Meso-Cenozoic multiple exhumation in the Shandong Peninsula, eastern North China Craton: Implications for lithospheric destruction

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Abstract

The Shandong Peninsula in the eastern North China Craton (NCC) forms part of the region that witnessed extensive tectonic reactivation with concomitant craton destruction and lithospheric thinning during the Meso-Cenozoic. Previous studies concentrated mainly on the timing, mechanism and tectonic setting of the Meso-Cenozoic magmatism, with inadequate evidence from low temperature thermochronology to constrain the thermo-tectonic exhumation history of the region. In this study, we present new apatite U-Pb (AUPb) and fission track (AFT) data with corresponding thermal history models for igneous rocks from the two flanks of the Tan-Lu Fault Zone (TLFZ) that bisects the Shandong Peninsula, with a view to gain insights into the Meso-Cenozoic exhumation history of this region and to evaluate its implications on the lithospheric destruction of the NCC. The newly obtained AUPb ages of 2.5-1.5 Ga for the Precambrian intrusive rocks and of 162-112 Ma for the Mesozoic igneous suite are mainly used to constrain their thermal history models. In addition, the Mesozoic AUPb ages of 162-112 Ma highly overlap with their corresponding zircon U-Pb ages (161-115 Ma), suggesting shallow granitoid emplacement and associated rapid post-magmatic cooling in response to the westward subduction of the Paleo-Pacific Plate. The AFT dating results yield two groups of AFT central ages at 122-113 Ma and 98-59 Ma, and the associated thermal history models also reveal two rapid cooling stages during the Early Cretaceous (130-105 Ma) and Late Cretaceous to Paleogene (85-55 Ma). By integrating previous low temperature thermochronological studies with this study, we interpret that the Early Cretaceous rapid exhumation corresponds to the peak timing of craton destruction, resulting from the Paleo-Pacific slab rollback within a back-arc extensional setting. The Late Cretaceous rapid exhumation is interpreted as a response to continuing craton destruction, derived by the NNW-directed Pacific Plate subduction. The Paleogene cooling might represent the termination of craton destruction of Shandong Peninsula associated with a dextral motion along the TLFZ, triggered by the change in direction of the Pacific Plate from NNW to WNW and/or far-field effect of the India-Eurasia collision.

Keywords: Apatite U-Pb dating; Apatite fission track; Thermal history modeling; Lithospheric destruction; Shandong Peninsula; North China Craton

1. Introduction

The North China Craton (NCC), the largest block in the easternmost Eurasian continent, was assembled and cratonized during the Neoarchean and Paleoproterozoic (Zhai and Santosh, 2011; Santosh et al., 2020). Following this, the craton underwent significant Meso-Cenozoic tectonic reactivation characterized by craton destruction and lithospheric thinning (Zhu et al., 2011, 2012a, b; Ratschbacher et al., 2000; Li et al., 2012; Yang et al., 2018a, b, 2019; Yang and Santosh, 2020). During this period, the NCC experienced multiple phases of thermo-tectonic reactivation in response to the following events: 1) the collision between the Yangtze Craton and the NCC during the Late Triassic (Chen et al., 2000; Zhang et al., 2002a; Tang et al., 2019), 2) the westward subduction of the Paleo-Pacific Plate and associated back-arc extension since Late Triassic (Northrup et al., 1995; Wu et al., 2005; Zhu et al., 2011; Zheng et al., 2018; Yang et al., 2018a, b, c), and 3) subsequent lateral extrusion of the eastern Asia toward the east in response to the far-field effect of the Paleogene India-Eurasia collision (Molnar and Tapponnier, 1975; Tapponnier and Molar, 1997; Zhang et al., 1995; Grimmer et al., 2002; Tian et al., 2018).

