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Abstract

Regional variation of formation water chemistry and diagenesis reaction in underpressured system: example from Shiwu depression of Songliao basin, NE China

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Abstract

Geochemistry of formation waters in the Shiwu depression of the Songliao basin, northeast China, shows a distinct variation in different pressured systems. The study area is composed of terrigeneous clastics in fluvial–lacustrine environments, which contain formation water with salinity ranging from less than 1000 to 12,000 mg/l. Water composition varies with depth and hydrochemical regions. In the underpressured strata deposited during the rifting period, formation water is characterized by water type of $CaCl_2$ with higher salinity. $NaHCO_3$-dominanted water with lower salinity occurs in the normally pressured strata deposited during the post-rifting period. In the transition area between the normally pressured and underpressured zones, total dissolved solid (TDS) content ranges from 1000 to 7600 mg/l and increases with depth. In this halite-free basin, brackish water may be attributed to the evaporation of formation water and water–rock interaction. In the deep buried underpressured water, a predominated diagenesis reaction resulting in Ca and Cl enrichment and reduction of Na may be related to albitization of plagioclase following the basinal fluid line (BFL). The results of this study indicate that salinity variation of formation water and diagenesis reaction is closely related to hydrochemical environments within different pressured systems.

Keywords: Underpressured system; Formation water; Diagenesis reaction; Shiwu depression

1. Introduction

Knowledge of the origin and evolution of formation water in sedimentary basins plays an important role in various geological processes. The evolution process of formation water, however, is not always clear, especially in abnormally pressured environments. A number of mechanisms responsible for the origin of saline groundwater have been proposed, such as membrane filtration or reverse chemical osmosis (Graf, 1982), halite and potash salt dissolution (Hanor, 1987), evaporatively concentrated seawater, and evaporation of non-marine fluids or water–rock interactions in sediments (Hardie, 1990). Variation of salinity in groundwater results likely from a combination of these processes and will depend on local hydrochem-

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ical environments and the degree to which water derived from various mechanisms has been mixed (Hanor, 1987; Hardie, 1990). In the abnormally pressured system, distinct hydrochemical environments constrain diagenesis reaction of pore fluid and variation of salinity because of the presence of a closed system (Land, 1995). It is widely recognized that salinity variation of subsurface water may provide a clue to interpret the processes of its origin and evolution.

The Shiwu depression has been explored for more than 20 years and comprises one of most important hydrocarbon-bearing province in the Songliao basin. Recent studies of the Shiwu depression have focused on the origin of underpressure, fluid flow system, and gas potential (He et al., 2000; Xie et al., 2003); however, regional variation of formation water chemistry is not yet clearly understood. In this paper, we discuss the relationship between diagenesis reaction and salinity variation of formation water within underpressured system, and interpret the possible origin of formation water chemistry.

2. Geological setting

The Shiwu depression, a NNE-trending sub-basin in the southeastern part of the Songliao basin, formed as a result of rifting and thermal subsiding in the Mesozoic period (Li et al., 1995). The sub-basin is bounded by the Sanshutai fault to the west, and by a monocline to the east, forming a wedge-shaped faulted basin with an area of about 1500 km^2 (Fig. 1). The fill of the sub-basin is composed of Jurassic, Cretaceous clastic sediments up to 7000 m thick. The evolution of the graben can be divided into distinct syn-rift and post-rift stages. During Late Jurassic to Early Cretaceous rift stage, the sediments are characterized by lacustrine–alluvial fan and fan–delta depositional systems. The post-rifting phase is represented by the Upper Cretaceous coarse

