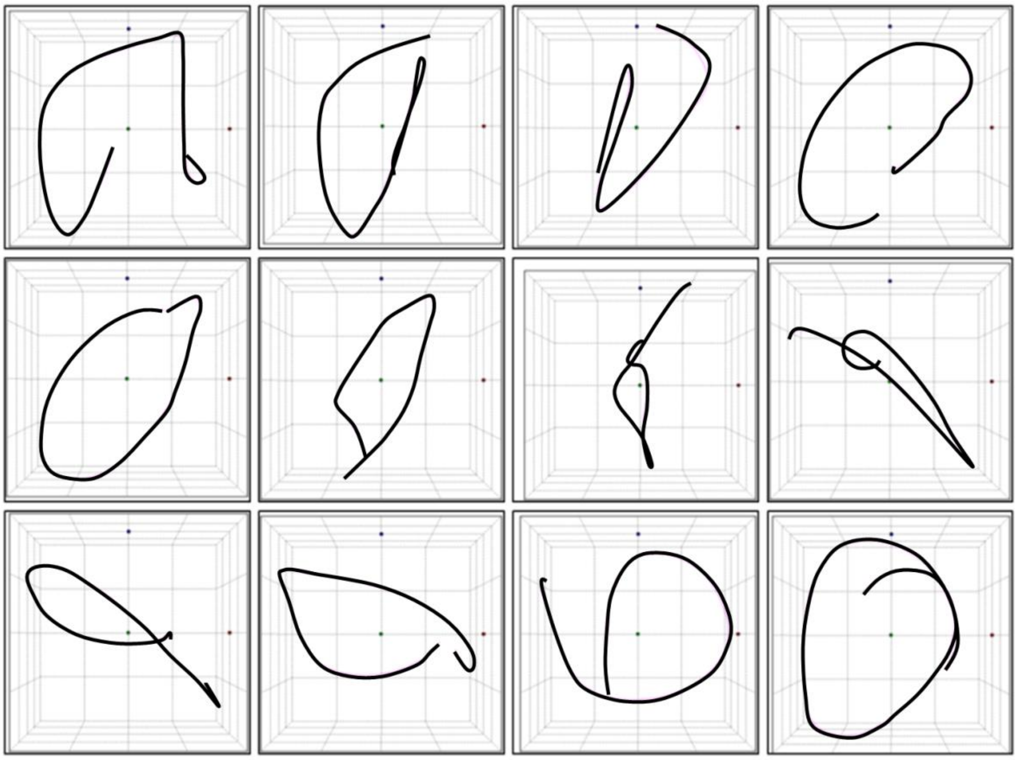


Fig. 6. Particle motion diagrams for selected seismic waves

Note that a change in the velocity of elastic body waves with direction (velocity anisotropy) leads to a change in the refraction angles, critical angles and amplitudes of transmitted waves. In addition, a change in polarization in an anisotropic medium leads to a converted particle motion for all types of body waves: P, SV, and SH. Since the depth of this earthquake was 8 km, and the hypocentric distance was 15 km, we represent the waves P, SV and SH as direct rays. Using the Wolf grid, we determined the incident angle and azimuth of the longitudinal and transverse seismic waves in each selected segment (Fig. 7, 8). Three main axes of a virtual polarization ellipsoid are displayed on the Wolf grid.

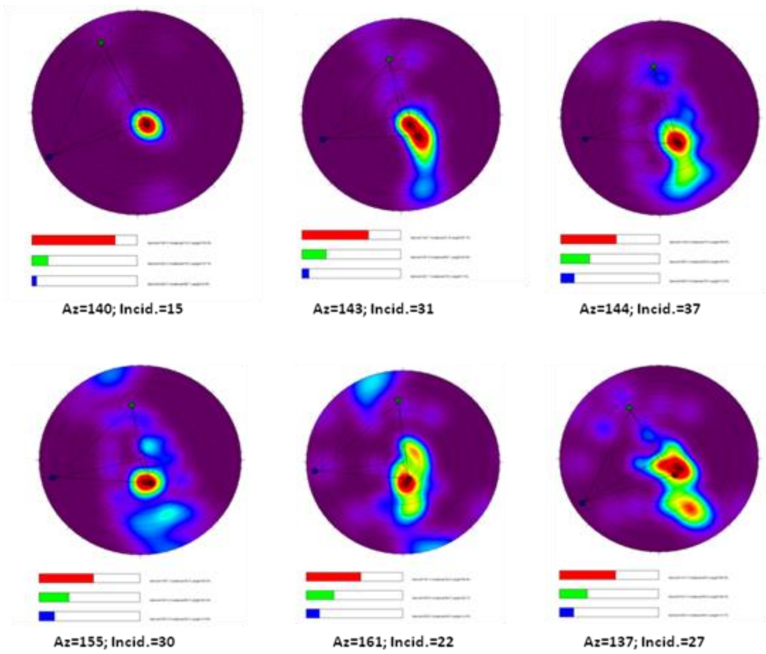


Fig. 7. An example of determining the incident angle of a longitudinal seismic wave and azimuth on the Wolf grid

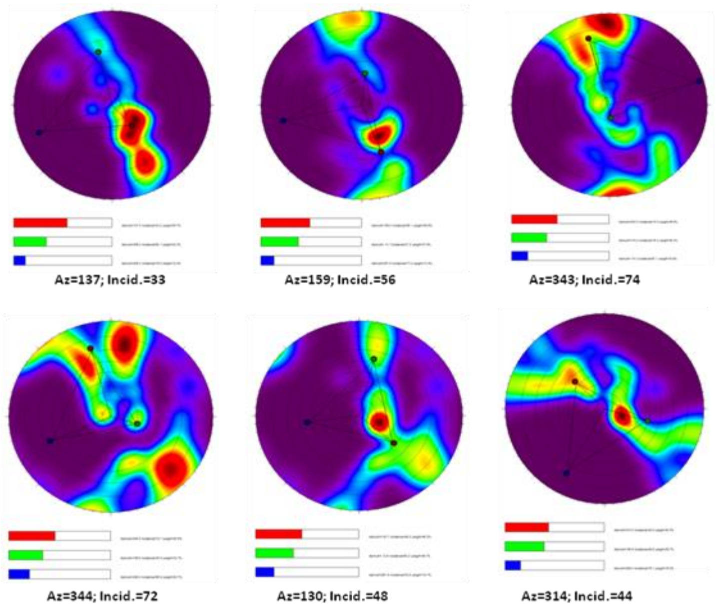


Fig. 8. An example of determining the angle of exit of a transverse seismic wave and azimuth on the Wolf grid

Discussion of the results and conclusions

Based on the obtained data, a graph of the dependence of the incident angle and azimuth of the considered seismic waves at 34 time intervals was constructed. As can be seen in the graph at the first 4 points corresponding to the longitudinal wave, the azimuth fluctuates in the range of 140-155º, and the incident angle – 15-37º. For linearly polarized oscillations, the recording form is preserved and the oscillations are in phase, regardless of the orientation of the components in space. The nature and polarization of the longitudinal wave are independent of the source and the forces acting in it. Therefore, at each individual observation point, the nature of the polarization of wave P caused by the earthquake will be the same and cannot provide information about the source.

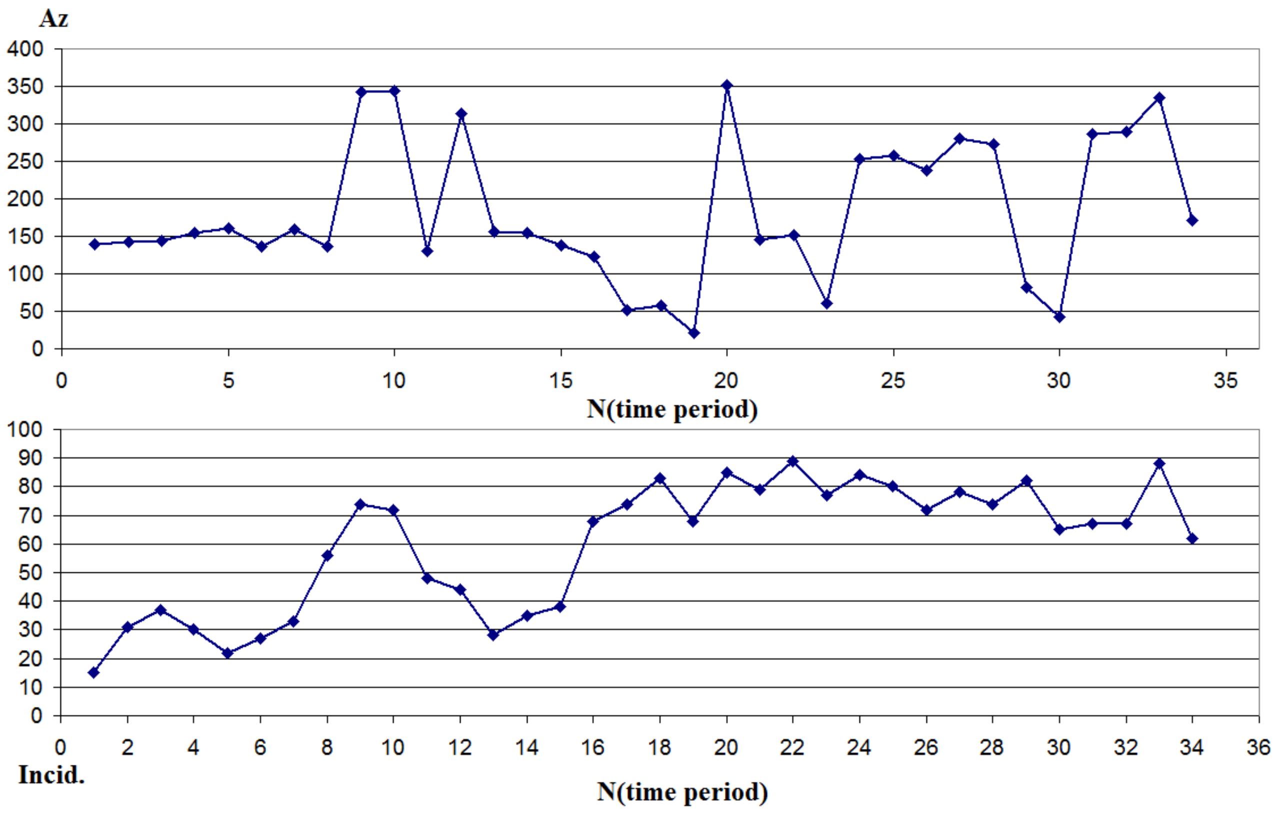


Fig. 9. Graph of the incident angle and azimuth of the considered seismic waves at 34 time intervals

In shear waves, the action of the waves on the geophone will depend on how the geophone is oriented and in what plane, passing through the direction of wave propagation, transverse vibration occurs. In homogeneous and isotropic media, shear waves are polarized in a plane directed to the P wave front, i.e., the particle motion vector lies in the indicated plane and is perpendicular to the beam. Unlike a longitudinal wave, where the polarization of the oscillations is determined only by the direction of wave propagation, the polarization of the oscillations in the transverse wave depends on the type of source.

Thus, it was established that the fast and slow S-waves are well distinguished in the wave field, their polarization vectors are mutually orthogonal. Subsequent waves have much smaller amplitudes, and their azimuths are close to the azimuth of the slow wave S2. The delay time between the first and second phase of the shear wave for the ZKT station is 3 seconds with the orientation of polarization vectors along the azimuths of 140º and 70º. As can be seen in the fig. 9, the azimuthal angle of the first shear wave (interval 5-8) was 130-150º, and the incident angle was 22-33º, however, in the following sections of the wave recording, the azimuthal angle sharply changes to 343-344º, and the incident angle – to 72-74º. Further, the azimuthal angle sharply changes to130º, and then again moves to the fourth decade (314º).

Thus, the orientation of the forces acting in the source determines the nature of the particle motion. For a vertical axis of symmetry and sources with a horizontally acting force in the direction perpendicular to the force action, SH shear waves polarized horizontally will propagate parallel to the force. These waves are of particular interest, since when they propagate in the axis of symmetric media at the interfaces no exchange waves arise, and the wave field is relatively simple. Therefore, the SH method is based on the method of transverse reflected waves. It is characteristic of these waves that the direction of motion of the particles changes with changes in the direction of the forces. SV waves are polarized mainly in the vertical plane, and they, unlike SH waves, are excited by different types of sources.

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ПОЛЯРИЗАЦИОННЫЙ АНАЛИЗ ЗАГАТАЛЬСКОГО ЗЕМЛЕТРЯСЕНИЯ 7 МАЯ 2012 ГОДА ПО ОДНОЙ СТАНЦИИ

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Резюме. В статье дан анализ параметров расщепленных поперечных волн от неглубокого (h=8 км) землетрясения, произошедшего в пределах Большого Кавказа в Загатальском районе 7 мая 2012 г. с ml=5.6. Пространственный анализ волновых форм ведется с использованием 3-х компонентных цифровых записей сигнала. Для выделенных участков 3-х компонентной записи в программе «DIMAS» строится трехмерный график траектории движения частиц и проекции траектории движения на плоскости NE, NZ, EZ. Установлен эффект двулучепреломления, т.е. поперечная волна расщепляется на две (S_1 и S_2), каждая из которых имеет свою поляризацию и скорость для широкополосных трехкомпонентных записей (HHE, HHN, HHZ) одной сейсмической станции «ZKT». Это дало возможность изучить мелкомасштабные деформации для лучшего понимания динамических процессов и изменения свойств среды с глубиной. В то же время зависимость параметров расщепленных S-волн от направления распространения и пространственной неоднородности физических свойств среды требует более детального анализа данных в пространстве и во времени. Было установлено что быстрая и медленная S-волны хорошо выделяются в волновом поле, их векторы поляризации взаимно ортогональны. Последующие волны имеют гораздо меньшие амплитуды, и их азимуты близки к азимуту медленной волны S_2. Время задержки между первой и второй фазами поперечной волны для станции ZKT составляет 3 секунды с ориентацией векторов поляризации по азимутам 140º и 70º.

Ключевые слова: *поляризация поперечных SH и SV волн, фигуры Лиссажу, угол выхода и азимут сейсмических волн*

7 MAY 2012-Cİ İLDƏ BAŞ VERMİŞ ZAQATALA ZƏLZƏLƏSİNİN BİR STANSİYANIN MƏLUMATLARI ƏSASINDA POLYARİZASİYA TƏHLİLİ

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Xülasə. Məqalədə 7 may 2012-ci il tarixində Böyük Qafqazın Zaqatala rayonunda baş verən, dərinliyi h=8 km, ml=5.6 olan zəlzələnin eninə dalğalarının parametrlərinin təhlili təqdim olunur. Dalğa formalarının məkan təhlili üçkomponentli rəqəmsal seysmik qeydlərindən istifadə etməklə aparılır. Dalğaların üçkomponentli rəqəmsal yazılışlarda ayrılmış sahələrin seçilməsi üçün «DIMAS» proqramında hissəciklərin hərəkətinin trayektoriyasının üçölçülü qrafikləri və NE, NZ, EZ mustəvisində hərəkətin trayektoriyasını proyeksiyası qurulmuşdur. Şuanın iki refraksiyası aşkar olunub, yəni eninə dalğaiki dalğaya bölünür (S_1 və S_2). Hər dalğa bir seysmik stansiya üzrə öz polyarizasiyasına və üçkomponentli (HHE, HHN, HHZ) yazılışların sürətlərinə malikdir. Bu, kiçik miqyaslı deformasiyaları öyrənməyə və dərin olmayan mühitin dinamiki proseslərini və xüsusiyyətlərini daha yaxşı başa düşmək üçün imkan vermişdi. Eyni zamanda, bölünən S-dalğaların parametrlərinin mühitin fiziki xüsusiyyətlərinin yayılma istiqamətindən və məkan qeyri-bircinsliyindən asılılığı məkan və zaman məlumatlarının daha ətraflı təhlilini tələb edir. Beləliklə, sürətli birinci və ikinci eninə dalğaları dalğa sahəsində yaxşi qeyd olunur, onların polyarizasiya vektorları qarşılıqlı ortoqonaldır. Sonrakı dalğaların daha aşağı amplitüdaları var və onların azimutları ikinci S_2 dalğasının azimutuna yaxındır. “ZKT” stansiyası üzrə birinci və ikinci eninə dalğaların arasındakı gecikmə vaxtı 3 san, polyarizasiya vektorlarının istiqaməti 140º və 70º azimutları üzrədir.

Açar sözlər: *SV və SH eninə dalğaların polyarizasiyası, Lissaju fiquraları, seysmik dalğaların çıxışbucağ və azimutu*

ANAS Transactions **Earth Sciences** **2 / 2020**

Geology and geophysics

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MINERALOGICAL AND ORE PETROGRAPHIC COMPARISON OF GEDABEY AND GADIR DEPOSITS IN GEDABEY REGION (WESTERN AZERBAIJAN)

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Keywords: *Porphyry-epithermal, Au-Ag-Cu-Pb-Zn deposit, Gadir, Gedabey, Lesser Caucasus*

Summary. Gedabey (Western Azerbaijan) mine province is located in the Lesser Caucasus region of Tethys metallogenic belt, which is one of the most important metallogenic provinces of the world. Mineralization occurred in the subduction zone within the Lok-Karabakh structural-formation zone of the Lesser Caucasus. The Gedabey ore province is one of the main producing mining of the Gedabey ore district in Azerbaijan and is the largest porphyry-epithermal ore zone of the country. Volcanic rocks and the Gedabey intrusive, which indurated these volcanic rocks, play an important role in the formation of mineralizations in the region. According to previous studies the volcanic rocks containing rhyolite and rhyodacite in the Gedabey ore region are Bajocian age, andesite tuffs and andesite dacites are Bathonian age, diorite and granodiorite within Gedabey intrusive are Upper Jurassic – Lower Cretaceous age. The magmatism of the Gedabey ore region is divided into 3 stages: Bajocian stage, Bathonian stage and Upper Jurassic stage. The Gedabey-Bittibulag fracture is the most important deeper fault in the region, which ore-controls both the Gedabey Au-Ag-Cu and the Gadir Au-Ag-Cu-Pb-Zn deposits within the Gedabey region.This study aims to compare the mineralogical-petrographical features and hydrothermal alteration zones of Gedabey Au-Ag-Cu and Gadir Au-Ag-Cu-Pb-Zn deposits by means of petrography, ore petrography and X-ray diffraction methods. Chalcopyrite, sphalerite, galena, pyrite, gold, covellite, malachite, azurite were commonly observed in these mineralizations.

1. INTRODUCTION

Gedabey ore district which is one of the world's major gold and copper ore districts in the Lesser Caucasus is located in the Tethys Metallogenic Belt extending to Turkey from Pakistan, Iran, Azerbaijan and Georgia (Fig. 1).The processing of copper ores is being carried out in numerous ancient copper mines such as Gedabey, Allahverdi, Shamlık, Mishana, Zangazur and Shanardara regions in Azerbaijan. The mining activities in Gedabey ore district started 2000 years ago, and the Ottoman and Azerbaijani Khanates handled the rich copper occurrences by changing hands after the first settlers (Singer et al., 2008).

The Gedabey Au-Ag-Cu and Gadir Au-Ag-Cu-Pb-Zn deposits are located around the axis of the Shamkir anticlinorium in the western part of the Dashkesan synclinorium in the Lok-Aghdam region of the Lesser Caucasus (Veliyev et al., 2018; İsmayıl et al., 2018). The Gedabey Au-Ag-Cu deposit is commonly observed in the east, northeast and south-eastern slopes of the Misdağ Mountain. The Gadir Au-Ag-Cu-Pb-Zn deposit located in Yoğundağ epithermal system in the south of Gedabey ore district was discovered by Gedabey Exploration Group (GEG) and geological consultant Allahverdi Agakishiyev in 2012. The Gadir Au-Ag-Cu-Pb-Zn deposit is located approximately 370 m from Gedabey Au-Ag-Cu deposit.

