Main Conclusions

1. Mud volcanoes in the Black Sea region have been known for a very long time. People of the early Paleolithic would have been aware of them and could have used breccia, hot water, and gas flares from mud volcanoes in their daily life. From ancient historic times, there exist singular and haphazard observations of anomalous phenomena associated with mud volcanoes. Serious scientific study began at the end of the eighteenth century, and by the nineteenth century, mud volcanoes had already been described by many researchers. These early descriptions were scattered and sporadic. Only in the twentieth century were terrestrial mud volcanoes of the Kerch-Taman region systematically studied by V.V. Belousov and L.A. Yarotskiy. In a number of subsequent works, the presence of recessed synclines near mud volcanoes was noted by K.A. Prokopov, G.A. Lychagin, Z.L. Maimin, and others. In the second half of the twentieth century, iron ore deposits were discovered in recessed synclines (e.g., Novoselovskaya, Kamenskaya, Uzunlarskaya, Baksinskaya, and others) by E.F. Shnyukov and P.I. Naumenko. In the last quarter of the twentieth century, as a result of numerous marine expeditions conducted by different organizations, up to 70 mud volcanoes located in different underwater areas of the Black Sea were discovered and most of them described. A number of marine mud volcanoes located below the ~700 m isobath in the Black Sea erupted fragments of gas hydrates, thereby identifying the existence of HG gas beneath the sea bottom.
2. From the modern point of view, mud volcanism is considered as a form of local gas flow involving deep hydrocarbons moving upward to the Earth's surface accompanied by emissions of mud breccia, rock fragments, gases, and water. The flow travels through eruptive channels that have numerous voids in their upper parts and complex forms in their depths, and the ejecta often produce peculiar forms of relief such as cone-shaped hills that reveal craters or round cavities at their tops filled with liquid mud. Exogenous factors then complete the final appearance of these modern landforms, in particular, by creating numerous characteristic ravines, such as barrancos, on their slopes. The roots of the Black Sea mud volcanoes have been seismically traced into sediments of the Mesozoic and even deeper – down to the Moho surface (e.g., the Mantiynyy mud volcano). It is most likely that with improved technologies, the connection of mud volcanoes with the mantle will be clearly established in the future. A deep origin for mud volcanoes is also supported by the presence of unusual minerals, such as native metals (gold, silver, osmium, iridium, platinum, iron, lead, zinc, aluminum, etc.), as well as carbides, sulfides (cinnabar, antimonite, realgar, orpiment), and peculiarly shaped formations, such as non-rolled individual particles, complex crystals, wires, spherules, etc. Especially unusual are the spherules of iron, iron oxides, alloys of iron and rare-earth elements, and iron-silicate spherules—all typical by-products of industrial metallurgy and

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indicating that they were formed under high temperature. According to A.Ye. Lukin, native minerals and carbides trace the movement of fluids and anhydrous super-compressed multi-component gas from great depths upward to the Earth's surface.

