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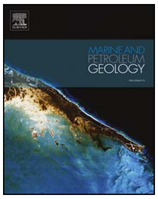

Research paper

Genesis of Upper Cambrian-Lower Ordovician dolomites in the Tahe Oilfield, Tarim Basin, NW China: Several limitations from petrology, geochemistry, and fluid inclusions

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ABSTRACT

Thick Upper Cambrian-Lower Ordovician carbonate units in the Tahe Oilfield of northern Tarim Basin were extensively dolomitized during their diagenetic history. Petrographic examination identified three types of matrix dolomites, one type of cement dolomite, and one type of saddle dolomite in these units: micritic to very finely crystalline, nonplanar matrix dolomite (D1); finely crystalline, planar-s(e) matrix dolomite (D2); medium to coarsely crystalline, nonplanar-a matrix dolomite (D3); finely to medium crystalline, planar-e cement dolomite (Cd); and coarsely crystalline, planar-s to nonplanar saddle dolomite (Sd). Isotopic studies (C, O, and Sr), elements measurements, and fluid-inclusion analysis were combined to constrain the origins of dolomitizing fluids. The occurrence of near-micritic dolomite crystals, as well as isotopic compositions which are consistent with the values and ratios of Upper Cambrian-Lower Ordovician marine limestones, coupled with the rare earth elements (REE) patterns with negative Ce anomalies, collectively suggest precipitation of D1 dolomite at low temperatures of near-surface settings from mesosaline to penesaline seawater. D1 dolomite, characterized by high Mg/Ca ratios and MgO values, moderate Sr concentrations, and low Mn and Fe values, was formed in the early diagenetic stage and scarcely experienced recrystallization. The dolomitizing fluid of D2 dolomite was derived from connate seawaters resulting from mechanical compaction and burial dissolution under shallow burial conditions, which is indicated by textures, isotopic compositions, and REE patterns. The relatively low MgO contents and Mg/Ca ratios constrain the formation of the D2 dolomite to a closed diagenetic system with a limited local supply of Mg^{2+} ions. The large overlaps of isotopic compositions between D3 dolomite and earlier dolomite, as well as the similar REE patterns and depleted Sr contents, indicate that D3 dolomite was likely the result of intense recrystallization upon previous matrix dolomites in a deeply buried formation-fluid system. The petrographic features and geochemical attributes of Cd dolomite strongly indicate progressive growth or recrystallization in the burial environment. Inclusions with high temperatures developed only in the outer edges of Cd crystals demonstrate diffusionally mediated recrystallization during the later hydrothermal activity. Sd dolomite is interpreted to directly precipitate from hydrothermal fluids, as evidenced by high homogenization temperature measured from fluid inclusions and high Sr contents. High salinity levels suggesting the existence of a very saline fluid (deep-basinal brine). The enriched radiogenic strontium isotope coupled with positive Eu anomalies indicate that hydrothermal fluids are likely to be crustal magmatic. Since Early Hercynian orogeny, long period tectonic activities were responsible for the hydrothermal alteration. High-angle faulting, which appeared as strike-slip faulting initiated along basement-rooted faults, likely acted as the important pathway that channeled the hydrothermal fluids from the depths. Initially, hydrothermal fluids with elevated pressure, high temperature, and low fluid/rock conditions were likely responsible for hydrofracturing and brecciation. When distal fluids of cooler temperatures flowed into permeable formations, the open fluid-dominated system with higher fluid/rock conditions facilitated the occurrence of dissolution vugs and precipitation of Sd dolomite. This study provides a basis for understanding the deep burial carbonate reservoirs in Tarim Basin by clarifying the process of dolomitization.

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1. Introduction

Dolomite is of interest because of its rich oil and natural gas resources worldwide. Compared with limestone, dolomite units are more resistant to porosity loss with depth. In addition, the porosity evolution and formation associated with dolomitization exert significant control on carbonate reservoir quality. Therefore, to predict the spatial distribution of a dolomite reservoir, it is essential to first understand the dolomitization process.

Although the study of dolomite has a nearly 200-years history, the formation mechanism of ancient dolomite is still disputed among geologists. Various models have been proposed to explain dolomitization under penecontemporaneous or shallow burial conditions, including sabkha-style dolomitization (Friedman and Sanders, 1967; Hsu and Schneider, 1973), seepage-reflux dolomitization (Adams and Rhodes, 1960), marine-meteoric mixing-zone dolomitization (Badiozamani, 1973), and organogenic/methanogenic dolomitization (Baker and Kastner, 1981). Recently, burial and hydrothermal dolomitization have attracted much more attention than before because of their convincing explanation for the widespread appearance of deep-burial dolomites (Machel and Mountjoy, 1986; Gregg and Shelton, 1990; Warren, 2000; Chen et al., 2004; Davies and Smith, 2006; Azomani et al., 2013). Since dolomite is a product of multistage dolomitization and may have undergone complicated diagenesis during burial stage, it is difficult to identify the source and nature of the dolomitization fluids (Gregg and Shelton, 1990; Al-Aasm and Packard, 2000). Therefore, we analyzed the multiple characteristics, including petrography, isotopic compositions, trace and rare earth elements, and fluid inclusions, to constrain the origin of dolomite.

