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Research Article

The Ordovician Retroarc Foreland Basin on the Yangtze Block Linked to the Final Assemblage of Gondwana

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Amalgamation of the Yangtze and Cathaysia blocks in the context of Gondwana assembly in the early Paleozoic has been addressed for decades, but the far-field effects on the Yangtze Block during the amalgamation remain unclear. In this study, we outline the sequence stratigraphic framework of the Ordovician succession in the central-upper Yangtze Block and analyze provenance records in sandstone compositions, distributions, and detritus zircon U-Pb dating. The Ordovician succession in the central-upper Yangtze Block is subdivided into six third-order sequences, which were deposited mainly in a carbonate platform with restricted sediments in Tremadocian to early Floian stages, mixed terrigenous-carbonate deposits in mid- to late Floian stages, and open circulation sediments in Dapingian to middle Katian stages. These sequences show the central-upper Yangtze Block experienced syn-tectonic deformation with northeast-trending long-wavelength uplift and depression alternatively and the depocenter shifting from the east during Tremadocian to mid-Floian stages to the southwest in late Floian to early Hirnantian stages. Provenance data indicate that detritus in the Ordovician succession was mainly from the northern India and Kangdian paleohighland to the southwest of South China Block. Incorporating the depositional and deformation variations, we propose a retroarc foreland basin that was developed on the South China Block in response to final suturing between the South China Block and East Gondwana at Sanya suture zone. The South China Block was thus involved in the global tectonics of the Gondwana supercontinental cycle during the Ordovician.

1. Introduction

As one of the major amalgamations of Asian continental fragments, the South China Block experienced several super-continental cycles of assembly, dispersal, subduction, and collision during the Precambrian and Phanerozoic [1–6]. Such tectonic frameworks have directly linked to orogenic cycles [4, 7–11] and significantly shaped climate patterns and biodiversification over time [5, 12]. These events and processes may have been preserved in records of basin filling, magmatism, metamorphism, and crustal deformation [9, 10, 13–15]. Therefore, detailed understanding of cratonic basin development and filling not only provides insights into the orogenic processes in the framework of paleogeography reconstruction but further tracks critical information regarding global paleoclimate changes and biological successions.

The South China Block was formed by Cathaysia amalgamating with the Yangtze Block along the Jiang-Shao suture between 980 Ma and 810 Ma during the assembly of Rodinia supercontinent [1, 11, 16–18]. However, controversy continues regarding subsequent paleogeographic expressions of the Nanhua Ocean [19, 20] and the intracontinental depressional basin [1, 4, 7, 21–24] in the central South China Block related to the following breakup of Rodinia supercontinent and assemblage of Gondwana in the Late Neoproterozoic to early Paleozoic. The former requires early Paleozoic sediments to have been deposited in the continental shelf and slope environments [19], while the latter suggests continuous depositional variations [1, 4, 23, 24].

Widespread unconformities between the Cambrian and Ordovician successions are marked by basal conglomerates in Cathaysia [1, 25]. Deformation was subsequently overprinted by extensive metamorphism, magmatism, and crustal deformation between the Anhua-Luocheng fault and the Zhenghe-Dapu fault in eastern Yangtze Block and Cathaysia Block during the early Paleozoic (460-420 Ma) [6–10, 23, 25–27]. Such unconformities also occur widely in the western margin of northern Yangtze Block as evidence of Caledonian paleouplift. Equivalent unconformities at the eastern and western margins of the South China Block may have evolved into a unified tectonic domain due to oblique collision between South China and Australia-India during the Late Cambrian and earliest Ordovician [1, 28, 29]. However, the controversy of tectonic affinities of the Ordovician basin allows for interpretations as either an intracontinental depression [6] or a foreland basin [1, 25], as well as subduction to collisional depression [9, 10], thus prevent clear linking of the simultaneous orogenesis effects to progressive deformation from southeast to northwest during early Late Neoproterozoic to early Paleozoic [19, 30].

To gain a better understanding of early Paleozoic orogenesis and basin coevolution in South China Block and their relationships to the assemblage of Gondwana, we outline the sequence stratigraphy and provenance records from the Ordovician strata in the central-upper Yangtze Block to track the development and characteristics of the early Paleozoic orogenic event in the context of the final assemblage of the Gondwana.

2. Geological Setting

The South China Block located in East Asia is classically separated by the Jiang-Shao fault into two tectonic domains: the Yangtze Block (northwest) and the Cathaysia Block (southeast) (Figure 1). Transition between the two blocks is occupied by Early Neoproterozoic strata in the Jiangnan-Xuefeng Shan orogenic belt that transformed into an intracontinental rift with the Late Neoproterozoic breakup of Rodinia supercontinent [18, 23, 31].

Westward transit of Ordovician successions from siliciclastic dominated in the Cathaysia Block to mixed platform carbonate and siliciclastic rocks in the Yangtze Block [23, 32]. The eastern Yangtze Block between Anhua-Luocheng and Jiang-Shao faults are filled by the semi-deep to deep water black shales in the lower part and limestone in the upper part during the Ordovician. Provenance indicators show detrital clasts were transported from southeast to northwest, implying existence of a paleohighland in easternmost Cathaysia Block [3, 23, 28], while sporadically exposed limestone and clastic rocks dominated Ordovician succession in the upper and central Yangtze Block.

Diachronous deformation and metamorphism, and granite intrusion of the pre-Devonian succession, are mainly concentrated between the Anhua-Luocheng fault in the Yangtze Block and Zhenghe-Dapu fault in the Cathaysia Block [6, 23]. Unconformities between the Cambrian and Ordovician successions in the Yunkai area suggest that the Early Paleozoic orogeny in Cathaysia was the response of Pan-Africa Events [1, 29], characterized by coeval reactivation of the Jiang-Shao fault, metamorphism, and sporadic migmatite and gneissic granites as early as 530-480 Ma [7, 33, 34]. Coincidentally, this unconformable relationship was also observed in the western margin of the Yangtze Block [19, 30] and revealed by seismic profiles in the Sichuan Basin.

Sedimentary, magmatic, and metamorphic records described above were subsequently overprinted by the early Paleozoic Kwangsian Orogeny which expanded westward to the Jiangnan belt in the central-upper Yangtze Block [6, 25]. Unconformities between Ordovician and Silurian, and between Silurian and Devonian strata, are expressed in the Yunkai and Xuefeng Shan regions, where large-scale magmatic and metamorphic events continued from >460 Ma to 400 Ma, systematically younger from east to west ([6, 7] and references therein).

3. Methods

3.1. Framework of Ordovician Sequence Stratigraphy. For an integrated framework of Ordovician sequence stratigraphy in the central-upper Yangtze Block, we correlated 37 lithostratigraphic units from different stratigraphic zones (Figures 2, S1, S2). On this basis, the 10 measured sections combined with 227 other field observations, 118 boreholes, and main seismic profiles (about 1.3×10^5 km long) (Figure 1) are used to identify two types of sequence boundaries [35]; type 1 (SB1) is expressed by unconformities marked by significant subaerial erosion and onlap of overlying strata, while type 2 (SB2) is characterized as the lithological transform surfaces or limited subaerial erosion associated with relative sea level variation. The sequence stratigraphic framework was established by two cross-well profiles in the central-upper Yangtze Block to analyze isochronous maps and the spatial-temporally depositional paleotopography in the Ordovician.

3.2. Modal Sandstone Petrology and Sandstone Ratio. The measured Xinjigu section in the southwestern margin of the upper Yangtze Block comprises more than 440 m of sandstone, siltstone, and sandy dolostone. Modal framework grain compositions of 42 samples of medium- to coarse-grained sandstones from the section were determined by point-counting standard thin sections according to the Gazzi-Dickinson method [36].

Analysis of sandstone content in total thickness of the sequence is an effective method for evaluating the paleodrainages and depositional environments. Sandstone thickness ratios in the third-order sequence were extracted by logging and electrical characteristics from boreholes and direct outcrop measurement. Then, the ratios of sandstone to other lithologies in each sequence were mapped to shed light on the distributary variations in each sequence.