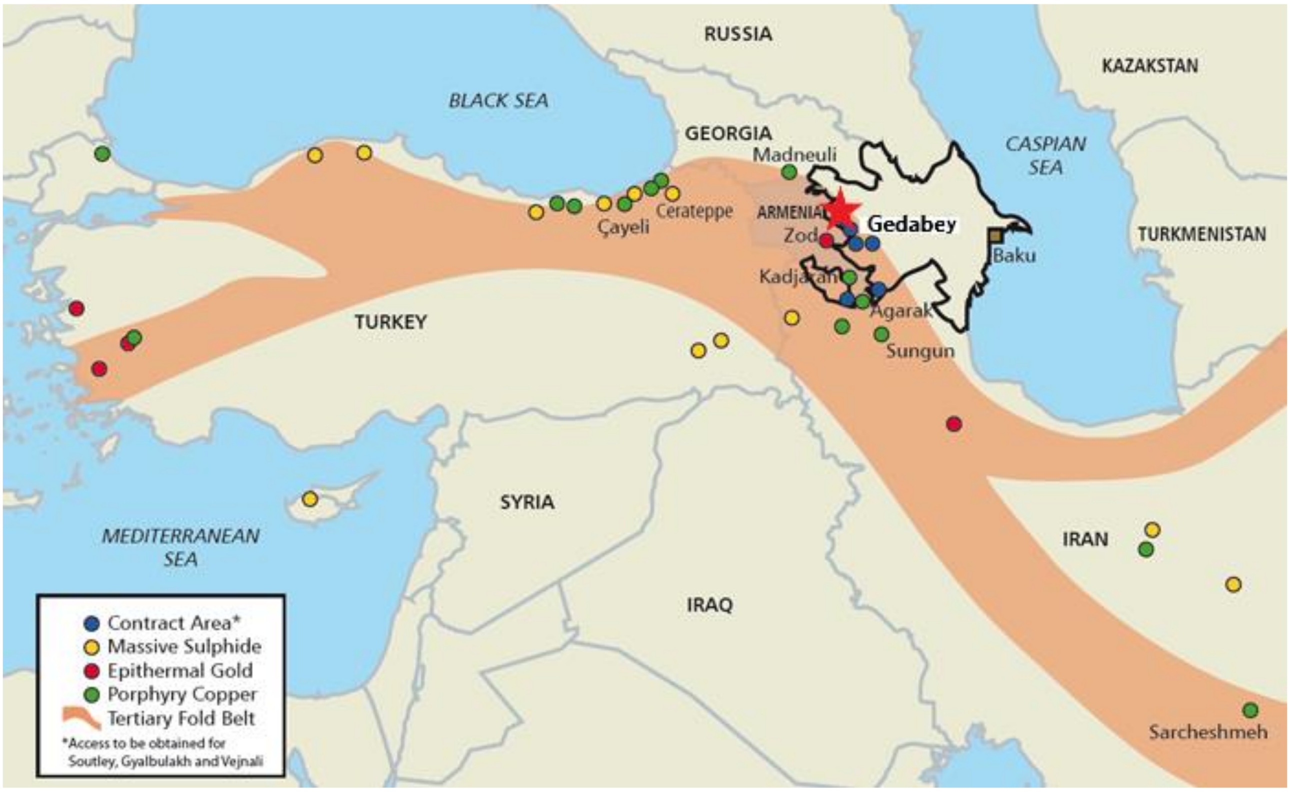

Fig. 1. Porphyry-epithermal deposits in Tethyan Metallogenic Belt (modified from https://www.angloasianmining.com/operations/overview/)

Yoğundağ Mountain is a porphyry-epithermal zone, with known deposits in the area (e.g.Gadir, Gedabey, Umid and Zefer) believed to represent the upper portion of the mineralizing system. The Gadir and Gedabey ore deposits are located within the large Gedabey-Garadag volcanic-plutonic system. This volcanic-plutonic system is characterised by a complex internal structure indicative of repeated tectonic movement and multi-cyclic activity (Bayramov, 2015; İsmayıl, 2019; Anglo Asian Mining PLC, 2019).The province is very complex due to the tectonic structure of the Gedabey region and the Shamkir anticline (Babazadeh et al., 2015). Gedabey Au-Ag-Cu and Gadir Au-Ag-Cu-Pb-Zn mineralizations are structurally controlled. The ore deposits of the Gedabey district are controlled by a deep-seated, ~NS oriented, orogen-transverse arc-shaped fault (Баба-заде и др., 1990). The Gadir and Gedabey ore body, which has a complex geological structure, contains intrusive rocks of different ages and compositions. Three sets of regional fault zones controlling mineralization have been identified and are characterised on the basis of strike direction and morphological characteristics: 1–NW-SE striking faults (e.g. Gedabey-Bittibulag Deep Fault, Misdag Fault), 2 –NE-trending faults (e.g. Gedabey-Ertepe Fault, Gerger-Arykhdam Fault, Gadir ore-controlling faults), 3 – local transverse faults (Bayramov, 2015; İsmayıl, 2019; Anglo Asian Mining PLC, 2019).

The magmatic activities in the region have been occurred in Bajocian-Bathonian (Middle Jurassic) and Early Cretaceous (Fig. 2; Bayramov, 2015). In the Gedabey district the plutonic rocks consist of Upper Jurassic – Lower Cretaceous aged gabbro, gabbronorite, diorite, granodiorite, and quartz-diorite; volcanic rocks contain Bajocian and Bathonian aged andesite, andesite lava, andesite porphyry, rhyolite and rhyodacitic volcanic rocks (Керимов, 1963; İsmayıl, 2019). In addition, alluvial sediments on the Gedabey Au-Ag-Cu deposit and silicification on the Gadir mineralization are observed (Veliyev et al., 2018).The deposits are genetically related with Gedabey intrusion (its quartz-diorite phase; Bayramov, 2016).

Late Jurassic – Early Cretaceous was dated for Gedabey diorite, granodiorite and subsidiary aplites (K-Ar; from 129-142 Ma to 150 Ma; Исмет и др., 2003), and 144±1 Ma for quartz-diorite (U-Pb; Late Jurassic-Early Cretaceous; Садыхов и др., 2018). The Gedabey Au-Ag-Cu deposit is commonly observed in the east, northeast and southeastern slopes of the Misdağ Mountain. The Gadir Au-Ag-Cu-Pb-Zn deposit is in the east of Yoğundağ Mountain, near Gedabey Au-Ag-Cu±Zn deposit. The mineralizations are represented by the quartz-porphyry body localized between subhorizontal andesite at the west and a diorite intrusion at the east. The quartz-porphyry intrusive rocks host gold mineralization in Gedabey and Gadir deposits (Novruzov et al., 2019). The Gadir mineralization was controlled by NW-SE faults. The faulting occurred in contact between the andesitic tuff and quartz porphyry. Au in the Gadir deposit is mainly hosted by intrusive bodies dominated by quartz porphyry. The host rocks were commonly altered by propylitic alteration, primarily in andesitic tuff (Novruzov et al., 2019). The Gedabey Au-Ag-Cu deposit occurred in the quartz porphyry which was formed at the contact of the Middle Jurassic andesitic rocks and the Lower Cretaceous granitoid (granodiorite-diorite).

This study aims to investigate and compare mineralogical-petrographical characteristics and hydrothermal alteration zones of Gedabey Au-Ag-Cu and Gadir Au-Ag-Cu-Pb-Zn deposits by means of petrography, ore petrography and X-ray diffraction methods.

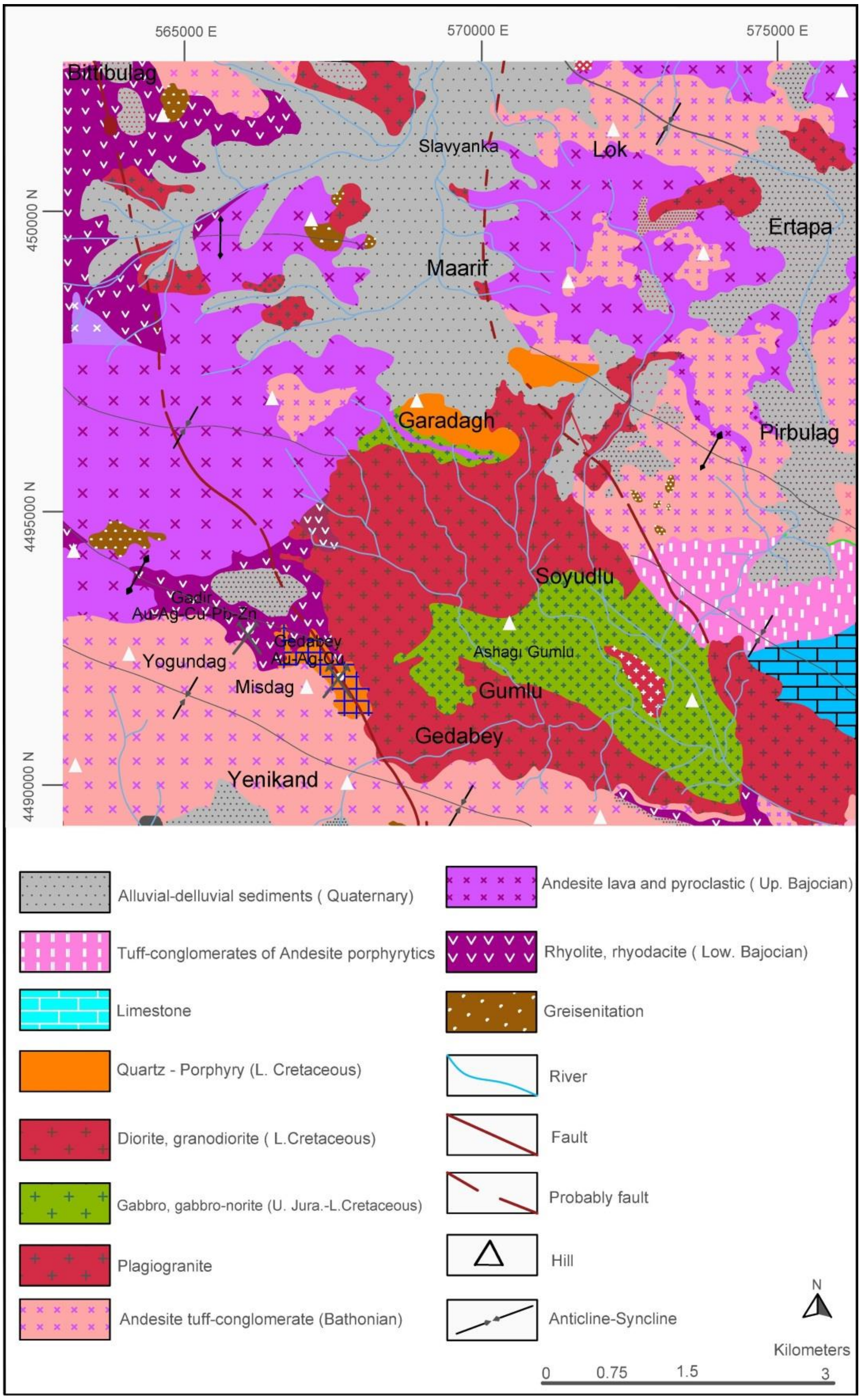

Fig. 2. The geological map of Gedabey ore district (modified from Bayramov, 2015)

2. MATERIAL AND METHOD

The field studies were realized, and outcrop and drill core samples (ore, wall rock, hydrothermal alteration samples) were collected from Gedabey and Gadir deposits in Gedabey ore district (Fig. 3).

Polished sections were prepared in the Seljuk University SÜKOP Gemstone Atelier for the determination of mineralogical and petrographic properties of the collected samples (Fig. 4a,b). Thin sections were prepared in the Pamukkale University Laboratory (Fig. 4c,d). Thin sections and polished sections were examined under Leica DM2700P microscope in Geological Engineering Department in Konya Technical University (Fig. 3 and Fig. 4). In order to carry out more detailed mineralogical research of the samples, XRD analyzes were performed in the mineralogical and petrographic research laboratory of the General Directorate Mineral Research and Exploration (MTA).

3. RESULT

3.1. Gedabey Au-Ag-Cu deposit

According to petrographical and mineralogical analyses of the samples, potassic, phyllic, advance argillic and propylitic alterations were determined in the Gedabey Au-Ag-Cu deposit. The Gedabey Au-Ag-Cu mineralization occurred in the quartz porphyry which was formed at the contact of the andesitic rocks and granitoid. The hydrothermal alterations associated with Gedabey Au-Ag-Cu mineralization are phyllic and advanced argillic alterations.

3.1.1.Petrography

Plagioclase, biotite, amphibole, chlorite, quartz, and opaque minerals were observed in diorite of the Gedabey granitoid (Fig. 5d). Andesite is composed of amphibole, plagioclase, chlorite, and pyrite (Fig. 5b). Potassic alteration sample collected from drill core is composed of K-feldspar, biotite, and quartz. Sericite, pyrite, quartz and barite were observed in the phyllic alteration (Fig. 5a,c). Kaolinite, alunite, pyrophyllite, barite, quartz, sericite, pyrite were identified in advanced argillic alteration. Propylitic alteration composed of chlorite, epidote, calcite, pyriteand quartz.

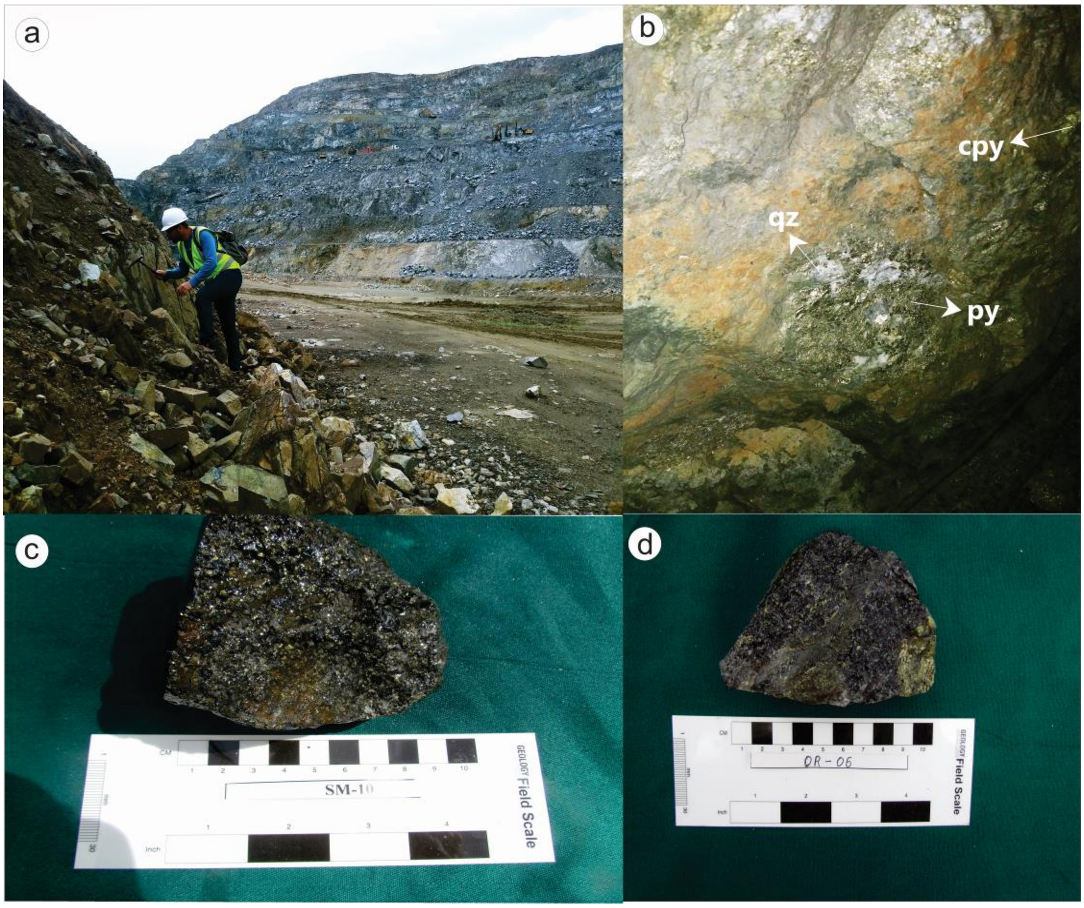

Fig. 3. (a) Open pit and (c) hand sample from Gedabey Au-Ag-Cu deposit, (b)Pyrite (py), chalcopyrite (cpy) and quartz (qz) in underground mining, (d) hand sample from Gadir Au-Ag-Cu-Pb-Zn deposit

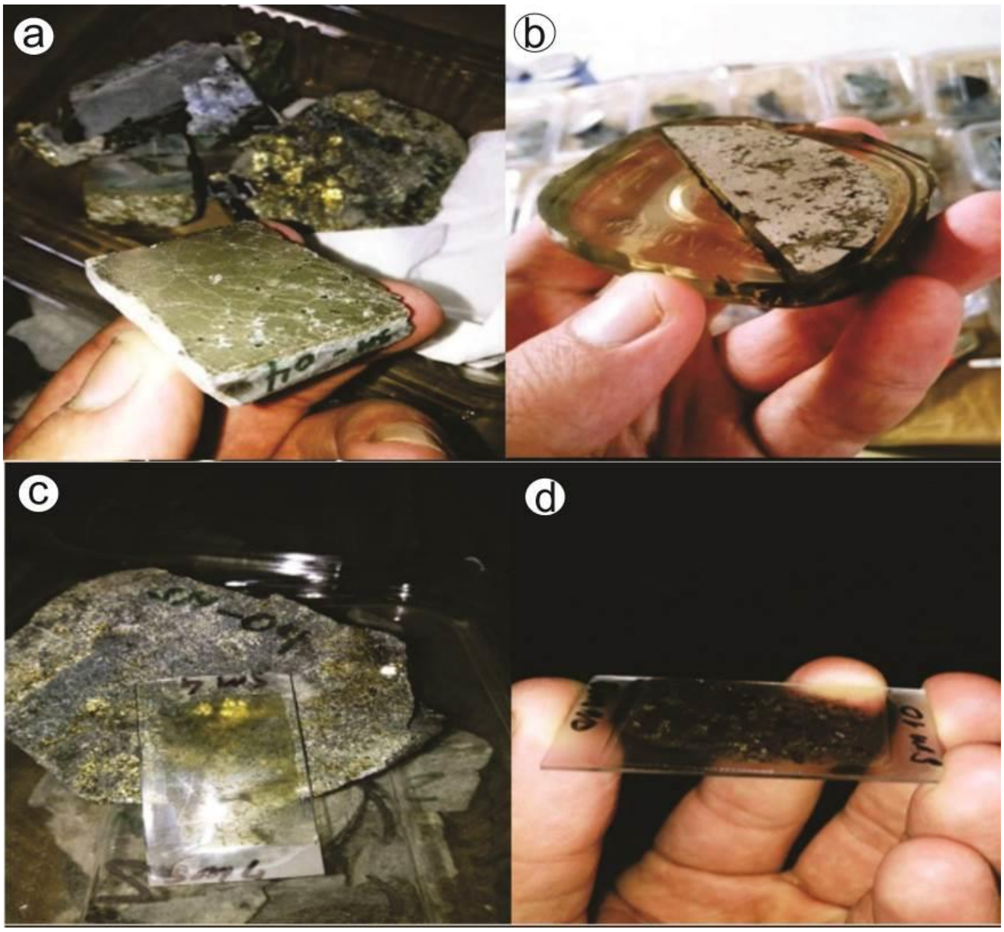

Fig. 4. Polished sections (a,b) and thin sections (c,d) from collected samples

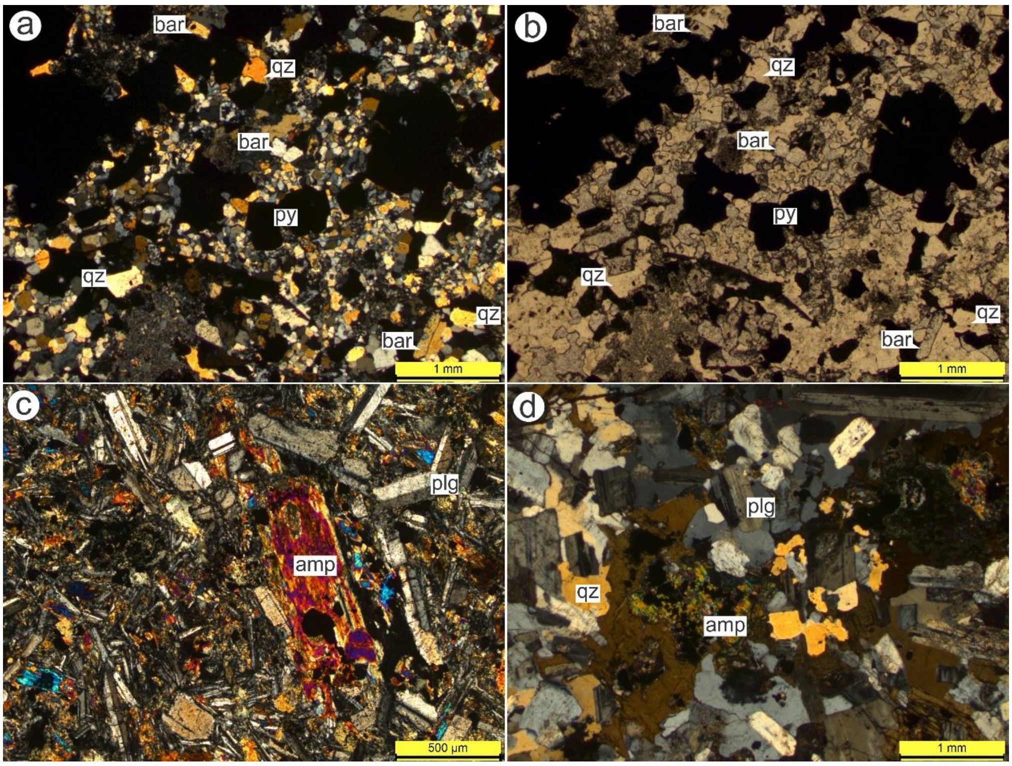

Fig. 1. (a-b) Sericite (ser), pyrite (py), barite (bar), quartz (qz) observed in petrographic studies of phyllic alteration, and **(c)** amphibole (amp) and plagioclase (plg) in andesite, and **(d)** amphibole (amp), plagioclase (plg) and quartz in diorite in Gedabey Au-Ag-Cu deposit (a,c,d: +N, b: //N)

3.1.2. Ore petrography

In the Gedabey Au-Ag-Cu mineralization chalcopyrite, sphalerite, galena, pyrite, magnetite, hematite, bornite, molybdenite and enargite were determined by ore microscopy studies as the main ore minerals. Covellite, chalcocite, malachite, goethite, limonite were identified as secondary ore minerals (Fig. 6). The gangue minerals are quartz, calcite and barite in Gedabey Au-Ag-Cu mineralization.

