*Lithology and Mineral Resources, Vol. 39, No. 2, 2004, pp. 95–113. Translated from Litologiya i Poleznye Iskopaemye, No. 2, 2004, pp. 115–135.*


# Problems of the Stadial Analysis and Development of Lithology

**V. N. Kholodov**

*Geological Institute, Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 119017 Russia*

Received July 28, 2003

**Abstract**—History of the evolution of concepts concerning stages of sedimentary rock formation is reviewed to show the conditional character of stadial boundaries and unreasonableness of their detailed subdivision. An insufficient knowledge of continental diagenesis is stressed and some problems of catagenesis are discussed. It is shown that metagenesis is irrelevant to the notion of sediment transformation stages and includes many purely geological processes. A rational succession of main stages of sedimentary rock formation is proposed. The main purpose of stadial analysis is shown to be the study of succession and mechanisms of mineral formation at different stages of sedimentary rock formation.

## REVIEW OF THE PROBLEM

At the end of the 19th century, many geologists and petrographers (I. Walter, G. Rosenbush, U. Grubenmann, P. Niggli, A.N. Zavaritskii, and others), who studied sedimentary rocks, supported an idealized model of sedimentary process mainly based on early concepts, according to which widespread sandstones, clays, conglomerates, iron ores, limestones, and carbonaceous rocks form as a result of the erosion of magmatic rocks and crystalline schists in the ancient basement. They believed that sedimentary process began with the weathering of parental substrate, aqueous transport of its disintegration products, and accumulation at the bottom of terminal runoff basins. Newly formed layers were subjected to various alterations and transformed into sedimentary rocks. Their subsequent metamorphism terminate the cycle of the geological transformation of sediments. Walter (1894) proposed the term *lithogenesis* for the whole process of sedimentary rock formation and divided it into the following *stages*: (1) denudation (destruction of rocks, transport of separated material in solid and dissolved forms and its disintegration); (2) deposition of material; (3) diagenesis; and (4) metamorphism.

Fersman (1922) probably casted doubt on the continuous succession and imperative character of stages outlined by Walter. Taking into consideration geochemical data and understanding the complexity of sedimentary rock formation, he proposed to distinguish three *genetic types* of lithogenesis: (1) hypergenesis (all chemical and physicochemical processes occurring at the boundary between the Earth's atmosphere and its solid shell); (2) diagenesis (all processes within the primary nonlithified mud layer at the basin bottom; and (3) catagenesis (all transformations of rocks after their burial under a newly formed sediment layer until their exposure on the land surface, i.e., exhumation to the land-atmosphere boundary.

Pustovalov (1940) developed "laws" of matter differentiation, sedimentation periodicity, and physicochemical heredity. In the two-volume monograph *Petrography of Sedimentary Rocks*, he presented a generalized and idealized model of the planetary-scale sedimentary process. In contrast to Fersman, Pustovalov proposed to divide lithogenesis into the following *stages* (Table 1): destruction of source rocks, transport of disintegrated products, deposition, early diagenesis (syngenesis), and late diagenesis (epigenesis). He emphasized their close interrelation.

Except for the vague and, therefore, lame terms "syngenesis" and "epigenesis," which were used since the middle of the 19th century by ore geologists for the description of deposits that are synchronous or younger, respectively, relative to country rocks (Kholodov, 1973), the stadial model of Pustovalov served as a basis for many subsequent (purely formal) stadial constructions.

It is evident from Table 1 that precisely this model provided the basis for the subsequent popular models. Only boundaries of stages, terminology, and some subdivisions were debatable.

Noteworthy among subsequent innovations is the stage of syngenesis or halmyrolysis proposed by Hummel (1923) and accepted (under different names) by L.B. Rukhin, M.S. Shvetsov, R.W. Fairbridge, and V.T. Frolov. According to these researchers, the syngenetic stage represents an oxidizing phase of the subaqueous reducing diagenesis (Strakhov, 1953) and corresponds to the upper oxidized film of lacustrine and marine sediments.

The stage of halmyrolysis or submarine weathering was initially defined by analogy with soil formation and weathering processes on continents. However, recent hydrogeological, pedological, biogeochemical, and geochemical data do not confirm the similarity of subaerial and subaqueous processes in sediments (B.B. Polynov, V.A. Kovda, D.S. Orlov, G.I. Bushinskii,

0024-4902/04/3902-0095 

**Table 1.** Evolution of concepts of lithogenetic stages

| Stages of sedimentary rock formation | | | | | | | | Author, year |
|---|---|---|---|---|---|---|---|---|
| Denudation and transport | Deposition of material | Diagenesis | Metamorphism | | | | | Zavaritskii, 1932 |
| Formation of sediments | | Transformation into rock | | | | | | |
| Catamorphism (destruction of primary rocks and formation of sediments) | Transfer and deposition of sediments | Diagenesis and lithification of sediments | | | | | | Tvenhofel *et al.*, 1936 |
| Destruction of source rocks | Transfer of destruction products | Deposition | Early diagenesis (syngenesis) | Late diagenesis (epigenesis) | | | | Pustovalov, 1940 |
| Weathering | Transfer and deposition | Diagenesis | | | | | | Shvetsov, 1948 |
| Formation of sedimentary material | Transfer of sedimentary material | Deposition | Syngenesis | Diagenesis | Epigenesis | | | Rukhin, 1953 |
| | | | Petrification | | | | | |
| Weathering (mechanical and chemical) | Transfer | Deposition | Halmyrolysis | Diagenesis (exodiagenesis) | Late diagenesiis | | | Shvetsov, 1958 |
| Mobilization of material in the weathering crust | Transfer and sediment formation in drainage areas | Sediment formation in terminal basins | Diagenesis | Catagenesis | Protometamorphism | | | Strakhov and Logvinenko, 1959 |
| Lithogenesis | | | | Metagenesis | | | | Strakhov, 1960 |
| Hypergenesis (epidiagenesis) | ? | Halmyrolysis | Syndiagenesis | Anadiagenesis | | | | Fairbridge, 1971 |
| Weathering (hypergenesis, halmyrolysis, edaphogenesis) | Disintegration | Mobilization | Transport | Sedimentogenesis | Diagenesis | Catagenesis | Metagenesis | Timofeev, 1986, 1994 |
| Sedimentogenesis | | | | | Lithogenesis | | | |
| Mobilization of sedimentary material | Transport | Sedimentogenesis | Diagenesis | Initial | Deep | Metagenesis | | Yapaskurt, 1985 |
| | | | | Catagenesis | | | | |
| Sedimentogenesis | | | Lithogenesis | | | | | |

A.I. Perel'man, and others). Therefore, the validity of this stage as an autonomous subdivision is very doubtful. This is evident from the distinct genetic relation between diagenetic interstitial solutions and the so-called "halmyrolytic" minerals (glauconite and phosphorite) on the mud surface reported in many works (Strakhov, 1953, 1956; Baturin, 2003; Kholodov, 2003, and others).

Limits and types of internal processes in the metagenetic stage are also uncertain. It is commonly manifested in orogenic regions with an intricate tectonic structure. Therefore, this stage should probably be considered a combination of various catagenetic and metamorphic processes that are sometimes atypical of lithogenesis.

Some researchers identified metagenesis with the stage of regional metamorphism (Vassoevich, 1957; Vassoevich *et al.*, 1967). This problem is considered below.

In the 1950s–1960s, lithologists tended to formalize and specify the stadial model of lithogenesis (Table 1).

For example, Fairbridge (1971) referred the weathering stage to as a process taking place between two cycles against the background of tectonic ascents involving the sedimentation basin. According to this model, hypergene transformations are already triggered by groundwaters in an *anaerobic* (?!) medium at deep levels of the system. These transformations somewhat correspond to regressive catagenesis and can be defined as a cryptogenetic substage. With further uplift and weathering, sedimentary rocks are transformed into eluvium or residual rocks (idiohypergenetic substage).

Finally, joint activity of tectonic process and weathering agents results in the destruction of sedimentary sequences and formation of starting material for the next sedimentogenesis cycle. This phase is identified as the spaohypergenetic substage (Greek prefix "spao," means to expose, tear off, tear to pieces, carry away).

The model proposed by Fairbridge (1971) can be presented in the following form:

1. External surficial hypergenesis zone

2. Spaohypergenesis

3. End of the particular lithogenesis cycle (and beginning of the next one)

4. Internal (deep) hypergenesis zone

5. Idiohypergenesis

6. Cryptohypergenesis

7. (Tectonic inversion, replacement of subsidence by uplifts)

It is apparent that the proposed model is highly speculative and applicable to a certain extent only to humid settings that develop under slow rates of tectonic rising. It should be quite different under glacial, arid, and, particularly, volcanogenic sedimentation conditions.

Logvinenko (1968) attempted to specify the catagenetic stage by correlating newly formed minerals and coal metamorphism degree. He subdivided the catagenetic stage into the early (lignitic–bituminous and high-volatile bituminous coals) and late (low-volatile bituminous coals) substages. The metagenetic stage was subdivided into the early metagenetic substage (semianthracites and anthracites) and the late metagenetic substage (metaanthracites). Although Logvinenko considered the model of a global generalization of postdiagenetic sedimentary rock alterations, it is primarily linked to coal-bearing sequences in the Donets Basin, i.e., humid sedimentation settings.

Vassoevich (1962, 1971) went even further in the formalization of diagenetic stages. He elaborated the most important aspects of the lateral migration theory of oil origin based on reconstruction of heat flow values in the past. Leaning upon works by Ammosov and Gorshkov (1971), he proposed to use the reflectance of vitrinite inclusions for reconstructing paleotemperatures in clayey sediments. He subdivided the catagenesis zone in hydrocarbon-bearing provinces into protocatagenesis (25–75°C), mesocatagenesis (75–280°C), and apocatagenesis (280–350°C) subzones.

In principle, such an objective subdivision of the catagenesis zone is important for estimating the behavior of dispersed organic matter and oil formation potential. The model proposed by Vassoevich (1962) still valid in this aspect. It is, however, unclear how the catagenetic mineral zonality of authigenic minerals related to interaction between gas–water fluids and sedimentary rocks fits in the defined subzones. Moreover, these subzones within subsided sedimentation basins are likely to reflect only one aspect of diverse secondary alterations, namely transformation of organic matter.

Vassoevich (1971) treated the stages of hypergenesis, diagenesis, and metagenesis (metamorphism) in a simpler manner. Based on analogy with catagenesis, and without any special studies, he identified proto-, meso-, and aposubstages. Thus, a rather intricate and formal stadial model was compiled (Fig. 1).

Attempts to refine the stadal model of sedimentary process continued in the 1990s. Timofeev (1986, 1994) voluntarily united subaqueous processes of sedimentary material transformation and redeposition (halmyrolysis and edaphogenesis) with subaerial processes of continental weathering (Table 1). Consequently, the term "lithogenesis" acquired a new meaning including all secondary alterations of sediments and sedimentary rocks (diagenesis, catagenesis, and metagenesis).

Yapaskurt (1985, 1989, 1999) proposed to subdivide secondary alterations of sedimentary rocks into initial and deep stages of catagenesis. Simanovich and Yapaskurt (2003) elaborated the geodynamic classification of sedimentary rock basins, where the presumable relationship between diagenesis, catagenesis, and metagenesis stages depends on the intensity and type of tectonic deformations.

Following Timofeev (1994), they also subdivided the sedimentary process into stages of early "sedimentogenesis" and late "lithogenesis". In my opinion, such an unjustified interpretation of terms violated the traditional terminology elaborated by I. Walter, A. Fersman, N.M. Strakhov, N.B. Vassoevich, N.B. Logvinenko, and others and provoked confusions in recent publications. At the last All-Russian Lithological Conference, for instance, some researchers interperted lithogenesis as a totality of sedimentary processes, whereas other researchers meant secondary alterations (diagenesis, catagenesis, and metagenesis).

It should be emphasized that detailed subdivision of stages in the idealized and formalized model of sedimentogenesis has no limits and permits a plethora of variants.

## REAL SEDIMENTARY PROCESS

The real sedimentary process is intricate and its diverse aspects are insufficiently studied.

The existence of humid, arid, glacial, and volcanosedimentary modifications of the sedimentary process hampers the exact definition of stages of sedimentary material mobilization, transport, and deposition, because every type of lithogenesis is characterized by a specific mechanism of material formation and burial (Strakhov, 1960, 1963).

Indeed, mobilization of sedimentary material in drainage basins of the humid zone is mainly realized through the formation of soils and weathering crusts with a decisive role of vegetation. The material transport is related to the activity of river system, and its composition is considerably governed by the autochthonous organic matter and true solutions.

