Cretaceous sedimentary basins in Sichuan, SW China: Restoration of tectonic and depositional environments

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A R T I C L E   I N F O

Article info

Article history:
Received 5 June 2014
Received in revised form 10 July 2015
Accepted in revised form 21 July 2015
Available online 25 August 2015

Keywords:
Cretaceous sedimentary basins
Restoration
Sichuan Basin
Tectono-depositional environment
Temporal-spatial evolution

A B S T R A C T

This study documents sediment infill features and their responses to the tectonic evolution of the Sichuan Basin and adjacent areas. The data include a comparison of field outcrops, well drillings, inter-well correlations, seismic data, isopach maps, and the spatial evolution of sedimentary facies. We divided the evolutionary history of the Sichuan Cretaceous Basin into three stages based on the following tectonic subsidence curves: the early Early Cretaceous (145–125 Ma), late Early Cretaceous to early Late Cretaceous (125–89.8 Ma), and late Late Cretaceous (89.8–66 Ma). The basin underwent NW–SE compression with northwestward shortening in the early Early Cretaceous and was dominated by alluvial fans and fluviolacustrine sedimentary systems. The central and northern areas of the Sichuan Basin were rapidly uplifted during the late Early Cretaceous to early Late Cretaceous with southwestward tilting, which resulted in the formation of a depression, exhibited southwestward compression, and was characterized by aeolian desert and fluviolacustrine deposits. The tectonic framework is controlled by the inherited basement structure and the formation of NE mountains, which not only affected the clastic supply of the sedimentary basin but also blocked warm-wet currents from the southeast, which changed the climatic conditions in the late Late Cretaceous. The formation and evolution of Cretaceous sedimentary basins are closely related to synchronous subtle far-field tectonism and changes in climate and drainage systems. According to the analysis of the migration of the Cretaceous sedimentation centers, different basin structures formed during different periods, including periods of peripheral mountain asynchronous thrusting and regional differential uplift. Thus, the Sichuan Cretaceous sedimentary basin is recognized as a superimposed foreland basin.

1. Introduction

The Cretaceous period is recognized as a key transitional period of plate tectonic evolution in China and adjacent areas and as a significant period during the Mesozoic intracontinental orogeny of South China (Wu, 2006; Li, Zhang, Dong, & Li, 2012a; Li, Zhang, Dong, Johnston, 2014), during which large-scale taphrogenic and magmatic activity occurred that generated the large “South China Extensional Basin and Igneous Province” (Zhou, Sun, Shen, Shu, & Niu, 2006; Shu et al., 2009; Li et al., 2014). This transition was mainly manifested by the transition from north–south divergence to east–west divergence during the Cretaceous (Wu, 2006). Neogenic structures played a dominant role in the eastern region of South China, and tectonic inheritance played a dominant role in the west (Li, 1996; Wu, 2006). Previous research studies regarding Cretaceous tectonics in South China have focused on the eastern region of South China (e.g., Shen et al., 2012; Hu et al., 2012; Wang, 2013; Wang, et al., 2013a; Li et al., 2012a; 2014). However, due to severe destruction, geologists have not considered complex tectonic evolution, wide deposition with subsequent erosion, or poor oil-gas accumulation conditions in the western region of South China as priorities.

The Sichuan Basin is located in the western area of the South China Block and represents this region. Reconstruction of the Sichuan Cretaceous sedimentary basins, which are related to the Mesozoic intracontinental orogeny, can provide significant clues to help reveal the Cretaceous temporal-spatial evolution of the tectono-depositional environment in the western part of the South China Block. Regional uplift following the Cretaceous converted the...
eastern part of the Upper Yangtze into an erosional area (e.g., Yuan et al., 2010; Tang, Yan, Qiu, Gao, & Wang, 2013; Li & Shan, 2011). Currently, residual Cretaceous rocks only exist in the southern, western, and northwestern Sichuan Basin, which are characterized by “gray beds” in the north and “red beds” in the south. Although many researchers agree that the Sichuan Basin entered a shrinking and decline stage at the beginning of the Cretaceous period, most previous studies that have focused on lithofacies paleogeography, paleostructure, paleoclimate, paleoenvironment, or sedimentary basin properties have focused on the present-day residual basin (e.g., Chen, 1987; Guo, Deng, & Han, 1996; Meng, Wang, & Hu, 2005; Long, Chen, Lin, Xu, & Cheng, 2011; Geng, 2011). However, no integrated studies have combined tectonics and sedimentology, and systematic and dynamic research is lacking. Consequently, the following questions must be answered: Did the Cretaceous hiatus in the eastern Sichuan Basin result from a lack of deposition in the late depositional period or from complete erosion during the uplift period? How large was the Sichuan Basin in the Cretaceous? What was the tectonic and depositional environment?

To answer these questions, our study attempts to reconstruct Sichuan Cretaceous sedimentary basins by interactively synthesizing available data. The data sets used in this study include comparisons of abundant field outcrops, well drillings, inter-well correlations, seismic data, isopach maps, and the spatial evolution of sedimentary facies. Although preliminary in nature, our study aims to provide a starting point for more comprehensive future studies.

2. Geological setting

2.1. Tectonic setting of the Sichuan Basin

The Sichuan Basin is located in central–southern Asia, in central China, and in the western area of the South China Block (Fig. 1), including the eastern Sichuan province and Chongqing City, and is surrounded by peripheral mountains (i.e., the Longmen Mts. in the west, Qiyao Mts. to the east, Daba Mts. to the north and Daliang–Dalou Mts. in the south) (Fig. 2) (e.g., Liu, Deng, Li, & Sun, 2012a). Bound by the current residual terrestrial stratigraphic boundary, the Sichuan Basin covers an area of 18 × 10^4 km², making it one of the four largest basins in China.

