Architecture, development and geological control of the Xisha carbonate platforms, northwestern South China Sea

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**Abstract**

Newly acquired seismic data allow improved understanding of the architecture and evolution of isolated carbonate platforms on the continental slope of the northern South China Sea. The Xisha carbonate platforms were initiated on a basement high, the Xisha Uplift, in the early Miocene and have remained active up to the present. Their distribution is limited to pre-existing localized, fault-bounded blocks within the Xisha Uplift so individual platforms were small in size at the beginning of the Miocene. However, during the middle Miocene, the platform carbonate factories flourished across an extensive area with 55,000 km². The platforms began to backstep in response to a relative sea-level rise in the late Miocene. Platform-edge reefs, patch reefs, pinnacle reefs, atoll reefs and horseshoe reefs, all developed on various platforms. The distribution of platform carbonates shrank significantly during Pliocene-Quaternary time to isolated carbonate platforms, represented today by Xuande Atoll and Yongle Atoll. Tectonics and eustasy were the two main controls on platform development. Tectonics controlled both the initial topography for reef growth and the distribution of platforms, including those that survived the drowning event associated with the late Miocene rapid relative sea-level rise. Eustasy controlled high-frequency carbonate sequence development.

**1. Introduction**

Carbonate platforms developed widely in tropical and subtropical settings, forming thick and extensive biogenic constructions. Carbonate platforms typically have life spans of millions to tens of millions of years. Their initiation, growth, and demise are governed by a combination of tectonics, eustasy, oceanography and climatic conditions (Fulthorpe and Schlanger, 1989; Sun and Esteban, 1994; Wilson, 2002; Bachtel et al., 2003). During the Late Cenozoic, extensive tropical carbonate platforms and reefs developed in the tectonically complex South China Sea region (Epting, 1989; Wilson, 2002; Sattler et al., 2009). On the southern margin of the South China Sea (Hutchison et al., 2004; Hutchison and Vijayan, 2010), many Tertiary carbonate platforms grew on basement highs created by faulted blocks during the Eocene to Early Oligocene rift phase (Fulthorpe and Schlanger, 1989; Sales et al., 1997; Willsam, 1997). Carbonate platforms also developed on the northern margin of the South China Sea, both on uplifted fault blocks and on volcanic seamounts. The northern platforms are younger than those on the southern margin (Qiu and Wang, 2001; Wei et al., 2005). Various examples of Indo-Pacific carbonate platforms have been described, and associated facies models presented, e.g., the Miocene Luconia platform (Epting, 1980), the Middle Oligocene Berai Limestone (Saller et al., 1992) and the Miocene Natuna buildup (Rudolph and Lehmann, 1989). However, the stratigraphic architectures of these systems and the geological factors controlling their development are often unclear. Tectonics can be an important factor in the initiation of carbonate platforms, such as the Eocene to the middle Miocene Tonasa carbonate platform of South Sulawesi (Pigram et al., 1989; Wilson et al., 1999, 2000; Bosence, 2005; Hutchison and Vijayan, 2010). Eustatic fluctuations have been considered to have played an important role in platform development and stratigraphic architecture of carbonate platforms likewise e.g. the Maldives (Belopolsky and Droxler, 2003, 2004). In addition, bottom currents can also be a key control on carbonate platform architecture (Betzler et al., 2009; Lüdmann et al., 2012, 2013).

The Xisha Islands (Paracel Islands) are seated on an elevated submarine plateau that rises from the lower slope southeast of Hainan Island and is surrounded by > 1000 m deep seafloor (Fig. 1). The Xisha carbonate factory is an example of the T-factory of Schlager (2005): shallow-water, biologically controlled deposits dominate. Previous studies of the Xisha carbonate platforms have been limited to analysis of shallow boreholes and examination of modern carbonate
deposits on the islands (He and Zhang, 1986; Zhao et al., 2011). However, in the course of rapidly advancing deep-water hydrocarbon exploration, both commercial and academic seismic surveys have been conducted in deep-water settings of the northern South China Sea. In particular, 2D/3D seismic data have been recently acquired in order to evaluate the potential of reef carbonate reservoirs (Wu et al., 2009; Ma et al., 2010). These data provide new insights into the architectures and evolution of the northern South China Sea carbonate platforms.

