Facies-succession and architecture of the third-order sequences and their stratigraphic framework of the Devonian in Yunnan-Guizhou-Guangxi area, South China

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Abstract The Caledonian orogeny at the end of the Silurian resulted in great changes in the palaeogeography in the Yunnan-Guizhou-Guangxi area of South China; the continental area of the Early Paleozoic evolved into the extensive Dian-Qian-Gui Sea in the Late Paleozoic. Early in the Devonian, as a result of a major transgression, seawater encroached gradually from the south to the north and clastic facies were deposited. Carbonate deposition was then established in the Yunnan-Guizhou-Guangxi area, with a palaeogeography marked by attached platforms, isolated platforms and narrow basins. As a result of the Ziyun movement towards the end of the Devonian, the Upper Devonian strata are regressive and thin out from the open-sea to the land areas. A study of the nature and distribution of sedimentary facies in space and time recognises 13 third-order sequences in the Devonian strata in Yunnan-Guizhou-Guangxi area, and these form two second-order sequences. The strata of the Lower Devonian comprise 5 third-order sequences (SQ₁ to SQ₅), which are dominated by transgressive clastics. 4 third-order sequences (SQ₆ to SQ₉) in the Middle Devonian are characterized by alternations of transgressive clastics and highstand carbonates. In the Upper Devonian, carbonates constitute 4 third-order sequences (SQ₁₀ to SQ₁₃), which are generally marked by the transgressive limestones and highstand dolomites. On the basis of earlier biostratigraphic studies, sea-level changes represented by the third-order sequences with their different facies successions are explored, and the sequence stratigraphic framework is established. Therefore, the Devonian strata in the study area provide an example for further understanding of depositional trends within the sequence-stratigraphic framework.

Key words sequence stratigraphy, Devonian, Yunnan-Guizhou-Guangxi area, South China

1 Introduction

In recent years, there has been increased interest in the well-exposed and fossiliferous Devonian strata of the Yunnan-Guizhou-Guangxi area in the southern part of Guizhou, the southeastern part of Yunnan and the western part of Guangxi (Fig. 1). Earlier comprehensive sedimentologic and stratigraphic research provides a useful foundation for sequence stratigraphic studies. The most influential research includes Zhou (1992), Zhao and Ding (1996), Dong (1997) and Yin (1997) on the lithostratigraphy; Wu et al. (1987) and Zeng et al. (1994) on the sedimentary facies and palaeogeography; Kuang et al. (1989),
Zhong et al. (1992) and Hou et al. (2000) on the biostratigraphy and chronostratigraphy; Wu (2000) on the tectonics and palaeogeography, and Chen et al. (2001a) on the palaeoclimate. Studies of the Devonian sequence stratigraphy in Yunnan-Guizhou-Guangxi area are included in the treatises published by Xu et al. (1993), Zeng et al. (1994), Wu et al. (1997), Yang et al. (1999) and Mei et al. (2001). Wu et al. (1997) recognised 20 third-order sequences in the Devonian strata in South China; Mei et al. (2001) and Mei and Tucker (2007) identified 1 second-order sequence that consisted of 13 third-order sequences in the southern part of Guizhou and the northern part of Guangxi. The studies of cyclostratigraphy by Bai et al. (1995), Chen et al. (2001b, 2001c) and Gong et al. (2001) were also valuable in this research.

The Devonian in the Yunnan-Guizhou-Guangxi area is dominated by a succession of carbonates that evolved from basal transgressive clastics that gradually wedge-out towards the continental area to the north. As a result of the obvious differentiation of facies formed by the large-scale transgressive event in the Late Devonian, the third-order sequences were developed in different sedimentary environments within the large-scale palaeogeography of platforms and basins (Fig. 1). Therefore, the Devonian strata in the study area provide an example for the further understanding of the depositional trend within the sequence-stratigraphic framework (Catuneanu et al., 2009).

2 Sequence stratigraphy of the attached platforms

From an examination of sections at Wudang in Guiyang, Lüyinqiao in Duyun and Dushan in Guizhou, the Devonian strata across the region show a gradual wedge-out at both the top and bottom parts of the succession from south to north across the attached platform. The lower wedge-out
is transgressive and is genetically related to the Caledonian orogeny. The upper wedge-out is regressive and genetically related to the Ziyun movement. By tracing sequence boundaries and examining the facies architecture, 13 third-order sequences (SQ₁ to SQ₁₃) can be discerned in the Devonian strata of the Yunnan-Guizhou-Guangxi area, although it is impossible to discern all 13 sequences in every location. This illustrates the incomplete nature of the stratigraphic record as a result of local tectonics and palaeogeography (Mei, 1996; Mei and Ma, 2001).

