

Stratigraphy, sedimentology and palaeoenvironment of the dinosaur-bearing Late Cretaceous Zhengyang Formation in the Zhengyang Basin, Chongqing, South China

Hui Dai

Chongqing Institute of Paleontology

Jun Wang

junwang@ynu.edu.cn

School of Earth Sciences, Yunnan University

Yu-Jie Yuan

School of Engineering, Edith Cowan University

Liang-Dong Luo

School of Earth Sciences, Yunnan University

Qian- Ru Wen

School of Earth Sciences, Yunnan University

Yu Lin

Chongqing Bureau of Geological and Mineral Resource Exploration and Development

Ming Xiao

Chongqing Institute of Paleontology

Hai Xing

National Natural History Museum of China

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Abstract

Situated within the southwestern segment of Chongqing, the Zhengyang Basin formed one of the intermountain basins among the Yanshanian orogenic belt that developed during the Late Cretaceous. The Zhengyang Basin preserves a > 100 m-thick Late Cretaceous terrestrial successions, named as the Zhengyang Formation characterized by debris-flow deposits and fluvial-lacustrine units. Recently, abundant dinosaur fossils have been collected from this formation, including hadrosaurs, titanosaurs and theropods, providing the first substantial evidence of a Late Cretaceous dinosaur fauna in South China. We herein report detailed stratigraphic architecture, dinosaur fossil assemblage, sedimentary and palaeoenvironmental features of the Zhengyang Formation in the Zhengyang Basin. The information suggests that the dinosaurs lived in a restricted intermountain basin, of which the palaeo-climate was significantly influenced by a transition from overall humid to arid sedimentary condition. Our data lead to new evaluation of early Late Cretaceous dinosaur evolution, and provide new clues for investigation on the contemporary terrestrial palaeoenvironmental and palaeoclimatic features in the mid-low latitude area of East Asia. The stratigraphic features of the Zhengyang Formation also provide new insights into showing lateral correlation of the Late Cretaceous terrestrial successions in East Asia.

Introduction

The Sichuan-Hubei-Hunan provinces tectonically spans the Middle-Upper Yangtze block, which experienced multiple phases of tectonic uplifting during the late Mesozoic to early Cenozoic, and thus resulted in a series of NE-SW orientated anticlines and synclines (Fig. 1; Yan et al. 2000). Within these fold belts, associated intermountain basins developed with accumulation of considerable thickness of terrestrial red beds. These deposits were referred to as the "Donghu Group" or "Donghu Sandstone" in previous studies, and were roughly assigned to be the Late Cretaceous or Early Cenozoic in age owing to lack of reliable fossils (Geological Bureau of Hubei Province 1968). Subsequently, local geological surveys reported abundant dinosaur fossils recovered from these red beds in the Zhengyang Basin, Qianjiang District, eastern Chongqing of South China, and renamed these units as the Zhengyang Formation (ZYF) and suggested the age as the Late Cretaceous (Wang 1975). The ZYF yielded numerous dinosaur elements, including teeth, limb bones, vertebrae and ribs, which were originally identified as ornithischia (hadrosauridae), sauropodomorpha (titanosauridae), and theropoda (carnosauria), with an age estimation of the Late Cretaceous (Wang 1975; Chen et al. 2018; CIGS 2024). Recently, a non-hadrosaurid hadrosauroid has been reported from the ZYF, and was named as *Qianjiangsaurus changshengi*, with an update on the dinosaur assemblage from the upper part of the formation, which confirmed the presence of non-hadrosaurid hadrosauroid material rather than hadrosaurid remains, together with titanosaurian and tyrannosauroid elements (Dai et al. 2025).

Even though the Zhengyang dinosaur fauna has been formally documented, detailed geological studies on the Zhengyang Basin and the ZYF are still lacking. The most recent work on the Zhengyang Basin shows that the normal fault named as the "Apengjiang Fault" that resulted by the retreat of the Pacific plate controlled the formation of the basin, and the source materials basically came from the west (Lin

et al. 2024). In this paper, we present a comprehensive evaluation on the stratigraphy, macrofossil assemblage, and sedimentary and palaeoenvironmental features of the dinosaur-bearing ZYF.

Geological background

The Zhengyang Basin was named after the Zhengyang town of the Qianjiang District of southeastern Chongqing (Fig. 1). It consists in part of the southeastern Sichuan-western Hubei-northwestern Hunan fold belt, which was mainly formed due to the Yanshanian orogeny during the Late Cretaceous (Yan et al. 2000). Because of the uplifting and folding, the basement of the Zhengyang Basin includes several sedimentary units that range from the Silurian to the Jurassic, and thus the Late Cretaceous ZYF overlies the basement with an angular unconformity (Fig. 1; CIGS 2024). Based on the lithology, the ZYF has been divided into two members, the lower and upper members, or the so-called first and second members (Lin et al. 2024). The lower ZYF (K_2z^1) consists of alluvial-floodplain facies conglomerates, the particles of which are predominantly limestones sourced from nearby terranes, and their matrix is characterized by purplish-red clay minerals. The upper ZYF (K_2z^2) is mainly composed of brick-red, purplish-red, light-yellow and grey-white calcareous quartz sandstone, occasionally interbedded with conglomerates, calcareous greywacke and siltstone (Lin et al. 2024). Dinosaur fossils are completely restricted to the sandstones from the upper ZYF (Figs. 2–3).

Stratigraphy of the dinosaur fossil-bearing Zhengyang Formation

The pioneer comprehensive studies on the stratigraphy and dinosaur fossils of the ZYF in the Zhengyang Basin were conducted in 1974 (Wang et al. 1975), in which the lithological features and dinosaur assemblage were firstly described with a retrieval of hundreds of fossil bones. In recent years, detailed regional geological investigations revealed that dinosaur fossils are primarily concentrated within two layers of the ZYF, and eight discrete high-density fossil sites with a total area of $\sim 4 \text{ km}^2$ were identified (Figs. 2–3). Based on detailed field geological investigation on different sections, we herein re-describe the lithological features of the ZYF as 13 layers with a higher resolution. The lower ZYF consists only of layer 1, and the upper ZYF consists of layer 2 to layer 13.

