SCIENCE CHINA
Earth Sciences

SPECIAL TOPIC: Destruction of craton and subduction of western Pacific plate
•REVIEW•

April 2018 Vol.61 No.4: 386–405
https://doi.org/10.1007/s11430-017-9136-4

Oceanic plate subduction history in the western Pacific Ocean: Constraint from late Mesozoic evolution of the Tan-Lu Fault Zone

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Received June 27, 2017; revised November 2, 2017; accepted November 7, 2017; published online January 31, 2018

Abstract The NE- to NNE-striking Tan-Lu Fault Zone (TLFZ) is the largest fault zone in East China, and a typical representative for the circum-Pacific tectonics. Its late Mesozoic evolution resulted from subduction of the Paleo-Pacific Plate, and can be used for indication to the subduction history. The TLFZ reactivated at the end of Middle Jurassic since its origination in Middle Triassic. This phase of sinistral motion can only be recognized along the eastern edge of the Dabie-Sulu orogenis, and indicates initiation of the Paleo-Pacific (Izanagi) Plate subduction beneath the East China continent. After the Late Jurassic standstill, the fault zone experienced intense sinistral faulting again at the beginning of Early Cretaceous under N-S compression that resulted from the NNW-ward, low-angle, high-speed subduction of the Izanagi Plate. It turned into normal faulting in the rest of Early Cretaceous, which was simultaneous with the peak destruction of the North China Craton caused by backarc extension that resulted from rollback of the subducting Izanagi Plate. The TLFZ was subjected to sinistral, transpressive displacement again at the end of Early Cretaceous. This shortening event led to termination of the North China Craton destruction. The fault zone suffered local normal faulting in Late Cretaceous due to the far-field, weak backarc extension. The late Mesozoic evolution of the TLFZ show repeated alternation between the transpressive strike-slip motion and normal faulting. Each of the sinistral faulting event took place in a relatively short period whereas every normal faulting event lasted in a longer period, which are related to the subduction way and history of the Paleo-Pacific Plates.

Keywords Tan-Lu Fault Zone, Sinistral displacement, Extensional activity, Izanagi Plate, Pacific plate

Citation: Zhu G, Liu C, Gu C C, Zhang S, Li Y J, Su N, Xiao S Y. 2018. Oceanic plate subduction history in the western Pacific Ocean: Constraint from late Mesozoic evolution of the Tan-Lu Fault Zone. Science China Earth Sciences, 61: 386–405, https://doi.org/10.1007/s11430-017-9136-4

1. Introduction

A major fault zone is a weak zone in lithosphere, thus sensitive to tectonic motion, and a good indicator for regional dynamic evolution in return. Tectonic evolution in an active continental margin is controlled by oceanic plate subduction, and is considered as indication to the subduction way and process of an oceanic plate. A major fault zone in the active continental margin, especially one parallel to a trench zone, is also an ideal recorder for the oceanic plate subduction and coupling relation between tectonism in a continental margin and the subduction. In this context, the huge Tan-Lu Fault Zone (TLFZ) in East China is a key window for revealing subduction history in the western Pacific region.

The NE- to NNE-striking TLFZ, the largest fault zone in East China, shows parallelism to the subduction zone strike in the western Pacific Ocean. Many studies (Okay and Şengör, 1992; Yin and Nie, 1993; Li, 1994; Lin and Li, 1995; Chung, 1999; Gilder et al., 1999; Zhang et al., 2007; Zhu et al., 2009; Zhao et al., 2016; Li et al., 2017) demonstrate that the fault zone originated in the Middle Triassic when the North China Craton (NCC) collided with the South China

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Block, and reactivated for several times in response to oceanic plate subduction in the western Pacific region. It is widely accepted that the poly-phases of motion along the TLFZ resulted from the subduction in the western Pacific region (Xu et al., 1987, 1993; Xu and Zhu, 1994; Zhang et al., 2003; Zhu et al., 2004; Zhu G et al., 2005, 2010, 2012; Wang, 2006; Mercier et al., 2007; Gu et al., 2016; Gu et al., 2017). Previous studies considered the sinistral faulting of the TLFZ as result of oblique compression or transpressive shearing due to low-angle, high-speed subduction in the western Pacific region (Xu et al., 1987, 1993; Zhu et al., 2004; Zhu et al., 2005, 2010; Wang, 2006; Gu et al., 2016), and the normal faulting as an response to the far-field, backarc extension related to rollback of the subducting oceanic plate (Zhang et al., 2003; Zhu G et al., 2012; Mercier et al., 2007; Gu et al., 2017). The NCC was involved in lithospheric thinning and craton destruction in the late Mesozoic under the dynamic setting of the oceanic slab rollback (Zhu R X et al., 2012). Insights into dynamic relation between the eastern NCC and the Paleo-Pacific (Izanagi) slab is crucial for further understanding the craton destruction and the continental margin evolution in the late Mesozoic.

In recent years, detailed studies on the TLFZ provide important information for revealing dynamics from the Paleo-Pacific slab in the late Mesozoic. This paper focus on summary of structural features and evolution history of the TLFZ in late Mesozoic, and reviews recent progress in studies of the fault zone. We tentatively use the late Mesozoic evolution of the fault zone to constrain subduction details of the Paleo-Pacific slab as well as dynamic processes of the NCC destruction.

2. Outline of the Tan-Lu Fault Zone

The TLFZ starts at Wuxue in Hubei Province, and extends northwards to Lujiang in Anhui Province, Tancheng in Shandong Province and Shenyang in Liaoning Province where it separates into two branches, i.e. the Yilan-Yitong Fault in the west and the Dunhua-Mishan Fault, also called the Mishan-Fushun Fault, in the east (Figure 1). It strikes NNE-SSW with a length of ca. 2400 km. The fault zone passes by the South China Block, the Dabie-Sulu orogens, the NCC and the Xingmeng Orogen in the eastern Central Asian orogenic belt. The TLFZ occurs in the eastern NCC as a huge tectonic belt with many phases of activities.

The TLFZ started as sinistral ductile shear belts in the Middle Triassic when the NCC collided with the South China Plate (Zhang et al., 2007; Zhu et al., 2009; Zhao et al., 2016). It occurred between the Dabie and Sulu orogens during the initiation and did not extend into the present Bohai Bay region (Zhu et al., 2009; Zhao et al., 2016). The fault zone initiated as one of the Paleo-Tethys structures and reactivated in the circum-Pacific realm under the control of oceanic plate subduction in the western Pacific region (Xu et al., 1987, 1993; Zhu G et al., 2005, 2010, 2012).

The TLFZ experienced several alternation between strike-slip and normal faulting in the late Mesozoic (Zhu G et al., 2005, 2010, 2012), and thus recorded details of structural processes in the active continental margin. It was subjected to several phases of intense activities in the Cenozoic. The fault zone was involved in normal faulting in Paleogene, leading to basalt eruption and development of the Hefei Basin and the eastern Bohai Bay Basin (Ren et al., 2002; Zhu G et al., 2012) along it. The zone experienced local activity and basalt eruption under weak extension (Zhan et al., 2013) in the Neogene and reverse dextral faulting in the Quaternary. It is the largest earthquake activity zone in the eastern NCC (Liu et al., 2015; Zhu et al., 2015b).

The polyphases and poly-types of evolution caused overprinting of different structures in the fault zone. The Mesozoic strike-slip structures are preserved as ductile shear belts in metamorphic rocks locally. The Cenozoic structures appear as brittle structures produced by normal, reverse and strike-slip faulting that affect an up to 40 km wide zone as a whole. The polyphases of normal faulting produced a series of normal faults and controlled development of several rifted basins, such as the Hefei Basin to the west of the Anhui part of the fault zone, the Yishu rifts along the Shandong and Jiangsu parts of the fault zone, the Jiaolai Basin to the east of the Shandong part and the Bohai Bay Basin along the Bohai part of the fault zone. The rifting also triggered intense magmatism, including intermediate magmatism in the Early Cretaceous and basalt eruption in the Cenozoic. The magmatism and geophysical prospecting demonstrate that the TLFZ cuts through entire lithosphere (Zhu et al., 2002; Niu et al., 2002, 2005; Chen et al., 2006).

3. Late Mesozoic evolution history of the fault zone

The TLFZ is characterized by its strike-slip movement, and has been considered as a typical representative for major strike-slip faults in East China for a long time (Xu et al., 1987, 1993). Recent studies demonstrate that the fault zone experienced complicated evolution as shown by several alternation between strike-slip and normal faulting.

3.1 Sinistral faulting at the end of Middle Jurassic

Many structural and geochronological studies (Xu et al., 1987, 1993; Zhu et al., 2005, 2010; Wang, 2006) suggest that the TLFZ first reactivated as a sinistral fault zone after its Middle Triassic initiation. This faulting event produced sinistral ductile shear belts along the eastern edge of the Dabie

