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GEOLOGY

Loss of Concentrated Organic Matter by Rocks during Catagenesis: A Factor of Geodynamic Destabilization

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Rocks with concentrated organic matter can be exemplified by oil shales,[1] where solid organic matter (OM) is one of the rock-forming components. Sapropel oil shales with OM content of 20% and higher[2] are widespread in the Precambrian–Holocene sections and characterized by very large reserves [1].

It is considered that typical oil shales are only confined to early catagenetic stages and such high-carbonaceous rocks are absent at later stages. Black shales and, less commonly, ordinary limestones, marls, and other rocks with low OM contents are viewed as their metamorphic OM-depleted analogues. High-carbonaceous rocks are converted into low-carbonaceous varieties during catagenesis and prograde transformation of the organic matter of shales. This process is accompanied by the formation and removal of large quantities of mobile products: H_2O, CO_2, H_2S, H_2, and hydrocarbons (HC) and their derivatives. The loss of OM by the end of catagenesis is as much as two-thirds of its initial quantity [2].

Thus, regional reduction of oil shales is determined (and accompanied) by generation of fluids, hydrocarbons included. The amount of oil generated during the decay of shales is comparable with that of oil produced by dispersed OM of ordinary source rocks [1]. Therefore, the phenomena of the reduction of OM in shales are of great interest.

One such phenomenon accompanying the decay and removal of OM is the simultaneous increase in the rock porosity. The reality of such processes in the Earth's interior is indicated by experimental works of Kalinko devoted to the heating of samples from the Bazhenovo Formation. The results obtained demonstrated that increase in the porosity of rocks is related to OM destruction [3]. In addition, the lower density of OM (approximately 1 g/cm^3) as compared with that of mineral substance makes the OM a significant volumetric component in the rocks under consideration.

In order to elucidate this phenomenon, let us compare weight and volumetric OM contents for kukersites of the Baltic region. Although the average kukersite has rather similar weight contents of OM and carbonates (35 and 40 wt %, respectively), their volumetric contents are appreciably different (54 and 25 vol %, respectively). Thus, the removal of equal weight contents of mineral and organic substances from the rock should result in higher contribution of the OM into formation of the secondary porosity. Therefore, the destruction of OM is considered as one of the main factors responsible for autonomous structural deformations (fissuring, brecciation, and others) related to the contraction and thinning of kukersites during their local destruction [4 and others].

The increase in porosity in the course of OM removal gives way to rock deformation at a certain stage, resulting in the formation of fractures related to the percolation of fluids along OM-rich microlaminae and relevant weakened zones in rock beds. The formation of weakened zones is accompanied by changes in some physical rock properties, such as porosity, permeability, density, and others. For example, fluid permeability in such rocks increases up to the point of their transformation into reservoirs in some places [3 and others]. The beds can lose their integrity in areas characterized by the intense removal of matter and the consequent loss of rock rigidity and solidity (Fig. 1).

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[1] Other rocks with concentrated organic matter (coals and other varieties) are not considered here.

[2] Some researchers attribute rocks with the OM content of 10% and higher to oil shales.

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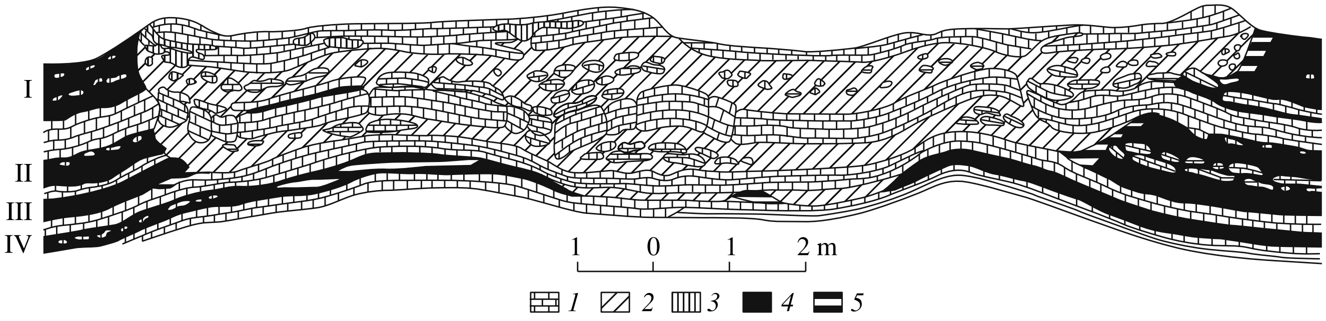

Fig. 1. Deformation, brecciation, and subsidence of limestone interbed I/II and practically complete destruction of interbed II/III due to local epigenetic thinning of oil shale beds II and III. The thinning of shale beds is determined by the almost complete removal of organic matter and carbonates and is traced by the terrigenous shale relict. Baltic shale basin, Leningrad deposit, O_2kk, early catagenesis, mine 2, panel drift 2 (modified after [8]). (*1*) Limestone; (*2*) terrigenous shale relict; (*3*) brown clay; (*4*) oil shale; (*5*) altered oil shale. (I–IV) oil shale beds.