Layer 13. Brick-red and yellowish-grey quartz sandstone, the overlying successions have been eroded away. (Thickness: $>2.9 \text{ m}$)

Layer 12. Interbedded purplish-red muddy conglomerate, with pebbles' proportion of 65%~90% and particle sizes ranging from 5 ~ 30 cm. The pebbles are poorly sorted with morphologies of sub-angular to sub-roundness. (Thickness: 5.9 m)

Layer 11. Brick-red interbedded feldspar-quartz siltstones and purplish-red muddy conglomerate with particle sizes ranging from 0.5–5 cm. Sporadic artificial dinosaur bone fossil debris are contained in this layer. (Thickness: 3.3 m)

Layer 10. Brick-red, purple-grey and greyish-white calcareous sandstone with a few of interbedded conglomerate layers. Pebble sizes ranging from 0.5–3 cm, and the matrix of the conglomerates are mainly composed of clay minerals. Sedimentary structures in this layer are featured by oblique beddings, including cross beddings and convolute beddings that developed in thick calcareous sandstones. Abundant dinosaur fossils are contained in the upper and lower sub-layers of this layer, which are typical brick-red argillaceous siltstones. The dinosaur fossils have been preliminarily identified as titanosauridae, hadrosauroid, dromaeosaurid and tyrannosauroid. (Thickness: 9.0 m)

Layer 9. Brick-red gravelly feldspar quartz siltstone, pebbles are mainly composed of limestone with sizes ranging from 4–6 cm and sub-rounded to rounded morphology. Sporadic dinosaur fossil fragments are contained in this layer. (Thickness: 3.1 m)

Layer 8. Brick-red interbedded gravelly feldspar siltstones and quartz siltstones, pebbles in which are mainly composed of limestone with sizes ranging from 0.5–3 cm. Sporadic dinosaur fossil fragments are contained in this layer. (Thickness: 10.2 m)

Layer 7. Brick-red, purplish-red and greyish-white intermediate sandstones, with abundant dinosaur fossils (titanosauridae and hadrosauroid). (Thickness: 4.6 m)

Layer 6. Brick-red interbedded feldspar siltstones and quartz siltstones with parallel lamination and sporadic dinosaur fossil fragments. The upper part of this layer contains a few thickly interbedded brick-red muddy conglomerates, pebbles in which are mainly composed of poorly sorted limestone with sizes ranging from 20–30 cm, with sub-angular morphology. (Thickness: 19.6 m)

Layer 5. Brick-red interbedded feldspar siltstones and quartz siltstone, contains a few conglomerates with sub-rounded limestone pebbles, and sporadic dinosaur fossil fragments. (Thickness: 21.3 m)

Layer 4. Interbedded brick-red and purplish-red feldspar siltstones and quartz siltstone, occasionally interbedded with muddy conglomerate that mainly composed of sub-angular and poorly sorted limestone pebbles with grain size of 5–20 cm. This layer is regarded as a regional marker below the dinosaur fossil layers. (Thickness: 12.8 m)

Layer 3. Brick-red interbedded feldspar fine sandstones and quartz fine sandstones. (Thickness: 7.3 m)

Layer 2. Brick-red quartz siltstones. The upper unit of this layer is mainly composed of brick-red interbedded feldspar siltstones and quartz siltstones. The lower unit of this layer is mainly composed of interbedded brick-red and purplish-red feldspar siltstones and quartz siltstones. (Thickness: 0.8 m)

Layer 1. Purplish-red mega-thick conglomerates. The pebbles are predominantly poorly sorted limestones with sub-angular to sub-rounded morphologies, with upward-increasing grain size, approximately 10 ~ 30 cm for the upper part, 30 ~ 50 cm for the middle part and up to 100 cm for the lower part. (Thickness: >80 m)

An angular unconformity is present between the ZYF and the underlying basement. The basement of the Zhengyang Basin is the Middle Triassic Badong Formation primarily composed of grayish-yellow siltstones and calcareous mudstones, interbedded with yellowish-gray shales.

The dinosaur fossils were located above layer 4 of siltstone, and abundant, relatively complete dinosaur elements were recovered from two beds, namely layers 7 and 10 of sandstone (Fig. 3b). Scattered fossil fragments are contained in the brick red sandstones with well-rounded quartz grains that covering on these layers. These fragments might have been recycled from the fossil-bearing beds.

The dinosaur fossils are exceptionally rich within the Upper Cretaceous of the Zhengyang Basin. The No.208 Hydrogeological and Engineering Geological Team of the Chongqing Bureau of Geological and Mineral Resource Exploration and Development conducted a paleontological excavation in 2022, and an incomplete, partially articulated hadrosauroid skeleton was unearthed from layer 10 of the ZYF (Fig. 3). Subsequent taxonomic study identified this skeleton as belonging to a non-hadrosaurid hadrosauroid *Qianjiangsaurus changshengi* (Fig. 4; Dai et al. 2025), representing a valid taxon outside of the Hadrosauridae. *Qianjiangsaurus* is the second formally named hadrosauroid from South China, following *Nanningosaurus dashiensis* from the Upper Cretaceous of Guangxi (Mo et al. 2007), and the discovery of *Qianjiangsaurus* provides critical insights into the Late Cretaceous dinosaur biogeography in East Asia (Dai et al. 2025). In addition to *Qianjiangsaurus*, isolated postcranial elements and teeth belonging to Titanosauria, as well as some tyrannosauroid teeth, were proved as part of the dinosaur assemblage of the upper ZYF (Dai et al., 2025). Our further examination recovers sporadic teeth of probable dromaeosaurid affinities from the upper ZYF: the tooth crowns are smaller and more distally recurved than those of Tyrannosauroida, and have a relatively narrow apex, with well-developed serrations along the posterior rim and particularly faint ones along the anterior rim, in contrast to the perfectly serrated anterior and posterior rims in Tyrannosauroida (Williamson and Brusatte, 2014; Brownstein, 2019).