The major landmasses in China began to converge during the late Indosinian period (the Late Permian to Triassic) (Zhang, Meng, & Lai, 1995; Ma et al., 2004a). Together with the Laurasian and Gondwanan continents, these landmasses converged to form Eurasia, and the Chinese terrestrial basin formed (Ma et al., 2004a). During the Late Jurassic to Early Cretaceous, the Paleo-Pacific plate was subducted below the Eurasian plate toward the north-northwest (Northrup, Rovden, & Burchfiel, 1995; Zhou & Li, 2000). The South China plate, the north part of the South China Sea plate and the East China Sea plate were subjected to oblique collision and shear orogeny, and the Tibetan plate was extruded eastward (Fig. 1). These movements subjected the southern area of China to multiple strong deformation episodes that formed the South China Yanshanian (Jurassic to early Early Cretaceous) intra-continental orogenic belt and the eastern Yanshanian “plateau” and resulted in widespread magmatic intrusions and volcanic activity in the southeast area and many strike-slip pull-apart basins (Zhou & Li, 2000; Wu, 2006; Chen et al., 2009; He et al., 2011; Wang, Fan, Zhang, & Zhang, 2013b). The tectonic framework of the Sichuan Basin and adjacent areas is restricted to three directions (the northwest, northeast, and southeast), with structural inversion between the east and west. In the Late Cretaceous, the interactions between the Neo-Tethys and the Pacific tectonic domains changed the tectonic character of South China to eastern strike-slip extension and western compressional thrusting, which resulted in the formation of a large number of extensional rifted basins in the Middle–Lower Yangtze and produced large-scale magmatic and hydrothermal activity in the east (Wang et al., 2013b).

2.2. Stratigraphy

The Sichuan Basin is a multi-cycle superimposed basin with a marine carbonate platform and a continental clastic rock system.
deposited on the Yangtze paraplatform in South China (Wang, Zhao, Zhang, & Wu, 2002; Ma et al., 2004a; 2004b; He et al., 2011). The Cretaceous deposits known as “red beds” are characterized by terrestrial brick-red clastic deposits with a thickness of approximately 3000 m and account for nearly 40% of the basin area (Guo et al., 1996; Wang et al., 2002). Red beds are widely distributed along the east side of the Longmen Mts., along the south side of the North Daba Mts., and in the south and southwest regions of the Sichuan Basin (Fig. 2). Cretaceous red beds are comparatively complete in the western Sichuan Basin but absent in the south and southwest Lower Cretaceous. The Lower Cretaceous is absent in different regions use different nomenclature (e.g., Guo et al., 1996; Wan, Chen, & Wei, 2007; Meng, 2012; Cao, 2013) (Fig. 3).

2.3. The regional tectonic uplift events

It is generally accepted that the Songpan–Garzé Belt has undergone at least two major orogenic events since the Mesozoic (Burchfield, Chen, Liu, & Royden, 1995; Arne et al., 1997; Harrowfield & Wilson, 2005; Zhou, Yan, Vasconcelos, Li, & Hu, 2008; Roger, Jolivet, & Malavieille, 2010), the Late Triassic compressional event related to convergence between the North China, South China, and Qiangtang Blocks (Enkin, Yang, Chen, & Courtillot, 1992; Roger et al., 2010; Yan, Zhou, Li, & Wei, 2011a) and the Paleogene to Neogene deformation related to the India–Asia collision (Burchfield et al., 1995; Arne et al., 1997). In addition, Roger, Malavieille, Leloup, Calassou, and Xu (2004) proposed that a major tectonic decollement in the Songpan–Garzé fold belt occurred before the Early Jurassic. When accounting for several pieces of geological evidence, we support the view that the uplift in the Longmen Mts. mainly occurred around the Early Pleistocene (e.g., Kirby et al., 2002; Godard et al., 2009; Tang, Guo, & Qiao, 2011; Wang et al., 2012; Li et al., 2012b; Tan, Lee, Chen, Cook, & Xu, 2014), with deformation progressively propagating northward and eastward (Yin & Harrison, 2000). The Dabashan fold-thrust belt formed before the Late Cretaceous based on the preservation of the age-elevation relationships and the lack of distinct age changes across the tectonic structures (Zhang et al., 2013a). The Daba Mts. began forming in the Early Cretaceous (120–110 Ma) and experienced rapid, steady, and accelerated periods of growth. In addition, the uplift dating shows progressively younger uplift with southwest extension (Shen, Mei, Xu, Tang, & Tian, 2007). Tian et al. (2012a) proposed that the onset of exhumation in the Daba Shan Foreland Basin began during Aptian–Albian time (~100–125 Ma). Rapid uplift processes occurred in the Micang–Hannan dome at approximately 90 Ma and 15 Ma (Tian et al., 2010; 2012b) and spread to the northern Sichuan foreland basin in the Mid–Cenozoic.
et al. (2007), Meng (2012), and Cao (2013). The later ages are adjusted according to the International Chronostratigraphic Chart v2015/01. The locations of basins are shown in Fig. 2.

Fig. 2. Stratigraphic correlation of the Cretaceous period in the Sichuan Basin and adjacent areas. The Cretaceous stratigraphic correlation is modified after Guo et al. (1996), Wan et al. (2007), Meng (2012), and Cao (2013). The later ages are adjusted according to the International Chronostratigraphic Chart v2015/01. The locations of basins are shown in Fig. 2.

A comprehensive study of the tectonic uplift of the Mesozoic—Cenozoic in the Sichuan Basin indicated the following regional variations in the Sichuan Basin. Rapid uplift occurred in northern Sichuan at 110–70 Ma, east central Sichuan at 110–70 Ma, and 20–10 Ma across the Sichuan Basin and that the regional apatite fission-track (AFT) age, regional AFT length, and regional AFT erosion rates with the oldest ages at the center and progressively younger ages towards the southwest.

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3. Data and methodology

Lithology, stratigraphy, paleogeography, sedimentary facies, and tectonic subsidence have been used to account for the restoration of the Sichuan Cretaceous sedimentary basins. The study approach presented here is an integration of points (wells or measured geological sections), lines (cross sections), and planes (planforms) data (Chen et al., 2014) and provides new information regarding the temporal and spatial evolution of the tectono-depositional environment. The data sets include a comparison of field outcrops, well drillings, inter-well correlations, seismic interpretations, and sedimentary facies in the Sichuan Basin.

