Uncover the black box of black shales

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Received: March 23, 2023; Accepted: May 16, 2023; Published Online: May 31, 2023; https://doi.org/10.59717/j.xinn-geo.2023.100005

Citation: Zhang X. (2023). Uncover the black box of black shales. The Innovation Geoscience **1(1)**, 100005.

Shales are loosely defined as fine-grained argillaceous sedimentary rocks with or without laminations, including mudstones and typical shales. Black shales are shales generally rich in organic carbon (> 1%), and their dark color is due to the enrichment of organic matter and/or finely disseminated pyrite.[1] The most characteristic components of black shales are biologically sourced organic matter and geologically sourced clays though they may contain variable amounts of other detrital and authigenic minerals, e.g. disseminated silts, finely crystalline calcite, and dolomite, as well as carbonate, silica, and/or phosphatic concretions of diagenetic origin. Accordingly, black shales are synergic products of biological and geological processes under interactions of multiple spheres in the spherical Earth–Life system.

ECONOMICAL IMPORTANCE

Black shales are important to the natural fuel–resource economy of the world because they constitute the most important accessible reservoir of organic compounds on Earth. It was estimated that more than 90% of the world's recoverable oil and gas reserves were generated from black shales. In China, a total of 35 important organic-rich shale units have been recognized, which range from Mesoproterozoic through Cenozoic strata in age. The black shales of the early Cambrian Niutitang Formation and late Ordovician to early Silurian Wufeng-Longmaxi formations in South China, the middle Permian Lucaogou Formation in the Junggar Basin, the Middle to Late Triassic Yanchang Formation in the Ordos Basin, the Late Cretaceous Qingshankou Formation in the Songliao Basin, and the Eocene Shahejie Formation in the Bohai Bay are key hydrocarbon source rocks and targets for unconventional shale gas and shale oil.[2] It is worth noting that the Longmaxi black shale is rich in uranium and thorium, and hence a large amount of helium was generated during gas genesis. The helium content reaches 1500 ppm in some gas pools, sufficiently high for commercial exploitation.

On global scale, black shales with great economic interest as the main source rock for hydrocarbon production were previously regarded to be mostly restricted to six stratigraphic intervals: Silurian, Upper Devonian-Tournaisian, Pennsylvanian-Lower Permian, Upper Jurassic, Middle Cretaceous, and Oligocene-Miocene.[1] However, marine organic-rich shales from Mesoproterozoic to lower Paleozoic were well developed in China and has become targets for commercial shale gas exploration.[2] Most recently, a high-yield industrial gas flow with commercial value was unlocked in the lower Cambrian black shale of South China, which was announced as the world's first high-yield industrial gas flow in rocks as old as the early Cambrian (ca. 539—509 Ma).

Black shale units also are important as they may host syngenetic and epigenetic ore deposits, including many mineral commodities that are critical to national economy and security, e.g., U, Mo, PGE, V, Mn, Au, Ag, Zn, Co, Se, P, barite, and witherite (https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals). Metals concentrated syngenetically in black shales either survived metamorphism to be retained in graphitic schists or were released by metasomatic and remobilized processes to be concentrated elsewhere. Conversely, black shales might be receptor beds for metals released in hydrothermal or metamorphic systems. Exploration strategies in the search for ore deposits are mostly based on these two concepts. Metal-enriched black shales ranging from Proterozoic to Cenozoic have been mined worldwide since the last century for multiple purposes. For example, the Cambrian to Ordovician Alum Shale Formation of Sweden, with organic carbon about 14%, have been used as a source of pyrolytic oil and uranium, and the black shales of the lower Cambrian Niutitang Formation in South China host widespread stratiform polymetallic Ni-Mo-PGE-Au phosphate- and sulfide-rich ore deposits. In recent years black shales have been of increasing interest as the mineral industry struggles to meet the demand caused by proliferation of critical mineral-based technologies. The grade and tonnage of critical minerals in metalliferous organic-rich black shales are generally superior to other metal deposits on Earth (P. Emsbo, 2022, GSA, Abstracts with Programs 54, 4.doi: 10.1130/abs/2022NC-374890). Therefore, increased production from this unconventional resource is increasingly eyed as a source to mitigate the shortages.