Age of the dinosaur fauna and depositional environments

During the Late Cretaceous, dinosaur fossil record in China is predominately concentrated in North China, with relatively fewer fossil sites in South China (Dong 1992; Han et al. 2017), including Zhengyang in southeast Chongqing as described in this study (Chen et al. 2018), Nanning in southern Guangxi Province (Mo et al. 2007, 2008), Tiantai in eastern Zhejiang Province (Jiang et al. 2011), Ganzhou in southern Jiangxi Province (He et al. 2017), and Zhuzhou in eastern Hunan Province (Han et al. 2017; Zhu et al. 2020). Most of the other fossil sites in south China, such as those in Guangdong Province, have primarily yielded dinosaur eggs and trackways (e.g. Fang et al. 2009; Yu et al. 2012; He et al. 2017; Yu et al. 2020; Fang et al. 2022; Huang 2024; Li et al. 2024b).

Among these regions, hadrosauroid, sauropod and megalosaurid material was recovered around Nanning, Guangxi Province (Mo et al. 2007, 2008). Various dinosaur fossils, including sauropod, hadrosaurid, oviraptorosaurian, dromaeosaurid, and tyrannosauroid elements, have been collected from Tiantai of eastern Zhejiang Province (Jiang et al. 2011). Zircon U-Pb dating for the interbedded crystalline tuff from relevant strata supported that these dinosaur-bearing layers were early Late

Cretaceous in age (100–92 Ma) (Jiang et al. 2016). In Ganzhou of southern Jiangxi Province, titanosaurs, oviraptorosaurs, hadrosauroids, and dinosaur eggs with embryos have been reported (He et al. 2017). The dinosaur fauna in Ganzhou spans a wide age range, predominantly with two age peaks of the early and late Late Cretaceous (Lü et al. 2016; Xing et al. 2021; Mo et al. 2024). In Zhuzhou of eastern Hunan Province, at least five types of dinosaur fossils have been identified, including sauropods, tyrannosaurids, carcharodontosaurids, theropods, and hadrosaurids (Cheng et al. 2008; Han et al. 2024; Mo et al. 2024). Based on the sporopollen record from the upper and lower units of the dinosaur-bearing layer in Zhuzhou, Zhu et al. (2020) estimated the age of the layer to be the Campanian-Maastrichtian stage in the Late Cretaceous.

In the Zhengyang Basin, the fossil assemblage is predominantly composed of hadrosauroids, with the presence of titanosaurian material, and thus Wang (1975) assigned the age of the upper ZYF and dinosaur remains to be the Late Cretaceous. This fossil assemblage contrasts with the Late Cretaceous dinosaur faunas from other regions of South China. Based on the phylogenetic correlation of *Qianjiangsaurus changshengi* with eight other hadrosauroid species outside of Hadrosauridae that together suggest a combined age range from the Santonian to the Maastrichtian, Dai et al. (2025) estimated the age of the upper ZYF (where dinosaur elements were found) to be within the late half of the Late Cretaceous.

The fossil-rich beds of the upper ZYF contain typical fluvial and lacustrine depositional facies, such as parallel bedding and oblique bedding (Lin et al. 2024). While the sandstones in the Jianshi Basin, approximately 150 km to the north of the Zhengyang Basin comparable to the upper ZYF, were thought to be alluvial-aeolian deposits (Yu et al. 2021). Based on field investigations and thin section observation (e.g. Figure 5, above the fossil bed) on the fossil-rich upper ZYF, we identified a few thin gypsum layers and gypsum grains that evenly distributed within sandstone layers, indicating that the dinosaurs were living in a generally humid but intermittently arid environment. Interestingly, the red bed above the fossil layer contains a few fossil fragments and a large amount of gypsum (Fig. 5a), with abundant well-rounded quartz grains (Figs. 5b, c and d). This may suggest that the source materials of the fluvial and lacustrine sediments were mixed with some desert debris, thus the climate may shift to be increasingly drier, and this may be the cause of the mass mortality of the dinosaur fauna in the ZYF of the Zhengyang Basin.

Taphonomy

We conducted in-situ three-dimensional laser scanning on one of the hadrosauroid bonebeds in the field of the Zhengyang Basin. As shown in Fig. 6, most of the dinosaur fossils that with greater volume and relatively symmetric morphology are generally distributed in a north-south direction, while the other fossils showing asymmetric outlines are distributed irregularly. This phenomenon aligns with depositional models for elongate skeletal elements in fluvial systems, where bones can orient either parallel or perpendicular to palaeocurrent directions depending on hydrodynamic conditions (Rees 1983; Nemeč and Steel 1984). Skeletal orientation is additionally influenced by taphonomic processes,

including differential transport of asymmetrical elements (heavier proximal ends anchored upstream) versus symmetrical bones preferentially deposited perpendicularly to flow (Morris et al. 1996). Sedimentological analyses on the sandstones of the upper ZYF, such as dip direction plots of the cross-lamination, has identified that the palaeocurrents were from west to east (Lin et al. 2024). Therefore, orientation of the fossil bones corresponds with the palaeocurrents (Fig. 6), suggesting a unidirectional fluvial and short distance transportation of the dinosaur bones.

Bio-stratigraphic correlation and the palaeoenvironment

During the Early-Middle Cretaceous, influenced by the subtropical high pressure, South China experienced extensive aridity, leading to the development of aeolian desert deposits in intra-mountain basins (e.g. the Tangbian Formation in the Xinjiang Basin, the Honghuatao Formation in the Jiangnan Basin, the Chishan Formation in the Northern Jiangsu-Jurong Basin, the Daijiaping Formation in the Hengyang-Chaling Basin, and the Zhengyang Formation in the Jianshi Basin, as compiled in Fig. 7). These successions are characterized by conglomerate-bearing alluvial-floodplain facies overlain by high angle cross bedding aeolian deposits or interbedded aeolian sandstone lenses, with west-to-east palaeowind directions (Cao et al. 2023).