The objectives of this paper are twofold: 1) to illustrate the architecture and evolution of the Xisha carbonate platforms; and 2) to understand the main factors controlling the development of carbonate factories in marginal seas. We focus on the impact of early tectonic movements, eustatic change, and terrigenous input, on the development of reefs and carbonate platforms in the Xisha region (Fig. 1).

2. Geological setting

The South China Sea is the largest marginal sea off East Asia. It is surrounded by the South China block, Taiwan, the Luzon arc, Palawan, Borneo, and the Indo-China Peninsula and was formed by seafloor spreading from 32 to 17 Ma (Taylor and Hayes, 1983; Tsai et al., 2004).

Main structural elements in the study area are the Xisha Uplift and adjacent depressions (Fig. 1). The Xisha Uplift was subaerially exposed prior to the Miocene, but subsided during the late Oligocene to early Miocene period of seafloor spreading (Fig. 1). Crustal thickness in the Xisha Uplift varies from 27 km to 6.8 km (Taylor and Hayes, 1983; Xia et al., 1998; Qiu et al., 2001; Yao et al., 2004). The Xisha Uplift had experienced rifting since the late Cretaceous and its crest in the early Miocene was broken into small, fault-controlled uplifted blocks and intervening...
grabens (Sun et al., 1996). Well Xiyong-1 documents that the acoustic basement on the uplift corresponds to Precambrian gray granite gneiss and Mesozoic volcanic rocks (Wang et al., 1979; Qiu et al., 2006).

Tropical carbonate platforms developed extensively on the Xisha Uplift and today form the Xisha Islands (Paracel Islands), which have been intensively studied (Wang et al., 1979; Chen and Hu, 1987; Zhang et al., 1989; Wei et al., 2005; Wu et al., 2009; Ma et al., 2010). Additional information is provided by two wells (Xiyong-1 and Xichen-1) drilled in Xuande and Yongle atolls during the 1980s (Fig. 1B), including biostratigraphy, lithology, and development of the platforms (Sun et al., 1996; Qiu and Wang, 2001; Xu et al., 2002; see also Fig. 2).

3. Data and methods

The seismic data used in this study were collected and processed by PetroChina in 2007. The data comprise 15,000 km of 2-D seismic profiles and a 1500 km² high-resolution 3-D seismic volume. All seismic profiles are located around the Xisha Islands (Paracel Islands) and in adjacent seas. Spacing of the 2D seismic profiles is 4 × 8 km in the deep-water sag of Qiongdongnan Basin and 32 × 32 km around the Xisha Islands (Paracel Islands). Well information from Xiyong-1 and Xichen-1 has been augmented by data from other boreholes in adjacent areas of the northern continental margin, such as wells drilled in the Qiongdongnan Basin and the Pearl River Mouth Basin, to constrain the mapped stratigraphic sequences. These data provide information on regional geology and the nature of the basement, which in turn influenced the development of reefs and carbonate platforms.

All seismic interpretation was conducted using GeoFrame software from Schlumberger. Carbonate platforms were identified on the seismic profiles and their distribution mapped. Seismic data was analyzed to determine carbonate platform geometries in order to establish a model of reef and carbonate platform development and constrain the factors controlling their development.

The tectonic subsidence history in Xisha waters was calculated using the software ‘Recovering and Simulation System of Thermal History’ developed at the Institute of Geology and Geophysics, Chinese Academy of Sciences (Dong et al., 2008). To analyze the subsidence history of each structural unit in the Xisha region, we selected pseudo-wells representative of each structural unit and determined their tectonic subsidence histories. We extracted common depth point gathers on seven stratigraphic reflectors: T20, T30, T40, T50, T60, T70, and T8 on selected seismic profiles on Fig. 1B and then calculated the tectonic subsidence at each pseudo-well, generating tectonic subsidence curves and distinguishing curves of different structural units. Estimation of paleo-water depths was inferred from nearby wells referenced to the Well data in the area of deep water basin and depositional facies interpreted from the seismic data. Sedimentation rates were calculated using 2Dmove software, and GeoFrame software was used for time-depth conversion.