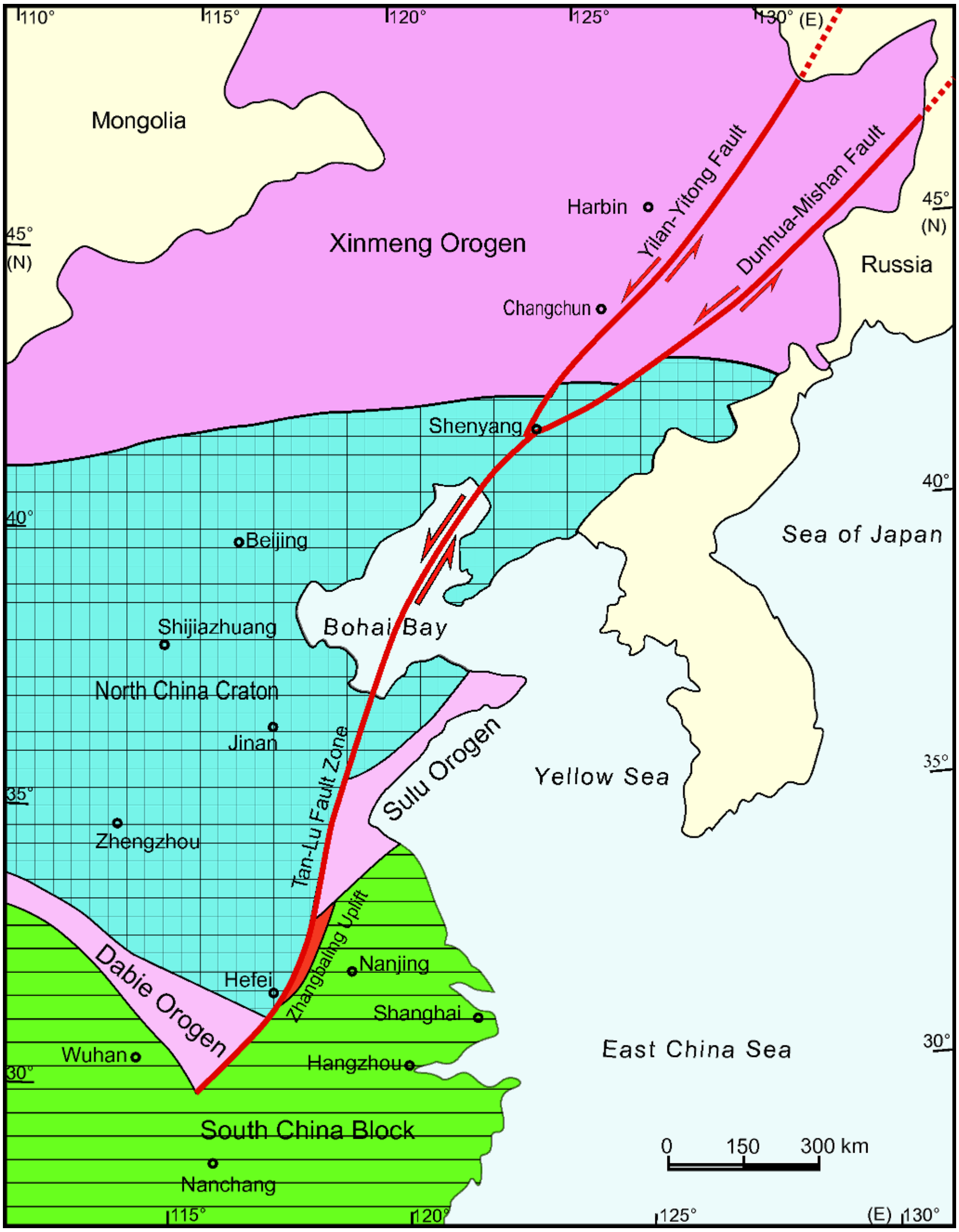

Figure 1 Tectonic sketch map for the Tan-Lu Fault Zone. Modified from Zhu et al. (2004).

Orogen (Figure 2). The shear belts show steep foliation and shallow mineral elongation lineation. Outcrop structures and microstructures all indicate sinistral motion for this event (Zhu et al., 2005, 2010). The ultrahigh pressure metamorphic belt and the Xiaotian-Muzitan Fault in the Dabie orogen were dragged and curved by the Tan-Lu ductile shear belts (Figure 2), showing sinistral displacement along the TLFZ after the orogenic exhumation. ^{40}Ar/^{39}Ar dating of muscovite from the ductile shear belts gave 162–150 Ma ages (Figure 2). The oldest ^{40}Ar/^{39}Ar age is closer to deformation time. The dating results constrain the sinistral event to be at the end of Middle Jurassic. These isotopic ages and synchronous magmatism have never been documented inside of the Dabie orogen, suggesting the absence of the latest Middle Jurassic tectono-thermal event in the orogen. Thus, the sinistral faulting event of the TLFZ is an only recognized event responsible for the obtained ages of 162–150 Ma. It is also noted that this phase of sinistral faulting event has not been recorded in other parts of the middle and southern segments of the TLFZ, demonstrating that the latest Middle Jurassic sinistral faulting took place only along the eastern edge of the Dabie orogen.

Many studies show that the TLFZ kept standstill in the Late Jurassic. No basin and sedimentation were recorded in

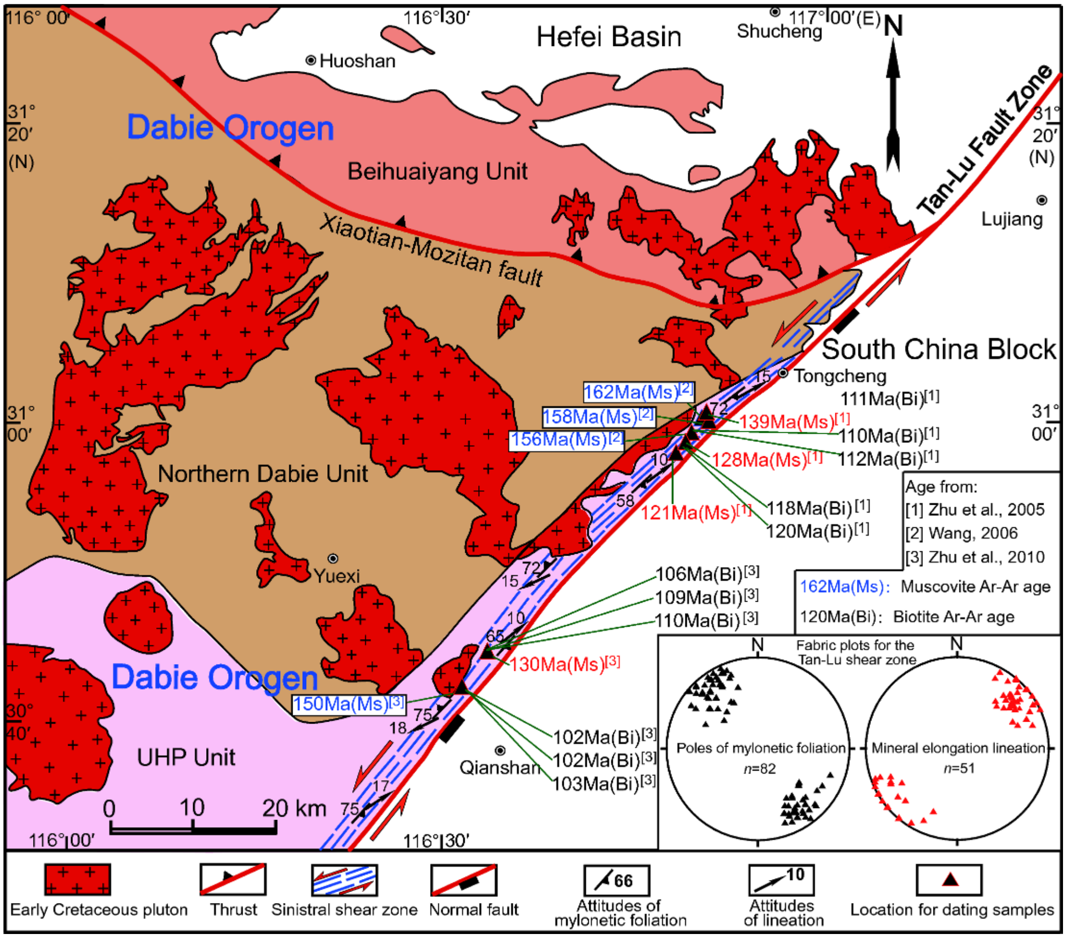

Figure 2 Structural map for the Tan-Lu ductile shear belts along the eastern edge of the Dabie Orogen. Modified from Zhu et al. (2005).

the fault zone during the quiet period, indicating an overall uplifting state. Late Jurassic magmatism was also absent from the fault zone.

3.2 Sinistral faulting at the beginning of Early Cretaceous

Many lines of evidence demonstrated that the TLFZ was subjected to sinistral faulting again at the beginning of Early Cretaceous (Xu et al., 1993; Xu and Zhu, 1994; Zhu et al., 2005, 2010; Mercier et al., 2007; Zhang and Dong, 2008). This phase of strike-slip structures have been documented widely in the southern and middle segments south of Bohai Bay. The ^{40}Ar/^{49}Ar dating for muscovite samples from the sinistral ductile shear belts along the eastern edge of the Dabie orogen also yielded a younger group of ages from 139 to 121 Ma (Zhu et al., 2005, 2010). The oldest age, 139 Ma, was considered to be close to the sinistral faulting time whereas other younger ages represent inhomogeneous cooling time (Zhu et al., 2005). Biotite samples from the same ductile shear belts gave cooling ages of 120–102 Ma (Zhu et al., 2005, 2010; Figure 2), which are consistent with time of the extensional activity in the Dabie orogen as shown by intense uplifting and magmatism (Wang Y S et al., 2011). These biotite ages are also simultaneous with normal faulting, rifted basin development and the rift shoulder uplifting along the TLFZ, suggesting no relation to the sinistral faulting. The sinistral ductile shear belts were intruded by undeformed plutons of Early Cretaceous (younger than 139 Ma; Zhu et al., 2010; Figure 2) locally, indicating that the sinistral faulting predated the Early Cretaceous magmatism.

The Zhangbaling uplift belt along the TLFZ lies along the western edge of the South China Block between the Dabie and Sulu orogens (Figure 1). The Hefei Basin in the NCC is situated to the west of the uplift belt. The southern Zhangbaling uplift belt is exposed with the low amphibolite facies Feidong Complex of Neoproterozoic age (Shi et al., 2009; Zhao et al., 2014) which was cut by the Tan-Lu strike-slip ductile shear belts (Figure 3). The exposed shear belts comprise a composite ductile shear zone with a total width of up to 10 km. Its northern part is exposed with lower levels that show penetrative ductile fabrics whereas its southern part is exposed with shallow levels that exhibit preservation of previous fabrics between the younger shear belts (Figure