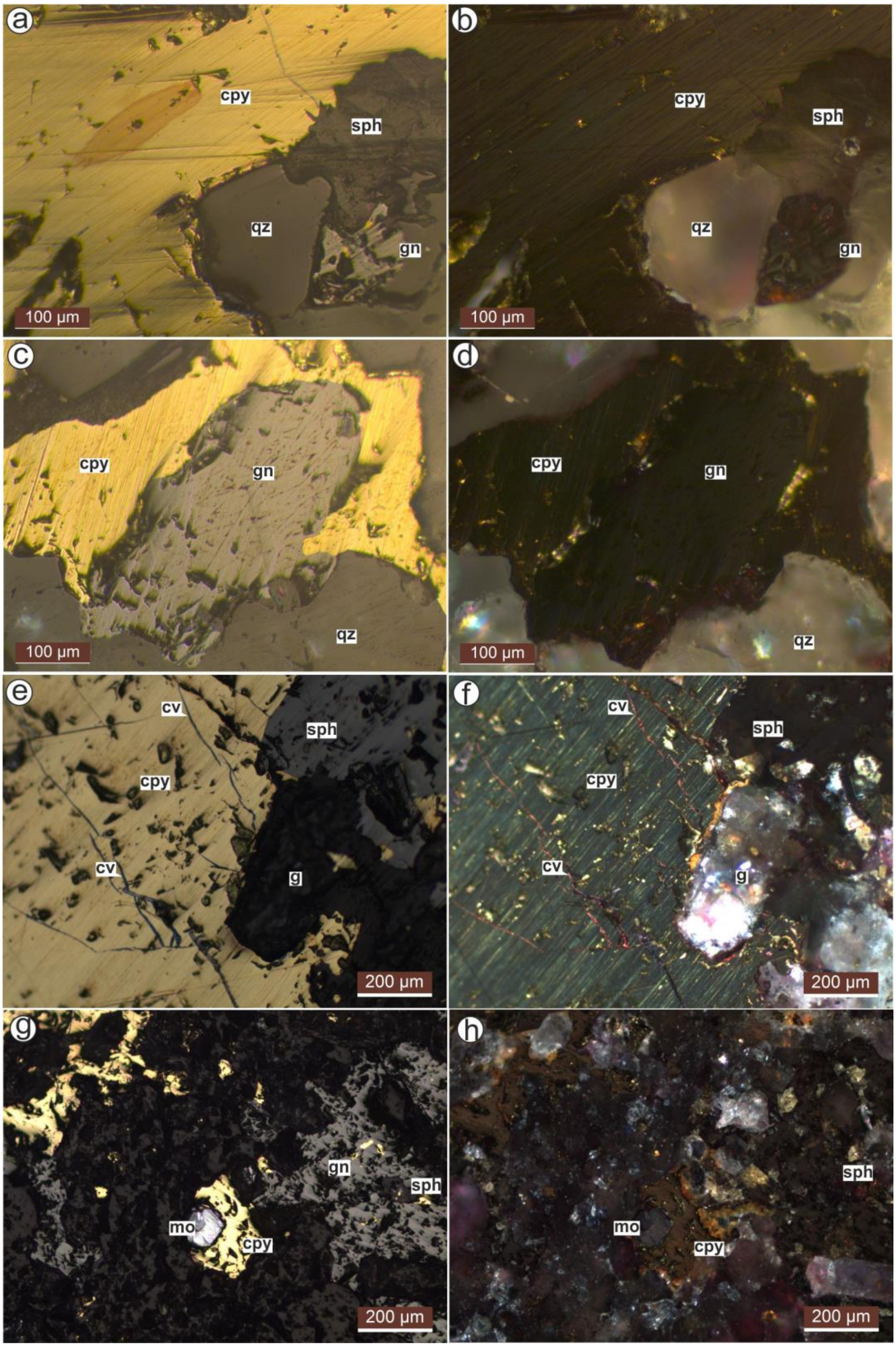

Fig. 6. Chalcopyrite (cpy), molybdenite (mo), sphalerite (sph), galena (gn), pyrite (py), covellite (cv), quartz (qz) in Gedabey Au-Ag-Cu deposit; a,c,e,g: //N, b,d,f,h: +N)

3.1.3. X-Ray Diffraction

Chalcopyrite, pyrite, sphalerite, magnetite, chlorite, K-feldspar, sericite, sodalite, wurtzite, plumbotellurite, kaolinite, alunite, illite, siderite, phlogopite, quartz and epidote were determined by XRD analysis of samples collected from Gedabey ore deposit. Sericite, pyrite and quartz were identified in the phyllic alteration (Fig. 7a). Kaolinite, illite, barite, quartz, sericite, pyrite were determined in advanced argillic alteration.

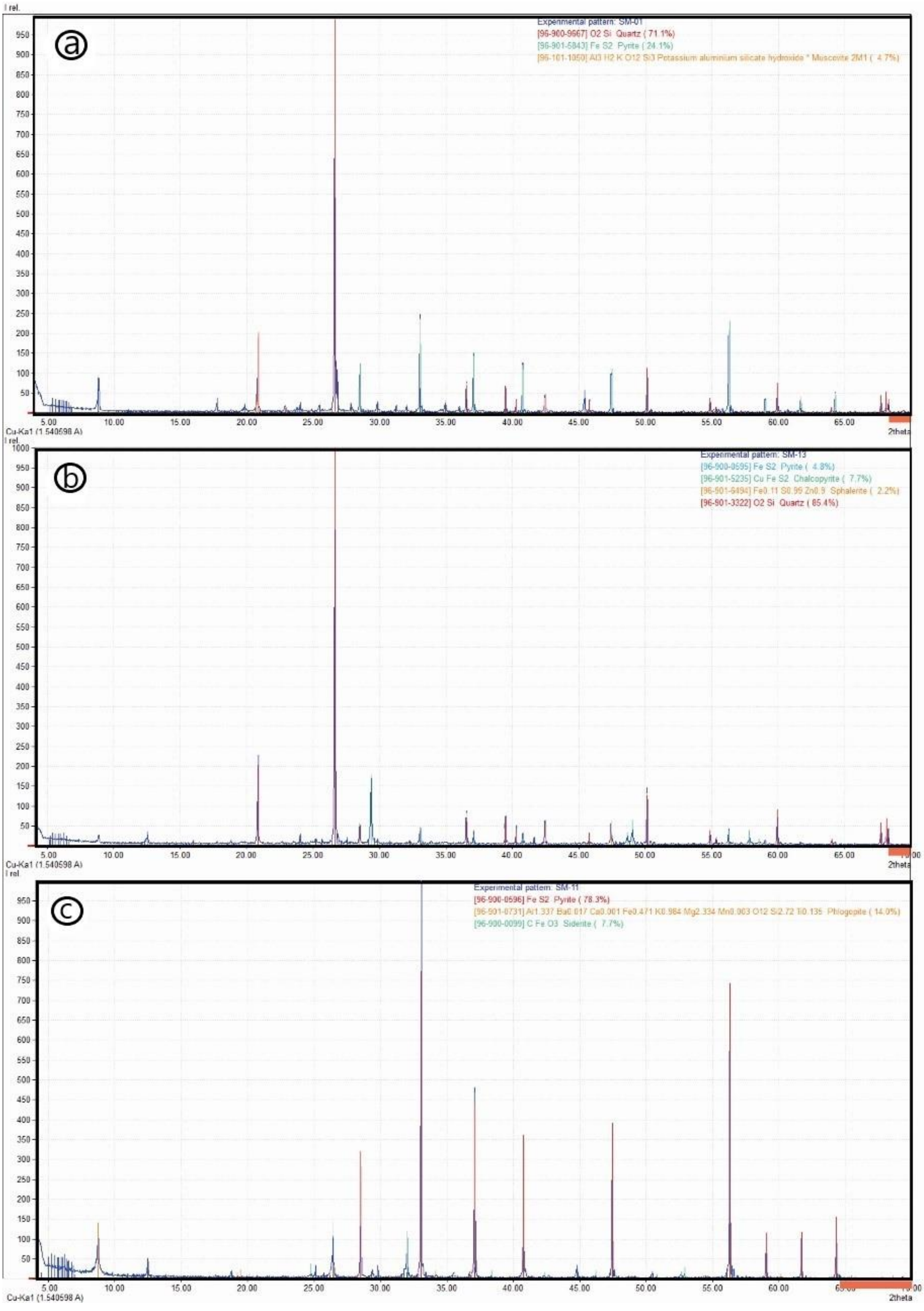

Fig. 7. X-Ray diffractograms of Gedabey Au-Ag-Cu mineralization

3.2. Gadir Au-Ag-Cu-Pb-Zn deposit

The Gadir mineralization occurred in contact of the andesitic tuff and quartz porphyry. The hydrothermal alterations associated with mineralization are quartz±adularia±sericite and propylitic alterations.

3.2.1. Petrography

In petrography studies of andesite collected from field studies in Gadir Au-Ag-Cu-Pb-Zn deposit, plagioclase, amphibole, pyroxene, muscovite, hematite, epidote, calcite, sericite, clay minerals and opaque minerals were observed. Amphibole, plagioclase, chlorite were observed in petrographic studies of andesite and andesitic tuff in Gadir Au-Ag-Cu-Pb-Zn deposit (Fig.8).

3.2.2. Ore petrography

In ore microscopy studies of Gadir Au-Ag-Cu-Pb-Zn mineralization, the main ore minerals were chalcopyrite, sphalerite, galena, arsenopyrite, pyrite, hessite and native gold. Sphalerite and chalcopyrite is replaced by galena in some polished sections (Fig.9e,f). Chalcopyrite is observed as inclusion in sphalerite and galena (Fig. 9c,d,e).

3.2.3. X-Ray diffraction

According to the XRD analyses from Gadir Au-Ag-Cu-Pb-Zn mineralization, $AuAgTe_4$, tetrahedrite, cordierite, jasper, titanomagnetite, augite, chamosite, muscovite, hematite, epidote, chlorite, sericite, pyrite, sphalerite, galena, magnetite, barite and wurtzite were identified (Fig. 10). Chamosite, epidote, calcite, quartz, sericite, and hematite were defined from propylitic alteration.

CONCLUSION

Gadir deposit located in the east of Yoğundağ Mountain and Gedabey deposit located in the northeast and southeastern slopes of the Misdağ Mountain are located in the large Gedabey-Garadag volcanic-plutonic system characterised by a complex internal structure indicative of repeated tectonic movement and multi-cyclic activity. The Gedabey and Gadir deposits are controlled by ~NS oriented regional fault zones controlling mineralizations.

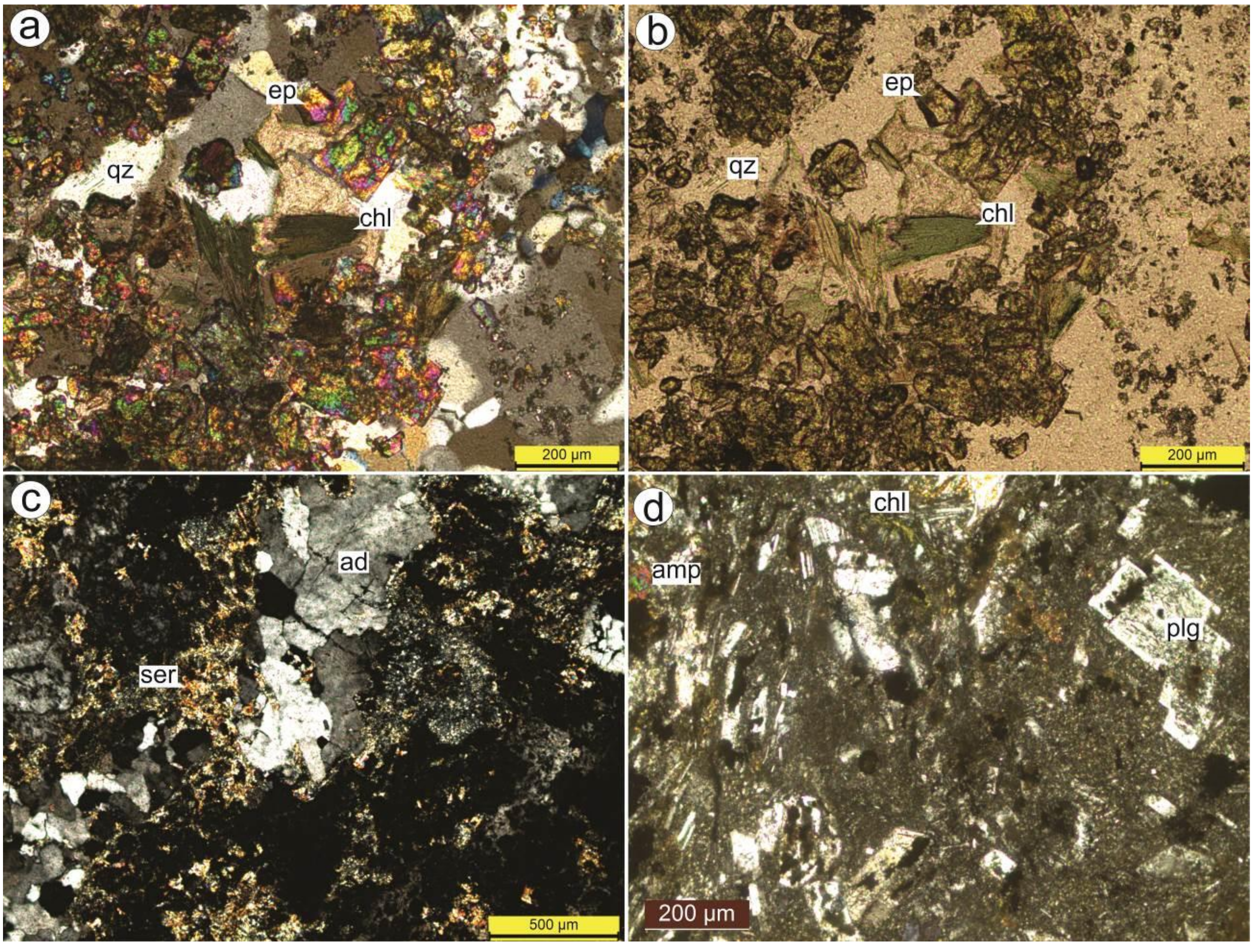

Fig. 8. (a,b) Epidote (ep), chlorite (chl), quartz (qz) in propylitic alteration, **(c)** adularia (ad) and sericite (ser) **(d)** amphibole (amp), plagioclase (plg), and chlorite (chl) mineral observed in petrographic studies of andesite and andesitic tuff in Gadir Au-Ag-Cu-Pb-Zn deposit (a,b: +N; b,d: //N)

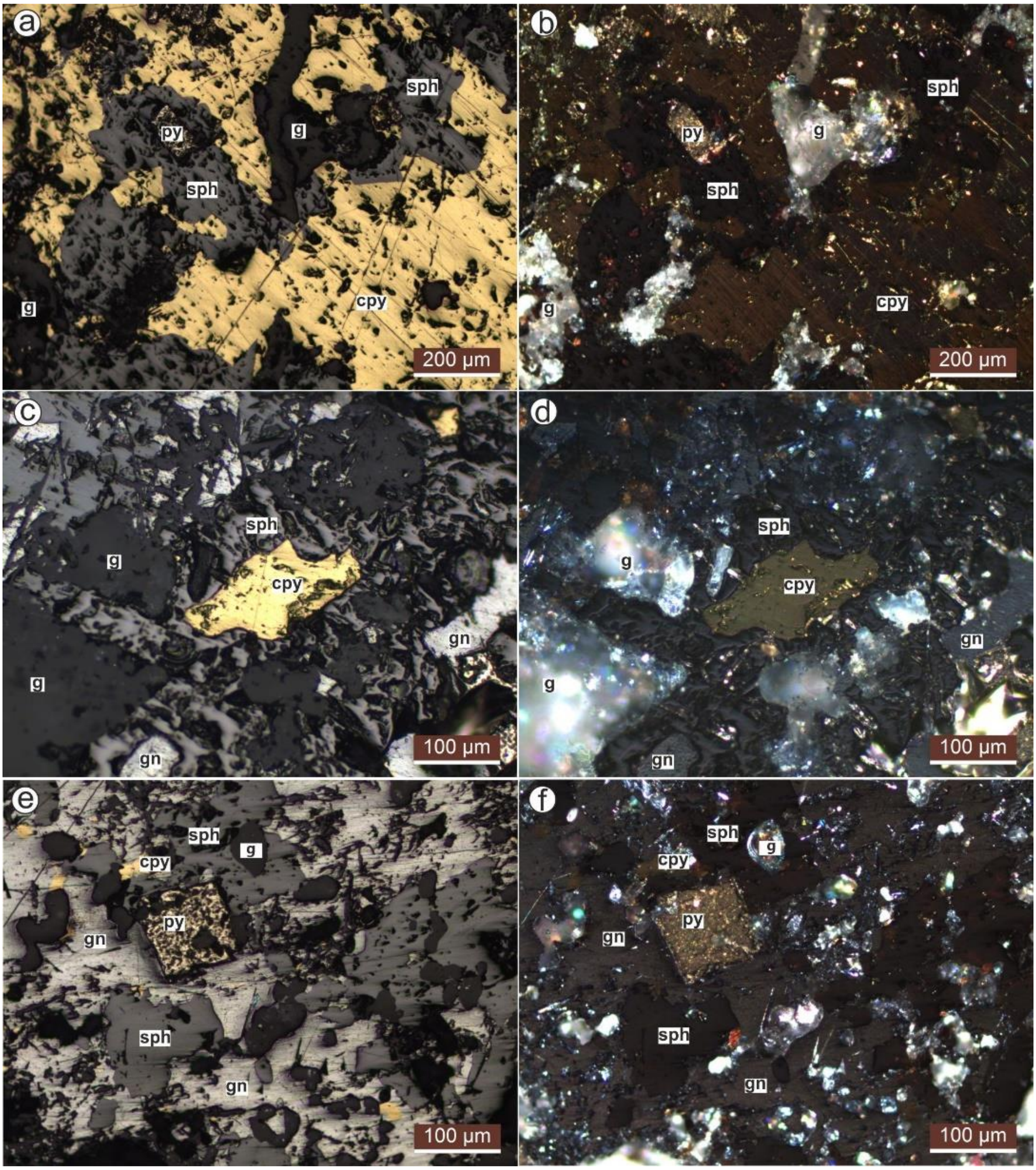

Fig. 9. Pyrite (py), chalcopyrite (cpy), galena (gn), sphalerite (sph), quartz (qz), gangue (g) in GadirAu-Ag-Cu-Pb-Zn mineralization (a,c,e: //N; b,d,f: +N)

The Gedabey Au-Ag-Cu deposit occurred in the quartz porphyry formed at the contact of the andesitic rocks and granitoid. The Gadir Au-Ag-Cu-Pb-Zn deposit occurred in the contact of the andesitic tuff and quartz porphyry. Chalcopyrite, sphalerite, galena, pyrite, magnetite, hematite, bornite, molybdenite, enargite, covellite, chalcocite, malachite, goethite, limonite, quartz, calcite, and barite were determined in the Gedabey Au-Ag-Cu mineralization. Also chalcopyrite, sphalerite, galena, arsenopyrite, tetrahedrite and pyrite were observed in the Gadir Au-Ag-Cu-Pb-Zn mineralization. While gold and silver occured as native gold, electrum, petzite and hessite associated with copper mineralization in Gedabey deposit, native gold and hessite were observed in Gadir deposit. The same hydrothermal alteration zones and similar mineral assemblage were identified in both ore deposit. Potassic alteration represented by biotite, K-feldspar, quartz was observed in drill core samples taken from deep horizons of Gedabey Au-Cu deposit. The phyllic alteration is represented by sericite, pyrite and quartz in the region,

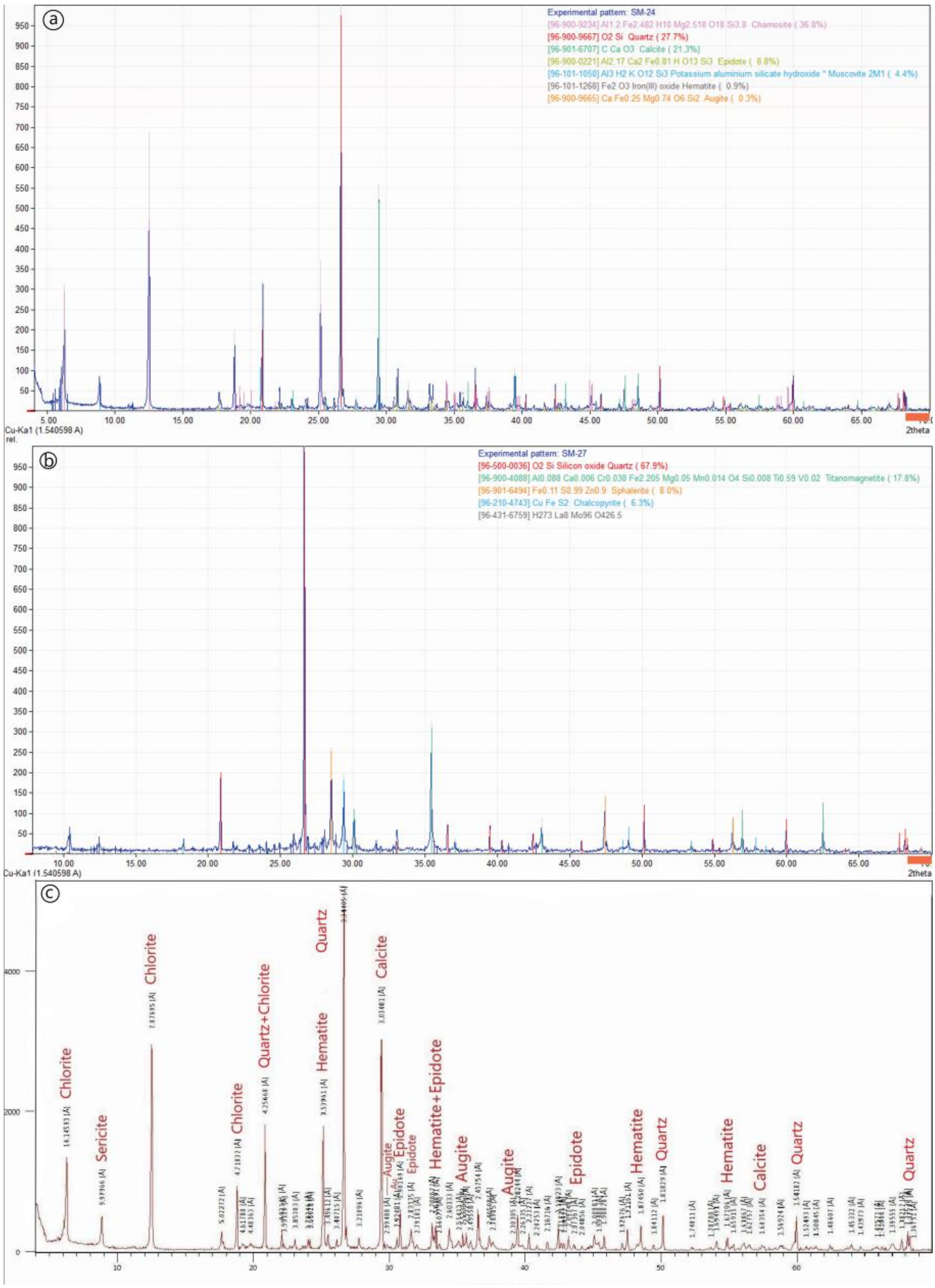

Figure 10. X-Ray diffractograms of Gadir Au-Ag-Cu-Pb-Zn mineralization

and also phyllic alteration and advanced argillic alteration are defined as the main ore bearing zones for Gedabey Au-Ag-Cu deposit. The advanced argillic alteration minerals were determined as kaolinite, alunite, illite, pyrophyllite, and smectite in the Gedabey region. On the other hand, propylitic alteration represented by epidote and chlorite isclearly observed in the both deposits. Gadir Au-Ag-Cu-Pb-Zn mineralization associated with propylitic alteration and quartz±adularia±sericite veins. Additionally, silicification was observed in Gadir mineralization. Enargite and molybdenite are observed in Gedabey Au-Ag-Cu mineralization, although they are not observed in Gadir mineralization. The main factor of epithermal deposit for Gadir deposit is a quartz±adularia±sericite vein type mineralization Also, the main factors of high-sulfidation epithermal system for the Gedabey Au-Ag-Cu deposit are vuggy quartz, enargite and advanced argillic alterations. The mineralizations are mineralogically similar to each other except for a few features mentioned. While the mineral assemblages in the Gedabey mineralization suggest a high sulfidation, in Gadir mineralization – an epithermal ore deposit associated with a porphyry system. However, fluid inclusion analyzes that will have recently completed will lead to a more accurate suggestion.

