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EDITED AND REVIEWED BY
Valerio Acocella,
Roma Tre University, Italy

*CORRESPONDENCE
Deyu Gong,
deyugong@126.com

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Editorial: The relationship between petroleum accumulation and mineralization in sedimentary basins

Dongming Zhi[1,2], Deyu Gong[3]*, Leon Bagas[4] and Hao Zou[4,5]

[1]Xinjiang Oilfield Company, PetroChina, Karamay, China, [2]Turpan-Hami Oilfield Company, PetroChina, Hami, China, [3]Research Institute of Petroleum Exploration and Development, PetroChina, Beijing, China, [4]Key Laboratory of Tectonic Controls on Mineralization and Hydrocarbon Accumulation of Ministry of Land and Resources, Chengdu University of Technology, Chengdu, China, [5]State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu, China

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Editorial on the Research Topic
The relationship between petroleum accumulation and mineralization in sedimentary basins

Introduction

Sedimentary basins are critical geological units that can host fossil fuel (oil, natural gas, and coal) as well as metallic and non-metallic mineral deposits (i.e., Pb, Zn, Cu, NaCl, and Li brines) (Carpenter et al., 1974; Kyser, 2000). Mineral deposits are often closely related to petroleum reservoirs in sedimentary basins (Oliver, 1986; Chen et al., 2001). Several low-to-medium-temperature hydrothermal ore deposits in sedimentary basins often have a coupling relationship of homology with hydrocarbon reservoirs (Williams-Jones and Migdisov, 2006). With economic development and population growth, the global demand for fossil fuels as well as metallic and non-metallic mineral deposits is increasing. Basinal fluids related to metallization and petroleum accumulation include hydrocarbon-rich organic, metal-rich aqueous, and hydrocarbon- and mineral-rich ore-forming fluids. The evolution of these fluids may determine the nature of coupled mineralization and petroleum accumulation in a basin (Sverjensky, 1984; Parnell, 1994; Hulen and Collister, 1999; Zhuang et al., 2000).

Several examples of global sedimentary basins show close symbiosis or association among minerals, oil, and gas reservoirs in space as well as striking similarities in material composition (Liu et al., 2006; Gu et al., 2010). There are three possible scenarios between mineralization and petroleum accumulation: 1) petroleum accumulation precedes mineralization, 2) petroleum accumulation and mineralization co-occur, and 3) petroleum accumulation occurs after mineralization (Liu et al., 2006; Gu et al., 2010). The first two reflect the close relationship between petroleum accumulation and mineralization. In the scenario 1), hydrocarbons and organic matter provide sulfur sources and reducing agents for mineralization. In the scenario 2), hydrocarbon accumulation and mineralization tend to be characterized by fluid homologation, co-transportation, and homogenization.

Owing to the relatively independent exploration, development, and utilization of solid minerals and petroleum in the industrial sector, the academic community has not paid much attention to the comprehensive interdisciplinary research of various resources (fossil fuels, metallic and non-metallic mineral deposits) for a long time. Thus, the synergistic exploration and integrated evaluation of multiple resources coexisting with sedimentary basins has not been achieved; this delays the discovery of related resources and increases the cost of scientific research, exploration, and development. Systematic theoretical and technical research is necessary to clarify the spatiotemporal relationships between mineral deposits and petroleum reservoirs in sedimentary basins.

In this report, we present a Research Topic on the relationship between petroleum accumulation and mineralization in sedimentary basins. A total of 18 papers are included in the Research Topic, mainly divided into two categories: the mineralization process (Wang et al.) and controlling factors for petroleum accumulation. The latter can be subcategorized into three: (1) source rock and oil-source correlation (Qin et al.; Gong et al.; Zhai et al.; Zhang et al.; (b) reservoir evaluation (Qin et al.; Wang et al.; Dan et al.; He et al.; Ning et al.; Wan et al.; Xu et al.; Zhao et al.; Zhi et al.); and (c) petroleum accumulation process (Ablimiti et al.; Kang et al.; Xiao et al.; Xue et al).