The arid provenance is dominated by the mechanical destruction and deflation of initial rocks. In addition to rivers, water flows and eolian activity play a significant role in material transport. Correspondingly,

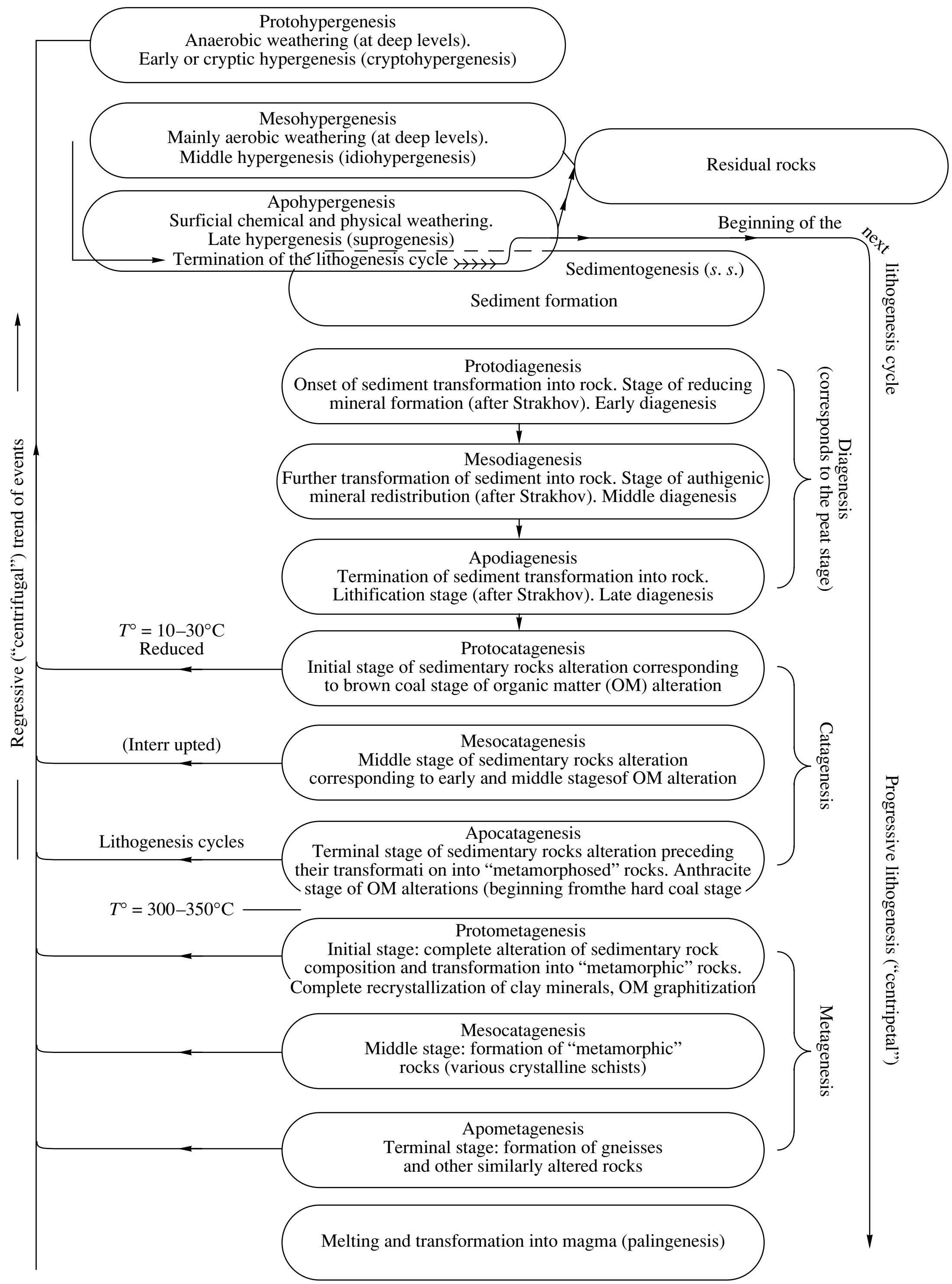



**Fig. 1.** Stages of the sedimentation process (Vassoevich, 1971).

sedimentary material in terminal basins is mainly composed on coarse-grained sediments enriched in iron hydroxides.

In both cases, the sedimentary process can be complicated by volcanic activity that supplies lavas, lapilli, gases, and thermal solutions to the sedimentation zone.

Both mobilization and transport of sedimentary material act simultaneously in glacial lithogenesis. The material transported by glaciers is produced by mechanical moraine weathering, landslides, or bed rafting. Less commonly, terrigenous material is mixed with ash in the case of volcanic activity. Glacier thawing results in the deposition of mobilized components. They form a cover of glacial and fluvioglacial sediments on continents or are transported by icebergs in seas and oceans where they settle down on the bottom and mark the most distant areas of their distribution. Sediments of glacial lithogenesis are poorly sorted. They commonly contain large rock fragments and blocks polished by erosion.

The reducing subaqueous diagenesis widespread in marginal and epicontinental seas and shelf zone of the World Ocean represents a model of diagenetic processes. This stage was studieds by A.D. Arkhangel'skii, K.A. Berner, R.R. Brooks, G.Yu. Butuzova, K.O. Emery, Yu.O. Gavrilov, M.R. Goldman, Yu.N. Gurskii, M. Hartmann, M.V. Ivanov, J.R. Kaplan, Y. Kolodny, A.Yu. Lein, N.A. Lisitsyna, P.J. Miller, A. Nissenbaum, B.J. Prestly, Z.V. Pushkina, A.G. Rozanov, O.V. Shishkina, N.M. Strakhov, M.G. Valyashko, I.I. Volkov, E.S. Zalmanzon, P.V. Zaritskii, and others.

The microbiological decay of organic matter accompanied by sulfate reduction and formation of large amounts of $CO_2$ and $H_2S$ is the leading process in the elaborated model. This process results in changes of interstitial water composition, reduction and dissolution of polyvalent elements, diffusion, and formation of additional authigenic minerals frequently transformed into concretions and nodules.

It should be stressed, however, that this mode of secondary alterations and formation of sedimentary rocks is not unique.

In the 1980s, oceanographers (Volkov, 1980, 1984) revealed that sediments are subjected to oxidizing subaqueous diagenesis in organic-poor pelagic areas. Here, apparent signs of reducing processes are missing, and the formation of deep-sea ferromanganese nodules is the main consequence of material transport.

It should be noted that both versions of subaqueous diagenesis are not obligatory stages for sediments accumulated at the bottom of sea and oceans. For instance, processes related to oxidizing and reducing diagenesis were not reliably established in reefal and bacterial–algal (framework-forming) limestones and dolomites, as well as numerous varieties of subaqueous evaporates (gypsum, anhydrite, halite, and other salts).

The situation with diagenetic transformations of sediments on the continental block is even more complicated. Shvetsov (1958) identified these processes as "exodiagenesis."

Processes of the transformation of sediments into sedimentary rocks on continents are extremely intricate. In addition to subaqueous diagenesis, temperature fluctuations and the consequent evaporation, freezing, precipitation (rains and snow), eolian activity, abundance and biochemical activity of vegetation, influence of soil and groundwaters, and so on play a significant role. It should also be kept in mind that the impact of all these factors depends on climatic and facies environments.

According to Strakhov (1963), thawing of glacial mixtures in terminal moraines result in their heaving and inundation in glacial settings. Oxygen stimulates the oxidation of $Fe^{+2}$, $Mn^{+2}$, and other polyvalent elements in these moraines, whereas the released $CO_2$ is redistributed to form carbonates and cement the sediments. The diagenetic transformation of moraines due to temperature rise begins from their upper parts and spreads downward gradually involving the entire sequence. At final stages of this process, communities of primitive organisms, such as bacterial–algal mats, fungi, and lichens, play an active role in the transformation of poorly sorted material in moraines.

Processes of exodiagenetic carbonatization are widespread in loess sediments formed from glacial silty dust deposited by winds (or flowing water) and spatially related to ancient glacial areas. Atmospheric and soil moisture, along with vegetation stimulates the deposition of carbonates cementing silty sediments, enveloping mineral grains and forming "lime nodules," "loess dolls," and other nodular inclusions (Pustovalov, 1940; Nalivkin, 1956; Shvetsov, 1958; and others).

In humid zones, the main exodiagenetic agents are precipitation and land vegetation.

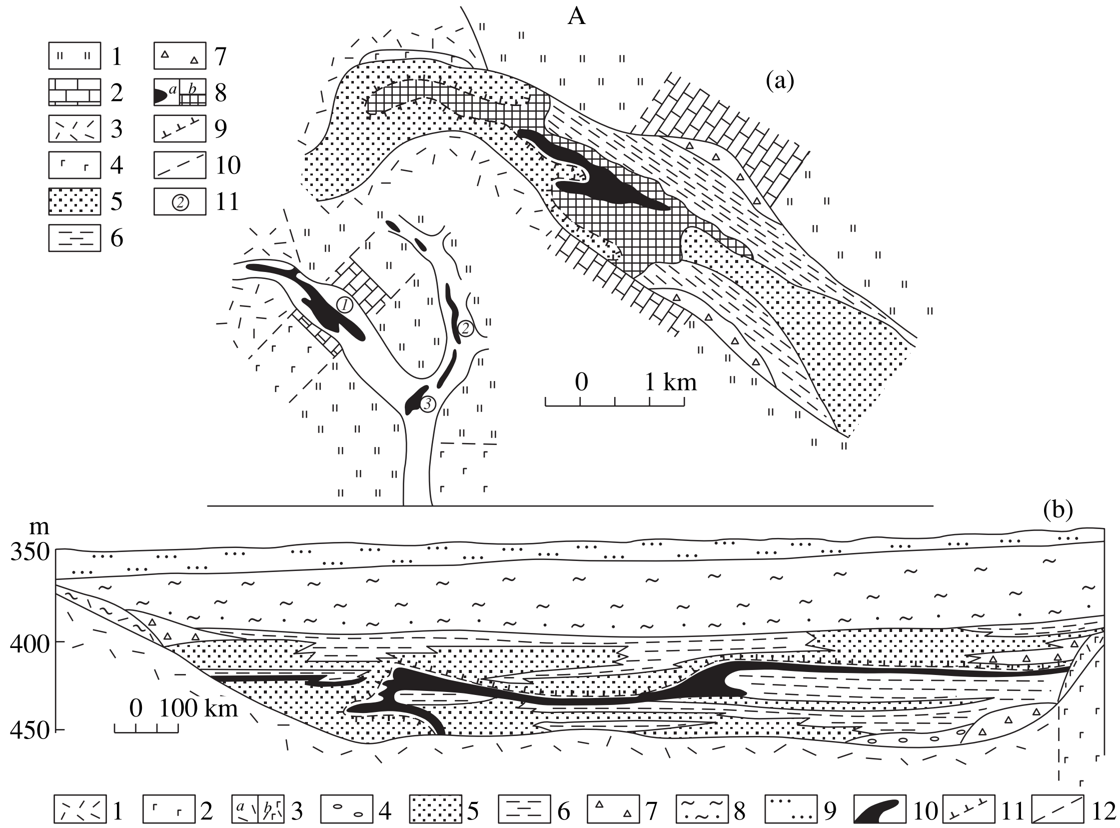
Swamping is widespread in forest and maritime landscapes. Plant remains accumulated in low and high peat moors undergo all stages of peat formation (decay by thermophilic bacteria, humification, and bituminization) that turn organic matter into peat and sapropel (V.N. Sukachev, D.A. Gerasimov, G.I. Panfil'ev, S.N. Tyuremnov, N.M. Strakhov, D.S. Orlov, G.I. Bushinskii, M.N. Nikonov, A.V. Makedonov, K.I. Lukashev, V.A. Kovalev, P.P. Timofeev, L.I. Bogolyubova). Oxygen contained in rainwater is rapidly consumed by oxidized organic matter, resulting in the development of a gleyey environment in bog waters. Acid gleyey waters dissolve carbonates of $Fe^{+2}$, $Mn^{+2}$, and some ore components, which are intensely redistributed to cement sand, shingle, and other permeable sediments in neighboring areas. Bog waters stimulate the intense transformation of clay minerals, e.g., illite into kaolinite (Keller (1968) and montmorillonite into kaolinite (Timofeev and Bogolyubova, 1985).

Exodiagenesis in bog systems has been scrutinized in several works (Orlov, 1939; Bushinskii, 1946, 1952; Koporulin (1966; Kossovskaya *et al.*, 1971; Kovalev, 1985).

