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RESEARCH PAPER

Diagenetic characteristics under abnormally low pressure: A case from the Paleogene of southern Western Sag, Liaohe Depression, Bohai Bay Basin

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Abstract: The effects of low pressure and abnormally low pressure on reservoir diagenesis and physical property of the Paleocene in southern part of Western Sag of Liaohe Depression, Bohai Bay Basin have been analyzed using large amounts of pressure, physical property and formation testing data. When formation pressure is low or abnormally low, the pore fluid has lower pressure, the overburden litho-static pressure is largely born by the sandstone framework, sometimes over compaction occurs, leading to densification of reservoir and stronger mechanical compaction; residual formation pressure has a negative correlation with carbonate cement content, low pressure or abnormally low pressure tight sandstone formations have higher carbonate cement content than sandstone formations with hydrostatic pressure or weak overpressure; pore fluid in sandstones with low pressure or abnormally low pressure has higher Si^{4+}, conducive to the siliceous cementation; when dissolution happens, reservoirs with low pressure or abnormally low pressure, poor in original physical properties, are not favorable for the injection of dissolution fluid and the expulsion of dissolution products, so they have weaker dissolution. In summary, reservoirs with low pressure or abnormally low pressure have poorer physical properties.

Key words: abnormally low pressure; diagenesis; reservoir physical property; tight sandstone; Western Sag; Liaohe Depression

Introduction

Previous studies have shown that overpressure can inhibit the thermal evolution of organic matter and transformation of clay minerals[1–3], and also inhibit diagenesis processes such as sandstone compaction and quartz cementation[4–6], protecting pore space and preserving abnormally high porosity zones. But more and more hydrocarbon reservoirs have been found with low pressure and abnormally low pressure, for example, Muddy Formation of Denver Basin, Mesaverde Formation of San Juan Basin, Prit River Formation of Alberta Basin, Clinton-Medina Formation of Appalachian Basin, and Permian Sulige gas field of Ordos Basin[7]. How abnormally low pressure affects the diagenesis and reservoir physical properties has been rarely studied and reported. The tight sandstone of Paleogene Shahejie Formation, southern Western Sag, Liaohe Depression, Bohai Bay Basin has abnormally low pressure[8–9]. Taking this area as an example, the diagenetic features of sandstone in abnormally low pressure, and the relationship between abnormally low pressure and tightening of sandstone reservoirs were investigated in this study, in the hope to provide insights into the formation mechanism and exploration potentials of tight sandstone reservoirs.

1. Regional geological setting

The study area, about 700 km^2 in area, and located in the southern Western Sag of Liaohe Depression, Bohai Bay Basin, can be subdivided into Huanshu slope zone, Xing-Leng structural zone, Shuangtaizi structural zone, Bijialing structural zone, and Xiaowa-Yuehai structural zone (Fig. 1). Sedimentary strata developed in the sag from bottom to top include the Paleogene Shahejie Formation (Es), Dongying Formation (Ed), Neogene Guantao Formation (Ng), Minghuazheng Formation (Nm), and Quaternary. With source rock, reservoir, and cap rock, Shahejie Formation is a main exploration target in this area. Shahejie Formation is subdivided into four members, and the third member is usually subdivided into lower, middle and upper sub-members. The third member mainly consists of lake floor fan and deep lake deposits.

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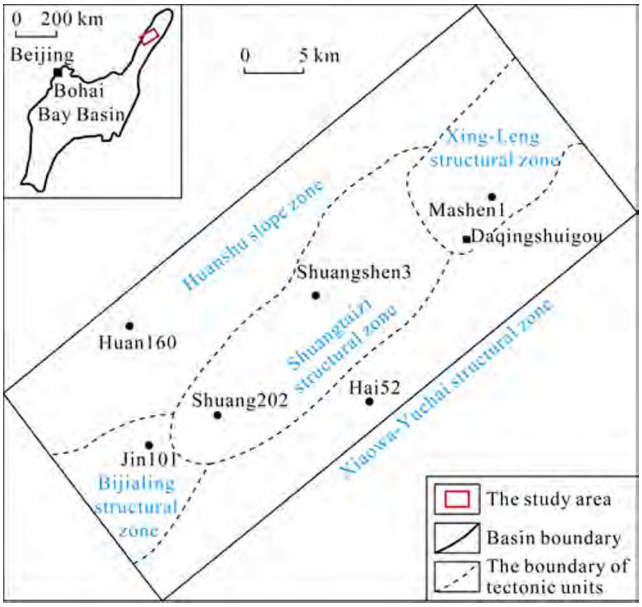

Fig. 1. Structure division of southern Western Sag, Liaohe Depression.

