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Origin of dolomites in the Lower Cambrian Xiaoerbulak Formation in the Tarim Basin, NW China: Implications for porosity development

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ABSTRACT

Dolomites occur pervasively in the Cambrian strata in the Tarim Basin, NW China. Although the Cambrian strata have been deeply buried and affected by multiple phases of dolomitization, some intervals in the upper part of the Lower Cambrian Xiaoerbulak Formation developed high porosity. The goal of this study is to understand the origin of different types of dolomites and the formation mechanism of the porosity in the Xiaoerbulak Formation. The geochemistry of matrix dolomites suggests that they formed from middle rare earth element (MREE)-enriched anoxic pore fluids, close to or within the zone of iron reduction. The similar REE + Y patterns and overlapping $\delta^{13}C$ values between pore-filling and matrix dolomites indicate that the fluids that were responsible for the precipitation of pore-filling dolomite apparently inherited the signatures of the formation waters that were stored in the host strata. Low $\delta^{18}O$ values coupled with high Ba, Zn, and rare earth element (REE) content of pore-filling dolomites indicate that pore-filling dolomites were formed at elevated temperatures. The precipitation of authigenic quartz and saddle dolomites and high Mn content in pore-filling dolomites indicate that hydrothermal fluids that mostly originated from Cambrian basinal clastic units or basement rocks were involved. The mixture of formation water and external hydrothermal fluids is the most likely explanation for the formation of significant porosity and precipitation of pore-filling dolomites at depth. Breccia dolomite, zebra dolomite, and saddle dolomite occur mostly in areas that are close to faults, which suggests that hydrothermal fluids passed through strike-slip faults in this area when these faults were activated. The development of permeable layers in the upper part of the Xiaoerbulak Formation overlain by impermeable layers of the Wusongger Formation suggests a possible potential diagenetic trap. When the faults were activated, high-pressure and high-temperature fluids flowed up through faults and hit low-permeability beds at the base of the Wusongger Formation. Then, the hydrothermal fluids flowed laterally into permeable dolomite strata at the top of the Xiaoerbulak Formation, and encountered the formation brines. Large volumes of secondary porosity formed when host dolomite was leached by the mixing fluids, and pore-filling dolomites and other minerals formed soon afterward. Both the faults and original host facies exerted important influences on the lateral extent of the dissolution.

1. Introduction

Dolomite reservoirs comprise one of the most important reservoirs in marine petroliferous basins (Sun, 1995), but the origin of dolomites and the formation of dolomite reservoirs have been some of the most intensively debated problems in carbonate sedimentology (Hardie, 1987; Morrow, 1998; Machel, 2004; Kirmaci and Akdag, 2005; Li et al., 2015; You et al., 2015). Dolomites occur pervasively in the Cambrian strata (that have thicknesses up to 1000 m) in the Tarim Basin, NW China, and host large quantities of hydrocarbons (Zheng et al., 2007). The Cambrian strata in the Tarim Basin have been buried deeper than four thousand meters and have experienced complex multiphase diagenetic processes (Dong et al., 2013). Because the interest in exploring deeply buried dolomites as potential reservoirs has been greatly aroused, the origin and characteristics of the Cambrian dolomite

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reservoirs in the Tarim Basin have been paid great attention in recent years (e.g., Jin and Yu, 2011; Li et al., 2011; Zhang et al., 2009; You et al., 2013). Primary porosity and permeability are commonly reduced by intensive compaction and cementation (Zhang and Yan, 2007), and secondary porosity is thought to play a major role as a productive reservoir space in deeply buried dolomite reservoirs (Zhang et al., 2009; Li et al., 2011). The secondary porosity in dolostones can be related to early, near-surface diagenetic processes and tied to subaerial exposure and freshwater dissolution (Longman, 1980; James and Choquette, 1984), and it can form under deep burial conditions through the dissolution of hydrothermal fluids (Dravis, 1989, 1992; Dravis and Muir, 1993; Wierzbicki et al., 2006), or mixture of fluids (Esteban and Taberner, 2003; Smith, 2006; Wendte, 2006), etc.

Despite having been deeply buried, the top layers of the Lower Cambrian Xiaoerbulak Formation developed high porosity and have become an important exploration target (Chen et al., 2010). A few studies have emphasized the porosity development in the top layers of the Xiaoerbulak Formation (e.g. Chen et al., 2010; Li et al., 2011). However, the formation and preservation mechanisms of the high porosity under deep burial conditions are not clear because of complex and multi-stage dolomitization and diagenetic processes (Qian and You, 2006; Zheng et al., 2007). During the long evolution from deposition to burial diagenesis, the dolomite strata in the Xiaoerbulak Formation have experienced multiple tectonic movement events and various types of fluid transformation, which led to the development of multiple generations of dolomites and produced secondary porosity, composing an important part of the reservoir's storage spaces (Li et al., 2011). The Lower Cambrian Yuertus Formation (ϵ_{1y}) mainly consists of black shale, which has high TOC values (up to 7–14%), and can act as the source rock, providing hydrocarbons to the Cambrian units in the Tarim Basin (Wang et al., 2014). Because dolomits of different origins commonly have distinct petrographic and geochemical relationships, geochemistry studies (such as trace elements, rare earth elements, and isotopes) have been widely used to characterize the temperature and composition of the dolomitization fluids and, thus, to understand the dolomitization and dissolution processes (e.g., Tritlla et al., 2001; Bau and Möller, 1992; Qing and Mountjoy, 1994).

