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# Evolution and development of Miocene “island dolostones” on Xisha Islands, South China Sea

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ABSTRACT

On Xisha Islands, located in the South China Sea, the Neogene succession includes the unconformity-bounded Huangliu Formation that is 210.5 m thick in well CK-2 and formed almost entirely of dolostones. The diverse biota in the Huangliu Formation, which includes corals, algae, bivalves and foraminifera, indicates that the original carbonate sediments accumulated in water that was < 30 m deep. The dolostones are formed of various mixtures of low- and high-calcium calcian dolomite with limpid dolomite lining the walls of many cavities. The $^{18}O$ and $^{13}C$ stable isotopes suggest that dolomitization was mediated by slightly modified seawater. The $^{87}Sr/^{86}Sr$ ratios from the dolostones suggest that dolomitization took place ~9.4 and 2.3 Ma ago, with the age of dolomitization becoming progressively younger towards the top of the formation. “Island dolostones” like these, found on many islands throughout the Pacific Ocean and the Caribbean Sea, have commonly been linked to eustatic changes in sea-level with dolomitization taking place during lowstands, highstands, or transgressive phases. Data from the Huangliu Formation in well CK-2 suggests that dolomitization was associated with (semi-) continuous transgressive conditions that were controlled by the interaction of tectonic subsidence and eustatic changes in sea level.

## 1. Introduction

Throughout the Pacific Ocean and Caribbean Sea there are numerous isolated islands that are characterized by thick successions of“island dolomite” (Budd, 1997). Prime examples include Grand Cayman (Jones and Luth, 2003; Ren and Jones, 2017, 2018), Kita-daito-jima (Suzuki et al., 2006), Mururoa (Aissaoui et al., 1986), Enewetak (Saller, 1984), Niue (Aharon et al., 1987; Wheeler et al., 1999) and the Bahamian Platform (Dawans and Swart, 1988; Swart and Melim, 2000; Vahrenkamp and Swart, 1994). Research on these successions has focused largely on resolution of the “dolomite problem” and explanation of how these thick successions of dolomite formed. It has been suggested that many of these island dolostones successions may have been developed through one or more episodes of dolomitization (Budd, 1997; Jones and Luth, 2003; Suzuki et al., 2006). Jones et al. (1984) and Pleydell et al. (1990), for example, argued that the dolostones in the Cayman Formation and Pedro Castle Formation on Grand Cayman formed during a single phase of dolomitization. Conversely, Ng (1990) argued that two phases of dolomitization had affected the Cayman Formation and Jones and Luth (2003) used the $^{87}Sr/^{86}Sr$ ratios of the dolostones to suggest that three phases of dolomitization affected this formation. On Kita-daito-jima three of four phases of dolomitzation have been proposed (Suzuki et al., 2006).

Based on comparisons of $^{87}Sr/^{86}Sr$ ratios from many carbonate islands in Caribbean Sea and Pacific Ocean, Budd (1997, his Table 5, Fig. 19) suggested that global dolomitization events included “early” (0.70896 to 0.70901) and “late” (0.70905 to 0.70910) phases that could be divided into parts A, B, C, D, E, F, and G. In addition, Machel (2000) suggested that the $^{87}Sr/^{86}Sr$ data in Pleydell et al. (1990) exhibited too great a range to warrant attribution to a single phase of dolomitization. These conclusions tacitly assumed that each phase of dolomitization was a time-restricted “event” with a unique $^{87}Sr/^{86}Sr$“signal” and that multiple phases of dolomitization should generate multimodal frequency histograms. Recent studies of

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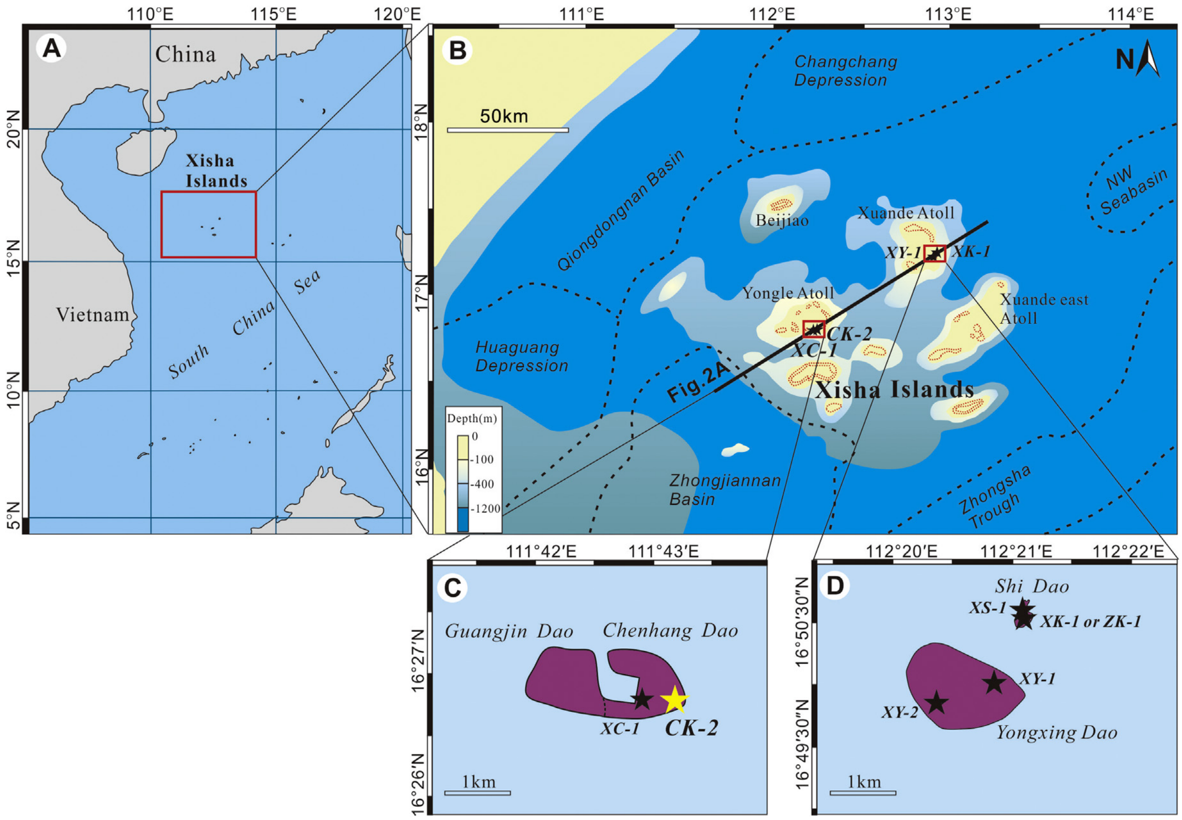