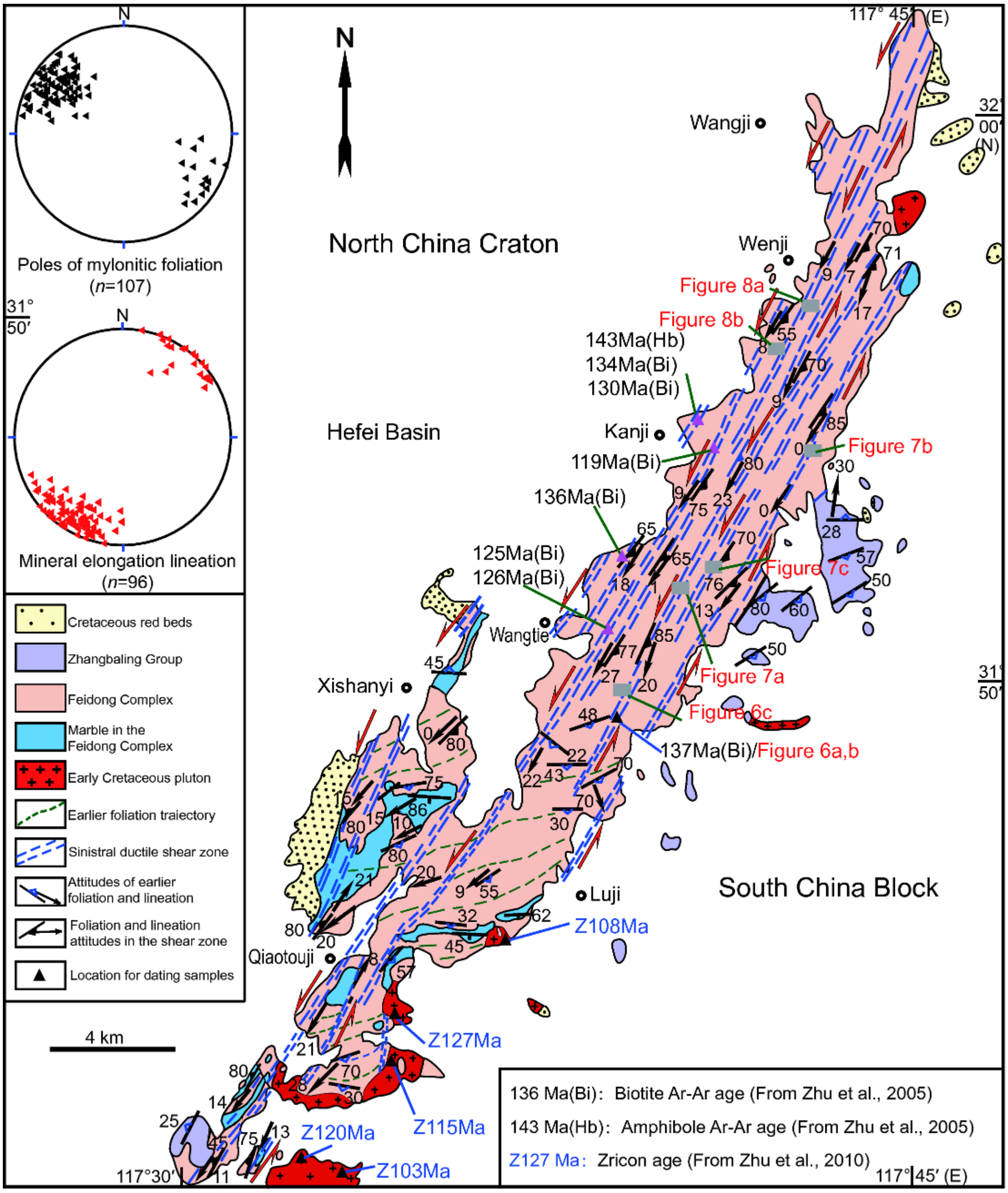

Figure 3 A map showing strike-slip structures in the southern Zhangbaling part of the Tan-Lu Fault Zone. Modified from Zhu et al. (2005).

3). The ductile shear belts dip toward SE steeply with mineral elongation lineation plunging SW shallowly. Various shear sense indicators suggest sinistral motion with small reverse component for the shear belts (Zhu et al., 2005). Mylonites in the shear belts gave a hornblende $^{40}Ar/^{39}Ar$ age of 143 Ma and biotite ages of 137–119 Ma (Zhu et al., 2005; Figure 3). The dating results constrain the sinistral faulting along the Zhangbaling uplift belt to 143 Ma (earliest Early Cretaceous). The younger biotite ages were considered as representing cooling ages related to the strike-slip uplifting and the following uplifting caused by younger extension. Thus, the southern Zhangbaling uplift belt recorded the sinistral faulting event of the TLFZ at the beginning of Early Cretaceous.

The Shandong part of the TLFZ, also called the Yishu Fault Zone, is located between the NCC and the Sulu orogen (Figure 1). This part of the fault zone controlled development of two grabens and one horst during the Cretaceous extension. The NNE-striking ductile shear belts of the TLFZ appear in metamorphic rocks in the horst (Zhu et al., 2010). The shear belts dips SE steeply with nearly horizontal mineral lineation. Various shear sense indicators demonstrate sinistral movement for the shear belts. A hornblende sample from mylonite in the shear belts yielded a $^{40}Ar/^{39}Ar$ cooling age of 132 Ma (Zhu et al., 2009), suggesting an origin of the earliest Early Cretaceous.

Recent studies (Gu et al., 2016) suggest that both the Yilan-Yitong and Dunhua-Mishan faults, two branches of the TLFZ in NE China, originated as major sinistral faults at the beginning of Early Cretaceous. This intense sinistral faulting led to the northward propagation of the TLFZ into NE China (Xu et al., 1987, 1993; Gu et al., 2016). The faulting also pushed the Dabie orogen to the west of the TLFZ to move southwards, and the sinistral faulting along the TLFZ was transferred to thrusting along the Xiangfan-Guangji Fault at the southern edge of the orogen (Li et al., 2009; Wang et al., 2012). In this case, the TLFZ did not propagated southwards during this faulting (Zhao et al., 2016). A series of NE- to NNE-striking sinistral faults were developed around the TLFZ in East China (Xu et al., 1987, 1993; Xu and Zhu, 1994), indicating widespread involvement of the sinistral transpression in the continental margin. All of these phenomena indicate that the earliest Early Cretaceous sinistral faulting was the most intense faulting event in the late Mesozoic, leading to the entire involvement of the TLFZ and the northward propagation into the NE China continent.

3.3 Extensional activity during the Early Cretaceous

After the sinistral motion at the beginning of Early Cretaceous, the TLFZ switched into normal faulting due to regional extension during the middle-late Early Cretaceous (Zhu G et al., 2010, 2012). The extensional activity along the fault zone caused development of many rifted basins and intense magmatism. The rifted basins along the fault zone in the NCC include the Hefei, Jiashan, Yishu, Jiaolai, Bozhong and Liaohe basins from south to north (Figure 4). The Hefei and Jiaolai basins show a half-graben texture whereas others exhibit a graben texture. The Yishu Basin consists of the Anqiu-Juxian and Mazhang-Suchunan grabens and the Gongdanshan horst between them, which were controlled by four parallel normal faults in the Shandong part of the TLFZ (Zhu G et al., 2012; Figure 5).

Two stages of extension along the TLFZ in the Early Cretaceous can be recognized (Zhu G et al., 2012), i.e. the earlier stage with intense activity (135–115 Ma, earlier and middle Early Cretaceous) and the later stage with relatively weak activity (115–100 Ma, late Early Cretaceous). Deposits related to the earlier stage include the Laiyang or Mengyin Formation and Qingshan Formation in Shandong Province and the Zhuxiang, Zhougongshan or Fenghuangshan Formation and Maodanchang Formation in Anhui Province whereas those deposited in the later stage are the Dasheng Group in Shandong Province and the Xiangdaopu Formation in Anhui Province (Wang et al., 2017). Measured fault-slip data indicate WNW-ESE extension (Figure 4; Zhu G et al., 2012) during the earlier stage, which was in favor of reactivity of the preexisting TLFZ as a normal fault zone. NE- to NNE-striking normal faults inside of and around the TLFZ show the most intense activity during the earlier extensional stage (Zhu G et al., 2012), leading to NE- to NNE-trending arrangement of depression belts (Figure 4). The intense extension during the earlier to middle Early Cretaceous was also shown by the large-scale presence of igneous rocks. Intermediate volcanic rocks, including the Qingshan Formation in Shandong Province and the Maotanchang Formation in Anhui Province, are widespread in the rifted basins along the TLFZ whereas intermediate plutons are common in the rift shoulders. Many zircon *in situ* U-Pb dating results (Zhu et al., 2010, 2017; Wang et al., 2017) show duration of the magmatism from 135 to 115 Ma.

The extensional activity along the TLFZ weakened during the later Early Cretaceous, resulting in shrink of the rifted basins and local appearance of the magmatism (Figure 5). The Hefei Basin was only present in the northeastern corner, and the Jiaolai basin was lack of deposition during this stage. In contrast, the Yishu grabens was developed continuously. In this case, the whole NCC showed a feature of the narrow rifts during the later extensional stage (Zhu G et al., 2012). The magmatic activity during this later stage only occurred in the southern Zhangbaling uplift belts as shown by local acidic plutons with zircon U-Pb ages of 108–102 Ma (Zhu et al., 2010). The fault-slip data for this stage show NW-SE extension (Figure 5), demonstrating a certain change in the extensional directions from the earlier to later stage.

3.4 Sinistral faulting at the end of Early Cretaceous

A great attention has been paid to the southern Zhangbaling uplift belt in the TLFZ due to its better exposures. As mentioned before, the NE-striking sinistral ductile shear belts of the earliest Early Cretaceous formed in the uplift belt (Figure 3). A west-dipping normal fault developed between the Hefei Basin to the west and the Zhangbaling uplift belt to the east during the Early Cretaceous extension (Figure 4), leading to uplifting of the belt as a foot wall with many intermediate plutons (135–102 Ma; Zhu et al., 2010).

Our field observation shows that the plutons formed during the extensional stage were not cut by the Tan-Lu sinistral ductile shear belts of the earliest Early Cretaceous. Some of the plutons intruded into the ductile shear belts without ductile deformation (Figure 6). The Tan-Lu sinistral ductile shear belt at a quarry to the east of Xiwei, Chaohu, with a $^{40}Ar/^{39}Ar$ biotite age of 137 Ma (Zhu et al., 2005), contains undeformed granitic dike with a zircon U-Pb age of 122 Ma (Zhu et al., 2010; Figure 6a). A similar undeformed granitic dike appeared in another ductile shear belt at the middle part of the same quarry (Figure 6b). Our zircon LA-ICP-MS U-Pb dating for the dike, conducted at the Analytical Center, Hefei University of Technology, yielded an intrusion age of 126 Ma (Figure 6b). A sinistral ductile shear belt at a railway