Abundant evidence of aeolian sediments support the existence of a near-zonal desert belt spanning low-to-mid latitudes in Asia during the Late Cretaceous, and this climate pattern was attributed to a latitudinally symmetric planetary wind system over Palaeo-Asia (Jiang et al. 2008; Hasegawa et al. 2012; Zhang et al. 2021), but climate modeling studies have since challenged this interpretation (Chen et al. 2013; Farnsworth et al. 2019). Emerging evidence highlights the underestimated role of topography in shaping Cretaceous Asian climates (Farnsworth et al. 2019; Zhang et al. 2021). By the early Late Cretaceous, the north-south trending East Asian Coastal Range had formed along the margin of South China (Chen 2000). When reaching an elevation of ≥ 2.5 km, this orogeny created a rain shadow effect that contributed to large-scale aridity in South China (Zhang et al. 2021; Li et al. 2024a). Concurrently, uplifting of the Proto-Tibetan Plateau to the west, combined with the pole-to-equator thermal gradient and Pacific warm pool dynamics, induced a persistent East Asian anticyclone that peaked in intensity (and aridity) at 84 Ma (Farnsworth et al. 2019). Stratigraphic records of dropstones, tillites, glendonites, eustatic fluctuations, and $\delta^{18}\text{O}$ isotope fluctuations revealed five glacial events during the Middle-Late Cretaceous period, which are the Albian-Cenomanian boundary, mid-Cenomanian, latest Cenomanian, mid-Turonian, mid-Coniacian, and early Santonian (Bornemann et al. 2008; Ladant and Donnadieu 2016; Scotese et al. 2021; Cao et al. 2023). Although the accurate timing of these glacial events relative to South China aeolian sand formation remains uncertain, they likely intensified westerly wind activity, and triggered pulsed deposition of large-scale aeolian sand systems in intracontinental basins (Cao et al. 2023).

Stratigraphic correlation of the dinosaur fossils in the upper ZYF with coeval aeolian sandstone strata across South China indicates that the depositional age of these strata is probably the early to middle Late Cretaceous, ~ 90 – 80 Ma (Wang et al. 2025), which is overlapped with the estimated age range of

the upper ZYF argued by Dai et al. (2025). The survival of dinosaurs was likely affected by aridification linked to the uplift of the southeastern coastal highlands and proto-Tibetan Plateau during that period. Thus the severe palaeoclimatic drying resulted in collapse of the ecosystem, and reduced available habitats and ultimately drove local extinction of the dinosaur fauna among the intermountain-basins, such as the Zhengyang Basin.

Conclusions

Dinosaur fossils from the upper part of the Late Cretaceous ZYF mainly include hadrosauroid, titanosaurian, dromaeosaurid and tyrannosauroid elements, which are identified as a new dinosaur assemblage in SW China. Relatively complete and partially articulated dinosaur elements in the upper ZYF were preserved within mottled sandstones, whereas sporadic fossil fragments were also found in the aeolian sandstones, suggesting potential redeposition of dinosaur bone remains from the lower layers. The dinosaur-bearing ZYF were estimated to be the early to middle Late Cretaceous (ca. 90–80 Ma) in age, and comparable dinosaur assemblages in other areas of southern China are rare. This regional discrepancy likely reflects mid-Late Cretaceous aridification, which induced desert expansion and ecosystem collapse, as well as local extinction of the dinosaur fauna. Further evidence from the palaeoenvironmental and palaeoclimatic proxies in the Zhengyang Basin is still required.