Mineralization process

Quartz is an abundant mineral on the Earth's crust and the most common gangue mineral in various hydrothermal deposits. Quartz commonly crystallizes at a wide range of temperatures (50°C–750°C) from fluids with diverse origins and compositions (Rusk and Reed, 2002; Rusk et al., 2008; Thomas et al., 2010; Götte et al., 2011). Recent advances in the use of LA–ICP–MS have allowed for the *in situ* analyses of numerous trace elements in quartz, such as Ti, Al, Li, Na, K, Fe, Ca, P, Mg, Mn, Cu, and Ge, at increasingly low detection limits. Wang et al. presented the petrographic description and trace element geochemistry of quartz in the Hongniu–Hongshan Cu skarn deposit in southwestern China, illustrating the genesis of their trace element tenures, quartz crystallization, and resorption of quartz phenocrysts. In addition, they discussed whether the igneous host rock at the deposit underwent magmatic mixing or recharge. Finally, quartz trace element data from 14 deposits were compiled to demonstrate the difference between magmatic and hydrothermal quartz.

Controlling factors for petroleum accumulation

Source rock and oil-source correlation

Source rocks refer to rocks rich in organic matter and capable of generating and discharging large quantities of oil and gas (Tissot and Welte, 1984); they are the material basis of petroleum formation. Therefore, accurate source rock evaluation is critical to clarify the exploration potential of petroliferous basins.

By analyzing organic geochemistry, organic petrology, and basin modeling, Gong et al. systematically evaluated a set of marine–terrigenous transitional source rocks developed in the Lower Carboniferous Bashan Formation in the Jimuar Sag, northwestern China, and revealed a potential giant petroleum system.

Previous studies have shown that several intervals of high-quality source rocks generally contain varying volcanic ash layers (Liu et al., 2019a,b). Extensive studies have been conducted on the impact of these volcanic ash layers on the development of high-quality source rocks (Duggen et al., 2007; Lee et al., 2018). However, these studies mainly focused on the development of hydrocarbon-forming organisms and the preservation of organic matter but rarely considered the differential development of hydrocarbon-forming organisms between multiple volcanic ash layers (Liu et al., 2019a,b). The Permian Dalong Formation in the northwestern Sichuan Basin, China, is a set of high-quality source rocks with multiple volcanic sedimentary layers. Considering the marine source rocks in the Permian Dalong Formation, southwestern China, as the research objects, Zhang et al. analyzed the types of hydrocarbon-generating materials of high-quality source rocks and the reasons volcanic activities affected the growth of hydrocarbon-forming organisms. They also explored the impact of volcanic activity on the development of different types of hydrocarbon-forming organisms.

Diamondoid, named considering its diamond-like structure, is highly resistant to thermal degradation and biodegradation. Thus, it is preserved and enriched during the long and complex geological process and carries geological information. Therefore, diamondoid has broad applications in petroleum geochemistry, such as oil maturity ascertainment (Chen et al., 1996), oil cracking extent assessment (Dahl et al., 1999), lithofacies discernment (Schulz et al., 2001), secondary change assessment (Jiang et al., 2020), thermochemical sulfate reduction (Wei et al., 2011), and oil spill source identification in an accident (Stout and Douglas, 2004; Wang et al., 2006) in marine strata. However, its application in coal measures and related petroleum systems is in its infancy. Based on gold tube thermal simulation experiments on the soluble components (extracts) and insoluble components of coal-measure mudstones, Zhai et al. quantitatively analyzed diamondoid compounds in the pyrolysis products as well as showed that diamondoid compounds in the extracts and extracted coal-measure mudstones formed and decomposed during thermal evolution. In addition, the evolution characteristics and some diamondoid maturity parameters in the extracts and extracted coal-measure mudstones showed a good linear relationship. However, the specific characteristics differed, which may enable the identification of the kerogen and secondary cracking of crude oil.

