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Location and sinistral displacement of the eastern Liaoyuan Accretionary Belt along the Tan–Lu Fault Zone, NE China

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Abstract

The NE- to NNE-striking, continental-scale Tan–Lu Fault Zone (TLFZ) in NE China is subdivided into the ~900 km long Yilan–Yitong Fault (YYF) in the west and the ~1000 km long Dunhua–Mishan Fault (DMF) in the east. Both faults record sinistral displacement during the earliest Cretaceous, leading to an obvious offset of the boundary between the Liaoyuan Accretionary Belt (LAB) and the North China Craton (NCC). Previous studies have demonstrated that the LAB in the south of the eastern Central Asian Orogenic Belt (CAOB) extends eastwards into an area between the YYF and the DMF. The boundaries between the LAB and NCC indicate a 35 km sinistral displacement upon the YYF. However, it remains unclear whether the LAB extends to the east of the DMF, and the amount of sinistral displacement on the DMF is poorly constrained. Here we present lithological observations and U–Pb and Hf isotopic data from zircon to constrain the age and position of the LAB to the east of the DMF. The data indicate an eastward extension of the LAB across the DMF, suggesting the continuous presence of the LAB east of the TLFZ in NE China. The U–Pb ages, εHf(t) values, and two-stage model ages of zircons from the study area constrain the boundary between the LAB and NCC to an extension of the NE-dipping Chifeng–Kaiyuan Fault to the east of the DMF. The geological boundaries on both sides of the DMF indicate a 170 km sinistral displacement along the fault. Thus, the TLFZ has a total sinistral displacement of 205 km in NE China. The eastern branch of
the TLFZ records significantly more movement due to its proximity to the Pacific Ocean, where
subduction of oceanic crust might have caused sinistral faulting along the TLFZ.

**Keywords:** Zircon U–Pb dating; zircon Hf isotopes; Dunhua–Mishan Fault; Tan–Lu Fault Zone;
magnitude of sinistral displacement; NE China

**1. Introduction**

The Central Asian Orogenic Belt (CAOB) and the Tan–Lu Fault Zone (TLFZ) in NE China
are examples of accretionary orogens and major fault zones, respectively, and together provide
clues for the understanding of the processes of continental evolution and dynamics. Northeast
China contains the eastern part of the Phanerozoic CAOB that is crosscut by the NE-striking
Mesozoic to Cenozoic TLFZ, which is the largest fault zone in eastern China (Fig. 1a).

The CAOB is the largest accretionary orogenic belt in the world (Wilde, 2015), and it
records south-directed subduction of the Paleo-Asian oceanic crust during the Paleozoic and
final closure along the Solonker Suture Zone during the Permian to Middle Triassic (Fig. 1a;
Xiao et al., 2003, 2009a, 2009b; Windley et al., 2007; Wilhem et al., 2012; Kröner et al., 2014;
Wilde, 2015; Liu et al., 2017c; Gu et al., 2018). The Liaoyuan Accretionary Belt (LAB), also
known as the Liaoyuan Terrane (Wu et al., 2004b, 2011), formed between the suture zone and
the North China Craton (NCC) due to southward subduction of the Paleo-Asian oceanic crust.
The location and evolution of the LAB to the west of the TLFZ, referred to here as the western
LAB, have been extensively studied (Xiao et al., 2003, 2009a, 2009b; Windley et al., 2007; Xiao
and Santosh, 2014; Wilde, 2015; Liu et al., 2017c; Gu et al., 2018). Recent geochemical and
geochronological data (Pei et al., 2014, 2016; Gu et al., 2018) indicate that the LAB is present
between the Yilan–Yitong Fault (YYF) and the Dunhua–Mishan Fault (DMF), which form the
two branches of the TLFZ in NE China (Fig. 1a). Although the LAB is expected to extend
eastwards across the DMF (Wu et al., 2011; Zhou and Wilde, 2013; Liu et al., 2017c), reliable
evidence is lacking.

The TLFZ is characterized by large-scale sinistral displacement, although the displacement amount remains controversial. The largest magnitudes proposed are ~800 km (Uchimura et al., 1996), 740 km (Xu, 1980, 1985a), 550 km (Xu, 1985b; Wang et al., 1992; Faure et al., 2003; Zhu et al., 2009; Zhao et al., 2016), or 430 km (Wan et al., 1996). The well-constrained northern boundaries of the Dabie and Sulu orogens show a 550 km sinistral displacement along the southern segment of the TLFZ (Fig. 1a; Xu, 1985b; Xu et al., 1987; Wang et al., 1992; Faure et al., 2003; Zhu et al., 2009; Zhao et al., 2016). In contrast, the magnitude of displacement of the northern boundary of the NCC along the northern segment is estimated to be 150–200 km (Xu et al., 1987; Wan et al., 1996; Zhu et al., 2009; Zhao et al., 2016). It has been proposed that 250–350 km displacement of the two orogens along the southern segment of the TLFZ was related to Middle Triassic orogenesis, and that another 150–200 km of displacement along both the northern and southern segments took place at the beginning of the Cretaceous (Zhu et al., 2009; Gu et al., 2016; Zhao et al., 2016; Liu et al., 2018). Determination of the amount of displacement of the northern boundaries of the NCC is important for understanding the origin and evolution of the entire fault zone.