The reservoirs of Shahejie Formation are mainly composed of arkosic lithic arenite, lithic arkose, and arkose. The sandstones consist of 36%–41% of quartz grains, 24%–40% of feldspar grains, and 20%–26% of lithic grains. Statistical analysis of 3 566 samples from 56 wells show that the grains of the reservoir sandstone span from silt to pebble, but are mainly medium to fine sand grains. The sandstone is poor in sorting and sub-angular to sub-rounded in roundness. Tight sandstone reservoir has been found in the middle submember of Sha3 Member, with a porosity of less than 10% and permeability of less than 1×10^{-3} μm^2 in general. Low-yield gas flow was tapped in this tight sandstone reservoir, and industrial gas flow was discovered in a few wells, such as Well Shuang 202, which has daily production rate of 2.5×10^4 m^3.

2. Formation pressure

Formation testing data of 1092 wells show that the reservoirs have an average pressure index of 0.9, lower than standard hydrostatic pressure[8–9], according to the common pressure dividing standard in China[10].

There are four types of pressure systems in this area, weak overpressure (pressure index of 1.2–1.5), normal pressure (pressure index of 0.9–1.2), low pressure (pressure index of 0.8–0.9), and abnormally low pressure (pressure index < 0.8). The formation pressure varies significantly in vertical direction (e.g., normal hydrostatic pressure in formations less than 1 700 m deep and low to abnormally low pressure in formations more than 1 700 m deep) (Fig. 2).

Hu Anwen et al. suggested that the abnormally low pressure in this area was the result of multiple factors, including temperature drop due to erosion after uplift, cold water induced pressure drop, dissipation of natural gas, formation of high viscosity oil, and over-compaction, etc[8–9]. The southern Western sag experienced three times of regional uplift and erosion at the depositional stage of third and first members of Shahejie Formation and Dongying Formation, which caused

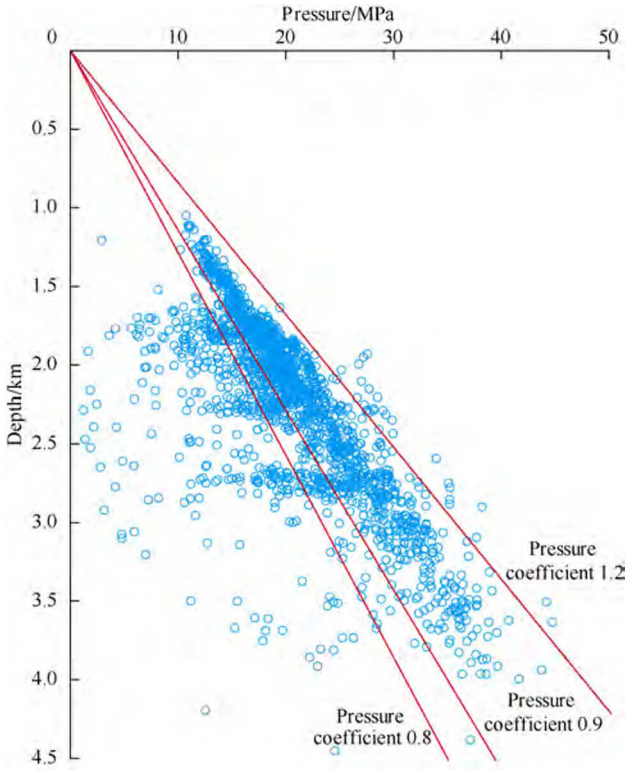

Fig. 2. Pressure profile of pore fluid in sandstone of Shahejie Formation.

ancient formation temperature drop and cold water induced pressure drop inevitably. Meanwhile, uplift would facilitate the infiltration of atmospheric precipitation into ground water, resulting in formation of high viscosity oil and lowering the formation pressure even further. After the deposition of upper sub-member of the third member of Shahejie Formation, the Shahejie Formation source rock entered middle diagenesis stage B to late diagenesis stage with R_o value of more than 2.0%[9], the liquid hydrocarbon in it started to crack into natural gas massively, and the dissipation of the natural gas was another factor leading to the abnormally low pressure. In the southern Western sag, the tightening of sandstone started from the Es_3^{upper}, and lasted to Ed[11], it can be seen that the formation of abnormally low pressure and tightening of reservoir sandstone coincided in time very well, that is to say the abnormally low pressure is closely related to the tightening of the reservoir.

In the southern Western Sag, abnormally low pressure is found at different depths in different structural units. Abnormally low pressure is mainly found in deeper intervals in the deep sag area, while in lower depth in slope zone. The top of abnormally low pressure interval is in positive correlation with the depth of basement[9], e.g., tops of the basement at Huanshu slope zone and Shuangtaizi structural zone average at 2 400 m and 5 200 m respectively, while the top of abnormally low pressure in the two zones average at 1 700 m and 2 500 m respectively. The difference in the pressure system resulted in different degree of diagenesis in the major structural zones: at the same depth, the sag area has lower degree of diagenesis and the slope area has higher degree of diagene-