The Golovkinsky strata formation model, basic facies law and sequence stratigraphy concept: Historical sources and relations

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[1] This paper reviews in the light of modern knowledge some research results obtained by the outstanding Russian geologist, Professor of Kazan Imperial University N. A. Golovkinsky and described in his remarkable work "The Permian Formation of the Central Kama-Volga Basin". In this work he introduced, for the first time in the Russian geological literature, the facies concept and the strata accumulation model that was later rediscovered by other researchers to become the basis for sequence stratigraphy. The fundamentals of the facies law, known in the West as Walther's Law and in Russia as Golovkinsky-Walther's Law, were also described in Golovkinsky's work long before Walther drew his conclusions on this subject. The present paper shows that the fundamentals of sequence stratigraphy were first set forth in the work of N. A. Golovkinsky. *INDEX TERMS:* 1641 Global Change: Sea level change; 3022 Marine Geology and Geophysics: Marine sediments: processes and transport; 8169 Tectonophysics: Sedimentary basin processes; 9335 Geographic Location: Europe; 9615 Information Related to Geologic Time: Permian; *KEYWORDS:* Permian, stratigraphy, sequence stratigraphy, N. A. Golovkinsky, facies, sea level variations, strata accumulation model, basic facies law, history of geology.

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Introduction

[2] Modern principles of stratigraphy are substantially different from those of the 19th century. This difference is largely due to the development of fundamental sciences and technology. However, some key concepts on relationships between sedimentary strata, outlined in the 17th–19th centuries, were reevaluated and experimentally confirmed only in the second half of the 20th century. One of these stratigraphic concepts is the basic facies law, which was fully evaluated only in the middle of the 20th century [*Sloss et al.,* 1949]. In the 1960–1970s, seismic images of sedimentary strata permitted the real geometrical visualisation of the strata accumulation in sedimentary basins [*Vail et al.,* 1977]. Today, sequence stratigraphy is an integral part of stratigraphy [*Miall,* 1997]. Its further progress depends on the acquisition of high resolution seismic images of sedimentary basins of various types and on the field and mathematical simulation of sedimentation and sequence architecture formation [*Einsele,* 2000]. Sequence stratigraphy is based on two concepts: facies variations of sediments within the basin, mainly depending on the basin depth and on the distance to the shore, and eustatic sea level variations. These concepts were introduced in the 19th century: the first by N. A. Golovkinsky in 1868 and the second by Suess in 1885–1890. Although the elements of sequence stratigraphy, such as the definition and the architecture of sequences, were formulated within a certain period of time [*Fraizer,* 1974; *Ross,* 1991; *Sloss,* 1963; *Vail et al.,* 1977; *Wheeler,* 1958], their prototypes were described in earlier works. The review of these works one can find in [*Dott,* 1992].

[3] The present paper shows that the classic work of N. A. Golovkinsky "The Permian Formation of the Central Kama-Volga Basin", published in St. Petersburg in 1868, contains not only the original formulation of the basic facies law but also some key concepts of sequence stratigraphy including geometry elements of sequences.

Some Excerpts from the Work of N. A. Golovkinsky, 1868

[4] In early April 1868, N. A. Golovkinsky submitted the manuscript of his doctoral thesis "The Permian Formation of the Central Kama-Volga Basin" [*Golovkinsky,* 1868] to the

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Department of Physics and Mathematics of Kazan University. This thesis was based on the materials acquired during the expeditions of 1866 and 1867.

[5] In spring 1866, The Imperial Mineralogical Society of St. Petersburg invited N. A. Golovkinsky to take part in detailed geological studies in the territory of Russia. The Mineralogical Society provided N. Golovkinsky with funds to conduct geological observations in summer 1866 with the main focus on the Permian limestone formation in the Kazan and, partially, Vyatka provinces. Golovkinsky surveyed the areas between Elabuga and Chistopol and those between Tetyushi and Sviyazhsk. In summer 1867, the Permian formation was surveyed further to the east, up to the town of Malmyzha. In winter 1867–1868, these observations were generalised to form the aforementioned manuscript. The thesis was defended on 20 December 1868.

[6] This work contains three chapters. The geological phenomena of the Permian basin are considered in the first chapter, main organic remains of the limestone formation in the second one, and the distribution of these remains in the third one [*Golovkinsky,* 1868; page 2[1]].

