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Discovery of ≥ 105 Ma continental redbeds in the Qiangtang Block: Implications for the early uplift of central Tibet

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Abstract

The Abushan Formation represents the oldest continental redbed deposit overlying Triassic-Jurassic marine strata in the Qiangtang Block. Knowledge of the exact depositional age of the Abushan Formation is important to reconstruct early history of surface uplift in central Tibet. Pollen and magneto-stratigraphy studies from central Qiangtang suggest that the Abushan Formation was deposited during the mid-Cretaceous; however, confirmation through isotopic geochronological data is still required. Here we describe the newly studied Madeng section exposing fluvial Abushan Formation redbeds at the base and felsic volcanic rocks at the top. SIMS U-Pb dating of zircons from one sample of these volcanic rocks yield a weighted mean $^{206}Pb/^{238}U$ age of 105.1 ± 0.9 Ma, indicating latest Early Cretaceous (late Albian) deposition of the Abushan Formation. Our data support the Abushan Formation redbeds were deposited in intermontane basins in an intra-plate tectonic setting following the collision, suturing, and amalgamation of the Qiangtang and Lhasa blocks.

Keywords: rise of Tibet, continental redbed, zircon U-Pb dating, sedimentology, Cretaceous

Introduction

The rise of Tibet as the world's largest orogenic plateau began from the sea level in the late Mesozoic Cretaceous (Kapp *et al*., 2019; Yin & Harrison, 2000; Ding *et al*., 2022). Constraining the age of the transition between marine and continental deposits is essential to establish the earliest possible initiation of surface uplift in Tibet. As the Tibetan Plateau is composed of several ribbon microcontinents (Fig. 1A), different regions may record seaway demise at different times. The southern Lhasa became subaerial in the mid-Cretaceous, as testified by the Upper Shexing Formation (Leier *et al*., 2007; Wang *et al*., 2020). In central and northern Lhasa, the marine limestones of the Aptian-Albian Langshan Formation are followed by the continental redbeds of the lower Upper Cretaceous Jingzhushan Formation, testifying to the rise of the Lhasaplano by that time (BouDagher-Fadel *et al*., 2015; Sun *et al*., 2015; Lai *et al*., 2019; Xu *et al*., 2022). The Bangong-Nujiang suture zone was suggested to have shoaled in the Late Jurassic, when the shallow-marine Shamuluo Formation capped the deep-marine Mugagangri Complex (Xia & Liu, 1997; Ma *et al*., 2018), though lower Cretaceous deep-marine deposits have been reported in local places along the suture zone (Kapp *et al*., 2007; Luo *et al*., 2020).

Compared to the Lhasa Block and the Bangong-Nujiang suture zone, less research has been carried out on the marine-to-continental transition in the Qiangtang Block. In southern Qiangtang, a major unconformity spanning the Late Jurassic to earliest Cretaceous separates marine and continental strata, whereas in northern Qiangtang marine deposition persisted into the latest Jurassic to earliest Cretaceous (Ma *et al*., 2017, 2023a; Zhang *et al*., 2019; Xue *et al*., 2020). The oldest continental strata in the Qiangtang Block, assigned as the Abushan Formation, are well preserved only locally. The best studied section is exposed at Abushan (shan means mountain in Chinese) in central Qiangtang near to a mélange containing blueschist-

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facies metamorphic rocks (Wu *et al*., 1986; Meng *et al*., 2018; Ma *et al*., 2023b), where pollens and magnetostratigraphy have suggested deposition lasting between 113 and 83 Ma at most (Wu *et al*., 1986; Meng *et al*., 2017; Ma *et al*., 2022). In other sections, the youngest cluster of U-Pb detrital-zircon ages—inferred to reflect a magmatic flare-up in southern Qiangtang (Li *et al*., 2017; He *et al*., 2018)—defines a maximum depositional age of ~100 Ma. We have documented sedimentary characteristic of the Abushan Formation in Biluoco area (Ma *et al*., 2017), however, the sedimentary successions exposed in the Madeng and Popu areas have been poorly studied so far.

In this new sedimentological, petrological and geochronological study, we focus on the > 100-m-thick section of Abushan Formation redbeds capped by volcanic layers exposed at Madeng (Fig. 1B) with the aim to gain new insights on the geological evolution of southern Qiangtang and age constraints on the early uplift of the Tibetan Plateau.