3.3. Zircon U-Pb Dating. We collected four sandstone samples from the lower Ordovician Hungshihyen Formation

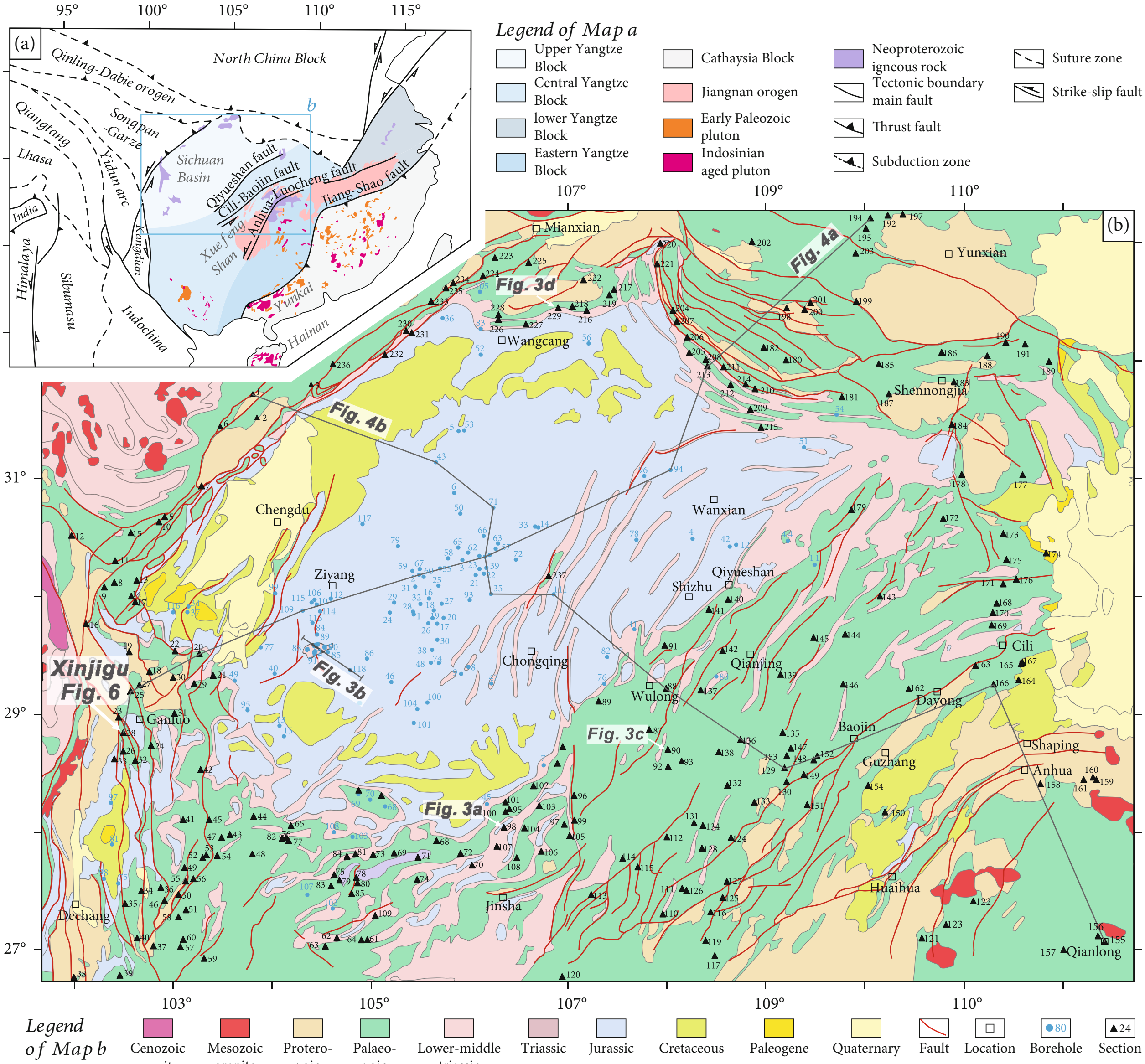

FIGURE 1: Geological setting of the central-upper Yangtze Block in the South China Block. (a) Tectonic map of South China Block and its adjacent regions. (b) Geological map of the central-upper Yangtze Block. The numbers represent the sites of boreholes and sections that are listed in Table S1.

(XJG-102.4 and XJG-175) and upper Ordovician Taching Formation (XJG-806 and XJG-836) for zircon U-Pb dating (Figures 3(a) and 3(c)). U-Pb geochronology of zircon was conducted by LA-ICPMS at the laboratory of carbonate sedimentary and diagenetic geochemistry, Southwest Petroleum University. Analysis involved ablation of zircon with a New Wave 193 nm UC Excimer laser by a spot of 35 μm, 8 Hz repetition rate, and 4-5 J/cm^2 energy. For each analysis, raw count rates of ^{29}Si, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th, and ^{238}U were collected for age determination. ^{29}Si and NIST SRM 610 were used as internal and external standards, respectively, to calibrate concentrations of U, Th, and Pb. U-Pb ages were calculated using Iolite 4.0 and calibrated for both instrumental mass bias and isotopic fractionation against zircon standard 91500. The reported uncertainty at the 1σ for both ^{206}Pb/^{238}U and ^{206}Pb/^{207}Pb involved only internal errors for individual analyses.

The discordant was accepted within ~20% for each analysis which included most of the age information from each sample to yield a more complete and accurate assessment of provenance components. The results are shown on age-distribution plots from Isoplot 4.15 [37] and are made from an Excel program that normalizes each curve based on the number of consistent analyses [38].

4. Sedimentology

Based on sequence boundary types, the Ordovician succession in the central-upper Yangtze Block is partitioned into three second-order sequences (SSQ1 to SSQ3) and six

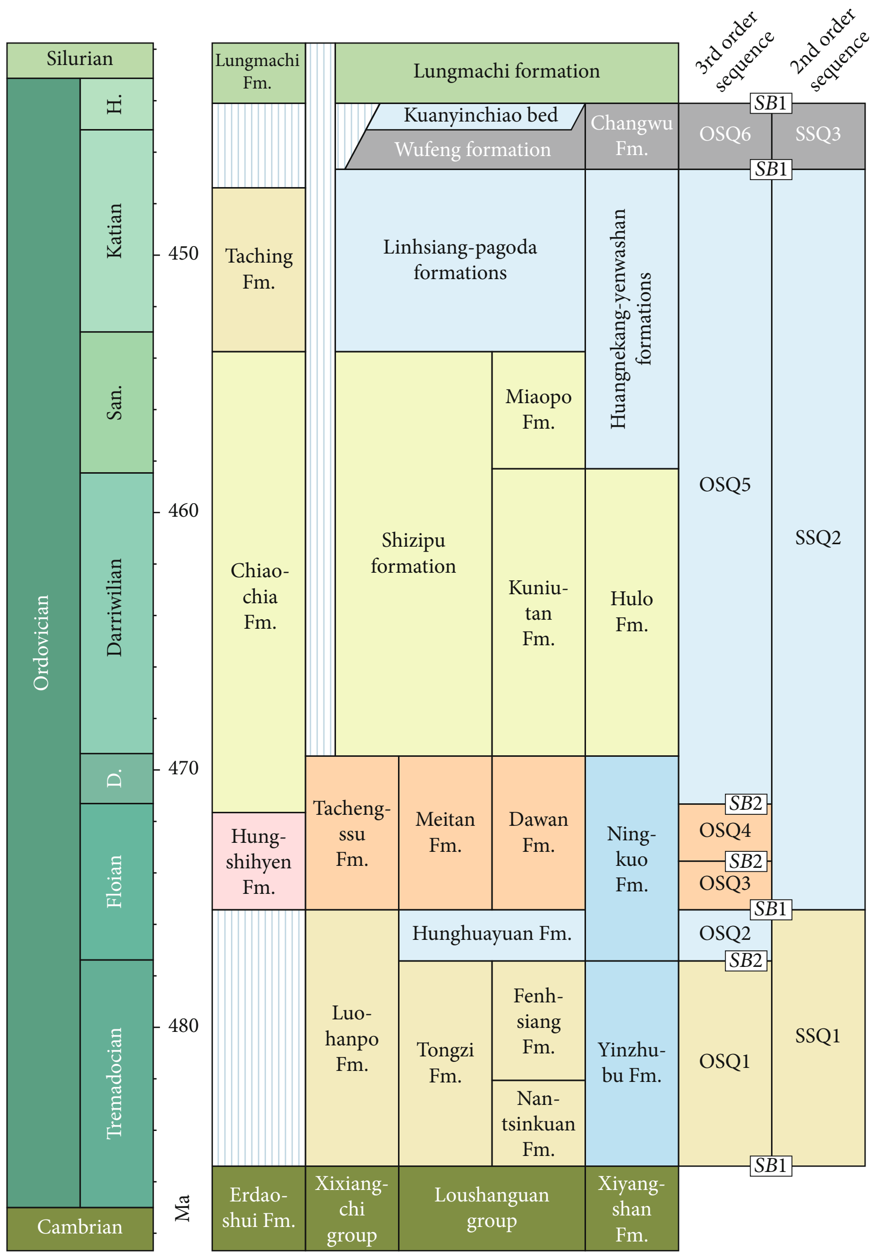

Figure 2: Chrono-, litho-, and sequence stratigraphy in the central-upper Yangtze Block [32]. D: Dapingian; San: Sandbian: H: Hirnantian; Fm: Formation. Please see Figure 5, Figure S1, Figure S2, and the text for more details.

third-order sequences (OSQ1 to OSQ6) by four type 1 and three type 2 boundaries (Figures 2, 4, S1, S2). With the thicknesses and lithofacies associations of the sequences, the Ordovician succession in the central is overall characterized by limestones, marls, and shales with thickness ranging from 300 to 500 m (Figure 5). The southwestern Yangtze Block at Kangdian-Qianzhong areas lacks early stage deposition and contains coastal or shallow marine sediments and mixed platform limestones in the lower-upper parts. The central-upper Yangtze Block has predominant platform limestones, mudstones, and siltstones.

4.1. Sequence OSQ1. The sequence OSQ1 unconformably overlies the Cambrian succession with a type 1 boundary and terminates at a type 2 boundary (Figure 2). The type 1 boundary is evidenced by an uneven erosion surface in the field (Figure 4(a)) and OSQ1 progressively onlaps the Cambrian succession, representing a continuous transgressive episode of the SSQ1 (Figure 4(b)). The type 2 boundary atop the OSQ1 is identified by lithofacies transformation from the dolomicrite to micritic limestone (Figure 5).

The thickness of OSQ1 spatially decreases from >400 m at the west of Xuefeng Shan to 0 m at the margins of western Sichuan, Kangdian-Qianzhong, and Shennongjia areas (Figure 6(a)). Isopach contours are generally elongated northeast where relatively thin strata correspond to belts of oolitic and bioclastic limestones. At the northern and eastern margins of the central-upper Yangtze Block,