Declarations

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Figures

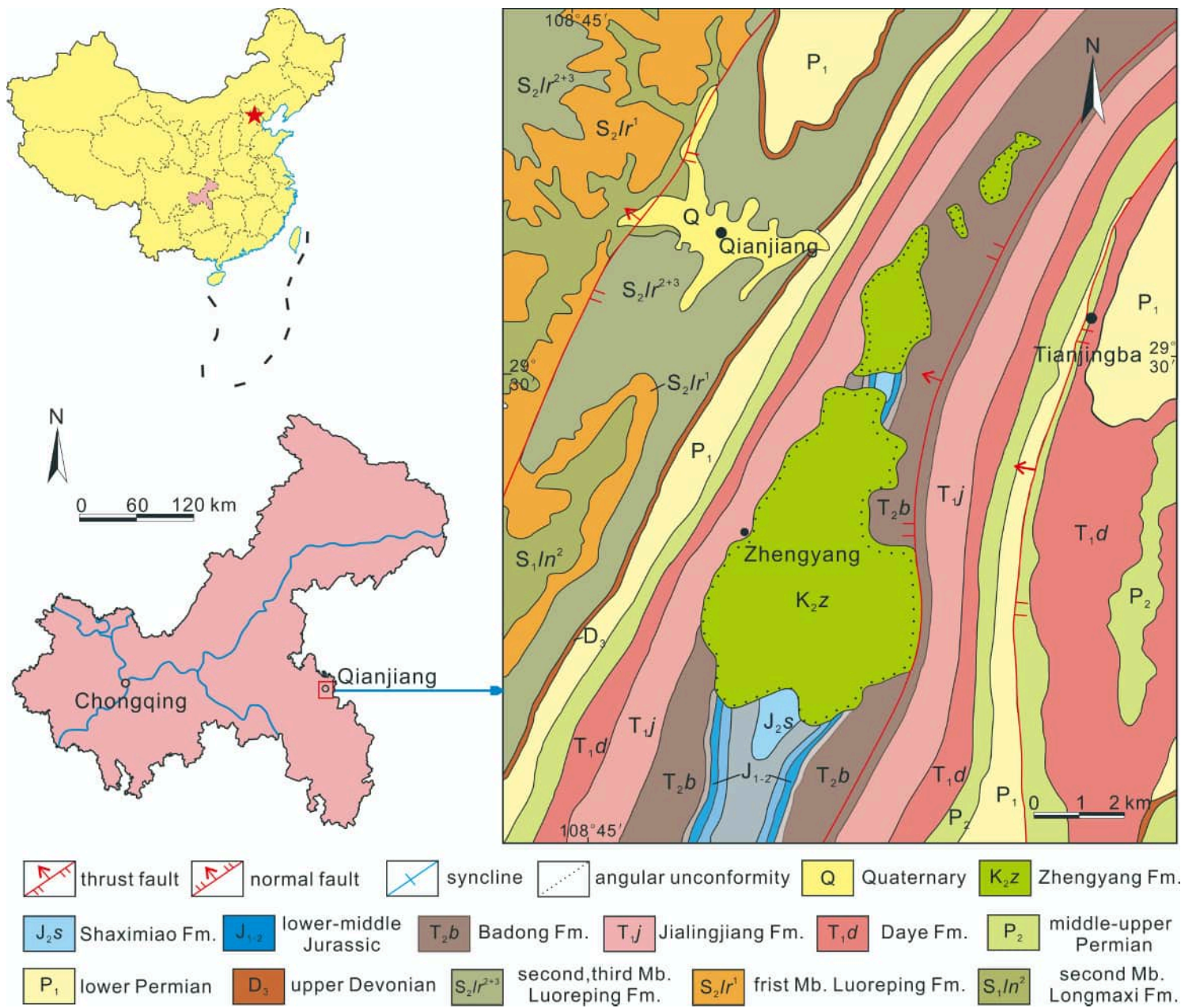


Figure 1

Geological map of the Zhengyang Basin, southeastern Chongqing, South China (modified after Lin et al. 2024 and Dai et al. 2025)

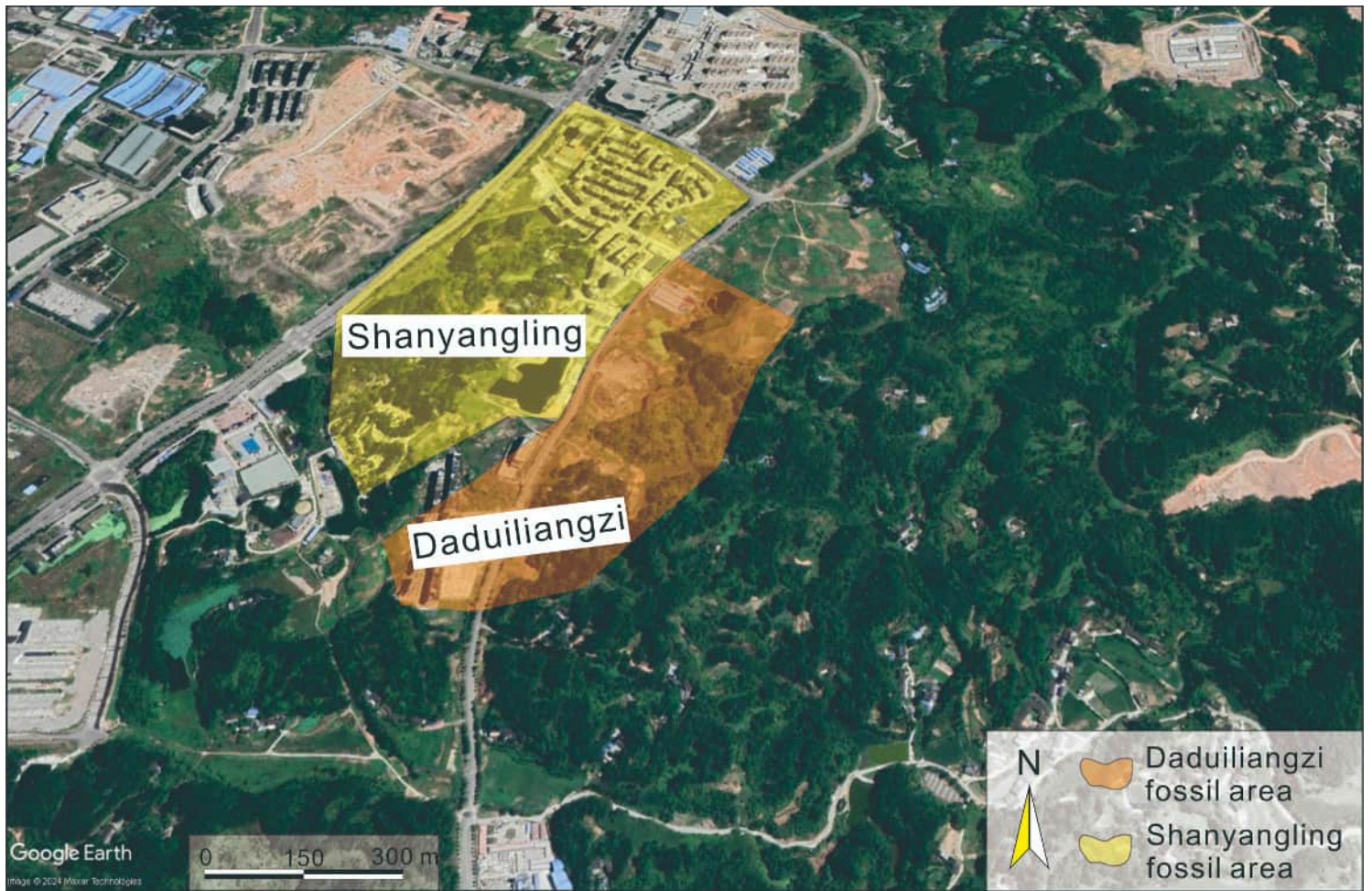


Figure 2

Distribution areas of the dinosaur fossils in the Zhengyang Basin, southeastern Chongqing, South China