Geological setting

The Tibetan Plateau formed through the accretion of a series of microcontinents during the Mesozoic to early Cenozoic. The core of Tibet is constituted by the Qiangtang Block, separated from the Lhasa Block in the south by the Bangong-Nujiang suture zone, and from the Sonpan-Ganzi-Hoh-Xil terrane in the north by the Jinsha suture zone (Fig. 1A). The collision between the Qiangtang Block and the Sonpan-Ganzi-Hoh-Xil terrane took place in the Late Triassic, whereas the Lhasa-Qiangtang collision occurred in multiple stages from the late Middle Jurassic to the Early Cretaceous (Ma *et al*., 2017, 2023a; Hu *et al*., 2022). The central part of the Qiangtang Block contains a quasi-longitudinal Triassic mélange containing blueschists that divides the southern and northern Qiangtang terranes (Li, 1987; Pullen & Kapp, 2014). The Qiangtang Block experienced widespread shallow-marine deposition during the Jurassic and was uplifted during the Cretaceous (Ma *et al*., 2017, 2023a).

The Madeng area in this study is located ~55 km to the west of Amdo, very near to the Bangong-Nujiang suture zone in its south. The Jurassic is dominated by shallow marine sandstone and limestone (Ma *et al*., 2023a). The sea disappearance in this area is not constrained, but to the south, the shallow marine deposits continued until the Late Jurassic in the northern part of the Bangong-Nujiang suture zone (Ma *et al*., 2020). The Abushan Formation redbeds are widespread in the Madeng area and to the