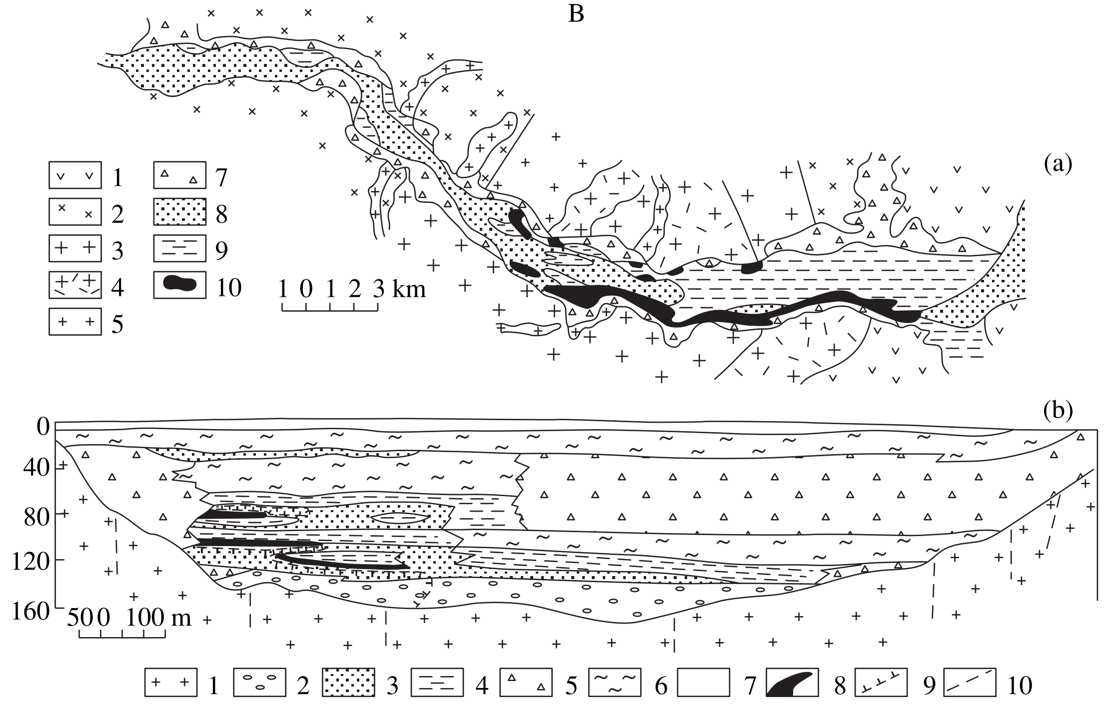
Exodiagenetic alterations are also realized in soils, where the combined action of atmospheric precipitation, land vegetation, microorganisms (bacteria, algae, and fungi), and groundwater results in the formation of various geochemical environments that influence the mineral composition of underlying rocks.

In humid soils, excess atmospheric precipitation stimulates an intense development of vegetation and removal of organic matter. Brown-colored and acid waters formed in such environment remove oxides of Fe and Al and carbonates from soils. In contrast, silica is concentrated to form podzol soils. In southern areas

A


(a)
1
2
3
4
5
6
7
8
9
10
11
0 1 km
(b)
m
350
400
450
0 100 km
1
2
3
4
5
6
7
8
9
10
11
12

B


(a)
1
2
3
4
5
6
7
8
9
10
1 0 1 2 3 km
(b)
0
40
80
120
160
50 0 100 m
1
2
3
4
5
6
7
8
9
10

with a lesser atmospheric precipitation but still abundant vegetation, plant remains are accumulated, and the soil becomes black it (chernozem). In this case, only carbonates are removed, while hydroxides of Fe and Al remain in situ and the environment becomes acidic.

In arid zones, reaction of soil waters becomes alkaline because of thin vegetation and decreased acidity, which stimulates the precipitation of carbonates and the formation of concretions and pseudomorphoses in sediments. Sometimes, the terrigenous material is cemented. Unlike carbonates, silica is dissolved and removed from soil, which results in the formation of light-colored soils.

Owing to exodiagenetic authigenic mineralization, the soils can be lithified and well preserved in coal-bearing and red-colored Paleozoic and older formations (Gerasimov, 1961; Keller, 1968; Feofilov, 1972, 1975), Retallack, 1990; Yakimenko *et al.*, 2000).

Recently, exodiagenetic processes related to alluvial sediments of various ages received much attention. Fluvial and floodplain sediments, which fill many paleoriver valleys incised into crystalline basement with acid intrusions (granites, rhyolites, and others), were found to enclose uranium and uranium–rare metal mineralization. Such ore occurrences and deposits are widespread in the Turgai Basin, Kazakhstan, western Siberia, and Transbaikal region.

The geological structure of two such deposits based on (Kondrat'eva and Nesterova, 1997) is shown in Fig. 2.

The Dalmatovka deposit is located on the eastern slope of the Urals. It is composed of gray-colored fluvial and floodplain sediments (Middle Jurassic–Cretaceous Koskol Formation), which fill the channel incision and grade upward into red-colored varieties. Some gray-colored sediments in the channel are oxidized and their contact with nonoxidized rocks is marked by beds and rolls with nasturane–coffinite mineralization.

Slightly altered gray-colored sandstones and gravelstones are cemented by kaolinite. Along with leucoxene, the kaolinite is locally developed after biotites. Such alterations are typical of humid exodiagenesis and related to the formation of humid weathering crusts.

Exodiagenetic processes in fluvial sediments of the Dalmatovka deposit were crowned by the penetration of oxygen- and uranium-bearing groundwaters and formation of ore bodies at the contact with reduced rocks (Khalezov, 1993; Kondrat'eva and Nesterova, 1997). This is confirmed by the $^{206}Pb/^{238}U$ mineralization age estimated at 130–140 Ma.

Similar geological structure is also typical of the Semizbai uranium-rare metal deposit located at the boundary between the Kazakh Highland and West Siberian Lowland. The river incision is filled with sediments of the Upper Jurassic–Lower Cretaceous (Valanginian) Semizbai Formation. The formation is composed of intricately alternating gray-colored alluvial and red-colored talus–proluvial sediments. They enclose abundant Fe-smectite (nontronite) that occasionally envelops terrigenous clasts. Various carbonate inclusions ranging from siderite lentils to calcite aggregates highly resembling caliche are also present. All these features can be referred to arid exodiagenesis.

The younger uranium-rate metal mineralization is usually localized at transition between red-colored oxidized and gray-colored floodplain sediments with coaly remains. Mineralization in the Semizbai deposit is strongly complicated by the hydrothermal alteration and other younger processes (Kondrat'eva and Nesterova, 1997).

Facts mentioned above suggest that exodiagenesis of alluvial sediments is highly variable. They reflect rather adequately paleoclimatic parameters of the relevant area.

The role of vegetation and atmospheric precipitation in arid exodiagenesis is probably minimal, whereas

**Fig. 2.** Structure of uranium deposits in paleoriver valleys. (A) Schematic structure of the Dalmatovka deposit: (a) geological map of the Central sector, (b) lithofacies cross section of the paleovalley (Luchinin *et al.*, 1992; Khalezov, 1993; Konoplev and Maksimova, 1989). (a) Basement rocks: (1) micaceous and carbonaceous schists (Pz), (2) marbelized limestone (Pz), (3) rhyolite ($T_1$), (4) basalt ($T_1$); Koskol Formation ($J_2$–3–$K_1$): (5) gray-colored gravelly–sandy–clayey, talus–proluvial, floodplain, (6) gray-colored, silty–clayey, floodplain, (7) red-colored, gravelly–sandy–clayey, talus–proluvial; (8) uranium mineralization: (a) high-grade and ordinary ores, (b) low-grade ores; (9) boundary of the ancient subsurface stratal oxidation zone; (10) tectonic dislocations; (11) deposit sectors: (1) Dalmatovka, (2) Uksyan, (3) Ust'-Uksyan. (b) Basement rocks: (1) rhyolite, (2) basalt, (3) weathering crust: (a) after rhyolites, (b) after basalts; gray-colored alluvial sediments of the lower Koskol Subformation: (4) pebbly–gravelly (channel) sediments, (5) sandy (channel) sediments, (6) clayey–silty (floodplain) sediments; (7) gravelly–sandy–clayey (fans) sediments; (8) red-colored talus–proluvial and lacustrine clayey–sandy and clayey sediments of the upper Koskol Subformation; (9) sandy sediments ($K_2$); (10) uranium mineralization; (11) boundary of the ancient subsurface stratal oxidation zone; (12) tectonic dislocations.

(B) Schematic structure of the Semizbai deposit (after L.L. Bobrova). (a) Geological map Basement rocks: (1) andesite, tuff ($O_2$), (2) diorite, granodiorite ($O_3$–$S_1$), (3) biotite granite ($S_2$–$D_1$), (4) porphyritic leucogranite ($D_2$–3), (5) granite–aplite dikes ($D_2$–3); (6–8) Semizbai Formation ($J_3$–$K_1$): (6) red-colored gravelly–sandy-clayey sediments, (fans), gray-colored, alluvial (7), pebbly–gravelly–sandy (channel) and (8) clayey–silty (floodplain) sediments; (9) uranium mineralization.

(b) Lithofacies cross section of the paleovalley; (1) granitoids of the paleovalley basement; gray-colored alluvial sediments of the Semizbai Formation: (2) gravelly–pebbly (channel) sediments, (3) sandy (channel) sediments, (4) clayey–silty (floodplain) sediments; (5, 6) red-colored sediments of the Semizbai Formation: (5) gravelly–sandy–clayey, talus-proluvial sediments, (6) silty–clayey, floodplain-lacustrine sediments; (7) Cretaceous, Paleogene, and Quaternary sediments overlying the Semizbai Formation; (8) uranium mineralization; (9) boundary of the ancient subsurface stratal oxidation zone; (10) tectonic dislocations.

evaporation and groundwater activity are decisive agents.

The arid exodiagenesis is particularly well developed in sebkhas (maritime coastal plains intermittently flooded by sea but located above the intertidal zone) with abundant bacterial–algal mats, newly formed carbonates (dolomite), gypsum, anhydrite, and halite that cement the coastal terrigenous–biogenic sediments.

Sebkhas were described by Friedman and Sanders (1970), Patrunov and Golubovskaya (1976), and many other researchers (W. Sudgan, A.J. Wells, A. Curtis, D.J. Sherman, E.A. Shinn, J. Evans, B.N. Purser, D.J. Kinsman, P. Bush, G.P. Butler, R.W. Peterson, B.C. Shreiber, J.M. West, and others). They are developed along coasts of the Persian Gulf and Mediterranean Sea, in the Nile River mouth area (Egypt), Spain, and California (United States).

Figure 3a demonstrates the facies structure of the Abu Dhabi sebkha located on the southern coast of the Persian Gulf. A system of reefal buildups and coral accumulations separates the Khor al Bazam Lagoon from the gulf with the TDS content of 40–50‰. Owing to hot climate and intense evaporation, the TDS content in the lagoon amounts to 70‰ or more, which is probably responsible for the high salinity of some groundwaters beneath coastal sediments.

Areas located southeast and south of the lagoon are occupied by pelletal, coral, and organogenic–algal sands laterally alternating with oolitic sands in the intertidal zone. The upper intertidal zone hosts bacterial–algal mats bounding the sebkha in the northwest.

Sediments of the sebkha include remains of algal mats, eolian material delivered from the coast, and carbonate pelletal and skeletal sands transported from the sea. The sediments are saturated with diagenetic crystals of gypsum and less common halite and carbonates owing to the intense evaporation of saline lagoonal and fresh continental groundwaters. Anhydrite concretions and gypsum nodules also form in these environments (Fig. 3b).

The typical mechanism of diagenetic salinization of loose sediments in sebkha can be observed in different desert areas, where groundwater receives a large quantity of salts transported by rivers. According to some calculations (Sidorenko, 1956; Kunin, 1959), the Tejen and Murgab blind rivers and the transit Amu Darya River supply the Karakum Desert with $3 \times 10^6$ t of water per year. As a result, an enormous volume of mineralized and, sometimes, fresh water accumulated beneath sands and clays.

Intense heating of the Earth's surface results in moisture deficiency, which is permanently compensated by ascending subsurface water. The capillary water inflow shown in works of Kovda (1947, 1954) is similar to groundwater ascent in sebkha (Fig. 4). As the groundwater rises to the day surface, one can observe the following sequential precipitation of minerals: low-soluble $Fe_2O_3$ and $Al_2O_3$, carbonates, sulfates, and readily soluble halite salts.

Such a differentiation of salts during the precipitation from groundwater implies that shallow groundwater promotes exodiagenetic carbonatization of sediments, whereas deep groundwater favors the formation of gypsum and even solonchak.

Indeed, Sidorenko (1956, 1958), Strakhov (1960), Allen (1974), Leeder (1975), and other researchers observed exodiagenetic carbonate crusts (thickness up to 6–10 m) beneath loose sediments in the deserts of Kara Kum, Kyzyl Kum, and Mexico. The formation of such is probably related to the development of caliche, calcretes, nari, and other specific local features of carbonatization in the Eastern Mediterranean (Yaalon, 1975), Algeria, Tunisia, Morocco (Raynel *et al.*, 1975), and other arid regions of the world.

Gypsum crusts and sandstones layers cemented by gypsum commonly occur in central areas of deserts, where groundwater is characterized by a high sulfate content and absence of carbonates (Kovda, 1947, 1954; Strakhov, 1960; Batulin, 1966; and others).