4. Stratigraphic framework across the Xisha carbonate platforms

Eight sedimentary sequences are interpreted within the Xisha carbonate platforms based on seismic profiles in combination with the Xiyong 1 well (Meng, 1989; Zhang et al., 1989). Five seismic reflectors
can be interpreted in Neogene section (T20, T30, T40, T50, T60; Fig. 2). In addition, seismic reflections reveal three additional reflectors (T70, T80 and Tg) in the lower section (Figs. 2, 3; Wu et al., 2009; Ma et al., 2011; Wang et al., 2013).

4.1. Eocene sequence

Sequence H is bounded below by reflector Tg and above by T80 and commonly shows basin-fill onlap in grabens. The sequence occurs in marginal depressions of the Xisha Uplift (Fig. 3). Reflections are of medium continuity and medium amplitude. Sequence H is inferred to comprise lacustrine facies (Zhu et al., 2010). However, there is no well data to confirm its lithology. It represents the oldest sedimentary unit deposited upon acoustic basement.

4.2. Early Oligocene sequence

Sequence G usually onlaps onto the upper surfaces of footwall blocks of the metamorphic basement and seamounts in the Xisha uplift. The top of this sequence is marked by a medium-amplitude reflection picked as reflector T70. Its lower boundary is reflector T80, which coincides with the base of the Oligocene, based on stratigraphic constraints at the northern margin of the platform (Fig. 3). The sequence is of variable thickness over the Xisha Uplift. It reaches a maximum thickness of >1 km at the western margin of the area and is absent beneath the middle of the Xisha Uplift (Figs. 3, 4).

4.3. Late Oligocene sequence

Late Oligocene sequence F is generally thick in the west and thin or absent beneath the middle of the Xisha Uplift. Reflections diverge in the block-bounded grabens, with no indication of progradation (Fig. 3). The lower boundary of the sequence is reflector T70. Its top is marked by a high-amplitude, continuous reflection picked as regional break-up unconformity T60, which represents the Oligocene–Miocene boundary at ~23.8 Ma (Pang et al., 2009; Wu et al., 2009).

Fig. 3. A: Seismic profile across Zhongjian Trough and the western Xisha Uplift south of Yongle Atoll (see Fig. 1B for location); B: Interpretation showing eight seismic sequences. Middle Miocene carbonate fore-slope facies, carbonate debris-flow facies, lagoonal facies and carbonate reefs and sands are all present.
Fig. 4. A. Seismic profile showing seismic characteristics of Miocene carbonate platforms in the northern Xisha Uplift (see Fig. 1B for location). B. Interpretation. Platform margin reefs developed near the northern edge of the profile. The carbonate platform-edge reefs are characterized by high amplitude reflectors and a mound external form. Reefs also backstep southward towards the structural highs.

Fig. 5. A: Uninterpreted seismic profile across Zhongjian Trough and the western Xisha Uplift (see Fig. 1B for location). B: Interpretation showing margin migration and drowning of carbonate platforms in response to rapid relative sea-level change. Patch reefs developed during the middle Miocene.
discontinuous reflections (Figs. 3, 7). The former are characteristic of marine deposits and the latter represent carbonate buildups, which mainly developed in the middle of the Xisha Uplift (Fig. 7). Its lower and upper boundary is delineated by reflector T30 and T20, respectively.

4.8. Quaternary sequence

Quaternary sequence A is similar to Pliocene sequence B. It consists of hemipelagic deposits, except for isolated carbonate platforms. The
seismic facies comprise medium-amplitude, parallel, continuous reflections (Fig. 3).

