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Lithospheric reworking and thinning by cyclical continental extension: a synthesis of Cretaceous extensional domes in the South China Block

Published online: 21 December 2023

Part of Special Issue: Geodynamics of Continents and Oceans – A tribute to Jean Aubouin

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https://doi.org/10.5802/crgeos.245

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www.centre-mersenne.org — e-ISSN : 1778-7025

Comptes Rendus. Géoscience — Sciences de la Planète
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Research article

Geodynamics of Continents and Oceans – A tribute to Jean Aubouin

Lithospheric reworking and thinning by cyclical continental extension: a synthesis of Cretaceous extensional domes in the South China Block

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Abstract. Continents with cratonic cores can resist deformation, and thus survive billions of years in the geological record. Tectonic reworking is a significant process that weakens and destructs cratons, but our understanding of the process remains incomplete. In the South China Block, Mesozoic cyclical tectonics destructed a large portion of its cratonic lithosphere. Here, we synthesized the structural evolution of extensional domes and illustrated the process of lithospheric thinning. Unlike the previous rapid, one-cycle delamination model, we propose a new model that multicycle compression and extension progressively destructed the lithosphere, which reconciles both surface geology and deep process.

Keywords. Continental reworking, Lithospheric thinning, Extensional domes, Cretaceous, Cyclical tectonics, South China.

Funding. This project has received funding from the National Science Foundation of China (Grant Numbers: U2344213 and 41872208), the State Key Laboratory of Lithospheric Evolution (Grant Number: SKL-Z202205), the Key Research Program of the Institute of Geology and Geophysics, Chinese Academy of Sciences (Grant Number: IGGCAS-202204), and the Youth Innovation Promotion Association (Grant Number: 2019065).

Manuscript received 14 May 2023, revised 20 October 2023, accepted 20 November 2023.

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1. Introduction

Continents with thick, rigid lithosphere are called cratons. They can survive destruction of multiple tectonic events for the last 2 billion years [Lee et al., 2011], while some of them have been destructed and lost their stability [Zhu et al., 2021]. Tectonothermal reworking is a key process in continental evolution because it alters composition and structure of some continents, weakens, and finally destructs or even dismembers them [Holdsworth et al., 2001]. Typical examples of reworked continents develop in subduction or collision settings, mostly situating in East Asia, Western North America, or the Tethyan collisional zones [Bao et al., 2015, Yonkee and Weil, 2015, Zhu et al., 2021]. In western Pacific, East Asian continental margins suffered extensive continental reworking and lost part of their continental lithosphere and developed a wide (>1000 km) extensional province [Chen et al., 2008, Zhu et al., 2011, Chu et al., 2019, Lin and Wei, 2020, Deng et al., 2021]. Mesozoic is an important era for the reworking, because the Paleo-Pacific subduction initiated and caused voluminous magmatism and cyclical contractional-extensional deformation that extensively deformed the continent through the entire era [Li and Li, 2007]. Such a strongly modified continent represents an ideal target to reveal the process and mechanism of continental reworking.

As two major constituents of East Asia, the South China Block (SCB) and the North China Craton (NCC) both experienced Mesozoic tectonic reworking and lithospheric destruction after their Proterozoic cratonization [Wang et al., 2013b, Li et al., 2014, Chu et al., 2019, Wu et al., 2019, Lin and Wei, 2020]. However, they show distinct surface geology and deformation patterns. The reworking of the NCC produced widespread Early Cretaceous extension that destructed and delaminated ~100 km thick continental lithosphere of the eastern craton [Wu et al., 2019]. This lithospheric delamination model is also referred to as cratonic destruction [Zhu et al., 2011]. In contrast, Mesozoic tectonic events changing the lithosphere structure of the SCB reflect episodic compression–extension and magmatic flare-up and lull intervals [Zhou et al., 2006, Li et al., 2014, Chu et al., 2019]. The timing and mode of lithospheric loss are less discussed and thus remain controversial.

From Triassic to Cretaceous, the SCB recorded at least three stages of compressional tectonics, Early to Middle Triassic, Late Jurassic, and late Early Cretaceous [Zhang et al., 2012, Li et al., 2014, Shu et al., 2015, Faure et al., 2016, Chu et al., 2019]. Following each of these compressional events, Early Jurassic, Early Cretaceous, and Late Cretaceous crustal extension, and magmatic flare-ups greatly reshaped these early compressional thrust belts covering almost the whole SCB. Although these events were slightly diachronous and unevenly developed between inland and coastal regions, the latter two stages of extension, Early Cretaceous and Late Cretaceous, are well manifested by extensional domes [Lin et al., 2000, Zhu et al., 2010a,b, Wei et al., 2016, Chu et al., 2019, Li et al., 2020]. The tectonic cyclicity characterizes the reworking process of the SCB and itself displays an uncommon mechanism of continental reworking. Structural work on different regions of the SCB has been well documented, but reconstructing the reworking process requires a comprehensive view of all extensional domes and comparison on the structural patterns and detachment evolution. In this review, we synthesize the Late Mesozoic extensional domes that document the main continental extension stages, and analyze the features of detachments, including structural patterns, detachment strain rates, and regional tectonic histories. Finally, we discuss the controlling factors of the heterogeneous extension, lithospheric removal, and geodynamics of this cyclical extension, and propose a new model of continental reworking distinct from the cratonic destruction model of the NCB and the Western North America.

2. Tectonic divisions and history of South China

The SCB consists of two subdivisions, the Yangtze Craton to the west and the Cathaysia Block to the east, but the cratonic lithosphere of the Yangtze Craton is only preserved beneath the Sichuan Basin that is bounded by orogenic belts with basin-vergent thrust belts, including the Dabashan, Longmenshan, Sanjiang Belt, and East Sichuan-Xuefengshan Belts (Figure 1). Except the long-lasting (Paleo-) Pacific subduction system at the eastern margin, the peripheral domains of the SCB are Triassic belts. To the west and southwest, they resulted from the closure of the Paleotethys and collision with the Qiangtang, and Indochina Blocks, while the Qinling-Dabie-Sulu belt to

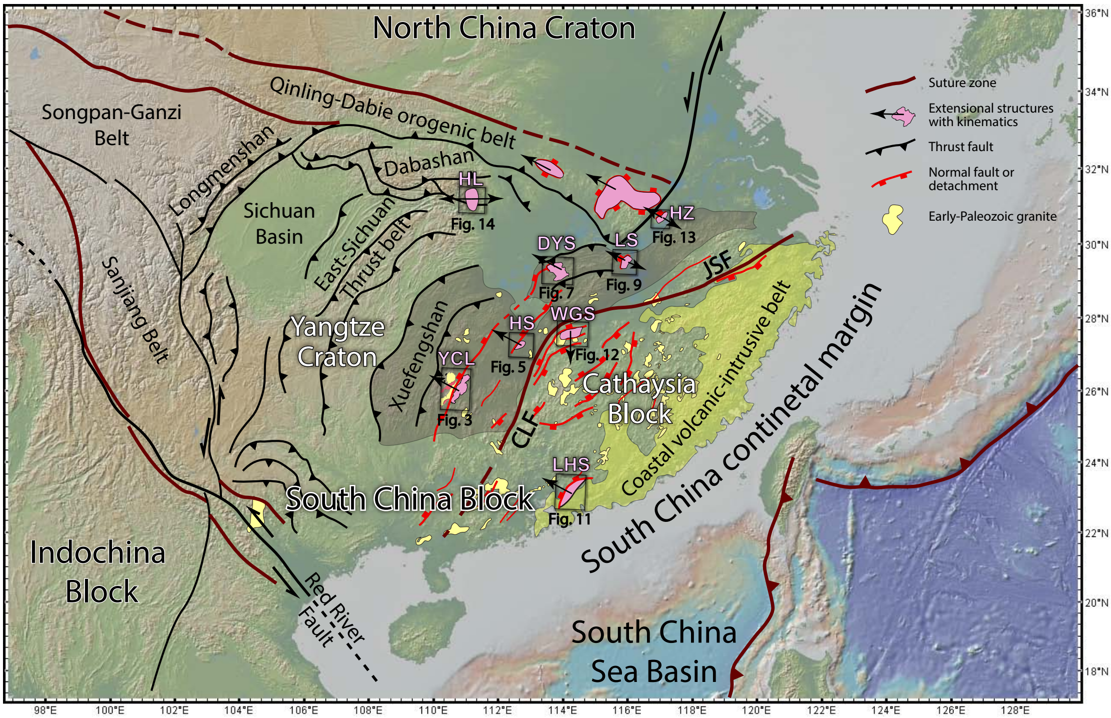

Figure 1. Tectonic map of the South China Block and adjacent regions [modified after Chu et al., 2019]. Mesozoic structures including fold–thrust belts and major extensional domes are highlighted on this map. JSF: Jiangshan-Shaoxing Fault. CLF: Chenzhou-Linwu Fault. ZDF: Zhenghe–Dapu Fault. Extensional domes: DYS: Dayunshan. HL: Huangling. HS: Hengshan. HZ: Hongzhen. LHS: Lianhuashan. LS: Lushan. WGS: Wugongshan. YCL: Yuechengling.

the north was formed by convergence between the SCB and NCB (Figure 1).

The Jiangnan collisional belt records the Neoproterozoic amalgamation of the SCB [Charvet et al., 1996, Shu and Charvet, 1996]. The northeastern segment of the suture zone, the Jiangshan-Shaoxing Fault, consists of well-preserved arc and high-pressure metamorphic rock assemblages [Li et al., 2009], while the southwestern segment vanishing under the Paleozoic to Mesozoic sedimentary cover is represented by the Chenzhou-Linwu Fault [Zhang et al., 2013]. This ancient suture zone serves as an important weak zone and is repeatedly reactivated by later tectonic events.

Early Paleozoic intracontinental orogeny involved almost half area of the SCB, lasted for over 80 million years (Myr), and greatly reworked the Cathaysia Block by high-grade metamorphism, middle-high temperature double-vergent ductile shearing, and syn- and post-orogenic magmatism [Lin et al., 2008, Li et al., 2010, Wang et al., 2013b, Feng et al., 2022b]. This orogeny is interpreted as bivergent compressional tectonics stemmed from the Neoproterozoic suture zone [Faure et al., 2009, Charvet et al., 2010, Chu and Lin, 2014].