In terms of formation mechanism, solonchaks, shors, and takyrs are close to carbonate and gypsum crusts. However, in addition to groundwater, fresh water (Nalivkin, 1956) or inflowing seawater, e.g., in Southern Australia (Black, 1976; Warren, 1982, 1985), also play a substantial role.

The exodiagenetic transformation of volcanosedimentary sequences significantly depends on glacial, humid, or arid environment of the subaerial volcanic field (Strakhov, 1963) and differences in superficial and deep physicochemical conditions. For example, degassing of thermal vents produces various travertines and geyserites in intricate relationships with sediments and sedimentary rocks, whereas pyroclastic material is rapidly transformed into smectites, zeolites, and other secondary minerals.

The next catagenetic stage is marked by a substantially decreased role of exogenic processes and higher significance of endogenic processes.

In the 1960s, following A.G. Kossovskaya, V.D. Shutov, and N.V. Logvinenko, many lithologists and mineralogists (A. V. Kopeliovich, V.I. Murav'ev, I.M. Simanovich, V.A. Drits, B.A. Sakharov, O.V. Yapaskurt, and others) assumed that catagenetic transformation of sedimentary rocks is a simple redistribution of chemical elements due to the increase of temperature and pressure in deep zones of stratisphere and the formation of several additional authigenic minerals.

From this standpoint, the catagenetic stage is a simple precursor of regional metamorphism. Sandy–clayey rocks are united into facies groups sometimes divided into certain vertical phylogenetic successions. For instance, Logvinenko (1968) supposed that mineral and structural features of quartz, feldspar–quartz, arkose–graywacke, and volcanogenic graywacke sandstones and *associated pelites* (clays) transformed at various depths correspond to different degrees of coal metamorphism.

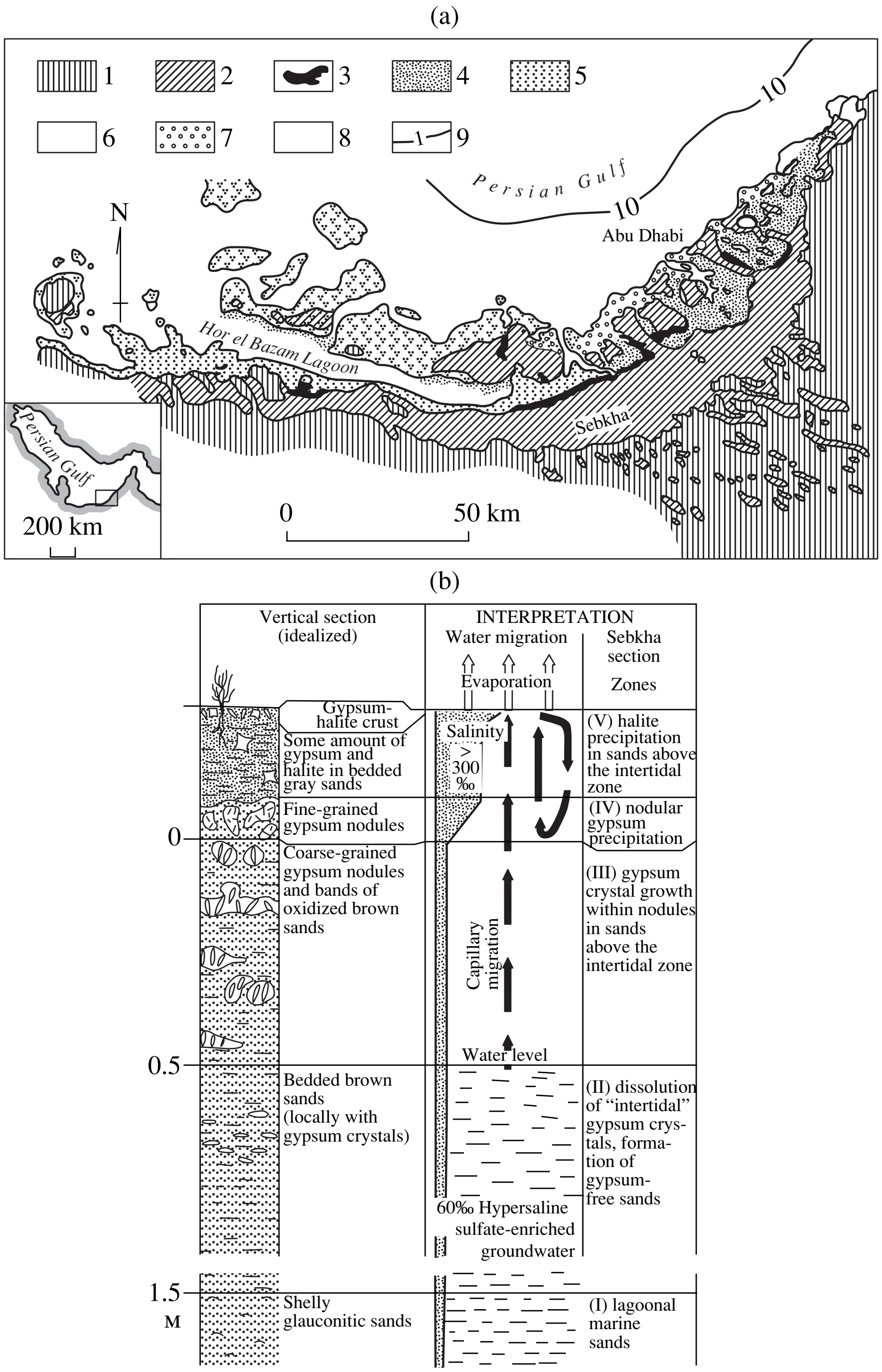



**Fig. 3.** Formation conditions of sebkha on the southern coast of the Persian Gulf and in the Nile Rive delta. (a) Facies map of coastal carbonate sediments in the Abu Dhabi area (Butler *et al.*, 1982). (1) Land; (2) sebkha; (3) algal mat; (4) pellets and mud; (5) pellets, grapestones, and skeletal sand; (6) oolites; (7) organogenic reefs and coral–algal sands; (8) skeletal sands; (9) depth, fathoms. (b) typical vertical sedimentary section of the majority of maritime depressions in the sebkha located along the Nile River delta near El Hammam (Egypt). In summer, the TDS content ranges from (31–61‰) below the water table to > 300‰ in the halite precipitation zone in uppermost sediment layer. Seawater is sulfate-saturated even below the water table (West *et al.*, 1979).

Kossovskaya and Shutov (1971) scrutinized the sandstone and clay association using the precise X-ray and crystatllochemical methods and revealed that clay minerals can serve as indicators of stages and substages (see articles by V.A. Drits, B.A. Sakharov, A.L. Salyn, G.N. Sokolova, and others in collection of papers "Epigenesis and Its Mineral Indicators").

In works of Kossovskaya and Shutov, facies (more exactly, associations) united sandy, silty, and clayey sediments. They characterized the prevalent textures

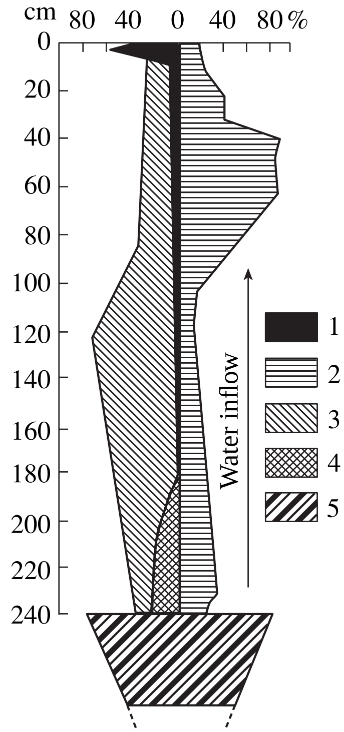



**Fig. 4.** Separation of salts during groundwater evaporation (Kovda, 1947, 1954). (1) Readily soluble salts; (2) $CaSO_4$; (3) $CaCO_3$; (4) $R_2O_3$; (5) salts in groundwater.

and presented a qualitative mineral composition (Fig. 5). However, quantitative relationships between facies constituents were ignored.

In the 1950s–1960s, lithologists, hydrochemists, and geologists also investigated the problem of catagenesis at uranium and rare metal–uranium deposits in the Fergana, Kyzyll Kum, Chu Sarysui and Syr Darya depressions, Kazakhastan, and other areas. Complex litological–mineralogical and hydrochemical studies carried out by A.I. Germanov, V.N. Kholodov, E.A. Golovin, E.M. Shmariovich, A.K. Lisitsyn, I.A. Kondrat'eva, G.V. Komarova, O.I. Zelenova, S.G. Batulin, M.F. Kashirtseva, V.G. Grushevoi, I.S. Onoshko, and others showed that waters and gas–water solutions circulating within sediments can substantially transform the initial mineralogical–geochemical composition of rocks and produce various associations of newly formed ore and other minerals. The relationship of mineral-forming process with subsidence depth and thermodynamic condition within the bed is often ambiguous.

The results obtained also revealed a principle difference between catagenetic transformations in reservoir rocks (sandstones, silts, and permeable limestone varieties) and cap rocks (clays, marls, halogenic rocks, and gypsum-bearing sequences). Moreover, their intensity and trend dramatically differ from each other with increase in depth.

Theoretical achievements in uranium and uranium–rare metal geology made it possible to consider catagenesis as a stage of interaction between oil-saturated and gas–water solutions with newly formed sedimentary rocks.

If we take into account the above conclusion, it becomes evident that models proposed in (Logvinenko, 1968,1984; Kossovskaya and Shutov, 1962, 1971, 1975; Karpova, 1972; Logvinenko and Orlova, 1987; and others) based on statistical mineralogical data need a serious correction and refinement by studying vertical and lateral lithogeochemical zoning in reservoir and confining beds.

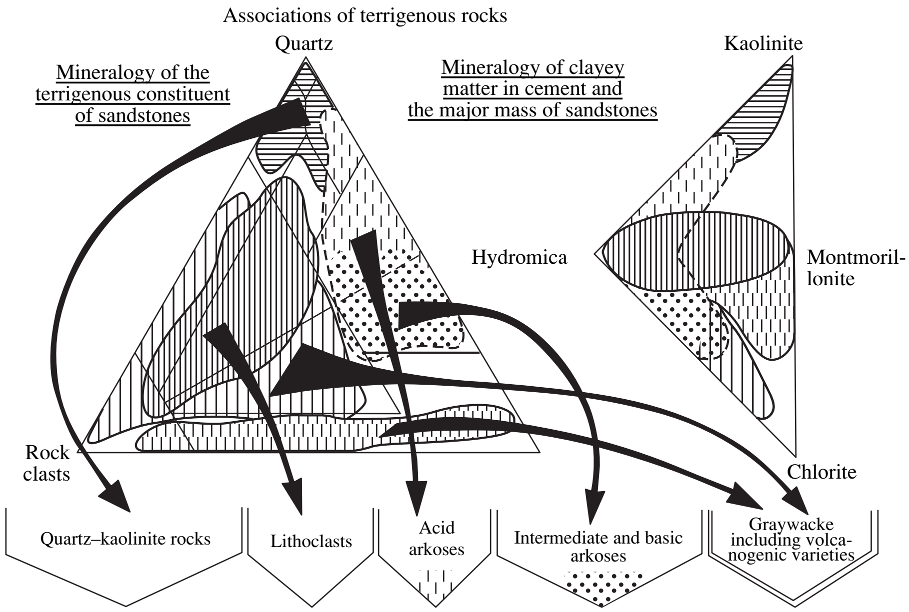
Based on differences in hydrodynamic conditions, infiltration and elision basins can be distinguished in the catagenesis zone (Kholodov, 1973, 1982a, 1982b; 1983a, 1983b, 1985, 1990, 1991, 1995, 2002b, 2002c, 2002d; Kholodov and Kiknadze, 1989; Kholodov and Butuzova, 1989; Kholodov and Nedumov, 2001; Kholodov *et al.*, 1998, 1999).

In infiltration basins, meteoric waters penetrate exposed sedimentary beds (reservoirs) and migrate to the discharge area under the influence of gravity. Such systems are usually located in tectonically stable areas with sedimentary cover less than 4–5 km thick. Contrasting redox conditions in these water solutions stimulate the formation of sulfides, hydroxides, carbonates, silica, and uranium minerals, as well as the development of sutures, stylolites, and dissolution breccias.

Elision basins are confined to actively subsiding blocks of the Earth's crust. They are characterized by a thick sedimentary cover (18–20 km); intricate hydrochemical zoning; development of anomalous formation pressures; migration of groundwater, oil, and gas–water solutions along reservoir beds and faults from central parts of the basin toward its periphery; wide development of rock decompaction in deep ones; hydraulic fractures; and mud volcanism.