The Shandong Peninsula is divided by the Tan-Lu Fault Zone (TLFZ), the largest continental-scale NNE-striking fault zone in the eastern NCC, into the Luxi and Jiaodong terranes (Xu and Zhu, 1994) (Fig. 1). These terranes underwent a complex tectonic evolution and intracontinental deformation during the Meso-Cenozoic (Grimmer et al., 2002; Wang et al., 2018). Previous thermochronological studies in the eastern NCC mainly focused on the Luxi terrane (Wang et al., 2007, 2008a, 2008b, 2010; Li et al., 2007, 2012, 2013, 2017, 2018; Li and Zhong, 2006; Tang et al., 2011; Wang et al., 2008; Yang et al., 2008; Shi, 2010; Xu et al., 2016; Hong and Miyata, 1999; Wang et al., 2009) and the Jiaobei uplift within the northern Jiaodong terrane due to the presence of numerous mineral deposits in this region (Liu et al., 2009; Zhao et al., 2018;

Wan and Wang, 1997; Zhao, 2015; Liu et al., 2010; Wu et al., 2018; Faure et al., 2003; Charles, 2010; Charles et al., 2013). The results from the previous studies revealed two stages of exhumation-related cooling during the Late Cretaceous and Paleogene in response to continuing craton destruction and lithospheric thinning associated with the Paleo-Pacific Plate subduction (Zhao et al., 2018). Craton destruction and lithospheric thinning of the NCC is considered to have started in the Middle-Late Triassic (Yang and Wu, 2009; Yang et al., 2010; Zhang et al., 2014). However, the timing of cessation for this extensional tectonics still remains debated, with some models suggesting that craton destruction ceased prior to the Late Cretaceous (Wu et a., 2005; Ying et al. 2006; Wu et al. 2008), whereas others consider that it continued into the Early Cenozoic (Xu et al., 2009; Li et al., 2015; Qiu et al., 2016). In addition, there is an absence of information from the southern Sulu orogenic belt in the southern Jiaodong terrane, inhibiting a more complete understanding of the exhumation history in the Shandong Peninsula.

In this study, we collected representative samples from magmatic suites along the two flanks of the TLFZ, targeting regions with an absence of thermochronological data. We conducted apatite U-Pb (AUPb) and fission track (AFT) double dating together with corresponding thermal history modeling studies in order to constrain the time-temperature evolution history of the Shandong Peninsula. Through integrating our findings with published multiple thermochronological studies from the eastern NCC, we attempt to provide more robust insights into the Meso-Cenozoic exhumation history and associated constraints on craton destruction and lithospheric thinning of the eastern NCC.

2. Geological setting

2.1 North China Craton

The NCC is dominantly composed of Precambrian metamorphic basement, Mesoproterozoic to Cenozoic sedimentary cover sequences and Mesozoic intrusions (Zhai and Santosh, 2011; Zhao and Zhai, 2013) (Fig. 1). The NCC is tectonically bordered to the north by the Central Asian Orogenic Belt, to the south by the Qinling-Dabie Orogenic Belt, to the west by the Qilian Orogen, and to the east by the Sulu HP-UHP Metamorphic Belt (Dan et al., 2016; Dong and Santosh, 2016). The NCC is divided into the Eastern Block (EB), Western Block (WB) and the intervening Trans-North China Orogen (TNCO) (Zhao et al., 2005; Zhao and Zhai, 2013). The EB consists of Archean-Paleoproterozoic basement rocks and underwent Paleoproterozoic rift-subduction-collision along the Jiao-Liao-Ji Belt during 2.2-1.9 Ga (Zhao and Zhai, 2013), the WB comprises the Yinshan and Ordos sub-blocks which were sutured along the intervening Inner Mongolia Suture Zone (IMSZ) at 1.95-1.92 Ga (Zhao et al., 2005), and the N-S trending TNCO in the central NCC is interpreted as a convergent orogenic zone suturing the EB and WB during the Late Paleoproterozoic (Zhao et al., 2005; Santosh, 2010). Recent studies also suggest that the NCC formed by the accretion of several Archean micro-blocks through closure of the intervening oceans which are now represented by major greenstone belts of 2.75-2.6 Ga and ~2.5 Ga age (Zhai and Santosh, 2011).

Although the NCC has underwent multiple periods of lithospheric modification before the Early Paleozoic, the cratonic root was still preserved (Chi and Lu, 1996; Zhao et al., 2010; Zhu et al., 2012a, b). Subsequently, the NCC underwent multiple subductions from different directions, such as the Paleozoic southward subduction of the Paleo-Asian Ocean from north (Li, 2006), Triassic northward collision/subduction with the Yangtze Craton from south (Gao et al., 1998), and westward subduction of the Paleo-Pacific Plate since Late Triassic from east (Yang et al., 2018a, b; 2019). Caught up at the center of this multiple subduction system, the NCC witnessed intense lithospheric thinning and craton destruction during the Meso-Cenozoic, particularly in its eastern part (Yang et al., 2019). Several basins also opened in the eastern NCC during the Meso-Cenozoic, including the Bohai Bay Basin associated with rifting during the Late Cretaceous and continued until the Late Paleogene (Zhao et al., 2018; Chang et al., 2018).