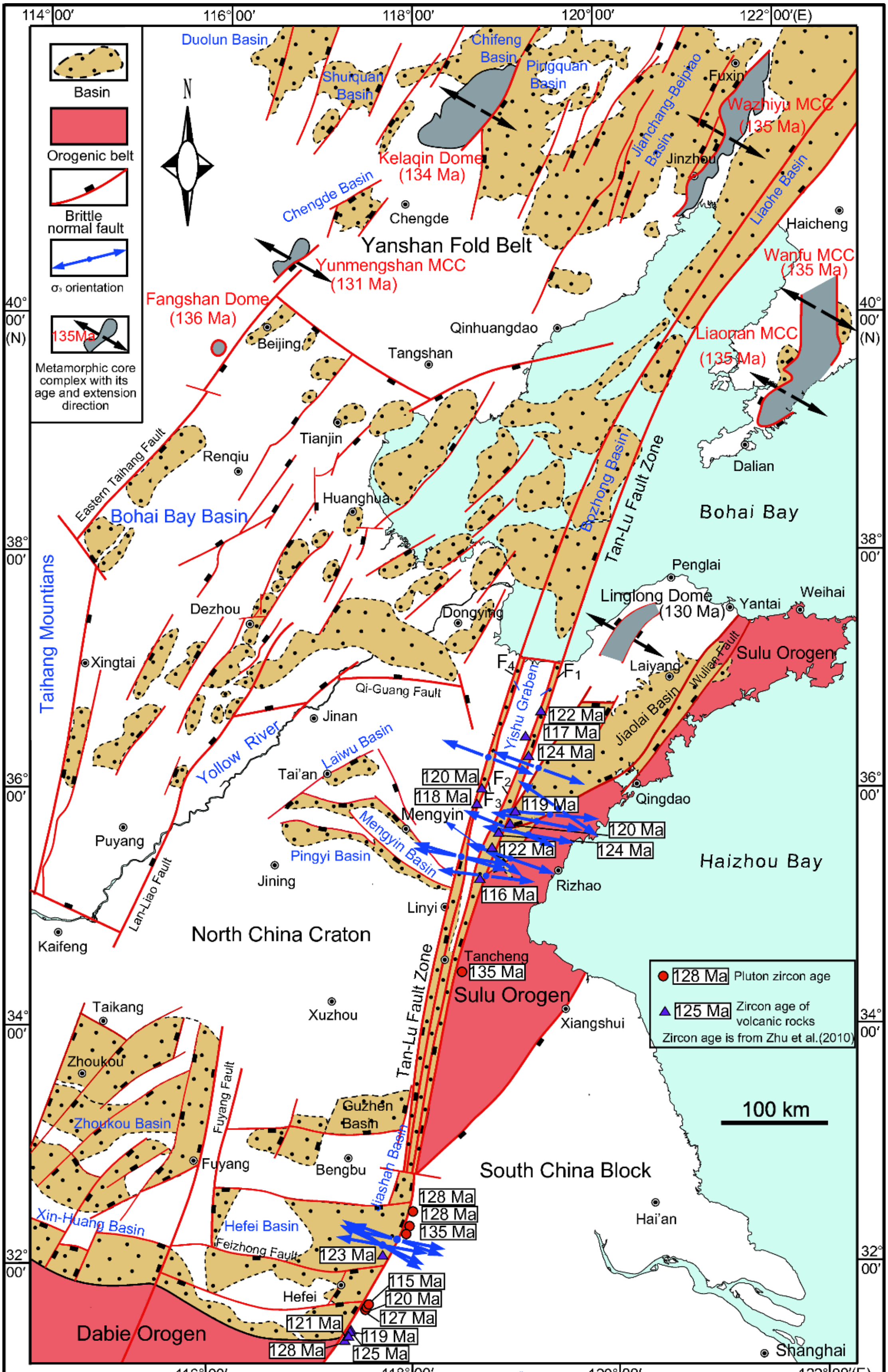

Figure 4 Extensional structures of the earlier to middle Early Cretaceous in and around the Tan-Lu Fault Zone. Modified from Zhu G et al. (2012).

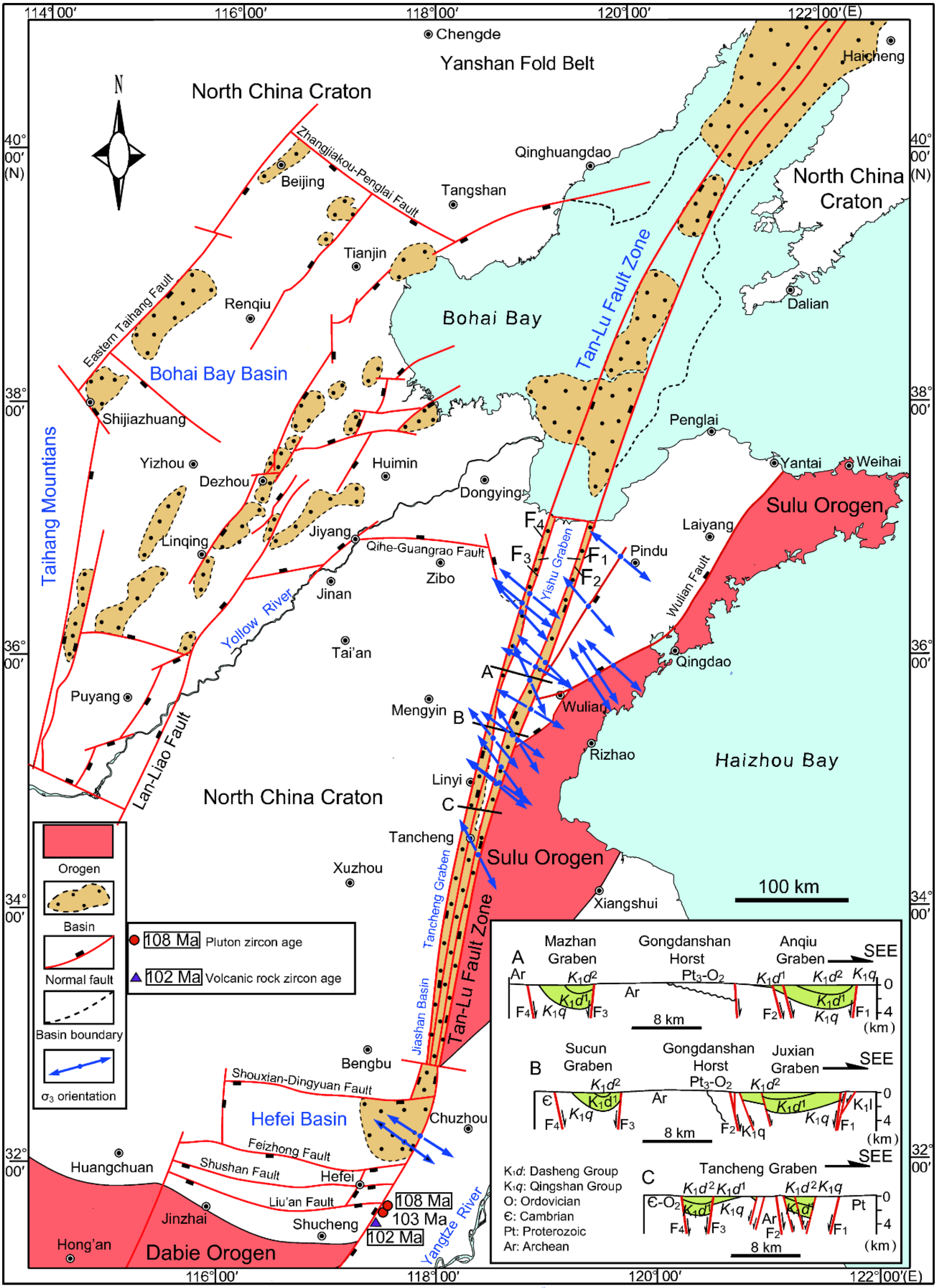

Figure 5 Extensional structures of the later Early Cretaceous in and around the Tan-Lu Fault Zone. Modified from Zhu G et al. (2012).

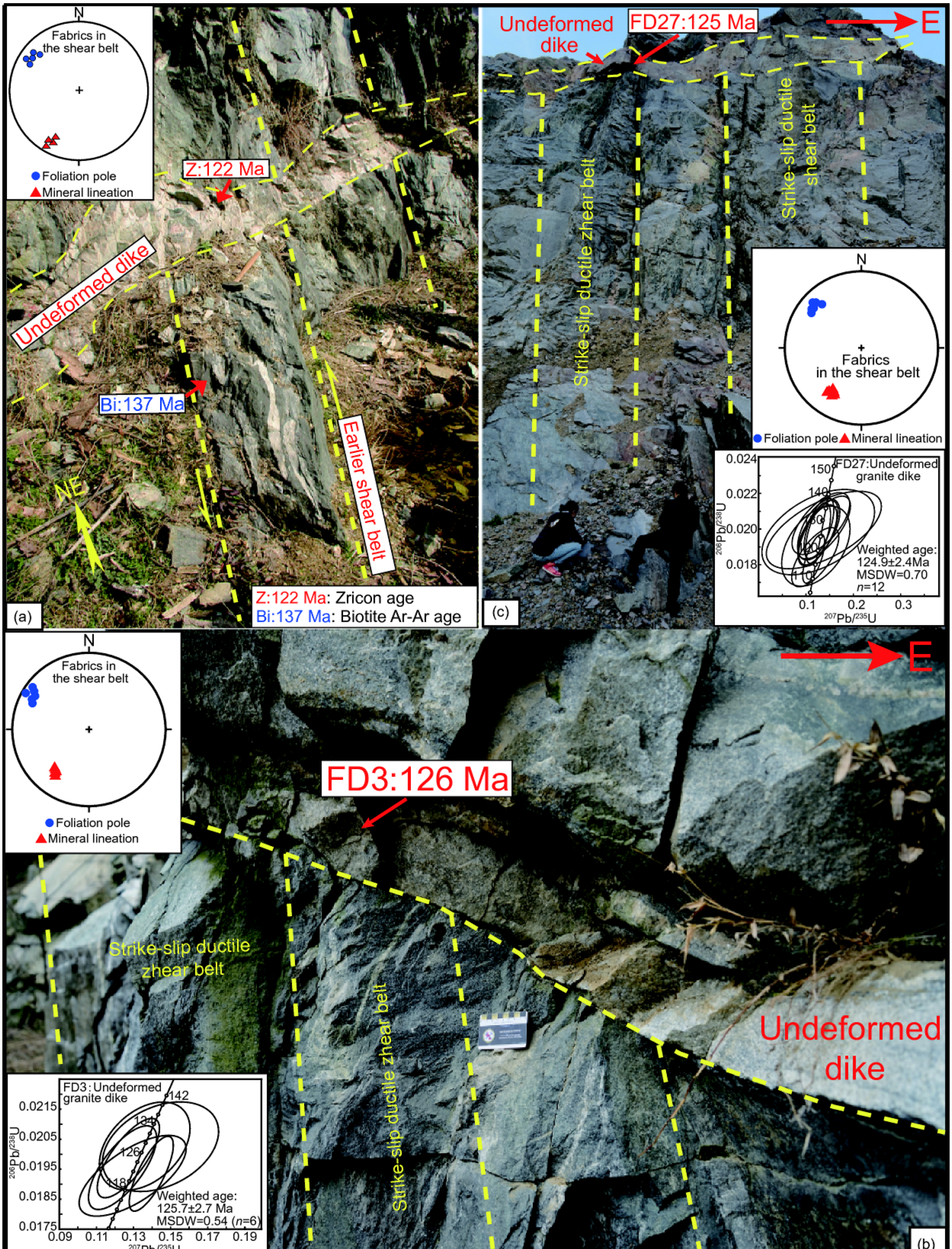

Figure 6 Outcrop photographs of strike-slip ductile shear belts of the earliest Early Cretaceous in the southern Zhangbaling part of the Tan-Lu Fault Zone with fabric stereograms, undeformed dike and zircon concordia diagrams. Their localities are shown in Figure 3. (a) Sinistral ductile shear belt intruded by undeformed dike at Xiwei, Chaohu with a biotite $^{40}Ar/^{39}Ar$ age for the shear belt (Zhu et al., 2005) and a zircon age for the dike (Zhu et al., 2010); (b) sinistral ductile shear belt intruded by undeformed dike at Xiwei, Chaohu with a zircon concordia diagram for the dike from this study; (c) sinistral ductile shear belt intruded by undeformed dike at a railway quarry in Fucha Hill east of Wangtie, Feidong with a zircon concordia diagram for the dike from this study.

quarry in Fucha Hill, east of Wangtie, Feidong was intruded by undeformed syenite dike that yielded a zircon intrusion age of 125 Ma (Appendix 1, available at http://earth.scichina.com). These results demonstrate a short period for the sinistral faulting at the beginning of Early Cretaceous and a longer period for the extensional and magmatic activities during the rest of the Early Cretaceous.