Both branches of the TLFZ offset the northern boundaries of the NCC (Fig. 1a). A recent geochronological and geochemical study by Gu et al. (2018) on the northern boundaries on both sides of the YYF, the western branch of the TLFZ, indicate a 35 km sinistral displacement. However, the amount of displacement along the eastern branch of the TLFZ, the DMF, is unclear. Proposed magnitudes of displacement of the DMF include 400 km (Wang et al., 2016a), 240 km (Yu, 1996; Li et al., 2002), 200 km (Xu and Ma, 1992; Liu et al., 2017b), ~150 km (Xu, 1980, 1985a; Xu et al., 1987; Hong, 1988; Wan et al., 1996; Guo et al., 2000), and 100 km (Guo et al., 2001). Although the boundary between the LAB and the NCC to the east of the DMF is the best site for determining the displacement, the region is complicated by voluminous younger
magmatic rocks along the boundary (Fig. 1b). The NW–SE striking Jiapigou Fault (Zhang et al., 2005; Li et al., 2010; Deng et al., 2014), Jinyinbie Fault (Zeng et al., 2014, 2017; Guo et al., 2016, 2017; Xie et al., 2017) and Fuerhe Fault (Yang et al., 2003; Li et al., 2007a, 2007b; Zhang et al., 2008) close to the boundary east of the DMF have all been considered to represent the boundary fault between the LAB and the NCC (Fig. 2a).

In this paper, we present lithological, and zircon age and Hf isotopic data to constrain the position of the eastern LAB to the east of the DMF. The data show the existence of the LAB to the east of the DMF. The results also indicate the position of the boundary between the LAB and the NCC east of the DMF. Correlation of the boundary with its equivalent to the west of the DMF accurately constrains a 170 km sinistral displacement along the fault. These data provide the first reliable estimate of the amount of displacement upon the entire TLFZ in NE China.

2. Geological setting

The eastern CAOB lies between the NCC to the south and the Siberia Craton to the north (Fig. 1a). The orogenic belt contains several microcontinents and suture zones. The microcontinents include, from west to east, the Erguna, Xing’an, Songliao, and Jiamusi blocks (Fig. 1a). The Erguna Block collided with the Xing’an Block along the Xiguitu Suture during the early Paleozoic (Liu et al., 2017c), the Songliao Block collided with the Jiamusi Block along the Mudanjiang Suture during the early Paleozoic (Meng et al., 2010; Xu et al., 2012), and collision between the Songliao and Xing’an blocks along the Hegenshan Suture took place in the Carboniferous (Fig. 1a; Zhou et al., 2015). Some authors (Xu et al., 2015) proposed that the three collisional events took place in Cambrian, Silurian and middle Devonian respectively, and the middle Devonian collision represents the final closure of the Paleo-Asian Ocean. Basement rocks in the blocks consist of the high-grade Mashan Complex that yields protolith ages of Mesoproterozoic to early Cambrian (Wilde, 2015; Liu et al., 2017c). Metamorphism in the
basement rocks has been dated at ca. 500 Ma (Wilde et al., 2000, 2003). Igneous rocks of Triassic to Early Cretaceous age are widespread in the eastern CAOB (Wu et al., 2011; Xu et al., 2013; Tang et al., 2018), and many rifted basins of Cretaceous to Paleogene age are present within the orogenic belt (Ren et al., 2002; Meng, 2003; Gu et al., 2017). The eastern margin of the CAOB joins the N–S trending Sikhote–Alin Terrane that formed through westward subduction of the Izanagi Plate during the Jurassic to Early Cretaceous (Faure et al., 1995; Kemkin et al., 2016).

The LAB along the southern margin of the eastern CAOB is situated between the Solonker Suture Zone to the north and the NCC to the south (Fig. 1a). The western LAB, to the west of the TLFZ, consists of the accreted Bainaimiao Arc of early Paleozoic age in the south and the Ondor Sum accretionary complex of late Paleozoic age in the north (Xiao et al., 2003, 2009a, 2009b; Windley et al., 2007; Xiao and Santosh, 2014; Wilde, 2015; Liu et al., 2017c; Zhou et al., 2018). The western LAB records the accretion of the Bainaimiao Arc to the NCC during the late Silurian, post-orogenic Devonian magmatism, arc magmatism and accretion in response to the southward subduction of the Paleo-Asian oceanic crust during the Carboniferous to early Permian, and collisional orogenesis during the final closure of the ocean during the late Permian to Middle Triassic (Xiao et al., 2003, 2009a, 2009b; Windley et al., 2007; Jian et al., 2008; Xiao and Santosh, 2014; Zhang et al., 2014c; Wilde, 2015; Liu et al., 2017c). Similarly to the eastern CAOB, the entire LAB experienced intense magmatism during the late Triassic to early Cretaceous.

The eastern LAB is dominated by Paleozoic to Mesozoic plutons and metamorphosed volcanic-sedimentary rocks of Paleozoic age (Wu et al., 2004b, 2011). Precambrian rocks are absent from this unit (Pei et al., 2016; Gu et al., 2018). The architecture and evolution of the eastern LAB remain unclear. Wu et al. (2011) suggested that the eastern LAB consists of late Paleozoic accretionary complexes produced by the southward subduction of Paleo-Asian oceanic
crust. Pei et al. (2016) proposed that the eastern LAB contains an early Paleozoic island arc that was accreted to the NCC during the latest Silurian to earliest Devonian. Several lines of evidence suggest that final closure of the ocean occurred along the eastern Solonker Suture Zone during the early to mid-Triassic (Cao et al., 2013; Wang et al., 2015b; Liu et al., 2017a; Ma et al., 2017; Gu et al., 2018; Tang et al., 2018).