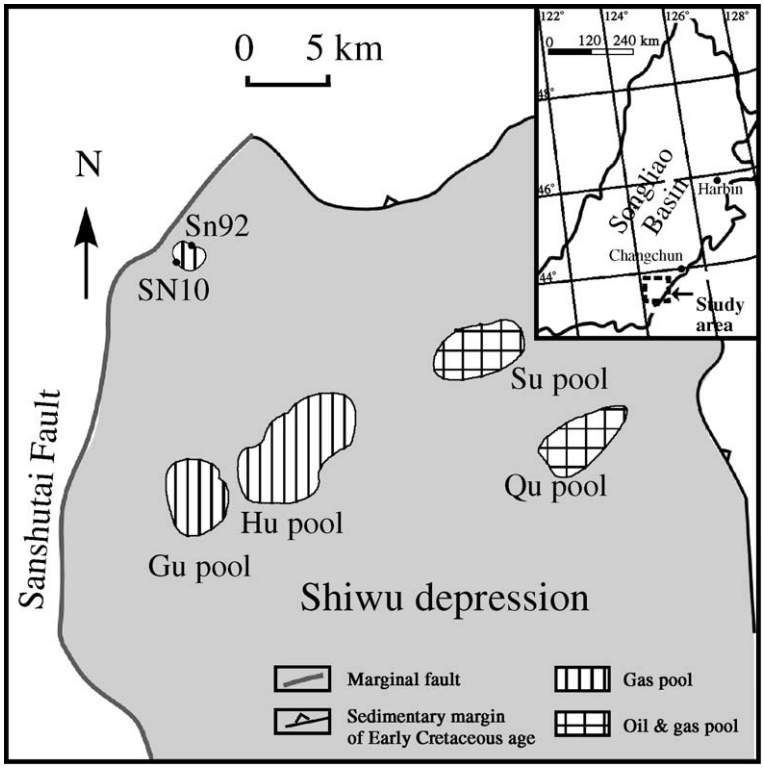

Fig. 1. Simplified location map of the Shiwu depression and the Songliao basin.

clastic deposits with large scales of delta and fluvial systems developed in the study area.

The pressure system in the Shiwu depression can be grouped into three zones as evidenced from drill stem tests (DST) measured by the Bureau of Northeast China Petroleum Exploration. The strongest underpressured zone commonly occurs in the Shahezi and Yingchengzi Formations deposited during Early Cretaceous rift, where pressure coefficients fall in the range of 0.5–0.8 with the depth below 1500 m (Fig. 2). The normally pressured region occurs at the post-rifting Quantou Formation and overlying strata of Late Cretaceous age. The Lower Cretaceous Denglouku Formation, the topmost stratigraphic unit in the rifting stage, is located in the transition region of underpressured rifting and normally pressured post-rift sections. Pressure coefficients vary from 0.6 to 0.9, depending on the burial depth and hydrochemical environments. The origin of the underpressured system has been discussed in some papers (He et al., 2000; Xie et al., 2003).

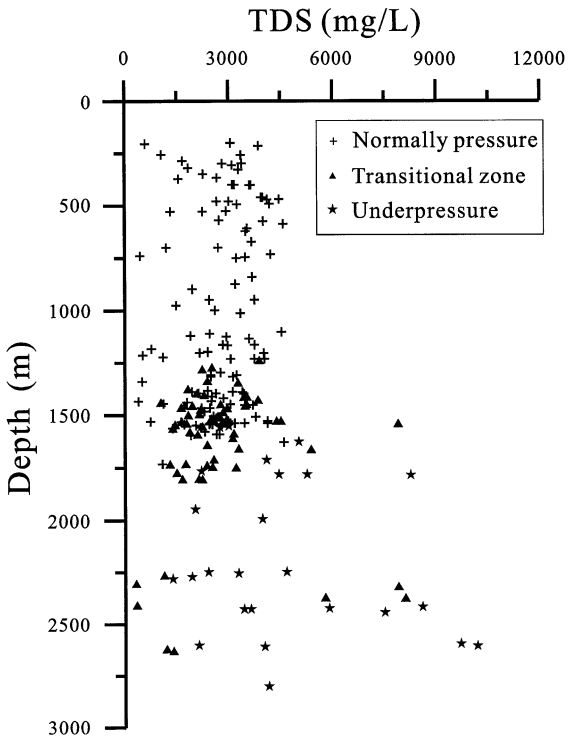

Fig. 2. Variation of total dissolved solid content with depth in the Shiwu depression of the Songliao basin.

3. Regional variation of formation water chemistry

The geochemistry of formation waters in the Shiwu depression shows a distinct variation in vertical section, which can be grouped into three zones based on the pressure regimes, that is, normally pressured, underpressured, and transitional zones. The geochemistry of the three zones has the following characteristics.

(1) In the normally pressured zone, the total dissolved solid (TDS) contents of water are less than 4500 mg/l. In all the water samples of this zone, sodium is the dominant cation, calcium and magnesium concentrations are depleted. The concentrations of calcium are less than 150 mg/l. The concentration of Cl is about 1500 mg/l and does not show much change with depth. Concentrations of HCO_3^- and SO_4^{2-} are usually less than 500 and 200 mg/l, respectively. In this zone, the dominant water types are $NaHCO_3$ and NaCl.