3. Mud volcanic breccia displays a primarily tectonic origin, having been formed through layer-by-layer rubbing, disharmonic crushing caused by diapiric bulging, and finally through reworking by water and gases that eject this breccia at the surface. The volume and size of fragments of erupted breccia vary greatly although very large pieces show up much less frequently. Lithologically, mud volcanic breccia is a clastic rock consisting predominantly of argillaceous sediments cemented by clay; it is often porous. Quite often, breccia is flamed and burned, occasionally kaolinized and carbonated. Marine mud volcanoes frequently erupt very small fragments of Jurassic coals, and possibly ferruginous quartzites, rounded fragments of porphyrite, andesite, and effusives. Accessory minerals in the composition of breccia are similar to those of the original rocks of the breccia, namely, Maikopian and, to a lesser degree, lower Cretaceous clay. Mud volcanic gases are unstable in composition. They contain predominantly methane, carbon dioxide, less often nitrogen, and heavy hydrocarbons, while helium, hydrogen, hydrogen sulfide, and carbon monoxide are present in small quantities. The waters of terrestrial mud volcanoes are characterized usually as chloride-hydrocarbonate-sodium, sulfate-sodium chloride, and sodium chloride with impurities of boron, bromine, and iodine.
4. As a result of the eruption from mud volcanoes of huge volumes of gases, mud breccia, detrital rock material, and water, weakened zones are formed nearby with dimensions proportional to the volume of ejected masses. On the surface, such zones are expressed by oval depressions called recessed synclines, and they can be divided into two main structural types. The first type includes those recessed synclines in which erupted material accumulates in the center of the structure, i.e., where the mud volcano itself is located. In this case, the calderas represent, in fact, the compensatory troughs (i.e., recessed synclines) that are filled with Neogene sediments that delineate its boundaries. The rocks composing the recessed synclines themselves form the frame of the caldera. The second type includes those recessed synclines in which erupted material accumulates in the vicinity of the mud volcano, not in the center of the recessed syncline. When this occurs, the development of compensatory troughs occurs to the side, and accumulated sediments do not outline the calderas, which apparently are eventually destroyed by weathering processes. As of today, 39 recessed synclines are known on the Kerch and Taman peninsulas. All of them are located in the arched parts of anticlines composed of Maikopian clay rocks. Many of them contain layers of Kimmerian iron ore deposits in their section. Undoubtedly, the mud volcanoes of the Black Sea must also be accompanied by recessed synclines but with a different sedimentary thickness compared to terrestrial recessed synclines. This question requires future investigation.
5. At least 4000 gas seeps are known in the Black Sea today. They are generally present at water depths from 50 to 800 m, forming either single occurrences or grouped seeps. The maximum depth for most of the detected gas seeps more or less corresponds to the stability zone for pure methane hydrate: a bottom temperature of 8.9 ° C in this part of the Black Sea. This enables us to say that gas hydrates play a buffering role for the ascending migration of gases and thereby prevent the seepage of huge amounts of methane into the water column. Some seeps are quite large in area, but most are localized on the periphery of the Black Sea, particularly in its northwestern part, on the Bulgarian and Kerch-Taman shelf (including the Kerch Strait), and along the coast of the Caucasus. Quite often, they are confined to paleo-deltas of the largest Black Sea rivers, the Danube, Dnieper, Dniester, and Don, and within the canyons formed by them. The deepest seeps are associated with faults and mud

volcanoes in the central Black Sea basin. On average, the height of the gas seeps above the surrounding seafloor is 100–200 m, and most of the emitted gases do not reach the water surface. Sometimes, it is difficult to distinguish gas seeps from mud volcanoes due to the location of seeps within small conical depressions on the sea bottom. As strong exhaust emissions of water-saturated gas pass upward through the sediment sequence, they can affect bottom morphology by forming rounded depressions or craters called pockmarks. Their locations indicate both the presence of gas seeps and methane biotopes on the seafloor. Within the Black Sea, a kind of specific zoning emerges: the central deepwater part of the sea is occupied by gas hydrates, while its periphery contains abundant gas seeps. It is quite possible that gas or, more precisely, gas-water seeps are localized within the area of the land adjacent to the sea—for example, in the Kerch-Taman region—but for the most part, they are not fixed with certainty because of the difficulty of observation. Many areas where seeps have developed are confined to the places containing paleoalluvial strata, but not all. The authors are more inclined to link gas seeps with the Maikopian horizon of the Black Sea geological section and with deep fluids. At the same time, they do not deny the participation of biochemical methane in the genesis of gas flares. Undoubtedly, this process accounts for gas seep generation in Quaternary bottom sediments, but its role, most likely, is subordinate.