Acknowledgements

The authors thank to Seljuk University for financial support of master thesis project (project number: 18201084) and anonymous reviewers for helpful comments.

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МИНЕРАЛОГИЧЕСКОЕ И РУДНО-ПЕТРОГРАФИЧЕСКОЕ СРАВНЕНИЕ ГЕДАБЕЙСКОГО И ГАДИРСКОГО МЕТОРОЖДЕНИЙ ГЕДАБЕЙСКОГО РАЙОНА (ЗАПАДНЫЙ АЗЕРБАЙДЖАН)

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Резюме. Гедабейская рудная зона (Западный Азербайджан) расположена на Малом Кавказе. Рудообразование происходило в субдукционной зоне Лок-Гарабахской структурно-формационной зоны Тетического металлогенического пояса. Гедабейская рудная провинция является крупнейшим порфирово-эпитермальным рудным районом в стране. Вулканические породы и Гедабейский интрузив, под влиянием которого уплотнены вулканические породы, играют важную роль в процессе оруденения данного региона. Согласно предыдущим исследованиям вулканические породы Гедабейского рудного региона с содержанием риолита и риодацита относятся к байосскому возрасту, андезитовые туфы и андезитовые дациты – к батскому, а диориты и гранодиориты Гедабейского интрузива представляют верхнеюрский и нижнемеловой периоды. Магматизм Гедабейского рудного региона делится на три стадии: байоский, батский и верхнеюрский. Гедабейско-Биттибулагский глубинный разлом является самым важным, а также рудоконтролирующим фактором как Гедабейского Au-Ag-Cu, так и Гадирского Au-Ag-Cu-Pb-Zn месторождений в данном регионе. Целью данного исследования является сравнение минералого-петрографических особенностей Гедабейского Au-Ag-Cu и Гадирского Au-Ag-Cu-Pb-Zn месторождений с помощью петрографического, рудно-петрографического и рентген-дифрактометрического методов анализа. В рудах отмечаются халькопирит, сфалерит, галенит, пирит, золото, ковеллин, малахит, азурит и другие минералы.
Ключевые слова: *Порфиро-эпитермальный, Au-Ag-Cu-Pb-Zn руда, Гадир, Гедабей, Малый Кавказ*

GƏDƏBƏY RAYONUNDA GƏDƏBƏY VƏ QƏDIR YATAQLARININ MINERALOJI VƏ FILIZ PETROQRAFIK TƏRKIBI (QƏRBI AZƏRBAYCAN)

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Xülasə. Gədəbəy (Qərbi Azərbaycan) filizləşmə zonası Kiçik Qafqaz bölgəsində yerləşir. Filizləşmə Tetis metallogenik kəmərinin Lök-Qarabağ struktur-formasiya zonası içərisində subduksiya zonasında əmələ gəlmişdir. Gədəbəy Azərbaycanın ən böyük porfir-epitermal filizləşmə sahəsi hesab olunur. Region haqqında bu günə qədər çox sayda fərqli tədqiqatçılar tərəfindən araşdırmalar aparılmışdır. Bölgədə Orta və Üst Yura yaşlı süxurlar geniş yayılmışdır. Regiondakı filizləşmələrin əmələ gəlməsində vulkanik süxurların və Gədəbəy intruzivinin önəmli rolu var. Əvvəlki tədqiqatlara əsasən Gədəbəy filiz rayonundakı riolit və riodasit tərkibli vulkanik süxurlar Bayos yaşlı, andezit tufları və andezit dasitlər Bat yaşlı, Gədəbəy intruzivindəki diorit və qranodioritlər Üst Yura-Alt Təbaşir yaşlı olduğu qeyd olunmuşdur. Gədəbəy filiz rayonunda magmatizm 3 etapa ayrılır: Bayos, Bat və Üst Yura mərtəbələri. Gədəbəy rayonunda həm Gədəbəy Au-Ag-Cu yatağının, həm də Qədir Au-Ag-Cu-Pb-Zn yatağının filizənəzarət faktoru Gədəbəy-Bittibulaq dərinlik yarılmasıdır. Bu araşdırmanın məqsədi Gədəbəy Au-Ag-Cu və Qədir Au-Ag-Cu-Pb-Zn yataqlarının mineraloji-petroqrafik xüsusiyətlərini və hidrotermal dəyişilmə zonalarını petroqrafik, filiz- petroqrafik və XRD metodu ilə açıqlamaqdır. Filizlərdə içərisində xalkopirit, sfalerit, qalenit, pirit, qızıl, kovellin, malaxit, azurit və başqa minerallar qeyd edilmişdir.
Açar sözlər: *Porfir-Epitermal, Au-Ag-Cu-Pb-Zn yatağı, Qədir, Gədəbəy, Kiçik Qafqaz*

ANAS Transactions Earth Sciences 2 / 2020

Geology and geophysics

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СТРУКТУРНАЯ ИЕРАРХИЯ Ca- И TR-ТРИОРТОСИЛИКАТОВ И ИХ ПРОИЗВОДНЫХ

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STRUCTURAL HIERARCHY OF CA- AND TR-TRIORTHOSILICATES AND THEIR DERIVATIVES

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***Keywords**: Ca- and TR-triorthosilicates, clusters, structural units, structural blocks, formation of structures*

Summary. It is known that physical and chemical properties and paragenetic peculiarities of minerals are related to their crystalline structure. The hierarchical scheme of mineral structure research shows that classification according to chemical composition does not give a complete picture of the minerals' properties. Taking into account the well-known works of M.I.Chiragov and F.C.Hawthorne on the structural classification of minerals, the structures of Ca- and TR-triorthosilicates and their derivatives are considered for the first time in this paper using the comparative crystal chemistry method and structural hierarchy. The structural hierarchy of minerals is based on the primary polymerization of different type coordination polyhedra which results in formation of the parent structural minals or clusters. Taking into account the symmetry of triorthosilicates and the form of polymerisation of tetrahedrons with Ca- and TR-octahedrons, four types of clusters with different configurations and chemical compositions have been identified: $|M(Si_3O_{10})(H_2O)_3|$, $|M\ (Si_3O_{10})_2|$, $|M(Si_3O_{10})(H_2O)_4|$ and $|M(Si_3O_{10})_2(H_2O)_2|$. Depending on the shape of clusters polymerization, a hierarchical scheme for the formation of structural types of Ca- and TR-triorthosilicates and their derivatives is presented. This results in the formation of structural blocks and mixed frames with calcium atoms in Ca-silicates and sodium or potassium atoms in TR-silicates. According to the chemical composition and shape of silicon-oxygen radical, such minerals as delhayelite and macdonaldite are included in one group. According to the structural classification with the extraction of clusters, it was found out that the structures of these minerals are formed from two different configurations of minals and, consequently, as a result of their polymerization, different structural types are formed. The substantiation of the structural hierarchy is reflected in the conditions of formation of the group of minerals delhayelite and macdonaldite. The formation of dolchayelite is associated with the high-temperature stage of pegmatite formation at the stage of entry of potassium-rich metamorphosing solutions. Hydro-delhayelite is a product of hypergenesis and hydrothermal change of delhayelite. Under these conditions the removal of sodium, partially potassium and all fluorine and chlorine takes place. The structural type of macdonaldite is associated with low temperature stage of pegmatite formation or with late hydrothermal stage of mineral formation. In all cases, however, the medium must be highly alkaline and calcium-rich for the macdonaldite structural type or rich in rare earth cations for the monterejianite structure. These structural features are tested indicators for mineral formation processes.

Введение

В силу известной аналогии между химическими особенностями кальция и редкоземельных катионов большой теоретический и практический интерес представляет сравнительная кристаллохимия их силикатов. Принимая во внимание известные работы М.И.Чирагова, М.Д.Дорфмана (1981) и F.C.Hawthorne (1983, 1985, 1986) о структурной классификации минералов, в настоящей статье рассматриваются структуры Ca- и TR-триортосиликатов и их производные.

Впервые в работе (Теймуров и др., 1979), учитывая первичную полимеризацию полиэдра металлического катиона с тетраэдрическим радикалом, выделены родоначальные структурные миналы (по Hawthorne, 1986 – кластер) и рассмотрены кристаллохимические особенности превращения двугидрата сульфата кальция – гипса $CaSO_4 \cdot 2H_2O$ в полуводный гипс – $CaSO_4 \cdot 0.5H_2O$, где в качестве кластера с составом $|CaSO_4(H_2O)_n|$ выделены Ca-полиэдры (где к.ч. Ca ≥7), обобщенные с ребрами $|SO_4|$-тетраэдра. С учетом формы и состава конфигурации кластеров изучено превращение гипса в полуводный гипс и обосновано появление вяжущих свойств последнего. Из кластеров с составами $|CaSiO_4 \cdot (H_2O)_n|$ и $|TRSiO_4 \cdot (H_2O)_n|$ формируются структуры Ca- и TR-орто- и диортосиликатов (Чирагов, 2002). Выявлено (Чирагов, Дорфман, 1981), что из разных кластеров образуются структуры с одинаковыми кремнекислородными радикалами (Si_8O_{19}) типов дельхайелита и макдональдита.

Цель настоящей работы: подтвердить идеи F.C.Hawthorne и М.И.Чирагова о структурной классификации с учетом строения ряда Ca- и TR-триортосиликатов и их производных, в которых по элементам симметрии выделяются триортогруппы трех типов – m, 2, 1. В структурах Ca-триортосиликатов с симметрией *2* впервые установлены (Чирагов, Пущаровский, 1991) полисоматические серии структур, для каждого члена определены параметры и симметрия ячейки. Выявлено, при каких кристаллохимических ситуациях образуются ромбическая, а при каких – моноклинная формы полисоматической серии.

Впервые в структурах силикатов с несоизмеримыми металлическими катионами установлено новое кристаллохимическое явление – смешанные структуры (Ширинова, 2018), которые формируются минимум из двух разных структурных миналов или кластеров.

Кластеры

В структурах Ca- и TR-триортосиликатов и их производных выделены наиболее стабильные кластеры четырех типов, в которых сохраняется плоскость зеркального отражения – m. Кластеры в двух проекциях представлены на рис.1A, B, C, D.

В кластере первого типа (рис.1A) каждый тетраэдр триортогруппы, расположенный в цис-конфигурации с октаэдром, обобщается одной вершиной и имеет состав $|M(Si_3O_{10})(H_2O)_3|$. Во втором типе (рис.1B) две триортогруппы Si_3O_{10} находятся в транс-конфигурации относительно октаэдра и одна из вершин каждого тетраэдра обобщается с одной вершиной октаэдра, образуя кластер с составом $|M(Si_3O_{10})_2|$. В третьем типе (рис.1C) в одной триортогруппе в цис-положении только боковые тетраэдры обобщаются с вершинами октаэдра и создают кластер с составом $|M(Si_3O_{10})(H_2O)_4|$. В четвертом типе (рис.1D) две триортогруппы, расположенные в транс-конфигурации относительно октаэдра, только вершинами боковых тетраэдров обобщаются с вершинами октаэдра, образуя кластер с составом $|M(Si_3O_{10})_2(H_2O)_2|$.

В зависимости от формы полимеризации кластеров классифицируются структурные типы Ca- и TR-триортосиликатов и их производных.

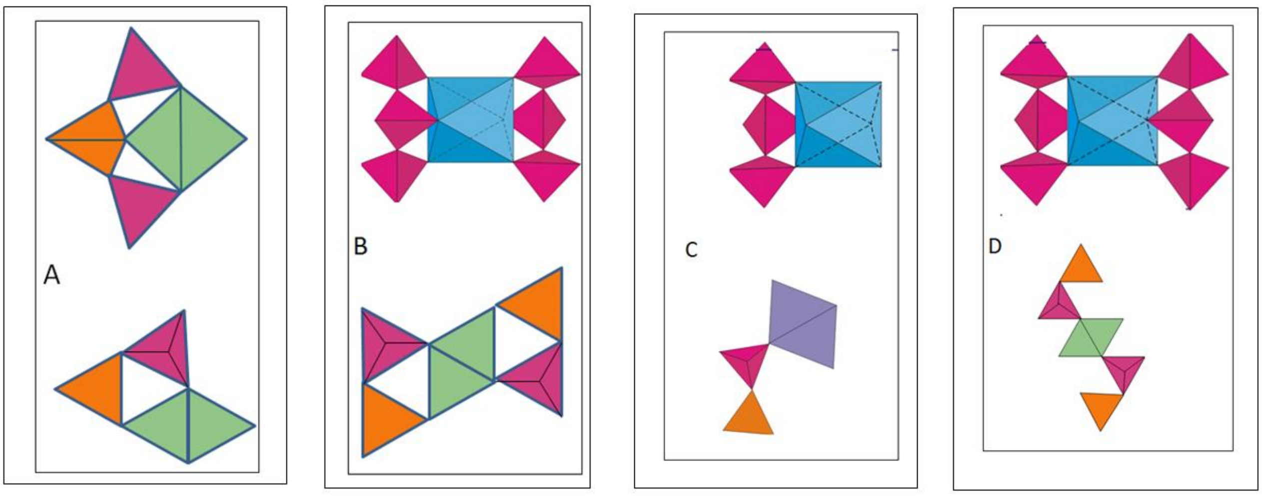

Рис. 1 A, B, C, D. Родоначальные структурные миналы – кластеры, характерные для структур Ca- и TR-триортосиликатов и их производных

Из кластера первого типа (рис.1А**)** формируются структуры К-, Но-гидросиликата и гидротриортосиликата, К-, Но-силиката, волластонита, фошагита и т.д.

Основные мотивы структуры гольмосиликата (Чирагов и др., 1979) представлены на рис. 2а,б в двух проекциях, на которых видно, что гетерогенный гольмокремнекислородный слой формируется из кластера типа А (рис.2а) с составом $|HoSi_3O_8(OH)_2|$ и симметрией m. Между эквивалентными слоями расстояние OH— O = 2.90Å (рис.2 в) показывает, что между ними существует водородная связь. Атомы калия располагаются в пустотах слоя и между слоями. При 580-650^{0}С гидроокисные группы превращаются в кислород ($OH^- \rightarrow O^{2-}$), гольмокремнекислородный слой полимеризуется и триортогруппы превращаются в волластонитовую цепочку с формированием гетерогенного каркаса с составом $K_3HoSi_3O_9$ (Чирагов, Рагимов, 1986).

В результате полимеризации со смещением на ½b двух разноориентированных кластеров типа А, образуются октаэдрические колонки атомов кальция, а триортогруппы превращаются в волластонитовые цепочки. Так формируется структурная единица волластонита, из которой образуется структурный блок с симметрией m. Присутствие в описанном мотиве плоскости зеркального отражения, перпендикулярной параметру b, согласуется с данными, представленными в работе (Ito et al., 1969), в которой указано на частичное присутствие в структуре волластонита плоскости зеркального отражения, связывающей часть атомов структуры. Понижение симметрии структуры волластонита связано с распределением атомов кальция между гетерогенными блоками. Структурный тип волластонита кристаллохимически мало вероятен для структур TR-силикатов.

Из кластера типа А (рис.1А) формируется структура фошагита (Чирагов, 2002), где разноориентированные кластеры со смещением на ***¼b*** так полимеризуются, что триортогруппы превращаются в волластонитовую цепочку, а октаэдры разноориентированных кластеров создают двойные колонки с пустыми Е-положениями. В результате образуется структурная единица с составом $Ca_2{}^ECa_2(Si_3O_9)_2(OH)_4$. Эквивалентные структурные единицы, обобщаясь свободными вершинами октаэдров и тетраэдров, создают структурный блок с симметрией m. Последний, цементируясь дополнительными атомами кальция, формирует структуру фошагита с понижением симметрии и кристаллохимической формулой $Ca_4|Ca_2{}^ECa_2(Si_3O_9)_2(OH)_4|$. Кристаллохимически вероятны TR-формы фошагита с химическим составом $Ca_4Na_2TR_2(Si_3O_9)_2(OH)_4$.

Из кластеров типа В (рис.1В) образуется структурная единица, где триортогруппы превращаются в волластонитовую цепочку, а между эквивалентными октаэдрами образуется октаэдрическая вакансия – Е-положение. В структурах кальциевых силикатов в Е-положении располагается атом кальция, в TR-силикатах – атом натрия, так происходит гетеровалентное замещение типа $2Ca^{2+} \leftrightarrow Na^+TR^{3+}$. Из описанной структурной единицы формируется структура бустамита, макдональдита и монтереджианита.

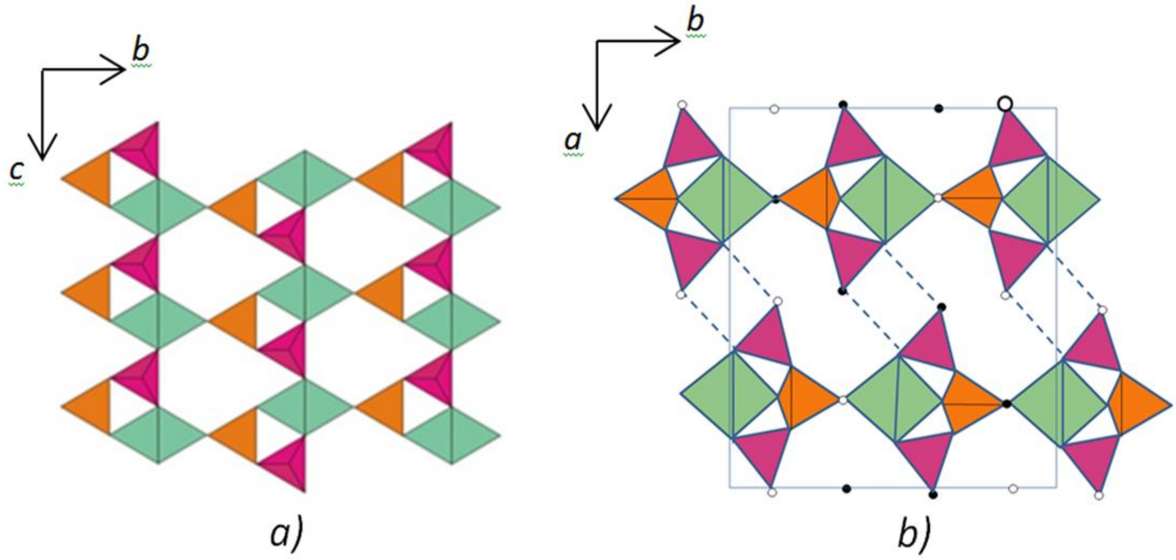

Рис. 2a,b. Кристаллические структуры К-гольмосиликата, сформированные из кластеров типа А (в двух проекциях)

В структуре бустамита (Aksenov et al., 2015) в кластере располагается октаэдр марганца, а в E-положении статистически распределяются атомы кальция и марганца. Эквивалентные структурные единицы, связываясь со свободными вершинами тетраэдра и октаэдра соседней структурной единицы, образуют бустамитовый блок с составом │$Ca_2{}^EMn_2(Si_3O_9)_2(OH)_4$│. Между этими блоками распределяются атомы марганца и кальция, следовательно, кристаллохимическая формула имеет вид: $(Ca,Mn)_8$│$(Ca,Mn)_2{}^EMn_2(Si_3O_9)_4$│. Кристаллохимически вероятна TR-форма бустамита с составом Ca_8│$Na_2TR_2(Si_3O_9)_4$│.