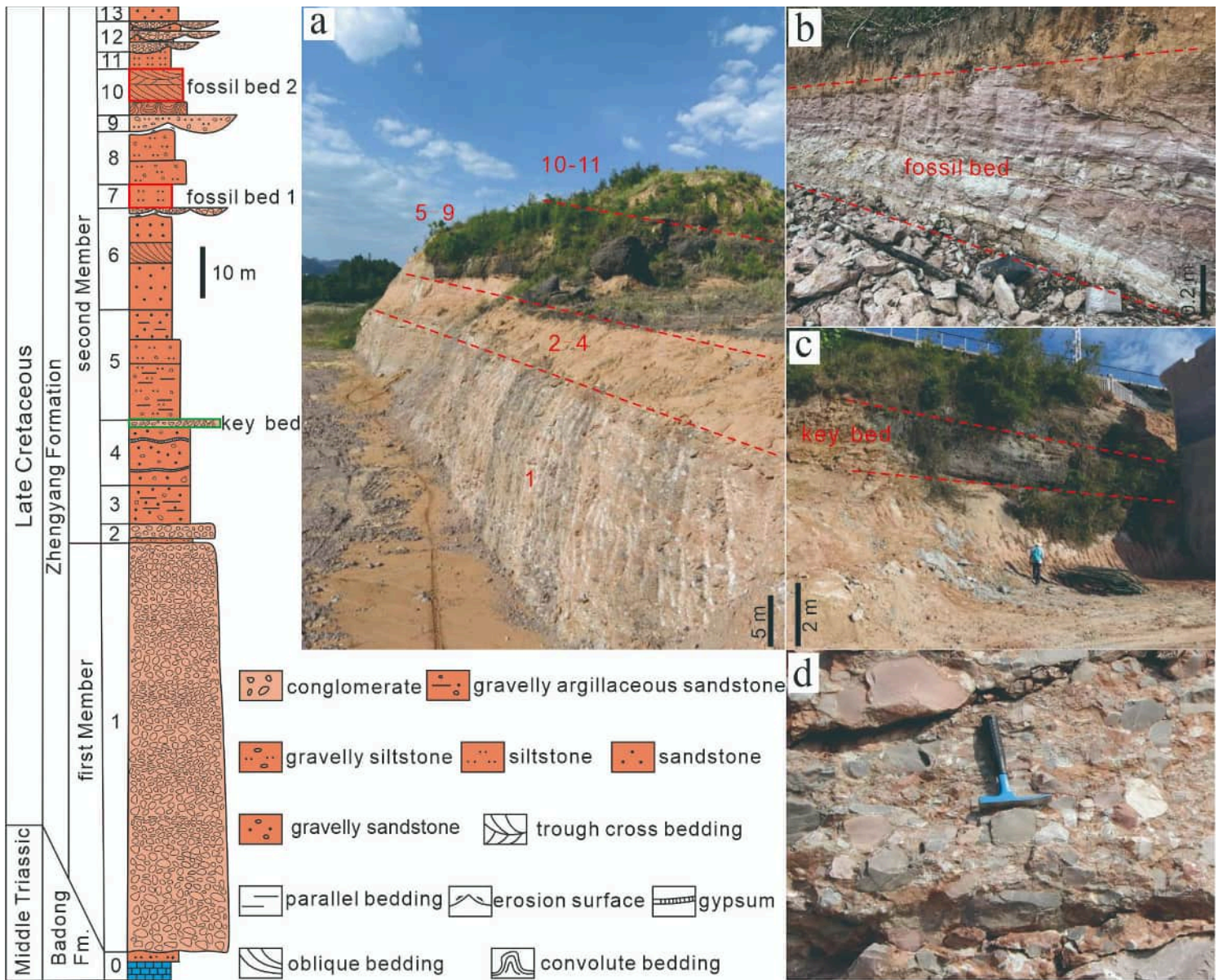


Figure 3

Lithologic column and representative outcrops of the ZYF in the Zhengyang Basin, southeastern Chongqing, South China. a-conglomerate Bed 1 and the overlying beds; b-Dinosaur fossil-bearing Bed 7 in the upper ZYF; c-Dinosaur fossil-bearing Bed 10 in the upper ZYF; d-Typical conglomerate in the lower ZYF.


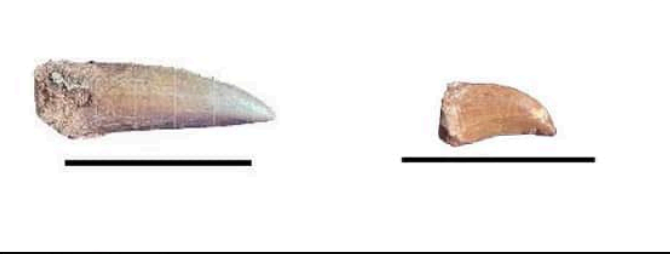

Class	Order	Suborder	Clade	Genus and species	Figure
Dinosauria	Saurischia	Sauropodomorpha	Titanosauria	Titanosauria indet. (not identified at the levels of genus and species)	
		Theropoda	Tyrannosauroidae Dromaeosauridae	Tyrannosauroidae indet. Dromaeosaurid indet. (not identified at the levels of genus and species)	
	Ornithischia	Ornithopoda	Hadrosauroidae	<i>Qianjiangsaurus changshengi</i>	

Figure 4

Late Cretaceous dinosaur assemblages from the upper ZYF, Zhengyang Basin, southeast Chongqing, South China (scale bar-5cm)