The NCC to the south of the LAB consists of Archean to Paleoproterozoic metamorphic basement, Mesoproterozoic to Paleozoic cover sediments, and several Mesozoic–Cenozoic terrestrial rift basins (Zhao et al., 2005, 2012; Zhu et al., 2012a; Zhu et al., 2012b). The basement comprises ca. 2.5 Ga TTG gneisses and 2.0–1.85 Ga magmatic rocks that were affected by ca. 1.85 Ga high-grade metamorphism related to collision between the Eastern and Western blocks of the NCC along the Trans-North China Orogen (Zhao et al., 2005, 2012; Faure et al., 2007). The northern margin of the NCC, termed the Yinshan–Yanshan fold-and-thrust belt, locally records Permian to Triassic deformation (Hu et al., 2003; Hu et al., 2005; Lin et al., 2013; Wang et al., 2013; Zhang et al., 2014b). Two compressive events, at the end of the Middle Jurassic and the beginning of the Cretaceous, have been documented in the Yanshan fold-and-thrust belt, which are collectively called the Yanshanian Movement (Wong, 1929; Meng, 2003; Dong et al., 2015; Zhu et al., 2015). The eastern NCC underwent intense extension during the Early Cretaceous in response to significant lithosphere thinning and cratonic destruction (Wu et al., 2005; Xu et al., 2010; Zhang et al., 2012a; Zhu et al., 2012b; Zhu et al., 2012a, 2015). This extension produced numerous rift basins and metamorphic core complexes along the northern margin of the eastern NCC. The Yinshan–Yanshan fold-and-thrust belt records arc magmatism during the late Paleozoic due to southward subduction of the Paleo-Asian oceanic crust in the north (Xiao et al., 2003; Zhang et al., 2009a, 2009b, 2016b; Wu et al., 2011). Intense magmatism due to extension is also recorded in the Late Triassic, Early Jurassic, Late Jurassic and Early Cretaceous (Zhang et al., 2014b; Tang et al., 2018).
The boundary between the LAB and NCC is marked by the Chifeng–Kaiyuan Fault (CKF; Fig. 1a; Wilde, 2015; Liu et al., 2017c). Geophysical data show that this fault dips towards the north or northeast at moderate angles and dissects the entire lithosphere (Xu et al., 2000; Xiao et al., 2003; Zhang et al., 2014a). The fault is thought to have originated as a thrust during late Silurian arc–continent collision and was reactivated as a south- or southwest-directed thrust in response to later intracontinental reworking (Xu et al., 2000; Xiao et al., 2003; Lin et al., 2013; Zhang et al., 2014a; Gu et al., 2018). However, the kinematic history of the fault is poorly constrained because the structure in the region is largely obscured by younger plutons and basins.

The TLFZ, which trends broadly NE–SW and extends for 2400 km, is the largest fault zone in East China (Fig. 1a; Xu et al., 1987, 1993; Zhu et al., 2005, 2009, 2010). The southern segment of the fault zone formed during the Middle Triassic due to collision between the NCC and the South China Block along the Dabie–Sulu orogens (Xu et al., 1987, 1993; Yin and Nie, 1993; Li, 1994; Lin, 1995; Zhu et al., 2009; Zhao et al., 2016). The northern segment of the fault in NE China is subdivided into the ~900 km long YYF in the west and the ~1000 km long DMF in the east (Fig. 1a). Both of these structures formed as sinistral faults at the beginning of the Cretaceous in response to rapid oblique subduction of the Izanagi Plate in the Pacific Ocean (Xu et al., 1987, 1993; Zhu et al., 2005, 2009, 2010; Gu et al., 2016; Zhao et al., 2016; Liu et al., 2018). The DMF experienced another phase of sinistral motion at the end of Early Cretaceous (Liu et al., 2018). The two faults also record a normal sense of movement during the Early Cretaceous and Paleogene, as shown by the formation of grabens and associated volcanism (Xu et al., 1987, 1993; Ren et al., 2002; Gu et al., 2017; Liu et al., 2018). Normal faulting during the Neogene caused local eruptions of basalt along both faults (Liu, 1987; Liu, 1990; Wang et al., 1999).
3. Geology of the study area and sample descriptions

This study aims at constraining the location of the eastern LAB to the east of the DMF. The study area includes both the LAB and the northern margin of the NCC between the DMF and the NE-striking Yalu River Fault (Figs. 1b and 2a). The Yalu River Fault is a sinistral fault of earliest Cretaceous age (Zhang et al., 2018). Five NW-striking faults occur in the area, namely the Jiapigou, Jinyinbie, Chifeng–Kaiyuan, Fuerhe, and Jiangyuan faults (Fig. 2a). All dip towards the NE and cut Archean to Jurassic rocks. The faults show multiple phases of movement, but are dominated by SW-directed thrusting. They record ductile or brittle–ductile structures in Paleozoic to Middle Triassic rocks and brittle structures in Late Triassic to Jurassic rocks. The CKF, which separates the LAB from the NCC in the study area, is examined in the current study. It cuts Jurassic plutons with brittle thrusts due to later reactivity (Fig. 2a and b). The exposed CKF is composed of several NE-dipping thrusts. They dip at 40°–65° with an average of 50°. The thrusts show down-dip striations, and shear sense indicators suggest SW-directed thrusting.

Although the precise location of the boundary between the LAB and the NCC in the study area is unclear, rocks from the two units are lithologically distinct (Fig. 2a and b). The LAB is dominated by late Paleozoic to Jurassic plutonic rocks (Zhang et al., 2004b; Liu et al., 2009, 2010a, 2012; Wu et al., 2011; Wang et al., 2013, 2015b). Metamorphosed volcanosedimentary rocks of late Paleozoic age (Zhou et al., 2017), unmetamorphosed volcanosedimentary rocks of Jurassic–Cretaceous age (Liu et al., 2009; Wang et al., 2013), and Neogene basalt (Liu, 1987; Wang et al., 1999; Zhao et al., 2015) occur within the LAB (Fig. 2a). Paleozoic to Middle Triassic rocks in the LAB record ductile deformation characterized by SW-directed thrusting. In contrast, Late Triassic to Jurassic rocks are only locally cut by brittle faults (Fig. 2b).