(1) Field outcrop data: Twelve columnar sections from Nanjiang Shafe, Wangcang Changle, Jian'ge Yaojia, Chongzhou Huauiyan, Qionglai Jiaguan, Tianquan Jinnmenguang, Hongya Zhongshaping, Leshan Dafosi, Yibin Sanhechang, Yiben Jinpingzen, Luzhou Hejiang Shizi, and Guizhou Xishui Tucheng (locality of each section is marked by triangles in Fig. 2) were collected and interpreted using sedimentary subfacies analysis based on lithofacies, grain size and sedimentary structures.

(2) Well data: Four wells, Chuanfeng 563, Chuanhe 100, Chuanxiao 107, and Chuanwen 303 (the location of each well is marked by circles in Fig. 2), were described and interpreted using sedimentary subfacies analysis based on logging data. Six wells with relatively complete logging data from the Western Sichuan, Chuanwen 303, Dayi 6, Dayi 7, Guankou 2, Baima 9, and Baidian 58 (their locations are marked by circles in Fig. 2) were selected to recover the Cretaceous subsidence history.

(3) Inter-well correlations: Two inter-well correlations, AA' and BB', were integrated with well data, and interpretations of outcrop sections were used for correlation, interpretation and sedimentology analyses. We partitioned the sedimentary facies in detail to clarify the spatial evolution of sedimentary facies with time.

(4) Seismic data: Seismic grid data (including 2-D seismic survey lines and 3-D pre-stack depth migration data) covering the entire basin and wells with synthetic seismograms were used to trace the horizons and constrain the thickness of the Cretaceous strata.

(5) Strata isopach maps: Isopach maps showing the current thicknesses were defined using data from wells, measured geological profiles, and seismic profiles.

(6) Data from sedimentary facies with planar beds: Sedimentary facies with planar beds were defined using comprehensive data from field outcrops, well drillings, inter-well correlations, and seismic interpretations.
In this paper, the standard 1-D backstripping technique (e.g., Watts & Ryan, 1976; Steckler & Watts, 1978; Watts, Karner, & Steckler, 1982; Scheck & Bayer, 1999) was employed to reconstruct basin subsidence during Cretaceous times. This technique restores the original thickness of sediment units by beginning from the lowest unit of a stratigraphic section and moving step by step through the overlying units (Sclater & Christie, 1980).

Drilling information (unpublished data of the CNPC and Sinopec) obtained during hydrocarbon exploration can be used to compile the lithological compositions for each well in which the fractions of sandstone, siltstone, clay, and carbonates were previously defined. The compaction corrections were conducted by using the standard exponential relations of porosity versus depth and the widely used North Sea basin lithological parameters proposed by Sclater and Christie (1980). The paleo-water depth was assumed to equal zero because deepwater formations were lacking; thus, the additional water load can be ignored. Eustatic change corrections were calculated from the long-term eustatic curve presented by Haq, Hardenbol, and Vail (1987). The ages of the Cretaceous sequence boundaries in the study area are listed in Fig. 3, and the later ages are adjusted according to the International Chronostratigraphic Chart v2015/01.

To provide a clear image of the evolution of Cretaceous subsidence in the Western Sichuan Basin, subsidence curves from six shallow wells were produced using Basin Mode 2009 and fit together on a computer screen using CorelDRAW. We only calculated “tectonic subsidence” curves that reflected the tectonic or driving mechanisms of a basin (Bond & Kominz, 1984) because a mirror-image relationship potentially occurred between the uplift of the longmen Shan thrust belt and the subsidence of the Western Sichuan foreland basin following ~60 Ma (Liu, Luo, Dai, Arne, & Wilson, 1996).

4. Results

4.1 Basin tectonic subsidence

The subsidence curves indicate that the western Sichuan Basin was characterized by episodic subsidence in the Cretaceous period; thus, we divided the evolutionary history of the western Sichuan Cretaceous basin (extended to the whole basin) into three stages:

1. Oscillating subsidence in the early Early Cretaceous (145–125 Ma): The rate of subsidence varies slightly in different areas and at different times with a short duration of uplifting in the late stage (Fig. 5).
2. Stable subsidence during the late Early Cretaceous to early Late Cretaceous (125–89.8 Ma) with an average subsidence rate of approximately 10 m/My (Fig. 5).
4.2.1. Description of SW

4.2. Sediment in the Tectonic subsidence curves of typical wells in the western Sichuan Basin. Every well is located.

Qionglai Jiaguan: The local lithostratigraphic subdivision contains the Jiaguan Fm. (Formation) (K1jm) and Guankou Fm. (K2g) (Fig. 6). The Jiaguan Fm. of the Lower Cretaceous is 210 m thick, is characterized by mottled, thick conglomerate, sandy-conglomerates, conglomerates with salt, and contains poorly sorted and moderately rounded conglomerates with pebble diameters of 1–10 cm. The Jiaguan Fm. of the Upper Cretaceous is 140 m thick and consists of coarse sandstones in the upper part and salt containing sandstones in the lower part. The Guankou Fm. of the Upper Cretaceous is 800 m thick and contains a brown-red cyclothem with unequal siltstone and mudstone thicknesses and comparatively thick marlstones, fine conglomerates, gypsiums (Fig. 7A), and salt layers (Fig. 7B).

Chongzhou Huaijuan: The Tianmashan Fm. (K1t) is 265 m thick and is characterized by thick conglomerates at the bottom that consist of cyclothem and unequal thicknesses of fine-sandstones, siltstones, and mudstones with increasing grain sizes with depth (Fig. 6). The Lower Cretaceous Jiaguan Fm. is 353 m thick and is composed of red siltstones, sandstones, pebbly sandstones, conglomerates with trough cross bedding and characterized by fine-grains in a matrix of coarse grains. The Upper Cretaceous Jiaguan Fm. is 194 m thick and has similar features and a finer grain size. The Guankou Fm. consists of 85-m-thick conglomerates at the top with poorly sorted and moderately rounded clasts.

