Chemie der Erde 73 (2013) 469–479

Contents lists available at ScienceDirect

Chemie der Erde

journal homepage: www.elsevier.de/chemer

Prediction of buried calcite dissolution in the Ordovician carbonate reservoir of the Tahe Oilfield, NW china: Evidence from formation water

Zhuang Ruan [a,*], Bingsong Yu [a], Lidong Wang [a], Yinglu Pan [a], Guanghui Tan [b]

[a] *State Key Laboratory of Geological Process and Mineral Resources, China University of Geosciences, Beijing 100083, China*
[b] *Exploration and Development Research Institute, SINOPEC Northwest Company, Urumqi 830011, China*

ARTICLE INFO

Article history:
Received 31 July 2012
Accepted 18 March 2013

Keywords:
Gibbs free energy
Equilibrium constant
Dissolving tendency

ABSTRACT

The Lower–Middle Ordovician reservoir of the Tahe Oilfield is dominated by limestones with reservoir spaces formed by the generation of dissolution pores, meaning that buried karst formation can be evaluated by studying water–rock reactions between groundwater and calcite. The hydrogeological information preserved in this reservoir indicates that the Ordovician groundwater were high-salinity and high-closure, characteristics that are of significance to water–calcite reactions. Theoretical chemical thermodynamics combined with equilibrium calcite solution ionization allowed us to establish a dissolution–precipitation evaluation model for calcite, with the theoretical activity of Ca^{2+} in solution ($a\mathrm{Ca}^{2+}_{\mathrm{eq}}$) controlled by temperature, pressure, $[\Sigma\mathrm{CO}_2]-[\mathrm{Ca}^{2+}]$ and solution pH, and with the actual activity of Ca^{2+} in solution (aCa^{2+}) being controlled by the concentration of various ions in solution. Ionization reaction directions are controlled by ΔG values; these values can be calculated using $a\mathrm{Ca}^{2+}_{\mathrm{eq}}$ and aCa^{2+}. Here, ground water data were collected from 34 wells that intercepted Ordovician sediments within the Tahe Oilfield, and calcite ΔG values were calculated for these wells. These data indicate that the groundwater in this oilfield favours the dissolution of limestone, with limestones in the west and south of the Tahe Oilfield being more susceptible to dissolution, consistent with observations within the oilfield. The methods employed during this study can also be used to quantitatively assess susceptibility to burial dissolution and to support reservoir evaluation.

1. Introduction

The reservoir capacity of carbonate rocks is controlled by the development of secondary porosity, which in turn is dependent on dissolution reactions between rocks and surface water that take place close to or at the surface, including penecontemporaneous and weathering karst formation, and dissolution in deep burial environments during reactions with groundwater (Scholle, 1977; Zenger et al., 1980). The majority of researchers believe that the surface or near-surface dissolution is the most important control on secondary porosity development in carbonates, a hypothesis that has been borne out during exploration and the development of carbonate oil and gas fields worldwide (Scholle and Halley, 1985; Heydari, 1997). However, although most researchers also agree that secondary porosity can form during diagenesis (Jin et al., 2009), the effectiveness of generation of diagenetic porosity in reservoir formation has not as yet been established, and no evaluation method for determining the effectiveness of dissolution in deep environments has been proposed.

Calcite is the most common authigenic mineral in sedimentary rocks, occurring not only as pore-filling cements in many clastic rocks but also as the dominant mineral within limestone. A number of advances have been made since the 1960s that have improved our knowledge of calcite stability in natural groundwaters or seawater at room temperature and pressure (Garries et al., 1960; Peterson, 1966; Berger, 1967). However, few studies have investigated calcite–water interactions under high-temperature and high-pressure diagenetic conditions.

Water–rock reactions during burial have been extensively studied (Kafri and Sass, 1996; Genthon et al., 1997; Coudrain et al., 1998; Morse and Arvidson, 2002), with Garries and Christ (1965) summarizing the importance of silicate mineral- and clay-based ion exchange processes, introducing basic chemical thermodynamic principles to mineral systems. Burley et al. (1985) concluded that elevated temperatures add energy to mesogenetic-stage systems involving water–rock reaction, and Kaiser (1984) predicted reservoir qualities and estimated diagenetic histories using groundwater solution-mineral equilibria, suggesting that diagenesis of the Frio Formation in Texas, USA, was controlled by temperature, pH, activity, and pressure. Furthermore, Lai et al. (2005), Liu et al. (2005), and Yu and Lai (2006) investigated chemical equilibrium relationships between fluids, plagioclase, and K-feldspar during sediment

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[*] Corresponding author. Tel.: +86 13810965707.
E-mail address: wofe0103@163.com (Z. Ruan).

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http://dx.doi.org/10.1016/j.chemer.2013.03.004

diagenesis, focussing on the impact of temperature and fluid compositions (pH, activity of K^+, Na^+, Ca^{2+}, etc.) on feldspar precipitation and dissolution equilibria, and suggested that feldspar is extremely easily dissolved in acidic, low-salinity pore waters at low temperatures. Yu and Lai (2006), and Yu et al. (2008) studied the precipitation and dissolution of carbonate cements in clastic rocks using theoretical water–rock interaction thermodynamic phase equilibria and the mass conservation law, concluding that calcite solubility is dependent on groundwater $[\Sigma CO_2] - [Ca^{2+}]$ values. Zhang et al. (2009) also experimentally examined interactions between two fluids with different salinities and a composite mineral system, and suggested that acidity was the most important control on the dissolution of minerals in the system, as differences were observed in the dissolving abilities of different acids on various mineral components at identical pH values.