**Fig. 1.** (A) Location of Xisha Islands (Paracel Islands) (red rectangle) in South China Sea. (B) Map of Xisha Platform surrounded by various deep-water basins and depressions. Black line indicates line of cross-section shown in Fig. 2. (C) Chenhang Dao showing locations of wells XC-1 and CK-2. (D) Yongxing Dao and Shi Dao showing locations of wells XY-1 and XK-1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

dolomitization on the Grand Cayman and Cayman Brac (Jones and Luth, 2002, 2003; MacNeil and Jones, 2003; Zhao and Jones, 2012a; Ren and Jones, 2017) followed that premise.

Worldwide synchronicity in the timing of dolomitization has led to the suggestion that dolomitization may be related to eustatic changes in sea-level (Budd, 1997; Jones and Luth, 2003; Suzuki et al., 2006; Zhao and Jones, 2012a). Budd (1997), for example, suggested that stable sea-level positions (lowstand or highstand) may favor dolomitization because that would allow vast quantities of waters to circulate through the strata over a long-time period and supply the Mg needed for dolomitization to take place. The dolostones on Kita-daito-jima, for example, may have been formed during a lowstand (Suzuki et al., 2006). Conversely, Jones and Luth (2003) suggested that dolomitization on Grand Cayman may have been associated with a transgression.

On Xisha Islands, located in the South China Sea (Fig. 1), the Huangliu Formation (average 235 m thick) is formed of dolostones that are similar to island dolostones found on other islands. Previous studies suggested that these dolostones formed through the circulation of super hypersaline brine during the Messinian (Wei et al., 2007; Wei and Jia, 2008; Zhao, 2010; Wang et al., 2015; Xiu et al., 2017) or slightly evaporated seawater (Wang et al., 2018). Based largely on the petrographic and geochemical characteristics of the Huangliu Formation in well ChenKe-2 (CK-2) on Xisha Islands (Fig. 1), this study considers the type of fluid that mediated dolomitization, uses the $^{87}Sr/^{86}Sr$ ratios to establish when dolomitization took place, and then compares the evolution of these dolostones with island dolostones found on other islands throughout the oceans of the world. Collectively, this information provides the basis for suggesting that the dolostones on Xisha Islands probably formed during a (semi-)continuous time-transgressive dolomitization process that resulted from the combined effects of tectonic subsidence and eustatic changes in sea level.

## 2. Geological setting

The Xisha Islands (Fig. 1A, B), also known as the Paracel Islands, are located in the northwest part of the South China Sea and encompass > 40 islands and reefs. The Xisha Platform on which these islands are located is surrounded by basins and/or depressions with ocean waters that are > 1000 m deep (Wu et al., 2014). Today, this area receives 1300 to 2000 mm rainfall each year, and the annual average surface temperature of the seawater is 22 to 30 °C with a near-surface salinity of 33.14 to 34.24‰ (Shao et al., 2017a).

Over the last 30 years, six wells (Xiyong-1 (XY-1), Xishi-1 (XS-1), Xishi-2 (XS-2), Xichen-1 (XC-1), Xike-1 (XK-1, also named ZK-1), Chenke-2 (CK-2)) (Fig. 1C, D) have been drilled to various depths on the Xisha Islands. Two of these wells (XY-1, XK-1) penetrated the entire Cenozoic carbonate succession (up to 1257.2 m thick) before terminating in the Paleozoic or older metamorphic basement rocks (Fig. 2A) (Zhao, 2010; Shao et al., 2017a). Well CK-2, located on Chenhang Dao (Fig. 1C), penetrated volcaniclastic rocks at a depth of 877 m (Fig. 2A). Some 2D/3D seismic data show that the Xisha Platform was initiated on a basement high, the Xisha Uplift (Fig. 2B), during the early Miocene (Wu et al., 2014). The Xisha Platform is formed of fault-bounded blocks (Fig. 2B) that developed during the Xisha Uplift (Wu et al., 2014). Available evidence indicates that carbonate deposition was initiated at the beginning of the Miocene and flourished throughout the middle Miocene before waning during the late Miocene as the platform was drowned and significantly reduced in size during Pliocene-Quaternary times (Zhao, 2010; Wu et al., 2014; Kuang et al., 2014; Shao et al., 2017a; Shao et al., 2017b).

The carbonate succession on the Xisha Platform (Fig. 3) is divided into the unconformity-bounded Sanya Formation, Meishan Formation, Huangliu Formation, Yinggehai Formation, and Ledong Formation (Zhao, 2010; Wu et al., 2014; Shao et al., 2017a; Shao et al., 2017b).