(2) In the underpressured zone, salinity of subsurface water ranges from 3000 to 12,000 mg/l. Most of water samples in this zone belong to brackish (Fig. 2). In the water samples collected from the deeper depression in the Shahezi and Yingchengzi Formations at depth below 1500 m, the concentration of Cl increases clearly with depth, and dissolved calcium concentration increases with chloride and depth. High saline formation water occurs in the abnormally low-pressured system in the central rifting strata of the depression, which is characterized by $CaCl_2$-water type. In general, the more significant the underpressure is, the higher the TDS content.

(3) The transition region between normally pressured and underpressured zones, corresponding to the Lower Cretaceous Denglouku Formation, is mainly characterized by $NaHCO_3$-water type. A few water samples show Na_2SO_4- and $CaCl_2$-type water. TDS content ranges from 1000 to 7600 mg/l, which commonly increases with depth in this zone.

4. Origin of formation water

The Shiwu depression is characteristic of continental clastic deposits without the presence of evaporite and halite. He et al. (2000) suggested that the relatively

high salinity is related to the trends of ionic evaporation of the formation water in the underpressured system. As will be discussed in the following sections, chemical analyses from this study indicate that the higher salinity of formation water is due not only to evaporation of fluids but also to significant modification by water–rock interaction, especially in the underpressured compartments of the Shahezi and Yingchengzi Formations.

4.1. Evaporation of non-marine formation water

TDS contents in subsurface water in normally pressured areas of this study are usually less than 4000 mg/l, which is about 30–50 times that of meteoric water. The Na/Cl ratio shows that most values, which are always much less than that in normal seawater, are close to or slightly larger than the seawater evaporation trajectory (SET), as demonstrated by He et al. (2000). This close relationship between the SET and the Na/Cl ratio of the Shiwu depression water samples suggests evapo-concentration of pore water.

4.2. Water–rock interaction

In the underpressured zone of the Shahezi and Yingchengzi Formations, there is a distinct difference in the chemistry of formation water between the margins and central part of the graben. In the margins of graben, the formation water has the TDS of less than 3000 mg/l and is dominated by water type of $NaHCO_3$, where pressure coefficients range from 0.7 to 0.85, such as the wells SN10 and SN92 near the Sanshutai fault to the west. However, in the central part of underpressured compartments, which has very significant abnormal pressures with pressure coefficient of 0.5–0.8, the formation water has CaCl-dominated water type and the TDS of larger than 3000 mg/l. The Na–Cl plot (Fig. 3) shows a significant variation of Na and Ca concentrations. In normally and transitional-pressured zone, formation water shows excess in Na concentration, and low content in Ca concentration. In the underpressured zone, however, formation water indicates a sharp decrease in Na concentration and increase in Ca concentration. Without the dissolution of halite or evaporite, the enrichment of Ca

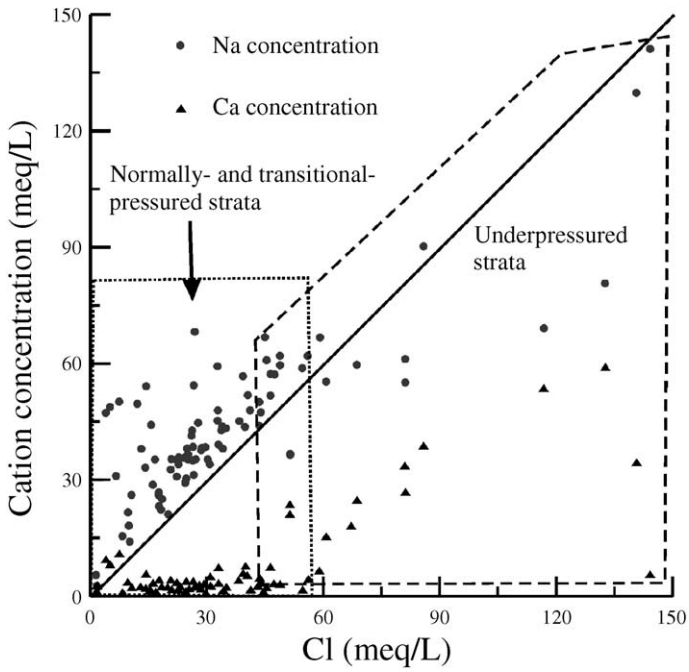

Fig. 3. Relationship among Na, Ca, and Cl concentrations showing Na/Cl and Ca/Cl ratios in the Shiwu depression.

and reduction of Na must have been attributed to water–rock interaction. Some diagenesis reactions, such as dissolution of $CaCO_3$ and $CaSO_4$ and dolomitization of calcite, only increase Ca concentration without changing Na ion content (Davisson and Criss, 1996). Albitization of feldspar occurs commonly at deep burial strata (Land, 1995). The results of this study show that diagenesis reaction in the Shahezi and Yingchengzi water followed a 2 Na for 1 Ca exchange ratio. This indicates that albitization of plagioclase acts as a predominating geochemical reaction, which produces the ionic balance between Na and Ca concentrations.