2.2 Luxi terrane

The Luxi terrane is tectonically bordered to the east by the TLFZ, to the west by the Liaokao Fault, and to the south by the Fengpei Fault (Zhang et al., 2007; Wang et al., 2018) (Fig. 2). It is mainly composed of Archean to Proterozoic metamorphic basement rocks, Paleozoic marine sedimentary rocks, and Mesozoic to Cenozoic continental clastic rocks, volcanic clastic, igneous rocks, mafic dykes, carbonatites and alkaline rocks (Xu et al., 2015; Wang et al., 2018). The TLFZ, which extends for more than 1000 km sub-parallel with the margin of Pacific in the eastern NCC (Xu and Zhu, 1994), underwent sinistral motion during the Late Triassic to Early Jurassic induced by the collision between the NCC and Yangtze Craton (Zhu et al., 2009). This was followed by thrust faulting or sinistral transpression during the Middle-Late Jurassic (Wan and Zhu, 1996), and Early Cretaceous normal faulting and extension associated with the westward subduction of the Paleo-Pacific plate (Wu et al., 2005a, b; Wang et al., 2018). The Luxi terrane is bounded by basins and plains, and is considered to be a significant region for topographic uplift with NW- to WNW-trending faults (Li et al., 2017). During the Late Jurassic to Early Cretaceous, the Luxi terrane inherited the strike of the Indosinian (257-205 Ma) fold- and thrust- structures, and initiated large-scale extension resulting in forming tilted strata along the early NW-WNW-trending fault surface. This phase of Mesozoic extension generated a series of nearly E-W-trending grabens and half-grabens, and eventually uplifted and accompanied by massive volcanic eruptions (Li et al., 2005; Li et al., 2017). During the Cenozoic, the Luxi terrane underwent intense normal faulting, and these faults not only controlled the subsequent development of the faulted basins but also caused the tilting of strata (Tang et al., 2011; Li et al., 2017).

2.3 Jiaodong terrane

The Jiaodong terrane within the eastern segment of the TLFZ is divided into the Jiaobei terrane and Sulu orogenic belt bounded by the Wulian-Yantai Fault (Zhai et al., 2000) (Fig. 2). The Jiaobei terrane is further subdivided into the Jiaobei uplift and Jiaolai basin (Mao et al., 2008), and is predominantly composed of Precambrian basement rocks and Mesozoic granites, bimodal volcanic rocks and mafic dikes (Yang et al., 2004). The Jiaobei uplift consists mainly of Archean tonalite-trondhjemite-granodiorite gneisses, Proterozoic metasedimentary sequences and basement rocks, and Mesozoic igneous rocks (Tang et al., 2008; Liu et al., 2008). The Jiaolai basin includes sedimentary cover sequence including mafic, intermediate-felsic volcanic rocks, olivine basalt, and mudstone and clastic rocks (Tan et al., 2012). The Sulu orogenic belt was offset to the north about 500 km through sinistral movement on the TLFZ (Xu and Zhu, 1994), and was formed by the Middle-Late Triassic collision/subduction of the Yangtze Craton beneath the NCC (Xu et al., 1992; Ye et al., 2000). The rocks in this belt include Paleoproterozoic metamorphic rocks, Neoproterozoic granite and amphibolite facies granitic gneisses, Triassic UHP metamorphic rocks and granitoids, Late Jurassic granitoids, and Early Cretaceous mafic to intermediate dikes (Huang et al., 2006; Zhang et al., 2014). These rocks preserved a complex tectonic history of the Middle-Late Triassic deep subduction of the Yangtze continental crust (Xu et al., 1992; Ye et al., 2000; Yang et al., 2005), and subsequently recorded post-collisional lithosphere thinning and craton destruction correlated with the Paleo-Pacific Plate subduction (Yang et al., 2018b).

3. Samples and methods

3.1 Samples

3.1.1 Sampling strategies

In this study, we sampled magmatic rocks along the two flanks of the regional main TLFZ together with their secondary fault zones (Fig. 2, Table 1). These samples were used for petrographic, AUPb and AFT double dating, and thermal history modeling studies. The samples include six Precambrian intrusive rocks (samples SD-1, SD-2, SD-3, SD-12, SD-14 and SD-15) taken from the Luxi terrane, and five samples of the younger Mesozoic igneous rocks (samples SD-4, SD-6, SD-9, SD-10 and SD-11) from the Sulu orogenic belt within the southeastern Jiaodong terrane.