The dominant NE–SW trending structural lines in most of the SCB was formed by the Mesozoic-to-present (Paleo-) Pacific subduction system [Zhou and Li, 2000, Li and Li, 2007]. Except the rigid Sichuan Basin, mountainous regions cover the entire SCB from its SE continental margin to its interior (Figure 1). At its southeast are the East-Sichuan Belt and Xuefengshan Belt that share a similar deformed pattern but have different tectonic stages. The East-Sichuan belt formed in Jurassic to Cretaceous [Yan et al., 2003], whereas the Xuefengshan-Jiuling Belt rose during the Triassic to Jurassic compression. Both belts stemmed from the reworking along the

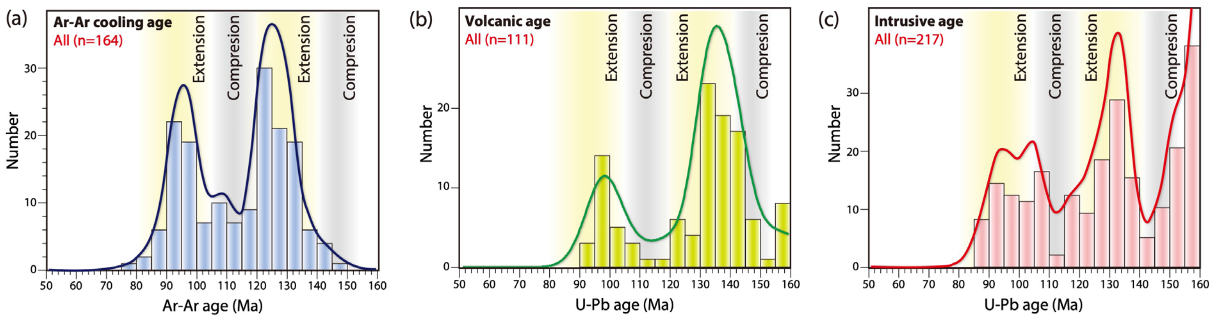

Figure 2. Age compilation of structural, igneous and volcanic events [modified from Chu et al., 2019].

ancient Neoproterozoic suture zone to the east [Chu et al., 2012, Chu and Lin, 2014]. The Xuefengshan-Jiuling Belt represents an important tectonic boundary, east of which Cretaceous extensional structures and magmatism are widespread. The southeastern Yangtze Craton and the entire Cathaysia block shared similar tectonic and magmatic history, except the coastal Cathaysia covered by Early Cretaceous volcanic rocks [Li and Li, 2007]. In the following, we shall consider the SCB with a rigid core and a reworked unit divided by the Xuefengshan-Jiuling Belt for further discussing the Mesozoic tectonic evolution.

During the Late Jurassic, the SCB underwent the most abundant magmatism, but record of extensional deformation is weak [Zhou et al., 2006]. Most plutons have a rounded cartographic shape. Some plutons show weak syn-magmatic extension during the magma emplacement [Wei et al., 2016, Ji et al., 2018a,b]. As key indicators for lithospheric thinning or destruction, Cretaceous magmatic flare-ups occurred in two stages (Figure 2) [Zhou and Li, 2000, Li, 2000, Li et al., 2014, Chu et al., 2019]. Extensional structures, including extensional domes/metamorphic core complexes and normal fault-controlled basins, prevailed in the two stages of Late Mesozoic and gave rise to large normal faults or detachments [Shu et al., 2009]. These low-angle normal faults or detachments therefore provide a window to reveal a detailed extensional process and interaction between intracontinental extension and plate margin tectonics.

3. Deformation of extensional domes with detachment

In this section, we review several recent structural studies on major Cretaceous extensional domes in South China. Here, because the detachments and structural geometry of extensional domes are different from the classic model of MCC in western America which has curved detachment plane and breakaway faults, we prefer to use extensional dome instead of MCC to define all the Cretaceous extensional structures. These extensional domes, from interior to coastal regions, are Yuechengling, Huangling, Hengshan, Dayunshan, Wugongshan, Lushan, Hongzhen, Lianhuashan (Figure 1). They characterize the Late Mesozoic South China extensional province. It is noteworthy that in some domes, a few muscovite ages are younger than that of biotite, and our preferred interpretation is that the muscovite ^{40}Ar–^{39}Ar system may have been disturbed by later fluid-assisted dissolution or deformation. In this work, we only use ^{40}Ar–^{39}Ar ages from the same mineral (biotite or muscovite) to retrieve the rates of different domes [Foster et al., 2010]. This can avoid the age discrepancy and closure temperature difference between biotite and muscovite.

3.1. *Yuechengling*

3.1.1. *Deformation pattern*

The Yuechengling dome is located in the Xuefengshan Belt and is the westernmost extensional dome of South China. It consists of Neoproterozoic to Triassic sedimentary rocks, the Yuechengling–Miaoershan pluton, and Cretaceous red beds. The

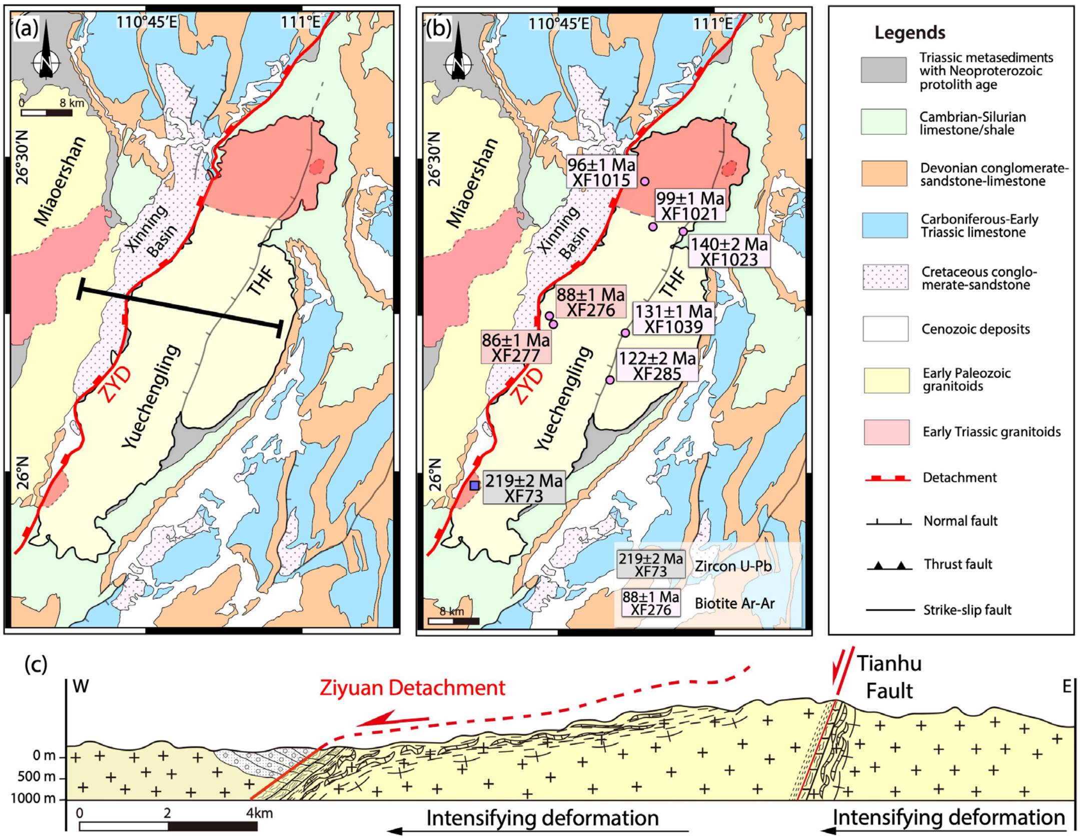

Figure 3. Geological map (a), map with published ages (b), and cross-section (c) of the Yuechengling dome [modified from Chu et al., 2019]. ZYD: Ziyuan Detachment. THF: Tianhu Fault.

age of the Yuechengling-Miaoershan biotite granite/monzogranite varies from 420 Ma to 380 Ma, and some small dikes or stocks intruded into the main pluton during the Triassic and Jurassic [Zhou, 2007, Chu et al., 2012, Zhao et al., 2013]. The main detachment controlling the Yuechengling extensional dome is the Ziyuan Detachement (Figure 3) developed between the Miaoershan and Yuechengling plutons. Another ductile normal fault, the Tianhu Fault, separates the Yuechengling Pluton into the strongly deformed western Yuechengling Pluton and weakly to non-deformed eastern Yuechengling Pluton [Cheng et al., 2016, Chu et al., 2019, Feng et al., 2022a].

The Yuechengling Pluton and Neoproterozoic-Early Paleozoic metasediments comprise the footwall of the Ziyuan Detachment. This detachment deformed a ~10–15 km-wide proto-mylonitic to mylonitic zone in the western Yuechengling Pluton. The deformed zone is ~15 km wide in the middle and shrinks towards the north and south. This detachment shows a shallow dip angle of ~20–30°, top-to-the W shear sense, and a complete faulted rock sequence with tectonic breccia, cataclasite, mylonite, and gneissic granite (Figure 3c). The deformation temperature varies between the two ductile faults, in which the Ziyuan Detachment records a high temperature at ~500 °C and the Tianhu Fault deforms the rocks at ~300 °C [Chu et al., 2019].

In the hanging wall, the Miaoershan Pluton and the Xinning Basin are undeformed, but brittle faults and joints related to the detachment can be observed [Chu et al., 2019]. The sedimentary sequence of the Xinning basin starts with poorly sorted breccia and gradually changes to coarse grain sandstone with a major component from the exposed Yuechengling granite and Paleozoic rocks. The tilted strata and conjugate joints by E–W extension indicate that the Xinning basin formed during the development of the Yuechengling dome [BGMRGX (Guangxi Bureau of Geology and Mineral Resources), 1985, Chu et al., 2019].

3.1.2. *Timing of deformation*

The Yuechengling dome has the best record of the Cretaceous two-staged extension of the SCB. The Early Cretaceous extension is localized in the high-angle brittle–ductile Tianhu Fault. ^{40}Ar–^{39}Ar cooling ages suggests that the fault was active at 140–120 Ma and continuous tectonic uplifting of the eastern Yuechengling Pluton [Chu et al., 2019]. Whether the main Ziyuan Detachment was also active in Early Cretaceous remains elusive, because it lacks early cooling ages and the initial age of syn-extensional basin sequence is still undetermined. The Late Cretaceous extension resulted in the final exhumation of the Yuechenling dome, while the Ziyuan Detachment played a dominant role in strain accumulation, rock deformation and tectonic uplifting. Detailed age constraints demonstrate an increasing age trend dependent on the distance to the detachment, which rapidly cooled at 99–87 Ma (Figure 3). The early stage has a slow slip rate at 0.05 mm/y (millimeter per year), while the rate is 10 times higher at 0.5 mm/y for the Late Cretaceous detachment activity (Figure 4).

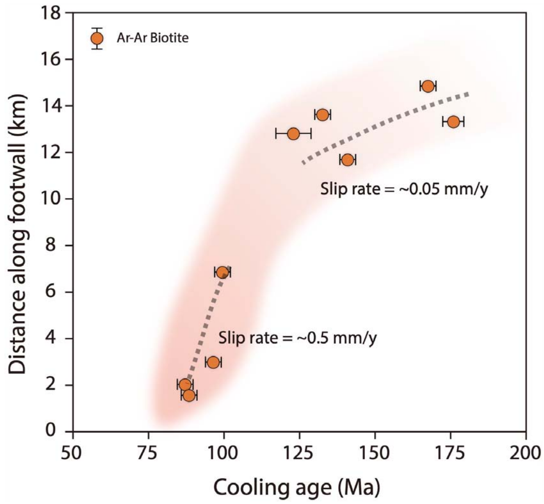

Figure 4. Sample ages plotted against fault-perpendicular distance from the Ziyuan Detachment. Age information and references are listed in Supplementary Table S1. The dashed lines are calculated in Excel by generating a trendline and a function of it. The slip rate is the slope of trendlines.

