Mud Volcanoes of the Black Sea Region and their Environmental Significance

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Springer

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ISBN 978-3-030-40315-7 ISBN 978-3-030-40316-4 (eBook)
https://doi.org/10.1007/978-3-030-40316-4

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The book is dedicated to the centenary of the founding of the National Academy of Sciences of Ukraine

Foreword

Humans have known about the existence of mud volcanoes for a very long time. Archaeologists have suggested that early Paleolithic groups migrated to the Black Sea region of Eurasia via mud volcanic provinces. They base this idea on comparisons made between maps showing the locations of mud volcanoes and showing early Paleolithic sites. Paleolithic localities such as Sinyaya Balka, Il'skaya, and Bogatyr are found in proximity to mud volcanoes on the Taman Peninsula of Crimea (Zenin 2012). Furthermore, stone tools have been discovered within some mud volcanoes; for example, a Paleolithic scraper was recovered from within the Akhtarma-Pashalinskaya mud volcano in Azerbaijan (Kovalevskiy 1935). Mud volcanic landscapes could have appealed to ancient people due to the presence of erupted breccia that could be used for making stone tools, as well as the hot water and gas flares produced by mud volcanoes.

The use of the term "mud volcano" dates back to the nineteenth century. It was introduced by Helmersen and Schrenck (1885) as a translation from the German *mudevulkan* previously used by Abikh (1873). Pallas (1795) provided the first scientific description of mud volcanic events when he described the frequently exploding Golubitsky mud volcano in the Sea of Azov and connected its activity to earthquakes.

The intensive study of mud volcanoes in the Black Sea region (largely on the Kerch and Taman Peninsulas) began in the early twentieth century with the work of Vernadsky and Popov (1899–1900), Felitsyn (1902), Borisyak (1907), Chirvinskiy (1908), Zhivilo (1909), Yushkin (1909), Steber (1909–1910), Gubkin (1913), and many others.

After the Second World War, the Kerch-Taman mud volcanoes were investigated as part of a geological survey focused on oil and gas exploration. For the first time, the geological complexity of the anticlinal structures within which mud volcanoes develop was explored (Lychagin 1952), and their composition and geochemistry were summarized (Ronov 1951). In addition, estimated ages of erupted gases as well as the oil and gas potential of mud volcanic hearths were studied (Gattenberg 1954), and the first overview of Tertiary mud breccia (from Maikopian to Pontian on the geological section) from the Kerch Peninsula was published (Alyaev 1947, Maymin 1951). Particular attention was focused on the origins and roots of mud volcanoes of the Taman Peninsula (Shardanov et al. 1962; Shardanov and Znamenskiy 1965); these authors concluded that the roots of the Taman mud volcanoes begin in Lower Cretaceous rocks and that they contain large reservoirs of oil and gas. Later, these conclusions were confirmed by Shnyukov and Netebskaya (2013). The hydrogeology of the Kerch Peninsula's mud volcanoes was also described (Kurishko et al. 1968).

Research on the Kerch-Taman mud volcanoes was renewed in the 1960s due to increased industrial interest in rare elements—mercury, lithium, arsenic, and boron.

The most important breakthrough in the study of the Kerch-Taman mud volcanoes came when ore-bearing deposits in compensated, or recessed, geosynclines formed during the Kimmerian orogenic cycle were discovered. This new finding initiated serious geological exploration carried out by the Department of Mining and Geology of the USSR. A large field of oolitic iron ores was located within the Novoselovsky mud volcanic hearth. Called the Novoselovskoe field, it is estimated to contain 125 mln t of conditional iron ore, and together with non-conditional iron ores, up to 200 mln t were recognized by the USSR Commission of Reserves as being an important source of iron ore. Data obtained through this research was summarized in a fundamental monograph by Shnyukov et al. (1971).

Along with applied investigations into mud volcanoes, its classical geological study has also been ongoing (Nesterovskiy 1990; Shnyukov et al. 2013a; Shnyukov 2016).