The Tahe Oilfield, situated in the northern Tarim Basin, contains reserves of more than 1 billion tons of oil equivalent in Cambrian–Ordovician carbonate formations at burial depths exceeding 5000 m. Well TS1 (Fig. 1B) was first drilled to a depth of 8408 m in 2006 in order to evaluate the Upper Cambrian-Lower Ordovician dolomite reservoir (Zhang et al., 2009; Zhu et al., 2015). Since then the deep-burial dolomites with increasing porosity have become the focus of Chinese geologists, but no agreement has been concluded about the mechanism of dolomitization in this area (Ye, 1992; Gu, 2000; Shao et al., 2002; He et al., 2006; Wu et al., 2008; Zhu et al., 2008; Wang et al., 2009; Zhang et al., 2014; Guo et al., 2016). This paper presents new data from subsurface dolomite reservoirs (core) of Upper Cambrian-Lower Ordovician formations. New data have been collected by cathodoluminescent petrology, scanning electron microscopic studies, fluid-inclusion analysis, elements measurements, and Sr, C, and O isotope analysis to detail the genesis and features of dolomitization fluids and development mechanisms of the dolomites.

Specifically, we address the following objectives: (1) identify and characterize petrographic and geochemical variations of Upper Cambrian-Lower Ordovician dolomites in order to establish diagenetic paragenesis; (2) decipher and describe the origin and nature of the dolomitizing fluids responsible for the formation of these dolomites; and (3) elucidate the mechanism and model of hydrothermal alteration.

2. Geological settings

The Tarim Basin, which is surrounded by the Kunlun-Altyn Mountains of the Tethys system to the south and Tianshan Mountain of the Paleo-Asian system to the north (Xu et al., 2011), is located in northwestern China, and covers approximately 560,000 km^2 (Fig. 1A). Multiple evolutionary stages induced by tectonic events (the Caledonian, Hercynian, Indosinian and Himalayan orogeny) (Jia, 1999; Tang et al., 2004) led to today's tectonic configuration of the Tarim Basin, consisting of three major uplifts (North, Central-Bachu, and Southeast) and four depressions (Kuche, Manjiaer-Awati, Southwest, and Southeast-Tanggu) (Wang et al., 1992) (Fig. 1A). Tahe Oilfield is situated in the Akekule Arch that is located in the North Uplift (Shaya Uplift) of the Tarim Basin (Fig. 1A and B). As a result of an extensional setting, Cambro-Ordovician formations consist of a large shallow carbonate platform, slope facies (limestone and marlstone), and basinal facies (mudstone and shale), from the west to the east of the basin. Subsequently, Carbonate deposition was terminated and changed into a mixed carbonate-siliciclastic sedimentary system in the late Ordovician, due to transition from extension to compression (Gao et al., 2006; Lin et al., 2011).

Using this information, the area was located in the restricted lagoon inside the inner platform that emerged in the Late Cambrian and Early Ordovician periods. The sedimentary framework of the Early Ordovician and the Late Cambrian are similar (Gao and Fan, 2014, 2015) (Fig. 2A and B). However, tectonic movements and sea level variations resulted in the positional changes of the marginal slope in the northern Tarim basin (Gao et al., 2006; Feng et al., 2007) (Fig. 1B). The platform margin altered from microbial buildups to sandy shoals at the end of Late Cambrian (Gao et al., 2006) (Fig. 2A and B). The Lower Qiulitage Group, demonstrating a reduction in thrombolites/stromatolites and escalation in oolites/grainstones in lithology, was virtually dolomitized (Zhao et al., 2010) (Fig. 1C). The overlying Penglaiba Formation of the Lower Ordovician is dominated by thick dolomites intercalated with grainstones (Guo et al., 2010) (Fig. 1C). Further up, the lithofacies of the Yingshan Formation evolved from peloidal-bioclastic limestones and interbedded dolomites into micrite limestone (Fig. 1C).

Burial and thermal history modeling (Li et al., 2011) (Fig. 3) of the Upper Cambrian to Lower Ordovician strata in Tahe oilfield shows that significant uplifts took place during the Late Ordovician to Early Silurian (Late Caledonian orogeny), the late Devonian to early Carboniferous (Early Hercynian orogeny), and the late Permian (Late Hercynian orogeny). The studied sequences did not undergo temperatures above 110 °C before the final uplift in the Late Hercynian orogeny and surpassed the temperature just following the deposition of Eocene.

3. Samples and methods

More than 300 dolomite, limestone, and void-filling calcite samples were collected from wells with depths exceeding 6000 m that were drilled by the Northwest Exploration and Production Company, SINOPEC. Detailed descriptions and macro-petrographic characterization were carried out first. Dolomite samples were collected from cored intervals of the Penglaiba Formation and the lower Qiulitage Group in wells TS2, S88, and YQ6 (Fig. 2C). The wells TS2, S88, and YQ6 studied in this paper, as well as TS1 reported previously, are the only wells drilled into the Penglaiba Formation and even the Lower Qiulitage Group. And their coring was mainly aimed at the deep strata. To clarify the geochemical characteristic of seawater, limestone samples were collected from cored intervals of the Yingshan and Penglaiba formations in 9 other wells. Subsequently, a further detailed micro-petrographic study was conducted on more than 200 selected samples at the Key Laboratory of Marine Reservoir Evolution and Hydrocarbon Accumulation Mechanism, Ministry of Education of P. R. China, at China University of Geosciences (Beijing). About 50 polished thin sections were stained with Alizarin Red S to distinguish calcite from dolomite (e.g. Dickson, 1966). Then, cathodoluminescence (CL) microscopy was carried on a Zeiss Axio Imager A2 microscope with a RELIOTRON III stage performing at 0–15 kV with a gun current of 0–1.3 mA. Selected samples were examined by scanning electron microscope (SEM) to observe minerals and pores using a HITACHI S-4800 with a working current of 10 kV and a working distance of 8 mm.

All geochemical analyses were conducted at the Analytical Laboratory of Beijing Research Institute of Uranium Geology (ALBRIUG). Fine powder samples were extracted using a low-speed dental drill and were used for carbon and oxygen isotopic measurements ($n = 108$), strontium isotopic analysis ($n = 81$), major element analysis ($n = 33$) as well as trace elements including rare earth element