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Age moving of layers: facts and geological consequences (to the 150th anniversary of N.A. Golovkinsky's fundamental work)

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Abstract. The fundamental facial law, determining the relationship between facies of sedimentary rocks in the sedimentary basin in lateral and vertical extensions, was formulated by the Russian geologist N.A. Golovkinsky a century and a half ago. Theoretical statements and views proposed by Golovkinsky have not lost their importance and relevance nowadays. In the article considered an important aspect of diachroneity (heterochroneity) of layer associations and their litho- and biostratigraphic boundaries. The methodological approach of measuring its degree (the window of age moving) is proposed. Golovkinskiy's conceptions are developing fruitfully within the framework of Seismostratigraphy and Sequence Stratigraphy, and their main content remains in demand in the light of new realities of cognitive process (nonlinear science, NBICS convergence, endovision).

Keywords: Golovkinsky's law, facies, sedimentation, diachronism, cognitive process

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The background

A century and a half ago, an event took place, the great importance of which the geological community of Russia understood and realized much later. On December 20, 1868, Nikolai Alekseevich Golovkinsky (1834-1897), Privatdocent and Head of the Geological Cabinet and the Department of Geognosy (Geology) and Paleontology of the Imperial Kazan University, defended and published his doctoral dissertation on the Permian formation in the central part of the Kama-Volga basin "(Golovkinsky, 1868). In this work, for the first time in Russian geology, the concept of "facies" was used for practical and theoretical purposes, which was previously introduced into geological science by Swiss geologist A. Gressly (Amanz Gressly, 1814-1865). In the late 1830s Gressly found that even age sediments have paleontological and lithological heterogeneity when tracing them laterally, and he suggested calling the different parts of the same age layers "facies" (Shatsky, 1986; Cross, Homewood, 1997). N.A. Golovkinsky, who applied one of the first among Russian geologists "facies theory and methodology", took the next, really significant step. It consisted in establishing a "reverse" rule, which states that the boundaries of the lithologically and paleontologically similar layers, when traced along the lateral lines, regularly "slide" in time.

Assessing the age slip of biostratigraphic boundaries, he wrote: "... with each new study, new facts are discovered that reveal the incorrectness of the doctrine of the simultaneous existence and simultaneous disappearance of widespread faunas. The concept of a slow change in the organic population and facies gradually developed and now hardly any geologist..., will reject for different areas the different time of existence of similar forms and the simultaneity of different ones" (Golovkinsky, 1868, p. 152). . Thus, Golovkinsky substantiated the primary asynchrony of any biostratigraphic boundaries. At the same time, the age-related moving of the boundaries was associated not only with the facial differentiation of same-aged layers, but also with the paleobiogeographic features of the faunas.

N.A. Golovkinsky clearly realized that this was in contradiction and hard confrontation with the well-established "ordinary" views on the process of sedimentation. Having formulated the thesis: "the common belief in the sequence of formation of successive layers *is not true*" (Golovkinsky, 1868, p. 125; italics of the author), he also made a reservation that this term is "apparently paradoxical" (ibid.).

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Russian researchers, Golovkinsky's contemporaries, did not understand and did not accept this revolutionary idea. As a result, the fundamental facies law, which is directly derived from N.A. Golovkinsky's work, was formulated by A.A. Inostrantsev four years later for a different sedimentation mechanism (Inostrantsev, 1872). In the world literature, it is known under the name of J. Walther's law, after the name of German geologist (Johannes Walther, 1860-1937) "re-discovered" and outlined it in his capital report (Walther, 1893-1894). The analogy is with the scientific achievements of the outstanding Russian neurologist and psychiatrist V.M. Bekhterev, who occupied in the years 1885-1893 department of Psychiatry, Kazan University, and delivered at the solemn annual meeting in 1888, the act speech "Consciousness and its boundaries", in which he, long before the founder of psychoanalysis Z. Freud, introduced the concept of the unconscious. The most concise and comprehensive modern wording of fundamental facial law is as follows: "Facial varieties of sedimentary rock from any basin of sedimentation are changed along the stratigraphic vertical in the same order as horizontally" (Sharapov, 1989, p. 97).

In the post-war Soviet period, attention was drawn to the "forgotten" Golovkinsky's law, and it became known in the late 1940s thanks to the articles of G.I. Socratov, associate professor of the Leningrad Mining Institute (Socratov, 1949; Vassoevich, 1949).

To date, a large number of papers of various sizes and contents have been published, in which the history, the essence and significance of fundamental facies law are considered, and among which we especially note the researches of outstanding Russian sedimentologist S.I. Romanovsky (Romanovsky, 1979, 1985, etc.). Some of the publications, concerning the facies law are written by authors of the present article, for example (V.P. Alekseev, 2013; Alekseev, Amon, 2017; Zorina, 2018, etc.).

Avoiding repetition of the main conclusions set forth in the publications of S.I. Romanovsky and other researchers, we highlight here some relevant aspects and patterns that follow from the ideas of N.A. Golovkinsky. We are talking about the diachroneity (or, more generally, heterochroneity) of layered formations and litho- and biostratigraphic boundaries, and the methodological possibility of measuring its (diachroneity) degree, which can be conventionally and very approximately called as the "age-moving window". This is seen in terms of the "prism of time", encompassing both the past and the future.