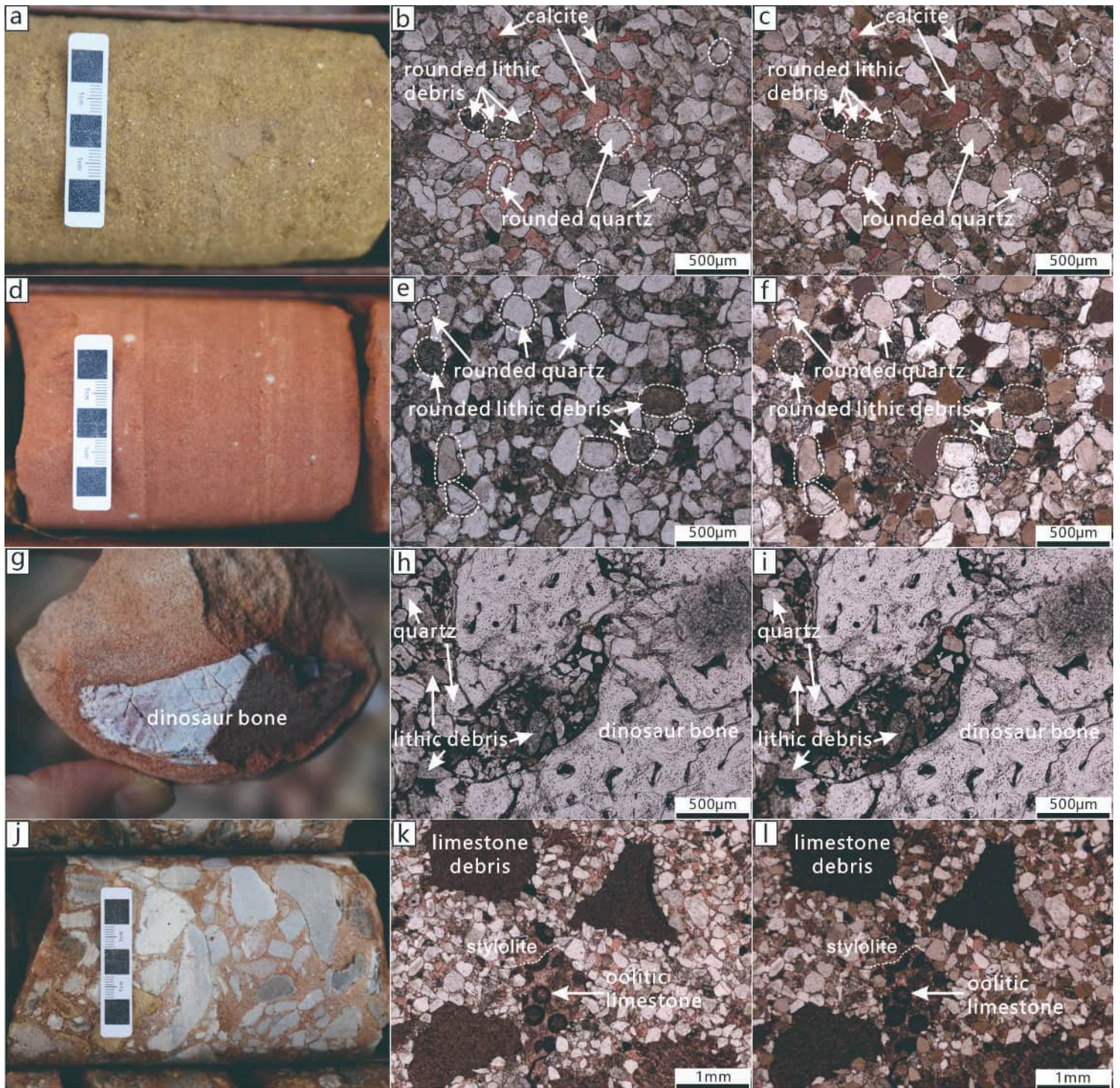


Figure 5

Representative rock type of the ZYF in the Zhengyang Basin of southeast Chongqing, South China. Samples were collected from bore holes. a, b, c-yellowish-grey quartz sandstone with well-rounded quartz grains and calcite cements from the Upper ZYF. d, e, f-Brick-red quartz sandstone with well-rounded quartz grains and well-rounded lithic debris from the Upper ZYF. g, h, i-Shallow brick-red quartz sandstone with dinosaur bone fossil debris from the Upper ZYF. Note that there are no obvious signs of weathering on the surface of the fossil debris, indicating a possibility of in-situ burial. j, k, l-Purplish-red mega-thick conglomerates from the lower ZYF. The pebbles in these conglomerates are predominantly

poorly sorted limestones with sub-angular to sub-rounded morphologies that may come from different units of the basement. Note the oolitic limestone pebble with stylolite structures (k, l).