2.1 Sequence stratigraphy of the Devonian at Wudang, Guiyang

Located near the basin margin, the Wudang section lacks some Devonian strata. These include those belonging to the Lochkovian and Pragian Stages (Lower Devonian) that constitute the third-order sequences SQ₁ to SQ₄ elsewhere, and those belonging to the upper part of the Frasian and Famennian Stages that form the third-order sequences SQ₁₁ to SQ₁₃ elsewhere. Consequently, only 5 third-order sequences, SQ₅, SQ₆, SQ₇, SQ₉, and SQ₁₀ can be discerned at the Wudang section (Fig. 2). The lack of SQ₈ could be related to the hiatus resulting from the Haikou tectonic movement and uplift in the Late Eifelian to Early Givetian. The lack of SQ₁₄ at the base of the Carboniferous and SQ₁₁, SQ₁₂ and SQ₁₃ in the Upper Devonian is the result of a major unconformity caused by the Ziyun movement.

The 3 third-order sequences (SQ₅, SQ₆, and SQ₇) in the lower part of the Devonian succession are mostly sandstones within the Mangshan Group. Fossil fish include *Kueichowlepis sinensis*, *Sinopetalichthys kueiyangensis*, *Neoduyunaspis minuta* etc; fossil brachiopods such as *Oriential spirifer wangi* and plant fossils, such as *Zosterophyllum* sp. and *Drepanophycus spiniformis* also occur. This biota indicates an Emsian to Eifelian Age. Meter-scale cycles of the elastic tidal-dynamic type (Mei et al., 2000) are well developed and constitute regular vertical stacking patterns in these third-order sequences (SQ₅ to SQ₇). In response to the third-order sea-level rise, meter-scale cycles are marked by thickly-bedded basal subtidal sandstones; by way of contrast, thin-sandstone based cycles with thinly-bedded subtidal clastic facies developed during sea-level falls. Palaeosol beds of purple-red ferruginous sandy mudstones on the top part of SQ₅ demonstrate a regional unconformity which is genetically related to the Haikou tectonic movement, and which leads to the absence of SQ₆.

The upper part of the Devonian in the Wudang section consists of dolomites of the Gaopochang Formation, and two third-order sequences (SQ₉ and SQ₁₀) are recognised. The lower part of each third-order sequence is mainly formed of thickly-based meter-scale cycles of the carbonate peritidal type; the upper part is marked by the development of the thinly-based variety. Hence, each third-order sequence consists of an upward-shoaling succession of facies. Fossil brachiopods such as *Stringocephalus* in sequence SQ₉ indicate a Late Givetian age; *Cyrtospirifer* in SQ₁₀ indicates Early Frasnian.

![Fig. 2 Diagram showing the division of the Devonian third-order sequences at Wudang in Guiyang. The legend for this figure and figures 3–7 is the same as illustrated in Fig. 8. SQ₅ to SQ₁₀ refer to the third-order sequences in this section. The Devonian comprises the Mangshan Group and Gaopochang Formation (GPC). The underlying strata are the Gaozhaitian Formation (GZT) of the Middle Silurian (S₃); the overlying strata are the Carboniferous (C) Xiangbai Formation (XB) marked by coal-measures. The third-order sequences show a generally upward-shoaling succession of sedimentary facies, in which meter-scale cycles show a regular vertical stacking pattern: St–subtidal flat, It–intertidal flat, Sup–supratidal flat. In the chronostratigraphic system, Dt–the Datangian Series of the Carboniferous, Js–Jiusian Stage; Em–Emian Stage, Eif–Eifelian Stage, Giv–Givetian Stage, Frs–Frasian Stage. I–conformity of the Haikou movement, II–conformity of the Ziyun movement, III–curve of the third-order sea-level changes.](Image 311x455 to 534x737)
2.2 Sequence stratigraphy of the Devonian at Lüyinqiao, Duyun

The Devonian strata at Lüyinqiao can be grouped into three units: a lower part of transgressive sandstones of the Mangshan Group; a middle part of dolomites of the Dushan Formation, and an upper part of limestones of the Wangchengpo Formation. Seven third-order sequences from SQ4 to SQ10 can be distinguished (Fig. 3). As at Wudang, there are no strata at Lüyinqiao corresponding to SQ1 to SQ3 at the base of the Devonian, nor to SQ11 to SQ13 in the Upper Devonian. At the base of the Carboniferous, there is no equivalent of SQ14 as a result of uplift and erosion related to the Ziyun tectonic movement.

Meter-scale cycles of the elastic dynamic-type are developed in the transgressive Mangshan sandstones. Their regular vertical stacking patterns constitute 3 third-order sequences from SQ4 to SQ6. Fish fossils, e.g., *Kueichowlepis sinensis*, and brachiopods such as *Orienspirifer wangi* and *Euryspirifer* sp. indicate a Late Pragian to Early Eifelian Age.

Brachiopods such as *Stringocephalus obesus* and *Stringocephalus burtini* in the Dushan Formation suggest a Late Eifelian to Givetian Age. Three third-order sequences from SQ7 to SQ9 can be discerned in the Dushan Formation. Each of them is composed of meter-scale peritidal carbonate cycles arranged in a regular vertical stacking pattern of transgressive, thickening-upward, thick-bed based cycles and regressive, thinning-upward, thin-bed based cycles with more dolomites. In general, compared with the equivalent strata at Wudang, the intensity of dolomitisation at Lüyinqiao is weaker.