[7] The first two chapters are dedicated to the regional structure of the Permian formation and the layer-by-layer description of individual sections, folding, rock formation processes, secondary alteration of rocks (dolomitisation, gypsum formation, etc.) and palaeontological characteristics. Fundamental issues of strata formation are considered in the third chapter.

[8] Golovkinsky wrote at the beginning of this chapter: "Let us now try to thoroughly investigate the meaning and causes of the distribution of organic remains in the Permian limestone formation described in the previous chapter" (Page 112).

[9] After analysing the distribution of organic remains, he developed a faunal zoning scheme (Figure 1), in which "a continuous layer of the shallow-water fauna envelops the deep-sea fauna" (Page 120).

[10] It was later found that there was no lower conchiferous bed in this formation. (This stratum was initially identified by several observations near the village of Bogorodskoye but was later found to be the upper conchiferous bed). Nevertheless, Golovkinsky's concept that shallow-water environments are replaced by deep-water ones and then again by shallow-water ones has been proven to be principally true and solid. This proposition states that sedimentation is characterised by cyclicity. Golovkinsky further used this concept to build the first geological sedimentation model for the littoral environment (from this point on, the bold font was created by the authors of the present paper and the italics are according to Golovkinsky's original text). Golovkinsky built his model in the following way [*Golovkinsky,* 1868]:

[11] "Let A (see Figure 1a) represent the rock mass composing the land and gradually plunging below the sea level oo′. The coastal portion co′ accumulates materials delivered from the land, conglomerates, sandstones and clays; the open-sea portion ab contains limestone formed by mollusc shells; the bc portion contains deposited marl, an intermediate rock formed through the mixing of limestone with the littoral drift.

[12] The subsidence of the basin's bottom and of the land should in some time produce new masses of limestone, marl and sandstone at the $o^1o^{1\prime}$ level in a similar position (Figure 1b), but marl, corresponding to bc, is above sandstone co′, and the limestone portion, corresponding to ab, above the marl portion bc and the sandstone portion co′. As the level changed gradually, the rocks did not form any highs, as shown in Figure 1b, but were shaped as continuous layers as shown in Figure 1c that also depicts further stages of the same process. Let us assume that the subsidence of the bottom and the infilling of the basin took place gradually, and that the infilling rate was two thirds of the subsidence rate, as in the preceding figures. In this case, the depth of the left portion of the basin gradually increases to become four times higher at the level $o^3o^{3\prime}$ than at the level oo′. If the subsidence rate is then decreased and the basin infilling rate remains unchanged, the latter will finally be higher than the former will only change by o^3o^4 during the period of time corresponding to that between level positions o^3 and o^2, o^2 and o^1, o^1 and o (Figure 1d), and the mass of coastal rocks transferred to the basin will also remain unchanged. Therefore, without being deposited into the mass of the same thickness as before, it will gradually fill in the coastal shallow-water zone and will extend towards the centre of the basin to e (Figure 1d) to cover limestone... It can be assumed that the coastline will in this process be elevated to h. During a subsequent, slower change of the level to o^5, marl and then sandstone will extend further towards the centre of the basin to f. Because of the continuity of the process, the stratification shall finally assume the shape shown in Figure 1e; (Pages 122–123).

[13] "The previously assumed subsidence and basin infilling rates only affect secondary features of the geological lens (only half of which is currently considered) that is formed by this stratification, thickness of the strata, sharpness of their bends and other parameters, but the overall pattern generally remains unchanged. If the subsidence rate does not decrease and remains unchanged or increases, then only the lower portion of the lens is formed with the strata gently sloping from the coast; if the elevation precedes the subsidence, then the upper and lower parts in the resulting pattern swap places" (Page 124).

[14] "The consequences of this process should be studied in full detail. Let us consider a formation consisting of the overlapping sandstone, marl and limestone strata as shown in Figure 1f. Conventionally, these strata are considered to have been deposited one after another during consecutive periods of time. However, if these strata represent only the lower, non-eroded portion of the geological lens, then this concept can only be valid in the limited area. Figure 1e shows that the lines that pass through simultaneously deposited portions of the formation, i.e. those showing the position of the bottom, intersect all the three strata, and the continuous tracing of any bed from left to right, – for instance, sandstone – brings us to another formation. This can lead to the following, apparently paradoxical, conclusion: the generally accepted concept that successive strata are formed consecutively is not true. The initial consider-

[1]Here and below referred pages are related to the paper of *Golovkinsky,* [1868].