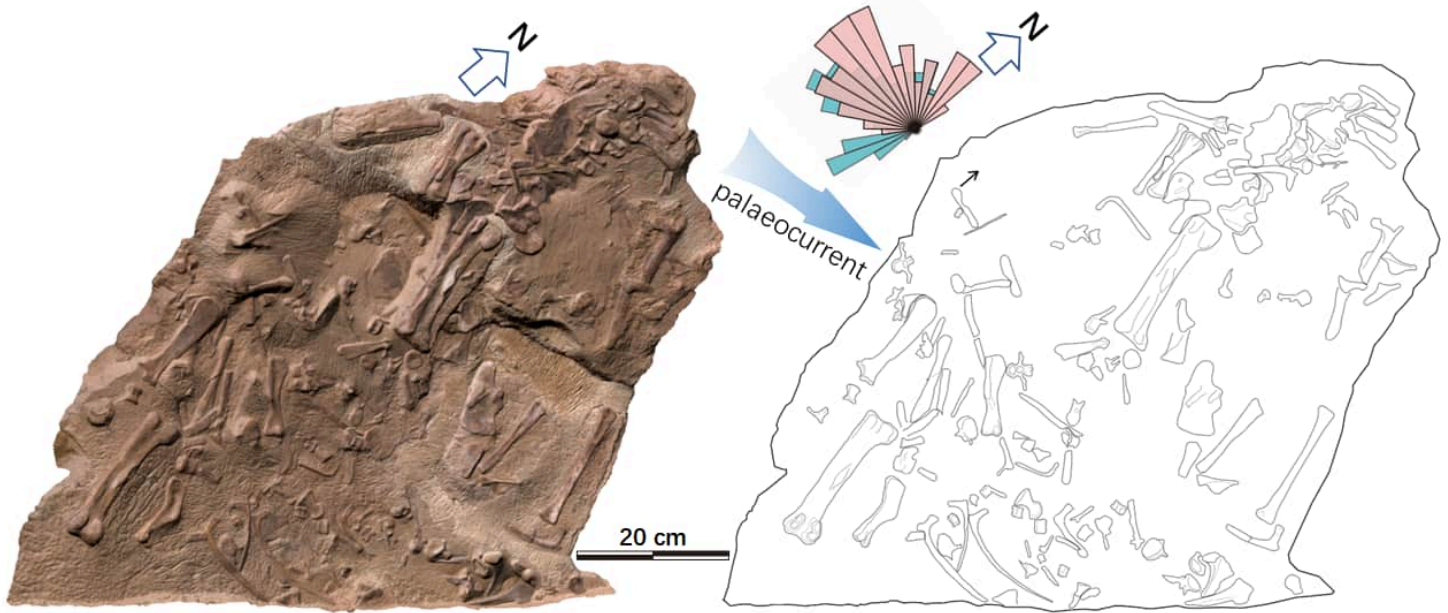


Figure 6

Three-dimensional laser scanning on the dinosaur fossils in the field of the Zhengyang Basin, which are dominantly composed of non-hadrosaurid hadrosauroids, with palaeocurrent marks. Pink triangles show compilation of the dip direction of the maximum flat surface of the pebbles from the lower ZYF, blue triangles show the palaeocurrent direction inferred from cross-bedding in the upper ZYF (Lin et al. 2024), indicating that the upstream came predominantly from the west.

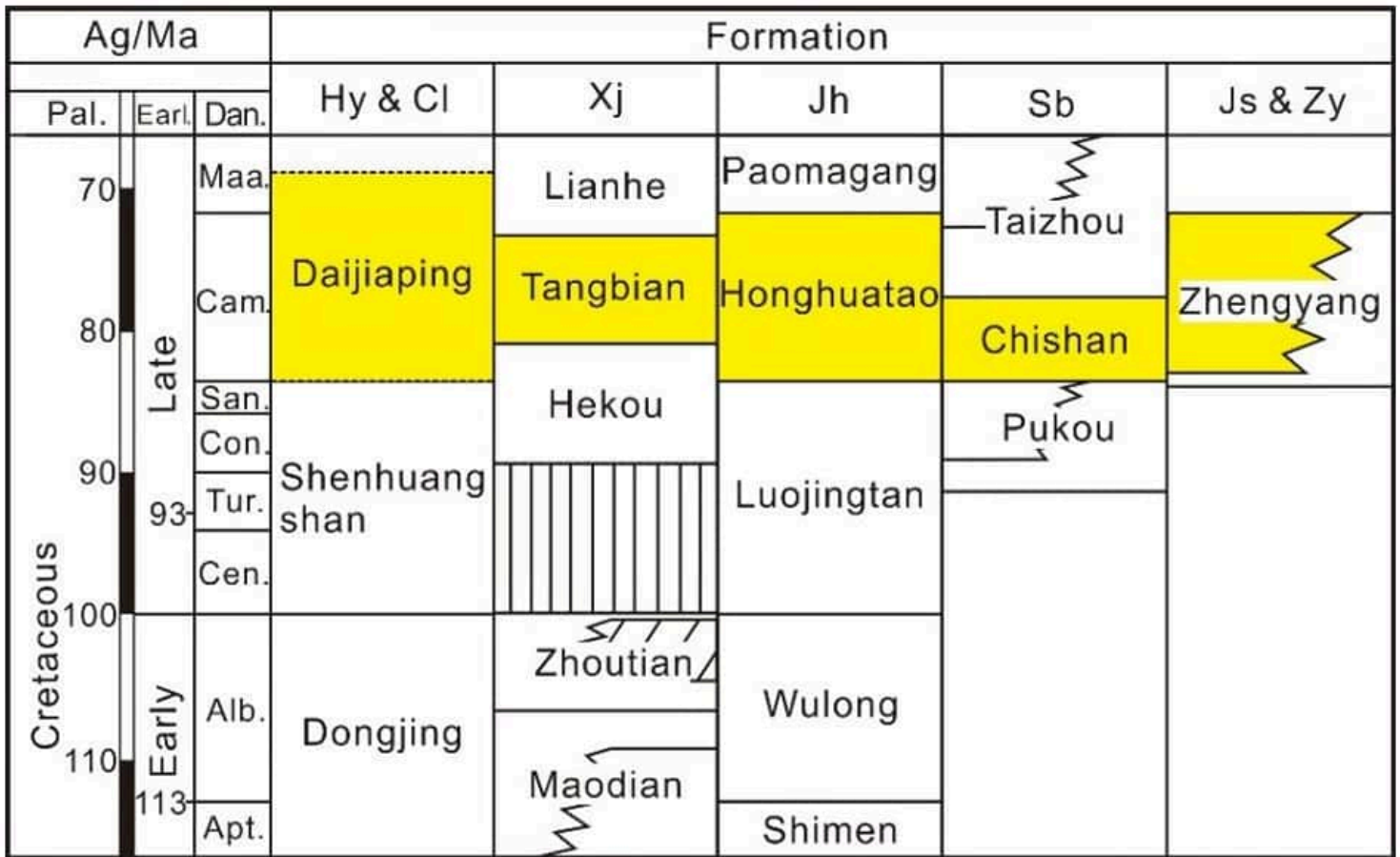


Figure 7

Representative Cretaceous aeolian desert deposits in the intra-mountain basins in eastern China, with highlighted aeolian beds (data were compiled from Chen et al. 2008; Cao et al. 2020, 2023; Yu et al. 2021)