Age-moving boundaries

The issues of identifying and recognizing the facts of heterochroneity of the layers boundaries and the asynchrony of correlated geological bodies and events, measured by any of the methods used in stratigraphic practice (morpholithic, bio-, climatic, magnetic, seismic, radiochronic, etc.), are one of the most "inconvenient" and "undesirable" for discussion in the Stratigraphy and Physical geology (Alekseev, Amon, 2008, 2017). The situation is quite similar with reluctant recognition of the significant role of stratigraphic gaps in the reconstruction of the history of sedimentogenesis in sedimentary basins (Baraboshkin et al., 2002; Amon, Alekseev, 2012; Alekseev, Amon, 2017). This is largely due to the dominance in the minds of specialists of linear paradigms, and, in particular, with the belief in the infallibility of the so-called "onion" model of the concentric-layered structure of the Earth of A.G. Werner (Abraham Gottlob Werner, 1749-1817), who captured the minds of geologists for centuries. As S.V. Meyen noted: "The same age of fragmented areas of one layer should have been taken ... as a matter of course" (Meyen, 1989, p. 140). V.N. Vereshchagin wrote about the formation: "The formation should be characterized by the unity of the time of accumulation, and, thus, the lower and upper boundaries of the formation (in its full extent) should be isochronous. Only a slight difference in the age of the basal layers of formations is allowed" (Vereshchagin, 1980). Such a linear sweep in the 2D metric in its most general form is a consequence of the Stenon principle (Niels Stensen, 1638-1686), according to which in a space filled with a rock, the gradient and time vector at any point are directed oppositely to gravity, and isochronous surfaces are horizontal planes (Gomankov, 2007).

It is noteworthy that in the editions of the USSR-Russia Stratigraphic Code (1977, 1992, 2006 editions) there was no place for gaps, diachronism and cyclicity, just as in the review setting out the achievements and main problems associated with improving the General Stratigraphic Scale (GSS) of Russia (Zhamoida, 2013). Only in supplements to the code, the Appendix 11 "Stratigraphic Gaps" (Supplements to the Stratigraphic Code ..., 2000, pp. 51-54) appeared, in general having the formal and impersonal character. The theme of the diachroneity of strata was practically not reflected in the thematic collection of articles with the promising title "Stratigraphy at the Beginning of the XXI Century – Trends and New Ideas" (2013). Only in the article of A.Yu. Gladenkov in this proceedings briefly labeled "The problem of the diachroneity of the boundaries of biostratigraphic zones", for the solution of which it was rightly suggested: "In specific situations, you must be guided by common sense ..." (Gladenkov, 2013, p. 46).

In translated into Russian the International Stratigraphic Guide, which in our literature was sometimes called the "Code" or " Handbook", the theme of "diachroneity" was related very carefully – for example, it is present in the semi-recognition that biofacies "can be diachronic" (International Stratigraphic Guide..., 2002, p. 24), or in the statement that "the boundaries of subunits limited by unconformities are always diachronic, to a greater or lesser extent, and therefore never correspond to the boundaries of chronostratigraphic units" (ibid., p. 36).

Meanwhile, in modern stratigraphy, diachroneity (diachronism, diachrony) of layers is understood as a widespread phenomenon, equally inherent in the lithosphere and the paleobiosphere (Alekseev, Amon, 2008, 2017; Amon, Alekseev, 2012, etc.). This state is confirmed by numerous examples described in the new paleontological and stratigraphic literature. Famous stratigrapher F.M. Gradstein in the chapter "Biochronology" of the fundamental work "The Geologic Time Scale 2012" specially noted that "significant diachrony is observed for bioevents, e.g., by plotting them against magnetochrons or isotope spikes in two or more sections" (Gradstein et al., 2012, p. 44). V.S. Tsyganko (2007) supposed that the diachronism of boundaries can be considered as a universal property of formations, series, and other stratigraphic units, and proposed to single out a special type of moving boundaries – parastratigraphic boundaries. S.O. Zorina gave examples of typical diachrony of litho- and biostratigraphic units of the Middle Jurassic, Lower Cretaceous and Paleocene in the Volga region (Zorina, 2006).

According to A.Yu. Guzhikov, asynchrony of paleontologically justified boundaries, which were considered as same-aged, were repeatedly observed in distant sections using independent methods, while the time shift could reach 10 million years (Guzhikov, 2013, 2016; Guzhikov, Baraboshkin, 2006). A.S. Alekseev noted that because of the "obvious diachrony of the borders chosen on a palaeontological basis, the priority was given to physical markers – paleomagnetic, chemostratigraphic, and other events, which are considered to be isochronous" (Alekseev A.S., 2013, p. 10). A direct recommendation on improving the subregional stratigraphic scheme is proposed – that it is necessary to monitor the diachronism of the boundaries of the mapped units and the duration of stratigraphic gaps (Pervushov et al., 2013). The correct consideration was expressed that the bathymetric differentiation forms the litho- and biofacial heterogeneity of sediments, their spatial migration with changes in sea level, and creates a diachronic units a priori, in full accordance with the "moving" of their boundaries according to N.A. Golovkinsky (Sukhov et al., 2013).

The North American Stratigraphic Code not only introduces, explains, and codifies the concepts of "Diachroneity", " Diachronous Categories", but also regulates the basic operations with diachronic units (North American Stratigraphic Code ..., 2005, Articles 64, 91-94).