At the end of the twentieth century, the "center of gravity" for mud volcanism research moved to the Black Sea. Over the course of dozens of marine expeditions conducted on board different research vessels (e.g., "Mikhail Lomonosov," "Kiev," "Professor Vodyanitskiy," "Vladimir Parshin," and some others), a substantial number of underwater mud volcanoes was discovered (Shnyukov et al. 2005).

Recent studies of Black Sea mud volcanoes have been conducted during the course of multiyear programs pursued by many Russian and Ukrainian research teams from various organizations—such as "Yuzhmorgeologiya," Moscow State University, the National Academy of Sciences (e.g., the Geological Institute, Department of Marine Geology and Sedimentary Ore-Formation, Institute of Biology of the Southern Seas, Geophysical Institute, and Marine Hydrophysical Institute), Odessa I.I. Mechnikov National University, and others. Significant contributions have also been made by Bulgarian, Romanian, German, and other European scientists, who worked together with Russian and Ukrainian specialists.

This volume contains an introduction, 11 chapters, a conclusions section, and an extensive reference list for each chapter. Chapter 1 presents a history of mud volcano studies and details the basic investigative methods used within the Black Sea region. Chapter 2 provides an overview of the study area that includes the Black Sea, the Sea of Azov, the Kerch and Taman peninsulas, and the adjacent northern Caucasus. Chapter 3 reviews the materials and methods used in the study of terrestrial and offshore mud volcanoes of the Black Sea region. Chapter 4 revises modern ideas about mud volcanism. Chapter 5 describes the morphostructures related to mud volcanoes, including compensated, or recessed, geosynclines. The massive Chap. 6 is illustrated by 205 figures and covers the entire panorama of mud volcanoes within the Black Sea region. Chapter 7 provides an overview of other types of degassing in the Black Sea, such as gas seeps, acoustic plumes, or gas torches.

Chapter 8 discusses the origin of mud volcanoes in the Black Sea region. Chapter 9 explores the connection between mineral resources and mud volcanism. Chapter 10 explores the impact of mud volcanoes on the environment and, in particular, the dangers that may arise from mud volcanic activity on land and underwater. Chapter 11 is a case study that examines the relationship between meiobenthos distribution and concentrations of hydrocarbon gases, primarily methane, in seafloor sediments of the northwestern Black Sea.

As can be seen, this book covers a wide range of aspects relating to the science of mud volcanoes in the Black Sea region, including their geology, structure, and dynamics. For example, it describes new discoveries of iron ore deposits in mud volcanic structures of the Kerch Peninsula, forecasts future promising areas of research, outlines ways to make greater use of mud volcano resources, puts forward a new idea about the deep origin of mud volcanoes, proposes to open a multilocation mud volcanic reserve in order to preserve the natural phenomena and reduce the destructive consequences of a catastrophic eruption in densely occupied areas, offers an explanation of the causes for some shipwrecks and a suggestion to modify the sea-lanes of maritime transport when they approach too closely to mud volcanic foci, and shows the important environmental significance of both terrestrial and underwater mud volcanoes in the Black Sea region. The spectrum of issues addressed is extremely broad, and it is clearly apparent that the authors have brought years of experience to the subject. This unusually informative work, however, is based not only on the 50 years of geological work by the authors but also on the results produced by hundreds of their colleagues and scholarly predecessors, who traveled thousands of kilometers on land and thousands of nautical miles on scientific research vessels.

The results of this work are impressive. It is an encyclopedia of mud volcanoes in the Black Sea region and serves not only to document our current knowledge of a particularly significant region but also to lay the groundwork for future research.

It is my great pleasure to introduce the book. I strongly believe that readers will appreciate this fundamental compilation of useful information, much of which appears here in English for the first time.

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Preface

A lengthy book does not need a lengthy preface, so these introductory words will convey only some essential matters, including the circumstances that led to the present publication, some of the background to the research it contains, and words of gratitude to those who helped in the effort.

In these prefatory paragraphs, the authors want to present some necessary information that includes the background for the creation of this book, the process by which it came to be, and appreciative words for those who made this publication possible.