3.1.2 Petrography

Samples SD-1 and SD-2 taken from the Precambrian pluton nearby the TLFZ are pink to grayish, and show granitic texture and massive structure (Fig. 3a, b), which are characterized by euhedral K-feldspar (0.10-1.00 mm) (20-30%), corroded euhedral plagioclase (0.10-1.50 mm) (30-40%), anhedral quartz (0.05-1.00 mm) (25-30%) and altered biotite (0.01-0.30 mm) (1-5%) (Fig. 4a, b). Sample SD-3 also collected near the TLFZ displays granitic texture, with a mineral assemblage of anhedral K-feldspar (0.05-1.50 mm) (30-40%), polysynthetic plagioclase (0.10-0.50 mm) (10-20%), fine quartz (0.10-0.50 mm)

(30-40%) and altered polychrome biotite (0.05-0.50 mm) (5-10%) (Fig. 4c). Samples SD-12, SD-14 and SD-15 taken from the Precambrian pluton nearby the Mengyin Basin within the secondary fault zone away from the TLFZ, are pink to light gray, granitic texture, and partially underwent feldspar weak alteration (Fig. 3c, d), which mainly comprise corroded K-feldspar (0.10-3.00 mm) (30-45%), hypautomorphic plagioclase (0.10-2.50 mm) (25-45%), anhedral quartz (0.05-2.00 mm) (20-35%) and sporadic biotite inclusions and vermiform quartz within the plagioclase (Fig. 4d, e, f). Samples SD-4 and SD-6 , collected near the NE-trending Wulian-Yantai Fault, are pink to gray green colored volcanic rocks characterized by typical porphyritic texture (Fig. 3e, f), with phenocrysts of strongly altered plagioclase (0.10-1.00 mm), corroded olivine (0.10-1.50 mm) and anhedral pyroxene (0.05-0.50 mm) and intersertal textural matrixes including microcrystalline plagioclase, dark volcanic glass and pyroxene for SD-4 basalt (Fig. 4g, h), and corroded anhedral to euhedral quartz (0.05-1.50 mm), altered K-feldspar (0.10-1.50 mm) and green colored biotite (0.05-0.10 mm) phenocrysts within tiny felsic and volcanic glass matrix for SD-6 rhyolite (Fig. 4i). Samples SD-9, SD-10 and SD-11 collected from Dadian alkaline intrusive complex, are pink to gray, and show granitic texture (Fig. 3g, h, i), which are characterized by anhedral K-feldspar (0.50-1.50 mm) (35-45%), irregular quartz (0.05-1.00 mm) (20-30%), green amphibole (0.05-0.50 mm) (10-25%) and polychrome biotite (0.10-0.30 mm) (1-5%) for SD-9 and SD-10 granites (Fig. 4j, k), and anhedral quartz (0.05-2.00 mm) (20-30%), euhedral plagioclase (0.10-0.50 mm) (30-40%), coarse K-feldspar (0.10-0.20 mm) (30-35%), anhedral amphibole (0.10-0.50 mm) (5-10%) and polychromatic biotite (0.05-0.50 mm) (1-5%) for SD-11 monzonite (Fig. 4I).

3.2 Methods

3.2.1 Apatite fission track thermochronology

Apatite grains were picked and mounted, set in epoxy resin on a slide, and then ground and polished to expose the smooth internal section of each grain. The apatite mounts were etched in 5 M HNO_3 solution at 20 ± 1 °C for 20 s to reveal the spontaneous fission tracks (Donelick et al., 1999; Malusà and Fitzgerald, 2019), and the fission track densities and confined track lengths within individual apatite grains were measured by using an automatic counting routine in the Fast Tracks software after imaged on a Zeiss AXIO Imager M2m Autoscan System at Adelaide Microscopy of the University of Adelaide (Gleadow et al., 2009).