В результате полимеризации бустамитовых блоков волластонитовая цепочка превращается в океннитовую ленту (Si_6O_{16}) и образуется смешанный каркас с E-положениями, в котором располагаются дополнительные атомы кальция. Кристаллохимическая формула описываемой гипотетической структуры – Ca_6│$Ca_4(Si_6O_{16})_2$│$(OH)_4$.

Кристаллохимический механизм формирования структуры макдональдита (Cannillo et al., 1968) представлен на рис.3a,b, где из кластеров типа B(I) формируется структурная единица с составом $M(Si_3O_9)_2$(II). Тетраэдры триортогруппы связываются с дополнительным тетраэдром и образуют структурный блок с составом M│$Si_4O_9(OH)$│$_2$(III). Энантиоморфные структурные блоки, повторяясь на 0 и ½*b* и связываясь свободными вершинами тетраэдров, формируют смешанный каркас структуры типа макдональдита (IV). В шестичленных каналах располагаются атомы натрия, а в восьмичленных – атомы Ba и молекулы воды. Появление псевдопериода (таблица) в структуре связано с распределением атомов Ba и молекул H_2O в пустотах гетерогенного каркаса.

Если в структуре макдональдита происходит замещение типов: $Ba^{2+}\rightarrow 2K^+$, $2H^+ \rightarrow 2Na^+$, $2Ca^{2+}\rightarrow Na^+Y^{3+}$ или $4Ca^{2+}\rightarrow 2Na^+2Y^{3+}$**,** то минерал макдональдит превращается в монтереджианит (Ghose et al., 1987).

Из кластеров типа C (рис. 1C) формируются структуры минералов группы дельхайелита (Чирагов, Дорфман, 1981). Схема последовательности образования структуры типа дельхайелита представлена в двух проекциях на рис.4a,b. В результате полимеризации двух разноориентированных кластеров (I) образуется структурная единица (II), где Ca-октаэдры создают колонки, а триортогруппы – волластонитовую цепочку. Последняя, связываясь с дополнительным тетраэдром, образует структурный блок – (III) (рис.4) с составом │$Ca_2(OH)_2Si_4O_9(OH)$│. Энантиоморфные структурные блоки, полимеризуясь со свободными вершинами тетраэдров, формируют структуру типа дельхайелита (IV), в пустотах которой распределяются атомы натрия и калия. Подобный структурный тип имеют гидродельхайелит (Чирагов и др., 1980; Чирагов, Рагимов, 1986) и родезит (Hesse et al., 1992).

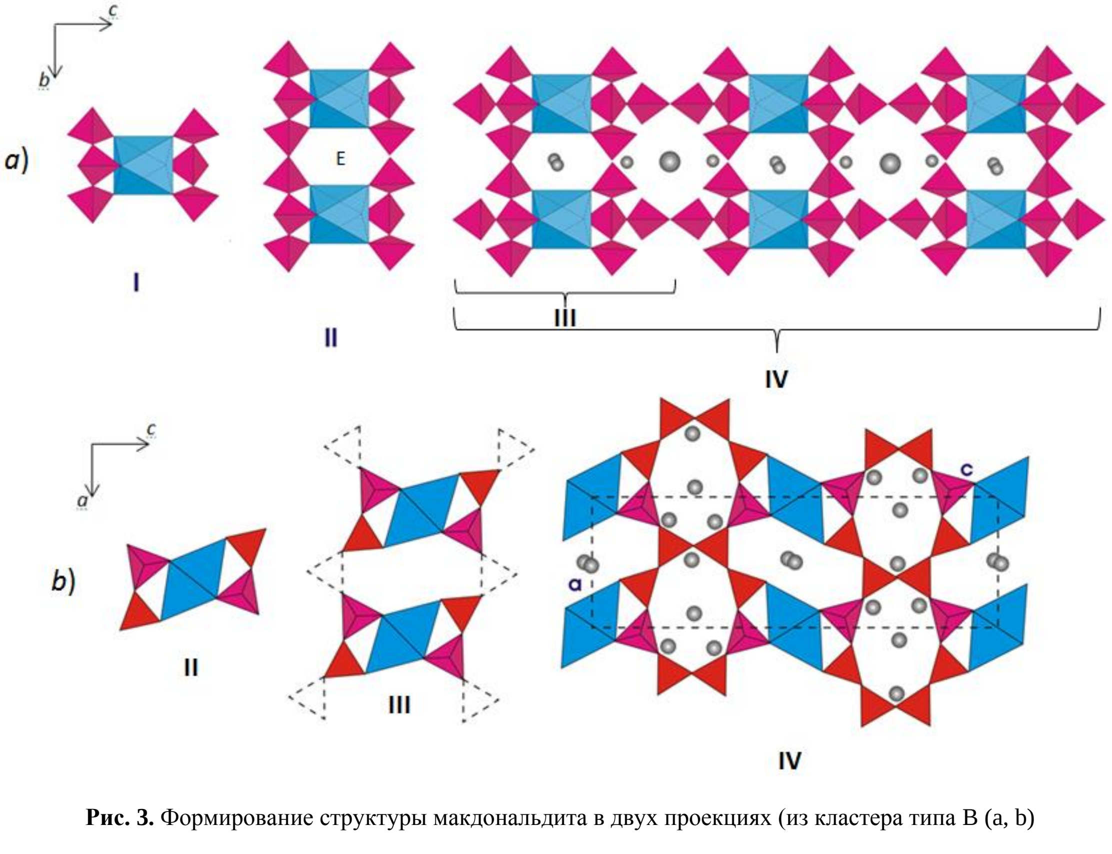

Рис. 3. Формирование структуры макдональдита в двух проекциях (из кластера типа B (a, b)

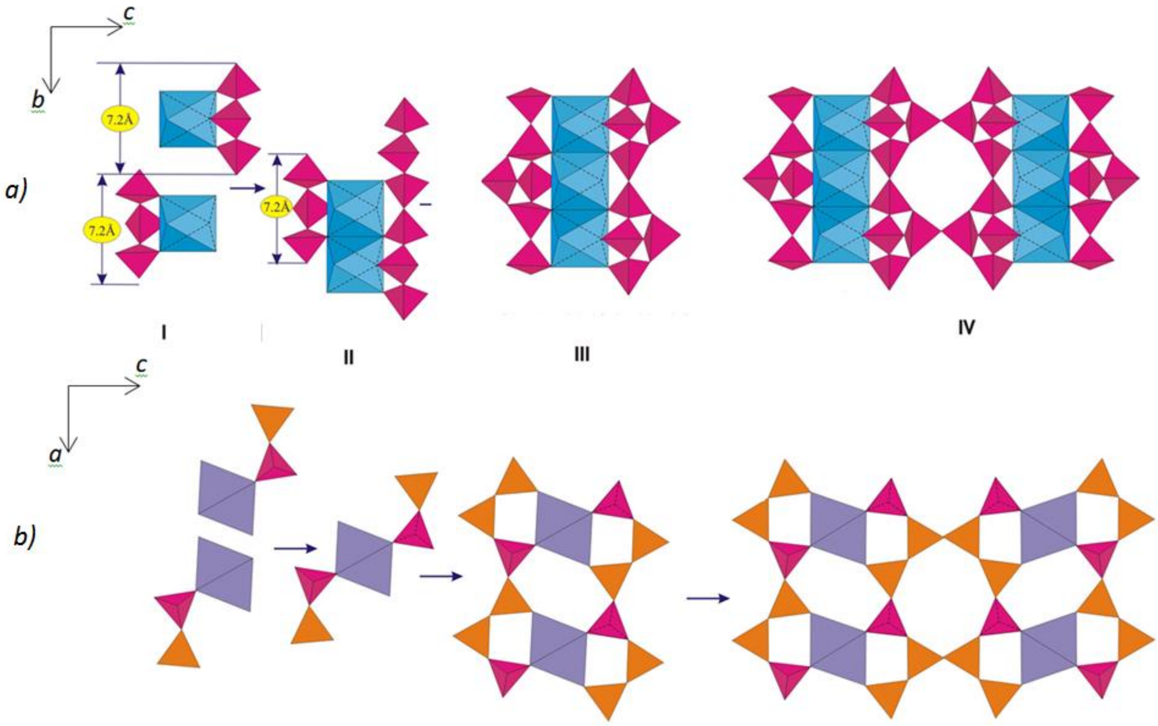

Рис. 4. Формирование структуры дельхаелита в двух проекциях из кластера типа С (a, b)

Из кластеров типа Д (рис.1 Д) при их полимеризации с вершинами боковых тетраэдров, триортогруппы превращаются в волластонитовую цепочку. Между октаэдрами структурной единицы в Е-положении располагаются атомы Ca другого типа. В связанной параметром ***c*** структурной единице центральный тетраэдр триортогруппы одной вершиной обобщается со свободной вершиной октаэдра соседней октаэдрической колонки, а другой связывается с соответствующей вершиной тетраэдра соседней цепочки. В результате волластонитовые цепочки превращаются в ксонотлитовую ленту и создают гетерогенный структурный блок с составом $|Ca^{E}Ca(Si_6O_{17})(OH)_2|$. Тригональные призмы атомов кальция цементируют эквивалентные структурные блоки с формированием структуры типа ксонотлита с кристаллохимический формулой: $Ca_4|Ca^{E}Ca(Si_6O_{17})(OH)_2|$ (Hejny, Armbruster, 2001).

Структуры сажинита (Camara et al., 2006) и Na-, Nd-силиката (Чирагов, 2002) формируются из структурных блоков типа ксонотлита. В результате полимеризации двух энантиоморфных ксонотлитовых блоков ленты Si_6O_{17} превращаются в гофрированную тетраэдрическую сетку с составом Si_6O_{15}. Структура сажинита состоит из двух, а Na-, Nd-силиката – из четырех ксонотлитовых блоков. В пустотах гетерогенного каркаса располагаются атомы Na и молекулы воды.

Описанная структурная иерархия отражается и в условиях образования минералов группы дельхайелита (Чирагов, Дорфман, 1981) и макдональдита (Cannillo et al., 1968). Образование дельхайелита связано с высокотемпературной стадией пегматитообразования на этапе поступления метаморфизующих растворов, богатых калием. В парагенезисе с дельхайелитом постоянно находятся фенаксит, канасит, вадеит и т.д. Гидродельхайелит является продуктом гипергенезиса и гидротермального изменения дельхайелита. В этих условиях происходит вынос натрия, частично калия и всего фтора и хлора.

Структурный тип макдональдита связан с низкотемпературной стадией пегматитообразования или поздней гидротермальной стадией минералообразования. Однако во всех случаях среда должна быть сильно щелочной и богатой кальцием (для структурного типа макдональдита) или редкоземельными катионами (для структуры монтереджианита). Эти структурные особенности являются апробированными индикаторами для определения процессов минералообразования.

Кристаллоструктурные параметры триортосиликатов и их производных

№	**Названия минерала и химич. состав**	**a (Å) α**	**b (Å) β**	**c (Å) γ**	**Пространст. группы**	**z**	
1	$K_3HoSi_3O_8(OH)_2$	5.385	13.552	13.198	Pcmn	4	A
2	$K_3HoSi_3O_9$	14.05	13.60	5.90	$Pm2_1n$	4	
3	волластонит $Ca_3Si_3O_9$	7.88 90^0	7.27 95.16^0	7.07 103.27^0	P_1^-	2	
4	фошагит $Ca_4[Si_3O_9](OH)_2$	10.32 90^0	7.36 106.4^0	7.04 90^0	P_1^-	2	
1	бустамит $Mn_{0.67}\ Ca_{0.33}SiO_3$	7.605 89.95^0	7.102 94.39^0	13.568 102.53^0	P_1^-	**12**	B
2	макдональдит $BaH_2(Ca_4Si_{16}O_{38})\cdot 10H_2O$	14.081	13.109	23.560	Cmcm	4	
3	монтереджианит $Na_4K_2(Y,Ce)_2Si_{16}O_{38}\cdot 8.3H_2O$	9.512	23.956 93.8^0	9.617	$P2_1/n$	4	
1	дельхайелит $K_7Na_3Ca_5Al_2Si_{14}O_{38}F_4Cl_2$	24.86	7.070	6.53	Pmmn	1	C
2	гидродельхайелит $(Ba,K)_{0.76}Ca_2AlSi_7O_{17}(OH)_2\cdot 6H_2O$	23.9532	7.032	6.605	Pmmn	2	
3	родезит $HKCa_2Si_8O_{19}\cdot 5H_2O$	23.428	6.557	7.063	Pmam	2	
1	ксонотлит $Ca_6Si_6O_{17}(OH)_2$	16.530	7.330 90^0	7.040	P2/a	2	D
2	сажинит-(Ce) $Na_2Ce[Si_6O_{14}(OH)_2]\cdot H_2O$	7.5	15.02	7.35	Pmm2	2	
3	Силикат - Na, Nd $Na_2Nd[Si_6O_{14}(OH)_2]\cdot H_2O$	30.87	7.387	7.120	Cmm2	4	

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СТРУКТУРНАЯ ИЕРАРХИЯ Ca- И TR-ТРИОРТОСИЛИКАТОВ И ИХ ПРОИЗВОДНЫХ

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Резюме. Известно, что физико-химические свойства и парагенетические особенности минералов связаны с их кристаллической структурой. Иерархальная схема исследования структур минералов показывает, что классификация по химическому составу не дает полного представления о свойствах минералов. Принимая во внимание известные работы М.И. Чирагова и F.C.Hawthorne о структурной классификации минералов, впервые в настоящей статье используя метод сравнительной кристаллохимии и структурную иерархию, рассматриваются структуры Ca- и TR-триортосиликатов и их производных. Структурная иерархия минералов основывается на первичной полимеризации разнотипных координационных полиэдров, в результате которой формируются родоначальные структурные миналы или кластеры. С учетом симметрии триортосиликатов и формы полимеризации тетраэдров с Ca- и TR-октаэдрами, выделены кластеры четырех типов, отличающиеся по конфигурациям и химическим составам $|M(Si_3O_{10})(H_2O)_3|$, $|M(Si_3O_{10})_2|$, $|M(Si_3O_{10})(H_2O)_4|$ и $|M(Si_3O_{10})_2(H_2O)_2|$. В зависимости от формы полимеризации кластеров, представлена иерархальная схема формирования структурных типов Ca- и TR-триортосиликатов и их производных. В результате образуются структурные блоки и смешанные каркасы, в пустотах которых в Ca-силикатах располагаются атомы кальция, а в TR-силикатах – атомы натрия или калия. По химическому составу и форме кремнекислородного радикала минералы дельхайелит и макдональдит включены в одну группу. Согласно структурной классификации с выделением кластеров выявлено, что структуры этих минералов формируются из двух разных по конфигурации миналов и, следовательно, в результате их полимеризации образуются различные структурные типы. Обоснование структурной иерархии отражается в условиях образования минералов группы дельхайелита и макдональдита. Образование дельхайелита связано с высокотемпературной стадией пегматитообразования на этапе поступления метаморфизующих растворов, богатых калием. Гидродельхайелит является продуктом гипергенеза и гидротермального изменения дельхайелита. В этих условиях происходит вынос натрия, частично калия и всего фтора и хлора. Структурный тип макдональдита связан с низкотемпературной стадией пегматитообразования или с поздней гидротермальной стадией минералообразования. Однако во всех случаях среда должна быть сильно щелочной и богатой кальцием для структурного типа макдональдита или редкоземельными катионами для структуры монтереджианита. Эти структурные особенности являются апробированными индикаторами для процессов минералообразования.

Ключевые слова: *Ca- и TR-триортосиликаты, кластеры, структурные единицы, структурные блоки, формирование структур*

Ca- VƏ TR-TRİORTOSIİLIKATLARI VƏ ONLARIN TÖRƏMƏLƏRİNİN QURULUŞ İYERARXİYASI

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Xülasə. Məlumdur ki, mineralların fiziki-kimyəvi xassələri və paragenetik xüsusiyyətləri onların kristal quruluşları ilə əlaqəlidir. Mineralların quruluşunun iyerarxik sxeminin tədqiqi göstərir ki, onların kimyəvi tərkibə görə təsnifatı mineralların xüsusiyyətləri barədə tam məlumat vermir. M.İ.Çiraqovun və F.S.Hautornenin mineralların quruluş təsnifatı barədə elmi əsərlərini nəzərə alaraq, ilk dəfə müqayisəli kristallokimya üsulu ilə quruluş iyerarxiyasına əsaslanaraq Ca- və TR- triortosilikatları və onların törəmələrinin quruluşları öyrənilmişdir. Mineralların quruluş iyerarxiyası müxtəlif növ koordinasiya poliedrlərinin polimerləşməsinə əsaslanır və nəticədə ilkin quruluş minalları və ya klasterləri formalaşır. Triortosilikatların simmetriyasını və tetraedrlərin Ca- və TR oktaedrləri ilə polimerləşmə formalarını nəzərə alaraq konfiqurasiyaları və kimyəvi tərkibləri ilə fərqlənən dörd tip klasterlər ayrılmışdır: │$M(Si_3O_{10})(H_2O)_3$│, │$M(Si_3O_{10})_2$│, │$M(Si_3O_{10})(H_2O)_4$│ və │$M(Si_3O_{10})_2(H_2O)_2$│. Klasterlərin polimerləşmə formasından asılı olaraq Ca- və TR triortosilikatları və onların törəmələrinin quruluş növlərinin əmələ gəlməsi üçün iyerarxik bir sxem təqdim olunur. Nəticədə, boşluqlarında kalsium atomlarının Ca-silikatlarda, TR silikatlarında isə natrium və ya kalium atomlarının yerləşdiyi quruluş blokları və qarışıq karkaslar formalaşır. Silisium-oksigen radikalının kimyəvi tərkibinə və formasına görə delxayelit və makdonaldit mineralları bir qrupa daxil edilmişdir. Klasterlərin ayrılması ilə quruluş təsnifatına əsasən təyin edilmişdir ki, bu mineralların quruluşları iki fərqli konfiqurasiyada olan minallardan formalaşır və bunların polimerləşməsi nəticəsində müxtəlif quruluş tipləri yaranır. Struktur iyerarxiyanın əsaslandırılması delxayelit və makdonaldit qruplarının minerallarının əmələgəlmə şəraitlərində əks olunur. Delxayelitin əmələ gəlməsi yüksək temperaturlu peqmatitəmələgəlmə mərhələsində kaliumla zəngin metamorfik məhlulların daxil olması ilə əlaqələndirilir. Hidrodelxayelit delxayelitin hipergenezinin və hidrotermal dəyişilməsinin məhsuludur. Bu şəraitdə natrium, qismən kalium və bütün flüor və xlor xaric olunur. Makdonaldit tip quruluş peqmatitəmələgəlmənin aşağı temperatur mərhələsi ilə və ya gec hidrotermal mineraləmələgəlmə mərhələsi ilə əlaqədardır. Bununla birlikdə, bütün hallarda mühit yüksək dərəcədə qələvi olmalıdır və makdonaldit quruluş növü üçün kalsiumla, monterecianit quruluşu üçün isə nadir-torpaq kationları ilə zəngin olmalıdır. Bu struktur xüsusiyyətlər mineraləmələgəlmə prosesləri üçün sübut olunmuş indikator göstəricilərdir.

Açar sözlər: *Ca- və TR triortosilikatlar, klasterlər, quruluş vahidləri, quruluş blokları, quruluşların formalaşması*

ANAS Transactions Earth Sciences 2 / 2020

Geology and geophysics

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ИССЛЕДОВАНИЕ ГЕОЛОГИЧЕСКОГО СТРОЕНИЯ МЕСТОРОЖДЕНИЯ НАФТАЛАН И ЕГО ОКРЕСТНОСТЕЙ НА ОСНОВЕ АНАЛИЗА СЕЙСМИЧЕСКИХ АТРИБУТОВ ПО МЕЗОЗОЙСКИМ ОТЛОЖЕНИЯМ

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STUDY OF GEOLOGICAL STRUCTURE OF NAFTALAN FIELD AND ADJACENT AREAS BY USE OF SEISMIC ATTRIBUTE ANALYSIS OF MESOZOIC DEPOSITS

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Keywords: *attribute analysis, 3D seismic survey, seismic horizon, attribute cube, Cretaceous formations, dislocations*

Summary. The paper is devoted to the application of attribute analysis of 3D seismic survey data in order to clarify the geological structure of Naftalan – Northern Naftalan area of Ganja oil and gas province.

It gives information about Naftalan field, which is considered to be an ancient brachyanticline type deposit in Azerbaijan. A brief history of field exploration by geological and geophysical methods is considered. It is especially noted that there are two types of oil produced in the field: heavy oil with curative properties and light fraction of oil of commercial (industrial) meaning.

Our goal was to study in more detail the geological structure of the field to detect intervals and zones of light oil accumulation. Therefore, in 2012 3D seismic survey works were carried out at the Naftalan field. With the help of geological evaluation of the data cube obtained as a result of 3D seismic data processing, the interval of deposits was selected, in which the V seismic horizon was traced, reflecting the surface of Upper Cretaceous deposits, which were confidently traced throughout the study area.