Currently, the fundamental facies law and the conclusions of N.A. Golovkinsky concerning the moving boundaries of the layer associations acquired a special meaning and significance due to the introduction and widespread use of the International Geological Time Scale (GTS2012) in everyday geological practice (Gradstein et al., 2012; Ogg et al., 2016). When designing GTS2012, the new and newest, sometimes debated, theoretical achievements in stratigraphy were used; in particular, an event-based approach (event stratigraphy, biological, fossil, climatic, magnetic, geochemical and other events) is widely used, and the term "stage" is given an unambiguous chronostratigraphic meaning. The lower boundaries of the Phanerozoic stages , Proterozoic systems, and the Archean erathems are characterized by specific dates of astronomical (absolute) age (a – Ka – Ma – Ga). Most of the Phanerozoic stage boundaries are labeled with the GSSP-standard points (GSSP – Global boundary Stratotype Section and Point).

There is a strict accounting registry of GSSP, their stratigraphic and geographical coordinates; they received the very popular metaphorical name of "golden spikes" (Alekseev, Amon, 2017; Gradstein et al., 2012; Zorina, 2015). The dual essence of the standard manifests itself: on the one hand, this is a rock sequence, and on the other, a point in it, and it is believed that "golden spikes" are traced in sedimentary basins by means of a principal correlative event (Gradstein et al., 2012) .

Many stratigraphers understand and accept the nature and principles of the GTS2012 scale too literally and straightforwardly, quite in the spirit of the traditional "onion-like model" linear paradigm. But such a perception of it contradicts the Golovkinsky's law, which contains a warning that the boundaries of litho- and biostratigraphic units undergo an age-related moving to a greater or lesser degree. For example, taking into account that the rates of spatial distribution of fossil organisms were not instantaneous, we have to admit that the more farther from the GSSP the point of the first appearance of any index-species (FAD – first appearance datum) is found, the more this FAD point will be declined from the virtual isochron level (Zorina, 2006, 2015).

It is well known and does not require additional substantiation that different faunistic groups in different geological epochs inhabited marine and continental sedimentary basins and disappeared from them at different speeds, therefore the boundaries, based on traced biological events are diachronic in varying degrees. At the same time, the sequences of biozones that form the basis for most local and provincial zonal scales can be correctly used for age correlation only within a limited area (sedimentary basin or part of it), but not for global correlations. This means that tracing the stage boundaries on a global scale based on the biostratigraphic approach is difficult, since the relatively slow change of one bio-event to another is mainly used (Zorina, 2006, 2015).

This difficulty can be overcome by applying the method of searching and identification in sections the traces of high-speed events or phenomena (Zorina, 2006). Comparing, for example, sequences of magnetic inversions with sequences of much slower events, such as biological events, it is possible not only to show the "slowness" of biological events, but also to determine the "age moving window" of the boundaries of individual biozones and formations.

While providing the comparison, the event of the "greatest stratigraphic weight" (Meyen, 1981, 1989) should be selected, in other words, the fastest events should be chosen (Zorina, 2006, 2015).

Such a comparison was made for magnetostratigraphic and ammonite scales of the sections of the Aptian deposits (Lower Cretaceous) of the eastern Russian Platform and the Western Mediterranean (Guzhikov, Baraboshkin, 2006). The key to answering the question of which of the ammonite zones identified in both areas is the most diachronic and to what is the extent of the diachroneity was the identification of the magnetic chron M0. It turned out that, in accordance with the different position of this chron in the ammonite scales of the regions under consideration, the diachroneity of the ammonite deshayesi zone in the east of the Russian Platform reaches ~ 6 million years.

A significant age-related moving of the lower boundary of the Lower Cretaceous Albian Khanty-Mansiysk Formation was revealed by foraminifera in the West Siberian sedimentary megabasin. Here, the inner sea was ingressed during the Albian with low speeds, and the "moving window" between observation points in the stratotype locality in the Khanty-Mansiysk area and the Southern Urals area is ~ 8 million years (Amon, 2005).

The noticeable diachroneity of the lower boundaries of several formations was recognized in the Paleogene