3.2. *Hengshan*

3.2.1. *Deformation pattern*

The Hengshan dome is located in the center of the SCB and adjacent to the Neoproterozoic suture zone (Figure 1). This extensional structure is bounded by a lengthy normal fault that controlled evolution of the Hengyang basin. The dome consists of a composite pluton intruding low-grade Neoproterozoic metasediments, and a large Early Cretaceous red-bed basin (Figure 5a). In the composite pluton, the east Nanyue pluton yields a Triassic age at ~230 Ma, while the west Baishifeng pluton crystallized in Early Cretaceous, around 150 Ma [Li et al., 2013]. The Jiepai Detachment acted as the main discontinuity separating the extensional basin and the Baishifeng pluton (Figure 5b). Geological and geophysical evidence on undeformed plutons points to a two-stage granite emplacement supplied by several magma channels [Wei et al., 2016].

The Jiepai detachment is ~5–8 km wide, deforming the western part of the Baishifeng pluton, as well as the western end of the Nanyue pluton [Zhang, 1994, Li et al., 2013]. Curving along the pluton, this ca 30° detachment developed a 2–4 km-thick fault zone by fluid injection and foliated or mylonitized the granite and micaschist with an average angle of 30° [Zhang et al., 2012]. Well-preserved mineral and stretching lineation and quartz microstructures indicate intermediate deformation temperature between 300–500 °C [Li et al., 2013, Wei et al., 2016].

The hanging wall is mostly undeformed. The lower part of the Cretaceous red bed continental deposits exposes poorly sorted conglomerates with some pebbles broken by tension gashes [Wei et al., 2016]. The major component of pebbles in the conglomerate derived from deformed and undeformed granite exposed by the detachment, suggesting a protracted activity of the detachment and an early un-

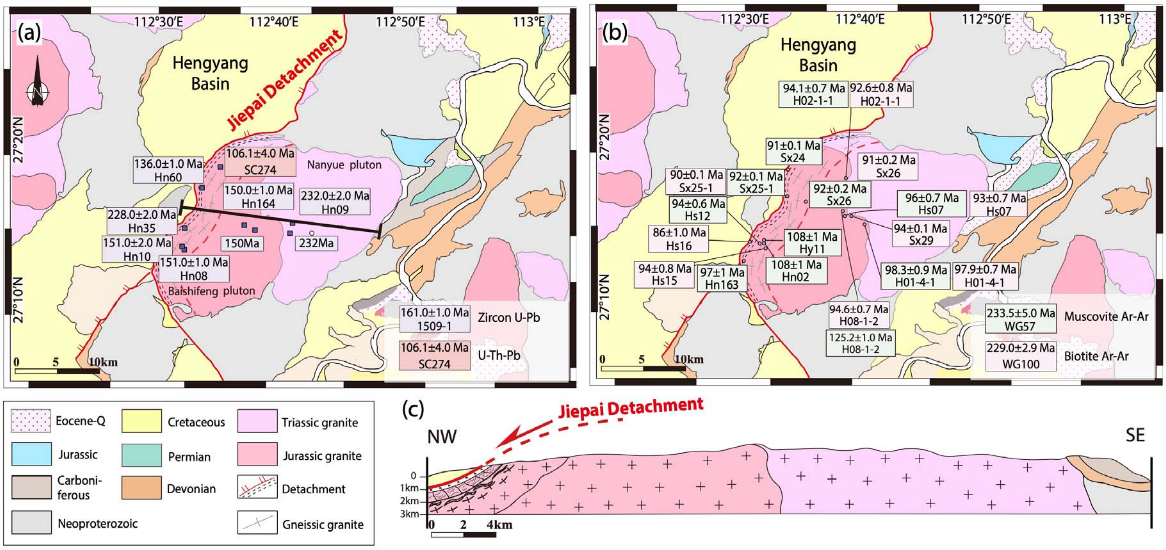

Figure 5. (a) Geological map, (b) map with published ages, and (c) cross-section of the Hengshan dome [modified from Li et al., 2013, Wei et al., 2016].

roofing of the pluton [Li et al., 2016]. The overlying Early Cretaceous lacustrine basin develops arrays of high-angle listric normal faults, suggesting syn-extensional deposition [Ge et al., 1994].

3.2.2. *Timing of deformation*

Several thermochronology studies have been conducted in the Jiepai detachment of the Hengshan dome [Li et al., 2013, 2016, Wang et al., 2015]. Age of the syn-deformation granitic veins and magnetic fabrics of magmatic rocks show an early stage of ductile shearing. Deformation in the shear zone occurred in Early Cretaceous coeval with or shortly after the pluton emplacement [Li et al., 2013, Wei et al., 2016]. As a matter of fact, the biotite and muscovite ^{40}Ar–^{39}Ar ages from mylonitic rocks cluster in 100–90 Ma, except for two ages at 108 Ma (Supplementary Table S1). These concentrated cooling ages show a major fault movement period at early Late Cretaceous. During this time, the fault slip rate reaches values as high as 2.4 mm/y if we use biotite ^{40}Ar–^{39}Ar ages for calculation (Figure 6). Although the early fault activity has some indirect evidence, it is still less robust because the late event has strongly overprinted the early deformation fabrics and thus uplifted and eroded those rocks bearing early information.

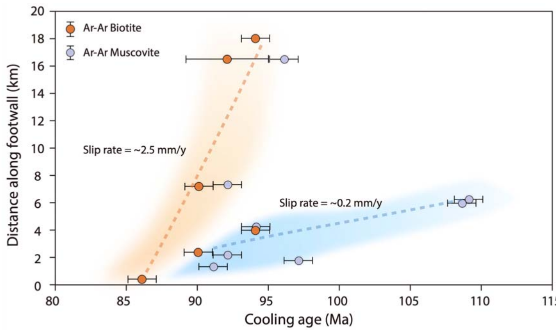

Figure 6. Sample ages plotted against fault-perpendicular distance from the Jiepai Detachment. Age information and references are listed in Supplementary Table S1.

3.3. *Dayunshan*

3.3.1. *Deformation pattern*

The Dayushan (-Mufushan) dome is one of the largest Mesozoic plutons in the north SCB (Figure 1). Two phases of magmatic rocks form this composite pluton (Figure 7a,b), including a Late Jurassic biotite granite of ~150 Ma, and Early Cretaceous two-mica granites of 131–127 Ma [Wang et al., 2014, Ji et al., 2017]. Host rocks of these plutons are micaschist, phyllite and slate, derived from Neoproterozoic to Early Paleozoic sandstone and mudstone protoliths [Shi et al., 2013]. The contact metamorphism produced biotite, muscovite, garnet, and andalusite. The Dayunshan detachment is restricted to the NW border, bounding the Cretaceous to Paleogene basin filled by red beds [Ji et al., 2018b]. This detachment can be interpreted as the northeastern extension of the Ziyuan Detachment of the Yuechengling dome (Figure 1). At the southeast margin, a brittle normal fault strikes parallel to the Dayunshan detachment and probably develops in the similar tectonic setting [Wang et al., 2014].

The narrow ductile shear zone varies from 100 to 2000 m in the Dayunshan dome (Figure 7c). Within the detachment and footwall, deformation increases from protomylonitic to mylonitic granite. Cataclastic and brecciated mylonite argues for a brittle overprint on the detachment. Consistent NW–SE trending lineation is common on foliation parallel to the tongue-shaped pluton margin and kinematic indicators show top-to-the NW shearing [Ji et al., 2018b]. Mineral microstructures imply a deformation temperature at 400–500 °C [Ji et al., 2018b]. This structural observation also concurs with rock magnetic fabrics on post- and sub-solidus deformation in granites of the west, suggesting a syn-tectonic emplacement of the Early Cretaceous pluton [Ji et al., 2018a,b]. In the hanging wall, conglomerate with granite pebbles lays on top of the fault plane, as a direct indicator of tectonic unroofing and erosion of the pluton.

A Late Jurassic compression occurred during the Late Jurassic granite emplacement. This compressional deformation foliated the margin of biotite granite and folded and sheared the host rocks by top-to-the SSW kinematics at ~150 Ma [Ji et al., 2018b]. Intracontinental compression can explain the tectonic impact here and in the adjacent Jiuling belt as well [Chen et al., 2014, Li et al., 2016].

3.3.2. *Timing of deformation*

The deformation stages correlate with the granite emplacement, which are precisely constrained by zircon U–Pb ages of ~150 Ma and ~130 Ma, respectively (Figure 7b). Compression appeared at ~150 Ma, and the detachment only preserved one stage of extensional deformation between 135 Ma and 120 Ma [Ji et al., 2018b]. In contrast, the thermochronology data reveal a two-staged cooling pattern, one fast cooling at ~120 Ma, and one slower cooling at ~95 Ma. During the Early Cretaceous, the detachment was active at a high rate of ~1.5 mm/y (Figure 8). From 120 Ma to 95 Ma, the detachment slowly slipped at a very low rate, or possibly became inactive. During the Late Cretaceous, the existed detachment resumed its normal faulting activity and exhumed the previously mylonitized rocks [Ji et al., 2018b].

3.4. *Lushan*

3.4.1. *Deformation pattern*

The Lushan dome almost reaches the north margin of the Yangtze Craton (Figure 1). This dome has been considered as an extensional structure since the 1990s [Xiang et al., 1993]. Then Lin et al. [2000] carried out a careful structural investigation to establish multi-phased deformation and tectonic architecture of this area. This dome has a NW–SE trending elliptical shape cored by Mesozoic metamorphic rocks with Neoproterozoic protolith ages [Lin et al., 2000, Wang et al., 2013a, Yang et al., 2015, 2017]. A complex deformation history that includes at least four phases since the Phanerozoic has been recorded due to the influence from the Dabie orogenic belt and Triassic orogenic belt of the SCC [Faure et al., 1998, 2016, Chu et al., 2012]. The first two pre-Cretaceous events are related to the Late Paleozoic to Triassic collision between the SCB and NCC, causing an amphibolite-facies metamorphism in the Neoproterozoic–Paleozoic series [BGMRJX (Jiangxi Bureau of Geology and Mineral Resources), 1984, Lin et al., 2000]. The latter two played a key role in the formation of the Lushan dome during Cretaceous and the prevailing NE–SW-striking structures with NW–SE kinematics.