The northern margin of the NCC in the study area is dominated by high-grade basement rocks (Fig. 2a). The basement rocks include ca. 2.5 Ga TTG gneiss, amphibolite, plagioclase amphibolite, quartzite and schists. They show amphibolite to granulite facies metamorphism
Volcanosedimentary rocks of late Paleozoic to Jurassic age, Jurassic plutons, and Neogene basalt occur locally on the margin of the NCC (Fig. 2a; Liu, 1987; Wang et al., 1999; Zhang et al., 2004b, 2008; Li et al., 2007a, 2007b, 2009; Zhang et al., 2012b; Zhao et al., 2015; Xie et al., 2017; Zhou et al., 2017).

Eight samples were collected for LA–ICP–MS zircon dating, of which five were also analyzed for in situ zircon Hf isotopes (Figs. 2a and 3). Two gneiss samples and two plutonic rocks from the area to the southwest of the newly assigned CKF, referred to here as the southwestern area, were analyzed. Three plutonic samples are from the area between the CKF and the Jiangyuan Fault, referred to here as the transitional area. A single plutonic sample is from the area to the northeast of the Jiangyuan Fault, referred to here as the northeastern area (Figs. 2a and 3). The results are listed in Table 1.

4. Analytical methods

4.1 Zircon U–Pb dating

Zircons were separated by conventional magnetic and heavy liquid methods before handpicking under a binocular microscope. About 500 zircon grains were placed on adhesive tape and mounted in epoxy resin and polished to reveal their cores. Cathodoluminescence (CL) images of zircons (Fig. 4) were acquired using a JXA-8100 Electron Probe Microanalyzer equipped with a Gatan CL3+CL detector. High-precision zircon U–Th–Pb data were generated by LA–ICP–MS employing an Agilent 7500a ICP–MS equipped with a 193 nm Geo-Las2005 laser at the Geological Laboratory, School of Resource and Environmental Engineering, Hefei University of Technology, Hefei, China. The 91500 zircon standard was used for standardization and a NIST SRM 610 silicate glass standard was used for instrument optimization. The full analytical procedure is outlined by Yan et al. (2015). Uncertainties on individual LA–ICP–MS analyses are quoted at the 1σ level. Common Pb was corrected following Andersen (2002) and
the results (given in Supplementary Table S2) were generated using ICP–MS–Data Cal 9.6 (Liu et al., 2010b) and ISOPLOT 3.3 (Ludwig, 2003). Ages quoted below are between 90% and 100% concordant (Supplementary Table S2), and are $^{207}\text{Pb}/^{206}\text{Pb}$ ages for grains older than 1.0 Ga, and $^{206}\text{Pb}/^{238}\text{U}$ ages for younger grains.

## 4.2 Zircon Hf isotopic analysis

*In situ* zircon Hf isotopic analyses were conducted using a Neptune MC–ICP–MS equipped with a 193 nm laser at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS), Beijing, China. A laser beam with a 44 μm diameter and a repetition rate of 8 Hz was used. The detailed analytical procedures, including corrections for interferences, are described by Wu et al. (2006). The $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of the zircon standards MUD Tank and Plesovice were $0.282511 \pm 0.000007$ ($n = 24$, MSWD = 0.76) and $0.282485 \pm 0.000009$ ($n = 13$, MSWD = 0.63), respectively, which are in agreement with the recommended values within 2σ error (Woodhead and Hergt, 2005; Sláma et al., 2008).

The initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios (Supplementary Table S3) were calculated with reference to the chondritic reservoir (CHUR) at the time of magmatic zircon growth. Calculation of $\varepsilon_{\text{Hf}}(t)$ is based on the chondritic values of $^{176}\text{Hf}/^{177}\text{Hf}$ (0.282772) and $^{176}\text{Lu}/^{177}\text{Hf}$ (0.0332) reported by Blichert-Toft and Albarède (1997). The $\varepsilon_{\text{Hf}}(t)$ value was calculated using the previously measured U–Pb ages. Plots of zircon U–Pb age vs $\varepsilon_{\text{Hf}}(t)$ are used to show the spread of $\varepsilon_{\text{Hf}}(t)$ values relative to CHUR and depleted mantle (DM) evolution lines (Fig. 7). The DM line is defined by the present-day ratios of $^{176}\text{Hf}/^{177}\text{Hf}$ (0.28325) and $^{176}\text{Lu}/^{177}\text{Hf}$ (0.0384) (Griffin et al., 2000). Magmas dominated by a mantle-derived component plot close to the DM line, whereas magmas derived from juvenile or older crustal rocks plot above or below the CHUR line.

The two-stage model ages ($T_{\text{DM2}}$) used in this study are probably more accurate than depleted mantle model ages. The two-stage model ages ($T_{\text{DM2}}$) were calculated by projecting the initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of the zircon back to the depleted mantle model growth curve assuming
a $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.015 for the average continental crust (Griffin et al., 2004).

5. Analytical results

5.1 Zircon dating

Samples of both igneous rocks and orthogneiss were dated as part of this study. A younger group of magmatic zircon ages from each sample, as indicated by their CL characteristics (Fig. 4) and Th/U ratios (>0.1; Supplementary Table S2), was used to calculate a weighted mean age for the protolith, intrusion, or eruption age as appropriate. The dated samples also contain older, inherited zircon ages (Table 1; Fig. 4; Supplementary Table S2).

Two high-grade gneiss samples from the NCC basement in the southwestern area (Fig. 3a and b) yielded $^{207}\text{Pb}/^{206}\text{Pb}$ weighted mean ages of 2502 ± 16 Ma ($n = 29$, MSWD = 1.70, sample DM045) and 2505 ± 15 Ma ($n = 30$, MSWD = 1.30, sample DM049), respectively (Fig. 5a and b). Both ages are interpreted as the protolith ages of the orthogneisses. Two plutonic samples from the NCC in the southwestern area (Fig. 3c and d) gave $^{206}\text{Pb}/^{238}\text{U}$ weighted mean ages of 165.5 ± 1.5 Ma ($n = 59$, MSWD = 1.30, sample DM048) and 169.1 ± 2.1 Ma ($n = 74$, MSWD = 3.10, sample DM058) (Fig. 5c and d). Both ages are considered to represent intrusion ages of the dated samples.