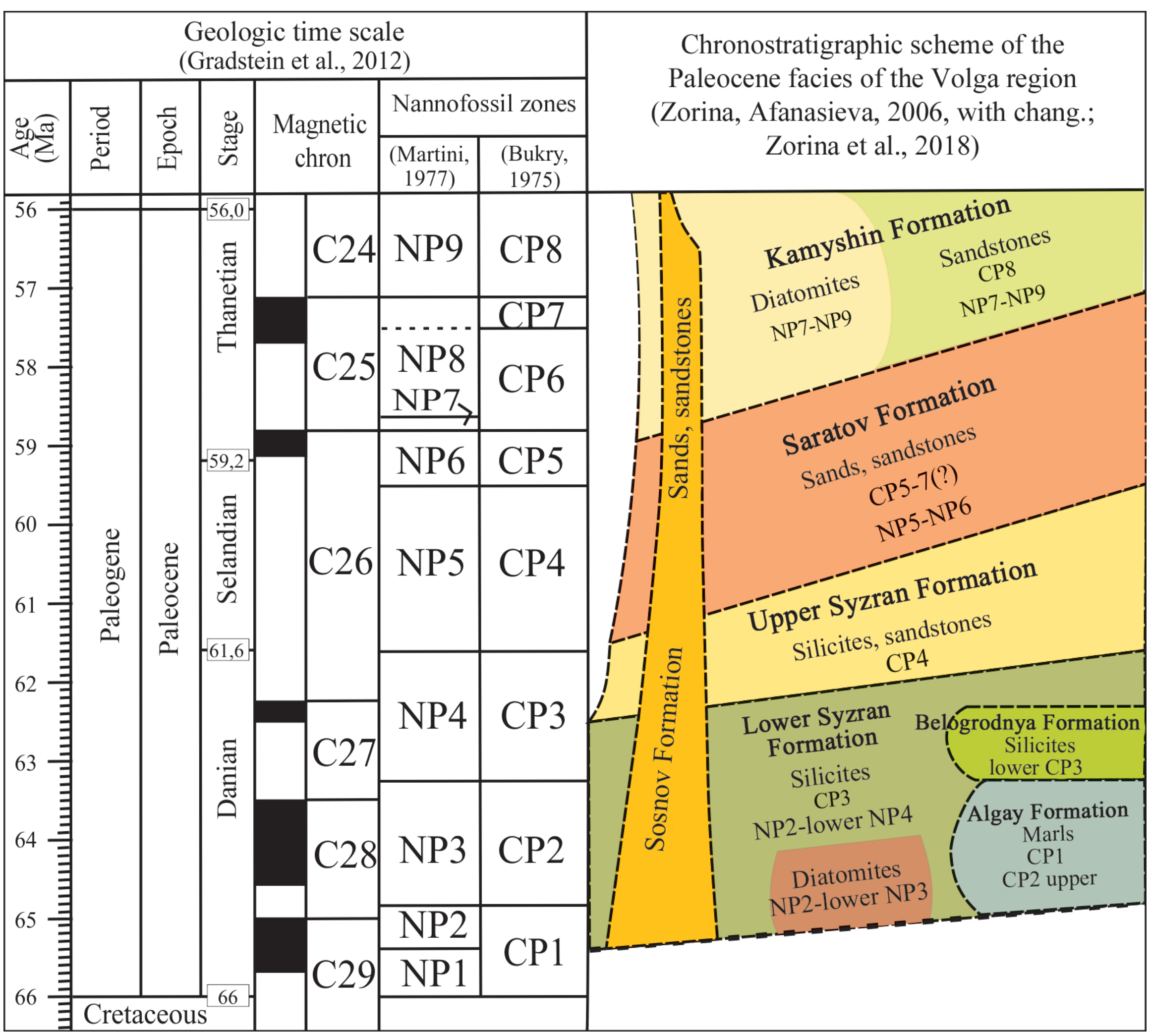

Fig. 1. The diachroneity of the Paleogene strata of the Volga region (Zorina, Afanasieva, 2006, with additions and changes)

sandy-clay-siliceous stratum of the Volga region (Zorina, 2006; Zorina, Afanasieva, 2006; Zorina et al., 2018) (Fig. 1).

Comparison of high-speed bio-events (nannofossil zones) with more short-term litho-events (the formation of lower boundaries of flithostratigraphic units) allowed to state that the end of the accumulation of the base of the Upper Syzran Formation and the beginning of the accumulation of the base of the Saratov Formation coincide with the beginning of the NP5 nannofossil zone from the Martini scale (Martini, 1977) or CP4 zone from the Bukry scale (Bukry, 1975). In other words, the virtual isochronous line drawn on the base of the NP5 zone crosses the entire Upper Syzran Formation from the base to its superface. The "moving window" of the lower and upper boundaries of the Upper Syzran Formation, measured according to the dates in GTS2012 (Gradstein et al., 2012), is 2.1 million years (Fig. 1).

It was also proposed to fix the diachroneity and moving of some levels by metric position of points in sections, measured in meters from the important marker: for example, the level of disappearance of *Samlandia mayii dinocyst* in the Gremyachinsky section in the south-west of the Volgograd area of Lower Volga region, which marks the lower boundary of the Maastrichtian at the base of foraminifera zone LC19, is diachronic relatively ammonite zonation. In the Tersis (Tercis les Bains) section in the south-west of France, which is the GSSP for the lower Maastrichtian, *S. mayii* disappears in 6 meters above the foot of Maastrichtian, and in the Danish basin in 12 meters above this boundary (Benyamovskiy et al., 2013).

We emphasize once again that Golovkinsky's statement about the asynchrony of the litho-and biostratigraphic boundaries allows to apply a methodical technique that reveals and describes the diachroneity of the boundaries and calculates the "moving window". Additionally, we note that the physical nature of high-speed events, as well as isochronous levels, is different, and we can discuss the limits of their resolution and what is more accurate. These may be, for example, equally applicable:

(a) units of geomagnetic polarity scales due to the short duration (<10^4 years) of geomagnetic inversions (Guzhikov, 2016);

(b) isotope chronometry (Zorina, 2015);

(c) nannofossil zones, for example nannofossil zones in the Paleogene of the Volga region (Zorina, 2006; Zorina, Afanasieva, 2006; Zorina et al., 2018), or marine diatom zones in the Cenozoic of the Pacific region (Gladenkov, 2013);

(d) biological events on dinocysts, as in the Maastrichtian of the Lower Volga region (Benyamovskiy et al., 2013); (e) tempestites, talidites, and black shale episodes in a wide range of regions, systems, and stages (Zorina, 2006, 2013; Dronov, 2013, etc.).