5. Discussion

In terrigeneous clastic basins, variation of salinity in formation water mainly depends on local hydrochemical environments and degree of mixing among fluids derived from various sources. Water–rock interactions commonly occur during the evolution of a basin, especially at deep burial strata. In the closed hydrochemical environments, evidence from the chemistry of pore water may be taken as a good indicator for diagenesis reaction.

In order to identify the possible causes of formation water resulted from different water–rock interaction, Davisson and Criss (1996) introduced a mathematical transformation of Na, Ca, and Cl concentrations. In Davisson and Criss' plot, a highly correlated regression termed the basinal fluid line (BFL) has been found based on the analysis of larger than 800 samples from numerous fluid reservoirs. This BFL line indicates that an exchange of 2 Na for 1 Ca is attributed to albitization of plagioclase.

Fig. 4 shows an excess Ca–Na deficit plot on basis of the chemical results analyzed from water samples collected in the Shiwu depression. The values of Ca_{excess} and $Na_{deficit}$ in most of the water samples show excess in Ca (positive Ca_{excess}). Obviously, all the results from the underpressured water give a good correlation of $Ca_{excess} = 0.83\ Na_{deficit} + 19.48$ as shown by the broken line in Fig. 4. The regression line is parallel to the BFL, but the intercept of 19.48 is different from that of BFL. The intercept of 140.3 for BFL is attributed to the dissolution of halite prior to albitization (Davisson and Criss, 1996). In the halite

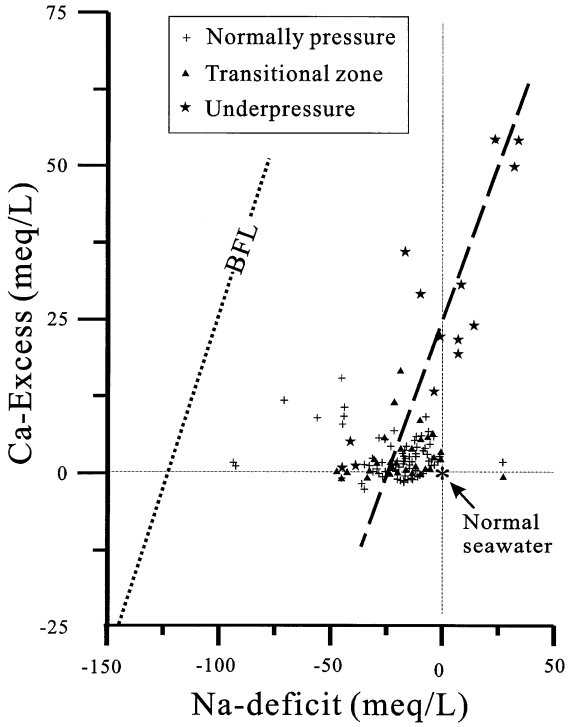

Fig. 4. Excess-deficit relations of formation water in the Shiwu depression showing modes and processes of different water–rock interaction that may have affected fluid composition. The basinal fluid line (BFL) is referred to Davisson and Criss (1996).

and evaporite-free Shiwu graben, however, the intercept for the underpressured water may be contributed to Ca-rich meteoric water. This trend line indicates an exchange ratio of 2 Na for 1 Ca, which is believed to be caused by the albitization for plagioclase (Davisson and Criss, 1996). These predominant water–rock interactions occur in the underpressured zone of the Shahezi and Yingchengzi deposits and the deep segments of the Denglouku Formation.

6. Conclusions

In the Shiwu depression of the Songliao basin, regional variation of formation water chemistry can be divided into three zones. Salinity in subpressured sediments is much higher than that in normally pressured strata. The brackish formation water is considered to be caused by evaporation of pore water and strong water–rock interaction. The $CaCl_2$-dominated water with the

enrichment of Ca and Cl and reduction of Na suggests that albitization of plagioclase is a predominant diagenesis reaction. The mixture of formation water from different pressured systems has been observed in the Shiwu depression. Therefore, a better understanding of geochemistry in formation water plays an important role in the exploration of hydrocarbon.

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