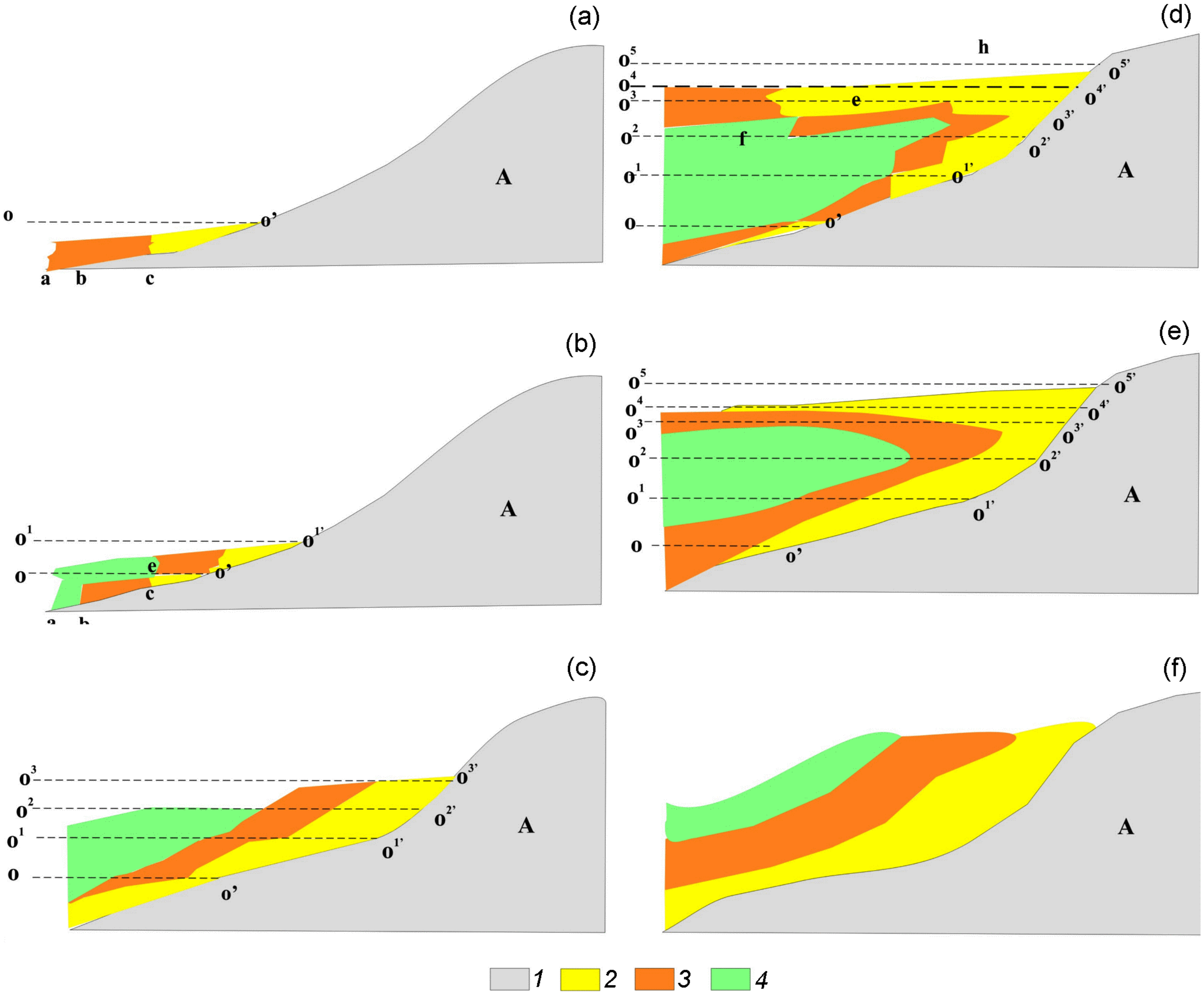

Figure 1. The model of sequence formation by [*Golovkinsky,* 1868] (reducted). 1 – land, 2 – sands, 3 – silts and clays, 4 – carbonates.

ation of this conclusion and of strata belonging to different formations would naturally lead to the following serious objection: if the adjacent strata of sandstone, marl and limestone were formed from gradually deposited sediments, as shown in Figures 1a, 1b, and 1c, then the transition from one stratum to another would have to be gradual because there could of course be no sharp boundaries between the deposition zones of sandstone, marl and limestone (Page 125)."