A recommendation was made when discussing the problem of the boundaries of bio-horizons that: "despite the potential diachroneity, [the boundaries of the bio-horizons] should be regarded as presumptively isochronous" (Gulyaev, Rogov, 2016, p. 57). We believe that the "presumption of isochronism" of the boundaries is valid until the moment when their diachroneity is proven and shown by any of the stratigraphic methods, including those mentioned above.

Seismic and Cyclic Stratigraphy

The statement of the age-moving of the boundaries of the layers and groups of layer implies the practical need to take into account the diachroneity in two aspects:

(a) identifying and fixing the most high-speed event with the minimal "moving window" and tracing it in the largest number of sections;

(b) the selection of the moment of "fracture" in the change of sedimentation regimes with tracking it laterally.

The first aspect fruitfully develops within the framework of seismic stratigraphy and is based on the isolation and tracing of the unconformities. Undoubtedly, they are very fast, and, in geological terms, almost "instantaneous" events, if we consider one or another sequence of "top down", that is, from younger sediments to more ancient. It should not be overlooked, as is often done, that the surface of the slice (unconformity) is always diachronic, and the "depth" of the gap can be from minimum to as many as you like.

The second aspect is reflected in the Golovkinsky's schemes, who in his work actually stopped "half a step" from establishing the principle of cyclicity in lithology. Moreover, according to S.I. Romanovsky, the "geological lentil" of N.A. Golovkinsky is the model of migration type cycle (Romanovsky, 1985). The figurative name "lentil" was used by N.A. Golovkinsky to characterize the sequence of layers that have a distinctly flattened shape along the periphery and are similar to the "lentil covering the core" (Golovkinsky, 1868, p. 119). Note that the missing "half-step" was made by Yu.A. Zhemchuzhnikov in the report at the Geological Coal Meeting held in April 1944. He expressed a capacious slogan: "A geologist should think of in cycles" (Zhemchuzhnikov, 1947). At the same time, an extremely important position was formulated, which, unfortunately, is not often taken into account when studying sedimentary strata: "Cyclicity without thorough facies analysis is only a formal, mechanical method. Analysis of facies without cyclicity – like embroidery without canvas – is devoid of a guide rod. Only a combination of these two principles makes the efforts fruitful and leads to the development of each"

(Zhemchuzhnikov, 1947, p.16).

These two aspects illustrate two fundamentally different approaches to identifying sedimentary sequences. The first approach, adopted and developed in seismic stratigraphy, is based, as has been said, on identifying and tracing unconformities in monotonous sequences (Seismic stratigraphy ..., 1982; Supplements to the Stratigraphic code of Russia..., 2000), between the sequences of several orders. The smallest of them – parasequences – have a thickness of several to the first tens of meters and are usually identified from the geophysical well survey data. The two leading types have an asymmetrical structure and are depicted in the form of isosceles triangles, directed by the tip of the vertex in the direction of decreasing the size of particles (in terrigenous strata). They are interpreted as retrogradation (reduction of the size of particles up the section) and progradation (increase in such), corresponding to hemicycles (half cycles) or several cycles (Botvinkina, Alekseev, 1991).

Competent synthesis of seismic, geological, and lithological data can give a lot for theoretical and practical stratigraphy. For example, careful analysis and correlation of data obtained from seismic profiling by reflected waves and deepwater drilling in the Northwest Plate of the Pacific Ocean allowed a deeper understanding of the structure and features of the formation of the sedimentary cover of this region. A warning was issued to "classical" stratigraphers, who, adhering to outdated schemes, often perceived the history of marginal zones of the oceans in the past too straightforwardly; in particular, they did not take into account the lateral diachroneity and rejuvenation of the deposits, accretionary prisms were considered as evidence of the subduction of oceanic sediments, relatively shallow deposits of many areas of the oceans were regarded as deepwater, etc. (Patrikeev, 2013).

The second approach corresponds to the drawing of "lentils" of N.A. Golovkinsky, in which, speaking figuratively, "proelements of the geometry of sequences" are laid (Nurgalieva, 2016). This approach is focused on the identifying of a turning point (from transgression to regression) fixed by the maximum flooding surface (mfs). In recent decades, it has been intensively used in foreign studies in the framework of genetic stratigraphy, focusing on the identifying boundaries with the highest possible isochronism (Biju-Duval, 2012; Posamentier, Allen, 2014).

Figure 2 shows the correlation of the Lower Cretaceous (Middle Aptian) sediments of the Vikulovskaya Formation at the Kamenny field of the Krasnoleninsk oil and gas bearing area in Western Siberia (Composition, structure and conditions of formation ..., 2011). The near to "plane-parallel" structure of the sequence, established by tracing the intervals of relatively fine-grained rocks (green color), is distinctly revealed. The thickness of sandy reservoirs VK_{1-4} (beige color) is characterized by variations in thickness in the range of 5-15%, which can be caused both by changes in facies composition and differences in post-sedimentary compaction. The information on the structure of the reservoir VK_2 is of the most interest. At relatively small distances (between wells about 2 km), the prograde cyclite in well 160 changes to retrograde ones in well 162, undergoing a distinct inversion of its structure in well column 161, which indicates a greater legitimacy for identifying cycles when the transgressive phase of the development of facies changes to regressive.