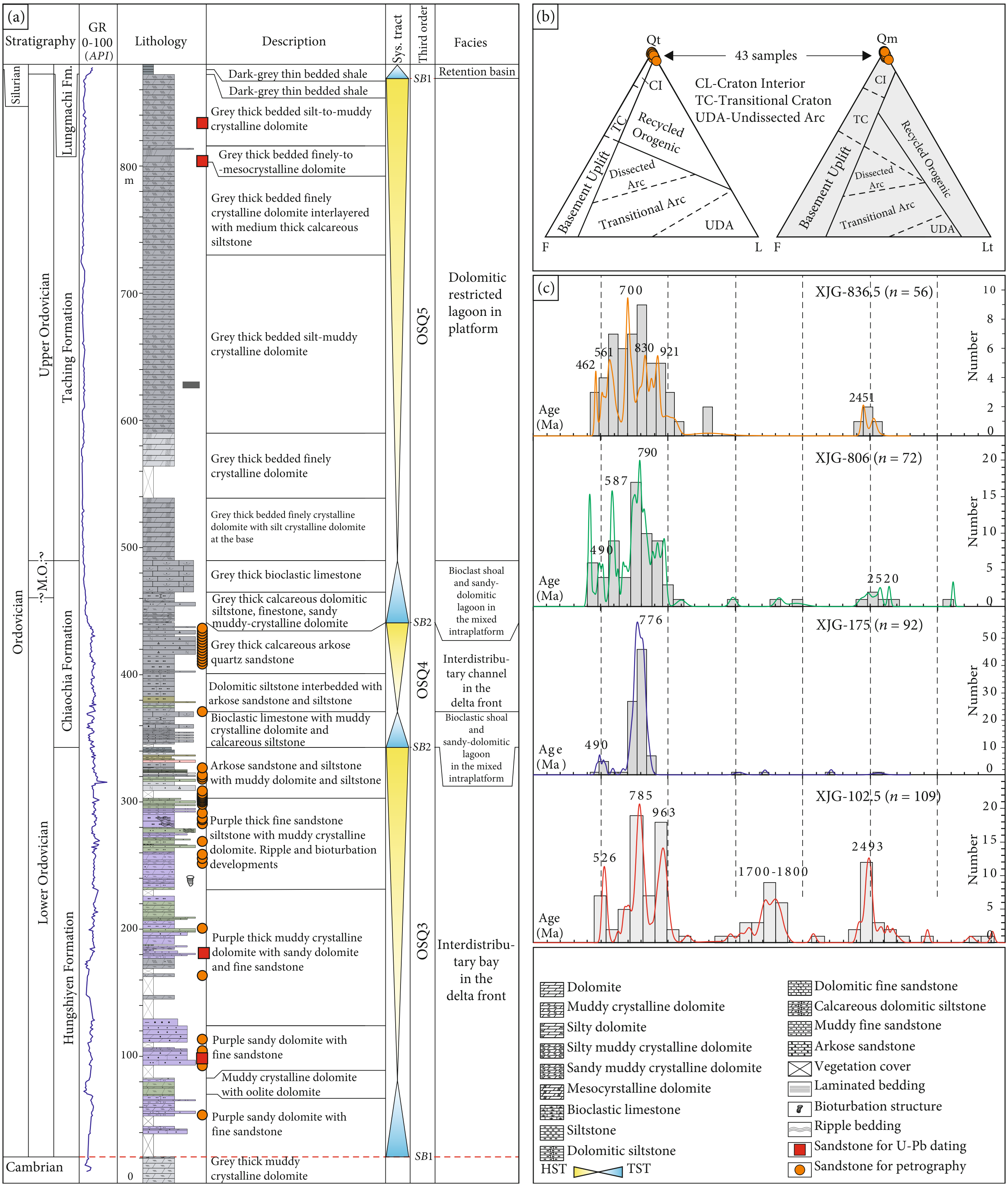

Figure 3: Interpretations of the Ordovician section at Xinjigu site. (a) Integrated sequence stratigraphic column. (b) Qm-F-Lt and Qt-F-L triangular diagrams of sandstones of the Xinjigu section. (c) U-Pb age spectrum of detrital zircons of sandstones from the section.

OSQ1 thicknesses increase outward to more than 200 m, which consists of thin-bedded micrites and argillecious micrites (Figure 5). Along the present Xuefeng Shan domain, OSQ1 was partly eroded.

We interpret OSQ1 sediments were mainly deposited in a protected to semi-protected carbonate platform (Figure 6(a)). Oolitic and bioclastic deposits were products of reefal and shoal environments with relatively shallow

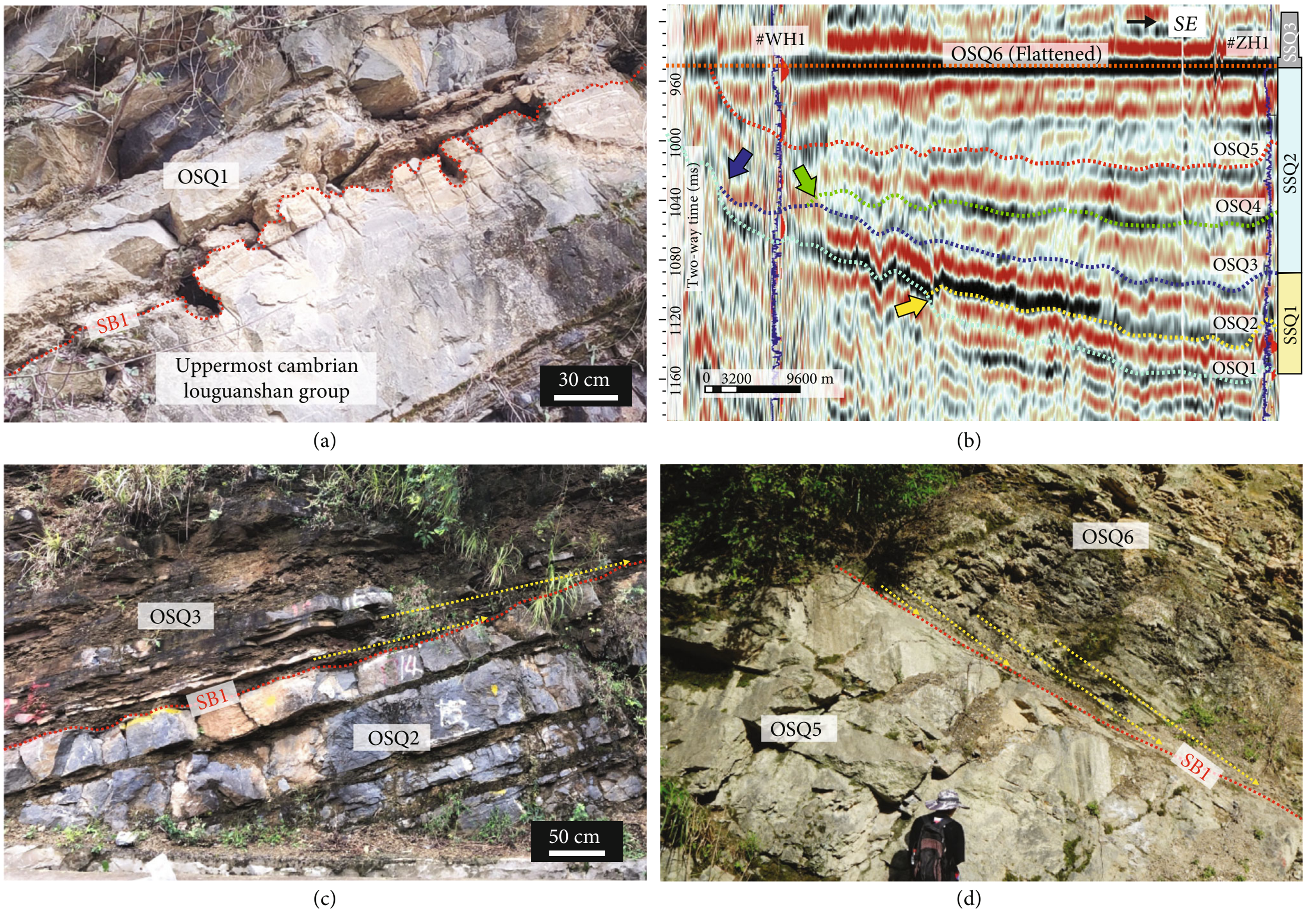

Figure 4: Typical sequence boundaries shown in outcrops and seismic profile. (a) The type I sequence boundary at the base of the Ordovician succession from the Houtan section which is expressed as erosional surface of the paleo-karst (red dotted line). (b) The seismic profile shows the OSQ1 (yellow arrow) and OSQ2 (blue arrow) onlap the underlain Cambrian succession, which are in turn onlapped by the OSQ3 (green arrow). The profile position is shown in Figure 1(b). (c) An angular unconformity indicates a type I sequence boundary between OSQ2 and OSQ3 at Sanquan section. (d) The type I sequence boundary is characterized as an angular unconformity between OSQ5 and OSQ6 at Shatan section. Scaled by a person.

and agitated condition, while the micrites were developed in the lower-energetical and relatively deep sags. Argillaceous dolostone and siliciclastic rocks were deposited in tidal flat and shoreline environments. Mudstones and slates are considered deposits in the shelf and slope. Paleohighlands in the west of central-upper Yangtze and Shennongjia regions are inheritance of the late Cambrian paleogeography, indicating a depositional hiatus. In contrast, the present Xuefeng Shan area may be an underwater paleouplift where the OSQ1 sequence may have been moved away by the late-stage uplifting and denudation.

4.2. Sequence OSQ2. OSQ2 is composed of lower Floian sediments with a type 1 sequence boundary atop (Figure 2), which is evidenced by the onlapping of OSQ3 to the west (Figure 4(b)) and the slightly angular unconformity in the field (Figure 4(c)). OSQ2 shares similar lithological associations and isopachous distributions with OSQ1 but has a higher proportion of limestones and a broader depositional area (Figures 5 and 6(b)). Specifically, the Shennongjia area was emerged and accumulated < 60 m thick sediments.

OSQ2 is interpreted to have been deposited in a semi-protected to open carbonate platform inheriting OSQ1 paleotopography (Figure 6(b)). Continuous transgression of SSQ1, however, resulted in horizontal facies being thinner in distribution and retreating westward while the platform became more open. Shelf and slope facies continuously developed in the northern and eastern margin of the central-upper Yangtze Block to accumulate thick mudstones and shales.

4.3. Sequence OSQ3. OSQ3 consists of middle-upper Floian deposits with type 2 sequence boundary atop (Figure 2) and onlaps the underlying sequence (Figures 4(b) and 4(c)). The lithological association and distribution are significantly different from the underlying OSQ2 (Figures 5 and 6(c)). Thick fine sandstones and dolomitic siltstones are more than 600 m thick in the southwestern Yangtze Block. Siliciclastic rocks gradually transit into bioclastic limestone interbedded with gray shales towards center and east with thickness correspondingly decreasing to 100 m on average. Outside the northern margin of the Yangtze Block, the