AFT ages were calculated using ^{238}U concentrations of each mounted apatite grain measured by 30 μm spot analyses on a New Wave 213 ablation system coupled to an Agilent 7900 Quadrupole ICP-MS (LA-ICP-MS) at Adelaide Microscopy in the University of Adelaide of Australia. More detailed procedures on this approach are reported in previous studies (Hasebe et al., 2004; Glorie et al., 2017). C-axis parallel shards of Durango apatite were used for the LA-ICP-MS fission track zeta age calibration (Vermeesch, 2017), the Cl concentration of each grain was measured against Durango apatite as primary standard with LA-ICP-MS, and the software of RadialPlotter (Vermeesch, 2009) was used for processing AFT central ages (Galbraith et al., 1999).

3.2.2 Apatite U-Pb geochronology

Apatite U-Pb (AUPb) ages preserve records of thermal events through the temperature range of 450-550°C (Chew and Spikings, 2015), and were synchronously conducted on the same mounts for AFT analysis by using the LA-ICP-MS mentioned above. Analytical procedures are described in previous studies (Glorie et al., 2017). NIST 610 and Madagascar apatite (473.5 ± 0.7 Ma; Chew et al., 2014) were used as primary standards, Durango apatite (31.44 ± 0.18 Ma; McDowell et al., 2005) and McClure Mountain apaite (523.51 ± 2.07 Ma; Thomson et al., 2012) were used as secondary standards, which were used to correct for downhole U-Pb fractionation, mass bias, and intra-session instrument drift. A ^{207}Pb correction (Gibson and Ireland, 1996) was applied on the ^{206}Pb/^{238}U ages by using the initial measured ^{206}Pb/^{238}U and ^{207}Pb/^{206}Pb ratios which were used to correct for common Pb (Chew et al., 2014). The upper-intercept ^{207}Pb/^{206}Pb ratio of the common-Pb trend by a linear regression through the spread in common Pb values on a Tera-Wasserburg plots was used for common Pb estimate for the individual analyses. Data reduction was conducted using Iolite extension to the Igor analytical software (Paton et al., 2011), and the concordia plots were generated in Isoplot 4.15 (Ludwig, 2012).

3.2.3 Thermal history modeling

Thermal history modeling was generated by inputting AFT ages, confined track length data, and other geological or thermochronometric constrains into the QTQt (5.6.0) to explore the possible low-temperature cooling histories. The QTQt uses the approach of ‘Bayesian transdimensional Markov Chain Monte Carlo (MCMC)’ to construct thermal history models (Gallagher, 2012). In this work, we used the annealing model of Ketcham et al. (2007), D_{par} (Burtner et al., 1994; Donelick et al., 2005) as kinetic parameter, and the obtained AUPb age data as initial temperature constraints at 400 ± 50°C to produce the thermal history models. More details can be found in previous studies (Gillespie et al., 2017; Fernie et al. 2018), and corresponding thermal models outputted from QTQt (5.6.0) are in the Supplementary Figure 1.

4. Results

4.1 Apatite U-Pb geochronology

4.1.1 Luxi terrane

Six samples of Precambrian rocks from Luxi terrane were used for AUPb dating, and their Sr/Mn values show large variation in the range of 0.16-1.34 (Fig. 5, Table 2, Supplementary Table 1). For sample SD-1, two Tera-Wasserburg linear arrays can be drawn, with two lower intercept ages ($AUPb_{Inter}$ age) at 2226 ± 75 Ma (MSWD = 2.0) and 1848 ± 110 Ma (MSWD = 2.2), and corresponding ^{207}Pb corrected weighted mean ^{206}Pb-^{238}U ages (AUPb$_{\mathrm{Mean}}$ age) of 2266 ± 34 Ma (MSWD = 1.7) and 1867 ± 52 Ma (MSWD = 1.5). The AUPb data for sample SD-12 also show two groups of Tera-Wasserburg linear arrays, with the old one yielding AUPb$_{\mathrm{Inter}}$ ages of 2292 ± 86 Ma (MSWD = 2.4) and corresponding AUPb$_{\mathrm{Mean}}$ age of 2305 ± 40 Ma (MSWD = 1.6), and another younger one exhibiting AUPb$_{\mathrm{Inter}}$ ages of 2001 ± 78 Ma and corresponding AUPb$_{\mathrm{Mean}}$ age of 2003 ± 33 Ma (MSWD = 1.4). Samples SD-2, SD-3, SD-14 and SD-15 constitute one linear array on a Tera-Wasserburg plot and yield a AUPb$_{\mathrm{Inter}}$ age of 1826 ± 27 Ma (MSWD = 0.74) and AUPb$_{\mathrm{Mean}}$ age of 1825 ± 14 Ma (MSWD = 0.67) for sample SD-2, 1828 ± 39 Ma (MSWD = 0.73) and 1838 ± 21 Ma (MSWD = 0.59) for sample SD-3, 2273 ± 85 Ma (MSWD = 2.9) and 2306 ± 32 Ma (MSWD = 2.7) for sample SD-14, and 2090 ± 86 Ma (MSWD = 3.0) and 2057 ± 39 Ma (MSWD = 2.5) for sample SD-15.