The Wangchengpo Formation of the Upper Devonian constitutes sequence SQ10. Its transgressive systems tract (TST) and early highstand systems tract (EHST) are mainly composed of limestones of open-platform facies. In its late highstand systems tract (LHST), dolomites of restricted-platform facies are developed. A regular vertical

![Diagram showing the third-order sequences at Lüyinqiao in Duyun. The strata are divided into the Mangshan Group, and Dushan and Wangchengpo Formations (WCP). The underlying strata belong to the Silurian Wengxiang Group (WX), and the overlying strata are the Carboniferous Xiangbai Formation (XB). SQ4 to SQ11 are the third-order sequences marked by various facies successions; the abbreviations for the facies are as follows: St—subtidal-flat facies, It—intertidal flat facies, Sup—supratidal-flat facies, Op—open-platform facies, Tf—tidal-flat facies, Rp—restricted platform facies. Compared with those at Wudang, one difference is that SQ4 is Pragian in age (Pra). The symbols of I to III and the abbreviations of chronostratigraphy are the same as in Fig. 2.](image-url)
stacking pattern of meter-scale cycles is observed within SQ10; in the TST, the meter-scale cycles are thick-bedded, open-platform carbonates and thin-bedded dolomites or dolomitic limestones of restricted-platform facies, which indicates the rare “exposed beats”. The subtidal meter-scale cycles in the EHST are thick-bedded packstones and grainstones of open-platform facies with interbedded shelf marls, which shows the clear “drown beats”. Meter-scale cycles of the thin-based peritidal carbonate type with dolomites are developed in the LHST, which demonstrate the obvious “exposed beats”.

2.3 Sequence stratigraphy of the Devonian at Dushan, Guizhou

Compared with Wudang and Lüyinqiao sections, the Devonian strata at Dushan are more completely developed. 10 third-order sequences can be distinguished within the Danlin, Shujiaping and Longdongshu Formation of the Lower Devonian; the Bangzhai and Dushan Formations of the Middle Devonian; the Wangchengpo, Yaosuo, and the Wangchengpo, Yaosuo,

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**Fig. 4** Diagram showing the third-order sequences at Dushan in Guizhou Province. Apart from those marked in the figure, other abbreviations for the lithostratigraphic units are as follows: WX—Wengxiang Group (Silurian), SJF—Shuijiaping Formation, LDS—Longdongshu Formation, BZ—Bangzhai Formation, WCP—Wangchengpo Formation, ZW—Zhewang Formation, GLH—Gelaohe Formation, TBG—Tangbagou Formation (Carboniferous); 1 to 4 refer to four members of the Dushan Formation: 1—Jipao Member, 2—Songjiqiao Member, 3—Jiwozhai Member, 4—Hejiashai Member. Besides those illustrated in Fig. 2, other facies codes are as follows: Sh—shelf facies, Bh—biothermal limestones, Tf—tidal-flat facies. Moreover, I—unconformity of the Haikou tectonic movement, II—unconformity of the first phase of the Ziyun movement, III—unconformity of the second phase of the Ziyun movement, IV—curve of third-order sea-level changes, Yg—the Yanguanian Series (Carboniferous), Tbg—Tangbagouan Stage (Carboniferous), Fam—Famennian Stage; other chronostratigraphic abbreviations are the same as those in Figs. 2 and 3.
Zhewang and Gelaobe Formations of the Upper Devonian (Fig. 4).

The Danlin Formation forms sequence SQ4, and fossils present in the overlying Shuijapiang Formation suggest a Pragian age. Conglomerates at the base of SQ4 unconformably overlie the Silurian Wengxiang Group, as a result of uplift due to the Caledonian orogeny. Palaeosol facies composed of ferruginous sandstones and mudstones at the top of SQi indicate a phase of exposure. The general features of the facies succession of SQi are similar to those from SQ4 to SQ9 at the Liuyinqiao section described above.

At Dushan, the Shuijapiang and Longdongshui Formations constitute SQi, in which brachiopods, e.g., *Eury spirifer* and *Zdimir cystotabulata* can be collected. Accordingly, the sequence belongs to the Emsian. The transgressive sandstones of the Shuijapiang Formation (Fm.) make up the transgressive systems tract (TST) of SQi, in which are developed many meter-scale cycles of the eustatic tidal-dynamic type. The limestones of the Longdongshui Formation constitute the highstand systems tract (HST) of SQi, in which thick-bedded massive biothermal limestones of open-platform facies and thin-beded dolomitic limestones of semi-open platform facies form numerous meter-scale cycles of carbonate peritidal type. In the transitional period from TST to HST, a condensed section (CS) of SQi is recognised consisting of marls and calcareous shales of shelf facies in the lower part of the Longdongshui Formation. Palaeosol beds composed of ferruginous sandy mudstones at the top of SQi record subaerial exposure.