Recent detailed studies (Wang et al., 2015; Han et al., 2015) suggest another sinistral faulting event in the southern Zhangbaling part of the TLFZ after the Early Cretaceous normal faulting and magmatism. Overprinting of the two phases of ductile shear belts can be recognized in the field (Figure 7). A NE-striking sinistral ductile shear belt of the earliest Early Cretaceous in the Feidong Complex at Taohuayuan, Chaohu, the first phase shear belt, was intruded by granitic dike dated at 131 Ma (Figure 7a; Han et al., 2015). Zircon U-Pb ages of 133 and 129 Ma were also obtained from the same dike (Wang et al., 2015). The dike was then deformed by a second phase of NE-striking sinistral ductile shear belt (Figure 7a), but kept no deformation outside of the second phase of shear belt. These data constrain the second sinistral faulting to postdating 129 Ma.

At an iron mining quarry to the east of the Yiantoushan Dam, Chaohu, the first phase of the Tan-Lu strike-slip ductile shear belt deformed granitic dike with a 165 Ma U-Pb age. The shear belt was folded during the second sinistral faulting that also deformed the nearby dioritic dike dated at 127 Ma in this study (Appendix 1).

The two phases of sinistral ductile shear belts can also be recognized at a quarry in Zhaishan Hill at Chaohu (Figure 7c). The late ductile shear belt cut the earlier one and caused shear folding (a-type folds) of previous mylonitic foliation in the earlier shear belt. Granitic dike, dated at 124 Ma in this study, was deformed into mylonite by the later shear belt, but mylonitic foliation in the deformed dike shows no folding.

More sinistral ductile shear belts were recognized in Early Cretaceous plutons with more detailed investigation in the southern Zhangbaling part of the TLFZ (Figure 8). A NE-striking sinistral ductile shear belt appears in granitic dike, dated at 128 Ma by the LA-ICP-MS zircon U-Pb method in this study (Appendix 1), at the southeast of Liangxiang, Xieji, Feidong (Figure 8a). A similar ductile shear belt deformed granitic and dioritic dikes at a quarry to the southeast of Dashou, Xieji, Feidong (Figure 8b). The dikes were dated at 132 and 124 Ma respectively in this study (Appendix 1). All of the phenomena indicate another sinistral faulting event after the Early Cretaceous magmatism associated with the normal faulting of the TLFZ.

The structural investigation shows the presence of the spaced NE-striking ductile shear belts produced by the later sinistral faulting along southern Zhangbaling part of the TLFZ. In contrast to the penetrative deformation of the earlier faulting, the later faulting did not cause penetrative deformation in the southern Zhangbaling part. In this case, the Early Cretaceous dikes show ductile deformation in the later shear belts (Figures 7 and 8) and no deformation outside of the later shear belts (Figure 6). The intrusion ages of 134–124 Ma for the deformed dike in the later shear belts constrain the later sinistral faulting to postdating 124 Ma. The magmatism related to the Early Cretaceous normal faulting of the TLFZ in the Zhangbaling uplift belt lasted to 103 Ma (Figure 3; Zhu et al., 2010), suggesting that the later sinistral faulting took place at the end of Early Cretaceous.

Many geological phenomena also suggest an important event for the TLFZ at the end of Early Cretaceous (or beginning of Late Cretaceous). The rifted basins controlled by the TLFZ widely experienced uplifting, inversion and depositional hiatus at the end of Early Cretaceous (Zhu G et al., 2012). Angular unconformity between the Early Cretaceous Xiangdaopu Formation and the Late Cretaceous Zhangqiao Formation in the Hefei Basin was clearly shown by seismic profiles (Liu et al., 2004), indicating a shortening event at the end of Early Cretaceous. The angular unconformity between the Early Cretaceous Dasheng Group and the Late Cretaceous Wangsi Formation was recognized in the Yishu grabens controlled by the TLFZ (Zhang et al., 2003). These facts indicate a regional compressive event responsible for the sinistral faulting of the TLFZ at the end of Early Cretaceous. This compressive event at the end of Early Cretaceous was also documented in NE China (Li and Shu, 2002) and SE China (Shu and Zhou, 2002; Shu et al., 2009). It is suggested therefore that the East China continental margin was widely involved in the compression at the end of Early Cretaceous.

3.5 Normal faulting during Late Cretaceous

The TLFZ turned into weal normal faulting during the Late Cretaceous (Figure 9). In contrast to the intense and widespread magmatism during the Early Cretaceous, Late Cretaceous magmatism was absent from the TLFZ. The Yishu grabens showed overall uplifting with local sediments during the Late Cretaceous extension (Zhu G et al., 2012). The northern Shandong part of the TLFZ was subjected to weak normal faulting that did not control development of the nearby Jiaolai Basin. The basin was bounded by the NE-striking Jingzi Fault in the west, and controlled mainly by E-W striking normal faults which showed more intense activity and caused E-W arrangement of Upper Cretaceous depocenter (Figure 9b). The TLFZ along the eastern edge of the Hefei Basin also showed weak normal faulting during the Late Cretaceous (Zhu G et al., 2012). E-W striking normal faults inside of the Hefei Basin have more intense activity during the Late Cretaceous and controlled E-W arrangement of depocenter in the basin (Figure 9c). Inversion of the measured fault-slip data (Zhu G et al., 2012) shows nearly N-S extension during the Late Cretaceous. The oblique exten-

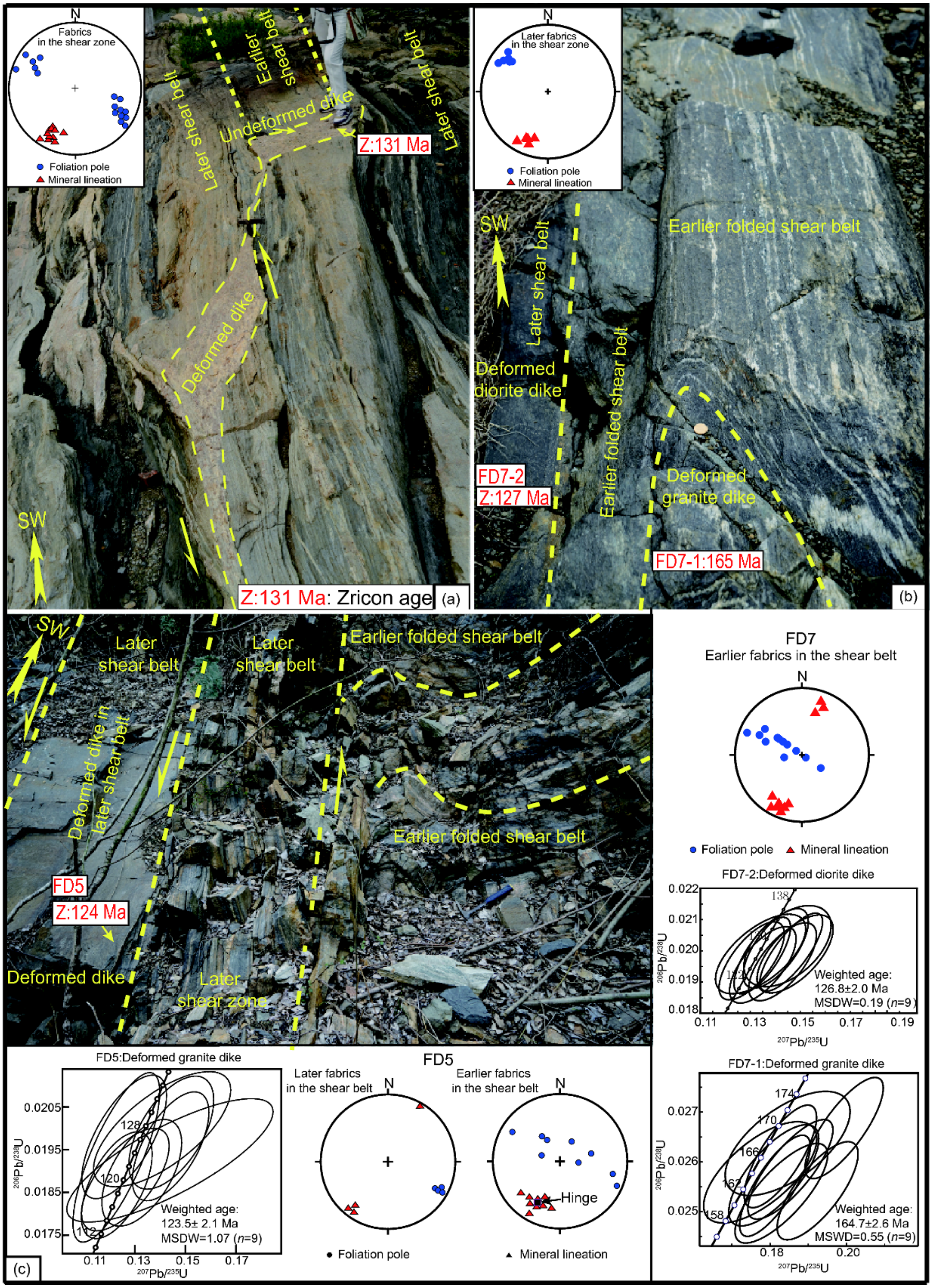

Figure 7 Outcrop photographs of the two phases of sinistral ductile shear belts in the southern Zhangbaling part of the Tan-Lu Fault Zone with fabric stereograms and zircon U-Pb concordia diagrams. Their localities are shown in Figure 3. (a) Two phases of sinistral ductile shear belts and deformation of Early Cretaceous dike in the later shear belt with a zircon age from Han et al. (2015); (b) two phases of sinistral ductile shear belts and deformed dikes at an iron mining quarry to the east of the Yiantoushan Dam, Chaohu with zircon concordia diagrams from this study; (c) two phases of sinistral ductile shear belts and deformed granitic dike in the later one at Zhaishan, Chaohu with zircon U-Pb concordia diagram from this study.