We note in passing that much earlier than for genetic stratigraphy, this was introduced into the facial-cyclical analysis developed by Yu.A. Zhemchuzhnikov, L.N. Botvinkina, and others in the 1950s for terrigenous deposits of the Donetsk coal basin. The basic provisions are described in a number of publications (Botvinkina, Alekseev, 1991; Alekseev, Amon, 2017), which shows the importance of the cyclostratigraphic method for studying a wide variety of sediments, including coal-free strata and oil and gas basins.

Prospects for further research

S.I. Romanovsky, analyzing the creative heritage of N.A. Golovkinsky, noted the subtle and precise aspect that is important for any geological work containing elements of scientific and methodological novelty: "The results of scientific research, no matter how significant they are, inevitably recede before new achievements of regional geology. ... Therefore, it is the creators of theoretical ideas that are forever included in the history of science, but the abundant works on regional geology created by almost every geologist, completely lose their significance over time" (Romanovsky, 1979, p. 6). Indeed, for the knowledge of the Permian deposits of the Kama-Volga basin, the N.A. Golovkinsky`s studies now represent only archival and historical interest. Fundamentally different is the case with the theoretical constructions carried out in his work. Important issues raised a century and a half ago have not lost its relevance, and continue to retain its methodological value, as evidenced by many developments of the 21st century (Berto, 2002; Zorina, 2006, 2015; Krinari, 2010; Lebedev, 2015 and others). Similar issues will excite the minds of researchers in the future, but without being able to predict all possible directions, we'll dwell on two possible vectors for the development of ideas associated with the name of N.A. Golovkinsky.

The first vector refers to the phenomenon of

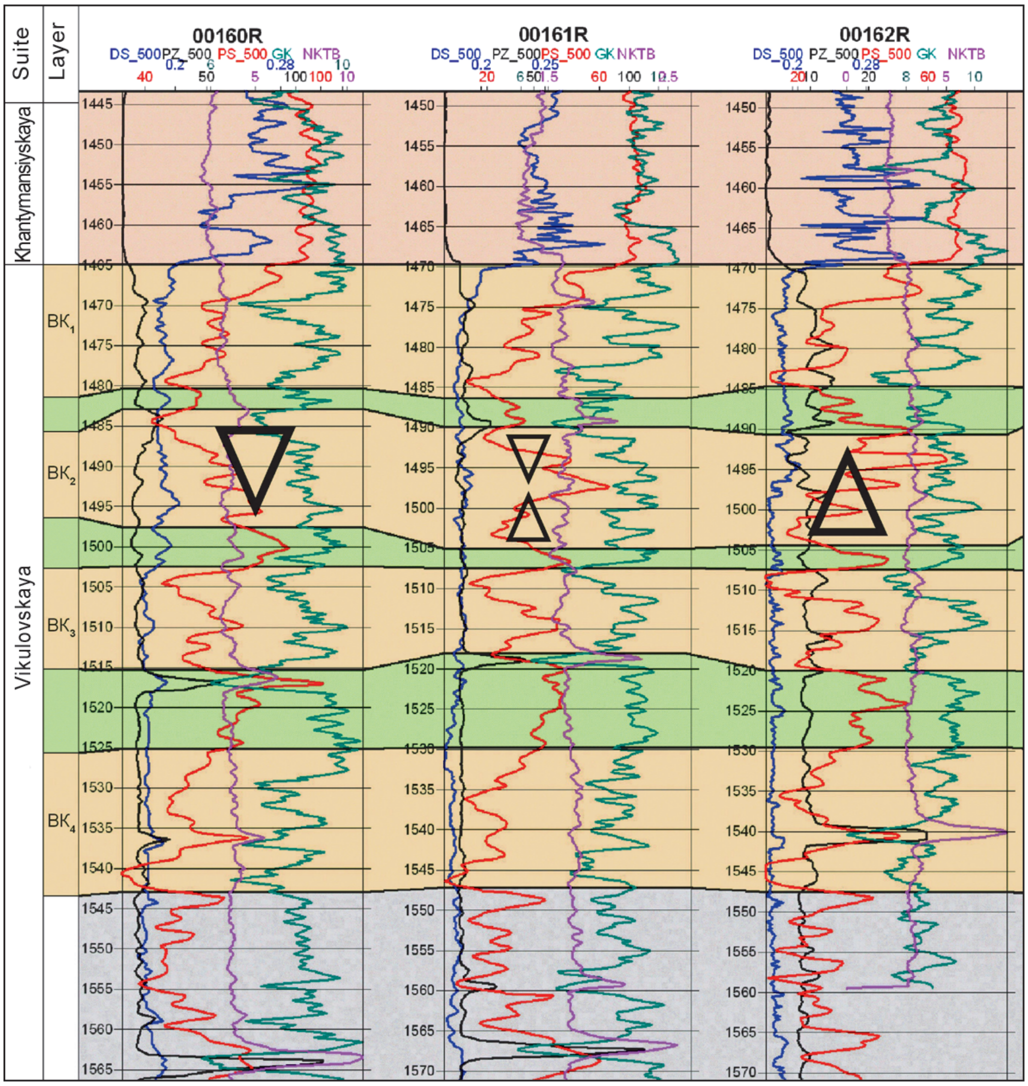

Fig. 2. Well log correlation in the Kamenny field of the Krasnoleninsk oil and gas region, Western Siberia (Composition, structure and conditions of formation ..., 2011). For the reservoir VK_2, the triangular symbols show the direction of the change in the particle size distribution (the top of the triangle indicates a decrease in the particle size)