6. For many years, the idea of a connection between mud volcanoes and associated recessed synclines with mineral ore content was explored during geological studies. This hypothesis was proposed in the early 1960s by Shnyukov and others and has been tested for many years, even up to the present day. It turned out to be accurate and led to the discovery and exploration of seven new iron ore deposits and manifestations and also revealed the elevated boron content of some of them. The largest ore deposit, Novoselovskoye, contains 125 million tons of ore reserves deposited within its recessed syncline. Less significant ore deposits are associated with the mud volcanoes Baksinskiy, Rep'yevskiy, Achinskiy, and some others. This idea that underwater Black Sea mud volcanoes could contain useful resources was shown to be true as well, as one can expect the accumulation of methane gas hydrates in recessed synclines lying at depths of more than 700 m—a thermodynamically favorable environment for their development. Particularly valuable are ring-shaped (isometric) structures that follow the outline of mud volcanoes and are complicated by subsidence phenomena. In this way, many mud volcanoes and their associated recessed synclines, terrestrial and offshore, can be used as indicators in the search for various mineral resources (gas, oil, gas hydrates, iron ore, sulfur, chemical raw materials, building materials, raw mineral and clay materials, etc.) as well as for production of metallurgical pellets and recreation. In Azerbaijan, a number of discoveries of oil and gas fields in the areas of mud volcanoes indicate their great potential for such prospecting, and this potential should be relevant for the Kerch Peninsula as well. A number of wells drilled to a depth of 500 m on the Bulganakskiy mud volcano were unsuccessful, however, probably because they did not reach the required depth. Given the geological history of the Kerch Peninsula, oil and gas fields should be located at much deeper horizons.
7. The activity of mud volcanoes on land can be dangerous for humans, as eruptions can cause the death of people and animals as well as great damage to homes and other infrastructure constructed in close proximity to mud volcanoes. There is another ecologically dangerous aspect to the influence of mud volcanoes on the environment: a geochemical one. Together with its gases, mud volcanoes emit mercury, bromine, iodine, boron, and possibly arsenic. As a rule, mud volcanoes release gas clouds of mercury, the concentration of which is 1–2 orders of magnitude higher than safe background levels. Under certain conditions,

emissions of hydrogen sulfide can be hazardous. The clear risks should serve as a warning to tourists and visitors that attempts to approach the volcano's center or multiple vents to view the semi-liquid sedimentary deposits can result in great harm or worse, and therefore excessive curiosity can be quite hazardous. Mud volcanic activities in the shallow sea are often catastrophic. Breccia and mud emissions can rapidly produce islands and shoals along the routes of seagoing vessel movement. One case of a vessel running aground in the Kerch Strait has been recorded. In the deeper areas of the Black Sea, there are known cases of emission and ignition of large masses of gases, events that pose great danger for navigation and can lead to the foundering of ships.

8. Mud volcanism and the related degassing of methane from the seabed affects living organisms (exemplified by meiobenthos), their metabolism, and activities. A case study conducted in areas of methane outlets within the northwestern part of the Black Sea examined the relationship between the distribution of meiobenthos and concentrations of hydrocarbon gases, primarily methane, in the sediments. The dual analysis of abiotic characteristics (physical and chemical parameters of the water column, gasmetrical, geochemical, lithological, mineralogical properties of the sediment) and biotic ones (quantitative and taxonomic composition of foraminifers, nematodes, and ostracods) shows the noxious effects of methane upon organisms but also afforded a means by which the taxonomic and quantitative distribution of foraminifera, ostracoda, and nematodes could be used as indicators of potential methane reservoirs lying beneath the seabed.

In this paper, we have transliterated Cyrillic letters into the Latin alphabet according to the BGN/PCGN Romanization system for Russian used by Oxford University Press. Exceptions are the names of authors, which we have left in their own preferred transliterations, as well as geographical names as presented most commonly in the majority of English papers.

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Index

E. Shnyukov, V. Yanko-Hombach, *Mud Volcanoes of the Black Sea Region and their Environmental Significance*, https://doi.org/10.1007/978-3-030-40316-4