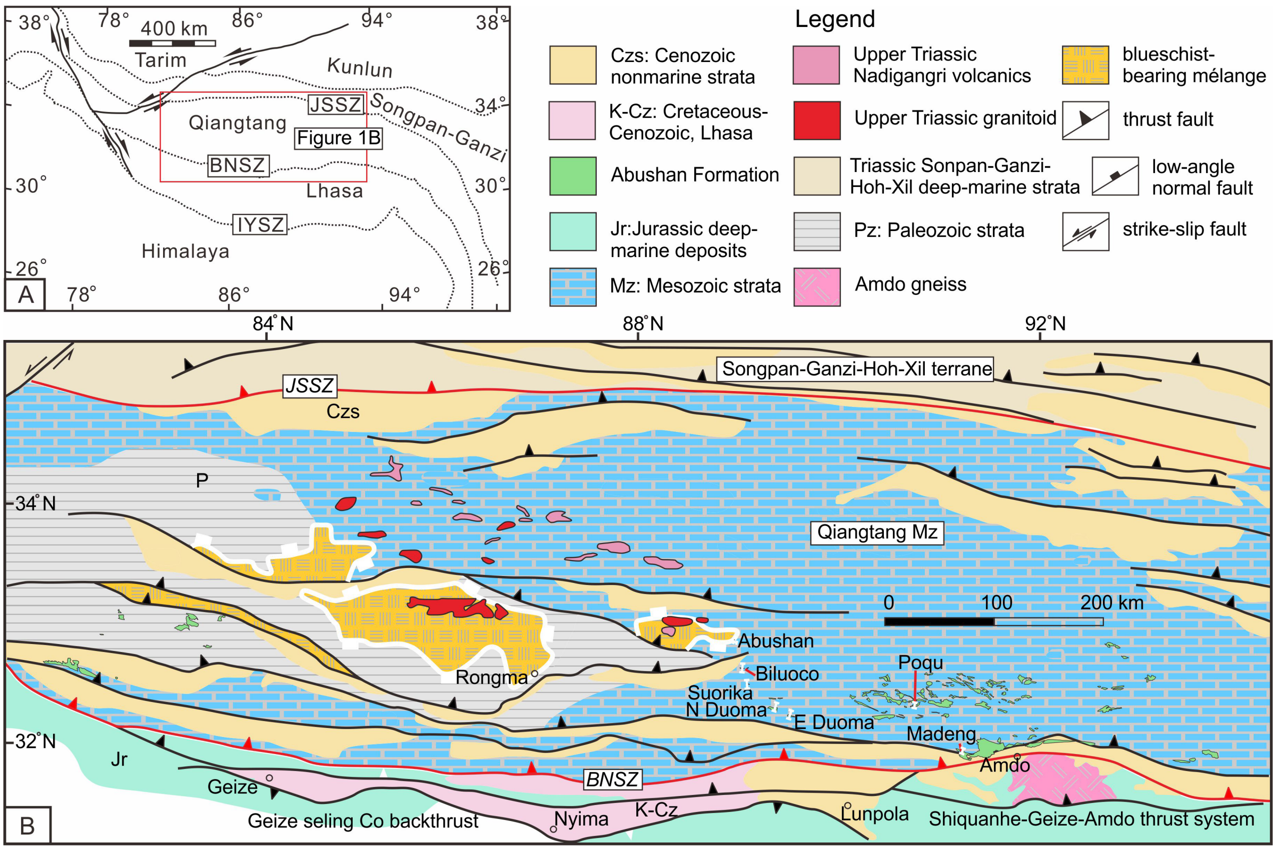

FIGURE 1. Tectonic and geological map of the research area. **A**, Tectonic framework of Tibet (a; modified from Pan *et al*., 2004). **B**, Geological map of the Qiangtang Block (modified from Kapp *et al*., 2005). Suture zones: BNSZ, Bangong-Nujiang; IYSZ, Indus-Yarlung; JSSZ, Jinsha.