[15] Golovkinsky points out that the model proposed by him is a substantially simplified one:

[16] "However, it should be remembered that the accuracy and simplicity of the strata shown in Figures 1c and 1e could only be imagined if the process that formed them were ideally simple; it would require that littoral sediments be distributed equidistantly from the coast and that the margin of the sand formation c (Figure 1a) be moved to the right by the same distance as the coastal point of the sea level o' due to its lowering. In reality, such accuracy is impossible: under the influence of rainy and dry seasons with abundant and rapid or shallow and quiet rivers bringing various quantities of suspended or rolling material distributed over large or small areas and under the influence of storms and temporary flows littoral sediments constantly reshape their distribution zone, which extends into the open-sea limestone area during one period and regresses towards the coast during another. These processes make strata unevenly serrate; the dents, very sharp and long, are in the form of thin interlayers that alternate with rocks of the adjacent layer ... (Page 126)."

[17] In this context, Golovkinsky considers correlation of sedimentary formations in the following way: "A distinction should be made between chronological, stratigraphical, petrographical and palaeontological horizons. Generally, a geological horizon is a zone containing those portions of a

formation that are similar in one of the above criteria. For instance, Figure 1c shows sandstone and marl strata that are single petrographical or stratigraphical horizons throughout their extent. However, these are not identical: the stratigraphical horizon of a pinched-out stratum continues further into the zone where its petrographical one does not exist..., so it is a palaeontological horizon that can be not only different from the above one but also not parallel to the petrographical horizon ...

[18] The above relation of a petrographical horizon to a chronological one is also fully applicable to palaeontological horizons. All faunas with a lens-like distribution at various depths within the formation existed at the same time; these represent different facies of a given geological period, which depended on depth and gradually moved due to sea-bottom movements. Figure 1e shows the general trend of their movement. To study this trend in more detail, some additional data should be taken into consideration. The works of Forbes and other researchers demonstrate that the distribution of marine organisms depends, apart from the depth, on many other factors, including the mineral nature of the bottom that will be considered here. Both the deep-sea facies and shallow-water facies are subdivided into sandy, silty, rocky and other facies, each characterized by its specific forms...

[19] ... The study of gradual changes of the forms in time is possible through tracing the faunas' movement." (Pages 127–129).

[20] "... The apparent lack of transitional form in the vertical direction indicates nothing but insufficient attention to the known facts on the distribution of recent marine organisms and on its strong dependence on the complex combination of external conditions. ... If transitional forms really existed in time, these should be horizontally traced within geological formations, along the strike of palaeontological horizons, but not in a perpendicular direction, according to conventional practice." (Page 131).

[21] "If geological parallelism means isochronism, then parallelization (correlation) should be based on facies. As expected, the vertical succession of forms in one country may totally disagree with that in another, which may be puzzling to researchers. And the conventional practice of chronological parallelization suggests that the strata under study should be correlated with other strata of previously studied basins formed at the same time. This can be done in a very simple way: focusing attention on those forms that occur in a desired succession and rejecting the others as insignificant, local exceptions. Moreover, geologists use coincidental occurrences of fossils as a convincing proof of the simultaneous formation of strata." (Page 133).

[22] "... Some formations appeared in different times but within one geological period with the unchanged fauna, and these formations are nothing but facies. There is nothing puzzling in their similar successions, just as in recurring successions of seasons; similarly to the transition from winter to summer through spring, the transition from littoral, sandy deposits to purely marine limestone is implemented through clay and marl and through the deep-sea fauna" (Page 134).

[23] "Numerous books claim that geological science is complete with perfect principles, and one only has to accommodate some new facts in the ready-made framework. Unfortunately, this is the illusion that has nothing to do with the reality.