Four third-order sequences from SQi to SQ9 occur in the Bangzhai and Dushan Formations of the Middle Devonian. The Dushan Formation can be separated into Jipao Member limestones, Songjiaqiao Member sandstones, Jiwozhai Member limestones and Hejiazhai Member limestones and dolomites. The transgressive sandstones of the Bangzhai Formation constitute the TST of SQi, the Jipao Member limestones of the Dushan Formation make up the HST of SQi. Similar to SQi, the TST of SQi is composed of transgressive sandstones of the Songjiaqiao Member, and its HST consists of the limestones of the Jiwozhai Member. Therefore, the features of facies successions that make up SQi and SQ9 are generally the same as SQi described above. At the top of SQi, there are dolomites of restricted-platform facies (15 to 20 m thick). This shows that its top boundary is an exposure surface, similar to type I sequence boundary defined by Vail et al. (1977). This boundary also corresponds to the unconformity produced by the Haikou tectonic movement in the research area.

Two third-order sequences, SQ8 and SQ13, can be discerned in the Hejiazhai Member limestones and dolomites. The general facies succession of SQ8 and SQ13 can be described as follows: in the deepening phase of the rising third-order sea-level TST, more thick-bedded limestones of open-platform facies are developed; in the shoaling process resulting from the fall of third-order sea-level, more dolomites of restricted-platform facies were formed, especially near the top of SQ8.

Four third-order sequences from SQ10 to SQ13 can be distinguished within the Upper Devonian carbonates (Fig. 4). The general characters of the facies succession can be described as follows: in the TST off-platform facies biothermal limestones are developed, otherwise, more dolomites of restricted-platform facies are developed. The dolomitization is relatively more intense in the upper parts of SQ11 and SQ13, where more palaeosol beds are developed. Hence, the upper boundaries of SQ11 and SQ13 are both long-term exposure surfaces, similar to the type I sequence boundary defined by Vail et al. (1977); they are also unconformities correlating to the first and the second episodes of the Ziyun tectonic movement.

3 Sequence stratigraphy of the isolated platforms

During the Devonian, a major sedimentary basin developed in the southern part of Guizhou, western part of Guangxi and the southeastern part of Yunnan. Its northern boundaries are two contemporaneous fault zones: the “Ziyun-Luodian-Nandan-Duan” fault zone and the “Mile-Shizong-Puan” fault zone. This sedimentary basin has been referred to as the “Dianqiangui Basin” by Zhao et al. (1996), the “Youjiang Basin” by Zeng et al. (1994), and the “Nanpanjiang Basin” by Enos et al. (1998). A variety of isolated platforms were developed within this sedimentary basin including the Jingxi Platform, Nanning Platform and Longlin Platform. Between the platforms, narrow inter-platform basins were formed. The Devonian strata are marked by carbonate facies developed in the central parts of the isolated platforms, as shown by the De’e section in Longlin, where there is an absence of Lochkovian to Pragian strata. On the margins of the isolated platforms, such as that at the Liujing section in Hengxian, the succession is more fully developed. Thus, the De’e and Liujing sections are selected to illustrate the general features of the Devonian sequence stratigraphy of the isolated platforms.
3.1 Sequence stratigraphy of the Devonian at De’e, Longlin

This locality lacks Lochkovian to Pragian strata and the succession consists of the Pojiao Formation, Yintang Formation, Donggangling Formation and Rongxian Formation, with 9 third-order sequences as shown in Fig. 5. The Emsian Pojiao Formation unconformably overlies the Cambrian Loushanguan Group, the long hiatus a reflection of the Caledonian orogeny. The Rongxian Formation is unconformably overlain by the Carboniferous Baizuo Formation, as a result of the Ziyun movement.

The Pojiao Formation constitutes the third-order sequence SQ_5. Its TST is composed of black argillaceous lime mudstones and marls of swamp facies, passing up into open-platform carbonates, which become thickly-bedded upward. The HST is composed of numerous meter-scale peritidal carbonate cycles formed of thick-bedded open-platform facies and thin-bedded dolomitic limestones and dolomites of restricted-platform facies; the dolomite beds are more common and thicker upwards. Between the TST and HST, the black organic-rich shelf shales, 2-3 m thick, constitute the condensed section (CS) of SQ_5. In SQ_6, there are abundant brachiopods and bivalves including the *Howellella secunda-Reticulariopsis ertangensi* assemblage, as well as the *Euryspirifer* assemblage with *Acrospirifer subregularis, A. ordinaris, Howellella yukiangensis, H. papaoensis, Euspirifer wangi*, and *Otospirifer* sp. These fossils indicate a mid-Late Emsian age for SQ_5 at this locality.

Numerous meter-scale peritidal carbonate cycles are developed in the Yingtang Formation and Donggangling Formation. They are composed of thick-bedded massive biohermal limestones, open-platform grainstones and packstones with interbeds of thin-bedded lledolomites and dolomitic limestones of restricted-platform facies. There is a regular vertical stacking pattern of the cycles in the third-order sequences, on the basis of which 4 third-order sequences from SQ_6 to SQ_9 can be discerned in the Yingtang and Donggangling Formations. Their general characters are: the TST and the Early HST (EHST) are chiefly composed of thick-bedded cycles while the Late HST (LHST) consists of thin-bedded cycles.