In this interval, several attributes were calculated and their results were analyzed. Attributes that are similar or weakly informative in the results of the analysis were not used in subsequent studies to avoid repetition. In order to identify and trace disjunctive dislocations of different amplitudes, the most effective attributes, such as Chaos, Variance, Ant tracking, were identified and used to clarify the geological structure of the study area. All results of 3D seismic data processing were given in the form of cubes of seismic attributes. By analyzing the attributes cubes, the geological structure of the field was studied across the surface of Upper Cretaceous deposits and the most effective attributes were selected. As a result, a structural map for V-SH (top of Upper Cretaceous) was drawn.

Введение

Одним из древних месторождений брахиантиклинального типа в Азербайджане является месторождение Нафталан. Площадь исследования расположена в предгорье Малого Кавказа, на территории Геранбойского района, к югу от железнодорожной станции Горан. На юго-востоке протекают Тертерский канал, р.Инджичай, а на северо-западе р.Горанчай (рис.1).

Геологическое строение площади было изучено геофизическими методами, структурным картированием на основе разведочных данных и данных глубинного бурения. Структура Нафталан является асимметричной брахиантиклиналью, характеризующейся субмеридиональным простиранием по отложениям майкопа, с крутым (40-45°) западным и относительно пологим (15-25°) восточным крыльями. На месторождении Нафталан в майкопских отложениях было обнаружено несколько нефтеносных горизонтов (I, мергели, II). Из верхних трех горизонтов была получена тяжелая нефть с лечебным эффектом, а из нижних горизонтов (III, IV, V и VI) – нефть относительно легкой фракции. В результате буровых работ, проведенных на месторождении, была обнаружена нефтеносность III, IV, V, VI, VII горизонтов, залегающих ниже II горизонта, а также нефтеносность глинистых прослоек песчаных слоев малой мощности. Таким образом, глинистая прослойка, залегающая между II и III горизонтами, была принята как нижняя граница лечебной нефти (Мамедов, Мириев, 2009; Рахманов, 2007). Во время испытательных работ в некоторых скважинах на площади Нафталан была получена малодебитная нефть (0.2-0.3 тонн/сутки) из отложений мергелей и песчаников палеоцен-датского яруса (Ализаде и др.,1966). Перспективы нефтегазоносности на площади связаны с отложениями майкопа, эоцена и верхнего мела.

Кровля структур Нафталан и Северный Нафталан, будучи на участке скважин Нафталан-39, 56, 61 и др., была определена как единая антиклинальная структура, осложненная большими разломами в основном в направлении простирания структуры. Структурная карта, составленная по сейсмическому горизонту, приуроченному приблизительно к подошве I горизонта майкопа, отражает структуру Нафталан в форме антиклинали меридионального направления с тремя ундуляциями.

Рис. 1. Общая схема площади исследования

Несмотря на длительный период эксплуатации данного месторождения и изучения геологического строения, ее большая часть еще недостаточно изучена вследствие сложной картины сейсмического волнового поля. В связи с этим в 2012 году с целью детального изучения геологического строения площади Нафталан по мезокайнозойским отложениям здесь была проведена 3D сейсморазведка. Интерес, проявляемый и в настоящее время к изучению данной площади, связан с расположением здесь древнего месторождения Нафталан, находящегося в эксплуатации уже в течение длительного периода, с достаточно хорошо развитой инфраструктурой и расположением основных нефтегазоносных объектов на большой глубине (Ахмедов, Агаева, 2020).

Известно, что 3D сейсморазведка играет важную роль в обнаружении и прослеживании неантиклинальных ловушек и дизъюнктивных дислокаций (Ахмедов, 2016; Воскресенский, 2010; Шерифф, Гелдарт,1987). Данная статья посвящена 3D сейсморазведке, и в частности, исследованию возможностей атрибутного анализа в уточнении геологического строения площади исследования.

Методы исследования

В 2012 году геологическое строение, форма, а также протяженность структуры Нафталан были частично изучены по данным 3D сейсморазведки. Полученные результаты показывают, что данная структура – это асимметрическая антиклинальная складчатость, расположенная в юговосточном направлении. Согласно временным разрезам, площадь Нафталан – Северный Нафталан осложнена многочисленными разломами.

В западной части площади зона разлома большой амплитуды, простирающаяся в направлении север-юг, разделяет участок на две части. В западной части сейсмические горизонты под воздействием разлома прослеживаются на большой глубине. В основной, восточной частях площади исследования горизонты, будучи на меньшей глубине, прослеживаются на более широком участке. Сейсмические записи в зоне разлома хаотичные, и можно сказать, что прослеживание записей скорее условное. Информативность сейсмических данных по площади и разрезам изменчива; корреляционные свойства фронта синфазной волны, относящиеся к интервалу, характеризующему комплексы отложений эоцена и миоцена, ухудшаются в направлении от центральной части площади к югу. Здесь оси отраженных синфазных волн короткие и хаотичные. Фронты синфазных волн, характеризующих комплексы отложений мела и палеоцена, проявляются более упорядоченными динамическими свойствами и хорошо коррелируются по площади.

Во временных разрезах по месторождению Нафталан картина сейсмического волнового поля более сложная. В центральной части площади прослеживание волн ухудшается, и это в основном связано с присутствием в этой части поселений и промышленных объектов, которые вызывают затухание волны.

Несмотря на то, что сложное тектоническое строение на площади исследования, петрофизические свойства пород, составляющих отражающие границы, в определенной степени усложняют прослеживание сейсмических горизонтов, они не оказали серьезного воздействия на результаты кинематической интерпретации отражающих горизонтов.

Как видно из вертикальных разрезов İnline 190 и crossline 500, достаточно высокая информативность полученного сейсмического материала наблюдается во временном интервале 0-4500 мс, и поэтому указанный интервал (рис. 2, а и б) был выбран для последующей обработки и интерпретации (в частности для атрибутного анализа). Анализ полученных разрезов указывает на присутствие структурных элементов (или объектов) различного типа и размеров. Рассмотрим наблюдаемое в данных разрезах сейсмическое волновое поле.

В двух вертикальных временных разрезах (рис. 2), проходящих по площади исследования в перпендикулярном направлении, вышеуказанные продольные и поперечные разломы явно прослеживаются вследствие хорошо наблюдаемых кинематических и динамических параметров дизъюнктивных дислокаций в нарушенных зонах.

Несмотря на достаточно значительный вклад данных 3D сейсморазведки в изучение геологического строения площади исследования, некоторые свойства дизъюнктивных дислокаций здесь остаются невыясненными, что требует разработки нового подхода к изучению разломов малой амплитуды. В связи с этим применяемый нами атрибутный анализ преследует две цели:

1. Обнаружение и прослеживание тектонических разломов малой амплитуды;

2. Определение эффективности структурных и прочих атрибутов в решении задачи (проблемы), поставленной в таких сложных сейсмогеологических условиях. С этой целью был проанализирован и рассчитан по 3D сейсмическим данным ряд атрибутов программы *Petrel,* таких как *Chaos*, *Ant tracking* и *Variance* (Абетова, Абетов, 2017; Кирилов, Закревский, 2014).

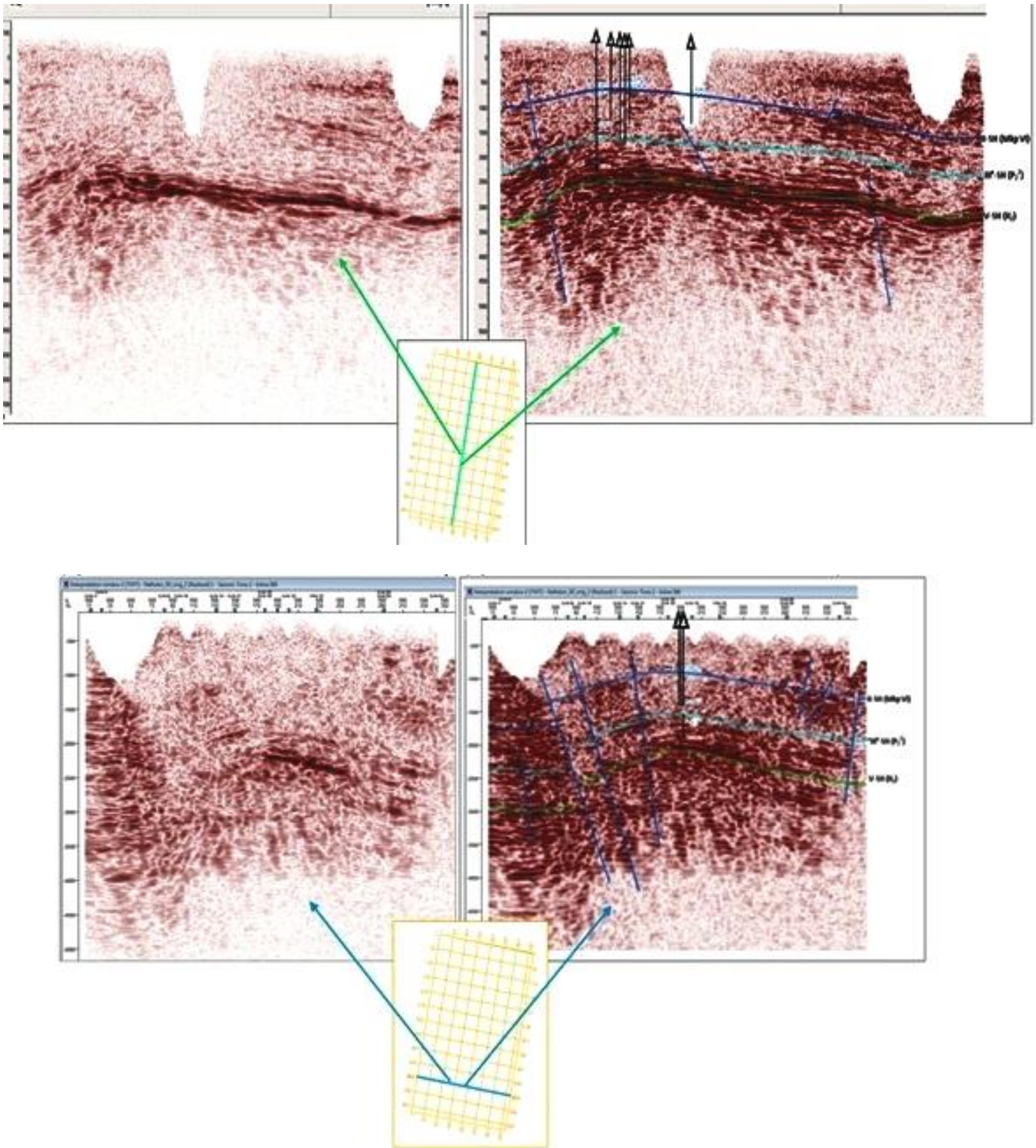

Рис. 2. Информативность сейсмических данных; временные разрезы a – inline 190 и b – inline 500

Результаты и обсуждения

Сравним разрез атрибута *Chaos*, служащий индикатором разломов и дизъюнктивных дислокаций, с традиционным временным разрезом. При этом можно видеть, что разломы малой амплитуды, с трудностью прослеживаемые в традиционном временном разрезе, явно прослеживаются в разрезе атрибута *Chaos*. С использованием атрибута *Chaos* непрерывность в прослеживании горизонтов позволяет обнаруживать и прослеживать разломы малой амплитуды (Sanhasuk et al., 2014; Chopra, Marfurt, 2005).

Таким образом, анализ разрезов, проходящих в различных направлениях по площади исследования, позволяет прослеживать разломы большой амплитуды на западе и разломы малой амплитуды в восточной и юго-восточной частях площади. Как результат, очень наглядно можно увидеть блоковое строение складчатости, вызванной дизъюнктивной дислокацией.

Наряду с атрибутами *Chaos*, атрибуты *Ant tracking* и *Variance* дают в кубе 3D точную информацию об изменениях волновой картины, наличии аномалий, трещиноватости и вообще дизъюнктивных дислокаций. Атрибут *Ant tracking* дает важную информацию при определении расположения разломов по площади исследования (рис. 3).

Из рис. 4 сравнением разреза, полученного из 3D куба, рассчитанного по *Ant Tracking*, с разрезом, полученным из обычного куба, можно заметить, что сейсмические отражения, наблюдаемые в обычном временном разрезе, отражаются и в рассчитанных разрезах. Как видно из этого рисунка, несмотря на то, что разломы, наблюдаемые в разрезе, имеют малую амплитуду, они отражаются в хаотичной форме.

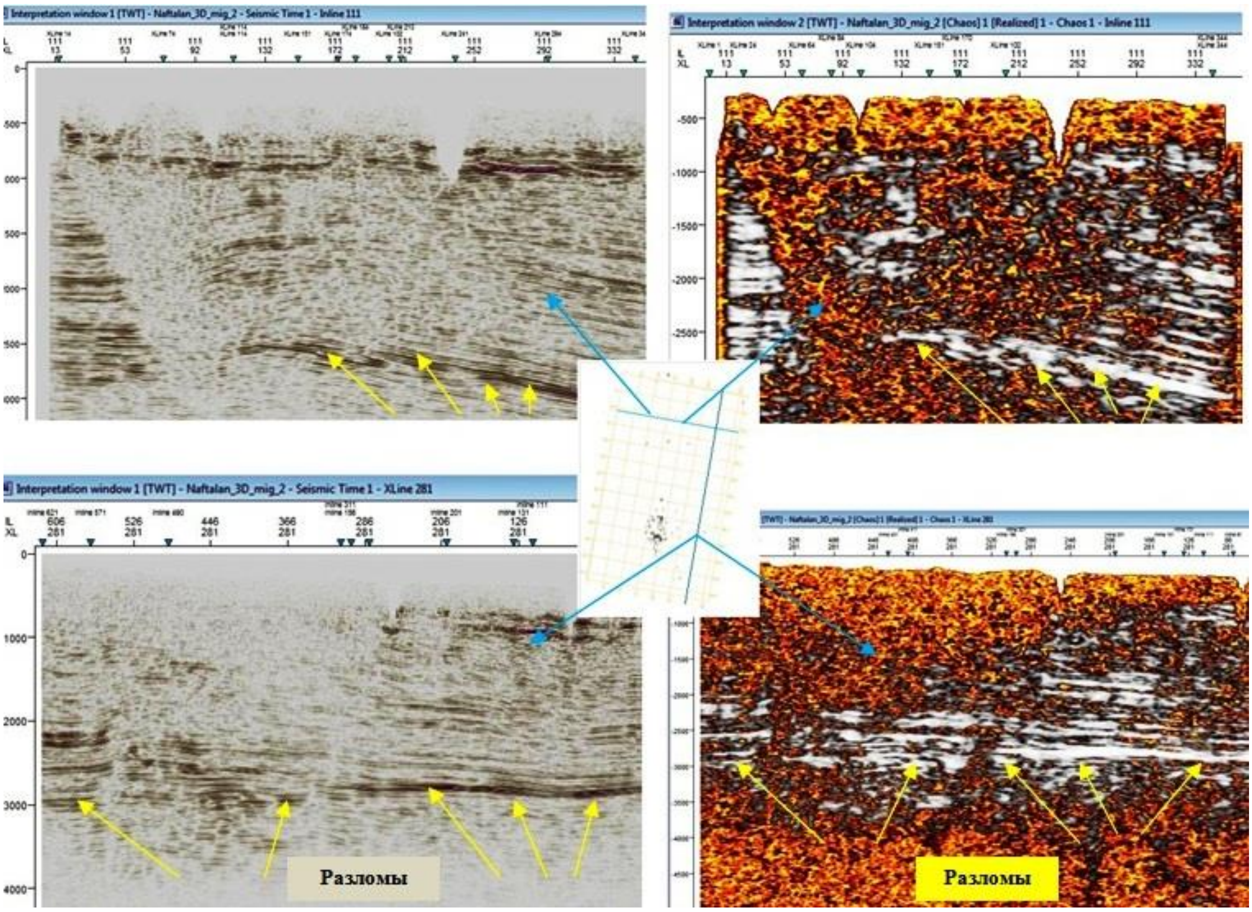

Рис. 3. Атрибут *Chaos*, рассчитанный по 3D кубу

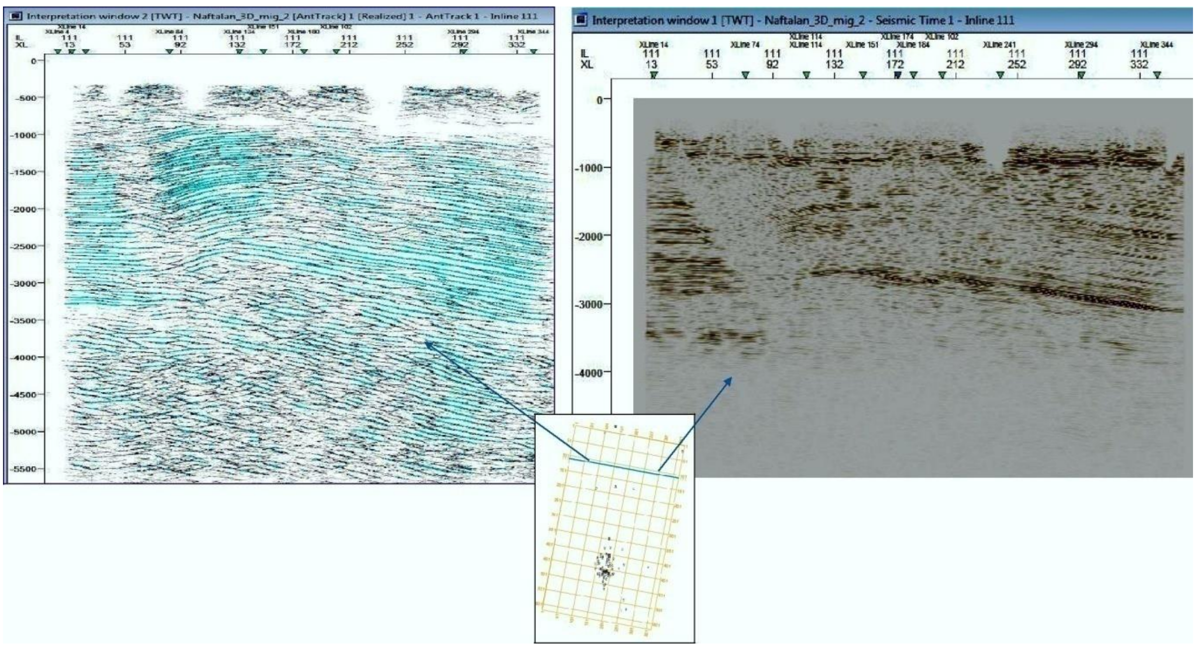

Рис. 4. Фрагмент атрибута *Ant tracking*

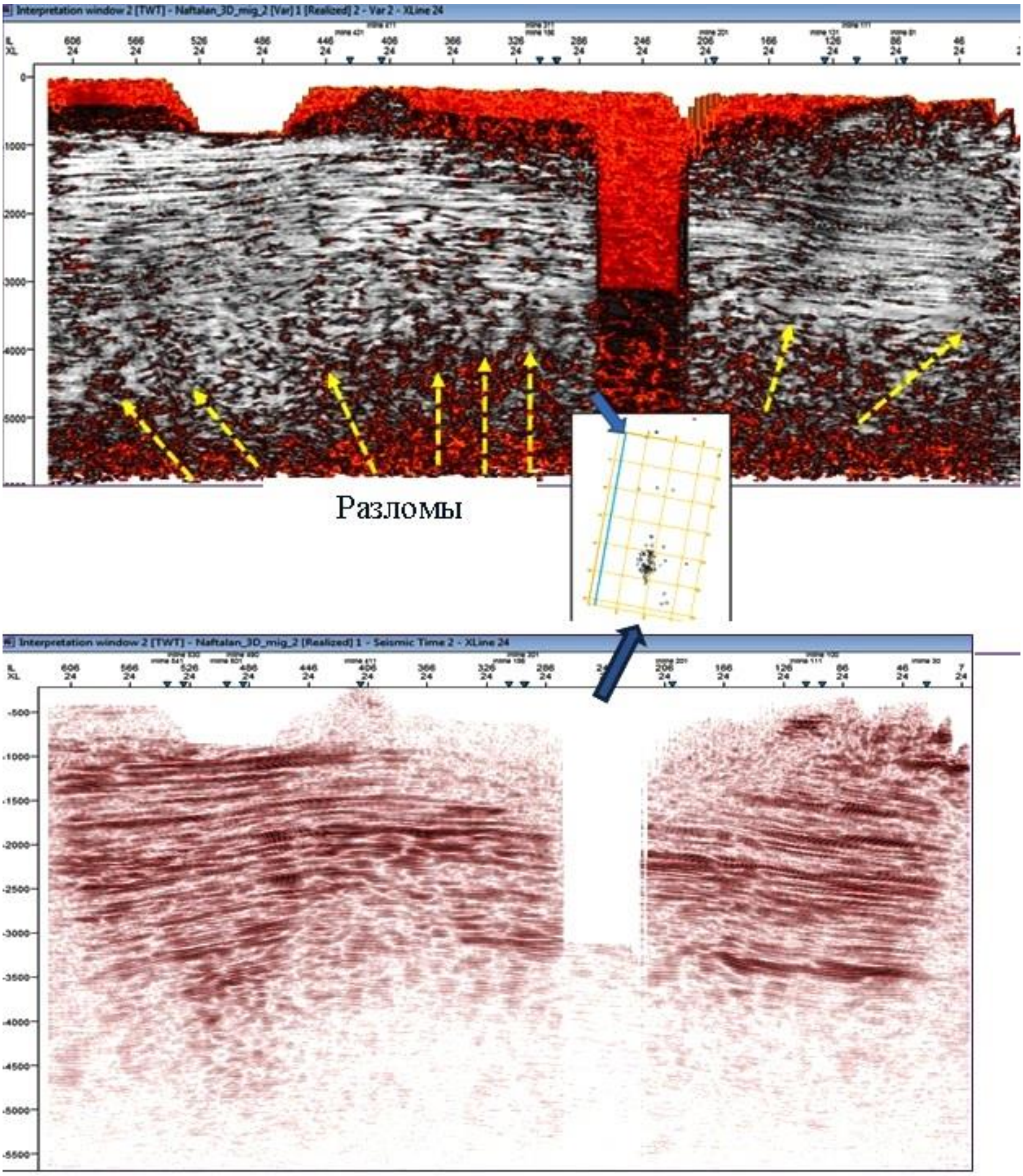

Рис. 5. Фрагмент атрибута *Varianc*e, рассчитанного по 3D кубу

Как видно из рис.5, на котором показан разрез атрибута *Variance,* все разломы, наблюдаемые в разрезах других атрибутов, нашли свое подтверждение и в разрезе атрибута *Variance*.