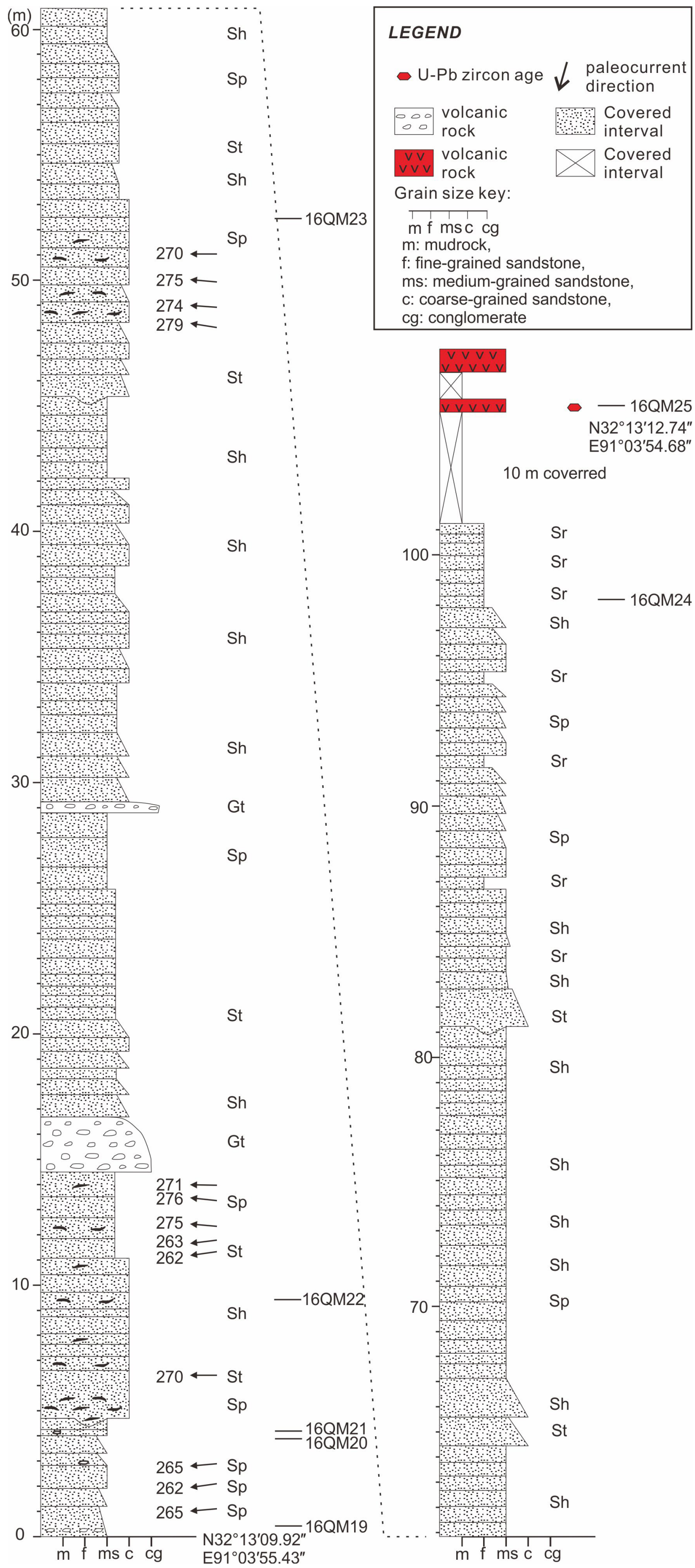

FIGURE 2. The measured Madeng section of the Abushan Formation. Lithofacies codes are based on Miall (1977): Gt: trough-laminated conglomerate; Sh: parallel-laminated sandstone; St: trough-oblique-laminated sandstone; Sp: planar-oblique-laminated sandstone; Sr: rippled sandstone.

north, with related felsic volcanic rocks and granitoids of ~100 Ma documented (Li *et al*., 2015, 2017).

Material and methods

The Madeng stratigraphic section was measured, and sedimentological observations were conducted bed by bed. Lithofacies were determined following the approach outlined in Miall (1977).

A volcanic rock sample collected from the top of Abushan Formation redbeds was crushed, sieved, and zircon grains were selected using elutriation and magnetic methods. Zircon crystals were mounted in epoxy and polished. Cathodoluminescence (CL) images of zircons were obtained to reveal the internal structure, which was referred when choosing potential target sites prior to U-Pb dating. The U, Th, Pb isotopes were analysed by Cameca IMS-1280HR Secondary Ion Mass Spectrometry (SIMS) at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIGCAS), following the methods described in Li *et al.* (2009) and An *et al*. (2021). The in-house standard Qinghu zircon yielded a consistent weighted mean ^{208}Pb/^{236}U age with the recommended value of 159.5 ± 0.2 Ma (Li *et al*., 2013a). Data were plotted for concordia and the weighted mean age was calculated using IsoplotR (Vermeesch *et al*., 2018). The complete dataset is provided in Table S1.

Results

Sedimentology and petrography

In the Madeng section, the >100-m-thick Abushan Formation (Figs 2, 3A) is dominated by sandstone (Fig. 3B) with a few conglomerate layers with trough oblique lamination. The basal sandstone and conglomerate contain mud clasts, limestone and sandstone gravels. Rip-up mud clasts occur at the base of sandstone layers, which typically show upward fining and planar or trough oblique lamination (Fig. 3C–E) indicating mainly westward paleocurrent (see measurements in Fig. 2). Sandstones are quartzo-lithic (Fig. 4A–C), with mainly limestone and felsic volcanic rock fragments and a few sandstone clasts. Sedimentary features suggest deposition in a braided river environment with strong unidirectional flows. The overlying section, covered over ~10 meters, is capped by porphyritic felsic volcanic rocks (Fig. 3F) containing quartz and feldspar phenocrysts and microcrystalline feldspar in the groundmass (Fig. 4D).

Geochronology

Zircon crystals in the felsic volcanic rock, 100 to 300 μm in length, show clear oscillatory zonation typical of magmatic origin in cathodo-luminescence images (Fig. 5). Out of 15 dated zircons, 14 concordant ^{206}Pb/^{238}U ages yielded a weighted mean of 105 ± 1 Ma (1σ, MSWD=1.8) (Fig. 6). The unique zircons yielded a ^{206}Pb/^{238}U age of 92 ± 5 Ma (1σ) and a ^{207}Pb/^{235}U age of 94.8 ± 7.4 Ma (1σ), which were not considered because of a much larger error (other ^{206}Pb/^{238}U ages have a 1σ uncertainty typically ranging between 1.5 and 1.8 Ma).

Discussion

Age of the Abushan Formation

Although the contact between the lava and the Abushan Formation sandstones is buried, the consistent strike and dip, along with the absence of faults evidence in both this section and the surrounding region (Li *et al*., 2015), support the interpretation of a conformable contact. Therefore, the 105 ± 1 Ma (1σ) U-Pb zircon age of felsic volcanic rocks capping the Abushan Formation indicates that the underlying redbeds are older. Assuming a depositional rate as rapid as 500 m/Ma (Leeder, 2011), the 100-m-thick redbeds may have accumulated in a time span as short as 0.2 Ma.