The phase of deformation of the detachment is still debated because of multiphase tectonic overprinting. The core of the Lushan dome is Cretaceous granites and metamorphic rocks. A NW-dipping main detachment, the Wenquan Fault, controlled the deformation and exhumation in the Cretaceous [Zhu et al., 2010a,b, Yang et al., 2015], while the Wuli Fault acted as a brittle–ductile boundary normal fault accompanied with brittle faulted rocks (Figure 9c). The detachment consists of secondary shear zones and normal faults at the west flank, separating the

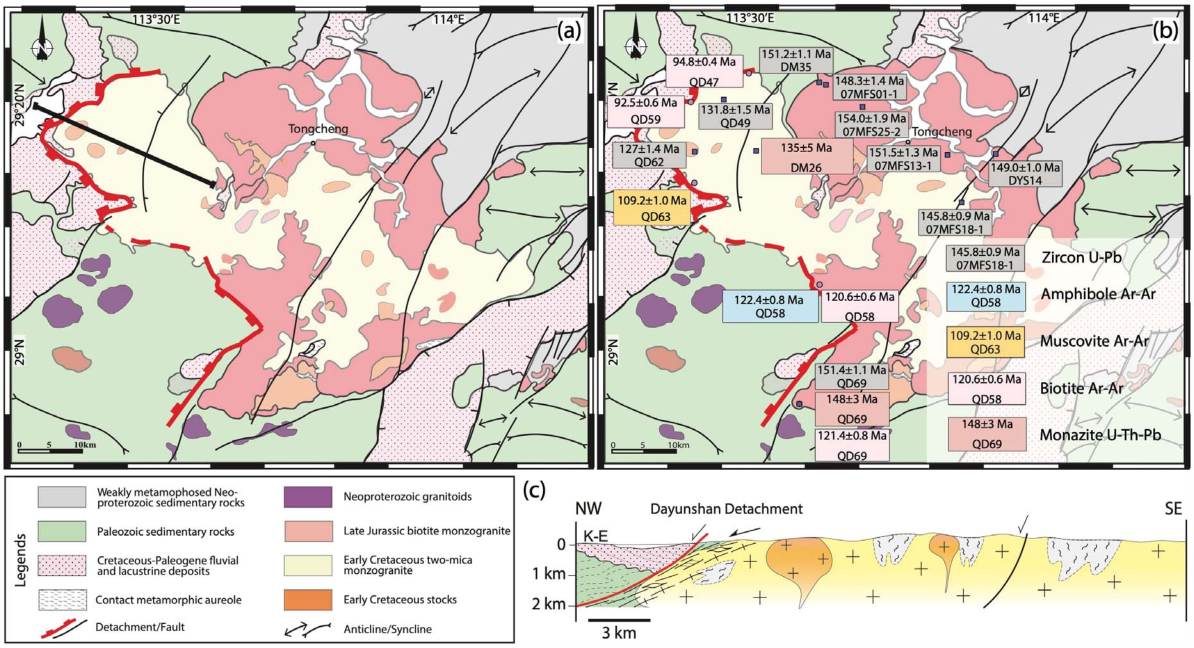

Figure 7. Geological map (a), map with published ages (b), and cross-section (c) of the Dayunshan dome [modified from Ji et al., 2018a,b].

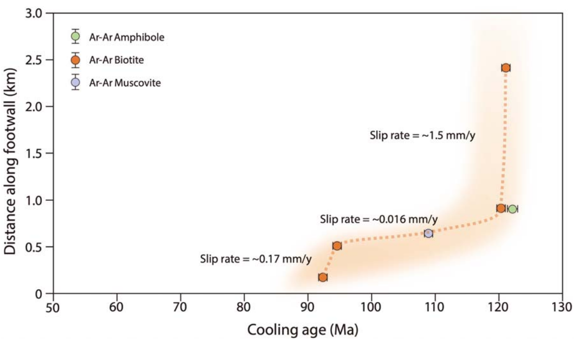

Figure 8. Sample ages plotted against fault-perpendicular distance from the Dayunshan Detachment. Age information and references are provided in Supplementary Table S1.

metamorphic rocks in the center, the Neoproterozoic sedimentary-volcanic unit, and the Late Neoproterozoic (Sinian) sedimentary rocks (Figure 9a,c). The low-grade metamorphic units above the gneissic core are characterized by dip-slip ductile deformation towards the NW, and quartz fabrics from metamorphic rocks determine the deformation temperature at 300–400 °C [Lin et al., 2000, Yang et al., 2015]. The Wuli fault cutting this dome at the east flank, and later, brittle, top-to-the SE normal faulting crosscut early extensional structures [Lin et al., 2000]. Hence, the Lushan dome is an atypical extensional dome with bivergent but diachronous slip sense at its two flanks. The detachment system of the west and its related ductile deformation controlled the doming process, while brittle normal faulting finally established the current geometry.

3.4.2. *Timing of deformation*

Previous studies on U–Pb dating clearly revealed an Early Cretaceous metamorphic core of the Lushan dome (Figure 9a,b). Except analysis in Sinian rocks, zircon and titanite U–Pb ages of the metamorphic core range from 127 Ma to 180 Ma, peaking at ∼135–140 Ma [Lin et al., 2000, Yang et al., 2015]. The ^{40}Ar–^{39}Ar cooling ages are younger with one major group from 105 to 95 Ma and another group around 125 Ma [Lin et al., 2000, Zhu et al., 2010a,b, Yang et al., 2017]. Relating this age difference between U–Pb

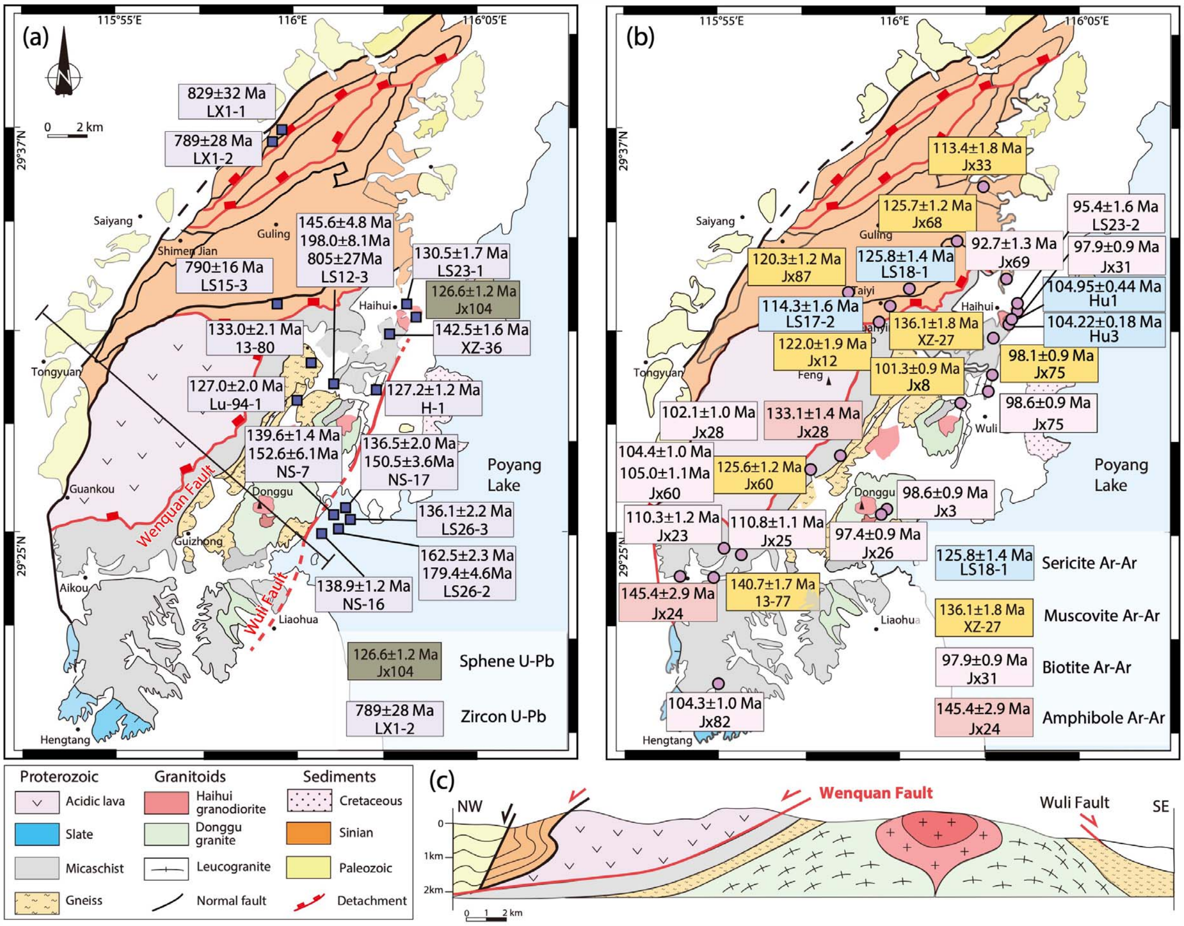

Figure 9. Geological map (a), map with published ages (b), and cross-section (c) of the Lushan dome [modified from Lin et al., 2000].

and ^{40}Ar–^{39}Ar methods to the temperature difference between intermediate-temperature ductile deformation and amphibolite-facies metamorphism, we find that NW–SE extension may postdate the metamorphism in the core, and can be identified with a low-temperature ductile phase in Early Cretaceous and a lower temperature brittle phase in Late Cretaceous. The early phase has a slow cooling because of a low slip rate of the detachment, while the late brittle normal faulting leads to a relatively fast cooling with a higher fault slip rate (Figure 10).

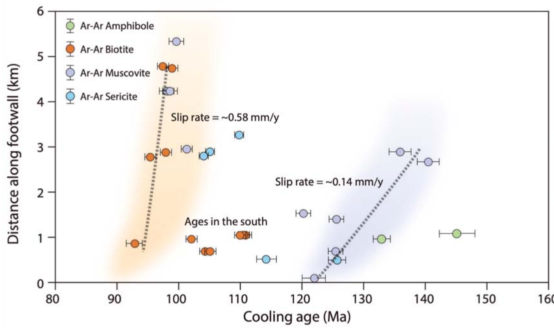

Figure 10. Sample ages plotted against fault-perpendicular distance from the Lushan Detachment. Age information and references are listed in Supplementary Table S1.

3.5. *Lianhuashan*

3.5.1. *Deformation pattern*

The Lianhuashan dome is a newly discovered extensional dome. It situates in the south of the SCB, far from the rest of extensional domes located in the central or northern SCB (Figure 1). This structure has the same NE–SW long-axis as other domes but mainly consists of Mesozoic rock assemblages, including Jurassic to Cretaceous batholith, Early to Middle Jurassic sedimentary rocks, Jurassic to Cretaceous volcanic rocks and Late Cretaceous sediments [BGMRGD (Guangdong Bureau of Geology and Mineral Resources), 1988]. The Wuhua Fault represents the boundary detachment and juxtaposes the Cretaceous basin with the Lianhuashan batholith (Figure 11). Southwards, this fault connects the Danshui Fault and constitutes a 200 km-long ductile normal fault system.