The development of anomalous formation pressures in elision systems is related to the transformation of clay minerals. The smectite – hydromica transition accompanied by dehydration is particularly important. Owing to the existence of hydraulic relation between different hydrogeological stages, the hydrodynamics of a basin is mainly governed by high pressures, which have a strong impact on both clayey beds and the entire elision system.

The transformation of various clay constituents (dispersed organic matter, carbonates, silica, and others) during the subsidence to high *PT* depths produces various fluids containing $CO_2$, $H_2S$, liquid and gaseous bitumens, and other chemically active components in the elision system. Initially, they fill up pores in clayey sediments. When the interstitial pressure increases, they migrate, from the source bed to reservoirs, fissures, and faults to form gaseous hydrocarbon deposits, oil and bitumen pools, and thermal ore-bearing solutions.




| Stage | Quartz–kaolinite rocks | Lithoclasts | Acid arkoses | Intermediate and basic arkoses | Graywackes |
|---|---|---|---|---|---|
| Initial epigenesis | Facies of clastic material with inherited composition<br>Variable composition of newly formed minerals mainly inherited from diagenetic stages<br>Detrital textures (note the development of incrustate cement textures) | | | Heulandite–analcite facies<br>Transformation of tuff glass and basic plagioclases into analcime and heulandite<br>Clastic textures | |
| | | | | Facies of vermiculite-type phases and relicts of majic minerals | |
| | | | | Formation of vermiculite-type phase after biotite and trioctahedral hydromicas. Interlayer dissolution of mafic minerals. Clastic textures | |
| Deep epigenesis | Quartz–dickite facies<br>Newly formed quartz, dickite, titanium minerals, hematite<br>Mosaic and conform–regeneration textures | Hydromica–chlorite facies<br>Newly formed minerals: quartz, albite, chlorite, hydromica, mixed-layer minerals | | Laumontite facies<br>Formation of laumontite, albite, quartz, chlorite, and dioctahedral mica after tuff glass and basic feldspars | |
| | | Mosaic, conform, and conform–regeneration textures | | | Mosaic, metasomatic, and conform–regeneration textures |
| Early metagenesis | Quartz–pyrophyllite facies<br>Newly formed minerals: quartz, pyrophyllite<br>Mosaic, of conform–regeneration and blastic textures | Muscovite–chlorite facies<br>Disappearance of clays and mixed-layer minerals. Newly formed minerals: muscovite, chlorite, albite, quartz<br>Mosaic, blastic, and spiniform (differential sliding) textures | | Prehnite--muscovite–chlorite facies<br>Newly formed minerals: prehnite and pumpellyite (replacement of laumontite), muscovite, chlorite, albite, quartz<br>Mosaic–blastic and spiniform textures | |
| Late metagenesis | | Epidote–muscovite–chlorite–stilpnomelane facies<br>Newly formed minerals: epidote, albite, actinolite, stilpnomelane, Mn-garnet; development of chlorite and muscovite; disappearance of prehnite and replacement of potassium feldspars by muscovite<br>Lepidoblastic and argen textures with segregation structures | | | |
| Regional metamorphism | Kyanite facies<br>Newly formed minerals: quartz, kyanite<br>Mosaic and blastic textures | Biotite facies<br>Newly formed minerals: biotite (related to interaction of muscovite, chlorite, and rutile), garnet<br>Lepidoblastic textures with segregation structures | | | |

**Fig. 5.** Main associations of terrigenous rocks and facies of regional catagenesis (Kossovskaya and Shutov, 1971).

Clayey sequences of basins are marked by zoning that reflects the removal of components and formation of new minerals, such as illite $2M_1$, chlorites, sulfides, and carbonates (Kholodov and Nedumov, 2001).

The sandy reservoirs are often characterized by the carbonatization and decomposition of minerals (feldspars, plagioclases, micas, chlorites, and glauconites), intense corrosion of quartz, and formation of pores and cavities filled with bitumen (Kholodov *et al.*, 1985).

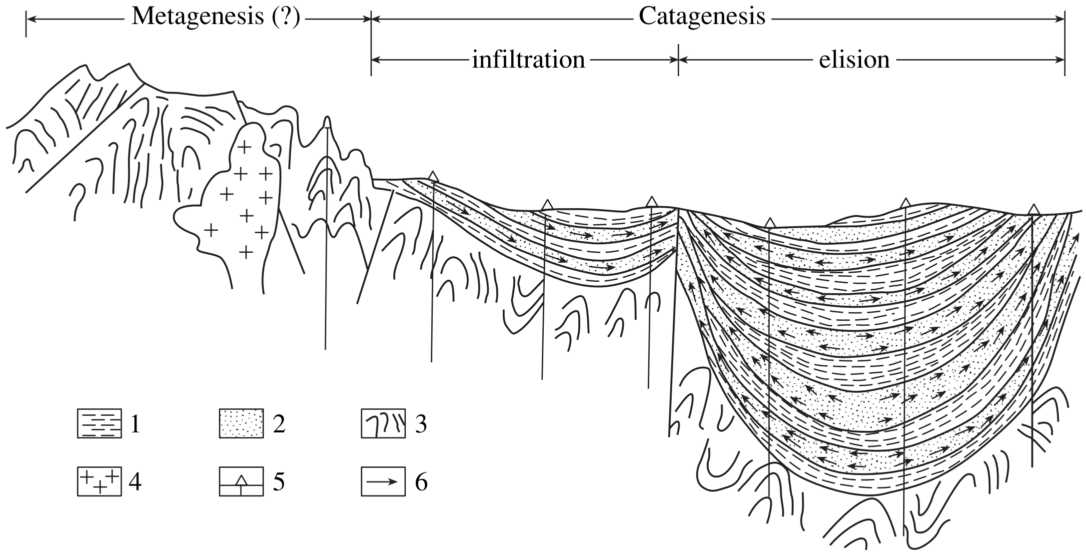



**Fig. 6.** Geological relationships between catagenetic and metagenetic stages. (1) Clayey cap; (2) sandy reservoir; (3) metamorphosed sequence; (4) intrusive bodies; (5) borehole; (6) direction of gas–water fluid migration.

These data provide new insights into processes of mineral formation at the catagenetic stage and make it possible to outline new approaches in the study of this phenomenon.

Further alterations of sedimentary rocks are determined by a combination of processes usually termed as metagenesis. Some researchers consider them an autonomous stage of lithogenesis (Logvinenko, 1968; Kossovskaya and Shutov, 1971; Yapaskurt, 1989; Makhnach, 2000; and others). For example, Logvinenko (1968, p. 34) wrote: "… Strong textural and mineralogical alterations of sedimentary rocks in the lower part of the Earth's sedimentary cover similar to those typical of initial stages of regional metamorphism will be termed metagenesis…These alterations result in the transformation of granular rocks into quartzite sandstones, sandstone quartzites, and quartzites; clayey rocks into shales, aspid and phyllite-type schists; carbonate rocks into crystalline and marbelized limestones and dolomites; and fossil coals into hard coal, anthracite, and graphitized anthracite. Thus, this stage is marked by the formation of metamorphosed sedimentary rocks."

Unlike these researchers, Strakhov (1960) terminated the geological cycle of lithogenesis by stages of catagenesis and protometamorphism united under a common term "metagenesis" (Table 1).

In my opinion, the notion system proposed by Strakhov has a deeper meaning, because areas of the Earth's sedimentary cover marked by processes of catagenesis and protometamorphism do not fit a historical succession (Fig. 6).

Metagenetic alterations are usually manifested in geosynclines at the orogenic stage. This means that metasedimentary sequences of such orogen have a long history. Initially, they represented sedimentary rock basins with processes of infiltration or elision catagenesis, interaction between sediments and oil–gas–water fluids, and typical authigenic mineral formation.

Subsequent inversions, folding, fracture tectonics, and emplacement of plutons in the orogen were superimposed on the mineralogy of infiltration and elision processes, i.e., different types of catagenetic mineralogical–geochemical zoning.

At later stages, the orogen was subjected to erosion and weathering, which could significantly influence protometamorphism in local areas.

Thus, the phenomenon considered by Logvinenko and other researchers as a common stage of lithogenesis actually represents a combination of many different-aged processes. Mineralogical–geochemical observations should be correlated with tectonic history of the region, its magmatism, and erosion in order to reconstruct the succession of events and define real protometamorphic alterations. Simanovich and Yapaskurt (2003) have already made the first (although speculative) steps in this direction.

## BOUNDARIES OF DIFFERENT STAGES IN LITHOGENESIS

The sedimentary rock formation in natural environments is an intricate and multifactor phenomenon. Therefore, boundaries between stages of this process were always vague and ambiguous, which provoked acute debates between lithologists of different schools and different interpretations of the term "diagenesis." For example, it has a wider meaning in the interpretation of foreign researcher (all secondary alterations of sediments and rocks ranging from diagenesis to catagenesis), while Russian lithologists usually consider separately transformations of sediments and evolution of rocks (Table 1).

It should be emphasized that relationships between rock weathering, material mobilization, and its transport, which begin the process of sedimentation, depend on the environment. In glacial settings, they frequently coincide. For example, glaciers mobilize, transport, and deposit sedimentary material in thawing areas.

Early stages in some volcanosedimentary processes are substantially different. In hydrothermal systems, transport and accumulation of matter are close in both time and space.

In contrast, the early stage of sedimentogenesis in humid zones is distinctly divided into substages corresponding to the weathering of source rocks (soil and crust formation), mobilization (talus, colluvium, and proluvium formation), transport by rain water, creeks, rivers, ground and subsurface waters, and deposition in terminal basins (seas and oceans).

At first sight, dynamics of the process is simple. However, it is complicated by the presence of many intermediate accumulation basins (bogs, lakes, landlocked basins, and land areas temporarily occupied by sea) between the provenance, where the sedimentation process begins, and the terminal basin, where the sediments are buried and subjected to diagenesis. These intermediate basins serve as site for the temporal burial of sediments and their diagenetic transformations. They can turn again into provenances in a new tectonic situation.

Thus, continents are characterized by repeated mobilization and burial of sediments and the initial stage of sedimentary process can be as long as millions of years. In this situation, it is naturally impossible to distinguish boundaries of its separate phases.

The uncertainty of boundaries between different phases of this process was previously noted in the description of subaerial process (Shvetsov's exodiagenesis). Even less distinct these boundaries are in the mineralogical manifestation of subaqueous diagenesis. The upper boundary of the diagenesis zone is particularly vague.

It was established long ago that reducing diagenetic transformations in marine and oceanic sediments are closely related to bottom water. Persistent diffusion exchange by different components between interstitial and bottom waters imparts features of an *open* physicochemical system to diagenesis (Strakhov, 1953, 1956, 1960; Volkov, 1984; and others).

Anaerobic microbiological sulfate reduction and formation of sulfides in sediments, which are one of the most important processes of this stage, cannot be realized without diffusion influx of sulfates from bottom sea water.

In contrast, excess $H_2S$ and $CO_2$ generated in interstitial waters due to the mass burial of organic matter can enter bottom waters and form $H_2S$-contaminated zones of the Black Sea or Norwegian type under favorable hydrodynamic conditions (Strakhov, 1976; Volkov, 1984; Kholodov, 2002a). In the case of $H_2S$ contamination of water of the Black Sea type, some diagenetic processes (microbiological decay of organic matter, sulfide formation, and others) take place not only in sediments but also in zones located significantly above the sediment–water interface (Sorokin, 1982; Volkov, 1984; Morozov, 1991a, 1991b; Volkov *et al.*, 1998; and others).

Enormous quantities of P, Mn, and other dissolved components diffuse from interstitial waters into seas and oceans even when bottom waters are characterized by oxidizing environments (Baturin, 2003; Sval'nov, 1991; and others).

Processes of sedimentation and diagenesis are strongly complicated by the vital activity of bottom organisms. Biogenic extraction (bioassimilation), biofiltration, biosorption, and biological transport of components at the water–sediment interface are responsible for the removal of many components from sediments and their redistribution in the water column (Lisitsyn, 1977; Vinogradov and Lisitsyn, 1981). Issue of the discrimination between subaqueous sedimentation and diagenesis is even more complicated by processes of bottom erosion, mobilization, and redeposition of terrigenous–clayey sediments in seas and oceans. Like on land, underwater landslides and avalanches accompanied by the formation of gravitites, turbidites, and contourites, as well as processes of erosion and redeposition of sedimentary material, disturb the normal course of subaqueous diagenetic transformations (Lisitsyn, 1974, 1977, 1988; Sval'nov, 1991).

Sedimentary material flows intermittently deviate from the periphery to the central parts of terminal basins (seas and oceans), reflecting capricious patterns of basin hydrodynamics. Therefore, it is difficult to discriminate between sedimentation and diagenesis in this situation and draw a distinct boundary between these processes.

As was repeatedly noted in lithological publications, the lower boundary of the diagenesis zone is also arbitrary. Shvetsov (1958, p. 32) asserted that "… the diagenetic stage terminates at different depths in various basins, environments, and rock sequences."