5. Architecture of the carbonate platforms

5.1. Architecture of the Xisha carbonate platforms across the Xisha Uplift

Carbonate platforms first appeared during the early Miocene on fault-bounded blocks that had developed from the Eocene to the Oligocene within the NE-striking Xisha Uplift continental fragment. Most of the platforms were drowned in the late Miocene (Fig. 4) and then covered by Miocene–Pleistocene marine deposits characterized by mid- to low-amplitude, parallel, discontinuous reflections (Figs. 3, 5, 7). However, carbonate platforms continued to develop locally in the area covered by the modern Xisha Uplift from the middle Miocene to the Quaternary. The platforms decreased in size culminating in the atolls seen today (Fig. 8).

Reefs are common on the edges of the carbonate platforms. They grow on top of basement high formed by normal faults (Fig. 7). Faulting was pervasive at the edges of the Xisha Uplift during the Oligocene and into early Miocene, associated with breakup of the southwestern region of the South China Sea (Li et al., 2013). Fault-related uplift resulted in erosion of siliciclastic sediments that restricted reef development until faulting ceased, although a few faults may have been coeval with early Miocene carbonate platform growth around the Xisha Uplift. By the middle Miocene, platform tops are not affected by faulting and appear as smooth and convex upward surfaces (Fig. 7).

5.2. Reef development on Xisha carbonate platforms

Late Cenozoic reefs are well-developed on the Xisha Uplift. Five types of carbonate reefs have been identified based on high-resolution seismic data: platform-edge reefs, patch reefs, pinnacle reefs, atoll reefs and horseshoe reefs (Figs. 4, 5, 6, 7). Platform-edge reefs typically

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Fig. 8. Sedimentary facies and distribution of carbonate platform on the Xisha Uplift. A: Earliest middle Miocene carbonate platforms were widely distributed. The platforms covered 55,900 km$^2$ and were separated by a narrow Zhongjian Trough. B: Late middle Miocene carbonate platforms decreased in size and backstepped eastward. C: Late Miocene carbonate platforms were limited in the central Xisha Uplift. Large mass transport deposits and deep-water channel systems occurred around the platform margins. D: Pliocene–Quaternary carbonate platforms grew to form the Xisha Islands (Paracel Islands) and Zhongjian Islands.
fringe carbonate platforms. These reefs are usually large in size and display high-amplitude, continuous, mounded reflections at their tops and low-amplitude internal reflections (Fig. 4). Patch reefs are found mainly at the margins of small depressions and occur during the early development of carbonate platforms in the western part of the study area. Such reefs are characterized by high-amplitude, continuous, mounded reflections at their tops, chaotic internal reflections, and low-amplitude reflections at their bases. Some small patch reefs are indicated only by high-amplitude reflection hyperbolae in the seismic image (Ma et al., 2011). Patch reefs mainly grew upon flat-topped structural highs throughout the Xisha Uplift and could develop into horseshoe reefs. Under these conditions, horseshoe reefs grew to large sizes, with numerous solitary reefs agglomerating to form large reef communities (Fig. 6B). Horseshoe reefs are identified on seismic profiles by high-amplitude, mounded reflections at their tops, chaotic internal reflections, and high-amplitude, discontinuous reflections at their bases (Fig. 6B). Pinnacle reefs develop during a steady relative sea-level rise. This reef type is characterized by vertical aggradation of high-amplitude mounded reflectors. The evolution of pinnacle reefs can be subdivided into three stages (Fig. 5). Atoll reefs developed upon structural highs where carbonate production could keep pace with the rising sea-level. Atoll reefs occurring in the Xisha Uplift are represented by high-amplitude, parallel, continuous reflections at their tops, because they were subaerially exposed (Fig. 7).

6. Development of the Xisha carbonate platforms

The evolution of the Xisha carbonate platforms can be divided into four stages: 1) Early Miocene initiation with small carbonate platforms occurred only on local basement highs in the eastern Xisha Uplift, while large shelf-margin carbonate platforms occurred on the western of the Xisha Uplift, which was then connected to the Vietnamese continental shelf; 2) Middle Miocene large-scale carbonate platform growth associated with basinward prograding sequences; 3) Late Miocene carbonate platforms and reef drowning induced by rapid subsidence; 4) Quaternary isolated carbonate platform build-up on local topographic highs concomitant with relative sea-level changes.