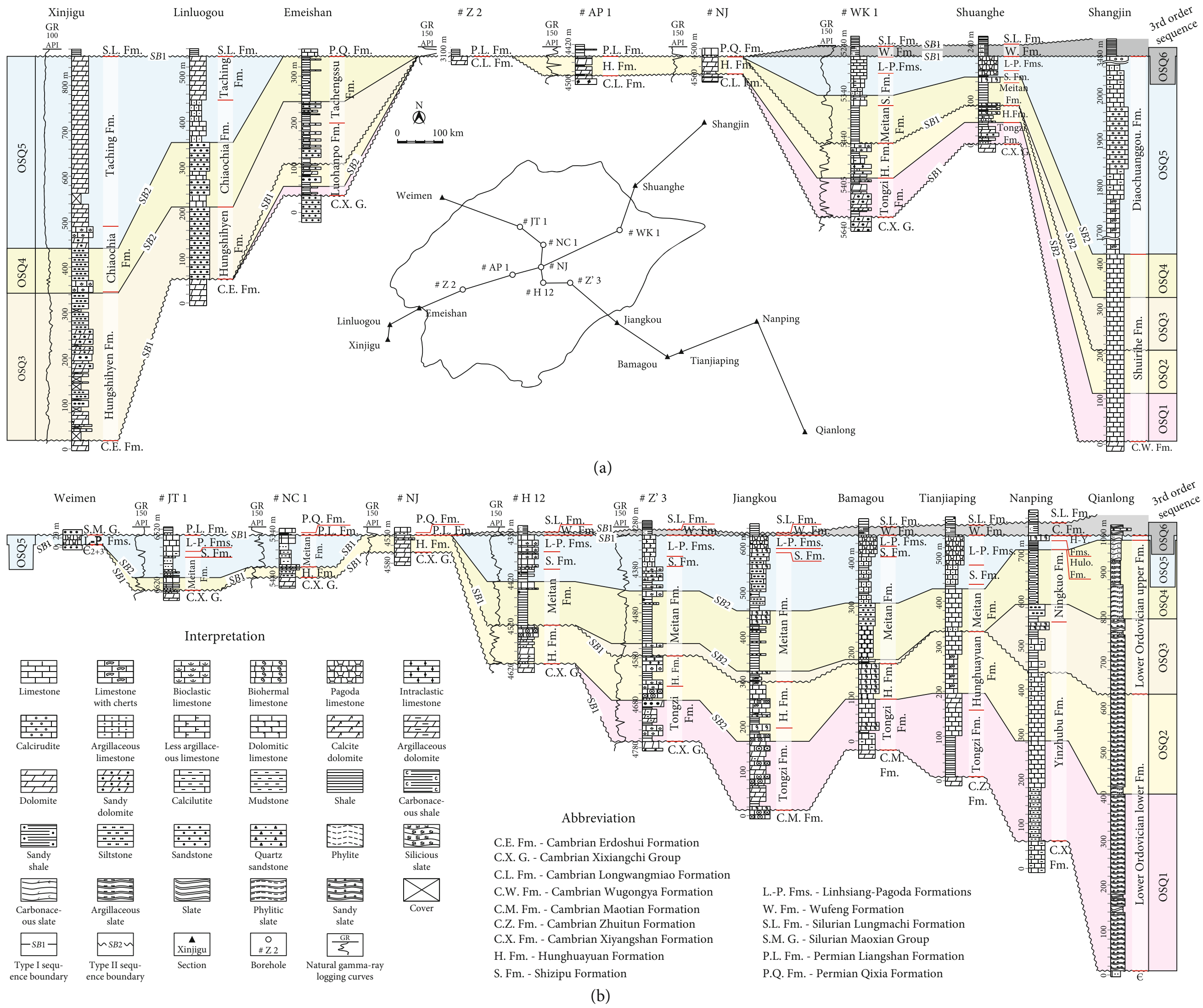

Figure 5: Sequence stratigraphic correlation profiles across the central-upper Yangtze Block. (a) SW-NE profile. (b) NW-SE profile. The positions of profiles are shown in Figure 1(b).

sequence increases over 200 m in thickness and consists of argillaceous limestones, sandy limestones, and shales. This is different from the lithological association to the east of the Xuefeng Shan where shales with thickness of maximum 400 m were deposited. However, the sequence is absent from the central-western Sichuan to the Shennongjia areas, as well as the Xuefeng Shan area.

We interpret OSQ3 to have been deposited in a mixed siliciclastic-carbonate platform during the early stage of SSQ2 transgression (Figure 6(c)). The northern part of central-upper Yangtze Block and Xuefeng Shan domain were significantly uplifted and siltstones and mudstones were deposited in the tidal environment. The southern part of central-upper Yangtze Block was a mixed carbonate platform surrounded by the elevated areas. Shelf and slope were still preserved in the northern and eastern margin of central-upper Yangtze Block. It is noted that the thick siliciclastic rocks were filled in the southwest of the central-upper Yangtze Block implicating a new depression for mega-deltaic deposits filling. It is different from the Indosinian foreland in southwestern China [13], instead of being likely associated with the compression from the southwest.

4.4. Sequence OSQ4. OSQ4 comprises upper Florian sediments, separated from the conformably overlying OSQ5 by a type 2 sequence boundary (Figure 2). OSQ4 lithologies vary from southwest to northeast (Figure 6(d)). Coarse to fine sandstone dominates in the southwestern corner of the Yangtze Block. The Xinjigu section exposes ~100 m thick-bedded sandstone with abundant feldspar and quartz clasts (Figure 3). This unit spreads westward to the Huaihua area decreasing in clastic grain size and increasing in carbonate content. To the central and eastern parts, sediments gradually pass into brownish mudstones interbedded with bioclastic limestones. Nodular, micritic, and bioclastic limestones dominate in the northern and northeastern part with gray-green shales and rare mudstones; and sequence thickness gradually reduced from more than 200 m in the southwest

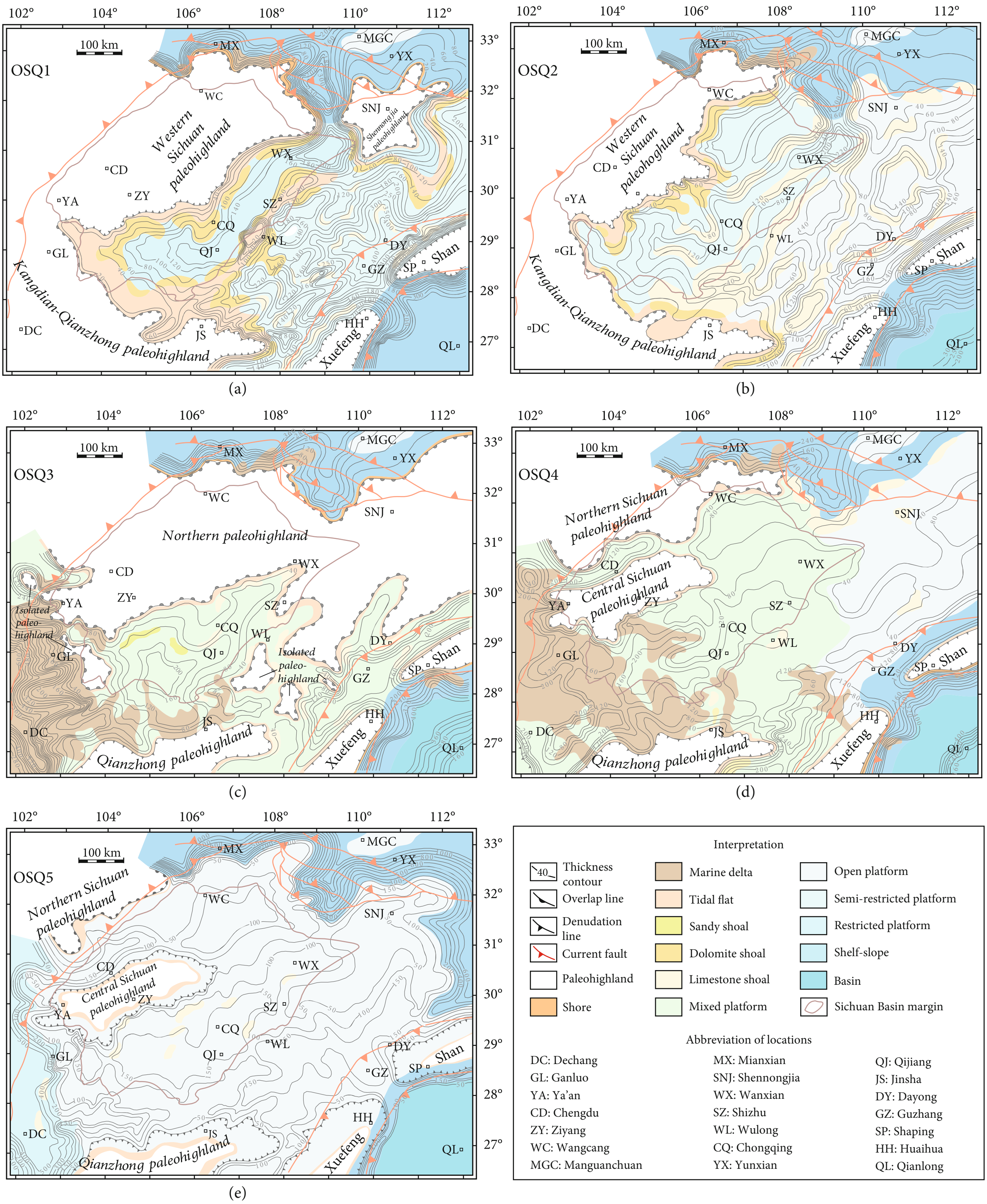

Figure 6: Paleogeographic maps from the OSQ1 to OSQ5 illustrating the evolution of Ordovician depositional environments in the central-upper Yangtze Block.

to less than 40 m in the northeast. In the east of the Xuefeng Shan, lithofacies is the sandy shale interbedded with argillaceous shale with thickness eastward varying from 160 to 400 m.

OSQ4 was interpreted as mixed siliciclastic-carbonate platform sediments during transgression of SSQ2 (Figure 6(d)). Erosional areas were sharply submerged, with only western margin of the Yangtze Block and Xuefeng Shan Domain left to form isolated islands. The submerged northeast is dominated by micrites and bioclastic limestones indicating an open carbonate environment, whereas the shales and limestones in the central-east region represent a mixed terrigenous-carbonate platform. A large volume of sandstone in the southern part was the product of mega-deltas within a continuously expanding depression. Inheriting the previous sedimentary environment, the northern and eastern margins were the relatively stable shelf and slope environments.

4.5. Sequence OSQ5. OSQ5 consisting of Dapingian, Darriwilian, Sandbian, and lower Katian sediments unconformably underlies the OSQ6 with a type 1 sequence boundary (Figure 2). OSQ5 occupies most of the central-upper Yangtze Block except for several isolated paleohighlands, representing the maximum depositional range during the Ordovician (Figure 6(e)). Lithological associations and distributions are consistent and variable in the central-upper Yangtze Block. In the southwest, OSQ5 comprises dolostones, bioclastic limestones, and sandstones of the upper Chiaochia and Taching formations, and varies in thickness ranging from 100 to 500 m laterally. To the east, these thick sediments pass into the 80 to 150 m thick association of argillaceous and bioclastic limestones. The thin-bedded (siliceous) shales still appear outside of the northern Yangtze Block and to the east of Xuefeng Shan Domain with thicknesses of more than 1000 m and less than 100 m, respectively. It is worthy to be noted that a few previous studies divided the OSQ5 into three third-order sequences by difining the top surfaces of the Meitan and Shizipu formations as sequence boundaries (i.e., [39, 40]). However, the two boundaries are not unconfomities and do not significantly modify the variation trends of both natural gamma curves and lithological facies (Figure 5); if the boundaries are sequence boundaries, they would be lower than the third-order.