The late Albian age thus inferred for the Abushan Formation in the Madeng section is broadly consistent with that assessed for the Abushan (Ma *et al*., 2023b), Biluoco, Suorika (Ma *et al*., 2017), and East Duoma (Wen *et al*., 2023) sections. In addition, this age is older than for the North Duoma section, where the redbeds' interbedded volcanic rocks were dated as ~80 Ma (Li *et al*., 2013b). Therefore, the redbeds in the North Duoma section should be considered to be different from the Abushan Formation. The nearby volcanic rocks, which yielded a LA-ICP-MS U-Pb zircon age of ~103–101 Ma (Li *et al*., 2015), may correlate with the volcanic rocks capping the Abushan Formation in the Madeng section for very similar zircon ages.

Implication for early uplift of central Tibet

The early uplift of Tibet took place in multiple steps during successive events of microcontinent collision and accretion. Palaeoaltimetry research indicates that, in the early Cenozoic, a northern Qiangtang mountain range was divided by a valley along the Bangong-Nujiang suture zone from a southern Gangdese mountain range (Xu *et al*., 2013; Ding *et al*., 2014; Li *et al*., 2018; Lin *et al*., 2020; Ding *et al*., 2022; Xiong *et al*., 2022). Age constraints on the initial uplift of the Qiangtang mountain range is