The Rongxian Formation contains 4 third-order sequences from SQ_10 to SQ_13. Their general facies characters are similar to those of SQ_6 to SQ_9. The dissimilarities include: in the TST and EHST of SQ_11 and SQ_12 oncoid-bearing grainstones are common. At the top of SQ_11 and SQ_13 palaeosols composed of nodular ferruginous mudstones are developed, with a clear exposure surface as their upper boundary, corresponding to the unconformity of the first and the second episodes of the Ziyun movement.

3.2 Sequence stratigraphy of the Devonian at Liujing, Hengxian

The Liujing section is developed in the slope facies of the isolated platform. Fossils of both shelf and plankton biofacies are present, which makes this section a key sec-
tion for stratigraphic correlation between the platform and deep-water strata (see the book on this locality by Kuang et al., 1989 for details). At Liujing, the Lower Devonian includes the Lianhuashan, Nagaoling, Yujiang and Moding Formations; the Middle Devonian contains the Najiao and Mintang Formations, and the Upper Devonian contains the Gubi and Rongxian Formations (Fig. 6). Since Quaternary sediments cover most parts of the Rongxian Formation, only 11 third-order sequences from SQ₁ to SQ₁₁ can be recognised at Liujing. The Devonian sequence stratigraphy at Liujing is unusual: First, obvious transgressive events are indicated by the TST of SQ₅ and SQ₈. Second, the unconformity of the Haikou movement is very clearly demonstrated at this section, as a result of the forced regression which led to deposition of dolomites, the Najiao Formation and the palaeosol beds at the top of SQ₇. Third, the Devonian strata directly overlie the Cambrian Huangdongkou Formation, and the latter is marked by basinal turbidite facies.

The Lianhuashan Formation, generally belonging to the Lochkovian age, is marked by a set of transgressive sandstones where a few fossils such as *Linguula* sp. can be collected. This formation could be grouped into two third-order sequences SQ₁ and SQ₂. The basal conglomerates at the bottom part of the Lianhuashan Formation directly lie on the Cambrian Huangdongkou Formation marked by a set of turbidites. This illustrates an unconformity due to the Caledonian orogeny characterized by long-term stratigraphic breaks and an angular unconformity. Many meter-scale cycles of clastic tidal-dynamic type are developed in SQ₁ and include well-developed trace fossils such as *Skolithos* in sandstone beds of subtidal flat facies and *Scoyenia* in sandy mudstones of intertidal to supratidal flat facies. In the middle part of SQ₂, more argillitutes of shelf facies are developed and form the CS of SQ₂. The lower and upper parts are mainly composed of sandstones with the development of meter-scale cycles of tidal-dynamic type. Therefore, the strata from SQ₁ to SQ₂ form a retrogradational succession.

Two third-order sequences, namely SQ₃ and SQ₄, can be discerned in the strata of the Nagaoling Formation and the basal part of the Yujiang Formation. The TST and EHST of SQ₃ are chiefly composed of shales of shelf facies with storm-rewomed shell beds. The LHST is mainly composed of meter-scale cycles of alternating limestone-marl. The features of the TST and the EHST of SQ₄ are similar to those of SQ₃, but the LHST is chiefly composed of thick-bedded sandstones of peritidal facies of the basal part of the Yujiang Formation.

Shelf and basinal mudrock facies in the middle and upper parts of the Yujiang Formation and siliceous dolomites of tidal-flat facies of the Moding Formation constitute SQ₅. This sequence is marked by a similar symmetrical
sedimentary succession as a result of long-term deepening and then shallowing due to the third-order sea-level change. The lower part of its TST is composed of sandy shales of shoreface facies, but the upper part is mainly a set of shelf mudrock facies with storm-reworked shell beds. Basinal mudrock facies occurs in the upper part of the TST of SQ₅, and forms the CS. The EHST of SQ₅ is chiefly composed of shelf mudrock facies with thin interbeds of sandstones or limestones, and the LHST is composed of dolomites (the Moding Fm.). In the sequence SQ₆, the relatively large thickness of the TST, CS and EHST that are mainly composed of shelf and basinal mudrock facies, and the relatively small thickness of the LHST composed of dolomites of tidal-flat or restricted-platform facies, implies an obvious large-scale transgressive event that leads to the clear differentiation of facies in space in the research areas. Different from the underlying strata, the LHST dolomites of SQ₇ with intensive dolomitization and silicification demonstrate that shallowing of the environment resulted from a third-order sea-level fall.

The Najiao Formation is composed of dolomites about 280 m in thickness, and 2 third-order sequences SQ₆ and SQ₇ can be discerned there. Brachiopods including Eospirifer, Zdimir and Luofugia indicate an Eifelian age (Middle Devonian). As shown in Fig. 6, the boundary between the Lower and Middle Devonian clearly lagged behind the changing depositional surface at the top of SQ₅. The general characters of SQ₆ and SQ₇ can be described as follows: in the deepening period of the rise of third-order sea-level, meter-scale peritidal carbonate cycles are composed of thick-bedded massive biohermal dolomites with interbeds of medium-to thin-bedded micritic dolomites. Hummocky and wavy stromatolites are present within the biohermal dolomites. With the shallowing of the environment due to the fall of third-order sea-level, the intensity of dolomitization increased, and fossils become rare; consequently, the meter-scale cycles are mainly thin-bedded, with clear evidence of exposure. More remarkably, palaeosol beds of 15 to 25 cm thick, marked by purple ferruginous mudstones, are developed in the top part of SQ₇, and reflect the unconformity produced by the Haikou movement.