Deformational changes inside beds are aggravated by their gradual thinning. For example, the expansion of shales at depths of 1–2 km in the North Caspian Depression can be as much as 60 vol % [2]. According to [6], thinning of mudstones of the Menilite Formation in the course of oil and gas generation is equal to 15–30 vol % (locally, 50 vol %).

The effect of thinning is intensified by destruction of carbonate and some other components of shales by aggressive products of OM transformation (CO_2, H_2S, and organic acids). The deformational effect of rock contraction is also aggravated by lateral variability of OM concentration in beds. The OM concentration within the same kukersite beds may differ 2.0–2.5 times, e.g., 16.6– 45.0 wt % in bed C and 0.0–9.7 wt % in the limy interbed C/D [8].

The irregular lateral distribution of OM provokes irregular catagenetic losses and, correspondingly, irregular thinning and contraction of the bed. For example, respective potential contraction of oil shales and coals (initial thickness 70–180 and 8–120 m, respectively) in the Fushun deposit (China) as the result of complete catagenesis should be equal to ~18.7–112.8 m [9].

The irregular thinning of the bed is responsible for autonomous deformations (flexure-shaped bending of the roof and overlying bed, crushing, and brecciation; development of vertical fissures and formation of block-shaped bed with gentle benches; complication of the hypsometric position of its surface; and others).[3]

In this case, overlying sediments should adapt to the irregular contraction of beds. The adaptation is manifested as irregular subsidence above different-scale weakened zones up to the point of the loss of rock solidity and the formation of vertical fissures, crush zones, blocks, micrograbens, and dip-slip faults (Fig. 2). In homoclinal areas, rocks of the weakened zones become mobile and they can form folds and slip downward.

The loss of organic matter (and other components) should be accompanied by micro- and macrodistortions of the rock up to the point of the loss of its rigidity, solidity, disintegration, and previous compactness. At terminal catagenetic stages, residual material of some lenses and interbeds are converted into a new "postcarbonaceous" rock with new physicomechanical properties. The appearance of irregularly consolidated sectors in the section fosters the redistribution of stresses with the squeezing out and displacement of delithified rocks along weakened interlayer zones and fissures between rigid blocks. Such displaced rocks may form dike- and stock-shaped bodies during their further subsidence and lithification.

The repeated alternation of the stressed-strained state and intensification of rock dislocations creates additional conduits in line with the concept of conjugate ascending–descending migration of groundwater and hydrocarbons as elements of a single fluid system at global to microscopic scales [10]. For example, the formation of a local zone with elevated permeability due to the removal of concentrated OM produces a decompressional fluidodynamic regime in the hydrocarbon generation source and the consequent migration of hydrocarbons from upper rock complexes into the fissured areas. However, the subsequent appearance of excess fluids during the subsidence of such areas to deeper levels with higher *PT* parameters (and more intense fluid generation) may result in higher fluid pressures. Owing to the anomalously high formation pressure, fluids may migrate subsequently from these areas to the lower pressure zones along the rise of beds or into the over- and underlying reservoir beds, where the pressure is usually close to the hydrostatic one [3]. In deeper zones characterized by the attenuation of fluid generation and degradation of the anomalously high formation pressure, the highly permeable zone can

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[3] It should be emphasized that we consider here only irregular thinning of rock due to catagenetic losses of OM and leave aside gravitational compaction and relevant deformations.

again absorb fluids from overlying rocks, provided that the zone is not sealed by secondary minerals.

Irregular changes in the thickness of beds may transform initial boundaries between hydrocarbon-generating formations and reservoirs in some places. This can be exemplified by the formation of fault-line contact zones between hydrocarbon generation and collector beds. Such junctions are characterized by the summation of vertical and lateral components of fluid migration [11].

Thus, the hydrocarbon generation stage can be characterized by the development and intensification of stresses in some sectors. Rocks of the hydrocarbon generation zone and, partly, overlying beds are characterized by elevated instability and dislocation (unconsolidation of rocks, jointing, disintegration, formation of new structural relationships, and others). Rocks in such sectors acquire properties of an unstable system, which cannot usually exist for a long period. Stresses can repeatedly be released, for example, in the form of shallow-focus seismicity in such zones.