Based on petrographic and geochemical data, the major objectives of this study are to (1) identify the origin of different types of dolomites in the Xiaoerbulak Formation and (2) define the burial conditions and fluid properties that induced the development of dissolution pores. The results of this study can improve our understanding of and ability to predict deeply buried carbonate reservoirs.

2. Geological setting

The Tarim Basin, which is surrounded by the Kunlun, Tian Shan and Altyn Tagh mountains, is a large superposed complex basin that is composed of a Paleozoic cratonic basin and a Mesozoic–Cenozoic foreland basin (Jia, 1999). The Tarim Basin has experienced multiple stages of tectonic evolutions, including the Caledonian, Hercynian, Indosinian and Himalayan cycles (Tang, 1997). Six evolution stages in the Tarim Basin during the Phanerozoic can be distinguished (Zhang et al., 2009; Tang et al., 2004): (1) an intra-cratonic extensional basin stage during the Sinian–Early Ordovician, (2) an intra-cratonic compressional basin stage during the Middle Ordovician–Middle Devonian, (3) a back-arc extensional basin stage during the Late Devonian–Early Permian, (4) a retro-arc foreland basin stage during the Late Permian–Triassic, (5) a collisional reactivated foreland basin stage during the Jurassic–Paleogene, and (6) an Indian–Tibetan collisional successor basin stage during the Neogene–Quaternary.

During the Cambrian and Ordovician, the western Tarim Basin was located on a relatively stable marine carbonate platform, with highly frequent sea level fluctuations (Gu, 2000; Cai et al., 2001; Zheng et al., 2007). Extensive Cambrian to Early Ordovician dolomitic deposits developed in the Tarim Basin, which are up to 1692 m thick in the west (Shao et al., 2002). During the Permian, intense volcanic activity and faulting occurred extensively in the Tarim block because of the southward convergent subduction of the Middle Tianshan arc to the north of the Tarim block (Chen et al., 1997; Tang et al., 2004). Near the end of the Permian, the northwestern flank of the Tarim block experienced extensive uplift and subsequent exhumation and erosion because of further amalgamation between the Middle Tianshan island arc and the Tarim plate, which caused most of the Mesozoic sequences to disappear along the northwestern flank of the basin (Jia, 1997). Since the Cenozoic, higher positive relief along the northwestern flank of the Tarim block was reinforced because of the collision between the Indian plate and Asian plate, which formed a series of NEE-striking, imbricated overthrust nappes, including the Keping uplift (Burchfiel et al., 1999; Dong et al., 2013).

The study area, the Keping area, is located near the city of Aksu (Xinjiang Autonomous Region, north-western China) on the north-western margin of the Tarim Basin (Fig. 1A) and was situated in a passive continental margin environment during the Cambrian and Early Ordovician (Jia, 1999).

Two well-exposed outcrop sections, the Penglaiba section and the Xiaoerbulak section, were selected as the research objects in this

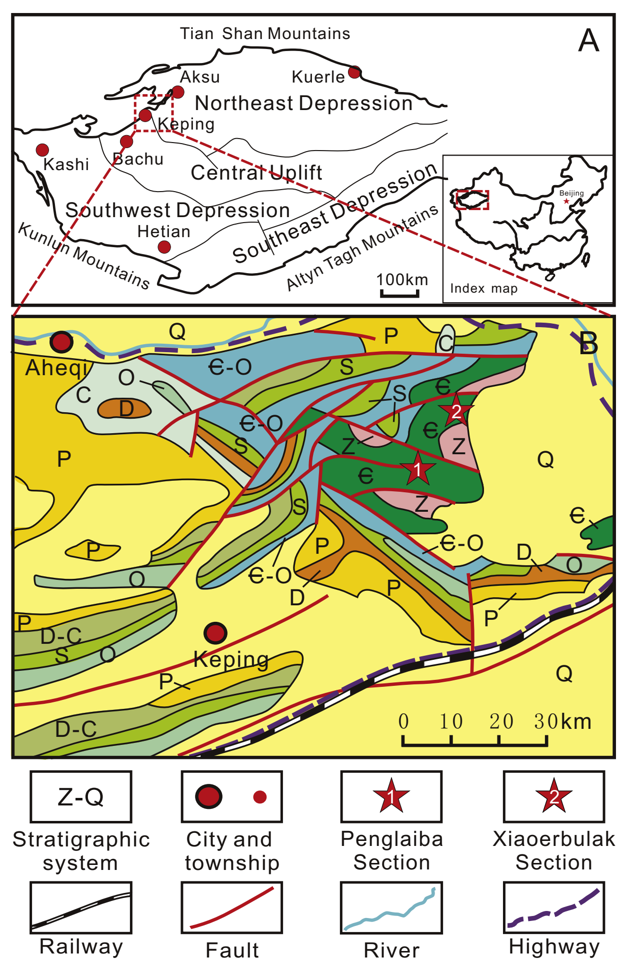

Fig. 1. (A) Tectonic setting of the Tarim Basin, north-western China, and the location of the study area; (B) distribution of the geological units in the Keping area (modified after Dong et al., 2013; You et al., 2013).