The Black Sea region encompasses the Black Sea, the Sea of Azov, and their coasts, and the area has been inhabited by humans for at least the last 1.8 million years. It was formed at the end of the Mesozoic as a back-arc basin of the early Cretaceous (revealed as a result of continental rifting at the end of the Albian). This led to the splitting of the crust along the axis of the Albian volcanic arc and the subsequent opening of the Cenomanian-Coniacian deepwater trough, a severe thinning of the continental and/or oceanic crust, and the separation of two basins, which became the Western and the Eastern Black Sea. Starting from the end of the Santonian and before the end of the Paleocene, the Black Sea depression experienced compressive phases. Within the Eastern Black Sea depression during the Eocene, a new phase of stretching began, which led to the formation of the Adzharo-Trialetskiy rift. Since the end of the Eocene and into the present, the bottom of the basin has been in a compressive phase, and as a result, it is broken by numerous cracks (Nikishin et al. 2003).

One of the most interesting features of the region is the extensive development of mud volcanism—a geological phenomenon that is widespread across the planet. The term "mud volcano" is generally applied to a more or less violent eruption or surface extrusion of watery mud or clay that is almost invariably accompanied by methane gas. The most ancient Early Paleozoic mud volcanoes are known from Decaturville, Missouri, in North America (Zimmermann and Amstutz 1972).

According to archaeological evidence, mud volcanoes of the Black Sea region have attracted the attention of humans since antiquity. The history of investigation into mud volcanoes goes back to the tenth century AD when Byzantine Emperor Constantine VII Porphyrogenitus, also called Constantine VII Flavius, described some rocks that spewed oil located near the town of Tamatarki on the Taman Peninsula. The first mud volcano described in the scientific literature was dubbed "Golubitsky" by Pallas (1795); it was located in the Sea of Azov near Temryuk. Subsequently, the study of mud volcanoes was conducted mostly by Russian scientists, e.g., V.V. Belousov and A.D. Arkhangelsky. Research intensified in the second half of the twentieth century as the search for oil, gas, and other mineral resources accelerated.

Currently, 180 mud volcanoes are known within the Black Sea region. Of these, 100 have been found on land (on the Kerch and Taman Peninsulas and in northwestern Caucasus), and 68 subaqueous mud volcanoes are present in the southeastern part of the Sea of Azov; in the northwestern Black Sea, including the Sorokin, Kerch-Taman, and Tuapse troughs; and in the western Black Sea depression. Judging by their geomorphology, two additional seafloor locations are presumably mud volcanoes, but future investigation is required to confirm this identification.

Multidisciplinary studies undertaken since 1990 enabled E.F. Shnyukov, the first author of this publication, to discover large fields of oolitic iron ores—including the Novoselovskoe field on the Kerch Peninsula, with a reserve of 150 million tons—that were formed by the activity of mud volcanoes. Shnyukov was also able to connect these ores to compensated or compressed geosynclines formed during the Cimmerian Orogeny cycle, as he had initially predicted based on scientific evidence.

All evidence discussed here supports the main ideas of Kropotkin and Valyaev (1979, 1980, 1984), Valyaev (2011), Dmitrievsky and Valyaev (2002), Pikovskiy (2002), and Lukin (2013), whose hypotheses proposed the degassing of a “cold” non-magmatic Earth. Letnikov et al. (2010) considered the development of the Earth as a monotonous extinguishing process, in which the depletion of high-temperature fluids into the lithosphere was followed by periodic pulses of intense degassing. The main transmitter of fluids is hydrogen, which forms two fluid systems—hydrogen-carbon and hydrogen-sulfide—that are located at different levels within the liquid core. The former may be responsible for the development of mantle plumes and mud volcanic activity. The dynamics of mud volcanoes are caused by the action of these hydrogen-carbon plumes, which generate fluid streams that break up as they transition first into a liquid state and then second into a gaseous state, eventually leading to the unusual mineralizations associated with mud volcanoes. High-temperature mantle plumes raise the flow rate of the fluids. Their modern analogue is lithospheric hydrothermal plumes, which are especially pronounced in spreading zones.

In general, the phenomenon of mud volcanism presents many dimensions, the study of which contributes significantly to improving the human condition, as it may aid in maintaining environmental integrity as well as providing a means for sustainable development of the region. Outbursts of submarine mud volcanoes located below 600–700-m isobaths commonly contain ice-like aggregates of gas hydrates (largely methane), which indicate the presence of mud volcanoes under the seafloor. The presence of both ore formations and gas hydrates is attributable to the compensated or compressed geosynclines, which can be used as reliable indicators in prospecting for mud volcanoes.