Five igneous samples were collected from the transitional area. Three plutonic samples (Fig. 3e–g) yielded $^{206}\text{Pb}/^{238}\text{U}$ weighted mean ages of 372.3 ± 3.6 Ma ($n = 69$, MSWD = 1.90, sample DM343), 221.0 ± 4.8 Ma ($n = 6$, MSWD = 0.52, sample DM352) and 180.3 ± 4.1 Ma ($n = 7$, MSWD = 0.53, sample DM057) (Fig. 6a–c), all of which are interpreted as intrusion ages.

A K-feldspar granite (DM056; Fig. 3h) from the northeastern area gave a $^{206}\text{Pb}/^{238}\text{U}$ weighted mean age of 267.7 ± 1.3 Ma ($n = 130$, MSWD = 1.04, Fig. 6d), interpreted as the intrusion age of the pluton.

5.2 Zircon Hf isotopes
To constrain the location of the LAB, zircon grains from the five igneous samples recording Phanerozoic ages were analyzed in situ to measure their Hf isotopic composition (Table 1; Fig. 4). The ages of the analyzed zircons range from 439 to 148 Ma (Supplementary Table S3).

Zircons from the two Middle Jurassic plutonic samples (DM048 and DM058) in the southwestern area gave initial $^{176}\text{Hf}^{177}\text{Hf}$ values of 282039 to 0.282645, with corresponding $\varepsilon_{\text{Hf}}(t)$ values of –22.4 to –0.4 (Fig. 7a) and two-stage model ages ($T_{\text{DM2}}$) between 2626 and 1255 Ma (Table 1; Fig. 8a).

Zircons from the 372 Ma granodiorite (sample DM343) from the transitional area yielded initial $^{176}\text{Hf}^{177}\text{Hf}$ ratios of 0.281917 to 0.282017 and $\varepsilon_{\text{Hf}}(t)$ values of –22.7 to –18.0 (Fig. 7a). The corresponding two-stage model ages ($T_{\text{DM2}}$) range from 2778 to 2538 Ma (Table 1; Fig. 8b). Newly crystallized zircons from the 180 Ma granite (sample DM057) gave initial $^{176}\text{Hf}^{177}\text{Hf}$ ratios of 0.282364 to 0.282475, $\varepsilon_{\text{Hf}}(t)$ values of –10.5 to –6.4, and two-stage model ages ($T_{\text{DM2}}$) of 1891 to 1637 Ma (Figs. 7a and 8b). In contrast, inherited zircons from samples DM057 yielded initial $^{176}\text{Hf}^{177}\text{Hf}$ ratios of 0.282276 to 0.282854, $\varepsilon_{\text{Hf}}(t)$ values of –10.5 to +8.2, and two-stage model ages ($T_{\text{DM2}}$) of 1995 to 747 Ma (Table 1; Figs. 7a and 8b).

Zircons from the 268 Ma K-feldspar granite (DM056) in the northeast area gave initial $^{176}\text{Hf}^{177}\text{Hf}$ ratios of 0.282604 to 0.282789 and $\varepsilon_{\text{Hf}}(t)$ values of –0.4 to +6.7. Their two-stage model ages ($T_{\text{DM2}}$) range from 1304 to 869 Ma (Table 1; Figs. 7a, 8c).

6. Discussion

6.1 Location of the LAB to the east of the DMF

The NCC and the LAB differ in their lithology, zircon age spectra, $\varepsilon_{\text{Hf}}(t)$ values, and two-stage model ages. These four characteristics can be used to indicate whether the LAB extends eastwards over the DMF and accurately constraint on the location of the boundary.
between the LAB and the NCC. The inferred location of the boundary coincides with the position of the CKF (Fig. 2a).

6.1.1 Constraints from lithological variations

The NCC contains high-grade basement rocks of Archean to Paleoproterozoic age, which are overlain unconformably by unmetamorphosed sedimentary cover rocks of Mesoproterozoic to Paleozoic age (Zhao et al., 2005, 2012). The presence of high-grade Archean rocks is a reliable indication that these rocks belong to the NNC. In contrast, Archean rocks have never been documented in the eastern CAOB (Xiao et al., 2003, 2009b; Wilde, 2015; Liu et al., 2017c). Precambrian rocks are absent from the LAB (Xiao et al., 2003, 2009b), whereas the Songliao Block in the CAOB contains Mesoproterozoic to Neoproterozoic rocks, such as the Mashan Complex, which experienced high-grade metamorphism at ca. 500 Ma (Wilde et al., 2000, 2003).

The Neoarchean TTG gneisses, as dated using the U–Pb zircon method (Zhang et al., 2008; Li et al., 2009; Guo et al., 2016, 2017; Xie et al., 2017; and this study), are widely exposed in the southwestern area (Fig. 2a). In contrast, rocks in the transitional and northeastern areas to the east of the DMF are dominated by late Paleozoic to Jurassic plutonic rocks (Fig. 2a; Zhang et al., 2004b; Liu et al., 2009, 2010a, 2012; Wang et al., 2013, 2015b; this study). Phanerozoic volcanosedimentary rocks occur locally and Precambrian rocks are absent from the two areas (Fig. 2a). These marked lithological differences suggest that the southwestern area to the east of the DMF is similar to the NCC, whereas the transitional and northeastern areas are similar to the LAB. Thus, the boundary between the LAB and the NCC must lie along the northern edge of the Neoarchean TTG gneisses (Fig. 1b), which follows the position of the CKF (Fig. 2a).