Каждый из вышеперечисленных атрибутов был рассчитан в отдельности с последующим проведением всестороннего анализа.

После проведения анализа атрибута *Chaos* полученные результаты были использованы при интерпретации сейсмических горизонтов, прослеживании разломов и построении структурных карт. Результаты анализа атрибутов *Chaos* и *Variance* были применены при геологической оценке и прослеживании разломов.

Использование атрибута *Ant tracking* дает возможность исследовать небольшие разломы при непрерывном прослеживании отражений (в основном в случае малоамплитудных разломов) при корреляции сейсмических горизонтов.

Таким образом, анализ разрезов, полученных с помощью атрибутов по V-СГ (кровле верхнего мела), позволил уточнить геолого-тектоническое строение площади исследования (рис. 6).

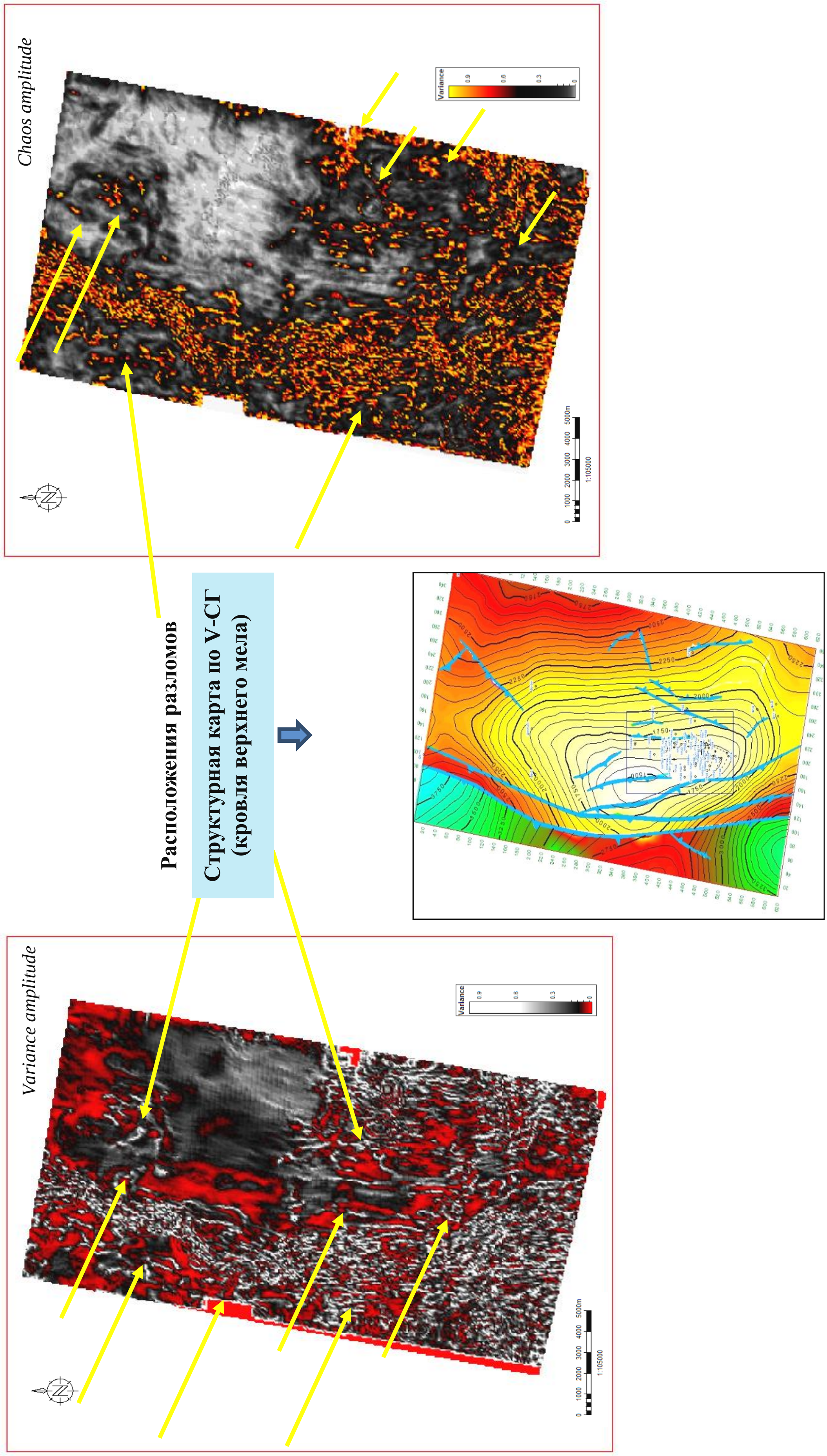

Рис. 6. Структурная карта по V-СГ (кровля верхнего мела)

Выводы:

1. На основе материалов 3D сейсморазведки был рассчитан ряд сейсмических атрибутов – атрибуты ***Chaos, Ant tracking, Variance*** по кровле верхнего мела (V-СГ), было уточнено геолого-тектоническое строение площади исследования (структура Нафталан).

2. В результате проведенного атрибутного анализа было выявлено, что если для выявления и прослеживания разломов более универсальными и информативными атрибутами считаются *Chaos* и *Variance*, то для получения более надежных результатов интерпретации можно использовать атрибут *Ant tracking*.

3. Была построена структурная карта площади исследования (кровля верхнего мела) по V-СГ.

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ИССЛЕДОВАНИЕ ГЕОЛОГИЧЕСКОГО СТРОЕНИЯ МЕСТОРОЖДЕНИЯ НАФТАЛАН И ЕГО ОКРЕСТНОСТЕЙ НА ОСНОВЕ АНАЛИЗА СЕЙСМИЧЕСКИХ АТРИБУТОВ ПО МЕЗОЗОЙСКИМ ОТЛОЖЕНИЯМ

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Резюме. Статья посвящена применению атрибутного анализа сейсмических 3D данных с целью уточнения геологического строения площади Нафталан – Северный Нафталан Гянджинского нефтегазоносного района.

В ней дается информация о месторождении Нафталан, которое считается древним месторождением брахиантиклинального типа в Азербайджане. Рассматривается краткая история изучения месторождения геологическими и геофизическими методами. Особо отмечается, что на месторождении извлекается нефть двух типов: тяжелая нефть, обладающая лечебными свойствами, и нефть легкой фракции коммерческого (промышленного) значения.

Наша цель заключалась в более детальном изучении геологического строения месторождения для обнаружения интервалов и зон накопления нефти легкой фракции. Поэтому в 2012 году на месторождении Нафталан были выполнены работы по 3D сейсморазведке. С помощью геологической оценки куба данных, полученного в результате обработки материалов 3D сейсморазведки, был выбран интервал отложений, в котором прослеживается V сейсмический горизонт, отражающий поверхность отложений верхнего мела, которые уверенно прослеживаются по всей площади исследования.

В данном интервале было рассчитано несколько атрибутов и были проанализированы результаты, полученные с помощью этих атрибутов. Атрибуты, схожие по результатам анализа или имеющие слабую информативность, не были использованы в последующих исследованиях во избежание повторов. С целью выявления и прослеживания дизъюнктивных дислокаций разных амплитуд были определены наиболее эффективные атрибуты, такие как *Chaos, Variance, Ant tracking*, и с их помощью было уточнено геологическое строение площади исследования. Все результаты обработки материалов 3D сейсморазведки были даны в форме кубов сейсмических атрибутов. Анализируя кубы атрибутов, было исследовано геологическое строение месторождения по поверхности верхних меловых отложений и были выбраны наиболее эффективные атрибуты. В результате была составлена структурная карта по V-СГ (кровля верхнего мела).

Ключевые слова: *атрибутный анализ, 3D сейсморазведка, сейсмический горизонт, куб атрибутов, меловые отложения, дислокации*

SEYSMİK ATRİBUTLARIN ANALİZİ İLƏ NAFTALAN YATAĞI VƏ ONUN ƏTRAFININ GEOLOJİ QURULUŞUNUN MEZOZOY ÇÖKÜNTÜLƏRİ ÜZRƏ TƏDQİQİ

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Xülasə. Məqalə Gəncə Neftli Qazlı Rayonunun Naftalan-Şimali Naftalan sahəsində geoloji quruluşun dəqiqləşdiliməsi məqsədi ilə 3D seysmik məlumatların atrbut analizinin tətbiqinə həsr olunmuşdur.

Məqalədə Azərbaycanın çox qədim braxiantiklinal tipli yatağı hesab edilən Naftalan yatağı haqqında məlumatlar verilmişdir. Yatağın geoloji və geofiziki metodlarla öyrənilməsinin qısa tarixi nəzərdən keçirilmişdir. Xüsusi qeyd olunur ki, yataqdan iki tip neft çıxarılır: müalicə əhəmiyyətli ağır neft və kommersiya (sənaye) əhəmiyyətli yüngül neft. Məqsədimiz yüngül neftin yığıldığı interval və zonaları aşkar etmək üçün yatağın geoloji quruluşunu daha dəqiq tədqiq etməkdir. Bu məqsədlə 2012-cü ildə Naftalan sahəsində 3D seysmik tədqiqatlar aparılıb. Aparılmış 3D seysmik tədqiqatları materiallarının emali nəticəsində alınmiş kubun geoloji dəyərləndirilməsi yolu ilə bütün sahə boyu inamla izlənilən Üst Təbaşir çöküntülərinin səthini əks etdirən V seysmik horizontun izləndiyi çöküntü intervalı seçilmişdir.

Bu intervalda bir neçə atribut hesablanmış və bu atributların verdiyi nəticələr analiz edilmişdir. Analizinin nəticələri oxşar və ya informativliyi zəif olan bəzi atributlar təkrarlığa yol verməmək məqsədi ilə sonrakı tədqiqatlarda istifadə olunmamışdır. Tədqiqatımızın hədəfi müxtəlif amplitudlu dizyunktiv dislokasiyaların aşkarlanması və izlənilməsi üçün daha effektiv atributlar, Chaos, Variance, Ant tracking kimi atributlar, müəyyənləşdirilmiş və onlardan geniş istifadə etməklə tədqiqat sahəsinin geoloji quruluşu dəqiqləşdirilmişdir. Bütün 3D materialların emalinin nəticələri hesablanmış bir neçə seysmik atributlar kubları şəklində verilmişdir. Alınmış bu atribut kubları analiz edilərək yatağın geoloji quruluşu Üst Təbaşir çöküntülərinin səthi üzrə müəyyənləşdirilmiş və ən effektiv atributlar seçilir. Nəticə olaraq V-SH (Üst Təbaşirin yuxarıları) üzrə struktur xəritə tərtib edilmişdir.

Açar sözlər: *atribut analiz, 3D seysmik kəşfiyyat, seysmik horizont, atributlar kubu, Təbaşir çöküntüləri, dislokasiyalar.*

ANAS Transactions Earth Sciences 2 / 2020

Theory and practice of oil and gas fields development

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CURRENT STATE AND PROSPECTS FOR THE DEVELOPMENT OF SMART FIELD TECHNOLOGIES (GENERAL REVIEW)

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***Keywords**: smart field, information support, mathematical support and software, organizational support, decision-making*

Summary. This article provides a brief analysis of the current state of the problem of creating the scientific foundations for the "smart field" concept which is considered as a system. It is noted that the objectives according to this concept are accomplished in four stages. Using the experience of various companies as examples, the results of this system functioning are given. In terms of support, the "Smart Field" system mainly includes three subsystems: information support, mathematical support and software, and organizational support. The obtained information allows you to make operational and correct management decisions, to ensure effective planning and implementation of geological and technical measures, repair and maintenance of equipment. In general, the focal point in the system is decision-making. At the same time, decisions are made under conditions of uncertainty. The development of the scientific foundations of the system therefore also includes the analysis of uncertainties which can be of a various nature.

It is proposed to form a list of specialists required for the modern oil and gas industry. It is noted that the most in demand are competencies that can be applied in any industry. To solve successfully problems related to "smart fields" it is necessary to combine the efforts of specialists of different profiles, namely: geologists, geophysicists, developers, drillers, programmers, professionals in economic and mathematical modeling, creation of automated control systems and decision-making.

1. Introduction

Making the right technological decisions in the development of oil and gas fields, drilling oil and gas wells and in general the tasks of oil field practice require a detailed study of geological sections, obtaining the necessary information about the section, the properties of hydrocarbons, used technical means and technologies. This problem is even more complicated in the case of a small and remote field. In this regard, when making decisions, it is also necessary to take this circumstance into account. Another problem that has to be encountered in finding solutions is related to the amount of information. In this case information plays a huge role and the lack of information makes it difficult to make the right decisions. This may be due to both a lack of data and an excess of data. It should be noted that the absence (or lack) of the necessary information, its untimely receipt negatively affects the efficiency and adequacy of decisions made during field development and well drilling. When trying to analyze such information technologists face great difficulties. This circumstance has contributed recently to the search for various ways of obtaining and analyzing information. Processing such a volume of data in order to obtain important information necessitates the development and application of modern tools, in particular artificial intelligence methods and methods that allow working in conditions of insufficient information. Technologies developed in recent years have taken a strong place in all spheres of human activity. The development of this direction is clearly noticeable in the activities of various oil and gas companies of the world that are involved in decision-making. The correctness of decisions to a significant extent also depends on the conditions: at the same time the same solutions that are effective in some conditions may be ineffective in others, in other words: the decision of some of them can only aggravate others. So for example, the wrong choice of oil recovery enhancement technologies can give a small increase to production but at the same time significantly increase capital or operating costs (for example, drilling additional production wells) or in drilling wells: bits selected based on the desire to ensure high speed may be ineffective for economic reasons. In this case a problem arises with uncertainty. This circumstance can also be encountered during modeling, etc. Under the mentioned conditions oil and gas producing companies need a management system that, using the information coming from the fields efficiently, will allow for constant monitoring of indicators and make decisions regarding investments in the development and implementation of new technologies, taking into account uncertainties. Judging by the preliminary results obtained, such a system which has recently attracted the attention of oil industry workers and called the "smart field" can take the oil and gas industry to a new level in the near future, ensuring the efficiency of companies in difficult geological conditions.

2. Brief analysis of the general concepts and current state of «Smart Field» systems

First of all, it is necessary to find out what these "smart fields" or as they are otherwise called "intelligent fields" actually are, what basic properties (attributes, features) characterize them and what technologies form the basis of this system. The methodology of the above system, the components and equipment for the operation of "smart" wells and fields have been developed and used with great success in various regions of the world including the USA, the North Sea, West Africa, the Middle East, Brunei, Australia, Russia, Kazakhstan, etc. Analysis of the «Smart Field» system development status and world experience in their creation (Smart wells – ROGTEC, 2014; Redutskiy, 2017) allows uncovering the essence and clarifying some definitions necessary for understanding the methodology for constructing these systems.

In particular the author (Redutskiy, 2017) summarizes the above review with the following definition: "smart" solution (in the narrow sense of the term, for the oil industry) is an approach to reservoir management which includes two closely related aspects: optimization of the life cycle based on research of development and production operations and determination of strategic, tactical and operational goals; advanced instrumentation as a leading technology for accurate monitoring and control of operations.

In order to study the concept of a smart field and identify the development trends a literature review was conducted and the main characteristic features of process solutions within the framework of this concept were determined. As examples of the technology introduction in various operations (Ерёмин, 2008; Smart wells – ROGTEC, 2014; Воробьев и др., 2018; Эфендиев, 2019; Лопухов, 2017; Rossi et al., 2000), the results of the activities of various engineering companies were analyzed.

Wells and fields are not made "smart" by the new technology, but by a successful combination of the existing advanced technologies, including wireless data transmission, remote sensors, remote control mechanisms and robotics. Remote sensors reproduce a real-time picture of what is happening downhole. The maximum effect from the operation of downhole sensors is achieved through the use of control systems that allow performing certain actions when downhole conditions change (Smart wells – ROGTEC, 2014; Воробьев и др., 2018; Интеллектуальная скважина, 2015). According to the authors of work (Воробьев и др., 2018), "…the core of the smart oil and gas reservoir management system is a hardware and software complex capable of analyzing a rather large volume of field information received in real time, resulting in quick identification of any deviations from the design (specified) parameters, formation of effective options for control actions and development of optimal technical, process and logistic solutions for them, and in some cases independent implementation of these solutions (still with the permission of the operator)".

So, a **"smart oil and gas field"** means a system (or class of systems) of automatic control of well drilling, oil and gas production operations, providing for continuous optimization of these processes, which requires integrated field modeling and drilling and production control modeling (Еремин, 2008; Демарчук, 2014a). In various literary sources and companies different analogues of the term "smart field" are used: digital oilfield, intelligent field, instrumented field, field of the future, integrated field operations control, etc. A specific concept of this term is the concept of a smart well. At present it is quite difficult to construct a fully automatic control of oil and gas production due to complexity and uncertainty in individual elements of an integrated model, in particular geological models. The term "intellectual deposit" is based, being strongly connected, on the concept of an intelligent control system, the elements of which are control methods using various methods of artificial intelligence. Modern categories of smart oil and gas technologies may include "smart" wells; new methods of studying well operation; new ways to obtain and use information; reservoir models, which are called "intelligent" in the framework of the system in question; well drilling process control; technologies for regulating the development of oil and gas fields; unconventional methods for classification of geological features, exploration, diagnostics, well drilling, field development, etc.

Based on the above we can conclude that creation of the scientific foundations of the "smart field" concept is relevant and meets modern requirements of oilfield theory and practice.

3. "Smart Field" system: basic principles

In terms of support the «Smart Field» system mainly includes three subsystems (Fig. 1). One of the main subsystems is an **information support system**. The large-scale introduction of SF technologies will require a qualitative change in the management system and organization at oil and gas enterprises. A "smart field" as an integrated system includes subsystems for the production and use of information, modeling (forecasting) of well drilling and field development processes and decision-making. As can be seen from the diagram the output of this information system is the information on the basis of which decisions are made. To build a smart system for monitoring the hydrocarbon production process, it is necessary, as noted by specialists, to create an automated system for receiving and using information, as well as its processing, analysis and storage. The baseline information for this represents a set of parameters characterizing both the characteristics of the geological section, the condition of drilling and production equipment, and the technology and process indicators (Efendiyev, Piriverdiyev, 2018).

Using this data, the control system, based on models and decision-making algorithms, calculates the technical and technological parameters that are used to optimize the well drilling and oil production processes. The information obtained thus allows making operational and correct management decisions, ensuring effective planning and implementation of well intervention activities, and equipment repairs and maintenance.

In general, as can be seen from the diagram, the focal point in the system is decision-making. At the same time decisions are made under conditions of uncertainty. When developing the scientific foundations of the system it is therefore necessary to analyze uncertainties which can be of a various nature (Efendiyev, Piriverdiyev, 2018).

Mathematical support and software are a combination of mathematical methods, models, algorithms and programs for implementing the goals and objectives of the system, as well as for normal functioning of the hardware complex and decision-making. Mathematical support means include: tools for modeling field development processes; typical modeling and decision-making algorithms; methods of mathematical programming, mathematical statistics, theories of reliability, fuzzy sets, etc. A wide range of theoretical, experimental and field studies are considered in the analysis allows identifying the characteristic features of the smart field solutions taken in the management of technological processes of well drilling and field development. In this regard a number of works are devoted to the classification of objects, because this problem is the basis in solving many problems. In recent works the problems of classifying geological features to assess the degree of hydrocarbon recovery difficulty, as well as the problems associated with well drilling are thus proposed to be solved using various mathematical methods (Efendiyev et al., 2016; Akhmetov et al., 2018; Efendiyev et al., 2018; Efendiyev et al., 2019; Bello et al., 2015) (statistical, hard, fuzzy cluster analysis). These works consider and analyze examples of successful application of artificial intelligence methods in the oil and gas industry, namely, in well drilling, indicating the results of application against the background of the trend existing in the industry, show the ways of using fuzzy clustering method and demonstrate the possibilities of using modern methods for classification of challenged hydrocarbon fields. They also provide a brief history and review the works on using artificial intelligence and its capabilities. It is noted that artificial intelligence methods were first used in the 70-80s of the last century to interpret well logs, to diagnose the condition of drill bits using neural networks, to make decisions in drilling and also to create a smart interface of a reservoir simulation program. In one of the works (Bello et al., 2015), it is proposed to use artificial intelligence to solve various problems of the oil and gas industry, including seismic pattern analysis, reservoir characterization, prediction of petrophysical characteristics (permeability and porosity), decision-making in general and many others. To date, artificial intelligence methods have been successfully applied in the evaluation and use of reservoir characteristics (Cuddy, Glover, 2002). A number of works are devoted to the use of fuzzy logic, neural networks, genetic algorithms in solving oilfield practical problems (Bello et al., 2015; Cuddy, Glover, 2002). Even in the past researchers in the sphere of natural sciences noticed that many, at first glance, random events are accompanied by certain patterns. In the eighteenth century scientists revealed a regularity in the change of any observation around its average value. Such patterns or distributions were approximated by continuous curves called "curves of normal distribution of errors" and assigned to the laws of probability (Cuddy, Glover, 2002; Efendiyev et al., 2019). Normal distribution is completely determined by the two parameters: average value and variance. In this case the variance depends on hidden, inherent parameters and measurement error. Variance about the average value is one of the main conditions causing fuzziness, and in connection with this the authors of another work (Cuddy, Glover, 2002) attempted to justify why this parameter characterizes fuzziness and requires the use of fuzzy logic.