Abundant fossils are developed in the Mintang Formation including brachiopods Stringocephalus and Leiorhynchu, corals Stringophyllum, Spinophyllum, Cystophyloides, Phillippsastraea and Truncicarinulum, stromatoporoids Plectostroma, Trumpetstroma, Stromatopora and Actino‑nostroma, all indicating a Givetian age. Two third-order sequences, SQ₄ and SQ₅, are present. The general char-

![Fig. 7 Diagram showing the third-order sequences at Luofu in Nandan County, Guangxi. Apart from the lithostratigraphic units named in the former figures, YL–Yilan Formation, XSD–Xiangshuidong Formation, LZ–Luzhai Formation (Carboniferous). Abbreviations of sedimentary facies are as follows: Bs–inter-platform basinal facies, Sh–inter-platform shelf facies, Sf–shoreface facies, Fs–foreshore facies. The chronostratigraphic abbreviations and indications from I to IV are the same as those illustrated in Figs. 2 to 6. SQ₁ to SQ₁₃ refer to the 13 third-order sequences recognized in the section. Ac-

acters of SQ₄ and SQ₅ can be described as follows: their TST are constituted by meter-scale cycles of alternating limestone-marl and shales or marls of deep-ramp or outer-shelf facies as well as nodular micritic limestones of middle-ramp facies; their HST are mainly composed of meter-scale cycles of subtidal carbonates composed of thick-bedded massive stromatoporoid biohermal limestones of shallow-ramp facies with interbeds of thin-bedded marls of deep-ramp facies with minor development of stromatoporoid reefs. Tentaculitids occur in the marls.
4 General features of sequences in inter-platform basins

Inter-platform basins are relatively deep-water regions between the isolated platforms and between them and the attached platforms. Many of these basins are similar to the starved pull-apart basin described by Chen et al. (2001c). The facies are mainly dark mudrocks that can be grouped into inter-platform shelf facies and inter-platform basin facies. The Luofu section in Nandan County is a good example to illustrate the general features. This section is located in a small basin controlled by the contemporaneous “Ziyun-Luodian-Nandan-Duan” fault zone. As shown in Fig. 7, the strata at Luofu can be grouped into three parts. The lower part consists of the Lianhuashan and Nagaoling Formations, marked by transgressive sandstones with brachiopods including Kuangsinynchus liujingensis and Orientospirifer wangi, indicating a Lochkovian to Pragian age. The middle part is characterised by inter-platform basinal mudrocks, which can be divided into the Yilan, Tangding, Nabiao and Luofu Formations. These range in the Emsian to Frasnian time, corresponding to the general features. This section is located in a small basin controlled by the contemporaneous “Ziyun-Luodian-Nandan-Duan” fault zone.

The facies succession of the Yangshuidong and Daihua Formations, which is marked in Fig. 7, is illustrated by the general features. The middle part is characterised by inter-platform basin facies, and constitutes the TST of SQ5. In the Tangding Formation, the inter-platform basin facies consist of meter-scale cycles of alternating micritic limestones and silty marls. From the base to the top, the micritic limestone beds become thicker and lenses of storm-reworked shell beds become more common. They belong to the inter-platform shelf facies, and the HST of SQ9 is mainly made up of them. Tentaculitites such as Nowakia subtilis and Nowakia richteri occur in the TST of SQ9, and brachiopods, e.g., Eury spirifer sp. occur in the HST of SQ9, indicating an Emsian age.

Four sequences from SQ6 to SQ9 can be discerned in the Middle Devonian strata in the Nabiao and Luofu Formations (Fig. 7). The Nabiao Formation generally constitutes SQ9. Its TST is chiefly composed of black shales and siliceous mudrocks with a few marl beds and some meter-scale limestone-marl cycles. In its HST more micritic limestone beds and marls are developed. Together with the thin-bedded shales, they constitute meter-scale limestone-marl and subtidal carbonate cycles. There are three sequences, SQ7 to SQ8, within the Lianhuashan Formation, as shown in Fig. 7. The general features of the facies succession are basinal shales becoming thicker and lenses of storm-reworked shell beds becoming more common. They belong to the inter-platform shelf facies, and the HST of SQ9 is mainly made up of them. Tentaculitites such as Nowakia subtilis and Nowakia richteri occur in the TST of SQ9, and brachiopods, e.g., Eury spirifer sp. occur in the HST of SQ9, indicating an Emsian age.

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can be discerned. Their general characters are similar to those of SQ10: their TSTs are a succession of meter-scale cycles of limestone-marl alternations constituted by black shales and siliceous mudrocks of inter-platform basin facies with interbeds of micritic limestones of inter-platform shelf facies. Their HSTs are characterised by a succession of meter-scale cycles composed of thin-bedded marls of inter-platform basin facies and medium to thick-bedded micritic limestones of inter-platform shelf facies.