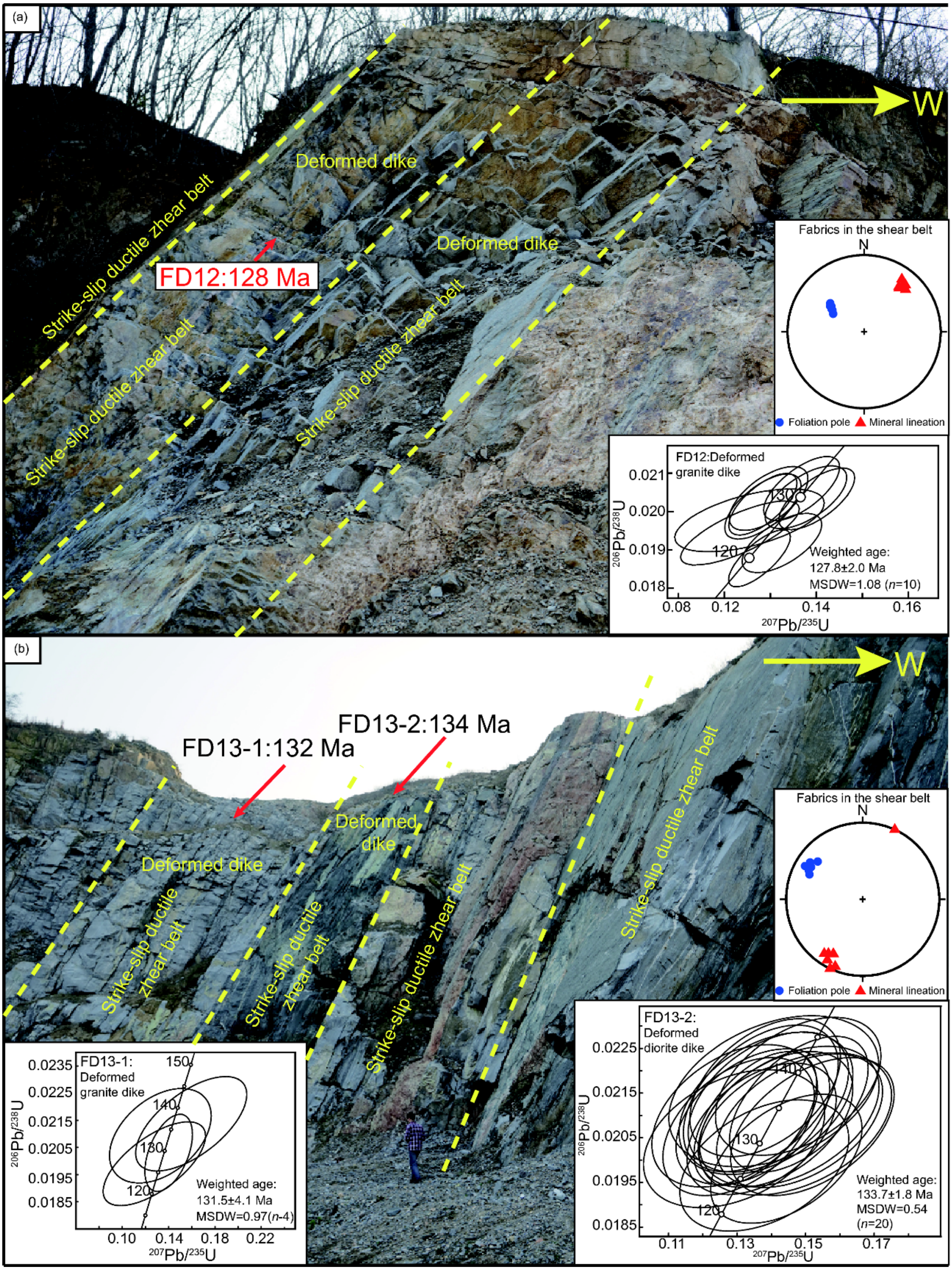

Figure 8 Outcrop photographs for later sinistral ductile shear belts in the southern Zhangbaling part of the Tan-Lu Fault Zone with fabric stereograms and zircon U-Pb concordia diagrams. Their localities are shown in Figure 3. (a) Later sinistral ductile shear belt at the southeast of Liangxiang, Xieji, Feidong; (b) later sinistral ductile shear belt at a quarry to the southeast of Dashao, Xieji, Feidong.

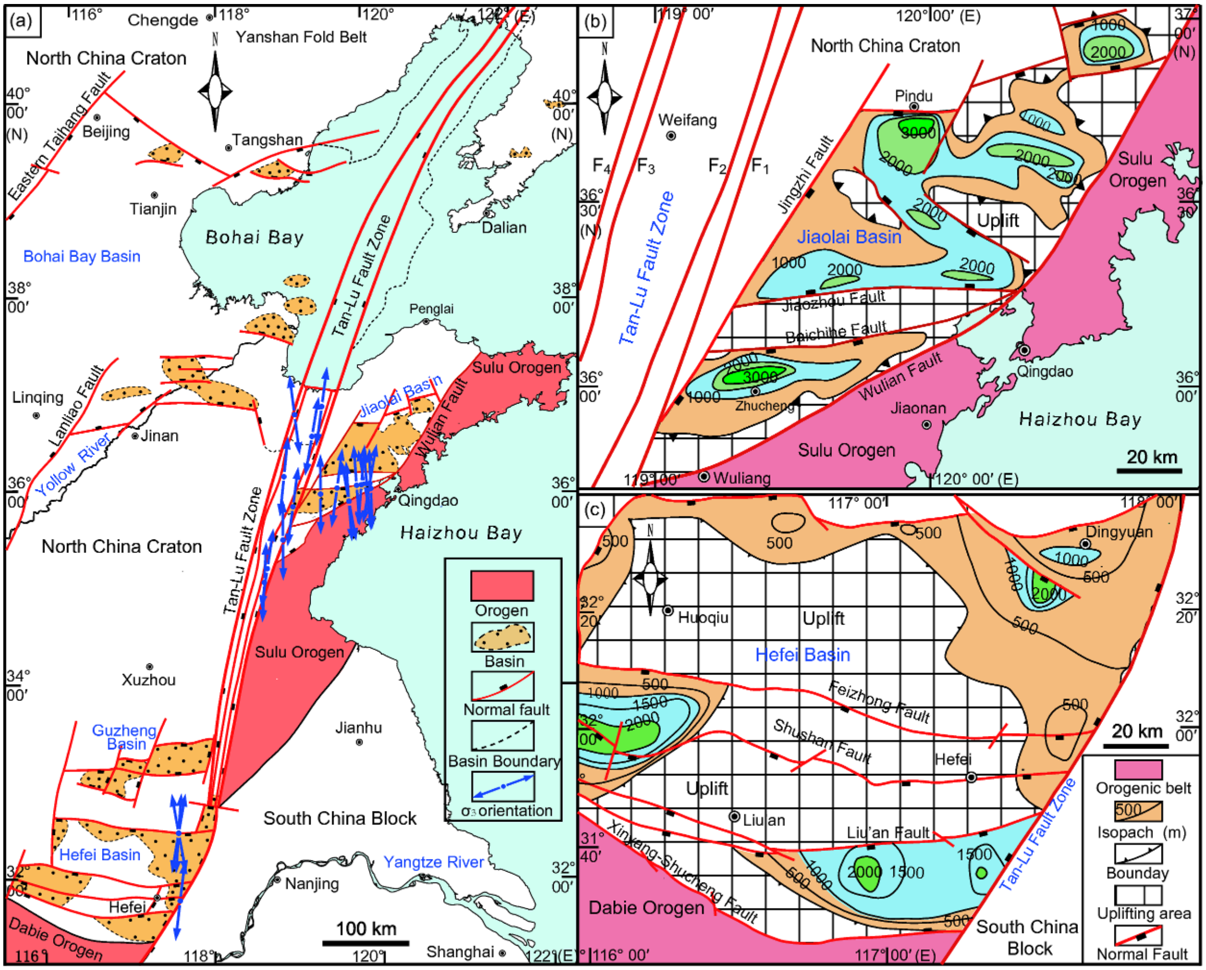

Figure 9 Extensional structures and basins of Late Cretaceous around the Tan-Lu Fault Zone (modified from Zhu G et al., 2012). (a) Extensional structures of Late Cretaceous around the middle segment of the Tan-Lu Fault Zone; (b) depositional pattern of Late Cretaceous in the Jiaolai Basin; (c) depositional pattern of Late Cretaceous in the Hefei Basin.

sion to the TLFZ and the regional weak stress state were responsible for the weak normal faulting of the TLFZ. The N-S extension caused the more intense activity of the E-W normal faults in the Jiaolai and Hefei basins and the resultant E-W trending depocenter arrangement.

4. Subduction history indicated by the fault zone evolution

4.1 Mesozoic evolution correlation between the TLFZ and NCC

4.1.1 Sinistral faulting and the A episode at the end of Middle Jurassic

The Yanshan tectonic belt in the northern NCC is well known for its involvement in the Yanshan Movement. The Yanshan Movement, named by Wong (1926, 1927), means tectonic movement taking place under regional compression during the Jurassic to Cretaceous. The movement includes the A episode indicated by the angular unconformity between the Late Jurassic Tiaojishan or Lanqi Formation and the underlying sediments as well as the B episode indicated by the angular unconformity between the Tuchenzi or Houzhenzi Formation and the overlying Early Cretaceous volcanic rocks. The angular unconformity between Upper and Lower Cretaceous was also called the C episode (Wong, 1929; Huang, 1960). The volcanic eruption period between the A and B episodes during the Late Jurassic was referred to as the middle episode (Zhao et al., 2004).

Previous zircon dating for volcanic rocks above and below the angular unconformity of the A episode constrained the shortening time to ca. 165 Ma (latest Middle Jurassic, Zhao et al., 2004; Liu et al., 2006; Li H L et al., 2014). It is suggested therefore that the sinistral faulting of the TLFZ at the end of Middle Jurassic is synchronous with the A episode of the Yanshan Movement, and both of them resulted from the regional compression.

A series of NE- to NNE-striking thrusts in the Yanshan tectonic belts formed in the A episode (Davis et al., 2001; Zhang et al., 2011; Wang Y et al., 2011). The structural orientations suggest WNW-ESE compression for the deformation event. The NNE-trending Taihang thrust belt, the Shanxi fold and thrust belt and the Luliang thrust belt occur in the central NCC from east to west. Many NNE-trending folds, such as the Qingshui, Lingjin and Datong synclines, appear among the thrust belts. These shortening structures were also produced by the WNW-ESE compression (Liao et al., 2007; Zhang Y Q et al., 2008; Liu S F et al., 2013). Upper Jurassic sediments are widely absent from the central NCC. $^{40}Ar/^{39}Ar$ dating results for the thrusting ductile shear belts in the central NCC indicate that the shortening took place at the end of Middle Jurassic (Wang and Li, 2008) and belongs to the A episode (Zhang Y Q et al., 2008). These show the widespread presence of the shortening deformation of the A episode in the middle and eastern NCC. The sinistral faulting of the TLFZ at the end of Middle Jurassic is consistent with the A episode deformation. The compressive direction of the A episode was nearly perpendicular to the TLFZ strike, leading to local reactivity of the preexisting, steep fault zone.