6.1. Carbonate platform initiation (early Miocene)

Our seismic data indicates that during the early Miocene transgression, the Xisha carbonate platforms were typically restricted to the west and southwest of the Xisha Uplift, a topographic high coinciding with the modern Xisha Islands (Paracel Islands) (Fig. 8D). At that time, the Xisha Uplift exhibits a shallow sea, perhaps partly subaerial, bounded by hemipelagic troughs, in the Qiongdongnan and Zhongjianan Basins (Figs. 8, 9A); terrigenous clastic sediments were also transported to the Guangle Uplift and some of them reached these troughs from the Indochina peninsula. However, formation of the hemipelagic Quang Ngai Graben along the offshore Vietnam Fault prevented terrigenous sediments from reaching the Xisha Uplift (Fyhn et al., 2013). Conditions therefore had become favorable for carbonate platform development in the early Miocene. As a result, a total of 30,000 km² of carbonate platforms (Triton Carbonate Platform) grew on the Mesozoic granite and pre-Paleogene sediments of the rifting blocks, where a neritic environment prevailed. This early Miocene platform was confirmed by the drilling well 120-CS-1X (Fyhn et al., 2013).

During this stage, reefs started to form with a limited extent on top of the carbonate platforms, dominated by fringing reefs along margins and/or patch reefs in the tectonically stable area west of the region occupied by the present-day Xisha Islands (Paracel Islands). The bases of early Miocene carbonate platforms are bounded by high-amplitude continuous reflections, indicating a strong impedance contrast. Within platforms, high-amplitude reflections alternate with low-amplitude reflections, probably reflecting environmental cyclicity during platform growth. Moderate amplitude and relatively continuous reflections around the platforms are interpreted as foreslope carbonate facies. The carbonate platforms and reefs grew both horizontally and vertically and their tops comprise mounded high-amplitude reflections. Well-developed sediment gravity flow deposits and sediment drifts with low-amplitude, continuous reflections occur adjacent to the platforms (Fig. 7).

6.2. Development of large carbonate platforms (middle Miocene)

In the middle Miocene, carbonate platforms occupied a large part of the Xisha Uplift (Fig. 8B). Progradation produced large carbonate platforms separated by the Zhongjian Trough (Fig. 8B). The sedimentary facies included reef flat, carbonate foreslope and possible lagoon (Fig. 8B). These facies conform to idealized facies belts for a rimmed shelf platform (Wilson, 1975; Read, 1987; Wright and Burchette, 1996).

Foreslope carbonate facies usually occurred at steep platform margins, within the inner Zhongjian Trough and surrounding platform margins. In the middle Miocene, the width of the trough varied: and it was <10 km wide at its gateway to the northwest and increased to 50 km at its southeastern end (Fig. 8B). The foreslope carbonate deposits were probably fed by the carbonate platforms and reefal detritus. On seismic profiles, the associated facies are characterized by middle- to high-amplitude, continuous reflections, with a prograding reflection pattern evident on some profiles. Two deep-water channel systems formed adjacent to the Xisha Uplift, one flowing NW and the other SE (Fig. 8B).

During the early stages of platform development (early and middle Miocene), small lagoons formed within the Xisha platforms. On seismic profiles, the lagoonal deposits are characterized by moderate- and low-amplitude, parallel reflections that indicate a stable sedimentary environment. Because lagoons provide a stable and siliciclastic-free sedimentary environment, patch reefs were able to grow in some lagoons (Ma et al., 2011; Figs. 5, 8B).

Four stages of middle Miocene carbonate platform development can be interpreted (Fig. 9). The first platform margin developed in the Huaguang depression as transgression progressed from Xisha Trough to Qiongdongnan Basin and reached the Huaguang depression from the north. This progressive flooding in the Xisha Uplift created favorable conditions for the development of reefs and granule banks on the tops of rifted blocks (Fig. 2). The second stage of platform shifted southward to the margin of the Xisha Uplift (Fig. 8B). The third and fourth stages of carbonate platforms were developed on central Xisha Uplift (Fig. 8C, D).