Well Chuanwen 303: The Cretaceous strata, from bottom to top, are assigned to the Cangxi Fm. (K1c), Bailong Fm. (K1b), Qiquisi Fm. (K1g), Jiaguan Fm. (K2jg) and Guankou Fm. (K2g) (Fig. 6). The Cangxi Fm. is 180 m thick and mainly consists of gray or yellow pebbly sandstones and mudstones with cross bedding. The Bailong Fm. is 258 m thick and consists mainly of sandstones and mudstones with horizontal bedding and ripple bedding. The Qiquisi Fm. is 216 m thick, and the lithostratigraphic subdivisions are similar to those of the Bailong Fm. The Jiaguan Fm. is composed mainly of brown-red or reddish sandstones with bimodal cross bedding and is 420 m thick. The Guankou Fm. consists mainly of brown mudstones and siltstones with interbeds of reddish laminated sandstones. This formation is also a salt-bearing layer with a thickness of up to 550 m.

Well Chuanxiao 107: Only the Cangxi Fm. (K1c) and Bailong Fm. (K1b) of the Lower Cretaceous remained in this well (Fig. 6). The Cangxi Fm. consists mainly of gray sandstones and mudstones interbedded with some pebbly sandstone layers, except for a ~65-m-thick layer of coarse-grained feldspathic pebbly sandstones at its base. The Bailong Fm. is composed of gray fine-grained sandstones and mudstones with horizontal bedding.

Well Chuanhe 100: The local lithostratigraphic subdivision of the Jiannenguan Fm. (K2jm) is ~750 m thick and contains different lithostratigraphic subdivisions between the lower and upper sections of the lithologic log (Fig. 6). The lower portion is 255 m thick and mainly consists of mudstones and siltstones interbedded with some sandstone layers. The upper part is composed of sandstones interbedded with some siltstone and mudstone layers.

Well Chuanfeng 563: The Jiamenguan Fm. (K2jm) is ~450 m thick and mainly consists of gray sandstones and siltstones and interbeds of gray mudstone (Fig. 6).

Jiang’ge Yaojia: The local lithostratigraphic subdivision includes the Jiamenguan Fm. (K2jm), Hanyangpu Fm. (K2h), and Jiang’ge Fm. (K2jg) (Fig. 6). The Jiamenguan Fm. is ~400 m thick and is characterized by poorly sorted and moderately rounded conglomerates with interbeds of sandstones (Fig. 7C). In addition, ~100-m-thick mudstones and siltstones with interbeds of laminated sandstones occur. Differences in the lithology and sedimentary structure occur among the lower, middle and upper portions of the Hanyangpu Fm. The lower, 105-m-thick portion consists mainly of gray coarse sandstones and mottled, well-sorted and rounded conglomerates. The middle part is 155 m thick and mainly includes mid-to fine-grained sandstones with trough cross bedding and scour surfaces. The upper part is 170 m thick and is characterized by gray siltstone with interbedded mudstone and parallel bedding and ripple laminations. The lower part of the Jiang’ge Fm. consists mainly of gray and fine conglomerates and coarse sandstones with trough cross bedding (Fig. 7D and D’). However, the grain-size of the upper part becomes fine and lateral accretion cross bedding is observed.

Wangcang Changle: The Cangxi Fm. (K1c), Bailong Fm. (K1b), and Qiquisi Fm. (K1g) in the Lower Cretaceous occur in this section (Fig. 6). The Cangxi Fm. consists of 4 sequences graded from coarse at the bottom to fine at the top. The first sequence, which is 95 m thick, is composed of reddish conglomerates with moderately sorted and rounded clasts. The second sequence is ~75 m thick and consists of interbeds of gray laminated sandstones and gray-blue mudstones and boulder clay in the lowermost interbed. The second sequence is ~265 m thick and mainly consists of gray coarse sandstones interbedded with thin laminated dark gray mudstones and gray-blue siltstones. The fourth sequence is 110 m thick and mainly composed of mudstone. The Bailong Fm. is 360 m thick, consists mainly of white-gray sandstones interbedded with some siltstone and
mudstone layers, and is characterized by the sandstones in mudstones in the sedimentary sequence. The Qiqusi Fm. is ~110 m thick and mainly consists of white-gray sandstones, siltstones, and mudstones interbedded with thick good sorted and rounded conglomerates.

- Nanjiang Shahe: The Jianmenguan Fm. (K1jm) and Hanyangpu Fm. (K1h) of the Lower Cretaceous remain in this section (Fig. 6). The Jianmenguan Fm. is > 500 m thick and contains four sequences with alternating layers of coarse and fine lithology (Fig. 6). This section begins with well sorted and rounded 3–10 cm diameter conglomerates with white-gray coarse sandstones and dark-gray mudstones that become finer upward with interbedded sandstones and siltstones containing mud pebbles and overlain by ~300-m-thick coarse clastic sediments with characteristic mudstones in sandstones and the development of trough cross-bedding. The uppermost part of the Jianmenguan Fm. is ~100 m thick and consists mainly of white-gray siltstones and mudstones. The sedimentary characteristics of the Hanyangpu Fm. are similar to those of the Jianmenguan Fm., except for the fining-upward sequence in the uppermost part (Fig. 6).

4.2.2. Description of NWW–SEE inter-well correlations

BB' is a NWW–SEE profile of sedimentary filling (Fig. 8) from Tianquan to Xishui (the location is shown in Fig. 2 BB'). Eight columnar sections were joined together with the lithofacies and sedimentary fillings described below.