4.1.2 Jiaodong terrane

Five samples of Mesozoic intrusions from Jiaodong terrane were selected for AUPb dating (Fig. 6, Table 2, Supplementary Table 1). The AUPb data for all the Mesozoic samples yield simple linear arrays on Tera-Wasserburg plots, and yield an AUPb$_{\mathrm{Inter}}$ age of 154.0 ± 22 Ma (MSWD = 0.84) and AUPb$_{\mathrm{Mean}}$ age of 162.0 ± 11 Ma (MSWD = 0.48) for sample SD-4, 124.0 ± 13 Ma (MSWD = 0.85) and 131.2 ± 9.5 Ma (MSWD = 0.58) for sample SD-6, 108.0 ± 22 Ma (MSWD = 0.81) and 112.6 ± 7.7 Ma (MSWD = 0.36) for sample SD-9, 121.4 ± 5.6 Ma (MSWD = 0.62) and 123.3 ± 2.1 Ma (MSWD = 0.45) for sample SD-10, as well as 126.7 ± 4.2 Ma (MSWD = 0.57) and 126.8 ± 2.1 Ma (MSWD = 0.50) for sample SD-11. Note that most analyses for samples SD-4, SD-6 and SD-9 are high in common Pb (plotting near the upper intercept), and therefore some caution is required in further interpretation of the AUPb ages for those samples.

4.2 Apatite fission track thermochronology

4.2.1 Luxi terrane

The Precambrian magmatic rocks from the Luxi terrane that were dated by AUPb method were also used for AFT analyses (Fig. 7, Table 2, Supplementary Table 2). Sample SD-3 yields the oldest AFT central age of 97.6 ± 4.6 Ma with a mean track length (MTL) of 12.15 ± 1.45 μm. Samples SD-1 and SD-2 produce AFT central ages of 81.9 ± 2.9 Ma and 64.2 ± 2.9 Ma, and MTLs of 12.18 ± 1.40 μm and 13.06 ± 1.35 μm, respectively. Samples SD-12, SD-14 and SD-15 reveal relatively young central AFT ages of 69.2 ± 3.8 Ma, 58.7 ± 2.9 Ma, and 63.5 ± 3.4 Ma, with corresponding MTLs of 12.71 ± 1.95 μm, 12.97 ± 1.13 μm, and 12.92 ± 1.54 μm. The two samples (samples SD-1 and SD-3) with the oldest AFT dates (97-82 Ma) from this study area pass the $\chi 2$ test, while the four other samples (samples SD-2, SD-12, SD-14 and SD-15) with younger AFT ages (69-59 Ma) show more single-grain dispersion (up to 24%).

4.2.2 Jiaodong terrane

The Mesozoic igneous rocks from the Jiaodong terrane used for AUPb dating were also used for AFT analyses (Fig. 8, Table 2, Supplementary Table

2). Samples SD-4 and SD-6 in vicinity to the Wulian-Yantai Fault yield the relatively old AFT central ages of 121.7 ± 5.7 Ma and 113.0 ± 5.1 Ma, as well as relatively long MTLs of 13.22 ± 1.69 μm and 13.47 ± 1.56 μm, respectively. Samples SD-9, SD-10 and SD-11 taken near secondary NE-trending faults produce relatively young AFT ages and similar MTLs, with AFT central ages of 76.6 ± 3.1 Ma and MTLs of 12.65 ± 1.46 μm for sample SD-9, 68.8 ± 2.9 Ma and 12.51 ± 1.43 μm for sample SD-10, and 66.5 ± 3.1 Ma and 12.33 ± 1.50 μm for sample SD-11. The three samples (samples SD-4, SD-6 and SD-9) with oldest AFT ages for this study area (122-77 Ma) pass the χ2 test, while the two samples (samples SD-10 and SD-11) with younger AFT ages (69-67 Ma) show more single-grain dispersion (19-21%). The larger dispersion values for the younger samples and their associated shorter MTLs values may be suggestive of a longer residence in the apatite partial annealing zone (APAZ) (O`Sullivan and Parrish, 1995; Glorie et al., 2017).