Carbonate rocks are composed of carbonate minerals such as calcite and dolomite, and the dissolution of these minerals directly contributes to the properties of a reservoir. Thus, the study of the dissolution trends of carbonate minerals in buried environments is a useful tool to predict the accumulated spaces in carbonate rocks in the diagenetic stage. Here, we extend the previous research undertaken on calcite in groundwater and establish a quantitative dissolution–precipitation model for calcite in groundwater based on basic chemical thermodynamic principles. This model is then applied to the Ordovician carbonate reservoir of the Tahe Oilfield of NW China. It should be noted that this modelling is still preliminary, and has a number of issues that will be addressed during future refinement. In addition, this study can only reflect the current status of carbonate reservoirs in buried environments, as groundwater data are collected from present-day formations, rather than reflecting the processes that occurred in the past.

2. Geological setting

The Tahe Oilfield is located in the southern portion of the Tabei Uplift in the Tarim Basin of NW China, and covers a total surface area of 3200 km^2. The Tabei or Northern Tarim uplift is surrounded to the north, south, west, and east by the Kuqu, Manjiaer, and Awati depressions, and the Kuluketage horst, respectively (Fig. 1). Ordovician sediments in this area were deposited in a platform environment and are now deeply buried (>5000 m; Fig. 1), with limestone, dolomite, and other evaporites dominating the geology of this area (Kang and Kang, 1996; Wei et al., 2000). The Ordovician carbonate reservoir in the study area can be subdivided into six formations: the Penglaiba ($O1_p$), Yingshan ($O1_y$), Yijianfang ($O2_{yj}$), Qiaerbake ($O3_q$), Lianglitage ($O3_l$) and Sangtamu ($O3_s$). The Yingshan ($O1_y$) and Yijianfang ($O2_{yj}$) formations, which are the focus of this study, consist of wackestones and packstones (Zhang et al., 2000; Ruan et al., 2012). Many faults are present in the study area,

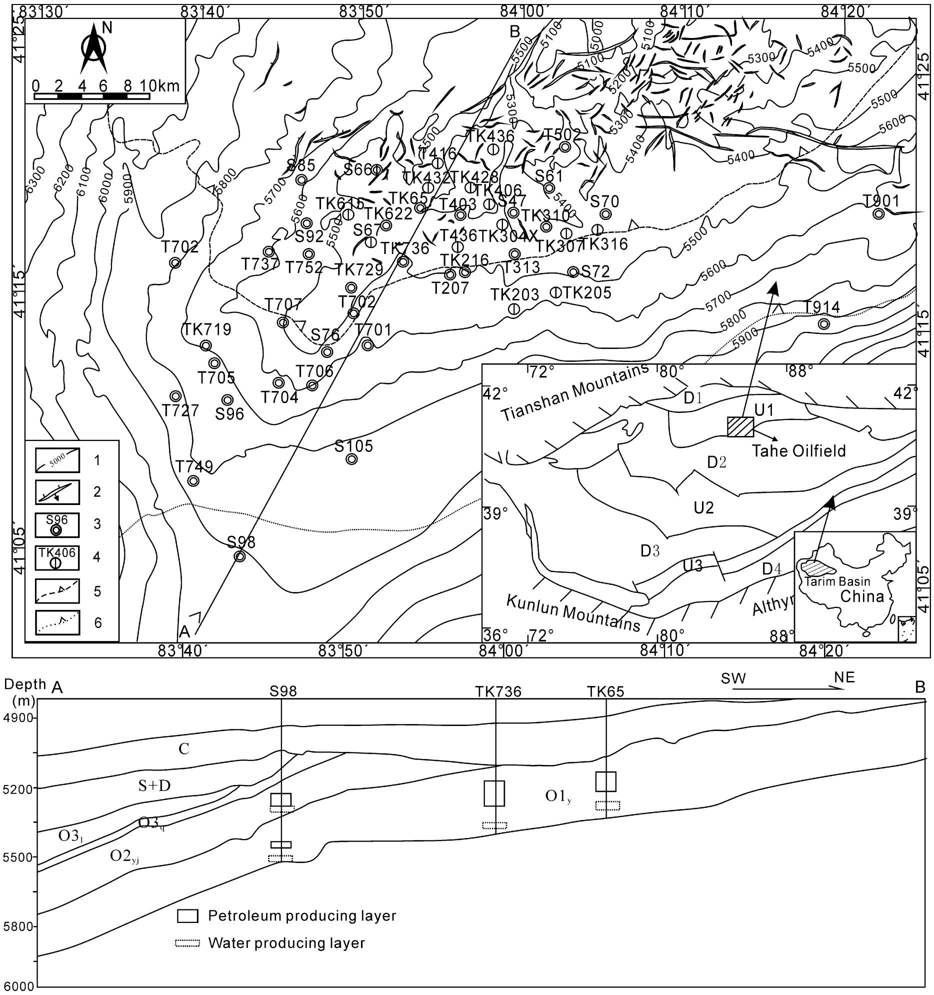

Fig. 1. Geology, tectonics, and locations of wells in the Tahe Oilfield sampled during this study, with a SW–NE cross-section; contours indicate depth to the top of the Lower Ordovician. U1, Tabei Uplift; U2, Central Uplift; U3, Southeast Uplift; D1, Kuqu Depression; D2, North Depression; D3, Southwest Depression; D4, Southeast Depression; 1, Depth line indicating the top of the Lower Ordovician; 2, Fault; 3, Sampled wells in Table 3; 4, Sampled wells in Table 2; 5, O2 + 3 absent line; 6, S + D (Silurian and Devonian) absent line.