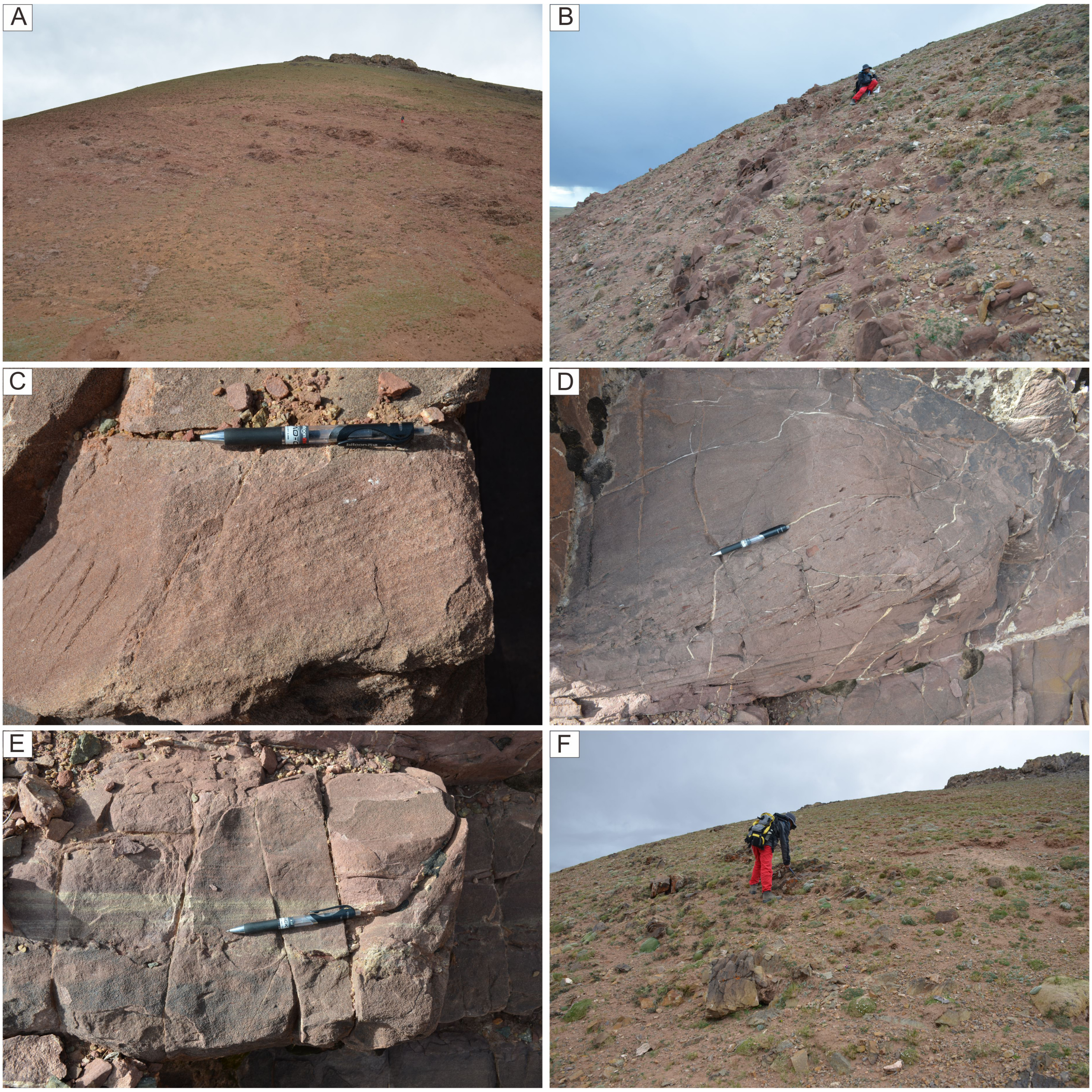

FIGURE 3. The Madeng section of the Abushan Formation. **A**, General overview (person in the upper right for scale; camera pointing north). **B**, Stacked thick-bedded sandstones. **C**, Planar oblique lamination in sandstone. **D**, Trough oblique lamination with mudclasts. **E**, Planar oblique lamination passing upward to parallel lamination in sandstone bed. **F**, Volcanic rocks at top of section.

however lacking. The results of our study indicate that intermontane redbeds accumulated in southern Qiangtang at late Albian times (*i.e.*, ≥ 105 Ma). At about the same time, there occurred locally fed alluvial fans in the southern and central Qiangtang, suggesting a significant elevation reached by the Qiangtang Block by that time.

A mid-Cretaceous magmatic flare-up nearly synchronous with the Abushan Formation redbeds has been documented in the Biluoco (He *et al*., 2018), Poqu and Madeng (Li *et al*., 2015), and East Duoma (Wen *et al*., 2023) areas (Fig. 1B). The Biluoco volcanic rocks are magnesian andesites with an age of 95 Ma (He *et al*., 2018). The Poqu volcanics are trachyandesites and andesites in the High-K calc-alkaline series, with ages ranging from 100 to 96 Ma (Li *et al*., 2015). The Madeng volcanics are dacites and rhyolites in the calc-alkaline series, with ages ranging from 103 to 101 Ma (Li *et al*., 2015). The Moku granite is slightly peraluminous and high-K calc-alkaline I-type of 100 Ma (Li *et al*., 2017). The East Duoma 98 Ma basalt and rhyolite are within-plate OIB-like and