6.1.2 Constraints from zircon age spectra

The NCC and CAOB, including the LAB and Songliao Block, have distinct zircon age spectra. Zircon ages from the northern margin of the NCC (i.e. the Yanshan fold-and-thrust belt)
show age peaks at 2510, 1862, 308, 224, and 166 Ma, with no evidence for Neoproterozoic or early Paleozoic age peaks (Fig. 9a; Ma et al., 2004; Zhang et al., 2004a; Wan et al., 2005; Feng et al., 2012; Peng et al., 2015; Liu et al., 2016b; Zhang et al., 2017; Liu et al., 2018). In contrast, zircon age spectra of the western LAB to the west of the DMF exhibit age peaks at 410, 360, 252, and 165 Ma, including early Paleozoic zircon, but an absence of Neoproterozoic ages (Fig. 9b; Gu et al., 2018 and references therein). The Songliao Block to the north of the LAB is characterized by age peaks at 1800, 854, 516, 486, 318, 218, and 185 Ma (Fig. 9c; Meng et al., 2010; Tang et al., 2011; Wang et al., 2012a, 2012b, 2014, 2015a; Yu et al., 2012; Zhou et al., 2012; Xu et al., 2013; Wang et al., 2016c; Luan et al., 2017; Ge et al., 2018; Guo et al., 2018).

Zircon age spectra of rocks from the southwestern area, of this and previous studies, show clusters at 2512, 1873, 322, 224, 166 Ma, without Neoproterozoic or early Paleozoic ages (Fig. 9d). The age spectra are similar to those from the northern margin of the NCC (Fig. 9a).

Zircon ages for the transitional area show peaks at 1846, 376, 263, and 165 Ma, without Archean or Neoproterozoic ages (Fig. 9e). The northeastern area shows age clusters at 268 and 180 Ma, without Archean or Neoproterozoic ages (Fig. 9f). The age spectra of the transitional and northeastern areas are similar to those of the western LAB (Fig. 9b), but differ from those of the NCC (Fig. 9a) and the Songliao Block (Fig. 9c).

The correlation between the age spectra shows that the southwestern area is correlative with the NCC, whereas both the transitional and northeastern areas can be regarded as belonging to the eastern LAB to the east of the DMF. The data also constrain the boundary between the NCC and LAB to lie along the CKF (Fig. 2b), consistent with the observed lithological variations.

**6.1.3. Constraints from $\varepsilon_{\text{Hf}}(t)$ values and two-stage model ages**

Previous work has demonstrated that Phanerozoic magmatic zircons from the northern margin of the NCC have $\varepsilon_{\text{Hf}}(t)$ values lower than $-1.5$ and two-stage model ages that are mostly Paleoproterozoic to Archean. In contrast, Phanerozoic zircons from the CAOB are characterized
by $\varepsilon_{\text{Hf}}(t)$ values higher than −4.2 and younger two-stage model ages that are mostly Mesoproterozoic to Neoproterozoic (Yang et al., 2006). The $\varepsilon_{\text{Hf}}(t)$ values and two-stage model ages of the LAB are broadly similar to those of the CAOB, but some of the data from the LAB, where it is near the NCC, show an affinity to the NCC (Zhang et al., 2014c, 2016b; Gu et al., 2018; Zhou et al., 2018). These observations provide another way of constraining the location of the LAB to the east of the DMF.

The $\varepsilon_{\text{Hf}}(t)$ values of Phanerozoic magmatic zircons from the southwestern area range from −22.4 to −0.4 (Table 1; Fig. 7a), corresponding to two-stage model ages between 2626 and 1255 Ma (Table 1; Fig. 8a). Previously published data from the same area also show negative $\varepsilon_{\text{Hf}}(t)$ values and model ages that are mostly Archean to Paleoproterozoic (Figs. 7b and 8d). These data suggest that the Phanerozoic magmas in the southwestern area were derived from ancient continental crust, supporting a genetic link to the NCC (Yang et al., 2006).

The $\varepsilon_{\text{Hf}}(t)$ values from the transitional area measured here are −22.7 to +8.2, with corresponding model ages between 2778 and 747 Ma (Table 1; Figs. 7a and 8b). Previously published $\varepsilon_{\text{Hf}}(t)$ values from the transitional area range from positive to negative, but are dominated by values higher than the −4.2 (Fig. 7b). Existing model ages show a large spread, but are dominantly Mesoproterozoic to Neoproterozoic ages (Fig. 8e). Most of the zircon data from the LAB show an affinity with the CAOB, but some grains from rocks close to the NCC have a NCC affinity (Zhang et al., 2014c, 2016b; Gu et al., 2018; Zhou et al., 2018). The north-dipping orientation of the boundary fault, the CKF, between the NCC and the LAB (Fig. 2b) has been invoked to explain the NCC-derived magmatism in the LAB (Gu et al., 2018). The mixture of the CAOB- and NCC-derived zircons is a characteristic feature of the southern LAB. The $\varepsilon_{\text{Hf}}(t)$ values and model ages documented above indicate that the transitional area between the CKF and the Jiangyuan Fault represents part of the LAB, and that the CKF follows the boundary between the LAB and the NCC (Fig. 2a).
The $\varepsilon_{\text{Hf}}(t)$ values obtained from this and previous studies from the northeastern area are mainly positive (Fig. 7b). Corresponding two-stage model ages are all younger than the Paleoproterozoic (Fig. 8f). No zircons with a NCC-affinity have been recognized in the northeastern area. These data suggest that the northeastern area represents the northern part of the LAB in the study area, as also indicated by the lithological data and age spectra (Fig. 9f).

Previous work has also demonstrated that whole-rock $\varepsilon_{\text{Nd}}(t)$ values of Phanerozoic igneous rocks are negative, positive and around zero for the NCC, CAOB and LAB respectively (Yang et al., 2006; Guo et al., 2010; Zhang et al., 2014c). Previously published whole-rock $\varepsilon_{\text{Nd}}(t)$ values from Phanerozoic igneous rocks in the study area are $-10.4$ to $-8.6$ for the southwestern area (Zhang et al., 2012b), $+1.1$ to $+2.5$ for the northeastern area (Huang et al., 2015) and $-5.0$ to $+0.8$ for the transitional area (Wu et al., 2004a; Liu et al., 2010a; Huang et al., 2015). The constraints on the three units from the whole-rock $\varepsilon_{\text{Nd}}(t)$ are consistent with those from the zircon $\varepsilon_{\text{Hf}}(t)$ data.