The NCC kept an uplifting state during the Late Jurassic, i. e. the middle episode between the A and B episodes. Except for development of Late Jurassic volcanic basins in the Yanshan tectonic, Late Jurassic sediments were absent widely from the other parts of the eastern NCC (Zhang Y Q et al., 2008; Chen et al., 2009). The Late Jurassic magmatism was also documented in the Liaodong, Jiaobei and Benpu regions in the eastern NCC (Wu et al., 2005b; Li S G et al., 2014; Lin et al., 2014; Song et al., 2016). Previous studies on the Late Jurassic igneous rocks (Gao et al., 2004; Zhang X H et al., 2008; Jiang et al., 2010; Yang et al., 2010, 2012) demonstrated an extensional setting in the eastern NCC. Recent structural studies on the Yiwulushan MCC (Zhang et al., 2012), Kalaqing MCC (Lin et al., 2014), Linlong extensional dome (Charles et al., 2011; Lin et al., 2013) and rifted basins in the northern NCC (Qi et al., 2015) also indicated the extensional activity of the Late Jurassic in the eastern NCC. In summary, the eastern NCC suffered regional uplifting and local magmatism under a weak extensional setting during the Late Jurassic. The TLFZ kept standstill at the same period.

4.1.2 *Sinistral faulting and the B episode at the beginning of Early Cretaceous*

Sequences above and below the angular unconformity of the B episode of the Yanshan Movement include volcanic rocks. Previous isotopic dating for the volcanic rocks suggest the 139–138 Ma age for the shortening event of the B episode, i. e. at the beginning of Early Cretaceous (Sun et al., 2007; Chen et al., 2013; and its references). These results show that the B episode is roughly simultaneous with the sinistral faulting of the TLFZ at the beginning of Early Cretaceous.

The Yanshan tectonic belt was widely involved in the shortening deformation of the B episode that produced a series of E-W trending folds and thrusts (Zhang et al., 2011). Pre-Cretaceous rocks were deformed by this phase of deformation, and thrusting ductile shear belts were recognized in the metamorphic basement. The Sihetang thrusting ductile shear zone in the northern margin of the Early Cretaceous Yunmengshan batholith (145–141 Ma; Zhu et al., 2015a) shows top-to-the-SSW shear sense. Many isotopic dating results constrain its thrusting time to 140–137 Ma (Davis et al., 1996; Passchier et al., 2005; Wang T et al., 2011; Zhu et al., 2015a), which is consistent with the B episode deformation. These structures indicate nearly N-S compression direction for the B episode. This regional stress field was in favor of sinistral faulting along the NE-striking TLFZ at the beginning of Early Cretaceous, and accounts for the most intense sinistral faulting at that time.

4.1.3 *Extension and craton peak destruction in the Early Cretaceous*

The peak destruction of the NCC occurred in the Early Cretaceous (Zhu R X et al., 2012). The peak destruction was associated with intense extensional activity and large-scale, intermediate magmatism. The extensional activity produced a series of metamorphic core complexes, extensional domes and rifted basins. The metamorphic core complexes and domes appear in the Yanshan tectonic belt and the Liaonan region. They include the Fangshan dome, Yunmengshan MCC, Kalaqing dome, Waziyu MCC, Liaonan-Wanfu MCCs and Linlong dome (Figure 4). Their formation ages range from 135 Ma to 129 Ma (Lin et al., 2008; Wang T et al., 2011; Zhang et al., 2012; Liu J L et al., 2013; Zhu et al., 2015a), and indicate initiation time of 135 Ma for the extension. The MCCs and dome indicate a WNW-ESE extension direction consistently, which is consistent with the extensional direction of the earlier to middle Early Cretaceous recorded by the TLFZ. The eastern NCC kept a stable stress state at this extensional stage. Like the rifted basins along the TLFZ, extensional basins of the Early Cretaceous in the eastern NCC were also controlled by NE-striking normal faults. The intense magmatism of the Early Cretaceous in the eastern NCC was shown by the widespread volcanic rocks and plutons with a peak age at 125 Ma (Wu et al., 2005a; Zhu R X et al., 2012).

In summary, the eastern NCC shows peak destruction in the Early Cretaceous. The peak destruction was associated with the intense extensional activity and magmatism, started at 135 Ma, shows a magmatism peak at 125 Ma and lasted to the end of Early Cretaceous. The Early Cretaceous intense normal faulting of the TLFZ took place under the peak destruction of the eastern NCC.

4.1.4 *Sinistral faulting and termination of the peak destruction at the end of Early Cretaceous*

The angular unconformity between Upper and Lower Cretaceous strata in the eastern NCC has been documented by many researchers (Huang, 1960; Zhu et al., 1999; Ma et al., 2002; Bing et al., 2003; Deng et al., 2004). This corresponds to the last shortening event in the Yanshan Movement, i.e. the C episode. This shortening event was considered as a turning point for the tectonic regime change and representing termination of the NCC peak destruction (Wu et al., 2005a; Zhu R X et al., 2012). The widespread rifted basins of the Early Cretaceous in the eastern NCC ended with inversion and uplifting caused by the shortening. The intense magmatism of the Early Cretaceous also terminated due to onset of the shortening. This regional shortening event was also responsible for the sinistral faulting of the TLFZ at the end of Early Cretaceous.

4.1.5 Weak extensional setting in Late Cretaceous

The eastern NCC is characterized by the magmatic absence, local development of the rifted basins (Figure 9a) and regional uplifting during Late Cretaceous. Structural studies of the Jiaolai and Hefei basins (Zhu G et al., 2012) demonstrate a regional extensional setting for the eastern NCC during the Late Cretaceous. In contrast to the intense extension activity in the Early Cretaceous, the Late Cretaceous structures indicate weak extensional activity in the eastern NCC. The normal faulting of the TLFZ and development of the Jiaolai and Hefei basins along the fault zone happened under this weak extensional setting. The TLFZ represents a relatively intense extensional zone in the eastern NCC during the Late Cretaceous.

Correlation of evolution histories between the TLFZ and the eastern NCC can constrain tectonic setting for the TLFZ evolution in late Mesozoic. The correlation also reveals the recorder action of a major fault zone for regional tectonic evolution. The correlation and comprehensive analysis can further constrain detailed dynamic processes of the late Mesozoic in the eastern NCC (Figure 10). As summarized before, the eastern NCC was subjected to three phases of compressive events, i.e. the A, B, C episodes of the Yanshan Movement in late Mesozoic. The three events were responsible for the three phases of sinistral, transpressive faulting along the TLFZ. The regional extension between the compressive events led to normal faulting and development of the rifted basins along the TLFZ. The evolution details for the both eastern NCC and the TLFZ indicate shorter duration for each of the compressive events and longer duration for each of the extensional stages (Figure 10). The eastern NCC experienced the evolution from weak extension in Late Jurassic, intense extension in Early Cretaceous to weak extension in Late Cretaceous. Each of the transformation periods suffered a compressive event. The intense extensional stage of the Early Cretaceous was associated with the intense lithospheric thinning and peak destruction of the eastern NCC. The peak destruction occurred after a compressive event and terminated with onset of a compressive event.

4.2 Constraints on the subduction history

The above correlation demonstrate that the TLFZ evolution illustrates tectonic processes of late Mesozoic in the eastern NCC. Further correlation with the evolution in NE China and SE China shows the similar tectonic evolution in the whole East China continental margin in late Mesozoic, but a change in geological features westwards (Xu et al., 1987, 1993; Li, 2000; Ren et al., 2002; Meng, 2003; Wu et al., 2005a; Zhu et al., 2010, 2012; Wang T et al., 2011; Li et al., 2012; Li J H et al., 2014; Gu et al., 2016). As mentioned before, the regional extensional direction around the TLFZ changed from WNW-ESE in the earlier-middle Early Cretaceous, NW-SE in later Early Cretaceous to N-S in Late Cretaceous, indicating a clockwise change. Motion directions of the oceanic plates in the western Pacific region show the similar change in the same period (Engebretson et al., 1985; Maruyama et al., 1997; Cottrell and Tarduno, 2003; Sager, 2006; Beaman et al., 2007; Zhu G et al., 2012). These consistence suggests that the Cretaceous extension in the eastern NCC happened under the backarc extensional setting triggered by the Paleo-Pacific plate subduction (Zhu G et al., 2012). These demonstrate that the late Mesozoic dynamic evolution in the eastern NCC was controlled by the Paleo-Pacific plate subduction, and the resultant tectonics belongs to the so-called circum-Pacific regime tectonics. The insights into the late Mesozoic dynamic evolution in the eastern NCC can also help to constrain the oceanic plate activity in the western Pacific region.

After the Middle Triassic initiation, the TLFZ first reactivated at the end of Middle Jurassic. This activity led to local sinistral faulting, and was synchronous with the A episode deformation in the NCC. Structures related to this event resulted from WNW-ESE compression, and are parallel to the subduction zone in the western Pacific region. They overprinted on the previous Paleo-tethys structures, and represent the first phase of structures parallel to the subduction zone. They are considered as results of the Izanagi slab subduction in the active margin. Initial subduction and motion details of the Izanagi slab remain unclear (Engebretson et al., 1985; Maruyama et al., 1997). The geological records in the eastern NCC at the end of Middle Jurassic imply that the initial subduction of the Izanagi Plate beneath the East China continent took place at the end of Middle Jurassic. It is proposed that the oceanic plate moved toward WNW at a low angle at that time (Figure 11a). The A episode deformation and the synchronous sinistral faulting of the TLFZ represent the initiation of the circum-Pacific regime in the East China continent. The absence of the Jurassic arc magmatism in the eastern NCC is prominent. It was as-