- Tianquan Jianmenguan: The Lower Cretaceous Jiaguan Fm. (K1j) consists of ~50 m thick well sorted and rounded conglomerates overlain by interbedded siltstones and mudstones (Fig. 8) with large-scale trough cross-bedding. Interbedded coarse sandstones and mudstones characterize the Upper Cretaceous Jiaguan Fm. (K2j). The lower part of the Guankou Fm. (K2g) consists of ~450-m-thick poorly sorted and moderately rounded conglomerates with a maximum pebble diameter of 65 cm. The middle portion is composed of sandstones, siltstones and mudstones with thicknesses of ~200 m. The uppermost part of the section consists of horizontally bedded siltstones and mudstones that contain salt.

- Qionglai Jiaguan: This profile shows the intersection of the inter-well correlation section AA' and BB', which is described above.

- Hongya Zhongshanping: The Lower Cretaceous Jiaguan Fm. consists mainly of interbedded siltstones and mudstones with trough cross-bedding and sorted and moderately rounded conglomerates at the bottom. The Upper Cretaceous Jiaguan Fm. is ~100 m thick and consists of red siltstones with thin, laminated mudstones (Fig. 8). The Guankou Fm. is up to ~750 m thick and is dominated by brown-red mudstones with interbeds of comparatively thick marlstones, siltstones and shales.

- Leshan Dafosi: The Lower Cretaceous Jiaguan Fm. mainly consists of thick red sandstones with large-scale cross-bedding and siltstones that are interbedded with thin brown-red mudstones. The Upper Cretaceous Jiaguan Fm. is ~200 m thick and is characterized by a set of brick-red sandstones (Fig. 8). Notably, the Leshan Giant Buddha, which is famous worldwide, was carved from this sandstone. The Guankou Fm. is >650 m thick, conformably overlies the Jiaguan Fm. and is mainly composed of brown or reddish mudstones and siltstones.

- Yibin Sanhechang: The Wotoushan Fm. (K1w), Daerdang Fm. (K2d), Sanhe Fm. (K2s) and Gaokanba Fm. (K2gk) were identified.
in this section with conformable contact relationships between each (Fig. 8). The Wotoushan Fm. is ~90 m thick and mainly consists of red sandstones in a thinning- and fining-upward sequence. The Daerdang Fm. is ~120 m thick with a set of brick-red, thick, massive, fine-grained feldspar-quartz sandstones characterized by highly developed cross-bedding with three-level interfaces and well-sorted, well-rounded grains (Fig. 9A and A’). The Sanhe Fm. is 156 m thick and consists of red sandstones interbedded with brown-red mudstones. The Gao-kanba Fm. is mainly composed of red or reddish sandstones with interbeds of brown-red mudstones and is ~540 m thick.

- Yibin Jinpingzhen: This profile has the same nomenclature and similar sedimentary infilling features, including the Wotoushan Fm., Sanhe Fm. and Gaokanba Fm., which are characterized by sandstone with calcareous concretions (Fig. 8), and the Daerdang Fm., which is characterized by aeolian sand with contact-porous calcite cementation and highly developed cross-bedding.
- Luzhou Hejiang Shizi: The Wotoushan Fm. and Daerdang Fm. are the only formations in this profile (Fig. 8). The bottom of the Wotoushan Fm. consists of ~210-m-thick red sandstones with calcareous concretions that become finer upward into the ~300-m-thick sandstones or siltstones with interbeds of brown-red mudstones. The Daerdang Fm. is ~210 m thick and is characterized by red, thick, massive, fine-grained feldspar-quartz sandstones with well-sorted and well-rounded grains.

Fig. 7. Typical outcrops and facies photographs. A. Brownish red mudstone with minor gypsum in dissolved pores and located in a Salt lake environment in the Guankou Formation southeast of Qionglai Jiaquan. B. Brownish red mudstone with argillaceous siltstone and glauberite in a Salt lake environment in the Guankou Fm., northeast of Qionglai Jiaquan. C. Thick, poorly sorted and moderately rounded conglomerates with interbeds of sandstones and a thickness of >400 m in an alluvial fan environment in the Jianmenguan Fm. Jian’ge Yaojia. D. (and its sketch map D’) Thick conglomerate with coarse sandstone and small cross-bedding developed in sandstone strata, in which the conglomerate is characterized by sub-rounded clasts with poor sorting and a clast size range from 5 to 30 cm in an alluvial fan deposit in the Jian’ge Fm. northeast of Jian’ge Yaojia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Guizhou Xishui Tucheng: The Wotoushan Fm. is ~180 m thick and mainly consists of red sandstones with interbeds of brown-red mudstones. The Daerdang Fm. is ~220 m thick and mainly consists of brown-red mudstones with interbeds of red sandstones and siltstones. The Sanhe Fm. and Gaokanba Fm. mainly consist of red fine-grained sandstones and brown-red mudstones that become coarser with decreasing depth (Fig. 8).

4.3. Interpretations of tectonic and depositional environments

4.3.1. The early Early Cretaceous (the Berriasian to Barremian, 145–125 Ma)

4.3.1.1. Tectonic environment. The Longmen Mts. and the western Sichuan Basin inherited the deformation framework of the Late Jurassic and the paleostructural framework of the Middle–Upper Yangtze area significantly changed (Wu, 2006). The Longmen Mts. continued to rotate counter-clockwise (Meng et al., 2005) as they were uplifted towards the piedmont zone and the south segment (Li et al., 2012b). The middle and north segments of the Longmen Mts. piedmont zone formed a flexural depression that was superimposed on the Late Jurassic foreland basin (Meng et al., 2005). Together, these zones continued to evolve into a superimposed flexural basin. At the end of the early Early Cretaceous (approximately 129–125 Ma), a short period of uplifting in the western Sichuan Basin resulted in varying degrees of denudation in the upper Tianmashan Fm. and produced small-angle disconformity and unconformity with the underlying Jiaguan Fm. Due to the combined effects of strong southward thrusting in the foreland zone at the north edge of Yangtze and the northwestward movement of the fold belt of the Xuefeng Mts., a trumpet-shaped structure developed in northeastern Sichuan. Because of the continued northward squeezing and obstruction of the clockwise rotation movement in the northwest and northeast, the South China block was severely squeezed towards the north into the