The dynamics of mud volcanoes pose many potentially serious risks to maritime activity and environmental security. Gas outbursts from offshore mud volcanoes affect the hydrochemical regime of the sea, producing currents and acoustics, and substantially affecting ecosystems, including especially seasonal fish migration routes. The entire biota of the Black Sea is to a certain degree determined by fluctuations in hydrogen sulfide and methane exposure levels (Yanko-Hombach et al. 2009, 2017). Mud volcanoes can also cause great damage to the physical environment, as powerful eruptions create ground subsidence in nearby areas, thereby presenting a serious threat to nearby urban agglomerations, for example, Kerch in Crimea and Temryuk in Krasnodar territory. Contamination of the air with mercury and other elements can also be hazardous to people. Mud volcanoes can pose a significant threat to maritime traffic, especially in narrow waterways. For instance, 7 mud volcanoes have been found offshore within the Kerch Strait, and every year, nearly 10,000 ships cleave their way through the strait. There have been cases of ships running aground even though they were within the navigational channel (e.g., S/S Caesar in 1914 and some others). The shoals that grounded them proved to be mud volcanic in nature. At times, mud volcanoes located within the strait have formed small islets composed of ejected materials. Some researchers have proposed that methane outbursts were the cause of ship loss in the Bermuda Triangle. Accidents of this kind are likely to happen in the Black Sea as well. The probability of such accidents has been shown experimentally. Mud volcanoes serve not just as regional signs for petrochemical prospection, but sometimes, they can be used for precise localization of oil traps, as they are good indicators of oil- and gas-bearing provinces. This generality can be exploited in the future for the development of earthquake forecasting criteria.

In general, mud volcanism in the Black Sea region is an extremely interesting phenomenon of multidimensional importance, deserving in-depth study primarily as an indicator of the Earth's oil- and gas-bearing capacity. Today, mud volcano studies are largely focused on their scientific rather than applied aspects. To date, no surveys of mud volcanoes as markers for gas hydrates have been performed, and no calculations of their contribution to the total degassing of the seafloor have been performed on a basin-wide scale. Likewise, no research on the hazards they pose has been conducted. At the same time, mud volcanoes are the seafloor's expression of endogenic processes and a "cheap window" (Golubyatnikov 1923) into the deep geosphere; they may be considered valuable tools for future industrial applications.

This book contains an introduction, 11 chapters, a conclusions section, and an extensive reference list for each chapter. Each chapter underwent a lengthy review process (two reviewers per chapter as a rule) as well as extensive editing of both language and graphics. The complexity of the graphics editing (done by Nikolay Maslakov and Alexander Paryshev) and that of the text editing (done mostly by Allan Gilbert) took longer than anticipated, leading to the unexpected 2-year delay in getting the volume published.

Chapter 1 includes the history of mud volcano studies and the basic investigative methods used within the Black Sea region. It contains a detailed overview of previous investigations and emphasizes the main achievements as well as the present gaps in our knowledge.

Chapter 2 provides an overview of the study area that includes the Black Sea, the Sea of Azov, the Kerch and Taman Peninsulas, and the adjacent northern Caucasus.

Chapter 3 provides an overview of the materials and methods used in the study of terrestrial and offshore mud volcanoes of the Black Sea region. The general strategies include geomorphological, geological, geophysical, gas-geochemical, paleontological, and micropaleontological dimensions.

Chapter 4 includes an overview of modern ideas about mud volcanism, including their morphology, geological structure, and the composition of their mud breccias, water, gases, and terrigenous material, as well as the main characteristics of their dynamics.

Chapter 5 is devoted to a description of the morphostructures related to mud volcanoes, including compensated or compressed geosynclines.

Chapter 6 covers the entire population of mud volcanoes that have developed within the Black Sea region, in particular the Kerch and Taman Peninsulas, the northwestern Caucasus, the Black Sea itself, and the southeastern part of the Sea of Azov.