Age		Sequences	Evolution stage of the Tan-Lu Fault Zone	Evolution stage of the eastern North China Craton	Yanshan Movement	Stress field	Dynamic background
Cretaceous	Late	Wangshi Formation/ Zhangqiao Formation	Extensional activity	Regional uplifting and local rifted basins		N-S weak extension	High-angle, N-ward subduction of the Izanagi slab and trench retreating
Cretaceous	Early		Sinistral movement		C episode	N-S compression	Low-angle N-ward subduction of the Izanagi slab and trench forward
Cretaceous	Early	Dasheng Group/ Xiangdaopu Formation	Intense extensional activity	Widespread rifted basins, MCCs and strong magmatism	Middle episode	NNW-SSE extension	High-angle, WNW- to NNW-ward subduction of the Izanagi slab and trench retreating
Cretaceous	Early	Qingshan Formation/ Maotanchang Formation	Intense extensional activity	Widespread rifted basins, MCCs and strong magmatism	Middle episode	Intense WNW-ESE extension	High-angle, WNW- to NNW-ward subduction of the Izanagi slab and trench retreating
Cretaceous	Early	Laiyang Group/ Mengyin Formation/ Zhugang Formation/ Fenghuangtai Formation	Intense extensional activity	Widespread rifted basins, MCCs and strong magmatism	Middle episode	Intense WNW-ESE extension	High-angle, WNW- to NNW-ward subduction of the Izanagi slab and trench retreating
Cretaceous	Early		Intense sinistral movement		B episode	Intense N-S compression	Low-angle, NNW-ward subduction of the Izanagi slab and trench forward
Jurassic	Late		No activity	Regional uplifting and local magmatism		N-S weak extension	High-angle subduction of the Izanagi slab
Jurassic	Middle		Local sinistral faulting	NW-SE shortening	A episode	NW-SE compression	Low-angle subduction of the Izanagi slab and trench forward
Jurassic	Middle	Santai Formation/ Sanjianpu Formation					
Jurassic	Early	Fangzi Formation/ Fanghushan Formation					

Figure 10 Summary for evolution history and tectonic setting of the Tan-Lu Fault Zone in late Mesozoic.

cribed to positioning in the backarc region to the west of the magmatic arc in the Korean peninsula and Japan islands (Maruyama et al., 1997). In view of the thick cratonic mantle wedge overlying the subducting Izanagi slab, however, slab dehydration could have not triggered the arc magmatism above the cold subduction zone (Zheng et al., 2016).

Tectonic activity was absent from the TLFZ during the Late Jurassic. The eastern NCC shows weak extensional activity, local magmatism and regional uplifting in the same period. These features in the active margin are consistent with results either from weak backarc extension or from cold subduction. It is inferred that the subducted Izanagi slab steepened and then got rollback with trench retreating in the Early Cretaceous, resulting in the remote backarc extension and regional uplifting in the East China continent (Figure 11b).

The TLFZ was involved in sinistral faulting again at the beginning of Early Cretaceous, and propagated into NE China. This sinistral faulting represents the most intense displacement for the fault zone in the late Mesozoic. The B episode structures occurred in the NCC at the same time, and indicate an N-S compressive state for this event. The Izanagi slab move toward NNW at high-speed and low-angle (Engebretson et al., 1985; Maruyama et al., 1997). This oblique subduction accounts for the shortening deformation in the East China continent at the beginning of Early Cretaceous (Xu et al., 1987, 1993; Meng, 2003; Zhu et al., 2005, 2010; Wang T et al., 2011; Li J H et al., 2014; Gu et al., 2016). Recent studies demonstrate that the final closure of the Mongol-Okhotsk Ocean and the resultant oblique collision took place in the earliest Early Cretaceous (Metelkin et al., 2010; Pei et al., 2011; Li et al., 2012). This collision could intensify the shortening in East China at the beginning of Early Cretaceous. The enhance of the compressive activity northwards in East China (Meng, 2003; Wang T et al., 2011; Zhu et al., 2015a) supports this inference. The united action imposed by the surrounding plates resulted in the intense sinistral faulting along the TLFZ and the B episode structures in the eastern NCC (Figure 11c).

The peak destruction of the eastern NCC in the Early Cretaceous was synchronous with the intense normal faulting of the TLFZ. The NCC destruction and the resultant lithospheric thinning could happen under the backarc extensional setting (Figure 11d) related to rollback of the subducted Izanagi slab and correspondent trench retreating (Wu et al., 2005a; Zhu G et al., 2010, 2012; Zhu R X et al., 2012; Kusky et al., 2014). The Izanagi slab moved from WNW-wards to NW-wards during the Early Cretaceous, leading to a change in the trench retreating direction from ESE-wards to SE-wards. Correspondingly, the extensional directions in the eastern NCC changed from WNW-ESE to NW-SE (Zhu G et al., 2012).

Motion of the Izanagi Plate speded up at the end of the Early Cretaceous (Maruyama et al., 1997), leading to its low-angle subduction below the East China continent. This subduction led to the regional compression in the eastern NCC (the C episode of the Yanshan Movement), sinistral faulting along the TLFZ (Figure 11e) and termination of the NCC peak destruction.

The Paleo-Pacific Plate move northwards slowly in the

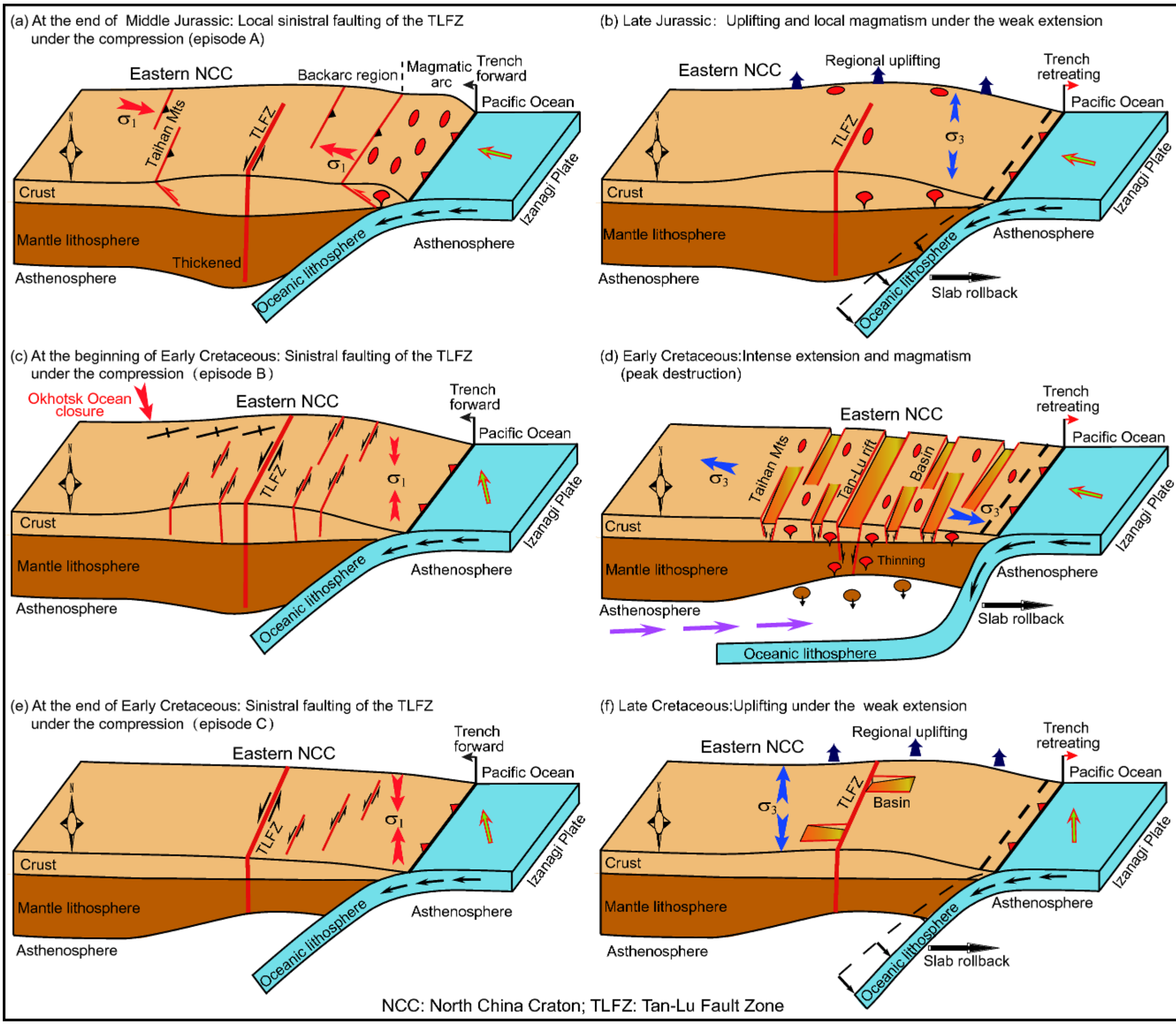

Figure 11 Geodynamic models for evolution of the eastern North China Craton and the Tan-Lu Fault Zone in late Mesozoic.

Late Cretaceous (Cottrell and Tarduno, 2003; Sager, 2006; Beaman et al., 2007), and the slab rollback and the trench retreating occurred during this period. The southward trench retreating was responsible for the N-S extension in the eastern NCC (Figure 9a). The eastern NCC was far away from the trench with its continuous retreating in Late Cretaceous, and stayed under the far-field, weak extensional setting. The weak normal faulting along the TLFZ and regional uplifting of the eastern NCC occurred under this setting (Figure 11f).

5. Conclusions

Following conclusions can be drawn from comprehensive analysis on the progress in the late Mesozoic evolution and new results for the TLFZ.

(1) The sinistral faulting structures of the TLFZ at the end of Middle Jurassic were only recognized along the eastern edge of the Dabie Orogen. This phase of sinistral faulting was simultaneous with the A episode of the Yanshan Movement, and both of them resulted from NW-SE compression. They represent the onset of the oceanic plate subduction underneath the NCC. Late Jurassic deformation and magmatism were absent from the TLFZ whereas the eastern NCC showed the weak extensional setting synchronously, implying the first trench retreating in the western Pacific Ocean.

(2) The TLFZ experienced the intense sinistral faulting at the beginning of Early Cretaceous. The B episode also took place at the same time as a result of regional N-S compression. The NNW-ward, high-speed, low angle subduction of the Izanagi Plate accounts for this deformation event in the eastern NCC. The final closure of the Mongol-Okhotsk

Ocean to the north might intensify this shortening deformation in the continental margin.

(3) The normal faulting of the TLFZ in the Early Cretaceous was associated with the peak destruction, intense magmatism and development of many rifted basins in the eastern NCC. The backarc extension caused by the slab rollback during the Izanagi Plate subduction was responsible for the extensional activity and peak destruction in the eastern NCC.

(4) The TLFZ was involved in sinistral faulting again at the end of Early Cretaceous. It turned into weak, local normal faulting in Late Cretaceous. The regional compression responsible for the sinistral faulting happened during the low-angle, high-speed subduction of the Izanagi slab whereas the extension resulting in the local normal faulting resulted from the slab rollback during the Paleo-Pacific Plate subduction.

Acknowledgements *This study was supported by the National Natural Science Foundation of China (Grant Nos. 41472186 & 91414301) and the National Key Basic Research Program of China (Grant No. 2016YFC0600102).*

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(Responsible editor: Yongfei ZHENG)