the jaggedness of the layer boundaries, which was characterized as follows: "... coastal sediments constantly change the area of their distribution, then pulling into the open sea, then retreating to the coast. This causes uneven serration of the layer; these "teeth" are extremely sharp and elongated, are in the form of thin layers, alternating with the rock of the adjacent layer ..." (Golovkinsky, 1868, p. 126). It also indicates that this jaggedness is due to the rapid displacement of environments during sedimentation in conditions of a small slope of the seabed surface, not exceeding a few angular minutes.

In the development of these ideas, a scheme has been proposed (Alekseev V.P., 2013), reflecting the general structure of the interrelationships of the main parameters controlling the morphostructure of layered units (Fig. 3).

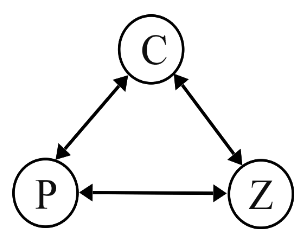

Fig. 3. Interrelations of the main parameters controlling the morphostructure of layered units (Alekseev V.P., 2013). C – moving of layers, interlayers, reservoirs; P – stratigraphic gaps of various durations; Z – lateral jagged borders

Herewith, issues related to the manifestations of gaps and diachroneity of the layer units are an object of independent study with their own history and achievements, however, the phenomenon of the jaggedness of the layer boundaries has not been studied much so far. The latter is especially applicable to deep-seated strata, where direct tracing of "thin interlayers" is impossible, due to insufficient resolution of remote sensing methods (seismic profiling), or with large distances between wells.

At the same time, the situation is changing literally "before our eyes" due to the intensive introduction of horizontal drilling into practice. The resulting materials bring invaluable material specifically for lateral tracking of changes or "intermittency" in the composition of "thin layers". In turn, this inevitably leads to a rational assessment of the orientation of production wells, which gives a significant technological effect.

The second vector is associated with the change of the general scientific paradigm that occured with the advent of the new Millennium. The transition to non-linear views embraces in all spheres of natural science and humanities, and is particularly evident in the wide development of interdisciplinary and transdisciplinary researches. One of the ways to consider them is the NBICS-convergence – the modern direction of basic science, which assesses the most diverse areas of knowledge at the nanoscale level. Earth sciences are still "on the sidelines" of these studies, but the use of such basic concepts typical of non-linear science as the fundamental facies law allows us to hope for a "breakthrough" in their inclusion in the general trend (Alekseev, Amon, 2017). Some idea of the great opportunities opening up to lithology is provided by the information in Table 1.

In particular, a wide spectrum of manifestation of the main facies law – from the displacement of thin layers in a fraction of millimeters to the moving of the Neocomian clinoforms of West Siberia – can impose a "bridge" from identifying, considering, and accounting for "nano-, micro" objects in geology, physics, biology, programming etc. to understand the patterns of existence and functioning of the complex "mega-, macro" structures. This is rightly said by K. Mainzer: using an approach based on the theory of complex systems is "... an interdisciplinary methodology to explain the occurrence of certain macroscopic phenomena as a result of nonlinear interactions of microscopic elements in complex systems" (Mainzer, 2009, p. 39).

In addition, modern "revolutionary paradigm changes", according to E. Morin, imply the rejection of widespread linear mechanistic determinism and recommend the adoption and use of a complex metaconcept, or endo-exo-causality, which corresponds to endo-exo-organization (Morin, 2005, p. 315). Here, "ordinary", external or exogenous causality should go into comprehension of the unconventional, internal or endogenous essence of the process (Fig. 4).

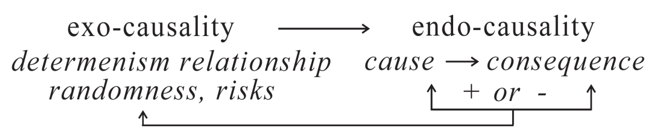

Fig. 4. Complex metaconcept diagram (according to (Morin, 2005))

The study of complex causality, which makes it possible to know and predict the characteristics of the existence and functioning of natural objects – in lithology from the finest layers to sedimentary megabasins – unfolds in an infinite combinatorial dialectic. And, thanks to the ongoing process of improving research

Discipline	System (example)	Elements in the system NBICS	Dynamics	Rank parameter
Quantum physics	Laser	Atoms	Quantum	Formation of quantum structure (for example, optic waves)
Biology	Genetic	Genes	Genetic reaction	Formation of genetic structure
Computer science	Neural networks	Byte	Computational rules, algorithms	Formation of computational network structure
Psycholgy, medicine	Brain	Neuron	Information dynamics	Pattern recognition
Sociology	Community	Certain individuum, meme	Social interaction	Formation of social structure
Geology: by K. Mainzer	Lava	Molecule	Geological dynamics	Formation of structures (for example, segmentation)
Our understandings	Sedimentary basin	Particle, grain	Accumulation of layers	Main facial law

Table 1. Interdisciplinary applications of the theory of nonlinear complex systems (Mainzer, 2009, p. 40-41; with changes and additions)

tools (horizontal and inclined drilling, isotopy and fine geochemical analytics, remote sensing instruments and methods, computer complexes, neural networks, "big data" technologies, etc.), such combinatorics will always be mobile and internally heterogeneous.