4.3 Thermal history modeling

4.3.1 Luxi terrane

Six samples from the Precambrian suite of Luxi terrane produced more than 70 confined fission tracks, which were input into the QTQt (5.6.0) for subsequent thermal history modeling (Figs. 7 and 9). Thermal history models from samples SD-1, SD-3, SD-12 and SD-15 indicate slow cooling through the Jurassic to Cretaceous. In contrast, samples SD-2 and SD-14 exhibit relatively rapid cooling through the APAZ between 70 and 55 Ma. Thus, thermal history modeling suggests that the Luxi terrane experienced one pulse of rapid basement cooling during the Late Cretaceous to Early Paleogene (Supplementary Fig. 1).

4.3.2 Jiaodong terrane

Five samples of Mesozoic suite from Jiaodong terrane, which yielded at least 80 confined fission tracks, were used for thermal history modeling (Figs. 8 and 9). Samples SD-4 and SD-6 both exhibit similar thermal histories with rapid cooling through the lower APAZ at 130-120 Ma and 115-105 Ma, and then cooled slowly to surface temperatures since the Late Cretaceous. The models for samples SD-9, SD-10 and SD-11 suggest rapid cooling through the APAZ at ca. 85-70 Ma. Therefore, samples from the Jiaodong terrane record two periods of rapid cooling, with the first in the Early Cretaceous (130-105 Ma) and the second during the Late Cretaceous (85-70 Ma). The model for sample SD-11 shows a return to upper APAZ temperatures (~60°C) at 30-25 Ma, before cooling to surface shortly after. However, given that this secondary thermal event still remains below the APAZ, it will not be discussed further in this study (Supplementary Fig. 1).

5. Interpretation and discussion

5.1 Apatite U-Pb geochronology

The Precambrian apatite U-Pb ages from Luxi terrane show a wide range from ~2.5 to ~1.5 Ga with two peaks at ~2.3 Ga and ~1.8 Ga, which are slightly younger than peaks at ~2.7 Ga and ~2.5 Ga for corresponding published zircon U-Pb ages on the same or nearby rocks (Dong et al., 2017; Gao et al., 2018) (Fig. 10a, b). Hence, the oldest (2.5-2.3 Ga) AUPb ages can be correlated with the compiled youngest zircon U-Pb ages, but the AUPb ages peaking at ~1.8 Ga are significantly younger than corresponding zircon U-Pb ages, likely resulting from 1) derived from more mafic source due to absence of numerous zircon growth, or 2) reset above the apatite U-Pb closure temperature (450-550°C) by volume diffusion during the Paleoproterozoic, or 3) grew during the late Paleoproterozoic (Kirkland et al., 2018; Glorie et al., 2019). The rather low Sr concentrations and Sr/Mn ratios for the apatite associated with the ~1.8 Ga AUPb age peak are similar to those for the associated with the older apatite (~2.3 Ga) (Fig. 5), it is unlikely that the ~1.8 Ma apatite represents a mafic population (Gillespie et al., 2018). Given the relatively low amount of single-grain scatter associated with the ~1.8 Ga apatite (samples SD-2 and SD-3) (Fig. 5), it is more plausible that the apatite (re-)crystallized at ~1.8 Ga, rather than recording volume diffusion (Kirkland et al. 2018). Therefore, we interpret that the ~1.8 Ga apatite population represents a significant metamorphic (Heinrichs et al. 2018) or metasomatic (Glorie et al., 2019) event. Accordingly, the Precambrian apatite U-Pb ages of 2.5 ~1.5 Ga are likely correlated with the crustal growth events of the rifting-subduction-collision (2.3-1.9 Ga) and subsequent high-grade granulite facies metamorphism (1.9-1.8 Ga) in the eastern NCC (Zhai and Peng, 2007; Zhai and Santosh, 2011; Santosh et al., 2012). Note that the obtained Precambrian AUPb ages are only used to constrain subsequent thermal history models, and thus further interpretation for these AUPb ages would not be continued in this study.