6.3. Drowned carbonate platforms (Late Miocene)

At the end of this middle Miocene growth phase, a rapid rise of relative sea-level in the late Miocene led to reef drowning (Fig. 2). The platforms began to backstep towards local basement highs and only a few isolated carbonate buildups persisted (Fig. 8C). The areal extent of individual platforms decreased and they migrated eastward to the area around Xuande Atoll (Fig. 8D). Well data shows that lagoons also developed on top of the Xuande Atoll during this stage (Zhang et al., 1989), but are difficult to identify on seismic profiles because of the large seismic grid spacing in this area.

6.4. Isolated carbonate platforms (Pliocene to Present)

The platforms on the western Xisha Uplift have drowned since the Pliocene due to both rapid relative sea-level rise and increasing siliciclastic input (Xu et al., 2002; Clift and Sun, 2006; Fyhn et al., 2013). The only well-developed isolated platforms remaining in the central part of the Xisha Uplift were those built on structural highs fringed by barrier reefs (Fig. 8D). These structures transformed into large scale atoll reefs, some of which have survived into the present, such as Yongle Atoll and Xuande Atoll (Fig. 1B).
7. Geological controls on post-rift carbonate platform development

Five principal controls on the architecture and development of carbonate platforms have been proposed (Epting, 1980, 1989; Wilson, 2002; Bachtel et al., 2003; Belopolsky and Droxler, 2003). These include: (i) the rate of skeletal carbonate production, (ii) tectonics, (iii) sea-level fluctuations, (iv) variation on input of terrigenous clastic material, and (v) paleo-oceanographic conditions. Beginning in the early Miocene,
high rates of production characteristic of skeletal carbonates in subtropical and tropical seas led to development of isolated carbonate platforms on rifted basement blocks bordered by abyssal plains and deep channels in adjacent grabens across the Xisha Uplift (Xu et al., 2002). The steep reeval platform margins owe their origins to basement structural controls (Erlich et al., 1990; Wilson, 2002). Bottom currents may also have influenced platform development. But, there are insufficient data to reconstruct the complex Miocene current pathways and paleo-oceanography. Therefore, we focus on tectonic subsidence, sea-level change and variations on terrigenous input.

7.1. Post-rift tectonic controls on carbonate platform development

7.1.1. Tertiary subsidence history

The breakup unconformity in the Xisha Uplift and adjacent Qiongdongnan Basin is thought to be of early Miocene age (21 Ma, Sun et al., 2009). Regional unconformity T60 marks the beginning of the post-rift stage at ~23.8 Ma, corresponding to the slope formation and thermal subsidence in the Pearl River Mouth Basin (Clift and Lin, 2001; Pang et al., 2009). Rates of deposition in the main depressions of the Xisha Uplift generally decrease during post-rift phase. Sedimentation rates are lowest in the late early Miocene (Fig. 10B), and slowly in the middle Miocene because of the input of carbonate debris generated by contemporaneous pervasive carbonate platform (Fig. 8A, B), and the terrestrial sediment input also contributed to this rise (Clift et al., 2006). After 5.0 Ma (T30), most tectonic activity ceased and the depositional facies were dominated by bathyal sediments. All of the depressions experienced relatively stable depositional rates. However, there was slow rise in sedimentation rates after 2.2 Ma (Fig. 10B), probably linked to northern hemisphere glaciation and increasing climatic instability (Clift et al., 2002).

Total subsidence of the Xisha Uplift was less than 2.5 km since the early Miocene, whereas the adjacent Qiongdongnan Basin has subsided more than 5 km during the Cenozoic. The other depressions also experienced high subsidence rates during the rifted stage and post-rifting (Fig. 10A). The average value of tectonic subsidence was about 4 km, and the maximum value reached to 6.5 km in the Changchang Depression (Fig. 10A).

Fig. 10. A: Cenozoic tectonic subsidence curves for the three main depressions (Huaguang, Changchang Depressions and Zhongjiannan Basin) in the vicinity of the Xisha Uplift. B: Sedimentation rates in the three depressions. See Fig. 1B for locations of depressions.
The post-rifting stage subsidence rates varied during the post-rift stage. The average values of tectonic subsidence rates between 15.5 and 10.5 Ma were low (Fig. 10A). These low rates led to slow progress of relative sea-level rise and favored widespread development of carbonate platforms over the Xisha Uplift during the middle Miocene.