OSQ5 is interpreted as a relatively pure carbonate platform during the maximum SSQ2 transgression (Figure 6(e)). Most areas were open platform except the restricted platform in the southwest where abundant dolostones are deposited. The shelf, slope, and basin facies continued to develop in the northernmost and easternmost areas. The extremely thin QSQ5 consisting of siliceous shale in the Qianlong area <100 m thick indicates starving of deposition in the easternmost basin, which is consistent with the maximum transgression.

4.6. Sequence OSQ6. OSQ6 consists of the upper Katian Wufeng Formation and the lower-middle Hirnantian Kuanyinchiao Bed in the central-upper Yangtze Block (Figure 2). Based on the discontinuity of graptolite zones between OSQ6 and the overlying Lungmachi Formation [41], a type 1 boundary atop OSQ6 is identified. The Wufeng Formation comprises thin-bedded black carbonaceous shales with a few siliceous interlayers, and the Kuanyinchiao Bed is characterized as <1 m thick shell-bearing argillaceous limestone. The thickness of OSQ6 ranges from 0 to 30 m in mostly central-upper Yangtze Block and increases to several hundred meters outside of the central-upper Yangtze Block (Figure 5). We interpret the shales are products of a quiet and restricted environment. On the contrary, the interlayered Kuanyinchiao Bed accumulated in shallower and ventilated seawater [41].

5. Provenance

5.1. Petrographic Data. Principal grain types from the Xinjigu section include monocrystalline (Qm, >95%) and small amounts of polycrystalline, feldspar, and lithic grains (Figure S3a). Lithic grains include mainly limestones, micas, and schists (Figure S3b). Figure 3(b) plots modal petrographic data. All sandstone compositions except two fall into quartzose group and plot within the stable craton interior provenance field. The other two samples from the middle-upper Ordovician succession are included into the quartzose-lithic group and plot within the recycle orogen provenance fields [42].

5.2. Terrigenous Clasts Distribution. Isopach maps of ratio of sandstone to sequence thickness allow assessment of distribution and propagation of sandstone bodies (Figure 7). The OSQ1 and OSQ2 sandstones were distributed as single bodies surrounding the paleohighland margins and thinned sharply into the central platform with sandstone sequence ratios decreasing from 0.8 to 0.2. Sandy deposits show reduction of the areas and ratios eastwards.

A large volume of the sand bodies is mainly concentrated in the southwestern Yangtze Block and a small amount occurs in the northern and eastern parts in OSQ3 and OSQ4. The southwestern Yangtze Block accumulated over 500 m thick sandstone beds in total, laterally extended as figure-like propagation to northeastward with the sandstone ratio decreasing from 0.8 to 0.2.

5.3. Detrital Zircon Ages. 229 zircon U-Pb data were obtained from four samples at Xinjigu section (Figure 3(c)). Zircon grains from the Hungshihyen Formation (XJG-102.5 and XJG-175) are subhedral or rounded crystals, generally 100-300 μm long, and oscillatory zoning in CL images. Sample XJG-102.5 gave 109 concordant U-Pb ages with Th/U ratios ranging from 0.2 to 5.3 (except two data), suggesting a magmatic origin. Age spectra show concordant ages mainly group as 2700-2400 Ma, 1800-1500 Ma, 1000-700 Ma, and 550-512 Ma. The 118 ages of sample XJG-175 display bimodal spectra with a prominent peak of 776 Ma and subordinate peak of 490 Ma. Th/U ratios ranging from 0.45 to 3.5 suggest magmatic origin that is consistent with biotite clasts in this sample (Figure S3b). The youngest age of 469 Ma constrains the maximum depositional timing of the Hungshihyen Formation during the Floian and Dapingian ages.

Zircon grains from the Taching Formation are generally 60-200 μm in length and display euhedral and subhedral morphology. CL images show both oscillatory zoning and homogeneous structures. The 72 zircon grains from the sample XJG806 gave concordant ages. Although the zircons with oscillatory zoning and Th/U ratios of 0.09-2.38 suggest a magmatic origin, six zircon grains with ages younger than

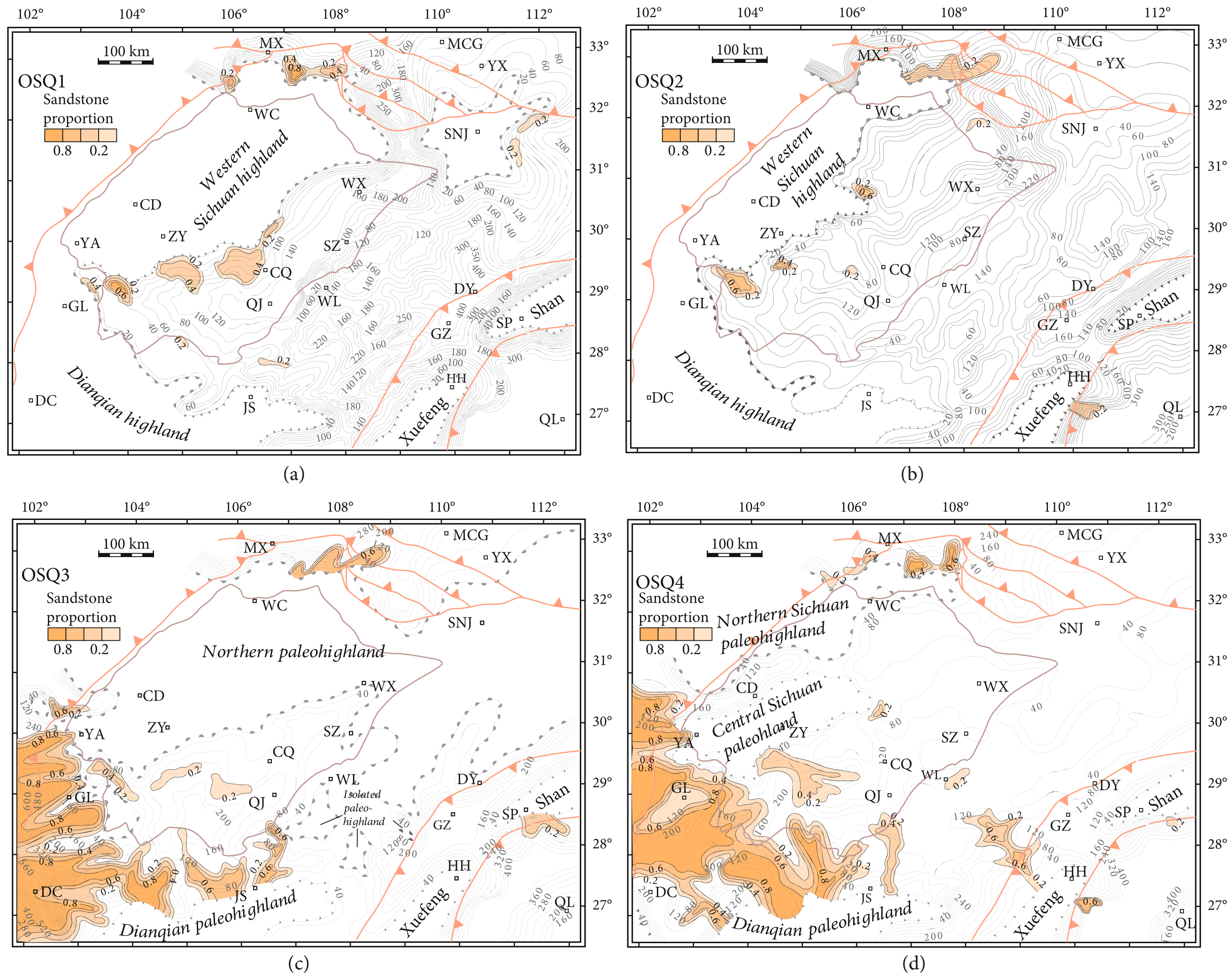

FIGURE 7: Isopachous maps of the sandstone proportion in OSQ1 (a), OSQ2 (b), OSQ3 (c), and OSQ4 (d).

445 Ma with Th/U ratio of 0.57-0.89 are inferred to indicate radioactive daughter Pb loss during Caledonian metamorphism or magmatism. The remaining 66 zircon U-Pb ages fall between 3119 Ma and 487 Ma with 3 peaks of 2520 Ma, 790 Ma, 587 Ma, and 490 Ma. Sample XJG-836.5 shows a similar age pattern with an older peak age of 2451 Ma and two age clusters of 950-700 Ma and 570-487 Ma. Two zircon grains yield youngest ages of 463 and 460 Ma, inferring the depositional timing of the Taching Formation was younger than Darriwilian age.

6. Discussion

6.1. Basin Architecture. High-resolution isopachs of the Ordovician sequence stratigraphy and depositional distributions provide critical information on the spatial-temporal tectono-lithofacies and paleogeography reconstruction in the central-upper Yangtze Block (Figure 6). The central-upper Yangtze basin was filled by four distinct depositional systems: a shoreface system propagation into delta and mixed tidal flat in the western and southwestern basin; an open carbonate platform connected to a slope-basin system in the central, northern, and eastern basin. Thickness variations in OSQ1 to OSQ5 indicate a structural folding system expressed by thicknesses varying from 20 to 400 m with wavelength of ~100 km. The folding system exhibits a thin-skin tectonic propagation from Xuefeng Shan domain in the southeast to the Cambrian-Ordovician paleohighland in the northwest. Their fold axes are parallel and extend northeast over hundreds of kilometers. The main depocenters of each sequence are preserved in the Guzhang-Dayong areas close to the western flank of the Xuefeng Shan domain but the accumulated thicknesses gradually decrease from over 400 m during the OSQ1 and OSQ2 time to less than 150 m in the OSQ3 to OSQ5 time. This thickness decrease is accompanied with a new depocenter formed in the Dechang-Xichang areas with thickness more than 1200 m, probably relating to the reactivation of compression and resulted in the NW-SE elongated uplift and depression alternately that were superposed upon the contemporaneous NE-trending structures in the southwest margin of the Yangtze Block.