Developing this idea, Logvinenko and Orlova (1987, p. 54) wrote: "… indeed, where and how this boundary should be drawn? Based on changes of physical properties or parageneses of authigenic minerals? The boundary will be located at different levels on the basis of these principles. Moreover, the boundary between diagenesis and catagenesis zones based on physical properties in different sediment types will also be located at different."

Based on the curve of compaction (and dehydration) of clayey sediments in the Gulf of California (Emery and Rittenderg, 1952) and experimental data on water squeezing from clayey sediments obtained at Moscow

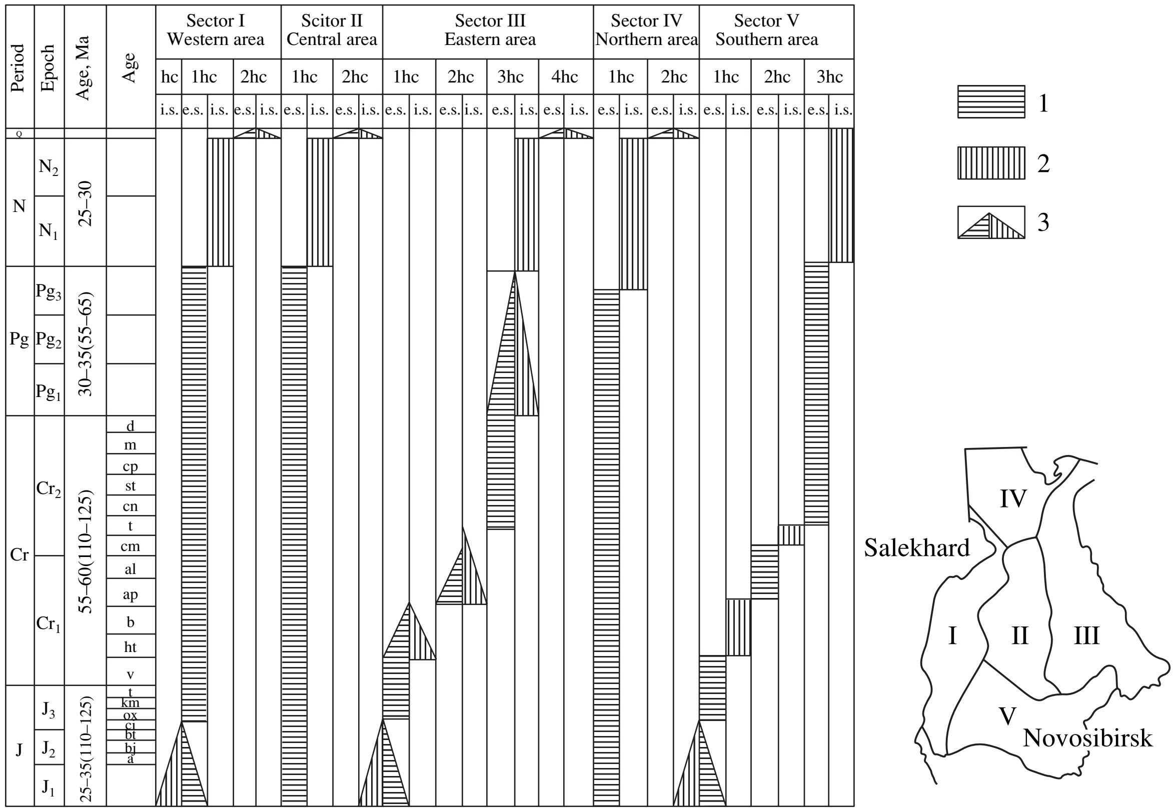



**Fig. 7.** Development of elision and infiltration processes in various areas of western Siberia (Kartsev *et al.*, 1969) (based on materials of I.V. Yavorchuk and T.I. Uvarova). (1) Elision stage (e.s.); (2) infiltration stage (i.s.); (3) local combination of elision and infiltration stages; (hc) hydrological cycles.

State University (Lomtadze, 1953), Strakhov concluded that the boundary between diagenesis and catagenesis zones in compacted clays is located at a depth of 250–300 m. A distinct bend is observed at the same depth interval in compaction curves compiled for clays and clayey sequences reported in (Vassoevich, 1966; Ozerskaya and Podoba, 1967; Avchan, 1972; Rike and Chilingarian, 1974; and others).

However, DSDP data show that the boundary between sediments and sedimentary rocks in the oceanic sedimentary cover is located at a significantly deeper level. Seismic study of the cover performed prior to deep-sea drilling (Nafe and Drake, 1967) revealed that sedimentary rocks are overlain by a 2-km-thick sequence of slightly compacted pelagic sediments. Later on, study of deep-sea cores obtained by the D/V *Glomar Challenger* showed that many holes did not penetrate the slightly compacted sediment zone, where the density of clayey and carbonate varieties ranges from 1.75 to 1.80 g/cm$^3$ at a depth of 50–1000 m (Kalinko, 1969; Sokolov and Konyukhov, 1975).

Sediment decompaction and inundation in oceans was explained in different ways (M.K. Kalinko, B.A. Sokolov, A.I. Konyukhov, L.A. Nazarkin, N.V. Logvinenko, L.V. Orlova, E.L. Hamilton, T.A. Davies, P. Sapko, and others). This stimulated researchers to revise old concepts concerning the lower boundary of the diagenesis zone and supplement the interval of active geochemical processes (250–300 m) with an almost 2-km-thick sequence of unconsolidated relatively inert sediments in deep zones of the ocean.

Thus, it is clear that all attempts to draw an exact formal boundary between sediment and rock "… would only be an example of false wisdom or sophistry in petrography" (Shvetsov, 1962, p. 229).

It is similarly difficult to separate different processes of catagenetic transformations. Indeed, when defining infiltration and elision basins, we take into consideration mainly *prevalent processes* of interaction between gas–water–oil fluids and sedimentary rocks. In natural environments, these processes are so intricately interlaced that it is often impossible to discriminate them.

This can be exemplified by the West Siberian Plate with separate regions characterized by different types of geological history and temporal relationships between infiltration and elision processes (Fig. 7). As follows from this diagram based on paleohydrological reconstructions reported in (Kartsev *et al.*, 1969, 1986), areas I, II, and IV were characterized by the prevalence of subsidences and elision processes throughout the Jurassic, Cretaceous, and Paleogene, while areas III

**Table 2.** Main stages of sedimentary rock formation modified after (Krasheninnikov, 1985)

| Stages | Main agent | Main process | Typification principle |
|---|---|---|---|
| I Mobilization | Weathering, soil formation, volcanism | Transformation of rock material into transportable state | Based on paleoclimate and paleotopography, eruption type and magma chemistry |
| II Transport | Dynamics and chemistry of transporting environments | Transport of material under active environments | Based on phase state of environments and transport distance |
| III Accumulation | Gravity, living organisms, chemistry and dynamics of environments | Formation of insoluble compounds, deposition, and fixation of sediments at the bottom | Based on physiographic settings (genetic types and facies) |
| IV Subaerial and subaqueous diagenesis | Ground and interstitial waters, organic matter | Biochemical decay of organic matter, transformation of sediment into rock | Based on physicochemical conditions in mud |
| V Catagenesis | Temperature, pressure, formation waters, gases, oil | Interaction between oil–gas–water solutions and sedimentary rocks | Based on catagenetic zoning type |

and V were marked by alternating elision and infiltration processes. Regional uplifts in the framing of the West Siberian Lowland in the Neogene provoked a wide development of infiltration processes in the entire region.

These paleohydrological interpretations undoubtedly need reliable confirmation by mineralogical–geochemical data. Study and dating of catagenetic zonation of sedimentary sequences in western Siberia should make it possible to decipher the intricate scenario of these processes. Consequently, issue of the genesis of oil and gas deposits can be more reliably and confidently solved.

## CONCLUSIONS

Facts and assumptions discussed above make it possible to conclude that stages in lithogenesis are *arbitrary* subdivisions of the *idealized* model of sedimentary process.

They cannot be applied to all versions of the sedimentary process. The stages presumably outline the temporal succession of processes in the general evolution of events, i.e., specific boundaries that help us to systematize educational and scientific materials.

It is also evident that the formal subdivision of stages only complicates the understanding of real processes involved in the formation of sedimentary rocks and ores. In most cases, this issue is insufficiently studied.

In my opinion, the system proposed by Krasheninnikov (1985) is the most rational model of main stages of sedimentary rock formation. As can be seen in the slightly modified version (Table 2), this system differs from other models by logic substantiation and simplicity. It lacks superstages, which substantially complicate the general scenario of the process. Stages defined in this system can undoubtedly serve as a basis for any modern curriculum on lithology, petrography of sedimentary rocks, or geochemistry of sedimentary process.

However, it should be emphasized that the scheme illustrated in Table 2 is far from being universal and the ranges of defined stages need substantial refinements.

Facts mentioned above compel us to be very careful with attempts of some lithologists to solve the problem of stages by the deductive method based on theoretical reasonings and *a posteriori* confirmations by mineralogical data. Such an approach canonizes the current, quite imperfect knowledge of lithogenetic stages and does not stimulate progress in lithology.

Further refinement of stadial analysis is undoubtedly related to inductive empirical studies based on the analysis of minerals, their parageneses, and spatiotemporal relationships (particularly, in the field of postsedimentary transformations). The investigations should lean upon thoroughly examined cross sections and boreholes sections, which would make it possible to reconstruct the general mineralogical–geochemical and hydrogeological zoning of the sedimentary rock basin. Correlation of this zoning with facies and lithological features of sedimentary sequences will allow us to reconstruct physicochemical processes that were active at different stages of lithogenesis.

Knowledge of processes of mineral formation and geochemical–mineralogical zoning will hopefully serve as a proxy for refining the stadial system of lithogenesis.

## ACKNOWLEDGMENTS

This work was supported by the grant of the President of the Russian Federation for Leading Scientific Schools (NSh-1440 2003.5) and the Russian Foundation for Basic Research (project no. 01-05-64722).

## REFERENCES

Allen, J.R.L., Studies in Fluviatile Sedimentation: Implications of Pedogenic Carbonate Units, Lower Old Sandstone, Angio-Weish Outcrop, *Geol. J.*, 1974, no. 9, pp. 181–208.

Ammosov, I.I. and Gorshkov, V.I., Paleotemperatures of Oil-Bearing Rocks, *Problemy diagnostiki uslovii i zon nefteobrazovaniya* (Problems of the Diagnostics of Oil Formation Conditions and Zones), 1971, Moscow: IGIRGI, pp. 19–30.

Avchan, G.M., *Fizicheskie svoistva osadochnykh porod pri vysokikh davleniyakh i temperaturakh* (Physical Properties of Sedimentary Rocks under High Pressures and Temperatures), Moscow: Nedra, 1972.

Batulin, S.G., The Uranium Content in Mountain Rivers with Mixed Sources, *Ocherki geokhimii endogennykh i gipergennykh processov* (Outlines of Geochemistry of Endogenic and Hypergene Processes), Moscow: Nauka, 1966, pp. 271–273.

Baturin, G.N., Phosphorus Cycles in the Ocean, *Litol. Iskop.*, 2003, vol. 38, no. 2, p.126 [*Litol. Mineral. Resour.* (Engl. Transl.), vol. 38, no. 2, p. 101–119].

Black, B.J., Sedimentation in Some Scottish Rivers of Low Sinuosity, *Trans. R. Soc. Edinburgh*, 1976, vol. 69, pp. 425–456.

Bushinskii, G.I., Sedimentation Environments of Siderites, Vivianites, and Brown Iron Ores in Bogs of Belarus, *Byull. Mos. O–va Ispyt. Prir., Otd. Geol.*, 1946, vol. 21, no. 3, pp. 65–80.

Bushinskii, G.I., *Apatit, fosforit, vivianit* (Apatite, Phosphorite, and Vivianite), Moscow: Akad. Nauk SSSR, 1952.

Butler, G.P., Harris, P.M., and Kendall, C.G., Recent Evaporites from the Abu Dhabi Coastal Flats, Deposition and Diagenetic Spectra of Evaporites, *SEPM Core Workshop, Calgary*, 1982, no. 3, pp. 33–64.

Emery, K.O. and Rittenberg, S., Early Diagenesis of California Basin Sediments in Relation to Origin of Oil, *Bull. Am. Assoc. Petrol. Geol.*, 1952, vol. 5, pp. 23–68.

Fairbridge, A.P., Diagenesis Phases and Authigenic Mineral Formation, *Diagenesis in Sediments*, Larsen, G. and Chilingar, G. (Eds.), Amsterdam: Elsevier, Amsterdam, 1967. Translated under the title *Diagenez i katagenez osadochnykh obrazovanii*, Moscow, Mir, 1971.

Feofilova, A.P., Concretions in Buried Soils of Carboniferous–Permian Sequences in the Donets Basin and Their Relation to Climate, *Litol. Polezn. Iskop.*, 1972, no. 5, pp. 28–54.