5 The Devonian sequence-stratigraphic framework

Through correlation of the sedimentary facies and sequences, a framework of Devonian sequence stratigraphy can be established, as shown in Fig. 8 and Fig. 9. As described in the above context, meter-scale cycles are similar to parasequences, and different types of meter-scale cycles are constituted by different successions of lithofacies (Mei et al., 2000). Systematic vertical changes in the natures of the meter-scale cycle reflect long-term onlap (transgression/relative sea-level rise) or offlap (regression/relative sea-level fall), i.e., long-term relative sea-level changes (Tucker, 2001). Therefore, the third-order sequence that is constituted by different sedimentary facies successions in different palaeogeographical settings has different vertical stacking patterns of meter-scale cycles. Two kinds of facies-changing surfaces, static and dynamic, as well as two kinds of diachronisms, diachronism of the facies-changing surfaces and diachronism of punctuated surfaces marked...
by sequence boundaries (Mei et al., 2001) are clearly demonstrated in Fig. 9. A map of sedimentary facies and palaeogeography as shown in Fig. 1, illustrates the different palaeogeographical settings of sequence-stratigraphic frameworks in the study area.

Four third-order sequences from SQ1 to SQ4 composed
of transgressive sandstones in the basal part of the Devonian, are distributed mainly in low-land areas (Figs. 8, 9). The sandstones gradually wedge out (Figs. 8, 9), as a result of the transgression after the Caledonian orogeny from the open sea towards land areas that were located to the north at the time. At Luofu, these strata occur in the Lianhuanshan and Nagaoling Formations, and four sequences from SQ$_1$ to SQ$_4$ can be discerned. They become thinner and form sequence SQ$_4$ at Dushan. However, at Lüyinqiao and Wudang near the margin of the basin, they wedge out. The central parts of most of the isolated platforms also lack these four sequences. These changing characters are clearly illustrated in Fig. 9.

As shown in Figs. 8 and 9, the strata of SQ$_5$ are widespread, as a result of a major transgression at the end of the Lower Devonian. For SQ$_5$, within the inter-platform basin, shales with siliceous interbeds form the TST, and silty marls with shale interbeds of inter-platform shelf facies form the HST as described at Luofu in Nandan (Fig. 7). On the attached platform, the facies of SQ$_5$ change regularly in space. Transgressive sandstones constitute the TST and open-platform limestones form the HST, as at Dushan (Fig. 4). Near the basin margin, such as at Wudang and Lüyinqiao (Figs. 2, 3), transgressive sandstones in the lower part of the Mangshan Formation constitute SQ$_5$. On the isolated platforms, such as at De’e in Longlin (Fig. 5), the strata of SQ$_5$ belong to the Lower Devonian. The TST contains mainly mudrocks of swamp facies, and the HST is mainly composed of open-platform limestones. Along the margin of the isolated platform, for example, at Liujing in Hengxian (Fig. 6), the TST of SQ$_5$ is composed of silty shales with marly interbeds and lenses of storm-reworked shelfal shelf beds. Its CS is marked by basinal shale facies, and sediments similar to the TST form the EHST. The LHST is composed of limestones overlain by siliceous dolomites called the Moding Formation. All these features of SQ$_5$ demonstrate that a large-scale transgression took place as a result of a rapid sea-level rise, and that the strata from SQ$_5$ to SQ$_6$ constitute a retrogradational succession of the third-order sequences. As a result of this transgressive event, the depositional range from the open sea towards the basin margin as a result of uplift due to the Haikou movement that took place at the end of the Eifelian. Other features related to this tectonic event are the lack of SQ$_5$ at the Wudang section, the intensive dolomitization in SQ$_5$ and SQ$_6$ at Liujing, the presence of transgressive sandstones in the lower parts (TST) of SQ$_8$ and SQ$_9$ at Wudang and Lüyinqiao, and the limestones in the HST at Dushan. After the regressive event related to the Haikou movement, the region became a mud-free open sea, in which carbonate sediments were deposited and these constitute SQ$_8$ and SQ$_9$. This situation continued until the Upper Devonian. Thus, the clastic strata in SQ$_1$ to SQ$_4$ form the basement to the carbonate platform, which persisted from SQ$_5$ to SQ$_14$; the period from SQ$_5$ to SQ$_8$ marks the more mature stage of the carbonate platform. Fig. 1 shows the general background of the sedimentary facies and palaeogeography, which overall is a complex of attached platforms, isolated platforms and narrow inter-platform basins, with reefs developed along some platform margins.