[24] Formations are usually correlated layer by layer as if this method is simple and perfect as an axiom. However, a closer look at this concept makes it clear that this is not an axiom but a relic of half-poetic, half-ignorant and outdated ideas that the outer portion of the earth consists of continuous, concentric, homogeneous layers. These ideas were amended and published on behalf of d'Orbigny to find numerous supporters due to their clearness and plainness. However, new studies revealed new facts that the concept of the co-existence and simultaneous disappearance of omnipresent faunas is incorrect. The theory of facies and gradual changes of the biotic population steadily progressed, and no geologists, even the most enthusiastic supporters of parallelism, are likely today to discard the existence of the same forms in various times and of different forms at the same time in various localities. Notwithstanding that the above obsolete principle is confronted by the obvious reality, it is largely obeyed through habits and inertia." (Page 135–136).

[25] In the authors' view, these excerpts from Golovkinsky's work most vividly demonstrate his understanding of the facies law and of the infilling of basins with sediments as well as the architecture (geometry) of the strata that are formed in the process. Unfortunately, the authors cannot quote any more fragments of this remarkable paper for space considerations and have to refer readers to the original.

The Modern View of Golovkinsky's Findings

[26] The above excerpts from Golovkinsky's work are truly impressive in terms of his large-scale scientific foresight and versatile analysis of the dynamic development of sedimentary basins.

[27] The most outstanding achievements related to this analysis can be listed as follows.

1. Development of the Terminology

[28] Golovkinsky was the first to introduce the term facies into the Russian scientific literature after its invention by the Swiss geologist A. Gressly in 1838. Golovkinsky first used this term in his earlier work "Post-Tertiary Formations on the Volga River and in its Middle Reaches" after studying Gressly's fundamental work in three volumes while being abroad [*Golovkinsky,* 1865; page 4]: "The idea that various geological processes could take place at the same time in different localities is very simple but the geological concept of facies developed very slowly and still lacks adequate attention in the modern scientific literature." In his doctoral thesis, the Russian version of this term was first used.

[29] In modelling the strata formation, Golovkinsky uses such notions as sea level, coastline, littoral rock mass (sedi-

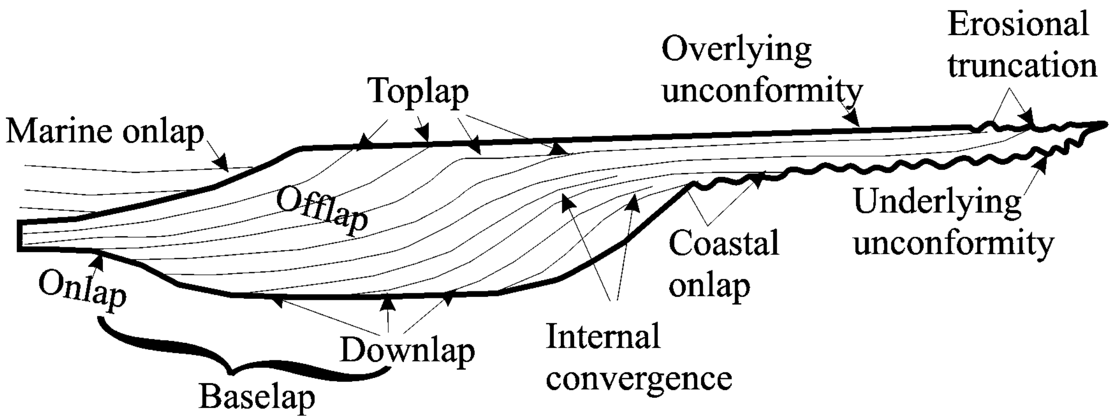

Figure 2. Sequence terminology by [*Vail et al.,* 1977].

mentary material in the modern literature), and sea bottom variations. These notions were developed to become the basic ones in modern sequence stratigraphy and cyclostratigraphy.

[30] Golovkinsky introduced the notions of chronological, stratigraphical, petrographical and palaeontological horizons and studied the relationships between them anticipating the concept of isochrones that intersect, as he indicated, stratigraphical, petrographical and palaeontological boundaries.