Feofilova, A.P., *Iskopaemye pochvy karbona i permi Donbassa* (Carboniferous and Permian Buried Soils of Donbas), Moscow, Nauka, 1975.

Fersman, A.E., *Geokhimiya Rossii* (Geochemistry of Russia), Petrograd: NKhTI, issue 1, 1922.

Friedman, J.M. and Sanders, J.I., Dolomite Genesis and Distribution, in *Carbonate Rocks: Origin, Occurrence and Classification*, Chilingar, G., Fairbridge, R., Bissel, J. *et al.* (Eds.), Amsterdam: Elsevier, vol. 1, 1967. Translated under the title *Karbonatnye porody: genezis, rasprostranenie, klassifikatsiya*, Moscow: Mir, 1970.

Gerasimov, I.P., Buried Soils and Their Paleogeographic Significance, *Materialy vserossiiskogo soveshchaniya po izucheniyu chetvertichnogo perioda* (Materials of the All-Russian Meeting on the Quaternary Study), Akad. Nauk SSSR, 1961, vol. 1, pp. 23–44.

Hummel, K., Die Entstehung eisenricher Gestain durch Halmyrolise, *Geol. Rundschau*, 1923, vol. 13, no. 1, pp. 38–54.

Kalinko, M.K., *Neftegazonosnost' akvatorii mira* (Oil- and Gas-Bearing Potential of Oceans and Seas, Moscow: Nedra, 1969.

Karpova, G.V., *Glinistye mineraly i ikh evolyutsiya v terrigennykh osadkakh* (Clay Minerals and Their Evolution in Terrigenous Sediments), Moscow: Nedra, 1969.

Kartsev, A.A., Vagin, S. B., and Baskov, E.A., *Paleogidrologiya* (Paleohydrology), Moscow: Nedra, 1969.

Kartsev, A.A., Vagin, S.B., and Matusevich, V.M., *Gidrologiya neftegazonosnykh basseinov* (Hydrology of Oil- and Gas-Bearing Basin), Moscow: Nedra, 1986.

Keller, W.D., Flint Clay and Flint Clay Facies, *Clays Clay Miner.*, 1968, vol.16, no. 2, pp. 82–96.

Khalezov, A.B., Uranium Deposits at the Southern Margin of the West Siberian Lowland, *Geologiya mestorozhdenii urana, redkikh i redkozemel'nykh elementov* (Geology of Uranium, Rare, and Rare Earth Element Deposits), Moscow: VIMS, 1993, issue 135, pp. 45–64.

Kholodov, V.N., *Osadochnyi rudogenez i metallogeniya vanadiya* (Sedimentary Ore Genesis and Vanadium Metallogeny), Moscow: Akad. Nauk. SSSR, 1973.

Kholodov, V.N., New Data in the Study of Catagenesis: Communication 1. Infiltrational and Gravitational–Brine Catagenesis, *Litol. Polezn. Iskop.*, 1982a, no. 3, pp. 3–32.

Kholodov, V.N., New Data in the Study of Catagenesis: Communication 2. Elisional Catagenesis, *Litol. Polezn. Iskop.*, 1982b, no. 5, pp. 15–48.

Kholodov, V.N., *Postsedimentatsionnye preobrazovaniya v elizionnykh basseinakh (na primere Vostochnogo Predkavkaz'ya* (Postsedimentary Transformations in Elision Basins (Evidence from the Eastern Ciscaucasia), Moscow: Nauka, 1983a.

Kholodov, V.N., Formation of Gas–Water Solutions in Sandy–Clayey Sequences of Elision Basins, *Osadochnye basseiny i ikh neftegazonosnyi potentsial* (Sedimentary Basins and Their Oil- and Gas-bearing Potential), Moscow: Nauka, 1983b, pp. 28–45.

Kholodov, V.N., Types of Catagenesis and Sedimentary–Hydrothermal Ore Formation, *Podzemnye vody i evolyutsiya litosfery* (Underground Waters and Evolution of the Lithosphere), Moscow: Nauka, 1985, vol. 1, pp. 236–253.

Kholodov, V.N., Sedimentary Shell as a Possible Source of Hydrothermal Solutions, *Priroda*, 1990, no. 4, pp.10–17.

Kholodov, V.N., Problem of the Genesis of Mineral Deposits in Elision Basins: Communication 1. The Cheleken-Boyadag Hydrothermal System, *Litol. Polezn. Iskop.*, 1991, no. 2, pp. 104–123.

Kholodov, V.N., Model of the Elision Ore-Forming System and Some Problems of Hydrothermal–Sedimentary Ore Formation, *Redkometal'no-uranovaya mineralizatsiya v osadochnykh porodakh* (Rare Metal–Uranium Mineralization in Sedimentary Rocks), Moscow: Nauka, 1995, pp. 195–205.

Kholodov, V.N., Mud Volcanoes, Their Distribution Regularities and Genesis: Communication 1. Mad Volcanic Provinces and Morphology of Mud Volcanoes *Litol. Polezn. Iskop.*, 2002a, vol. 37, no. 3, pp. 227 [*Litol. Miner. Resour.* (Engl. Transl.), vol. 37, no. 3, p. 197–209].

Kholodov, V.N., Mud Volcanoes, Their Distribution Regularities and Genesis: Communication 2. Geological–Geochemical Peculiarities and Formation Model, *Litol. Polezn. Iskop.*, 2002b, vol. 37, no. 4, p. 339 [*Litol. Miner. Resour.* (Engl. Transl.), vol. 37, no. 4, pp. 293–393].

Kholodov, V.N., Geochemistry of Elisional Catagenesis and Black Shale Ore Formation, *Izv. Sektsii Nauk Zemle Ross. Akad. Estestv. Nauk*, 2002c, issue 8, pp. 125–141.

Kholodov, V.N., The Role of $H_2S$-Contaminated Basins in Sedimentary Ore Formation, *Litol. Polezn. Iskop.*, 2002d, vol. 37, p. 451 [*Litol. Miner. Resour.* (Engl. Transl.), vol. 37, no. 5, pp. 393–411].

Kholodov, V.N., Geochemistry of Phosphorus and Origin of Phosphorites: Communication 2. Sources of Phosphorus on Continents and Genesis of Marine Phosphorites, *Litol. Polezn. Iskop.* (in press).

Kholodov, V.N., and Butuzova, G.Yu., Problem of the Genesis of Metalliferous Solutions and Stratiform Deposits in Redrocks, *Litogenez i rudoobrazovanie* (Lithogenesis and Ore Formation), Moscow: Nauka, 1989, pp. 157–176.

Kholodov, V.N., and Kiknadze, Z.P., *Kolchedannye mestorozhdeniya Bol'shogo Kavkaza* (Massive Sulfide Deposits of the Greater Caucasus), Moscow: Nauka, 1989.

Kholodov, V.N. and Nedumov, R.I., Zone of Catagenetic Hydromicatization of Clays–An Area of Intense Redistribution of Chemical Elements: Communication 1. Geological–Lithological Features and Formation Mechanism of Elision Systems in the Ciscaucasian Region *Litol. Polezn. Iskop.*, 2001a, vol. 36, no. 6, pp. 563–582 [*Litol. Miner. Resour.* (Engl. Transl.), vol. 36, no. 6, pp. 493–510].

Kholodov, V.N. and Nedumov, R.I., Zone of Catagenetic Hydromicatization of Clays–An Area of Intense Redistribution of Chemical Elements: Communication 2. Mineralogical–Geochemical Peculiarities of the Zone of Catagenetic Illitization, *Litol. Polezn. Iskop.*, 2001b, vol., 36, no. 6, pp. 582–610 [*Litol. Miner. Resour.* (Engl. Transl.), vol. 36, no. 6, pp. 511–536].

Kholodov, V.N., Nedumov, R.I., and Grigor'yants, B.V., Catagenesis and Deformations of Cenozoic Rocks in Chernye Gory, Ciscaucasus, *Litol. Polezn. Iskop.*, 1998, vol. 33, no. 5, pp. 504–534 [*Litol. Miner. Resour.* (Engl. Transl.), vol. 33, no. 5, pp. 451–468].

Kholodov, V.N., Petrova, R.N, and Dement'eva, O.F., Problem of the Formation of Secondary Porosity in Sandy Reservoirs of Elision Basins, *Kollektorskie svoistva porod na bol'shikh glubinakh* (Reservoir Properties of Rocks at Great Depths), Moscow: Nauka, 1985, pp. 58–72.

Kondrat'eva, I.A. and Nesterova, M.V., Lithogeochemical Features of Uranium Deposits in Mesozoic River Paleovalleys, *Litol. Polezn. Iskop.*, 1997, vol. 32, no. 6, pp. 577–595 [*Litol. Miner. Resour.* (Engl. Transl.), vol. 32, no. 6, pp. 505–520].

Konoplev, A.D. and Maksimova, M.F., Litholofacies and Mineralogical–Geochemical Peculiarities of Deposits in Paleovalleys, *Sov. Geol.*, 1989, no. 11, pp. 89–96.

Koporulin, V.I., *Sostav, fatsii i usloviya obrazovaniya uglenosnykh razrezov tsentral'noi chasti Irkutskogo basseina* (Composition, Facies, and Formation Conditions of Coal-Bearing Sequences in the Central Irkutsk Basin), Moscow: Akad. Nauk SSSR, 1966.

Kossovskaya, A.G., *Mineralogiya terrigennogo mezozoiskogo kompleksa Vilyuiskoi vpadiny i Zapadnogo Verkhoyan'ya* (Mineralogy of the Mesozoic Terrigenous Complex in the Vilyui Depression and Western Verkhoyansk Region), Moscow: Akad. Nauk SSSR, 1962.

Kossovskaya, A.G. and Shutov, V.D., Problem of Epigenesis, *Epigenez i ego mineral'nye indicatory* (Epigenesis and Its Mineral Indicators), Moscow: Nauka, 1971, pp. 9–35.

Kossovskaya, A.G. and Shutov, V.D., Mineral Indicators of Geotectonic Types of Regional Epigenesis and Its Relationship with Metamorphism on Continents and in Oceans, *Kristallokhimiya mineralov i geologicheskie problemy* (Crystal Chemistry of Minerals and Geological Problems), Moscow: Nauka, 1975, pp. 19–35.

Kossovskaya, A.G., Drits, V.A, and Sokolova, T.N., Specifics of Clay Mineral Formation in Various Facies and Climatic Settings, *Epigenez i ego mineral'nye indicatory* (Epigenesis and Its Mineral Indicators), Moscow, Nauka, 1971, pp. 35–54.

Kovalev, V.A., *Bolotnye mineral'no-geokhimicheskie sistemy* (Mineralogical–Geochemical Systems of Bogs), Minsk: Nauka Tekhn., 1985.

Kovda, V.A., *Proiskhozhdenie i rezhim zasolenykh pochv* (Origin and Regime of Salted Soils), Moscow: Akad. Nauk SSSR, 1947, vol. 2.

Kovda, V.A., Geochemistry of Deserts in the Soviet Union, *Doklady na 5-m Mezhdunarodnom kongresse pochvovedov* (Reports at the 5th International Pedological Congress), Moscow: Akad. Nauk SSSR, 1954, pp. 68–84.

Krasheninnikov, G.F., Works of L.V. Pustovalov and Modern Lithology, *Problemy formirovaniya ekzogennykh i metamorfogennykh porod i rud* (Problems of the Exogenic and Metamorphogenic Rock and Ore Formation), Moscow: Nauka, 1985, pp. 8–18.

Kunin, V.N., *Mestnye vody pustyn' i problemy ikh ispol'zovaniya* (Local Waters in Deserts and Problems of Their Usage), Moscow: Akad. Nauk SSSR, 1959.

Leeder, M.R., Pedogenic Carbonate and Flood Sediments Accretion Rates: A Quantitative Model for Alluvial, Arid-zone Lithofacies, *Geol. Mag.*, 1975, vol. 112, pp. 257–270.

Lisitsyn, A.P., *Osadkonakoplenie v okeanakh* (Sedimentation in Oceans), Moscow: Nauka, 1974.

Lisitsyn, A.P., Terrigenous Sedimentation, Climatic Zonality, and Interrelation between Terrigenous and Biogenic Material in the Ocean, *Litol. Polezn. Iskop.*, 1977, no. 6, pp. 3–22.

Lisitsyn, A.P., *Lavinnaya sedimentatsiya i pereryvy v osadkonakoplenii v moryakh i okeanakh* (Avalanche Sedimentation and Hiatuses in Seas and Oceans), Moscow: Nauka, 1988.

Luchinin, I.I., Pashkov, P.A., Dement'ev, P.K., *et al.*, Uranium Deposits in Paleovalleys of the Transural and TRansbaikal Regions, *Razv. Okhrana Nedr*, 1992, no. 5, pp. 12–15.