ENVIRONMENTAL IMPACT

In contrast to the beneficial use of ore deposits in black shales, environmental impact of black shales is non-negligible. Weathering of heavy metal enriched black shales may be one of the most important sources of environmental contamination in areas where black shales are exposed naturally or anthropogenically. The chemical and mineralogical composition of black shales is reflected in the quality of the surface waters, groundwater, topsoil, and crops as well. The contamination is characteristically polymetallic. Elevated concentrations of Cu, Ni, Pb, U, Zn, As, Cd, Co, Mn, and Mo were frequently detected, among which Cu, Ni, Pb, U and Zn are recognized as major pollutants.[3] The high incidence of endemic diseases including cancer was proposed to be linked with heavy metals released during the weathering of Cambrian black shales in South China. Therefore, integrated research approach was suggested for the comprehensive assessment of environmental risk caused by the weathering of black shales.[3]

ARCHIVE OF BIOTIC AND ABIOTIC PROCESSES

Apart from enormous economic importance and potential environmental risk, black shales are a comprehensive archive of evolution of life and Earth's habitability, including climate and environment changes, and biogeochemical cycles in the past (Figure 1). Black shale units do not constitute a large proportion of the sedimentary rock column, but they have been formed commonly throughout most of the history of the Earth-Life system in a range of geological settings. Thus, black shales have long been a target for multidisciplinary research.

Black shales are the end product of the complex interplay among a range of geological variables and processes[1] and yet amongst the least understood of all sedimentary rock types despite they have been studied by a broad range of geological disciplines including sedimentology, stratigraphy, paleooceanography, paleoecology, palynology, and geochemistry.[4] The dark color, fine grain size, and seemingly simple and uniform nature bring us challenges in extracting information from black shales both in laboratory and in field. The presence of pyrite and fine-grained sediments has long led geologists to believe that ancient black shales were typical deposits of the most distal, deepest portions of sedimentary basins in anoxic bottom waters, as were commonly described in many textbooks, although a range of deposition models have been proposed since 1970s.[4,5] No single model can explain the entire complexity of black shales. The accumulation of organic matter is controlled by three factors, i.e., input, decay, and dilution of organic matter, which in turn are linked with many interconnected variables, e.g., nutrient availability, primary production, redox condition, microbial activities, sediment supply, climate and relief in source region, and tectonism. Their tempo-spatial distribution was frequently linked with major geological events like supercontinent cycle, large igneous province, extreme climate condition.

Black shales are paleontologically important for yielding exceptionally preserved fossils that are critical in deciphering the evolution of life and its environments. Notably, a number of Cambrian Burgess Shale-type fossil Lagerstätten, e.g., Chengjiang and Qingjiang biotas of China, provide a wealth of information on the emergence of animals. Pyritized faunas are common in