- Guizhou Xishui Tucheng: The Wotoushan Fm. is ~180 m thick and mainly consists of red sandstones with interbeds of brown-red mudstones. The Daerdang Fm. is ~220 m thick and mainly consists of brown-red mudstones with interbeds of red sandstones and siltstones. The Sanhe Fm. and Gaokanba Fm. mainly consist of red fine-grained sandstones and brown-red mudstones that become coarser with decreasing depth (Fig. 8).
Qinling orogen (Meng & Zhang, 2000; Wang, Meng, Burchfiel, & Zhang, 2003; Meng et al., 2005). The northern area of Sichuan became a foreland basin (Fig. 10) under the influence of the Qinling intracontinental subduction (Liu, Li, Liu, & Luo, 2006). Meanwhile, the Xuefeng Mts. and the adjacent areas to the east experienced tensile deformation and NE strike-slip pull-apart basins began to develop. Thus, initial opening and sedimentary infilling of the Yuanma Basin occurred (Fig. 10) coevally with extensive Early Cretaceous magmatism, volcanism and extensional doming in South China (Li et al., 2012a). The Sichuan intracratonic depression basin to subside gradually westward and fluviolacustrine facies developed steadily in the Xichang foreland basin while connected with the Sichuan Basin (Fig. 10). The development of these basins is a hallmark of the formation of an E–W structural inversion framework in the Yangtze area.

4.3.1.2. Depositional environment. The early Early Cretaceous deposition has a maximum thickness of 1200 m and corresponds with the time of deposition of the Tianmashan Fm. Regional uplift during the Late Jurassic. This deposition resulted in differential erosion of the Penglaizhen Fm. followed by early Early Cretaceous deposition overlapping various strata of the Penglaizhen Fm. in many places and the subsidence center in the northwestern Sichuan Basin and southern Xichang (Fig. 10). Controlled by the peripheral tectonic environment, post-orogenic denudation, and basin tectonic subsidence, the Sichuan Basin received contributions from major sediment source areas located to the west and northwest (the Longmenshan thrust belt) and a secondary sediment source area to the north (the Dabashan thrust belt) during a depositional period in the early Early Cretaceous (Fig. 10). Thus, the distribution and depositional environment of the sedimentary facies is defined by the provenance system.

Alluvial–fluviol–laeustrine deposits developed in the western Sichuan Basin. The alluvial fan belt was distributed along the front of the Longmen Mts., with layers overlapping lengthwise and transversely skirting one another (Fig. 10). The well profiles of Chuanfeng 563, Chuanhe 100, Chuanxiao 107, and Chuanwen 303 (Fig. 8) indicate that the central part of the western Sichuan Basin consisted of a shallow lake deposit with a set of interbedded sandstone and mudstone during this stage. The depositional environment becomes a meandering river towards the east (Fig. 10). Braided river deposits of superimposed layers of watercourse sandstone containing lentoid mudstone mainly occur north and northeast of the Sichuan Basin. Without alluvial fan conglomerates,
the deposits gradually became a meandering river alluvial plain system that featured sand beaches and flood plains towards the south. The fluvial-lacustrine facies of the early Early Cretaceous in the southwestern Sichuan Basin was stable, and the Xichang Basin was probably connected to it as a complete unit (Fig. 10). This unit had a distinct lengthwise bisectability and consisted of fluvial positive rhythmite layers of coarse sandstone—siltstone and purple mudstone in the bottom and lacustrine siltstone, fine sandstone and dark mudstone in the top with grain size coarsening from east to west. The Lower Cretaceous of Yuanba Basin unconformably overlies various layers of the Pre-Sinian, Paleozoic, and lower Mesozoic (Zheng, 1998; Zheng, Lou, Hou, & Chen, 1998; Ding, Liu, Lv, & Pan, 2007), of which the lithofacies consist of a set of brownish red-maroon conglomerates and sandstones interbedded with mudstones and the depositional environments were mainly the alluvial plains of meandering rivers and lakes (Fig. 10).

4.3.2.1. Tectonic environment. Influenced by the movement in the late Yanshan period, tectonic compression from the Qinling spread to the Sichuan Basin and resulted in rapid uplift in the north and northeast parts of Sichuan (Shen et al., 2007; 2009) with south-westward tilting. This tectonic event ended continental deposition and resulted in a period of uplifting and weathering denudation. The sedimentary scope of the Late Cretaceous in the north and east of Sichuan then shrank to the southwest, with the depositional center migrated to the Qionglai area (Fig. 11). Next, the southwest Sichuan foreland basin and south Sichuan foreland basin emerged, which compounded early subsidence, gradually progressed towards the southeast, and subsequently formed the southeast Sichuan foreland basin. The tectonic regime of the Yuanba Basin changed in the late Early Cretaceous to NW–SE compression and NE–SW extension, causing inversion of this extensional basin (Li et al., 2012a). A group of small, NE-trending analogous wedge-top basins developed in the Enshi and Qianjiang areas among the fold belts of widely spaced anticlines and synclines to the east of the Qiyao Mts.