A second key feature of the Ordovician succession is that it rests unconformably directly upon Cambrian basement rocks without fault contact or structural disruption. Seismic profiles also reveal sequences OSQ1 to OSQ5 progressively onlapped the uplifted basement rocks in the western margin of the Yangtze Block, in a westward direction, where sequences OSQ1 and OSQ2 were generally absent and sequence OSQ3 directly unconformably overlies deformed late Cambrian strata (Figures 4(b) and 5). This tectonic regime resulted in the thickness of each isochronous sequence gradually reducing from southeast to northwest and contributed coastal and deltaic sediments with terrestrial detritus deposited surrounding the central-upper Yangtze Block.

6.2. Provenance and Paleogeographic Implications. Based on sedimentological analysis, the central-upper Yangtze Block was mainly a carbonate platform, but some clastic rocks accumulated in its southwestern margin and continental shelf-slope deposits in the northern and eastern margins (Figure 6). This variation provides the fingerprints to track source-to-sink relationship and paleogeography of the central-upper Yangtze Block.

Detrital zircon U-Pb geochronology provides a simplest test of the potential sources (Figures 3(c) and 8). Analyzed zircons from the Ordovician strata show age spectra are dominated by Neoproterozoic-early Paleozoic grains between ~1000 Ma and 460 Ma. Only minor Archean (2500 Ma) to Paleoproterozoic (1700-1800 Ma) detritus and lack of Mesoproterozoic zircon detritus occur in these samples.

The lower-middle Ordovician succession exhibits large amounts of rounded quartz, thus compositionally and texturally mature (Figure S3b, XJG-102.5), which are in contrast to the sandstones in the upper Ordovician succession that have immature compositions of biotite, lithic grains, and calcic plagioclase and textures of poor sorting and grain sizes up to granule (Figure S3b, XJG-175) [42, 45]. Coupled with the sedimentary structures, mature components indicate deeply weathered and uplifted source areas and long-distance transportation to the southwestern margin of the Yangtze Block (Figure 3(b)). In contrast, immature compositions indicate a basaltic to andesitic volcanic arc in the proximal source highland incised by a longitudinal river system.

Potential sources and transportation directions are indicated by spatial distribution of sand bodies (Figure 7). Sandstone sequence thickness ratios decrease from source to sink thus indicate the propagation direction of sand bodies. Variations of sandstone components in sequences OSQ1 to OSQ4 show that terrigenous detritus mixed into the deltaic and tidal flat environments with drainage networks mainly from paleohighlands in the southwest to coastal plains in the northeast. Intermittent uplift of the Xuefeng Shan and Shennongjia domains during the Ordovician became local and short-lived erosional areas to provide terrigenous materials to their surrounding sags.

The Neoproterozoic age clusters are robustly related to the magmatic events between 1000 Ma and 860 Ma as the results of amalgamation between the Yangtze and Cathaysia blocks along the Jiangshan-Shaoxing Fault [46, 47] and subsequent breakout of the South China block associated with rift-related magmatism and sedimentation between 830 and 745 Ma along the Panxi-Hannan belts [1, 48] (Figure 8). The latter cluster has the dominant ages in the four samples from the Xinjigu section, especially expressed by sample XJG-173.5 with abundant biotite clasts and a prominent age peak of 776 Ma. Considering the paleogeographic position, detrital compositions, and potential source directions, we suggest the Kangdian paleohighland affiliation to the Panxi-Hannan magmatic belt in the western margin of the Yangtze Block provided a major immature detritus mass to the mixed platform deposits on the Yangtze Block during the Ordovician (Figure 9(b)).

The most striking characteristic of our zircon analyses is presence of the Pan-African age peaks of 560 Ma and 490 Ma. Neither tectonic thermal events nor magmatic activity within both ages are known in the South China Block (Figure 8). Although individual metamorphic rocks with age of ~533 Ma have been found in the Wuyi Area [33], the Th/U ratios of these zircons are higher than 0.1 which indicate their magmatic origins and require detrital sources external to the craton. Notably, such ages are comparable with timing of tectonic events in east Gondwana where the magmatic and metamorphic events at 560-520 Ma in the East Africa Orogen and at 530-480 Kuunga Bhimphedian-Orogens associated with India and South China colliding with Australia during the Late Neoproterozoic to early Paleozoic, respectively [1, 23, 43, 49]. The mature quartzose components from these weathered terranes or recycling of quartzose sediments may have experienced long-distance migration and cut the Kangdian paleohighland to transport into the mixed tidal platform and delta in the western margin of the Yangtze Block (Figure 9).

Such distributions of Archean- to Mesoproterozoic-aged detritus are highly similar to the Cryogenian-Ordovician strata in the Tethyan Himalaya of the northern India and Qiangtang terranes ([1, 24, 38] and references therein) but are distinct from the detrital age patterns of time-equivalent strata marked by the Grenvillian orogenic ages about 1300-1100 Ma in the Sanya and Yunkai areas [28, 43, 50]. The absence of Mesoproterozoic detritus from our samples is evidence that the central-upper Yangtze Block has different sources from the eastern Yangtze Block and Cathaysia Block; those may have been derived from East Australia and Yunkai domains, respectively [23, 28].

Therefore, coupling our interpretations of sandstone compositions and distributions, and zircon U-Pb ages provide a paleogeographic link between these orogens through Tethyan Himalaya in northern India craton and Qiangtang terrane in Cimmerian and South China (Figure 9). The evidence supports our interpretation that the South China Block as a microcontinental fragment was located along the western margin of east Gondwana and captured detritus from these sources [1, 3, 5]. The tectonic and paleogeographic regime is further supported by angular unconformities between Cambrian and Ordovician strata that are widely distributed in the eastern Gondwana regions, e.g., Himalaya, Lhasa, Qiangtang, Australia, Yunkai, Sanya, and central-upper Yangtze Block [38, 49, 51, 52].

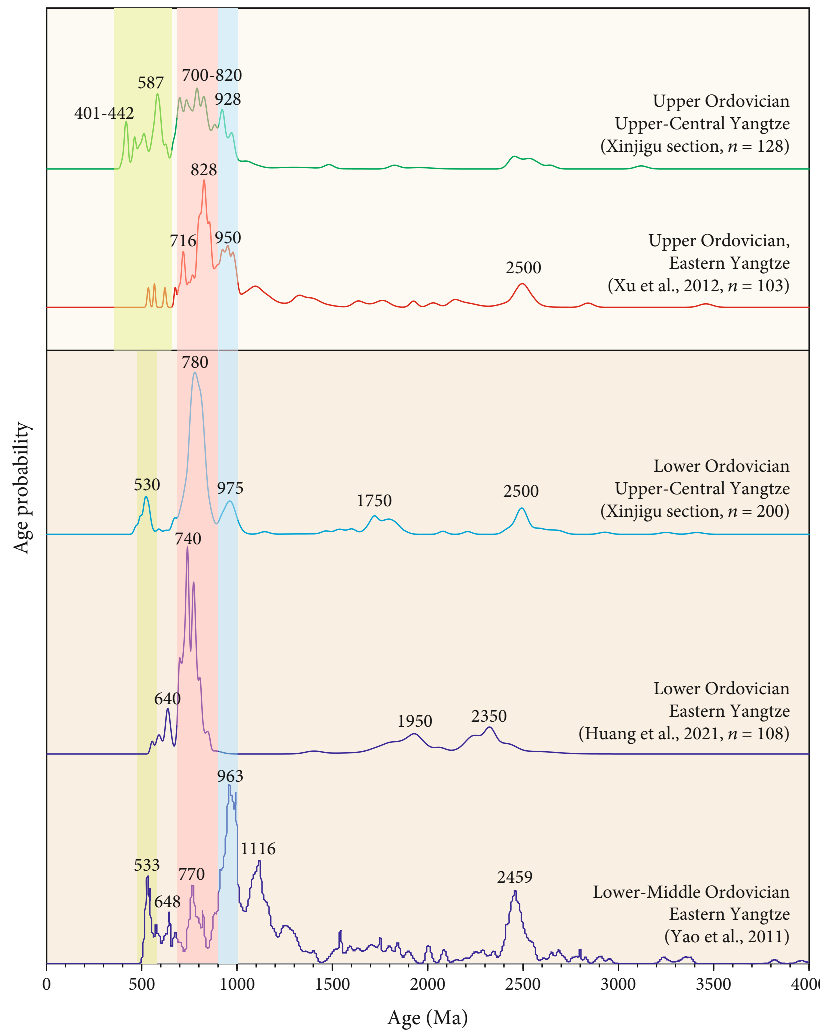

Figure 8: Comparisons of the U-Pb age spectrum of the detrital zircons between central-upper and eastern Yangtze Block. Ordovician detrital zircon U-Pb data from the eastern Yangtze Block from the published literatures [24, 43, 44].

6.3. Unroofing of the Xuefeng Shan Domain. The Xuefeng Shan domain that mainly exposed the Precambrian crystalline basements has been superposed by Caledonian and Indosinian intracontinental orogens in the Phanerozoic [6, 18]. During the Caledonian intracontinental orogeny, syndepositional faults and folds dipping to NW or SE were developed in the eastern Xuefeng Shan domain [44]. Synchronous massive granite emplacement and metamorphism between 467 Ma and 400 Ma with peak age ~440 Ma in the Xuefeng Shan domain to the east of the Anhua-Luocheng fault probably originated in Proterozoic metapelite and metaigneous rocks [6]. Both the deformation and massive granites indicate the crust of the Xuefeng Shan has thickened and continuously uplifted since early Ordovician time [6, 44].