Almost all subsidence curves reveal an acceleration of regional subsidence during 10.5–5.5 Ma, which caused the carbonate platforms to gradually wither between 10.5 Ma and 5.5 Ma (Fig. 8B, C). This rapid subsidence phenomenon also appeared in Qiongdongnan Basin (Xie et al., 2006). Subsidence rates rise after about ~2 Ma (Fig. 10A), which resulted in the further recession of carbonate platforms and now only a few isolated carbonate platform survived on the Xisha Uplift (Fig. 8A).

In addition, high siliciclastic sediment supply into the region resulted in the formation of thick continental shelf–slope systems in the Qiongdongnan Basin and Zhongjiaxi Basin (Hoang et al., 2010). This may have occurred because the Red River strike-slip fault changed its displacement from right to left lateral, potentially triggering mass transport deposits (Fyhn et al., 2009; Wang et al., 2013).

7.1.2. Tectonics control on carbonate platforms

Fault-bounded blocks formed during the rifting stage and controlled the initial establishment of the carbonate platforms. Numerous authors have discussed the predominant role of topography to carbonate platform formation in various tectonic settings (Longman, 1985; Fulthorpe and Schlanger, 1989; Purdy and Bertram, 1993; Wilson et al., 2000). For example, the late Eocene to Miocene Gunung Putih carbonate complex was influenced by differential subsidence that controlled the distribution of carbonate platforms and favored the development of small buildups on structural highs (Cucci and Clark, 1993). The Lihuua carbonate system on the Miocene was also originated on the Shenhu Uplift (Sattler et al., 2009). Post-rift isolated carbonate platforms on the Xisha Uplift grew on the rift shoulders of the faulted blocks during the early Miocene. Most uplifted fault blocks in the Xisha Uplift were exposed at this time and platforms, therefore, only developed around their margins where reached by transgression (Fig. 9A).

We propose that tectonics controlled late Cenozoic development and drowning of platforms in the South China Sea. The East Vietnam Transform Fault can be mapped seismically along the western boundary of the Xisha Uplift. It forms the early Miocene bathyal Quang Ngai Trough which was the southernmost extension of the elongated Yinggehai Basin. The trough accepted Paleogene syn-rift deposits and early Miocene hemipelagic siliciclastics. The East Vietnam Transform Fault also delineates a coast-parallel Neogene depocenter and seems to have been a control on the siliciclastic depositional system along this part of the margin (Fyhn et al., 2013). The Xisha Uplift was bordered by the Quang Ngai trough, Qiongdongnan central deepwater channel and Zhongjian Basin, which trapped siliciclastics. The uplift was therefore able to develop shallow-water carbonate platforms and develop reefs. The drowning event is considered to be a response to rapid tectonic subsidence during the late Miocene (from 10.5 Ma to 5.5 Ma).

7.2. Eustatic control of carbonate platform development

The development of Oligo–Miocene carbonate systems in Southeast Asia has been mainly studied from seismic or outcrop data, with special emphasis on 3rd-order depositional sequences (Epting, 1989; Cucci and Clark, 1993; Sun and Esteban, 1994; Wilson et al., 1999, 2000; Wilson and Evans, 2002). Higher-frequency eustatic cyclicity also strongly influences the carbonate deposits during the early Miocene and Pliocene, but such high-frequency eustatic fluctuations cannot be correlated precisely to seismic sequences (Bachtel et al., 2003; Belopolsky and Droxler, 2004).

The northern margin of the South China Sea has experienced an overall rise in relative sea-level since the Miocene, driven by regional subsidence although with superimposed high-frequency fluctuations (Fig. 2). This interpretation is supported by our seismic data, as well as the vertical and lateral distribution of the carbonate platforms in the Xisha Islands (Paracel Islands), whose depositional trends appear to have been strongly controlled by long-term changes in relative sea-level. Higher frequency sedimentary sequences may also have been controlled by changes in global sea-level of shorter duration. However, additional data are required to test this hypothesis.