Logvinenko, N.V., *Postdiageneticheskie izmeneniya osadochnykh porod* (Postdiagenetic Alterations of Sedimentary Rocks), Moscow: Nauka, 1968.

Logvinenko, N.V., *Petrografiya osadochnykh porod s osnovami metodiki issledovaniya* (Petrography of Sedimentary Rocks with Principles of Investigation Methods,) Moscow: Vysshaya Shkola, 1984.

Logvinenko, N.V. and Orlova, L.V., *Obrazovanie i izmenenie osadochnykh porod na kontinente i v okeane* (Formation and Alteration of Sedimentary Rocks on Continents and in Oceans), Moscow: Nedra, 1987.

Lomtadze, V.D., Change in Clays Moisture during Their Compaction under High Loads, *Zap. Leningrad. Gorn. Inst.*, 1953, vol. 29, no. 2, pp. 32–46.

Makhnach, A.A., *Stadial'nyi analiz litogeneza* (The Stadial Analysis of Lithogenesis) Minsk: Belorus. Gos. Univ., 2000.

Morozov, A.A., Some Features of Late Quaternary Sedimentation in the Black Sea: Communication 1. Bottom Sediments and Distribution Peculiarities of Diagenetically Active Components, *Litol. Polezn. Iskop.*, 1991a, no. 4, pp. 20–32.

Morozov, A.A., Some Features of Late Quaternary Sedimentation in the Black Sea: Communication 2. Formation of Labile Iron Forms, *Litol. Polezn. Iskop.*, 1991b, no. 5, pp. 19–32.

Nafe, J.E. and Dracke, C.L., Variation with Depth in Shallow and Deep Water Marine Sediments of Porosity, Density and Velocities of Compressional and Shear Waves, *Geophysics*, 1957, vol. 22, pp. 523–552.

Nalivkin, D.V., *Uchenie o fatsiyakh* (Treatise on Facies), Moscow: Akad. Nauk SSSR, 1956, vol. 2.

Orlov, A.N., Vivianites from the Western Part of the European Soviet Union, Tr. Tsentr. Opyt, Stantsii), 1939, vol. 7, pp. 9–62.

Ozerskaya, M.L. and Podoba, N.V., *Fizicheskie svoistva osadochnykh porod na territorii SSSR* (Physical Properties of Sedimentary Cover in the USSR Territory), Moscow: Nedra, 1967.

Patrunov, D.K. and Golubovskaya, T.N. Bays, Straits, and Lagoons, *Sovremennoe karbonatoobrazovanie. Dostizheniya v nauke i tekhnike. Obshchaya geologiya* (Recent Carbonate Formation: Achievements in Science and Technique. General Geology), Moscow: Gos. Komit. Nauke Tekhn. SSSR, 1976, vol. 7, pp. 67–72.

Pustovalov, L.V., *Petrografiya osadochnykh porod* (Petrography of Sedimentary Rocks), Moscow: GONTI, 1940.

Raynal, R., Dewolf, Y., and Joly, F., Repartitions des types de croutes calcaires en Afrique du Nord, *Colloq. Types croutes calcaire et repart. reg.*, Strasbourg, 1975, pp. 139–143.

Retallack, G.G., *Soil of the Past*, London: Unwin.-Hyman, 1990.

Riecke, H.H. and Chilingarian, G.V., *Compaction of Argillaceous Sediments*, Amsterdam: Elsevier, 1974.

Rukhin, L.B., *Osnovy litologii* (Fundamentals of Lithology), Leningrad: GONTI, 1953.

Shvetsov, M.S., *Petrografiya osadochnykh porod* (Petrography of Sedimentary Rocks), Moscow: Gos. Izd. Geol. Liter., 1948, 2nd ed.

Shvetsov, M.S., *Petrografiya osadochnykh porod* (Petrography of Sedimentary Rocks), Moscow: Gosgeoltekhizdat, 1958, 3rd ed.

Shvetsov, M.S., Processes of the Transformation of Sediments into Rocks (Halmyrolysis, Diagenesis, Exodiagenesis, and Metadiagenesis), *Problemy litologii i mineralogii osadochnykh porod* (Problems of Lithology and Mineralogy of Sedimentary Rocks), Baku: Akad. Nauk AzSSR, 1962, pp. 219–229.

Sidorenko, A.V., Main Features of Mineral Formation in Desert, *Problemy mineralogii osadochnykh porod* (Problems of the Mineralogy of Sedimentary Rocks), Lvov: Lvov Gos. Univ., 1956, parts 3/4, pp. 516–543.

Sidorenko, A.V., Calcareous Accumulations (Caliche) in Deserts of Mexico, *Izv. Akad. Nauk SSSR. Ser. Geol.*, 1958, no. 1, pp. 24–52.

Simanovich, I.M. and Yapaskurt, O.V., Geodynamic Types of Postsedimentary Lithogenetic Processes, *Vestn. Mos. Gos. Univ. Ser. 4: Geol.*, 2002, no. 6, pp. 20–31.

Sokolov, B. A. and Konyukhov, A.I., Specific Features of Diagenesis in Deepwater Sediments and Problem of Oil and Gas Prospecting in Oceans, *Vestn. Mos. Gos. Univ. Ser. 4: Geol.*, 1975, no. 3, pp. 59–63.

Sorokin, Yu.I., *Chernoe more (sreda, resursy)* (The Black Sea: Environments and Resources), Moscow: Nauka, 1982.

Schreiber, B.C., Taker, M.E., and Till, S., Coasts of Arid Zones and Evaporites, in *Sedimentary Environments and Facies*, Reading, H.G. (Ed.), Oxford: Oxford Univ. Press, 1978. Translated under the title *Obstanovki osadkonakopleniya i fatsii*, Moscow: Mir, 1990.

Strakhov, N.M., Diagenesis of Sediments and Its Significance for Sedimentary Ore Formation, *Izv. Akad. Nauk SSSR. Ser. Geol.*, 1953, no. 5, 12–49.

Strakhov, N.M., Perception of Diagenesis, *Problemy mineralogii osadochnykh porod* (Problems of the Mineralogy of Sedimentary Rocks), Lvov: Lvov Gos. Univ., 1956, Books 3–4, pp. 7–26.

Strakhov, N.M., *Osnovy teorii litogeneza* (Fundamentals of the Theory of Lithogenesis), Moscow: Akad. Nauk SSSR, 1960, vol. 1.

Strakhov, N.M., *Tipy litogeneza i ikh evolyutsiya v istorii Zemli* (Types of Lithogenesis and Their Evolution in the Earth's History), Moscow: Gosgeolizdat, 1963.

Strakhov, N.M., *Problemy geokhimii sovremennogo okeanskogo litogeneza* (Problems of the Geochemistry of Recent Oceanic Lithogenesis), Moscow: Nauka, 1976.

Strakhov, N.M. and Logvinenko, N.V., Stages of Sedimentary Rock Formation and Their Nomenclature, *Dokl. Akad. Nauk SSSR*, 1959, vol. 125, pp. 389–392.

Sval'nov, V.N., Geochemical Heterogeneities in the Pelagic Section as an Indicator of Hiatus, *Litol. Polezn. Iskop.*, 1986, no. 6, pp. 28–44.

Sval'nov, V.N., *Dinamika pelagicheskogo litogeneza* (Dynamics of Pelagic Lithogenesis), Moscow: Nauka, 1991.

Timofeev, P.P., Problems of the Study of Sedimentary Formations, *Formatsii osadochnykh basseinov* (Formations of Sedimentary Basins), Moscow: Nauka, 1986, pp. 3–9.

Timofeev, P.P., Aspects of the Development the Science of Sedimentary Formations (Theory of Formation Analysis), *Litol. Polezn. Iskop.*, 1994, no. 6, pp. 3–23.

Timofeev, P.P., and Bogolyubova, L.I., Facies and Alterations of Clay Minerals in Peats of the Rioni Intermontane Trough, *Litol. Polezn. Iskop.*, 1972, no. 3, pp. 48–75.

Tvenhofel, W.H. *et al.*, *Treatise on Sedimentation*, Baltimore: Williams and Wilkins, 1932. Translated under the title *Uchenie ob obrazovanii osadkov*, Moscow: ONTI NKTP SSSR, 1936.

Vassoevich, N.B., Terminology Applied for the Designation of Lithogenetic Stages and Phases, *Geol. Geokhim.*, 1957, vol. 1, no.7, pp. 156–176.

Vassoevich, N.B., Experience of Construction of Type Curve for Gravitational Compaction of Clayey Sediments, *Novosti Neftyan. Tekhn. Geol*, 1960, no. 4, pp. 11–15.

Vassoevich, N.B., Supplement to Terminology for the Designation of Lithogenetic Stages and Phases, *Tr. VNIGRI. Geol. Sbornik*, 1962, vol. 190, no. 7, pp. 220–243.

Vassoevich, N.B., Preface and Notes to *Diagenesis and Catagenesis of Sedimentary Rocks, Diagenez i katagenez osadochnykh porod* (Diagenesis and Catagenesis of Sedimentary Rocks), Moscow: Mir, 1971, pp. 5–8.

Vassoevich, N.B., Some Terms Related to the Study of Organic Matter and Sedimentary Rocks, *Organicheskoe veshchestvo sovremennykh i drevnikh osadkov* (Organic Matter of Recent and Ancient Sediments, Moscow: Nauka, 1971, pp. 218–238.

Vassoevich, N.B., Vysotskii, I.V., Guseva, A.N., *et al.*, Hydrocarbons in the Earth's Sedimentary Cover, *Vestn. Leningrad. Gos. Univ. Ser. 4: Geol.*, 1967, no. 5, pp. 36–48.

Vinogradov, M.E. and Lisitsyn, A.P., Global Regularities in the Distribution of Life in the Ocean and Their Reflection in Bottom Sediments: Regularities in Plankton and Benthos Distribution in the Ocean, *Izv. Akad. Nauk SSSR. Ser. Geol.*, 1981, no. 3, pp. 28–76.

Volkov, I.I., Main Regularities in the Transformation of Organic Matter during the Early Diagenesis of Recent Sediments, *Geokhimiya diageneza v osadkakh Tikhogo okeana (Trans-Tikhookeanskii profil')* (Geochemistry of Diagenesis in Sediments of the Pacific (Transpacific Profile)), Moscow: Nauka, 1980, pp. 99–106.

Volkov, I.I., *Geokhimiya sery v osadkakh okeana* (Sulfur Geochemistry in Oceanic Sediments), Moscow: Nauka, 1984.

Volkov, I.I., Diersenn, D., and Rozanov, A.G., Problem of Water Alkalinity and Anaerobic Mineralization of Organic Matter in the Black Sea, *Geokhimiya*, 1998, no. 1, pp. 78–88.

Walter, J., *Lithogenesis der Gegenwart. 1.3 Einleitung in die Geologie des historische Wissenschaft*, 1894.

Warren, J.K., The Hydrological Setting, Occurrence and Significance of Gypsum in Late Quaternary Salt Lakes in South Australia, *Sedimentology*, 1982, vol. 29, pp. 609–638.

Warren, J.K., On the Significance of Evaporite Lamination, in *Sixth Salt Symposium*, Cleveland: Northern Ohio Geol. Soc., 1985, pp. 15–32.

West, J.M., All, V.A., and Hilmy, M.E., Primary Gypsum Nodules in a Modern Sabkha on the Mediterranean Coast of Egypt, *Geoloogy*, 1979, vol. 7, pp. 354–358.

Yaalon, D.H., Some Data on the Nature and Origin of Nari (Calcrete) on Chalk in Israel, *Colloq. Types croutes calcaires et repart reg.*, Strasbourg, 1975, pp 12–13.

Yakimenko, E.Yu., Targul'yan, V.O., Chumakov, N.M., *et al.*, Paleosols in Upper Permian Sedimentary Rocks, Sukhona River (Severnaya Dvina Basin), *Litol. Polezn. Iskop.*, 2000, vol. 35, no. 4, pp. 376–391 [*Litol. Miner. Resour.* (Engl. Transl.), vol. 35, no. 4, p. 331–343].

Yapaskurt, O.V., *Stadial'nyi analiz litogeneza* (The Stadial Analysis of Lithogenesis), Moscow: Mos. Gos. Univ., 1985.

Yapaskurt, O.V., *Litogenez v osadochnykh basseinakh miogeosinklinalei* (Lithogenesis in Sedimentary Basins of Miogeosynclines), Moscow: Mos. Gos. Univ., 1989.

Yapaskurt, O.V., *Predmetamorficheskie izmeneniya osadochnykh porod v stratisfere. Protsessy i faktory* (Premetamorphic Alterations of Sedimentary Rocks in the Earth's Sedimentary Cover: Processes and Factors), Moscow: GEOS, 1999.

Zavaritskii, A.N., *Vvedenie v petrografiyu osadochnykh porod* (Introduction to Petrography of Sedimentary Rocks), Moscow: GONTI, 1932).