Chapter 7 provides an overview of other types of degassing in the Black Sea, which are referred to as gas seeps, acoustic plumes, or gas torches.

Chapter 8 covers the origin of mud volcanoes in the Black Sea region.

Chapter 9 explores the connection between mineral resources and mud volcanism. Mud volcanoes can be of practical assistance in the search for fossil fuels, iron ores, rare chemical elements, nonmetallic raw materials, therapeutic mud, and much more.

Chapter 10 discusses the impact of mud volcanoes on the environment and, in particular, the dangers that may arise from mud volcanic activity.

Chapter 11 represents another case study on the relationship between meiobenthos distribution and concentrations of hydrocarbon gases, primarily methane, in the sediments of the northwestern part of the Black Sea, including gases released by mud volcanoes and gas seeps.

In the Conclusions chapter, the authors propose some principal directions for future investigations in mud volcano research in the Black Sea region, together with possible applications to other basins. It is shown that mud volcanism is a complex and multidimensional phenomenon, the study of which requires a multidisciplinary and in-depth approach. It appears that there is a clear interrelationship between mud volcanoes and methane gas hydrates, which allows mud volcanoes to be used in the search for the latter below isobaths 600–700 m.

A reference list is appended to each chapter; the sources include numerous items, many of which were published in regional languages, and as such are not well known in the west.

The book is illustrated with 473 figures. It contains detailed descriptions and images of major Black Sea mud volcanoes, together with their coordinates, types of geomorphological structures, and the contents of their breccia—including unique chemical elements and minerals indicating that the deep roots of mud volcanoes extend downward to the mantle. The coverage incorporates a wide geographic region, encompassing both terrestrial and underwater areas, and a broad approach, ranging from geological subjects to environmental applications.

The authors have studied the mud volcanoes of the Black Sea region for more than 50 years, and the results of their research are presented in a significant number of monographs and articles, largely published in Russian. This book summarizes the authors' findings. Unfortunately, the recent change in the legal status of Crimea has precluded the opportunity to update a number of photographs, so that those appearing here had to be taken mostly from previous publications, e.g., Shnyukov et al. (2006, 2013b). Yet, this monograph represents the results of research conducted not only by the authors but also by a large informal team of geologists from many scientific and applied geological organizations. The contributions of individual experts are acknowledged in the text. Among these experts, it is especially appropriate to note the contribution of P.I. Naumenko, the head of the association "Ukrchermetgeologiya" in the Ministry of Ferrous Metallurgy of Ukraine. As a result of the close contacts between this organization and the NAS in Ukraine, many hundreds of wells were drilled, and new mineral fields were discovered and explored, and this collaboration has led to new and unique discoveries on the influence of mud volcanoes upon the environment.

Studies of recovered materials that provide the evidentiary basis for this book were conducted under the auspices of the National Academy of Ukraine in the Department of Marine Geology and the Sedimentary Ore Formation (OMGOR NASU, recently renamed the Center for Problems of Marine Geology, Geoecology and Sedimentary Ore Formation of the National Academy of Sciences of Ukraine, Institute of Geological Sciences) and Odessa I.I. Mechnikov National University.

All transliterations of cited sources published in languages using the Cyrillic alphabet comply with the requirements of the international standards for bibliographic references according to the US Library of Congress (https://www.loc.gov/catdir/cpso/romanization/russian.pdf). Exceptions are the names of the authors, which are left in their own preferred transliterations, as well as geographical names as presented most commonly in the majority of English papers.

The authors are grateful to all of the colleagues who have supported their work. Particular gratitude must be given to Dr. Nikolay Maslakov and Dr. Alexander Paryshev (Center for Problems of Marine Geology, Geoecology and Sedimentary Ore Formation of the National Academy of Sciences of Ukraine) for their assistance in drawing the illustrations.

They are also grateful to Prof. Allan Gilbert from Fordham University, USA, for editing the English text and for his valuable comments and to Alexander Motnenko, University of Manitoba, for the initial editing of Chaps. 1, 4, and 5.

Dr. Derman Dondurur (Dokuz Eylül University, Institute of Marine Sciences and Technology, Turkey) is thanked for his contribution on mud volcanoes in the Turkish sector of the Black Sea.