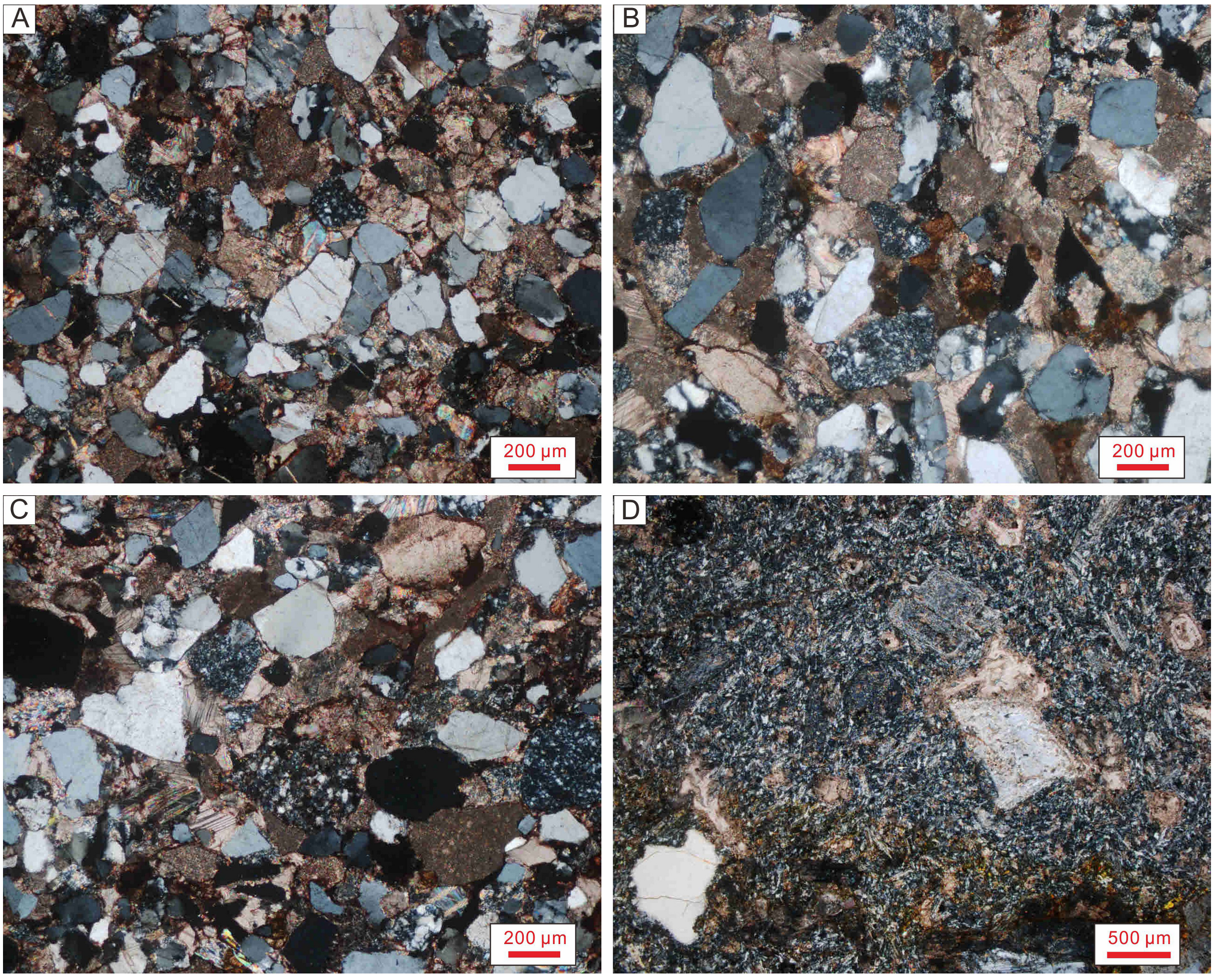

FIGURE 4. Thin-section microphotographs of quartzo-lithic sandstones of the Abushan Formation: **A**, 16QT19. **B**, 16QT21. **C**, 16QT23. **D**, Volcanic rock at the top of the Abushan Formation (16QT25). See sample horizons in Figure 2.

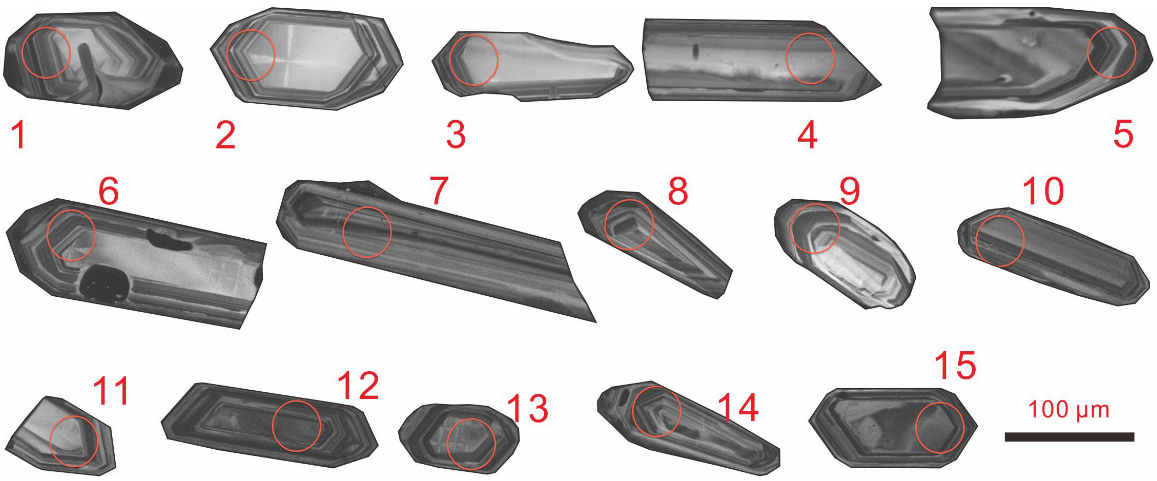

FIGURE 5. Cathodo-luminescence image of dated zircons from volcanic-rock sample 16QT25 collected at the top of the Abushan Formation.