In summary, the lithological variations, zircon age spectra, $\varepsilon_{\text{Hf}}(t)$ values, and two-stage model ages provide consistent constraints on the presence and position of the LAB between the DMF and the Yalu River Fault (Fig. 2a). These data demonstrate the presence of the LAB in the transitional and northeastern areas just to the east of the DMF. Furthermore, they indicate that the boundary between the NCC and LAB is located precisely along the CKF. However, the available data are unable to indicate precisely the position of the Solonker Suture Zone that defines the northern margin of the LAB.

6.2 Sinistral displacement along the DMF

The DMF, one of the largest faults in NE China, originated as a strike-slip fault at the beginning of the Cretaceous and was reactivated as a normal fault during the Late Cretaceous and Paleogene (Liu et al., 2018). The magnitude of sinistral displacement along the fault remains debated (Xu, 1980, 1985a; Xu et al., 1987; Hong, 1988; Xu and Ma, 1992; Wan et al., 1996; Yu, 1996; Guo et al., 2000; Guo et al., 2001; Li et al., 2002; Wang et al., 2016a).
The location of the boundary between the LAB and NCC just to the west of the DMF has been well constrained using lithological, zircon age, and Hf isotopic data (Fig. 1b; Gu et al., 2018). The determination of the equivalent boundary to the east of the DMF in this study makes it possible to calculate the magnitude of sinistral displacement on the DMF. The locations of the boundaries on either side of the DMF, which are defined by the CKF, indicate a sinistral displacement of 170 km along the fault.

The YYF, the western branch of the TLFZ in NE China, shows a 35 km sinistral displacement (Gu et al., 2018). With a displacement of 170 km, the DMF records significantly more strike-slip movement than the YYF. The larger magnitude of strike-slip movement upon the DMF might be related to its closer proximity to the Pacific Ocean, where oceanic plate subduction has resulted in sinistral faulting along the TLFZ at the beginning of the Cretaceous (Xu et al., 1987; Zhu et al., 2005; Gu et al., 2016; Liu et al., 2018; Zhang et al., 2018).

The two branches of the TLFZ show a total sinistral displacement of 205 km along the boundary between the LAB and the NCC. The 205 km displacement along the northern segment of the TLFZ is much less than the 550 km displacement along the southern segment, as indicated by the sinistral offset of the northern boundaries of the Dabie and Sulu orogenic belts (Fig. 1a; Xu et al., 1987; Wang et al., 1992; Zhu et al., 2009; Zhao et al., 2016). The large difference in the amount of displacement between the northern and southern segments of the TLFZ supports the interpretation that the two segments record different histories (Zhu et al., 2009; Zhao et al., 2016).

7. Conclusions

Lithological and zircon data from the boundary between the CAOB and NCC to the east of the DMF enable us to draw the following conclusions.

1. The U–Pb ages, $\varepsilon_{Hf}(t)$ values, and two-stage model ages of zircons demonstrate that the
eastern LAB extends eastwards over the DMF. Thus, the LAB is present to the east of the TLFZ.

(2) The lithological and zircon data provide reliable constrains on the location of the boundary between the LAB and NCC to the east of the DMF. The boundary coincides with the NE-dipping CKF, which was involved in SW-directed thrusting.

(3) Comparison of the boundaries between the LAB and NCC on the both sides of the DMF indicates a 170 km sinistral displacement along the fault. The two branches of the TLFZ in NE China, the YYF and DMF, produced a 205 km sinistral offset of the boundaries of the NCC.

(4) The amount of strike-slip movement of the DMF is much higher than that of the YYF in NE China. This difference supports the proposal that the dynamics of strike-slip kinematics of the TLFZ during the late Mesozoic resulted from westward subduction of the Paleo-Pacific Plate.

Acknowledgments

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References

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Figure captions

Fig. 1. (a) Tectonic outline of northeastern Asia (modified after Gu et al., 2018). (b) Geological sketch map of the southern Dunhua–Mishan Fault, showing zircon ages and $\varepsilon_{Hf}(t)$ values from Chen et al. (2006), Feng et al. (2011), Wu et al. (2011), Cao et al. (2012, 2013), Cao (2013), Wang et al. (2013, 2015b), Liu et al. (2016a), Pei et al. (2016), Wang et al. (2016b), Yuan et al. (2016), Zhang et al. (2016a), Li and Wei (2017), and Gu et al. (2018).

Fig. 2. (a) Geological map of the study area showing zircon ages and $\varepsilon_{Hf}(t)$ values of this study and those reported by Zhang et al. (2004b, 2008), Li et al. (2007a, 2007b, 2009), Liu et al. (2009, 2010a, 2012), Sun et al. (2009), Wu et al. (2011), Zhang et al. (2012b), Wang et al. (2013, 2015b), Huang (2015), Guo et al. (2016, 2017), Xie et al. (2017), and Zhou et al. (2017), and their details are listed in Table 1 and Supplementary Table S1. (b) Cross-section through the boundary between the Liaoayuan Accretionary Belt and the North China Craton.

Fig. 3. Field photographs of the dated samples from the study area. (a) Granodioritic gneiss (DM045) from the southwest of the study area; (b) hornblende–plagioclase gneiss (DM049) from the southwest; (c) granodiorite sample (DM048) from the southwest; (d) monzogranite sample (DM058) from the southwest; (e) gneissic granodiorite (DM343) from the transition area; (f) granite (DM352) from the transition area; (g) monzogranite (DM057) from the transition area; (h) K-feldspar granite (DM056) from the northeast. Sample localities are shown in Fig. 2a.