Oil (gas)-source correlation is an effort to determine the genetic relationship between oil and source rocks based on geological and geochemical evidence (Volkman, 1986; Dai et al., 1992; Peters et al., 2005). This Research Topic includes the correlation between oil (gas) and source rock as well as between oil and gas in different reservoirs. Consequently, the direction and distance of oil and gas migration and the secondary alterations of oil and gas can be judged by the comparative study to further delineate reliable oil-source areas, determine exploration targets, and effectively guide oil and gas exploration and development (Volkman, 1986; Dai et al., 1992; Peters et al., 2005). Qin et al. conducted a detailed geochemical anatomy of 18 oil samples collected from key oil-bearing structural units of the southern thrust belt of Junggar, northwestern China. Based on the characteristics of light hydrocarbons, adamantanes, biomarkers, and stable carbon isotopic composition of the bulk oil ($\delta^{13}C_{bulk}$), the geochemical classification and potential secondary alterations, such as biodegradation, thermal cracking, and evaporative fractionation, were discussed, thereby providing a classic case to bolster the understanding of the origin and accumulation process of oil and gas in a complex structural zone (Qin et al).

Reservoir evaluation

Reservoir evaluation is a comprehensive subject that applies various data to study and explain the sedimentary environment, diagenesis, and formation mechanism of petroleum reservoirs. By analyzing and determining reservoirs' geological information, oil and gas exploration and development efficiency will be improved significantly. Reservoir evaluation extensively uses geological, seismic, well logging, well testing, and other data and various reservoir testing methods. The research objects are mainly divided into carbonate and clastic rocks.

The sedimentary environment is the determinant factor controlling reservoir macroscopic distribution. Zhi et al. employed core observation, logging curve, and seismic data to determine the stratigraphic characteristics and sedimentary-filling process for the Lower Permian Fengcheng Formation in the Junggar Basin, northwestern China—the oldest alkali lake in the world. Storm deposits are helpful indicators for sedimentary facies and palaeogeographic analysis (Aigner and Reineck., 1982; Aigner., 1985a; Aigner., 1985b; Myrow et al., 2008; Immenhauser, 2009). In addition, tempestites are essential reservoirs for stratigraphic traps (Aigner, 1985a,b; Mohseni and Al-Aasm, 2004). He et al. discussed an unrecognized phenomenon known as storm deposition and tempestite in the Cretaceous Qingshankou Formation of the Songliao Basin, the largest proliferous basin in China. This work is significant for elucidating the formation environment and diagenetic process of the Qingshankou shale reservoir, providing a reference for oil and gas exploration and development.

Diagenesis is a key factor controlling reservoir quality. The diagenesis of carbonate and clastic rocks differs significantly. In sedimentary petrology, the identification of geologic fluids and the related fluid–rock interactions during diagenesis has attracted considerable attention. Authigenic calcite potentially provides a record of geologic fluids and it occurs heterogeneously in the Upper Permian Wuerhe Formation in the Shawan Sag, Junggar Basin, northwestern China, which has a complex history of geologic fluid activity. Xu et al. conducted petrological and mineralogical studies of the Wuerhe Formation and used the *in situ* major element, trace element, and carbon and oxygen isotopic compositions of calcite formed at different stages to reveal the possible composition of geologic fluids present as well as the fluid–rock interactions and alteration of the reservoir that occurred during diagenesis. In addition, considering the Wuerhe sandstone reservoir as the research object, Qin et al. employed rock-cast thin section, scanning electron microscopy, fluid inclusions, piezometric mercury analysis, and porosity–permeability analysis to illustrate the characteristics and genesis mechanism of the Wuerhe clastic reservoir and provided a basis for the preferential selection of promising targets and sweet-spot areas. The Qiangtang Mesozoic marine sedimentary basin is the least explored oil-bearing basin in China. In recent years, dolostone paleo-reservoirs were discovered in the Middle Jurassic Buqu Formation in the southern Qiangtang depression of Tibet, providing a new direction for oil and gas exploration in the basin (Chen et al., 2018; Wang and Fu, 2018; Sun et al., 2020; Wang et al., 2020; Yi and Xia, 2022). Wan et al. investigated the petrography, geochemistry, and origin of various types of dolomites collected from the boreholes using various methods, such as core description; petrographic observation, cathodoluminescence imaging, and carbon, oxygen, and strontium isotope analyses. Combined with fluid inclusion measurements and salinity analysis, they revealed the genetic mechanism of the dolostone in the Buqu Formation and provided a geological basis for evaluating the dolostone reservoir. Using the inclusions in the calcite of fracture caves in the Yingshan Formation of Central Tarim Basin, northwestern China, Dan et al. provided relevant evidence to judge the nature of the paleokarst fluid and karst environment as well as established a paleokarst reservoir prediction model for oil and gas exploration. Proven to be closely related to hydrocarbon accumulation, strike-slip faults are important hydrocarbon accumulation zones. To clarify the controlling effects of strike-slip faults on reservoirs, the characteristics of two types of carbonate reservoirs in the central Tarim Basin, northwestern China—strike-slip fault-controlled fracture caverns and strike-slip fault-dissolved fracture caverns—were delineated through detailed analyses of seismic data, tectonic evolution, and observations of the core and thin sections (Ning et al).