2. Development of the Principles of Facies Analysis

[31] Golovkinsky developed Gressly's facies method and indicated different ages of sediments in relation to sea-level changes and coastline movements. He pointed out at the lateral movement of facies, that is now called "progradation", and the cyclic change of facies, which was later supplemented by Johannes Walther with a vertical column and described in 1894 in his famous work "Introduction to Geology" [*Walther,* 1894], as formulated on page 979: "...dass primar sich nur solche Facies und Faciesbezike geologish uberlagern konnen, die in der Gegenwart nebeneinander zu beobachten sind" ("...originally, only those facies could superpose one another that are seen to be adjacent under present conditions"). Walther also introduces a scheme that demonstrated the cyclicity of sedimentation and highlighted the so called positive and negative phases. The concept of facies, formulated by Walther, became internationally known in the geological literature as Walther's Law. Walther was apparently unaware of the work of Golovkinsky, especially in view of the fact that Golovkinsky's theoretical formulas were hidden behind the regional character of his paper's name. And Walther probably did not know about the work of A. A. Inostrantsev, published in 1885, addressing the vertical change in facies and confirming Golovkinsky's model, which showed that the vertical periodicity of facies in a particular point of a sedimentary basin is similar to the lateral periodicity. Thus, Golovkinsky was the first to introduce the basic facies law that should have been named Golovkinsky-Walther Law [*Sokratov,* 1949].

3. Creation of the First Sedimentation Model as a Prototype of the Sequence

[32] Golovkinsky's sedimentation model is in fact one of the sequence formation models, in which he used the concept of sea level, i.e. one of the basic notions in sequence stratigraphy.

[33] The rapid development of sequence stratigraphy was stimulated by achievements in seismic stratigraphy and borehole geophysics. The EXXON team headed by P. Vail found that relative sea-level changes over the Earth's history were the cause of the sedimentation in the zones of interaction between the land and the sea and in shallow and deep-water seas [*Vail et al.,* 1977].

[34] The schematic diagram of the sequence and the terms used in its description are shown by *Vail et al.,* [1977; Figure 2]. This diagram is similar in shape to the "lens" described by Golovkinsky.

[35] The formation of sequences is affected by the following three key factors [*Einsele,* 2000]: tectonics, eustasy and sedimentary material. Interrelations between these factors (their directions, rates, amplitudes and cyclicities) define the relative sea level.

[36] The basic principles of sequence stratigraphy are as follows:

[37] Relative sea-level or basic-level variations affect the sedimentation capacity and the movement of sedimentation centres towards the sea or the land. This leads to the formation of progradational and inverse facies series (system or facies tracts).

[38] The system tract consists of sediments from various sedimentary environments (marine and continental). System tracts can be subdivided into parasequences, each with their own specific characteristics.

[39] The interaction between sea level variations, sedimentary material supply, sediments buildup and various subsidence rates creates a variety of sequences. Their structures are defined by sea level variations of various frequencies and amplitudes and by the varying supply of sedimentary material.

[40] As it appears from Golovkinsky's model, the sedimen-

tation is generally driven by relative sea level rises and the adequate amount of sedimentary material forming progradational sand bodies that occur in a bench-like manner. The landward or seaward migration of the littoral zone was governed by the interaction between sea level variations, sedimentary material supply, isostatic load and tectonic subsidence. If the subsidence rate is low and the amount of sedimentary material is insufficient, even very low rates of the eustatic level recession can reduce the sedimentary capacity and thus shift the littoral zone seawards. In the opposite way, fast sea level rises result in the sweeping flooding of littoral areas and in the landward movement of the coastal zone.

[41] This simple pattern varied substantially depending on the varying entry of sedimentary material. For example, abundant sedimentary material can fully prevent the littoral zone from migrating during the sea level rise.

[42] In the coastal areas, which are abundantly supplied with sand material, coastal sands reflect the relative sea-level fall and the seaward displacement of beach formations and barrier and lagoon complexes.

[43] The abundant supply of sedimentary material with a considerable fraction of sand results in the displacement of the coastline not only during the fall of the sea level but also in its steady state (normal regression). The littoral zone narrows and thickens to form spatially uniform bodies adjoining the erosion surface (regressive time lag) due to the activity of sea waves. If the level rise is fast (i.e. if the rate of eustatic changes is higher than rates of the sedimentary material supply and the basin depression), the coastline rapidly moves landwards.

[44] However, these are only a few of those numerous models that are created today for various conditions.

[45] And it should be emphasised again that the first such model was created by N. A. Golovkinsky.