4.3.2.2. Depositional environment. The Jiaguan Fm. was deposited in the late Early Cretaceous to early Late Cretaceous-equivalent. Inversion of the basin framework was dominated by tectonic amalgamation along its peripheral tectonic zone and associated intracontinental tectonisms and is important for providing sediments and defining provenance systems. Three sediment source areas were defined, the south segments of the Longmenshan thrust belt, the uplifting area of the Sichuan Basin, and the north segments of the Daloushan fold belt. The strong thrusting of the southern segments of the Longmen Mts. partially determined the development of two groups of alluvial fans in front of the Longmen Mts. and centered west of Pengzhou and Qionglai, respectively (Fig. 11). Due to aridity and torridness, the alluvial fan group west of Chengdu gradually changed to desert depositional conditions in the southeast and then to contiguous desert formed from the isolated and sporadic deserts of the early stage (Tian, 1990; Jiang & Pan, 2005; Long et al., 2011; Geng, 2011) trending NW–SE along the Chengdu–Zigong–Luzhou line (Fig. 11). Large-scale aeolian cross bedding with three-level interfaces (Yue & Ding, 1999) was observed in the Daerdang Fm. outcrop in the Yibin area, which was composed of brick-red, thick, massive, fine-grained mature feldspar-quartz sandstone with well-sorted and well-rounded grains (Fig. 9A and A’). This formation is a classic aeolian sand deposit with contact-porous calcite cementation (e.g., Kocurek, 1981; 1988; Ahlbrandt & Fryberger, 1982; Bristow & Mountney, 2013). The direction of the paleowind indicated by the foreset bed was SW, from which a central Sichuan Basin provenance was inferred (Fig. 11). The red color (in the web version) indicated that the aeolian sandstones formed in an arid and torrid paleoclimate and are the same type of sandstone that forms from lateral eolian dunes (Mountney, 2006; Bristow & Mountney, 2013). Due to the contributions of ancient water systems in southeastern Chongqing, central Guizhou, eastern Luzhou and southern Qijiang, a braided river depositional environment developed with sediments from south of the fold—thrust belt of western Hunan, Hubei, and eastern Chongqing (Fig. 11). The other alluvial fan group west of Qionglai became a braided river depositional environment trending NE–SW and evolved into a meandering river sedimentary environment towards the south and southeast with the converging water systems of the western Sichuan Basin and Xichang Basin. The Yuanba Basin also inherited the tectono-depositional environment of the early Early Cretaceous, meandering river and shallow lakes (Fig. 11).

4.3.3. The late Late Cretaceous (the Coniacian to Maastrichtian, 89.8–66 Ma)

4.3.3.1. Tectonic environment. Southeastward thrusting of the Songpan–Garze fold belt and northwestward squeezing of the Xuefengshan fold belt resulted in strong folding and uplifting in the eastern part of Sichuan, which resulted in a series of NE-trending orogens (Li, 2000; Yan, Hu, Lin, Santosh, & Chan, 2011b; Liu et al., 2012b), such as the Qiyao Mts. and Dalou Mts. The formation of these NE mountains not only affected the clastic supply to the sedimentary basins (Yan et al., 2011b) but also blocked the warm and wet air currents from the southeast, which altered the climatic conditions in the late Late Cretaceous. Furthermore, the constant eastward extension of the southwestern Sichuan foreland basin and the westward movement of the southeast Sichuan foreland basin were compounded by the development of a superimposed depression basin centered around the Zigong-Yibin area (Fig. 12). During this period, the Sichuan and Xicang basins sustained the basin architecture formed in the depositional stage of the Jiaguan Fm. The N–S extension prevailed in the Late Cretaceous and controlled Late Cretaceous subsidence (Li et al., 2012a), which resulted in the complete emergence of the Yuanna strike-slip pull-apart basin and gradual evolution into a separated foreland basin. The central Yangtze area experienced a comprehensive extensional structural transformation, and the NE–trending jianghan rift basin (the location is indicated in Fig. 1), which represents the rift basin group, formed and gradually developed into a basin and range province (Chen et al., 2009).

4.3.3.2. Depositional environment. The late Late Cretaceous is equivalent to the period when the Guankou Fm. was deposited in the western Sichuan Basin. In the late Late Cretaceous, two major subsidence centers and one secondary subsidence center developed (Fig. 12) due to superimposed coupling between the southwest and southeast Sichuan foreland basins. The main subsidence centers are the southwest Sichuan foredeep, which is centered in Yaan, and the southeast Sichuan foredeep, which is centered in Gulin, with thicknesses of more than 1400 m and 800 m, respectively. The secondary subsidence center is a superimposed depression in southern Sichuan that is centered in Yibin with a peak thickness of 800 m. Large-scale alluvial fans were deposited in front of the southern segments of the Longmen Mts. The conglomerate thicknesses at the ends of the fans are 400 m, 660 m, and 870 m, respectively, and rapidly become thinner towards the east (Fig. 12). The conglomerate and coarse sandstone were replaced by fine sandstone, siltstone, and mudstone. In the Qionglai-Yaan area and eastward, the lithofacies gradually becomes brownish-red fine sandstone, siltstone, and mudstone, and many
sets of thick stratiform marlstone, dolomite limestone, gypsum, and glauberite are present with decreasing sedimentary thicknesses from west to east. Pollen assemblages contain abundant Schizaeoisporites, Classopollis, and Ephedripites, which indicate an extremely arid climate in the late Late Cretaceous (Wang et al., 2008). In southern Sichuan, the depositional environment varied distinctly between the south and north (Fig. 12). The north mainly experienced braided river deposition that featured cycle deposition with mud layers sandwiched between sand layers along the Chengdu–Zigong–Yibin and major provenances in the uplifting area of Sichuan. The depositional environment along the Leshan–Junlian–Xishui was chiefly a meandering river feature cycle deposition with sand layers sandwiched between mud layers and a secondary provenance in the central and northern Daloushan fold belt (Fig. 12). The tectono-depositional environments of the Xichang Basin in the southwest and the Yuanma Basin in the southeast continuously evolved without great variations.

5. Discussion

During a long geological history, most sedimentary basins experience varying degrees of reformation and form "residual basins", Li, Lu, Liu, and Xu (2012c) proposed that a residual basin could be defined as the residual part of a sedimentary basin that has been modified by post–basin formation. All of our original data presented in this study were obtained from the Sichuan residual basin and are original sedimentary records of the Cretaceous sedimentary basins. Concrete evidence that can be used to investigate the tectonic–depositional environment of the Cretaceous remains lacking because Cretaceous sedimentary and stratigraphic records in eastern Sichuan are largely absent. Therefore, our study attempts to reconstruct Cretaceous basins by combining contemporaneous peripheral tectonic environments to provide evidence to evaluate previously stated hypotheses or develop alternative hypotheses regarding the evolution of the Sichuan Cretaceous basins.