Reservoir prediction is a process of predicting the longitudinal and transverse distribution characteristics and reservoir physical properties of reservoirs using various technical means in geophysical and geological aspects (including sedimentary facies analysis, small bed correlation, seismic data inversion, and attribute analysis) under the guidance and control of sequence stratigraphy and sedimentology to provide the geological basis for well location deployment and development program. Zhao et al. presented a case study of deep-water submarine fans in the Albacora Leste oilfield in Brazil and systematically established a sedimentary microfacies distribution model for each reservoir based on a detailed stratigraphic framework with a well-seismic joint characterization method and various data types (e.g., geological, well-log, and seismic data). Wang et al. predicted fractured reservoirs using coherence cubes and linearly enhanced attributes as well as identified fractured cave reservoirs with single-frequency attribute bodies in the Bongor Basin, southwestern Chad. In addition, they summarized a set of granitic buried hill reservoir prediction techniques for intensely-inverted rift basins in the Central African Rift System.

Petroleum accumulation process

Petroleum accumulation refers to the geological process in which oil and gas are generated in a sedimentary basin, migrated in the carrier layer, finally filled into the trap, and accumulated to form oil and gas reservoirs. Petroleum accumulation is the comprehensive result of various geological factors and is a temporary equilibrium state of oil and gas in the crust. Xue et al. proposed a model of natural gas enrichment and accumulation in a lacustrine basin. The model indicated that rapid subsidence and high gas-generating intensity during the highly-mature stages were the main contributors to the natural gas field formation. Archean metamorphic buried hill reservoirs and thick overpressured mudstone with the strong vertical sealing ability provide favorable storage space and preservation. Using the model, an integrated Archaean metamorphic buried hill condensate gas reservoir—Bozhong 19–6—was discovered in the Bohai Bay Basin, eastern China, with proven gas reserves of approximately 450 × 10^9 m^3. Based on research on the chemical composition of natural gas, carbon isotope features of source rock and natural gas, and geological feature differences between different regions in the northwestern Sichuan Basin, Xiao et al. determined the origins of natural gas, clarified the petroleum accumulation process, and fixed the main factors controlling natural gas accumulation. This work provided a favorable case study for petroleum exploration in the basin-mountain transition regions.

With the increasing difficulty in conventional oil and gas exploration, various countries and oil companies have paid considerable attention to unconventional oil and gas, such as volcanic reservoirs, coal bed methane (CBM), shale oil, and shale gas. To date, the CBM development targets are mostly undersaturated shallow coals in China and other countries (Kuuskraa and Wyman, 1993; Johnson and Flores, 1998). Kang et al. explained the reason for gas oversaturation in deep coals in the Ordos Basin, central China, and proposed that in most large tectonically compressed coal basins, there is a critical depth beyond which the oversaturation areas could occur, presenting opportunities and challenges for CBM development. As an unconventional petroleum reservoir, the volcanic reservoir is essential to find large-scale oil and gas reserves in deep sedimentary basins. Based on analog modeling of reservoir formation, including reservoir properties, hydrocarbon fluid phases, migration pathways, and source rock evolution history, Ablimiti et al. systematically illustrated the potential deep-buried volcanic petroleum system.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

Author DZ was employed by Xinjiang Oilfield Company, PetroChina, and Turpan-Hami Oilfield Company, PetroChina. Author DG was employed by Research Institute of Petroleum Exploration and Development, PetroChina.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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