Basin filling processes also revealed the continuous uplift of the Xuefeng Shan domain (Figures 6, S4). Although our isopach maps based on the residual thickness of each sequence show the Xuefeng Shan was an erosional area during the Ordovician, the development of deltaic deposits surrounding the Xuefeng Shan suggests that it did not emerge until OSQ3 was deposited (~470 Ma), which corresponds to the timing of initial massive granite intrusion and crustal deformation [8]. The youngest detrital magmatic zircon grains with U-Pb ages of 463 Ma and 460 Ma from the upper Ordovician sample XJG836.5 further verified such observations due to the absence of contemporaneous magmatism in central-upper Yangtze Block. A similar age cluster has also been found in central Yangtze Block and Cathaysia Block [23], which was considered to derive either from the Xuefeng Shan magmatic belts or the Wuyi-Yunkai orogen. Considering the relatively deep basin in the eastern Xuefeng Shan, the ~460 Ma magmatic zircon grains from Xinjigu section should be derived from only the Xuefeng Shan magmatic belt. This indicates that the Xuefeng Shan domain may have uplifted and unroofed as early as Middle Ordovician time (Figure 10). With continuous uplift of the Xuefeng Shan domain, the depositional depocenter of the central-upper Yangtze Block transited from the western front of the Xuefeng Shan to the southcentral-upper Yangtze Block

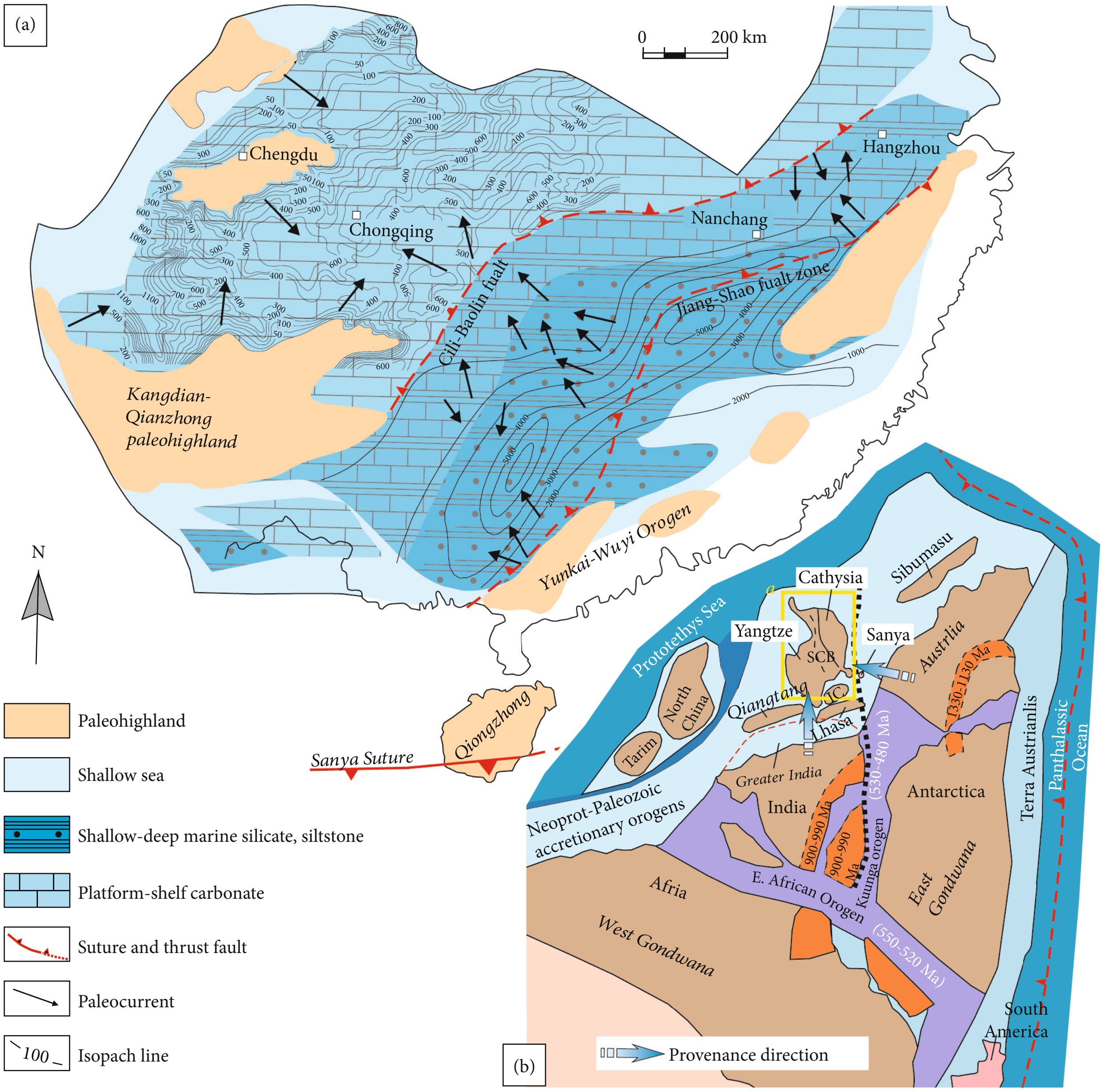

Figure 9: The Ordovician paleogeography of South China in the Gondwana supercontinent. (a) The Ordovician Gondwana paleogeography showing the position of South China located at the western margin of the eastern Gondwana [1, 3, 4, 28]. The blue arrows represent the provenances of the Ordovician succession in South China Block. (b) Paleogeography of South China Block indicates a retroarc foreland system with continuous depositional transition from the mixed silicates and shale in the Cathaysia and eastern Yangtze blocks to the platform carbonates in the central-upper Yangtze Block. Black and green arrows indicate the main provenance sources from the uplifted Wuyi-Yunkai Orogenic belt in the east and outside of the main land in the west (paleocurrent and thickness data in the eastern Yangtze and Cathaysia blocks from [4, 6, 16, 44]).

during the initial depositional timing of OSQ3 (Figure 10). Although the Cenozoic exhumation may play a role in the unroofing of the Xuefeng Shan domain [53, 54], all lines of evidence above indicate the Xuefeng Shan domain was unroofed during the Ordovician.

6.4. Backbulge Basin and Tectonic Regime. Our analysis of the basin filling, architecture, and provenance has revealed that the Ordovician succession was deposited in a continuously contractional setting in the central-upper Yangtze Block (Figures 9 and 10), contrasting previous opinions of stable cratonic platform or intracontinental depression environments [4, 6] or subduction to collision basins [9, 10]. Across the Jiang-Shao fault that was the pre-existing Neoproterozoic suture between Cathaysia and Yangtze blocks, interfingering distributions of the Cambrian-Ordovician terrestrial deposits and siliceous rocks and shales suggest a unified and continuous sedimentary environment [7, 22, 23, 28] (Figure 9(a)), rather than an abrupt sedimentary change by the Paleozoic suturing [20]. Additionally, unconformities

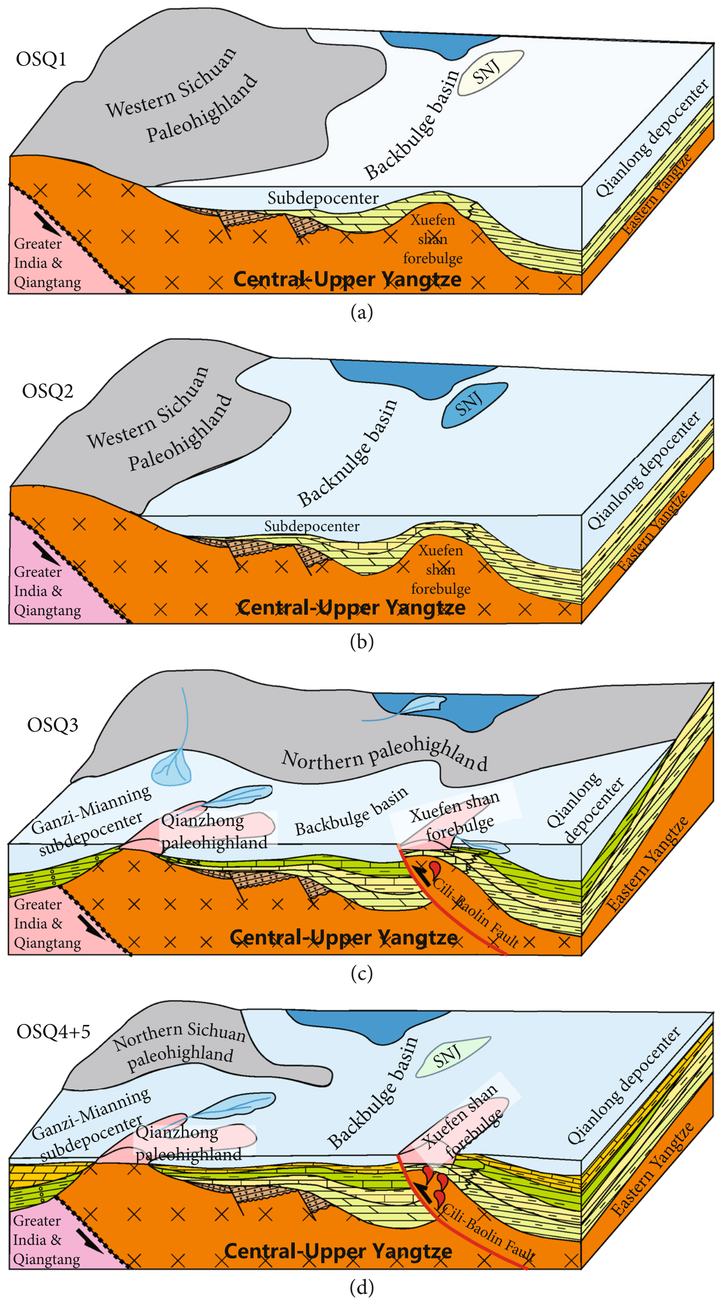

FIGURE 10: The evolution model of retroarc foreland basin system in the Ordovician Yangtze Block. (a) OSQ1. The central Sichuan and Kangdian-Qianzhong paleohighlands inherited the Late Cambrian paleotopography. While the eastern part of the upper Yangtze Block developed a depression with the initially submerged uplift of the Xuefeng Shan as a nascent forebulge. (b) OSQ2. As the SSQ1 transgression, paleohighlands retreated westward and the backbulge basin was down-ward and subsidence with the further uplift and compression of the Xuefeng Shan underwater forebulge. (c) OSQ3. Paleogeography changed significantly. Paleohighlands occurred in the north while the delta deposits rapidly accumulated more than 1000 m in thickness in the southwest probably by the tectonic loading in the southwest part of central-upper Yangtze Block attributed to the sustainably convergence between South China Block and western Gondwana. At the same time, the Xuefeng Shan had finally emerged with thickened crust, magmatic intrusion, and the development of Cili-Baoling Fault (i.e., the Dayong Fault, [55]). The elevated Xuefeng Shan separated the backbulge basin from foredeep basin and may also have prevented detritus from the west of the Yangtze Block (probably from the Tethyan Himalaya in the north of the Greater India) to transport into the foredeep in the eastern Yangtze Block. (d) OSQ4 and OSQ5. As SSQ2 transgression, the northern Paleohighland submerged again and formed the largest depositional areas in the central-upper Yangtze Block. Meanwhile, the Xuefeng Shan uplifted and compressed continuously along with the large volume of magma emplacement.