In general, the analysis shows that solving process modeling problems is significantly hampered by the presence of uncertainty associated with the use of both random and fuzzy variables. In (Cuddy, Glover, 2002; Efendiyev et al., 2019) the difference between random and fuzzy values is shown. It is noted that fuzzy variables may be preferable in case of insufficient statistical data and related information necessary for more accurate and reliable estimates.

Studies in the field of optimal decision-making should also be noted. Using mathematical methods, artificial intelligence methods for decision-making in oilfield practice (optimization of drilling and production processes, management of field development process, etc.) is thus aimed at providing decision-makers in the field with accurate and correct information about different stages of well drilling and field development, eliminating (minimizing) the effect of human factor, which repeatedly led to errors.

For several decades, researchers have been using optimization models and methods to gain insight into the planning and control of well drilling and field development. All of them together constitute the basis of the mathematical support of the "smart field" systems.

Organizational support is a set of methods and tools governing the interaction of workers with technical means and among themselves in the process of developing and implementing an information system (Fig. 1). Organizational support is created according to the results of preliminary study of organization functioning at the stage of project development and before. In the diagram shown in the figure according to a generalization of literature data, the functions implemented using organizational support are given.

The main objectives of constructing (improving) a «Smart Field» system, due to the goal set for the conditions under consideration, are roughly as follows: analysis of world experience in the practical use of the «Smart Field» system; analysis of the current state of equipment and technology used in the oil and gas complex under consideration and justification of the feasibility of introducing the «Smart Field» system in oil and gas fields; methodology of the «Smart Field» system; justification of the nature of the required information, data collection and processing; design of well construction (classification of a section by drillability, prediction of pressure characteristics, construction of a drilling model, prediction of the required density of a drilling fluid, selection of bits, justification and selection of cement mortar formulations, accident and risk assessment, etc.); classification of fields with hard-to-recover reserves and assessment of the degree of difficulty of oil recovery; analysis of the information received; decision-making when choosing oil fields for the priority implementation of the "Smart Field" system; assessment of «Smart Field» system implementation project economic efficiency through the example of a specific oilfield. One of the important problems among the above which have been attracting researchers' attention recently is the problem of classifying fields with hard-to-recover reserves and assessing the degree of difficulty of oil recovery, as well as classifying and predicting the characteristics of geological sections (Akhmetov et al., 2018). Thus, for successful construction of the «Smart Field» system it is necessary to use a clear methodology, set the objectives and apply modern analysis and decision-making methods which are the main ones.

In the work (Kyrnaev et al., 2017) key areas of the "smart field" concept were identified, integrated implementation of which allows increasing the reliability of calculations and evaluating the effectiveness of implementing the operational «Smart Field» system. These results clearly show the wide possibilities of using the implemented systems and great potential for achieving quantitative results, such as reducing the nonproductive time while drilling wells, daily downtime of the well stock and monthly losses in oil production. At the same time the synergistic effect allows minimizing the risk of additional operating expenditures without compromising process and environmental safety.

The results presented in the work (Kyrnaev et al., 2017) make it possible not only to improve qualitatively the methodological understanding of the «Smart Field» system which is very important for the modern oil industry, but also to increase the efficiency of well drilling process control and reservoir management by accumulating, analyzing and generalization successful cases with the results of testing approaches to intellectualization of fields useful for "benchmarking", i.e. comparative analysis based on reference indicators (in other words, it is a process of determining, understanding and adapting the existing examples of efficient company functioning).

In the process of analyzing the works related to the development of the "Smart Field" systems and their methodology, the work (Temizel et al., 2019) provides information about the past and the present of the smart oil field concept and its dynamics, about the methods and methodological approaches that it uses and applies, about technical problems in application, as well as the problems of oil and gas industry professionals regarding the use of those or other technologies as a whole. This article (Temizel et al., 2019) discusses in detail the history of smart/intelligent development of oil fields, the types of technologies currently used in it, details the technologies used in other industries and provides an overview of works in this area. This review takes into account the reliability, applicability and additional benefits that these technologies bring to different types of fields in modern economic conditions. Real practical applications are illustrated through examples in different parts of the world, where problems, advantages and disadvantages that lead to conclusions about the criteria for the use of smart technologies in a particular area are discussed and summarized. Judging by the work performed to date, at the initial stage the smart field concept has established itself as a promising area and has become widely used in oil and gas fields around the world.

In general the work performed allows creating the «Smart Field» system which can be implemented in four stages, namely (Эфендиев, 2019): **at the first stage** data is collected and systematized, which is carried out both online and offline by receiving data using various systems – telemechanics, mud logging, data on operation of downhole pumping equipment, etc. At this stage the collected data is also processed using statistical method, after which the received information is uploaded to the corporate database.

The second stage involves analysis of the information. This includes well history review and comparison with operation period indicators, analysis of emergencies, their prevention measures, efficiency of protection measures used, etc. (Забродин и Бортников, 2018). **The third stage** covers decision-making; development (improvement) of measures for further optimization of drilling and production processes. This stage is the most time-consuming as it requires an integrated approach to decision-making, modeling and predictive assessment. **The fourth stage** includes assessment of erroneous decision risk and technological and economic efficiency.

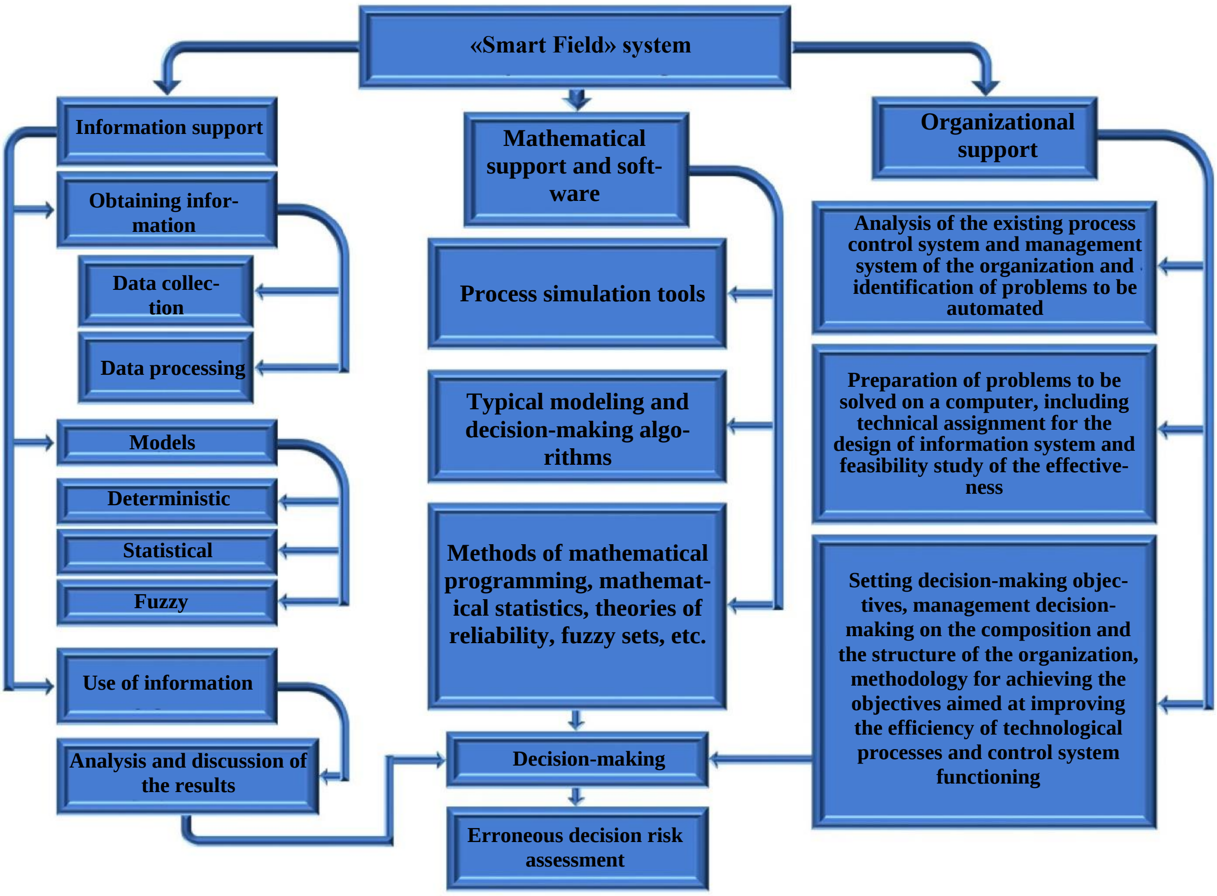

Fig. 1. «Smart Field» system support diagram

In the literature along with the principles of construction much attention is paid to the practical application of intelligent systems and the results of their functioning in various oil-producing regions of the world are presented. In light of the aforementioned it is necessary to analyze the results obtained in the framework of the experience of using these systems by various companies.

Some results indicate lower operating costs, reduction in operating expenditures (which is very difficult to calculate accurately), reduction in power costs of up to about 25%, according to various sources. As independent experts predict, with the development of smart technologies it will be possible to increase global oil recovery by 30-50%, or even by 60-70% with the transition to next-generation technologies. Some companies are already successfully mastering smart technologies in practice; however, this generally refers to individual components rather than an integrated system.

For example, you should pay attention to the experience of Russian companies. Samotlorneftegaz OJSC has been developing the “smart field” concept for several years. Another leader in the sphere of smart technologies is Tatneft OJSC (Демарчук, 2014b). Extensive experience in implementation of individual elements of “smart” systems has been accumulated by LUKOIL Group, including geological and hydrodynamic modeling, smart well completion and the introduction of smart well control stations (Демарчук, 2014b). In general according to (Козлова, Пигарев, 2018) in Russia in 2018 there are more than 40 projects of smart fields, the total production of which is 140 million tons or 27% of the total volume in the country.

In Kazakhstan an automated oil and gas field control system has been developed to achieve maximum efficiency by integrating separate systems into a single integrated information system. In 2016 a project was launched on the basis of Uaz field, the introduction of which allowed reducing electric power consumption by 33% and specific well workover costs by 25%. EmbaMunayGas introduced digital technologies in the Prorvinskoye field group in 2017, in Zhanatalap and East Makat in 2018 and in East Moldabek in 2019. Data processing and information analysis algorithms were automated according to procedures developed by Embamunaygas. All information goes to the head office. Data collection from the field allows you to quickly respond to deviations in the performance of wells and analyze data. According to Kazakhstan experts in the near future it is planned to increase the introduction of these technologies in other fields of KazMunayGas (https://neftegaz.ru/news/politics/202118-kazakhstan-razvivaet-proekt-tsifrovoe-mestorozhdenie/, 2018) and by 2022 their number may exceed 10.

As an example of remote monitoring and data collection from oil wells, the work (Лопухов, 2017) provides experience of Terra Ferma, a system integrator engaged in remote video monitoring and data collection at wellheads located in the Rocky Mountains area of the State of Colorado. Each wellhead system consists of automatic data recording, monitoring and control devices connected by cellular channels to central server and control center several miles away. Event-triggered data logs and full reports should be accessible through wired and wireless Ethernet network from smartphones, tablet computers and laptops, allowing operators to access control center data wherever they are (Лопухов, 2017). In these systems communication networks connect the company, remote personnel, field information and technological processes into a single system around the world. As an example, the BP system, with a length of 1280 km and a cost of $ 80 million, which connects the offshore platforms in the Gulf of Mexico, was completed in 2010, as well as the STATOIL system in the North Sea in 2009 (Еремин, 2011).

According to (Huiyuna et al., 2019), in 1997 the first SCRAMS electronic hydraulic intelligent well system (Jingmei, 2008) developed by Halliburton and Beihai Petroleum Service Engineering Company was installed on the Saga Tension Leg Platform in Beihai (a district in the Guangxi Zhuang Autonomous Region of the PRC). Since then the technology of smart wells in the field of oil and gas development has begun to develop rapidly: over the first 10 years the number of production wells with smart systems has grown with an intensity of 27% per year, and more than a thousand production wells have been reasonably transformed. In the second decade large foreign oil and gas companies including the Shell Petroleum Company took into account the technical requirements for smart wells and traditional means of production. More than 300 producing wells were equipped with a complete intelligent system. The work (Huiyuna et al., 2019) also gives a tabular form of data summarized for a number of studies on individual fields in the world where smart systems with the names of the executing companies were used. Analysis and synthesis of literature data shows the active involvement of leading oil companies in the development and implementation of the “Intelligent Field” systems. Among the countries it should be noted the USA, Norway, Mexico, the countries of Africa, Latin America, Russia, Kazakhstan, etc. Practical examples from fields in the Gulf of Mexico, the North Sea, Saudi Arabia and Africa show how intelligent technologies can help increase production at lower cost, significantly reduce water production in production wells, assess the potential of new fields, etc.

Summing up we note that in a review devoted to a very important area today, it is impossible to cover the whole variety of problems, to show the advantages and disadvantages of the system. It should be noted that in these systems great importance is attached to all issues related to the management of field development, well drilling, equipment and well protection. With the right and scientifically based approach to the construction of these systems, it is also possible to better identify anomalies and deviations from the operating ranges of parameter values during the implementation of technological solutions during drilling and production at early stages and to prevent them in a timely manner. In this case it is possible to better identify anomalies and deviations from the operating ranges of parameter values when implementing process solutions while drilling and producing at early stages and to prevent them in a timely manner. Thanks to “smart fields”, it is possible to improve the quality of reservoir management, as a result of which an increase in production can be achieved also due to an improvement in the quality of control over reservoir properties.

In general, due to the above measures, it is possible to mitigate risks in the sphere of technology, industrial, environmental and occupational safety. Automation of processes allowed successful performance of operations to optimize production in remote access mode. This is one of the main advantages of a smart field, i.e. the fact that it minimizes problems and their solution time associated with the field location, distance and time. At the same time control limits are expanding from regional office (or offshore platform and drilling rig) to sensors installed on downhole or surface equipment and to mobile personnel equipped with modern devices and communications. In favor of the aforementioned evidence is the analysis performed in (Еремин, 2011). As can be seen from the experience accumulated by leading companies to date, smart technologies in the oil and gas industry put forward good opportunities that increase the efficiency of well drilling control and oil and gas reservoir management by saving time and energy in relation to the technologies and manpower used, given that the technology applied is economical for the area under consideration.

4. Conclusion

As the review of studies shows, a sufficient number of works on the development and improvement of «Smart Field» systems have been accumulated, and a number of interesting results have been obtained to date. Despite the recent development of the “smart field” concept in the oil and gas industry there are still problems associated with various kinds of uncertainties that arise when evaluating geological conditions, solving problems of facility classification, justifying and choosing criteria for making the right decisions when drilling and producing in relation to the conditions under consideration, etc. The features of a given field development history as well as the management of production and economic activities of an oil field are insufficiently studied when implementing the «Smart Field» systems.

Leading oil and gas companies are currently working on problems, trying to ensure highly efficient well drilling and oil and gas field development operations aimed at obtaining high technical and economic indicators providing environmental safety. Field intellectualization contributes to the improvement and optimization of drilling and oil production processes. In this regard, it is necessary to carry out a set of studies aimed at the scientific substantiation of the features of oil and gas companies management processes in the construction and implementation of the «Smart Field» system under objective conditions of increasing cost of hydrocarbon production in fields with hard-to-recover reserves.

Based on the results of recent studies a list of specialists required for the modern oil and gas industry can be prepared. The most demanded are the competencies that can be applied in any industry (Анализ данных и научный подход…, 2018). To successfully solve the problems associated with “smart fields”, it is necessary to combine the efforts of experts in various fields, namely geologists, geophysicists, reservoir managers, drillers, programmers as well as economic and mathematical modeling, creation of automated control and decision-making systems. The methods considered in this review, when applied, can have a significant impact on the quality of various types of operations when constructing «Smart Field» systems, which in turn will save time, reduce risks and costs, increase efficiency and allow solving a large number of problems at various stages of «Smart Field» system design.

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СОВРЕМЕННОЕ СОСТОЯНИЕ И ПЕРСПЕКТИВЫ РАЗВИТИЯ ТЕХНОЛОГИЙ «ИНТЕЛЛЕКТУАЛЬНОЕ МЕСТОРОЖДЕНИЕ»

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Резюме. В настоящей статье приводится краткий анализ современного состояния проблемы создания научных основ концепции «интеллектуальное месторождение», которое рассматривается в качестве системы. Отмечается, что реализация задач согласно данной концепции производится в четыре этапа. На примерах опыта различных компаний приводятся результаты функционирования отмеченной системы. С точки зрения обеспечения в состав системы «интеллектуальное месторождение» в качестве подсистем главным образом входят три системы: информационного обеспечения, математического и программного обеспечения и организационного обеспечения. Полученная информация позволяет принимать оперативные и правильные управленческие решения, обеспечивать эффективное планирование и внедрение геолого-технических мероприятий, ремонтно-профилактического обслуживания оборудования.

В целом главное место в системе занимает принятие решений. При этом в большинстве своем решения принимаются в условиях неопределенности. Поэтому разработка научных основ системы включает также анализ неопределенностей, которые бывают разного характера. Показана необходимость комплекса исследований, направленных на научное обоснование особенностей процессов управления нефтегазодобывающими предприятиями при построении и внедрении системы «интеллектуальное месторождение» в объективных условиях роста себестоимости добычи углеводородов на месторождениях с трудноизвлекаемыми запасами.

Предлагается сформировать список специалистов, необходимых в современной нефтегазовой отрасли. Отмечено, что наиболее востребованными являются компетенции, которые могут быть применимы в любой отрасли. Для успешного решения задач, связанных с «интеллектуальными месторождениями», необходимо объединение усилий специалистов разного профиля, а именно: геологов, геофизиков, разработчиков, буровиков, программистов, а также работающих в сфере экономико-математического моделирования, создания систем автоматизированного управления и принятия решений.

Ключевые слова: *интеллектуальное месторождение, информационное обеспечение, математическое и программное обеспечение, организационное обеспечение, принятие решений*

"İNTELLEKTUAL YATAQ" TEXNOLOGİYALARININ MÜASİR VƏZİYYƏTİ VƏ İNKİŞAF PERSPEKTİVLƏRİ

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Xülasə. Təqdim olunmuş məqalədə "intellektual yataq" konsepsiyasının elmi əsaslarının yaradılması probleminin müasir vəziyyətinin icmalı verilir. Qeyd olunur ki, həmin konsepsiyaya əsasən məsələlərin həllinin həyata keçirilməsi dörd mərhələdə aparılır. Qeyd olunmuş sistemin işi müxtəlif şirkətlərin fəaliyyəti timsalında göstərilir. "İntellektual yataq" sistemi tərkibinə təminat nöqteyunəzərindən altsistem kimi üç sistem daxil olur: informasiya təminatı, riyazi və proqram təminatı, təşkilati təminat. Əldə edilmiş informasiya operativ surətdə düzgün idarəedici qərarların qəbulu üçün imkan yaradır, geoloji-texniki tədbirlərin seçilməsi, eləcədə avadanlığın təmir-profilaktik xidməti yollarının planlaşdırılması və tətbiqini təmin edir. Burada əsas yeri qərarların qəbulu tutur. Qeyd olunur ki, adətən qərarlar qeyri müəyyənlik şəraitində qəbul olunur. Bu baxımdan sistemin qurulması zamanı adətən müxtəlif xüsusiyyətlərə malik olan qeyri müəyyənliklərin araşdırılması tövsiyyə olunur.

İcmal nəticəsində, çətinliklə çıxarıla bilən ehtiyat yataqlarında karbohidrogen hasilatının maya dəyərinin artmasının obyektiv şəraitində "intellektual yataq" sisteminin təşkili və tətbiqi zamanı neft-qazçıxarma müəssisələrinin idarə olunması prosesinin xüsusiyyətlərinin əsaslandırılmasına yönəldilmiş kompleks tədqiqatlarının aparılmasının zəruriliyi göstərilir, bununla əlaqədar müvafiq tədbirlər qeyd olunur. Belə ki, məqalədə müasir neft-qaz sahəsi üçün zəruri olan mütəxəssislərin siyahisinin tərtib edilməsi təklif olunur. Qeyd olunur ki, ən çox tələb olunan mütəxəssislər istənilən sahədə işləmək bacarığına malik mütəxəssislərdir. "İntellektual yataq" konsepsiyası ilə əlaqədar məsələlərin müvəffəqiyyətlə həlli üçün müxtəlif ixtisaslı mütəxəssislərin qüvvələrinin birləşməsi ilə işçi kollektiv təşkil olunmalıdır, belə ki, bura aşağıdakı ixtisaslara malik mütəxəssislərin daxil olması nəzərdə tutulmalıdır: geoloqlar, geofiziklər, qazmaçılar, işlənmə üzrə mütəxəssislər, proqramlaşdırıcılar, riyazi-iqtisadi modelləşdirilmə, avtomatlaşdırılmış idarəetmə sistemləri və qərarların qəbulu üzrə mütəxəssislər.

Açar sözlər: *intellektual yataq, informasiya təminatı, riyazi və proqram təminatı, təşkilati təminat, qərar qəbulu*

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