5.1. Sedimentary boundary of the Sichuan Cretaceous basin

We present two main lines of evidence to argue the view that the scope during the Sichuan Cretaceous sedimentary basin construction period is much larger than the residual basin of the present day and that the missing Cretaceous units of the eastern Sichuan are not due to a lack of deposition during the construction period but result from suffering multiple denudation events during the late uplift.
First, no large-scale magmatic or hydrothermal activity has occurred since the late Mesozoic; thus, the cooling events reflect the uplift and denudation history. These uplift and denudation events are coupled with the distribution of the Cretaceous residual strata, which indicates that the sedimentary thickness and depo-
sition range of the original Early Cretaceous strata were much larger than the Cretaceous residual strata. Second, the widely
distributed and exposed Jurassic units in eastern and central
Sichuan experienced burial diagenesis that transformed sediment
deposits to diagenetic materials, which indicated that a certain
thickness of overlying sediments existed above the Jurassic strata.

5.2. Nature of Cretaceous sedimentary basins

The formation and evolution of the Cretaceous sedimentary
basins in Sichuan are affected by subtle far-field tectonism (Zhang
et al., 2013b) and changes in climate and drainage systems (e.g.,
Ratschbacher et al., 2003). Basin styles in south China exhibit a
range, from stretching-rifted types in the east to compressional-
derpression types in the west. The nature of the basins is
controlled by incomplete synchronized thrust nappes of peripheral
orogenic belts and regionally disparate uplift events in the basin,
which result in Cretaceous rocks that contain many coarse-to
medium-grained clastic rocks that were deposited in continental
environments and sourced from the erosion of mountain ranges
(Fig. 13). Consequently, the Cretaceous sedimentary basin has the
same characteristics as a typical foreland basin with several stages
of thrusting and reworking.

The intracratonic depression basin with foredeep settlement
features in the early Early Cretaceous (Fig. 13A) subsequently
transitioned to a converse foreland basin, which was characterized
by bidirectional provenance (Fig. 13B), and to a superimposed
foreland basin with multi-phase late-stage superimposition
(Fig. 13C). Thus, the Sichuan Cretaceous sedimentary basin could be
recognized as a superimposed foreland basin. In the eastern
Sichuan area (Guiyang to Enshi City), a series of NE-trending
intermontane basins with characteristics of a wedge-top depo-
zone (e.g., Conti, Fontana, & Lucente, 2008; Gugliotta, 2011; 2012;
Mazzoli, Szaniawski, Mittiga, Ascione, & Capalbo, 2012) devel-
oped under the effects of westward or northwestward compression
among the fold belts of widely spaced anticlines and synclines and
were superimposed or reworked during the Cretaceous period
(Fig. 13). The Yuanma Basin is composed of a group of disperse SW-
trending strike-slip pull-apart basins.
5.3. Some uncertainties

Defining the original boundaries of Cretaceous sedimentary basins in Sichuan is important but very difficult because of asynchronous thrusting of peripheral mountains, regional differential uplifting events, and post-orogenic denudation. Although we incorporated most of the available data interactively, our efforts do not guarantee an accurate estimate of the sedimentary basin boundary, especially in the early Early Cretaceous period. Thus, future research should focus on reconstructing the original sedimentary boundary during specific episodes of the basin’s geological history.

Although the Sichuan Cretaceous sedimentary basin is defined as a foreland basin by solid studies, no direct evidence has been found that define the mechanisms of the scattered basins (Guiyang-Enshi red basin, Xichang Basin, and Yuanma Basin) discussed in this paper. However, our study provides a relatively reasonable assumption that is consistent with the tectonic background of the study area. Moreover, many types of conditions should be investigated to determine the nature of the basin. Our preliminary work aims to provide suggestions for future basin analyses or tectonic and sedimentary analyses.

6. Conclusions

(1) According to tectonic subsidence patterns in the western Sichuan Basin, we divided the evolutionary history of the Sichuan Cretaceous basin into three stages, oscillating subsidence in the early Early Cretaceous (145–125 Ma), stable subsidence during the late Early Cretaceous to early Late Cretaceous (125–89.8 Ma), and rapid subsidence in the late Late Cretaceous (89.8–66 Ma).

(2) The temporal-spatial evolution of the Cretaceous tectono-depositional environment in the Sichuan Basin and adjacent areas is presented. The basin was subject to NW–SE compression with northwestward shortening in the early Early Cretaceous and was dominated by alluvial fan and fluviolacustrine sedimentary systems. The Longmenshan thrust belt is the main sediment source area, and the Dabashan thrust belt is a secondary source area. The central and northern Sichuan Basin was rapidly uplifted during the late Early Cretaceous to early Late Cretaceous with southwestward tilting, which developed into a depression, exhibited southwestward compression, and was characterized by aeolian desert and fluviolacustrine deposits. The tectonic framework was controlled by the inherited basement structure, and the formation of NE mountains not only affected the material provision but also blocked warm-wet currents from the southeast, which changed the climatic conditions in the late Late Cretaceous.

(3) The formation and evolution of the Cretaceous sedimentary basins are closely related to synchronous regional tectonic uplifting events. Controlled by asynchronous thrusting of peripheral mountains and regional differential uplifting events, the Sichuan Cretaceous sedimentary basin is recognized as a superimposed foreland basin.

Acknowledgments

This research was financially supported by the National Science and Technology Major Project (2011ZX05008-001), the National Natural Science Foundation of China (40739906), and the National...
Natural Science Foundation of China (41202147). We are very grateful to the Editor-in-Chief Prof. E. Koutsoukos for his constructive comments and suggestions that significantly improved the original manuscript. We acknowledge Dr. Andrei Khudoley of St. Petersburg State University and another anonymous referee for their critical and constructive comments. We thank Southwest Company, Sinopic for kindly supplying drilling data, and we also thank Chengdu University of Technology for supplying part of the outcrop data. Finally, we honor geologists at home and abroad for their remarkable work in Cretaceous research.

References