Ultimately, the hydrocarbon generation source should acquire typical features of the tectonodynamic center [12], although geodynamic instability is of an autonomous nature in this case. Processes of the gradual burial of a shale deposit in zones of catagenesis, generation of new hydrocarbon portions, irregular thinning of rocks, and repeated subsidences of overlying rocks are responsible for the long-term inherited character of geodynamic destabilization.

However, we cannot rule out the role of the tectonodynamic factor and associated strains, because many researchers have demonstrated that the intensity of oil and gas generation varies in areas with different types of geodynamic activity. It has been established that the dynamics of the stressed state of the Earth's crust plays a significant role in all processes responsible for oil and gas generation. Strains of different types and ranks provide changes in parameters of the rocks–hydrocarbons–subsurface fluids system owing to pulsed variations in the formation and interstitial pressures, decrease in the activation energy of chemical reactions, unconsolidation of rocks, fluctuations in the volume of the interstitial space and permeability, and so on [12 and others].

The well-known long-term works of Cherskii et al. [13] devoted to the modeling of natural conditions of sedimentary sequences subjected to the impact of tectonoseismic processes demonstrated that the tectonoseismic impact plays a significant role in the intensification of hydrocarbon generation, migration, and accumulation in different formations, including rocks with concentrated organic matter. We also carried out experiments in this field [14] and obtained interesting results related to interstitial waters squeezed out from oil shales under regimes imitating both the gradual geostatic pressure and the stress-related geodynamic loads. In the second case, the C_{org} removal was substantially more intense [14]. Hence, we should also expect the loss of concentrated OM at early catagenetic stages and, consequently, earlier (and, probably, more intense) deformations related to this process.

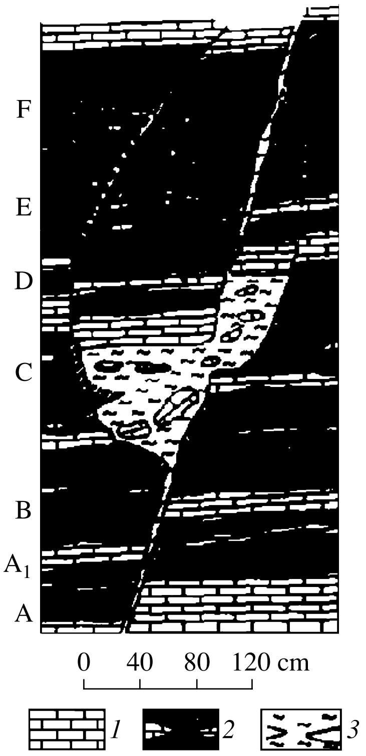

Fig. 2. Subsidence of limestone interbeds C/D and D/E due to the local epigenetic loss of organic matter and carbonates in oil shale bed C. Baltic shale basin, Estonian deposit, O_2kk, early catagenesis. (*1*) Limestone; (*2*) oil shale with carbonate concretions; (*3*) terrigenous shale relict. (A, A_1, B, C, D, E, F) oil shale beds.

It should be noted that many points of the above statement are also valid for source rocks with dispersed OM, e.g., irregularity in initial (precatagenetic) concentrations of OM and, correspondingly, irregular losses of mass and thickness of rock beds in the course of hydrocarbon generation; a higher degree of fluid permeability and rock dislocation; and the formation of additional conduits for new hydrocarbon portions. It is known that fluid generation and relevant phenomena (dehydration, hydrocarbon generation, and others) are processes of regional significance for the sedimentary rock basin. The migration of huge volumes of newly formed fluids is often characterized by a pulsed character. Excess pressure of such fluids provides the redistribution of stresses in some places and governs the localization of fractures and other (plicative and injective) dislocations and the emplacement of clastic dikes, as well as processes of sandy and clayey diapirism, mud volcanism, and seismicity (particularly in thick clayey sequences) [6, 15, and others].

However, many of these effects are more notable in OM-rich deposits (not only because of their more significant role in fluid generation). A substantial contribution is provided by the catagenetic loss of the volumetric component (e.g., concentrated OM) and other relevant phenomena, such as deformation-related changes of initial rocks and their notable (and irregular) thinning and dislocations. Owing to all processes described above, rocks with concentrated OM become a source of increasing catagenetic dislocations that are more intense here than in the main part of the basin.

Thus, processes of catagenesis and exhaustive hydrocarbon generation were responsible for significant transformations of oil shales up to the point of the loss of their lithological individuality. However, the sedimentary rock basins incorporate relicts of oil shales (it is difficult to recognize them at present), deformations of the geological space, and hydrocarbon.

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