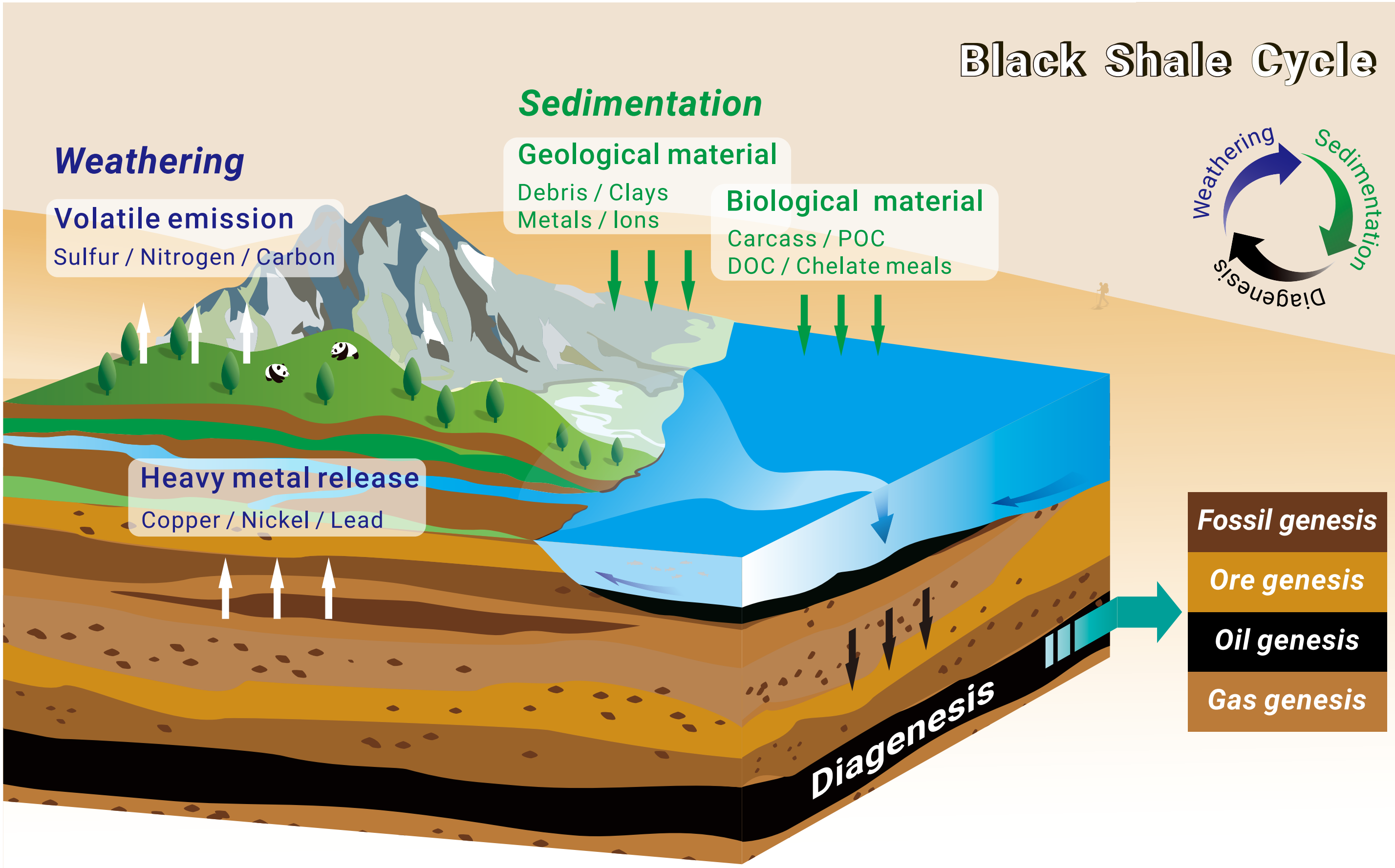

Figure 1. Black shale cycle as a black box recording the evolution of inhabited Earth and its economic importance and environmental impact DOC, dissolved organic carbon; POC, particulate organic carbon.

black shales. Qualified examples are the late Ordovician Beecher's Trilobite Bed of USA and the Devonian Hunsrück Slate of Germany. In addition, black shales usually contain fossiliferous chert, phosphorous, and/or carbonate nodules. In chert nodules, the Gunflint-type microfossil assemblages are robust evidence for exploring the Precambrian life world. The Orsten-type Lagerstätten from carbonate nodules of black shales yield phosphatized three-dimensional microfaunas preserved with remarkable anatomic details. Overall, those types of biotas are rich in fossils with high fidelity of preservation, provide remarkably complete views of life and its environment in the past, and hence are known as fossil treasure-houses for investigating the evolving Earth's ecosystem.

Black shales are rich in organic carbon resulting from photosynthesis and hence their formation is functioned as a carbon sink. The burial of each carbon atom means addition of an oxygen molecule to environment. Over geological time, accumulation of organic matter in black shales in magnitude may be partly responsible for the rise of oxygen and the fall of greenhouse gas CO_2 in atmosphere. Thus, the development of organic carbon rich black shales on global scale may have significant impacts on environmental redox and global climate change. Carbon cycle, particularly the burial of organic carbon in black shales, is linked to other global biogeochemical cycles, e.g., N, S, P, and trace elements Mo, V, Cu, Zn, Ni, etc. All are critical variables in our attempts to understand the history and evolution of life, environment, and climate.

OUTLOOK

It is apparent that black shales are closely tied to national development and people's life. Equally significant is the fact that the black shale like a black box (Figure 1) records the evolution of inhabited Earth in the geological past, which was listed as a major research theme in 2021–2030 Development strategy of Earth science of China. Secrets hidden in black shales, however, are not easily unlocked. Separate investigations or data interpretations from just one perspective may lead to conflict conclusions.[1] In this context, investigation of black shales in a multidisciplinary way and at multiple scales is proposed, including but not restrict to the following topics: sedimentology, stratigraphy, chronology, and tempo-spatial pattern of black shales, evolution of life and its environments, carbon cycle and climate, biogeochemical cycles, enrichment of hydrocarbon, ore deposit genesis, environmental impact of black shale weathering, and black shale big data. Since black shales are of significance in understanding the past of the inhabited Earth, in satisfying the demand of national economy, and in recognizing the threat to human health, it is necessary to fund and organize multidisciplinary research plans, in both regional and national scales, to uncover the black box of black shales.

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ACKNOWLEDGMENTS

We thank Peng Liu, Linhao Cui, and Chao Chang for technical assistance, Zongjun Yin for invitation. This work was financially supported by the Natural Science Foundation of China (41890845, 42242201, 41930319, and 41621003), 111 Project (D17013), and Natural Science Basic Research Plan of Shaanxi Province (2022JC-DW5-01).

DECLARATION OF INTERESTS

The author declare no competing interests.