The authors are grateful to Peter Gozhik, Academician of the NASU, Professor, Director, Geological Institute of NASU, for agreeing to introduce this book.

Grateful acknowledgment is offered for the thoughtful efforts of external reviewers—top scientists in the field—Vladimir Kobolev, Professor, Doctor of Geological Sciences, Chief Scientist of the Institute of Geophysics of NASU, and Adil Abbas Ogly Aliyev, Professor, Doctor of Geological Science, Head of the Department of Mud Volcanism of the Institute of Geology and Geophysics of the National Academy of Sciences of Azerbaijan, Laureate of the State Prize of Azerbaijan for the Atlas of Mud Volcanoes of the World.

Dr. Revinder Sidhu, Microscopy and Materials Characterization Facility Manager (Manitoba Institute for Materials, University of Manitoba, Canada), is sincerely thanked for her help in imaging of microfauna by SEM (Chap. 11).

Lastly, the authors thank the managing team at Springer, Ms. Malini Arumugam, Project Coordinator (Books), Margaret Deignan, and Petra van Steenbergen for, above all, their patience in awaiting the delivery of the finished manuscript.

The work was executed with the financial support of the EU-FP6 project HERMES (Hotspot Ecosystems Research on the Margins of European Seas) 2006–2010; the State Budget Themes # 0117U000775 “Mud Volcanism: Emergencies, Study, Forecasting and Minimization,” #0113U004857 “Lithologic-Mineralogical Composition of the Muddy Breccias of Mud Volcanoes of the Kerch-Black Sea Region,” #0117U000776 “Gas Volcanism in the Azov-Black Sea Province and Related Minerals,” and some others financed by the National Academy of Sciences of Ukraine; and the State Budget Themes #539 “Study of the Formation Processes and Spatial Distribution of Methane in the Black Sea and Theoretical Considerations of Their Influence on Basin Eco- and Geosystems” and #590 “Development of Predictive Search Criteria for Hydrocarbon Deposits in the Black Sea Based on the Theory of Fluidogenesis” financed by the Ministry of Education and Science of Ukraine.

This study is a contribution to UNESCO-IUGS-IGCP 610 project “From the Caspian to Mediterranean: Environmental Change and Human Response During the Quaternary.”

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Contents

About the Authors

Evgeny Shnyukov is an eminent Ukrainian scientist in geology, geochemistry, lithology, sedimentary ore-formation, marine geology, and minerals of the World Ocean. He is Academician of the National Academy of Sciences of Ukraine (NASU), Doctor of Geological-Mineralogical Sciences, Professor, Member of the International Academy of Sciences of Eurasia, Honorary Director of the Center for Problems of Marine Geology, Geoecology and Sedimentary Ore Formation of the NASU (formerly Department of Marine Geology and Sedimentary Ore-Formation of NASU), and Head of the Ukrainian Lithology Committee. He has received many awards, including the State Award of Ukraine in Science and Technology, two State Prize of Ukraine for a series of works devoted to the World Ocean, and gold medal "Leonardo da Vinci" of the International Academy of Sciences of Eurasia, among many others. He has authored, coauthored, and edited over 700 scientific publications, including 50 books, and supervised over 30 PhD students. As the first scientist to recognize the need for marine geological research in Ukraine, he established the School of Marine Geology and Sedimentary Ore-Formation and initiated a new stage in the study of sedimentary iron and manganese ores, geology of the Black and Azov Seas, as well as comprehensive geological–geophysical and metallogenic investigations of the World Ocean's bottom sediments. He embraces a wide range of geological problems and represents a striking example of the fruitful union of science and practice. He supervised and actively participated in building of the research vessel "Geochimik" and headed a series of geological–geophysical expeditions on it and other research vessels. Materials from these expeditions led to the discovery of a submarine massif of crystalline rocks (Lomonosov Ridge), tens of mud volcanoes, and hundreds of gas seeps suggesting the presence of oil and gas beneath the Black Sea. Some of his books, such as *The World of Minerals and Catastrophes in the Black Sea* as well as many others, have gained wide recognition and are already bibliographic rarities.

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