In the north, the detachment bounded and deformed the Lianhuashan pluton with a 1–2 km thick ductile shear zone. NW-dipping (<30°) mylonitic foliation, NW-trending lineation and shear indicators demonstrate a top-to-the NW shear sense. Both quartz fabrics and *c*-axis orientation patterns imply an intermediate deformation temperature at 350–500 °C [Li et al., 2020]. The footwall includes Jurassic to Cretaceous volcanic rocks, Late Jurassic plutons, and Early Cretaceous sedimentary rocks [BGMRGD (Guangdong Bureau of Geology and Mineral Resources), 1988, Zhuo et al., 2011]. Two phases of shortening are reported in this unit under intermittent NW–SE compression. The early one forms 400–500 °C ductile shearing with top-to-the-W kinematics, and the late one only develops brittle strike-slip faults [Li et al., 2020].

In the hanging wall, Late Cretaceous conglomerate and sandstone are directly deposited on the detachment. Most of the pebbles are metasandstone, volcanic rocks, and granite from the footwall. These syn-tectonic deposits are also truncated by NE–SW striking brittle normal faults. The detachment activity can be divided into two stages, an early stage of ductile deformation and a late stage of brittle deformation [Li et al., 2020], but they may belong to the same stage developed in different structural levels.

The Lianhuashan dome witnesses the whole compression–extension cycles of the SCB in the Mesozoic [Li et al., 2020]. Its final geometry was controlled by its boundary detachment fault, the Wuhua Fault. This asymmetrical dome-detachment model resembles the other extensional domes, which all have a sole detachment at one side to form the half-dome geometry.

3.5.2. *Timing of deformation*

The Lianhuashan dome's granitic core was crystallized from 164 Ma to 153 Ma; then the overlying Jurassic-Cretaceous volcanic rocks covered this pluton between 155 Ma and 133 Ma (Figure 11b). Disregarding the compression, all cooling ages suggest that the extensional deformation accommodated by the Wuhua Fault was exclusively active in Late Cretaceous, leading to the rapid exhumation of the sheared rocks at 100–96 Ma [Li et al., 2020]. All the cooling ages are very concentrated, which also underpins a stronger Late Cretaceous extension during the episodic extension of the SCB.

4. Domes without detachment

Three other extensional structures without detachment faults formed during the two extensional phases. Some of them have early ductile shear zones with perpendicular kinematics to the regional NW–SE extension direction, and late NW–SE brittle–ductile extension. Because of a possible compressional origin, we do not ascribe these ductile shear zones to dome-forming structures. Below, we briefly introduce their structural and geochronological features that also suggest a widespread Cretaceous extension in the SCB.

4.1. *Wugongshan*

The Wugongshan dome is one of the first well-investigated extensional domes in the SCB. It was initially interpreted as a Triassic dome induced by the intracontinental deformation of the Dabie orogen [Faure et al., 1996]. Although this dome was once interpreted as a metamorphic core complex, the symmetrical normal sense ductile shearing at the northern and southern flanks refutes a Cordillera-type metamorphic core complex model which show consistent kinematics [Wernicke, 1981, Lister and Davis, 1989]. The Neoproterozoic to Paleozoic magmatic-metamorphic complex is separated from unmetamorphosed rocks by the Triassic ductile shear zones

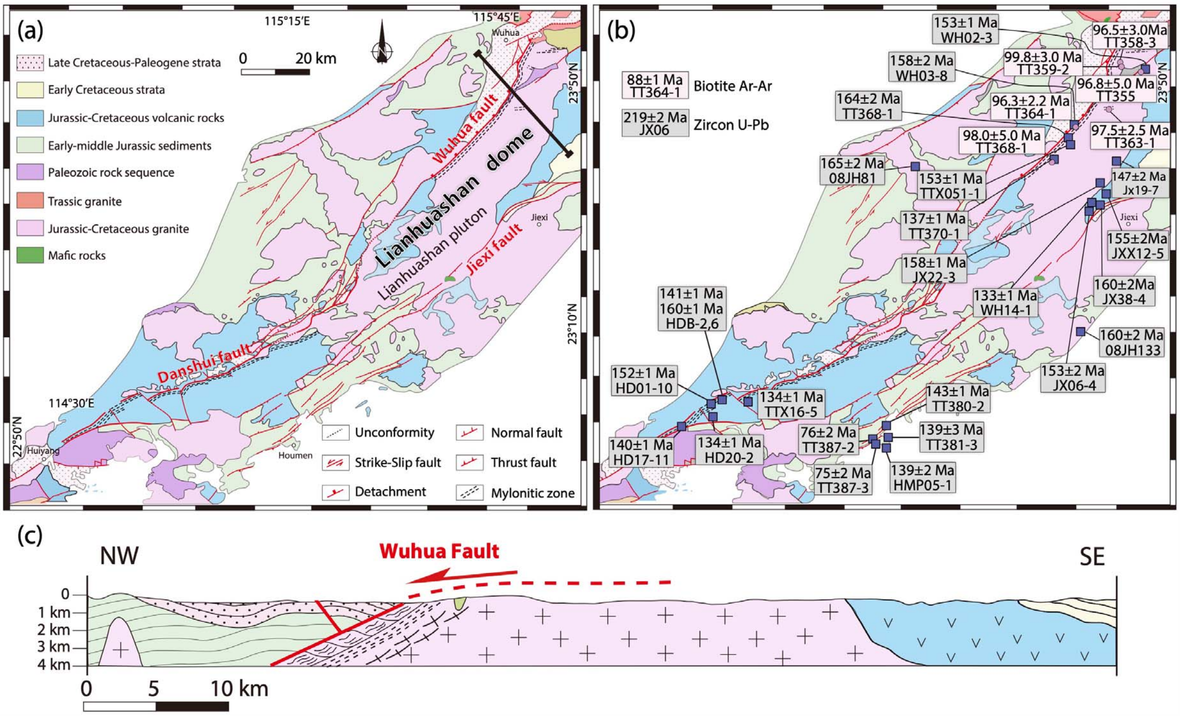

Figure 11. Geological map (a), map with published ages (b), and cross-section (c) of the Lianhuashan dome [modified from Li et al., 2020].

[Faure et al., 1996]. In the south, conglomerates are highly stretched in the Triassic sedimentary cover (Figure 12a). Two boundary ductile shear zones and their dip-slip activity formed this extensional structure, i.e. top-to-the N and top-to-the S shearing at the north and south margins, respectively (Figure 12c). The cooling ages of biotite and muscovite from mylonite clustered at 260–220 Ma suggest that the dominant deformation occurred in Permian-Triassic times.

Cretaceous extension across the SCB reactivated the dome and led to further uplifting and exhumation [Tang et al., 1991, Faure et al., 1996, Shu et al., 1998, Lou et al., 2002]. Ductile deformation with top-to-the S shear sense in the Cretaceous pluton and Early Cretaceous ^{40}Ar–^{39}Ar ages (~130 Ma) reveal a later event reactivating the boundary ductile faults. The related structures and their kinematic evolution to understand the Cretaceous doming process of Wugongshan, however, need more structural observation and thermochronology work to verify (Figure 12b).

4.2. *Hongzhen*

This dome preserves contrasting kinematics in the deep crustal units and the brittlely deformed hanging wall, reflecting a decoupled deformation pattern in this dome [Zhu et al., 2010a]. From east to west, the Hongzhen dome consists of undeformed Hongzhen granite, highly sheared Dongling metamorphic complex, Paleozoic strata, and Cretaceous half-graben basin (Figure 13) [Zhou et al., 1988, Zhu et al., 2010a]. Within the lower crustal unit, the Dongling complex displays a high-grade amphibolite-facies metamorphism, and extensive ductile shearing with a top-to-the SW sense. This stage is interpreted as an early shearing initiated at Late Jurassic to Early Cretaceous. Following this event is a second stage of NW–SE extension at ~128–120 Ma accompanied with the emplacement of the Hongzhen granite. NE–SW-striking brittle–ductile normal faults modified or cut the early structures in metamorphic rocks and the Paleozoic sedimentary cover [Zhu et al., 2007, 2010a,b, Liu et al., 2016], and established the final asymmetrical geometry with a low-angle boundary in the west and a high-angle boundary in the east.

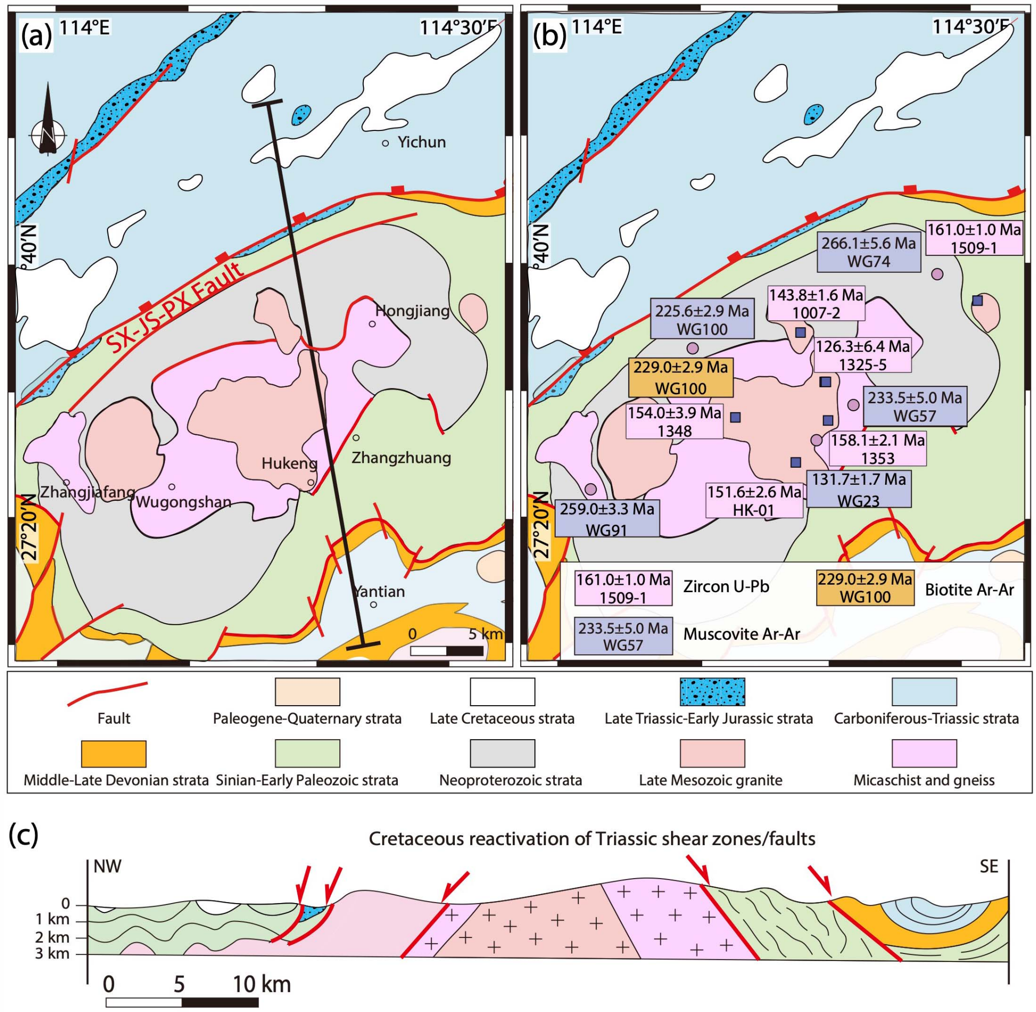

Figure 12. Geological map (a), map with published ages (b), and cross-section (c) of the Wugongshan dome [modified from Faure et al., 1996, Wang et al., 2014]. SX-JS-PX: Shaoxing-Jiangshan-Pingxiang.