4. The Fundamental Formulation of Correlation Analysis Problems

[46] Golovkinsky clearly outlined the problem of correlation of deposits or parallelisation as it was called at that time. His comments on the relationship between geological horizons identified by various indications are remarkably thoughtful.

[47] Geological reconstructions are always based on the stratification and correlation. Stratigraphic correlation is the demonstration of the equivalency of stratigraphic units. Correlation is an integral part of stratigraphy, and stratigraphers mainly aim at developing the stratigraphic basis that allows the regional and global correlation. Stratigraphy does not make sense without correlation.

[48] In spite of the fact that stratigraphy and correlation exist more than 150 years, there are different views of what correlation is. Two viewpoints on correlation have been historically formed. According to one of them, correlation is the demonstration of the equivalency of units that were formed during one period. Respectively, finding that two lithostratigraphic units are lithologically equivalent is not correlation. Golovkinsky was a supporter of this strict viewpoint on correlation. A more liberal approach permits the correlation on the basis of various criteria: lithological, palaeontological or chronological. In other words, two units can be correlated as belonging to the same lithostratigraphic or biostratigraphic unit even if these are of different ages. Most geologists are naturally inclined to share the latter approach for pragmatic reasons. For instance, petroleum geologists routinely correlate subsurface strata using the lithology, borehole logging signatures or characteristics of seismic reflections. By the 1980s, three key types of correlation had been formed:

- lithocorrelation, i.e. correlation of lithologically and stratigraphically similar units;
- biocorrelation, i.e. correlation of units that have similar fossil biocomplexes and occur in similar biostratigraphic positions;
- chronocorrelation, i.e. correlation of units of the same age occurring in equivalent chronostratigraphic positions.

[49] The interrelation between chronocorrelation and lithocorrelation should be given special attention. Chronocorrelation only determines whether the correlated units are of the same age. Same units can be locally correlated both lithologically and chronostratigraphically but some lithostratigraphic and chronological boundaries may intersect one another on a regional scale. Stratigraphic units, formed during major transgressions and regressions, are excellent examples of intersecting isochrones and lithological boundaries.

[50] The history of science gives numerous examples of the rejection of outstanding discoveries and ideas. Until the middle of the 19th century, geology was a purely descriptive science, and this fact makes the revolutionary character of Golovkinsky's analytical conclusions and theoretical principles even more remarkable. His achievements were not adequately understood or appreciated at that time. These have been confirmed by newly acquired data only recently.

[51] G. I. Sokratov, who played a major role in bringing Golovkinsky's work to light, wrote that this was accomplished "on the highest theoretical level that permitted him to be several decades ahead of international geological science of that time" [*Sokratov,* 1949; page 50].

[52] Golovkinsky's scientific legacy was filled with outstanding ideas, rediscovered both in the 20th and in the 21st centuries. This phenomenon can best be described using the following excerpt from Golovkinsky's work:

[53] "Basic principles in science change as slowly and insensibly as geological faunas – regressing and progressing, appearing in various facies – and it is as difficult to find a point on a winding curve at which the major faunal change occurs as to identify a turning point in the gradual change of opinions." (Pages 135–136).

Conclusions

[54] The above analysis of the remarkable work of

N. A. Golovkinsky from the viewpoint of modern geological science yields the following results:

[55] 1. For the first time, the succession of facies in a sedimentary basin and their vertical onlapping were described in the scientific literature. These ideas were later developed by A. A. Inostrantsev and shaped by Johannes Walther as the basic facies law [*Walther,* 1894].

[56] 2. For the first time in the Russian scientific literature, Golovkinsky introduced the notions of chronological, stratigraphical, petrographical and palaeontological horizons and studied the relationships between them anticipating the concept of isochrones that intersect stratigraphical, petrographical and palaeontological boundaries.

[57] 3. The basic principles of sequence stratigraphy relating to the architecture of sedimentary complexes in sedimentary basins were first introduced in this work.

[58] This indicates that N. A. Golovkinsky recognised not only the essence of the basic facies law but also its key scientific and practical applications. Apparently, his modesty, self-criticism and exactingness did not allow him to proclaim the discovered phenomena as the universal geological law.

[59] Only a few scientists of those times were able to fully understand the essence of Golovkinsky's discoveries and evaluate their scientific and practical meaning, and another 100 years had to pass until the others could do that.

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