volcanic arc-like, respectively (Wen *et al*., 2023). Based on the petrological and geochemical characteristics, such magmatic flare-up has been tentatively related to either post-collisional break-off of a northward-subducting slab (Li *et al*., 2017; He *et al*., 2018) or lithospheric delamination beneath Qiangtang (Wen *et al*., 2023). The > 1000-m-thick upward-fining megasequence of the Abushan Formation in the Abushan section of central Qiangtang may indicate an extensional tectonic setting, possibly related to lithospheric delamination (Ma *et al*.,

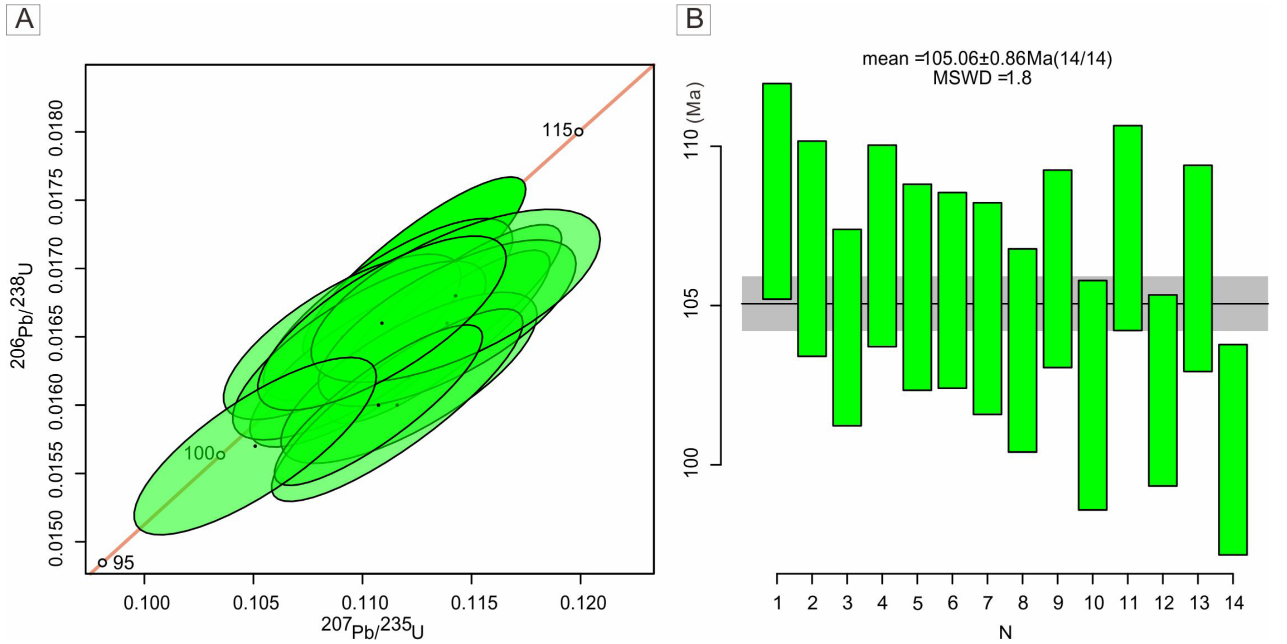

FIGURE 6. Concordia plot (**A**) and weighted mean $^{206}Pb/^{238}U$ ages (**B**) of zircon crystals from volcanic-rock sample 16QT25 collected at the top of the Abushan Formation.

2023b). In southern Qiantang, however, the Abushan Formation has been studied only in the Biluoco, Suorika, East Duoma, and Madeng sections, and basin evolution still needs to be ascertained.

Conclusion

Our study constrains the depositional age of the Abushan Formation in the Qiangtang Block to the late Albian (*i.e.*, ≥ 105 Ma), based on the zircon U-Pb age of felsic volcanic rocks at the top of the Madeng section. The Abushan Formation is here dominated by braided-river sandstone with a few conglomerates derived from proximal sources. Integration of data from diverse sections indicates that the Abushan Formation was deposited in an intermontane within-plate setting after the collision, suturing, and final amalgamation of the Lhasa and Qiangtang blocks.

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