E. Morin names 6 possible combinations of reactions of systems generated by complex causality, when the causes interact and intersect, overlapping each other randomly (Morin, 2005, pp. 315-316):

a) the same causes may lead to different and/or divergent effects;

b) different reasons can cause the same consequences;

c) small causes can lead to very large consequences;

d) great causes may lead to very minor consequences;

e) some reasons are followed by opposite effects, when the reason starts a counter-action directed in the opposite direction: heating → cooling, revolution → counter-revolution, etc.;

f) the consequences of the opposing causes are uncertain, i.e. it is not known whether the reverse actions that will prevail will be negative or positive.

Thus, a whole fan of forms of complex causality is born, and paradoxes of causality constantly arise, which cannot be resolved within the framework of the simplistic approach of mechanistic determination (Morin, 2005, p. 16). One of these paradoxes – the diachroneity of the boundaries of the layer associations, which cannot be solved in the mechanics of the Stenon-Werner models – was brilliantly overcome by N.A. Golovkinsky a century and a half ago, using, perhaps intuitively, the methodology we now call "complex causality." But there are not a little similar or analogous paradoxes in geology (from the confrontation of the ideas of «fixism» and «mobilism» to the proof of the existence of clinoforms in continental strata or identifying features of paleolandscapes of wetlands, marches and watts in Aptian Vikulovskaya deposits of West Siberia, etc.) and in the future. Note that the paradoxes of causality and their successful resolution stimulate the development of theoretical geological thought, for example, thanks to them, noncontradictory tectonics of lithospheric plates, event biostratigraphy, sequence stratigraphy, cyclostratigraphy, etc., were developed.

Complex causality is non-linear, it is correlative and cyclical, and, in general, constituting one of the foundations of the cognition program of the "method of nature of nature" (La Méthode. La Nature de la Nature) by E. Morin. It partially corresponds to endophysics or "physics from the inside" by O. Rössler (1998) and introduced into the basic principles of endolithology (Alekseev, Amon, 2017). The main facies law in endolithology is given a worthy place, with a statement of both great practical value and significant predictive capabilities.

Conclusion

In the modern-day turbulent process of knowing nature and the world, it is useful to stop, look back and make a comparison of a range of long-held ideas with today's realities, and sometimes this comparison shows that some of the former have not lost their relevance. Exactly one and a half centuries ago, in 1868, an event took place that was insufficiently appreciated by contemporaries, but determined one of the main routes in the development of the theory of sedimentary strata. This significant phenomenon was the defense and publication of a doctoral thesis by the privat-docent of the Imperial Kazan University N.A. Golovkinsky, in which a regular "moving" in time of the borders of the visually homogeneous (both lithologically and paleontologically) layers of sedimentary rocks is established. The unusual and revolutionary nature of this geological idea led to the fact that the facies law (namely: the same order of change of facies types of rocks horizontally and vertically) was "rediscovered" only a quarter of a century later by I. Walther, and in the USSR it became widely known only from the middle of the XX century.

The fundamental facies law or the Golovkinsky-Walther law remains in demand and highly significant in modern geological studies. In accordance with it, the diachronism (heterochronism) is characteristic of many geological events and processes. Specificity is manifested only in the accuracy of methods, tools and methods of research that are capable, or not able, to fix the speed of occurrence of events, the so-called "window of moving". Duration minima taken as "isochrones" are characteristic of episodes of paleomagnethochronometry, isotope chronometry, some short-term bioactivity, as well as the boundaries of complexes of genetically interrelated rocks (cycles, cyclites). In the framework of facies-cyclical analysis, the latter are distinguished by changing the transgressive branch of changing environments of sedimentation to a regressive one, and for genetic stratigraphy – along the surface of maximum flooding. However, the "presumption of isochronism" of the boundaries is valid exactly until the moment when their diachrony is proved and shown by any of the stratigraphic methods.

The relevance of the basic facies law can be extended for future research. On the one hand, this is due to the lack of knowledge of such a common phenomenon as "jaggedness" of layer boundaries, which is especially pronounced when tracing boundaries laterally along the coastline of the receiving reservoir. Here, unlimited prospects are revealed by 3D modeling, which is actively developing in the study of oil and gas objects. On the other hand, the surprising compatibility of the provisions contained in Golovkinsky's work with modern philosophical and methodological views and designs of the 21st century is revealed. So, they easily fit into the concept of NBICS convergence, illustrating the importance of interdisciplinary and transdisciplinary researches; in ideas about endo-exo-causality of events within the framework of a wide manifestation of self-organization, etc. This opens up new horizons in theoretical understanding of the processes of sedimentation, as well as prognostics.

Understanding the mechanisms of complex causality in facies-cyclical analysis allows to clarify and streamline the correlation of complex deposits, which is an intransigently important task in the search and exploration of petroliferous strata. These methodological approaches become even more relevant in the development of hard-to-recover resources (reserves) of hydrocarbons.

In general, the fundamental facies law of N.A. Golovkinsky is a striking visionary phenomenon which is inherent in rare (if not the rarest) fundamental geological discoveries.

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