As shown in Figs. 8 and 9, the general features of the Middle Devonian sequences from SQ$_6$ to SQ$_9$ show a transition from clastics to carbonates. This transition is affected by uplift related to the Haikou movement that took place at the end of the Eifelian. Other features related to this tectonic event are the lack of SQ$_6$ at the Wudang section, the intensive dolomitization in SQ$_5$ and SQ$_6$ at Liujing, the presence of transgressive sandstones in the lower parts (TST) of SQ$_8$ and SQ$_9$ at Wudang and Lüyinqiao, and the limestones in the HST at Dushan. After the regressive event related to the Haikou movement, the region became a mud-free open sea, in which carbonate sediments were deposited and these constitute SQ$_8$ and SQ$_9$. This situation continued until the Upper Devonian. Thus, the clastic strata in SQ$_1$ to SQ$_4$ form the basement to the carbonate platform, which persisted from SQ$_5$ to SQ$_14$; the period from SQ$_5$ to SQ$_8$ marks the more mature stage of the carbonate platform. Fig. 1 shows the general background of the sedimentary facies and palaeogeography, which overall is a complex of attached platforms, isolated platforms and narrow inter-platform basins, with reefs developed along some platform margins.

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13 third-order sequences are recognized in the Devonian strata of Yunnan-GuiZhou-Guangxi area and these form two second-order sequences. This pattern is different from the sequence stratigraphy of Devonian strata presented by Ross and Ross (1988) as well as by Johnson et al. (1985). This might suggest that the third-order relative sea-level changes are controlled not only by eustasy but also by regional tectonic movements. Definitely, further research is required, such as determining the relationship between facies changes and the response of organisms. Two kinds of facies-changing surface as well as two kinds of diachronisms in the stratigraphic records are the key to establish the sequence stratigraphic framework. Meter-scale cycles are the fundamental building block, defined by lithofacies repetitions with different facies in different palaeogeographic settings as described by Mei et al. (2000). There are regular vertical stacking patterns in both thickness and facies within the meter-scale cycles through the third-order sequences. Therefore, it can be concluded that the study of sequence stratigraphy is the study of the response of sedimentation, as well as diagenesis, to the rise and fall of relative sea level. Previously-published research confirms this, e.g., detailed discussions of the working methods and terminology for sequence stratigraphy (see Vail et al., 1977; Van Wagoner et al., 1988; Mitchum and Van Wagoner, 1991; Tucker, 2001), the relationship between sequence stratigraphy and facies models (Walker and James, 1992), and the new and evolving terminology for sequence stratigraphy (Hunt and Tucker, 1992). Therefore, the sequence-stratigraphic framework of the Devonian in the study area provides an example for the further understanding of two kinds of facies-changing surface as well as two kinds of diachronisms in the stratigraphic records.

6 Conclusions

Thirteen third-order sequences are recognized in the Devonian strata of Yunnan-Guizhou-Guangxi area and these form two second-order sequences. This pattern is different from the sequence stratigraphy of Devonian strata presented by Ross and Ross (1988) as well as by Johnson et al. (1985). This might suggest that the third-order relative sea-level changes are controlled not only by eustasy but also by regional tectonic movements. Definitely, further research is required, such as determining the relationship between facies changes and the response of organisms. Two kinds of facies-changing surface as well as two kinds of diachronisms in the stratigraphic records are the key to establish the sequence stratigraphic framework. Meter-scale cycles are the fundamental building block, defined by lithofacies repetitions with different facies in different palaeogeographic settings as described by Mei et al. (2000). There are regular vertical stacking patterns in both thickness and facies within the meter-scale cycles through the third-order sequences. Therefore, it can be concluded that the study of sequence stratigraphy is the study of the response of sedimentation, as well as diagenesis, to the rise and fall of relative sea level. Previously-published research confirms this, e.g., detailed discussions of the working methods and terminology for sequence stratigraphy (see Vail et al., 1977; Van Wagoner et al., 1988; Mitchum and Van Wagoner, 1991; Tucker, 2001), the relationship between sequence stratigraphy and facies models (Walker and James, 1992), and the new and evolving terminology for sequence stratigraphy (Hunt and Tucker, 1992). Therefore, the sequence-stratigraphic framework of the Devonian in the study area provides an example for the further understanding of two kinds of facies-changing surface as well as two kinds of diachronisms in the stratigraphic records.

Fig. 10 Correlation of sea-level changes between North America (the left of the figure) and the study area (the right of the figure). The curve of the sea-level changes of North America is adapted from Johnson et al. (1985). This correlation indicates that there is not only similarities but also differences. The similarities are simply shown from “[1]” to “[9]”, and the differences are exposed from “(1)” to “(7)”. I to V refer to the regional unconformities: I—the unconformity of the Caledonian orogeny, II—the unconformity of the Haikou movement, III—the unconformity of the first episode of the Ziyun movement, IV—the unconformity of the second episode of the Ziyun movement.
Acknowledgements

The thesis is part of the project “Regional Geology and the Potential Analysis of Petroleum Exploration in Guizhou and Guangxi” (No.1008/2–6) financed by China Petrochemical Corporation (SINOPEC).

We thank the anonymous reviewers for their encouragement and constructive comments. We aslo thank Dr. Wang Xinwen and Dr. Wang Guibin for their help in fieldwork. The authors hereby thank Professor Wu Yi, Professor Leng Dexun, Professor Dai Shaowu, Professor Li Changquan for their generous help in original data collection.

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(Edited by Wang Yuan, Liu Min)