Hence, this dome presents an early NE–SW deformation perpendicular to the late extension but is comparable with similar deformation recorded in Lushan and Dayunshan. Subsequently, the regional stress field changed to NW–SE extension and reshaped and exhumed the metamorphic core by NW-directed brittle–ductile shear zones.

4.3. *Huangling*

The Huangling anticline is a weakly deformed extensional dome without any tectonic discontinuities between the metamorphic basement and sedimentary cover (Figure 14). It has the oldest rocks of South China, the Kongling group of ~3.3–3.2 Ga, of the SCB [Qiu et al., 2000, Zhang et al., 2006a,b, Gao et al., 2011]. The Huangling granitoids of ~820 Ma intruded into the Archean to Paleoproterozoic basement rocks. On the both sides of the magmatic-metamorphic rocks, the sedimentary sequence is composed of Late Neoproterozoic to Jurassic rocks formations unconformably covering the basement rocks. This dome lacks a basal detachment. Cretaceous doming and uplifting exhumed the Huangling anticline, forming multi-horizon dip-slip in rheologically weak sedimentary layers and high-angle normal faults that controlled the Cretaceous red bed deposition of the eastern and western basins [Ji et al.,

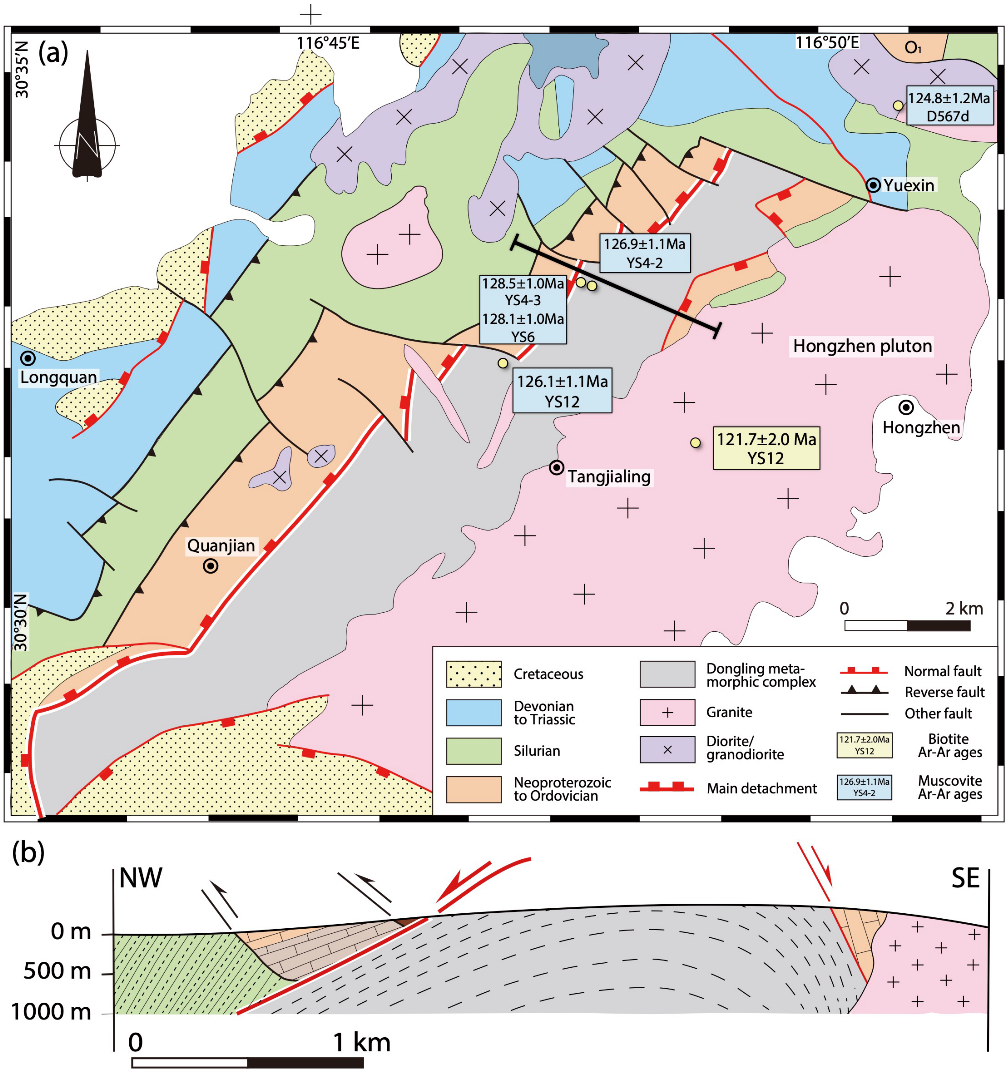

Figure 13. Geological map (a) and cross-section (b) of the Hongzhen dome [modified from Zhu et al., 2010a,b].

2014]. Sheared pebbles in pelitic matrix are good indicators to show a bivergent sense of extension, i.e., top-to-the W at its western margin, and top-to-the E at the eastern margin. The extension timing varies in different models, but structural and thermal modeling both reveal a long extensional process lasting from 160 Ma to 110 Ma [Hu et al., 2006, Shen et al., 2012, Ji et al., 2014].

5. Discussion

5.1. *Features of the two-stage extension*

Compilation of structural and geochronology data of the extensional domes in the SCB allows us to illustrate features of the extensional domes and thus establish the Cretaceous two-stage extension (Figures 16 and 17). Although the central part of all the domes is occupied by plutons of variable crystallization ages, they were formed in temporally and spatially heterogeneous continental extension

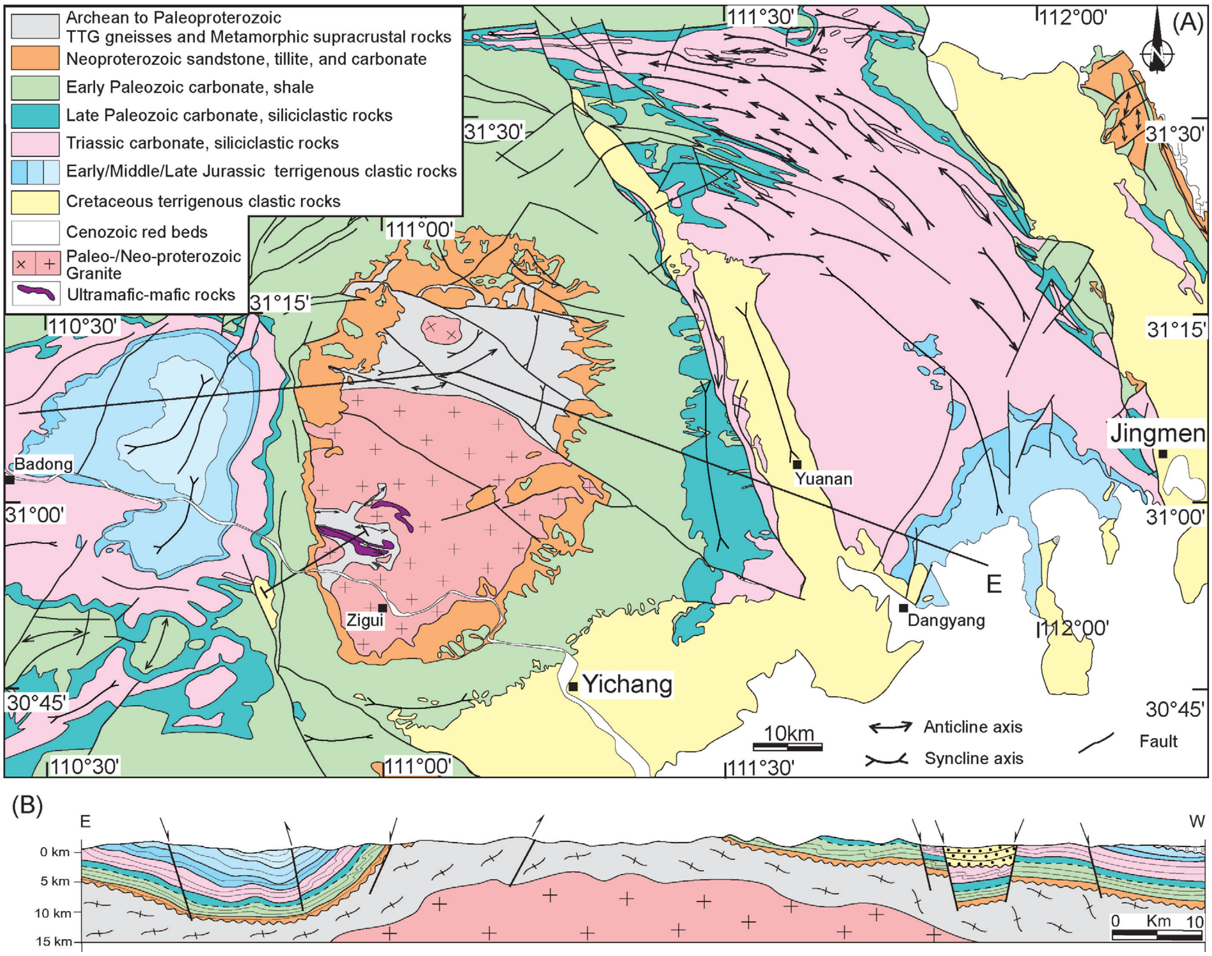

Figure 14. Geological map (A) and cross-section (B) of the Huangling dome [modified from Ji et al., 2014]. Ar–Ar ages are not shown because they are all Precambrian and not related to Cretaceous doming.

of the SCB. Firstly, their geometry varied when the crust of the SCB was stretched in the Cretaceous. There are three types of domes, (1) domes exhumed by a single detachment, (2) domes exhumed by a detachment with a high-angle normal fault, and (3) domes exhumed by buoyant doming without a detachment. Among the SCB domes, four of them that belong to type 1: Yuechengling, Hengshan, Lianhuashan, and Dayunshan (Figure 15a), while two domes, Lushan and Hongzhen, are type 2 domes showing quasi-symmetrical extension. The two types both have a shallow-dipping detachment at the western margin of the domes. They also develop northwest/west-dipping foliation and top-to-the NW/W shear sense. Ductile deformation formed in the similar thermal condition, at middle to high greenschist facies around 300–500 °C. In contrast to type 1, the type 2 domes developed high angle faults at the eastern sides (Figure 15b). These later faults cut the early, low angle foliation, facilitated the exhumation of the core pluton and metamorphic rocks, and finalized the shape of the domes. Type 3 domes (Figure 15c) including Wugongshan and Huangling show Cretaceous cooling and the corresponding deformation is mostly brittle faulting and layer-slip that accommodate the extension. This type of doming processes results in buoyancy-dominated exhumation that exposed the mid-crustal rocks and the overlying sedimentary cover, and forms several normal faults to accommodate crustal extension instead of a sharp discontinuity/detachment.

