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Geochemical and organic-petrographic constraints on the generation conditions and accumulation of Quaternary shallow biogenic gas in the Hetao Basin, North China

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Shallow biogenic gas is a potential unconventional clean energy resource with important prospects for future energy exploration and sustainable development. Abundant biogenic gas resources occur in Quaternary argillaceous sediments of the Hetao Basin, North China, but the favorable conditions for biogenic gas generation and the enrichment patterns remain poorly understood. This study integrates elemental geochemistry, molecular organic geochemistry, and petrology to investigate the depositional paleoenvironment, organic matter sources, favorable conditions for biogenic gas formation, and enrichment patterns of the source rocks. The results show that the source rocks are generally immature. Organic matter is dominated by Type III kerogen and is mainly derived from terrestrial C3 plants, while lacustrine primary productivity was low. Maceral compositions are dominated by huminite and inertinite, with minor liptinite. The source rocks formed under an overall cold and arid paleoclimate, and the depositional waters were characterized by brackish–saline and weakly reducing conditions. In the Middle Pleistocene gas-anomaly interval, TOC values are relatively high, with an average of 0.41%. A cold and dry climate reduced the dilution effect of terrestrial input on organic matter, and lacustrine paleoproductivity slightly increased during this period, while brackish–saline weakly reducing waters further enhanced organic matter preservation. Cold climatic conditions suppressed microbial activity and delayed the peak of biogenic gas generation, and elevated salinity slowed the conversion of sedimentary organic matter into biogenic gas. Adequate and continuous source rock supply provided the fundamental basis for biogenic gas accumulation. Multiple controlling factors acted together to form a shallow biogenic gas accumulation model characterized by continuous gas generation and dynamic accumulation in the Hetao Basin. These results improve the understanding of biogenic gas formation at low maturity and its environmental controls and provide a theoretical basis for the exploration and development of shallow biogenic gas resources in the Hetao Basin and similar continental basins.