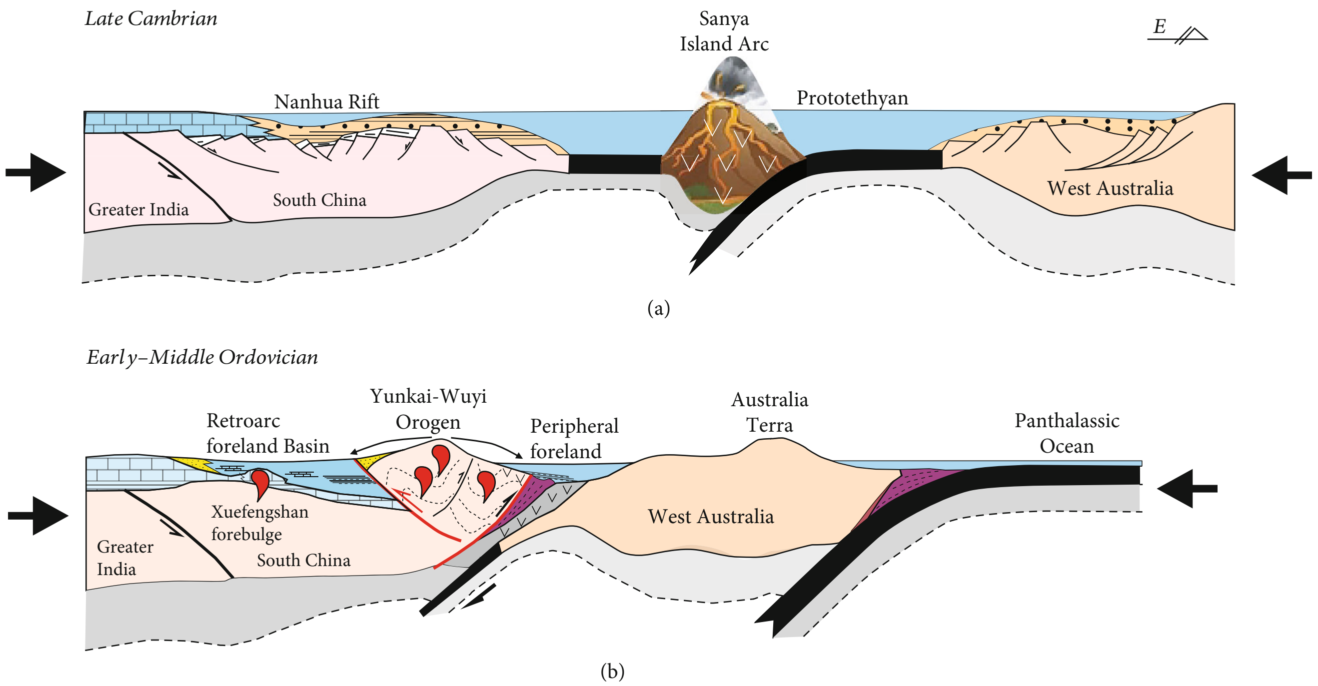

Figure 11: Tectonic model of the South China Block during the Ordovician. (a) During the Late Cambrian, the Prototethyan Ocean subducted the volcanic island arc (e.g., Sanya volcanic island arc, [28]). The South China with a passive continental margin at the eastern margin was filled by the carbonate and siliciclastic rocks in the failed Nahua rift basin. (b) During the Early-Middle Ordovician, the western Australia finally collided with the South China Block along with the Sanya block and formed the Wuyi-Yunkai orogenic belt [33]. A collision-related foreland basin system was developed in the both sides of the Wuyi-Yunkai orogenic belt with peripheral foreland basin on the Sanya block and western Australia and retroarc foreland basin on the South China Block. With the continuous subduction of the Panthalassic Ocean, the South China Block was on-going contracted and reactivated the pre-existence suture zone between the Yangtze and Cathaysia blocks to form the Xuefeng Shan domain as elevated forebulge zone. This process resulted in the stably central-upper Yangtze platform as the backbulge basin finally involved into the evolution of the retroarc foreland basin system.

between the Cambrian and Ordovician not only developed in the Yunkai domain at the conjunction of the Yangtze and Cathaysia but also occurred in the entire Yangtze Block. This indicates that South China Block has widely distributed contemporaneously contractional deformation or sedimentary hiatus, which may have evolved in a similar tectonic regime by the Yunkai Orogeny in the earliest Ordovician.

Lithofacies associations across South China continuously propagated westward from the slope facies with abundant of the terrestrial clasts supplied from the Cathaysia paleohighlands in the eastern margin of the eastern Yangtze Block [56] into the basin environment with shallow water structures [8, 44] in the middle part of the eastern Yangtze Block (Figure 9(a)). To the west, slope facies (our study area) occurred again in the eastern limb of the Xuefeng Shan domain and gradually passed into the platform facies with detrital clasts mainly from western paleouplifts in the central-upper Yangtze Block (Figure 6). Continuous facies transitions were also accordant with the continuous graptolite facies zone changes [41]. Detrital zircon assemblages of the early Paleozoic succession (Cambrian to Ordovician) in both sides of the Xuefeng Shan domain provide additional evidence that there was no Huanan Ocean to separate the two continents [6, 24, 43]. The inherited Cambrian Cathaysia orogen and paleohighland, as well as the continuously uplifted Xuefeng Shan domain in the central-upper Yangtze Block, provided detrital clasts in the basin.

Therefore, the entire South China Block was in a unified tectonic and depositional system during the Ordovician, which was involved with broad syn-tectonic belts, aged 530-470 Ma, of the Bhimphedian and Kuunga orogens along western Australia in response to the final amalgamation of India, South China, and Cimmeria with eastern Gondwana (Figures 9(b) and 10) [5, 23, 49]. This location allowed the earliest Paleozoic successions from the South China Block to share similar detrital zircon U-Pb age patterns with equivalent strata from Qiangtang, Tethyan Himalaya, and Indochina that are also evolved in these orogens [23]. However, the Cambrian successions from the Sanya block containing the detrital zircon U-Pb ages is accordant with the Meso-Protozoic Northampton complex in western Australia [1, 28], while the overlying Ordovician succession showed input of detrital zircons from the adjacent arc-related magmatic belt in the Hainan area (Figures 9(b) and 10) [57, 58]. The change of source areas in the Sanya area indicated collision between the Sanya block, as well as western Australia and the South China Block in the southeast margin during earliest Ordovician and formed a peripheral foreland basin [24, 59, 60] (Figure 11). In response to the convergence, the South China Block correspondingly changed from the Precambrian failed rift basin into a retroarc foreland basin system, resulting in forming the unconformity between the Cambrian and Ordovician successions, magmatism, and metamorphism along the southeastern margin of the present South China Block [6, 7, 9] (Figure 11). The foredeep with total thickness more than 5000 m was developed in front of the Yunkai-Wuyi orogen [4, 43], which became the major source areas of the clastic sediments in the retroarc foreland basin (Figure 9(c)). The Xuefeng Shan domain as the pre-existence of the Neoproterozoic suture zone between Yangtze and Cathaysia blocks [18] tectonically inverted from a rift basin to a compressional magmatic belt (470-410 Ma), which likely reflects the far-field effects in response to the propagated convergence between the South China Block and Australia driven by the eastward subduction of the Panthalassic Ocean [27] (Figure 11). The geochemical data indicated these intrusions mainly originated from the thickened Paleoproterozoic basement [6, 8] indicating a Xuefeng Shan domain crustal thickening and topographic uplifting to become the backbulge of the retroarc foreland basin system. Thus, the Xuefeng Shan domain not only prevented the detritus of the Tethyan Himalaya from being transported into the eastern Yangtze Block, e.g., quartz clasts and detrital zircons in the Cambrian from the northern India [61] but also provided detrital clasts into both sides of the depressions, e.g., ~460 Ma zircon grains in both western and eastern Yangtze Block [23, 44]. With the backbulge uplifted, the central-upper Yangtze Block became unstable and developed propagated fold system to deposit a suite of platform carbonates in the subbasins and grainstone in the fold axis (Figure 10). These sediments gradually unconformably onlapped the western inherited Cambrian paleohighlands. We thus propose that the upper Yangtze Block was the backbulge basin of the retroarc foreland basin that had experienced northwest-southeast directed contraction and eventually dominated the depositional differentiations.

7. Conclusion

The new basin-scaled outcrop and borehole data in the central-upper Yangtze Block indicate that the Ordovician succession is partitioned into six third-order sequences (OSQ1-OSQ6) deposited in an epeiric carbonate platform with inner and peripheric paleohighlands. Provenance analysis indicate detrital deposits were prominently sourced from the northern India and Kangdian paleohighland, indicating South China Block amalgamation onto the western margin of East Gondwana by early Ordovician time. Compiled with the depositional and deformation variations, we propose that a retroarc foreland basin system was developed in the South China Block in response to final assemblage of the South China and Australia, which consists of foredeep basin in Cathaysia, forebulge in the Xuefeng Shan domain, and backbulge basin in the central-upper Yangtze Block. The South China Block was thus involved into the global tectonics of the Gondwana supercontinental cycle during the Ordovician.

Data Availability

Supplementary data are provided on https://zenodo.org/record/6548147#.Yn9fv4xByUk.

Conflicts of Interest

No conflicts of interest exist.

Acknowledgments

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Supplementary Materials

Figure S1. Correlation of the lithological units in the Sichuan Basin. Figure S2. Correlation of the lithological units in the adjacent area of the Sichuan Basin. Figure S3. Photomicrographs of samples for Zircon U-Pb dating from the Xinjigu section. Table S1. Names of sections and boreholes in Figure 1. Table S2. Point-counting data of samples for the model sandstone petrology in the Xinjigu section. *(Supplementary Materials)*

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