Secondly, inconsistent timing of doming coincided with the varied dome structures, showing single or two-staged extension. Among them, Yuechengling, Lushan, Dayunshan, Lianhuashan, Hengshan, and Huangling are those which carry two-stage structural information, while Hongzhen and Wugongshan only preserve one stage of extension during the Early Cretaceous (Figure 16). The Early Cretaceous extension abounds in the eastern half of the SCB and is thermochronologically imprinted in every extensional dome, whereas the Late Cretaceous extension seems more localized and intense. Estimation of detachment activities shows that those domes that have experienced two-staged stretching display a faster detachment slip rate in Late Cretaceous than that of Early Cretaceous (Figures 4, 8 and 10). Structural evidence from the Yuechengling dome explicitly displays two extensional phases in the Tianhu Fault and Ziyuan Detachment [Chu et al., 2019, Feng et al., 2022b]. The first stage developed limited extension and exhumation, while the second stage has greater extension and deformation in this dome. The evidence supports a weaker extension during the early extension, and a faster and stronger extension in the later extension.

The two stages of extension characterize the Cretaceous tectonic evolution of the SCB by heterogenous deformation in the extensional domes. The higher rates of detachment (Figures 4, 6, 8 and 10) and crustal stretching of the Late Cretaceous extension also reflect a significant change of thermal state and structure of the South China lithosphere.

5.2. *Implications to lithosphere thinning/destruction of South China*

Since the identification of the MCC in the Western North America, continental extension has become an important continental tectonics revolutionizing our understanding of continental deformation [Davis and Coney, 1979, Wernicke, 1981]. The East Asia continent at the western Pacific margin is an important example of back-arc continental extension [Zhou et al., 2006, Li et al., 2014, Chu et al., 2019]. As the southern component, the SCB underwent significant tectonic reworking in this period, which consists of distinctive compression–extension intervals. This cyclical intracontinental compression and extension imposed by the subduction dynamics modified the lithosphere of the SCB and can be defined as another archetype of lithosphere thinning or destruction. Synthesis of the extensional domes reveals a stronger and faster deformation stage in the Late Cretaceous. In contrast, a major magmatic flare-up occurred in the Early Cretaceous, while in the Late Cretaceous flare-up produced less plutons and scarce volcanic formations (Figure 2b,c). The two stages of extension and related volcanism spatially overlap in a ~1000 km wide region of the central and eastern SCB. Their varied deformation patterns and settings may reflect thermal, compositional, and structural change of the lithosphere state between the two periods.

The Yangtze Block preserves a cratonic core in the Sichuan Basin whose lithosphere exceeds 150–180 km thick, while the rest of the block has a thinned lithosphere of ~100 km thick [Zhang et al., 2018, Deng et al., 2021]. The sparse distribution of Archean to Paleoproterozoic rock assemblages likely denotes an originally larger cratonic lithosphere beneath the Yangtze Craton [Zhang and Zheng, 2013, Tian et al., 2022]. Similar to the well-studied North China Craton destruction [Zhu et al., 2012, 2021, Wu et al., 2019, Lin and Wei, 2020], the Yangtze Craton also underwent extensive thinning of its lithosphere compensated by the Cretaceous crustal extension. During the Early Cretaceous extension, extensional domes popped up along a weak zone of the SCB, the Neoproterozoic suture zone of the JSF and CLF or the Triassic Xuefengshan–Jiuling Belt (Figure 1). Along this zone, detachments localize the deformation and stretch the crust under mid to high temperature (400–500 °C). Away from the weak zone, coeval deformation was either absent (Lianhuashan), or localized at high-angle brittle–ductile (~300 °C) normal faults (Yuechengling). Less deformed zones to the east and west of this N–S line of dome indicate a rigid, cool, and less modified lithosphere resistant to deformation. In the Late Cretaceous, extension propagated westerly and easterly and triggered mid to high-temperature (400–500 °C) ductile deformation in the neighboring regions, including Yuechengling and Lianhuashan domes. As exemplified in Yuechengling, the Late Cretaceous ductile shearing has a higher temperature and extension amount that the Early Cretaceous [Feng et al., 2022b]. It thus suggests a warmed, thinned and

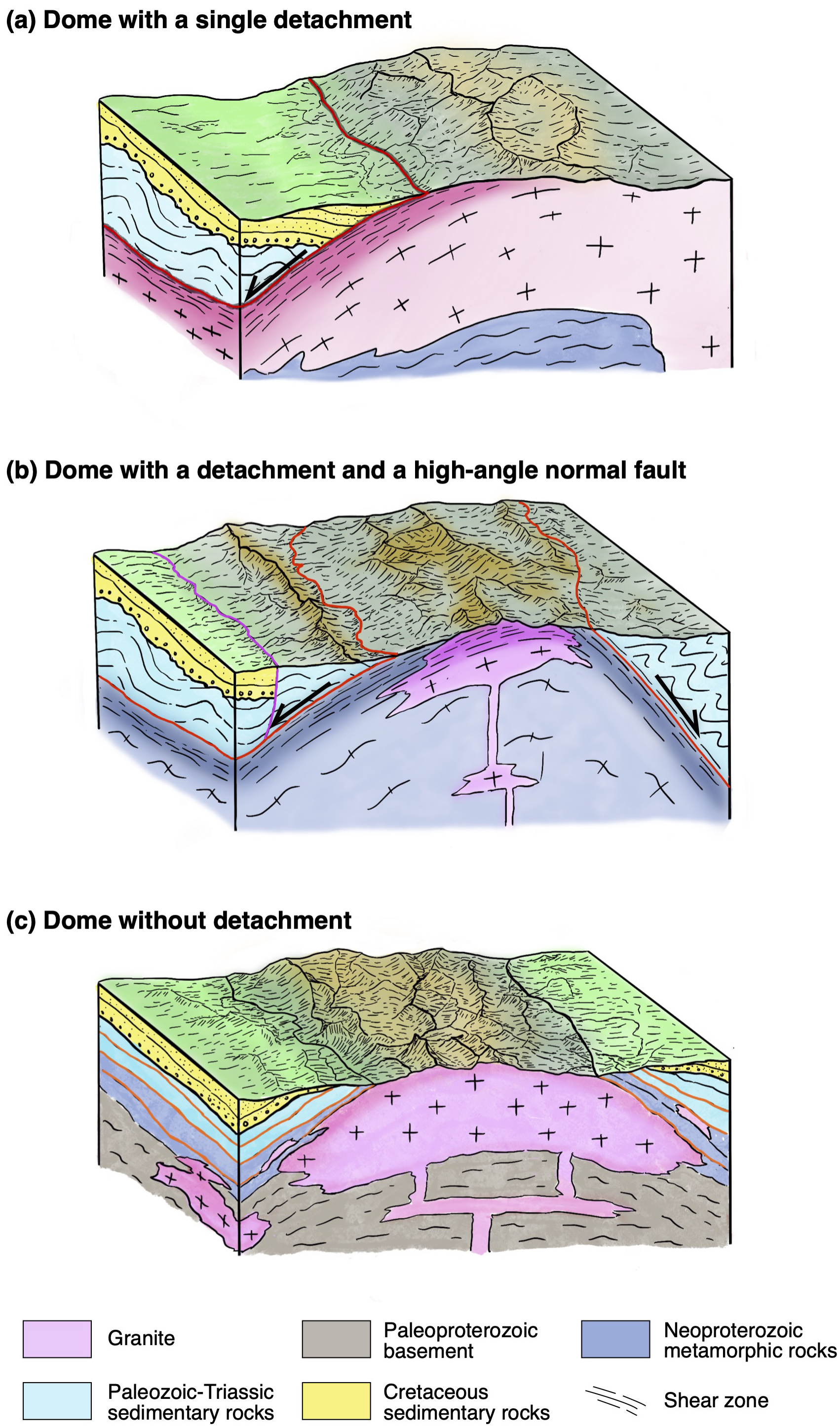

Figure 15. Geometry of the three types of domes. (a) Dome with one dominant detachment. (b) Dome with one detachment and one high angle fault both controlling the extensional process. (c) Dome formed by buoyant doming process without detachment. Note that there may be several slip layers within the sedimentary cover of the central granite.

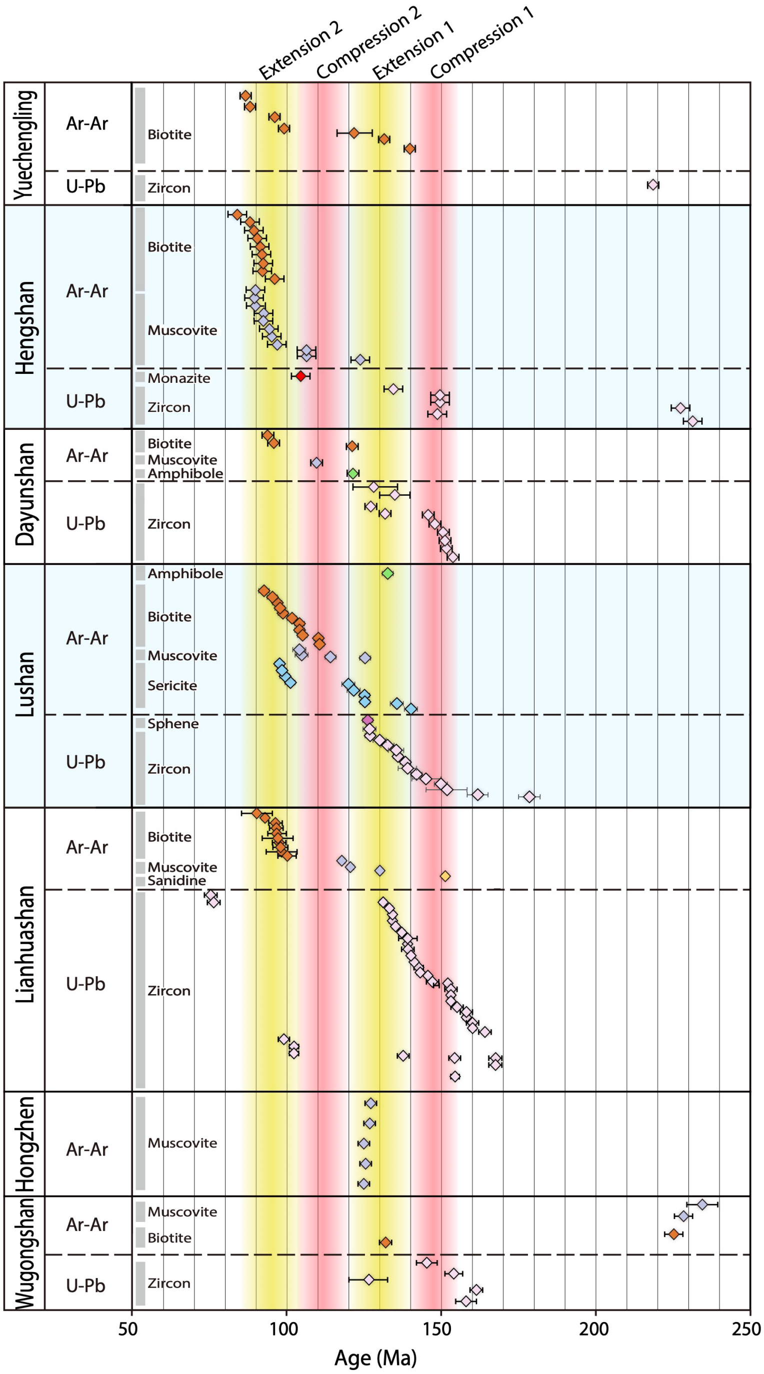

Figure 16. Age summary of all extensional domes with detachments reviewed in the text. Data are compiled in the Supplementary Table S1 of the appendix data. Different dating methods are indicated with colors.