The principal types of reefs and carbonate platform facies in the Xisha Uplift are highly sensitive to sea-level fluctuations. Falling relative sea-level led to subaerial exposure and development of karstified and denuded topography, whereas subsequent rising relative sea-level led to a resumption of the carbonate factory. However, a rapid rise may result in local drowning. In our model, paleo-water depths varied from neritic to bathyal. The influence of eustatic fluctuation on the development of the Xisha carbonate platforms involves the following sequence of events (Fig. 10).

1) Rising relative sea-level established carbonate production on submerged structural highs in the early Miocene under tropical climatic conditions, carbonate sequences display parallel continuous reflections and downlap onto the basement (Fig. 9A); 2) Carbonate production failed to keep pace with an acceleration in the rate of relative sea-level rise in the late middle Miocene. Carbonate platforms retreated toward topography highs and the area covered by carbonate platforms shrank significantly (Fig. 9B). 3) As the rate of relative sea-level rise decreased, the rate of carbonate production exceeded the rate of production of accommodation space, resulting in a lateral progradational expansion of the carbonate platforms (Fig. 9C); 4) Carbonate production could not keep pace with the rising relative sea-level in the late Miocene and most platforms were drowned. Only those developing on active uplifts survived and have continued their growth until the present, forming large atoll reefs (Fig. 9D).

7.3. Impact of terrigenous input on carbonate platform drowning

Input of terrigenous clastics inhibits carbonate production, especially reef growth. However, on the Xisha Uplift well Xijing-1 drilled a total of 1250 m of shallow-water carbonate deposits indicating that the input of terrigenous clastics had little impact on the development of the Xisha carbonate platforms (Fig. 2). The Xisha Uplift was far away from siliciclastic sediment sources and has been separated from them by deep-water troughs since the early Miocene (Fig. 8). Therefore, terrigenous clastics were unable to input to Xisha carbonate platforms. Hemipelagic deposition occurred in the Southern Yinggehai Basin, Qiongdongnan Basin and Zhongjiaxi Basin (Wu et al., 2009; Fyhn et al., 2013). Few terrigenous clastics were deposited on the Xisha Uplift. Siliciclastic input from the Indo-China Peninsula decreased in the middle Miocene, further improving conditions for reef and carbonate platform development in the Xisha region (Fig. 8A, B).

8. Conclusions

Cenozoic carbonate platforms are widespread in the Xisha Uplift, a continental fragment rifted from southern China which underlies the modern Paracel Islands. Several small, carbonate platforms arose during the early Miocene on fault-bounded uplifted blocks within the Xisha Uplift. The platforms have high-amplitude reflections at their tops and low-amplitude internal reflections. More extensive carbonate platforms developed in the middle Miocene, but most were drowned during the late Miocene. Locally, isolated carbonate platforms in the central Xisha Uplift continued to develop up to the present. These large atolls are common throughout the Paracel Islands and adjacent areas.

Tectonics strongly influenced the development of the Xisha carbonate platforms. The platforms were initiated on basement highs which thereby controlled the distribution of early Miocene platforms. The middle Miocene subsidence rate between 15.5 and 10.5 Ma was low and therefore favorable for reef and carbonate platform expansion. The sedimentation rate in the adjacent depressions, such as Changchang and Huaguang Depressions and Zhongjiaxi Basin, showed an abrupt
increase between 15.5 and 10.5 Ma. Rapid subsidence in the late Miocene led to drowning of most of the Xisha carbonate platforms, but isolated platforms continued to grow in areas undergoing localized uplift or reduced subsidence rates.

The Xisha Uplift contains a record of the establishment, growth, and development of multiple carbonate platforms. Relative sea-level change, driven primarily by tectonics, was the main control on platform evolution. Most of the platforms in the Xisha Uplift were drowned in the late Miocene, but isolated platforms continued to grow in areas undergoing localized uplift or reduced subsidence rate.

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