Fig. 4. Cathodoluminescence images of representative zircon grains, along with calculated U–Pb ages and $\varepsilon_{Hf}(t)$ values.

Fig. 5. Zircon U–Pb concordia diagrams (left), histograms, and relative probability curves of concordant zircon ages (center), and Th/U ratio versus age plots (right) for the dated samples from the southwestern area.

Fig. 6. (a) Zircon U–Pb concordia diagrams (left), histograms and relative probability curves of concordant zircon ages (center), and Th/U ratio versus age plots (right) for the dated samples from the transitional (a–c) and northeastern (d) areas.

Fig. 7. Correlations between the Hf isotopic compositions and ages of zircons from the Phanerozoic igneous rocks in the study area. Also shown are data from Liu et al. (2009, 2010a, 2012), Zhang et al. (2012b), Wang et al. (2013, 2015b), Huang (2015), and Zhou et al. (2017). The division between the eastern CAOB (including the LAB) and northern NCC is based on Yang et al. (2006).

Fig. 8. (a) Histograms and relative probability curves of two-stage model ages for magmatic zircons from Phanerozoic igneous rocks in the study area. Also shown are data from Liu et al. (2009, 2010a, 2012), Zhang et al. (2012b), Wang et al. (2013, 2015b), Huang (2015), and Zhou et al. (2017).

Fig. 9. Histograms and relative probability curves showing zircon ages for different tectonic units. For a–c, data are from Ma et al., 2004; Zhang et al., 2004a; Wan et al., 2005; Meng et al., 2010; Tang et al., 2011; Feng et al., 2012; Wang et al., 2012a, 2012b, 2014, 2015a; Yu et al., 2012; Zhou et al., 2012; Xu et al., 2013; Peng et al., 2015; Liu et al., 2016b; Wang et al., 2016c; Luan et al., 2017; Zhang et al., 2017; Ge et al., 2018; Gu et al., 2018; Guo et al., 2018; Liu et al., 2018. For d–f, the data are from Zhang et al., 2004b, 2008; Miao et al., 2005; Li et al., 2007b, 2009; Liu et al., 2009, 2010a, 2012; Zhang et al., 2012b; Chang et al., 2013; Wang et al., 2013, 2015b; Deng et al., 2014; Guo et al., 2016, 2017; Xie et al., 2017; Zhou et al., 2017; and the current study.
a. DM343 Gneissic granodiorite
   Weighted mean age: 372.3 ± 3.6 Ma
   n = 69, MSWD = 1.90

b. DM352 Granite
   Weighted mean age: 211.0 ± 4.8 Ma
   n = 6, MSWD = 0.52

c. DM057 Monzogranite
   Weighted mean age: 180.3 ± 4.1 Ma
   n = 7, MSWD = 0.53

d. DM056 K-feldspar granite
   Weighted mean age: 267.7 ± 1.3 Ma
   n = 130, MSWD = 1.04

Transitional area

Northeastern area
**Table 1** Results of zircon dating and Hf isotope analyses

<table>
<thead>
<tr>
<th>Loc.</th>
<th>Sample No.</th>
<th>Rock type</th>
<th>Crystallization/protolith age (Ma)</th>
<th>Captured zircon age (Ma)</th>
<th>Zircon $\varepsilon_{Hf}(t)$</th>
<th>$T_{DM2}$ (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southwestern area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM045</td>
<td>Granodiorite gneiss</td>
<td>2502 ± 16</td>
<td>2584–2677</td>
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<td></td>
</tr>
<tr>
<td>DM049</td>
<td>Hornblende–plagioclase gneiss</td>
<td>2505 ± 15</td>
<td>2596–2749</td>
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<td></td>
</tr>
<tr>
<td>DM048</td>
<td>Granodiorite</td>
<td>165.5 ± 1.5</td>
<td>209</td>
<td>−15.3 to −0.4</td>
<td>1255–2182</td>
<td></td>
</tr>
<tr>
<td>DM058</td>
<td>Monzogranite</td>
<td>169.1 ± 2.1</td>
<td>1732–1908, 2191, 2359, 221–253, 339, 373, 2387–2643</td>
<td>−22.4 to −1.4</td>
<td>1298–2626</td>
<td></td>
</tr>
<tr>
<td>Transitional area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM343</td>
<td>Granodiorite</td>
<td>372.3 ± 3.6</td>
<td>421, 439</td>
<td>−22.7 to −18.0</td>
<td>2538–2778</td>
<td></td>
</tr>
<tr>
<td>DM352</td>
<td>Granite</td>
<td>221.0 ± 4.8</td>
<td>415, 1762–1938, 2062, 2111</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>DM057</td>
<td>Monzogranite</td>
<td>180.3 ± 4.1</td>
<td>891, 1118, 1377, 1768–1966, 2607</td>
<td>−14.4 to +8.2</td>
<td>747–1995</td>
<td></td>
</tr>
<tr>
<td>Northeastern area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM056</td>
<td>K-feldspar granite</td>
<td>267.7 ± 1.3</td>
<td>—</td>
<td>−0.4 to +6.7</td>
<td>869–1304</td>
<td></td>
</tr>
</tbody>
</table>

Note: $\varepsilon_{Hf}(t)$ = initial Hf isotope ratio; $T_{DM2}$ (Ma) = two-stage model age
Graphical abstract
**Highlights**

Eastern Liaoyuan Accretionary Belt extends eastwards over the Dunhua-Mishan Fault.

Dunhua-Mishan Fault shows a 170 km sinistral displacement taking place in the late Mesozoic.

Tan-Lu Fault Zone has a total sinistral displacement of 205 km in NE China.

Dunhua-Mishan Fault records more strike-slip movement than the Yilan-Yitong Fault.