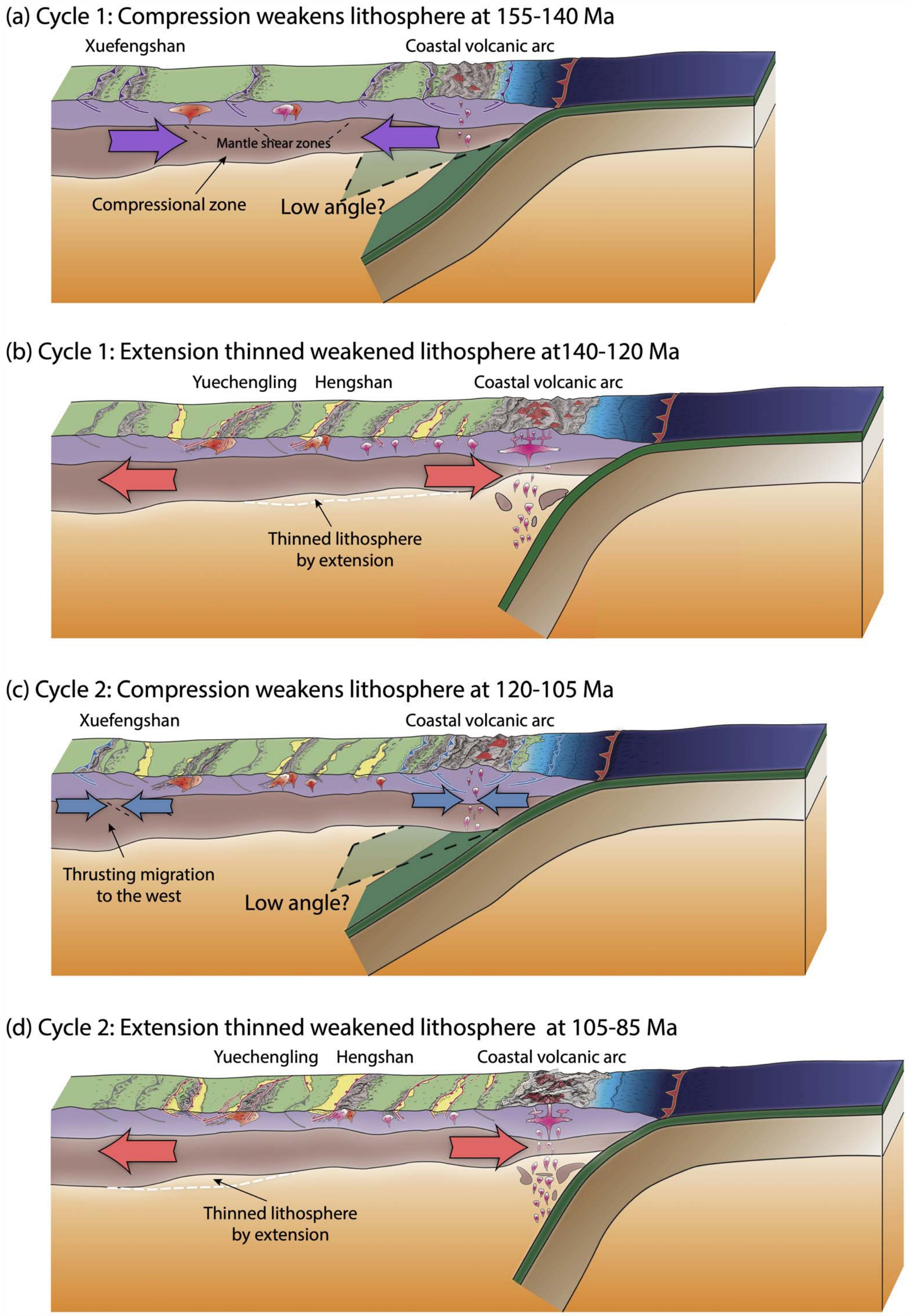

Figure 17. Tectonic models showing how cyclical reworking thinned the lithosphere of the SCB [modified after Chu et al., 2019, 2020].

easily deformed lithosphere of Late Cretaceous, and a cool and thick lithosphere in Early Cretaceous. This lithosphere thinning or destruction beneath Yuechengling or the adjacent regions along-strike occurred in the Late Cretaceous. Thus, the Early Cretaceous extension manifests a deep lithosphere removal along the JSF and CLF, and the Late Cretaceous extension enlarged this removal as attested by detachment in the further west regions.

Finally, we propose a progressively lithospheric thinning model to explain the process that destructed or dismembered the lithosphere of the Yangtze Craton. The SCB experienced a unique, cyclical compression–extension tectonic reworking in which both compression and extension facilitate the propagated lithospheric thinning. The first compression occurred in Late Jurassic-Earliest Cretaceous in response to the shallow subduction of the Paleo-Pacific slab [Chu et al., 2019, Li et al., 2020]. It shortened the crust of the interior SCB, and more importantly, it deformed the crust and the subcontinental lithosphere by creating thrust fault systems rooted in the JSF-CLF, a weak zone within the SCB (Figure 17a). These faults modified the lithosphere and generated weak zones within the lithosphere. The first extension and magmatism resulted from the Paleo-Pacific slab roll-back in the Early Cretaceous and caused the eastern edge of the thick lithosphere of the Yangtze Craton to dismember and collapse. This is the first stage of destruction that breached ~200 km wide of lithosphere (Figure 17b). Subsequently, the second phase of compression resulted from the shallowing of the subducted Paleo-Pacific slab and shut the regional magmatism in the SCB [Chu et al., 2019]. Within the SCB, the deformed zone migrated towards the Sichuan Basin and ruptured the crust and lithospheric mantle beneath Xuefengshan, where the lithosphere was intact or less destructed during the first stage of extension (Figure 17c). During the second stage of extension when the Paleo-Pacific slab rolled back again in Late Cretaceous, the lithosphere repeated the destruction process (Figure 17d). Extension was accommodated in detachments and normal faults that inversed the previous thrust faults. This extension detached the lithosphere of the Xuefengshan Belt, and therefore enlarged the lithosphere damage toward the west by another ~200 km. The rapid change of regional stress provoked switch between compression and extension, which resulted in a gradually destructed cratonic lithosphere, where lithosphere thickness varies significantly beneath the Xuefengshan Belt and eastern end of the East-Sichuan Thrust Belt [Deng et al., 2021]. In the second stage, our work suggests a more intense extension, but the magmatic response is weaker than the Early Cretaceous extension. One possibility is that the subduction zone dynamics is different between the two extensional stages. A less input of fluid-rich sediments or steep subduction after roll-back commonly cause less magmatism or restricted magma at the very east margin of South China. Another possibility is that the underlying lithosphere had already been extracted in the Early Cretaceous, thus became more refractory during the second extensional stage, so that the magma was less abundant in the later but stronger extension stage.

By compiling the existing data of extensional domes of the SCB, we propose a new model of multi-stage lithospheric destruction for the SCB (Figure 17), that is different from the fierce delamination of the North China Craton. This inconsistency between cyclical magmatism and deformation contrasts with the North China Craton where magma production is proportional to lithospheric extension, which culminated at ~130 Ma [Wu et al., 2008, Lin and Wei, 2020, Liu et al., 2021]. A long-lasting slab roll-back and continuous fluid injection promoted a rapid and extensive lithosphere delamination [Chen et al., 2008, 2014, Zhu et al., 2012, Wu et al., 2019]. Another endmember of mechanic lithospheric destruction operated in Mesozoic South China. Fast change of compression and extension prevented large-scale delamination but gradually and progressively impaired the thick cratonic lithosphere. This model concurs with recent geophysical observations in which several SE-dipping structures have been identified in the lithosphere of the Yangtze Craton. Their parallel distribution and NE–SW striking may preserve the tectonic advancing of cyclical intracontinental belts from SE to NW resulted from Paleo-Pacific subduction dynamics [Li et al., 2022, 2023].

6. Conclusion and perspectives

The Mesozoic Paleo-Pacific subduction systems at the East Asian continental margin produced a peculiar compression–extension cycle that greatly impacted the intracontinental tectonics of the South China Block. We synthesize the structural pattern and timing of the extensional domes in this highly reworked continental block and propose a new mode of lithospheric destruction. In contrast to the swift, one-cycle lithosphere delamination of the North China Craton, the destruction process operates in a cyclical, progressive manner in which compression destabilized the edge of the cratonic lithosphere and the following extension destructs the unstable part to thin the lithosphere. This process, as an endmember of lithospheric destruction mechanisms, requires cyclical tectonics of the subduction zone and the overriding plate, which has been widely reported in the Cordilleras of the eastern Pacific margin [DeCelles et al., 2009, 2015], and East Asia of the western Pacific margin [Chu et al., 2019, Meng and Lin, 2021]. The progressive lithosphere destruction model may also explain how ancient cratons shrink by subduction-related tectonics.

This working model still need further geological and geophysical investigation to verify the detailed process. Most extensional domes situate at the both sides of the Jiangshan-Shaoxing and Chenzhou-Linwu faults (Figure 1). Recent work exposes some new extensional domes and detachments [Chu et al., 2019, Li et al., 2020], but it remains poorly understood whether unidentified domes are developed in the exterior of this region. Precise reconstruction of the two extensional stages also requires the stretching amount and rate of all detachments, as well as cross-continent evaluation on thermal status of lithosphere. This work intends to attract more attention to the SCB which carries so much and so distinct information for continental reworking, with a craving for a complete view on the lithosphere destruction and new light to continent formation-reworking-destruction processes.

Declaration of interests

The authors do not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and have declared no affiliations other than their research organizations.

Acknowledgements

We thank two anonymous reviewers for their insightful comments and suggestions. We appreciate the insightful discussion with Dr. Fuyuan Wu and Dr. Ling Chen. This work also benefited from the discussions in Coffice 442 in IGGCAS. All data in this study are provided in the appendix files.

Supplementary data

Supporting information for this article is available on the journal's website under https://doi.org/10.5802/crgeos.245 or from the author.

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