The Mesozoic magmatic suite from Jiaodong terrane yielded AUPb ages that range between ~162 Ma and ~112 Ma, which are almost consistent with published zircon U-Pb ages from the whole Shandong Peninsula including same or nearby plutons (161-115 Ma; Yang et al., 2018a) (Fig. 10c, d). Thus, the Mesozoic AUPb ages not only represent their crystallization age, but also suggest fast cooling below ~450 °C during the Late Jurassic to Early Cretaceous. Tectonically, the NCC underwent dramatic lithosphere thinning and craton destruction in its eastern domains during the Mesozoic with the peak of destruction at ~125 Ma, and the Paleo-Pacific Plate subduction has been suggested to be the main tectonic mechanism for the magmatic pulses in the Jiaodong terrane (Griffin et al., 1998; Zhu et al., 2011; Zheng et al., 2018; Yang et al., 2018b). Combining geochemical, geochronological and isotopic studies for Late Mesozoic granitoids in its adjacent Junan and Juxian regions, Yang et al. (2018a, b) proposed that these granitoids were sourced from mixed arc- and subduction-related components, and involved crustal melting which was correlated with the Paleo-Pacific Plate subduction. Thus, the Mesozoic AUPb ages of 162-112 Ma could be interpreted as a response to lithospheric thinning and craton destruction of the NCC together with temporal records for the subduction of the Paleo-Pacific westward subduction. In addition, the data might also reflect shallow granitoid emplacement and associated rapid post magmatic cooling history associated with lithospheric thinning and craton destruction of the NCC induced by the westward Paleo-Pacific Plate subduction at this time.

5.2 Apatite fission track thermochronology

The AFT central ages in this study range between ~122 and ~59 Ma. The Luxi terrane records AFT age range of 98-59 Ma, while the Jiaodong terrane records slightly older AFT central ages of 122-67 Ma (Figs. 7 and 8). Resulting thermal history models revealed two rapid cooling stages during the Early Cretaceous (130-105 Ma) and Late Cretaceous to Paleogene (85-55 Ma), separated by a period of slow cooling during the Middle Cretaceous (105-85 Ma) (Fig. 9). Moreover, this thermal history characteristic is also illustrated by the AFT central age versus corresponding MTLs plot (Fig. 11a). The plots are characterized by typical "boomerang shape" (Green et al. 1986; Gallagher, 2012), with the longer MTLs for the Early Cretaceous cooling stage, followed by relatively shorter MTLs in the Middle Cretaceous, and eventually an ascending trend towards longer MTLs during the late Cretaceous to Paleogene for another cooling stage (Fig. 11a), supporting the two rapid cooling stages identified in thermal history models (Fig. 9).

Three different cooling signatures are confined to certain zones within the study area (Fig. 11b). Cooling stage 1 (rapid Early Cretaceous cooling) is preserved only to the northern Sulu orogenic belt of the Jiaodong terrane. Cooling stage 2 (slow Late Cretaceous to Paleogene cooling) is recorded for nearly all samples in the Luxi terrane, to the west of the TLFZ (Fig. 2), which suggests that the Luxi terrane records differential exhumation with respect to the northern Sulu orogenic belt. However, cooling stage 3 (rapid Late Cretaceous cooling) is defined to the southern Sulu orogenic belt, indicating a prominent divide between the northern and southern Sulu orogenic belt. There is no significant elevation difference between the samples in the northern versus southern Sulu orogenic belt to account for this difference (Table 1). However, there seems to be a significant correlation between AFT age and Cl concentrations, which can explain the differential preservation of the cooling signals (Fig. 11b). With the exception of sample SD-10, higher Cl concentrations generally correlate with older central AFT ages and vice versa. Elevated Chlorine concentrations are known to reduce fission track annealing in apatite (Green et al., 1986), leading to the preservation of older ages. Thus, the differential preservation of the cooling signals in the Sulu orogenic belt is likely chemically controlled. All samples in the Luxi terrane have low Cl concentrations, and thus do not preserve evidence for the rapid Early Cretaceous cooling. Here, the AFT age variation is controlled by the cooling rate and residence time in the APAZ (Figs. 9 and 11). Overall, it shows differential exhumation between the Luxi and Jiaodong terranes based on the distinct cooling signature above, likely resulting from kinetic mechanism of transition from continued sinistral strike-slip motion of the TLFZ to termination, and then to dextral motion of the TLFZ jointly induced by the successive NNW-directed Pacific subduction, far-field effect of the NNE-directed India-Eurasia collision and subduction direction of the Pacific Plate changing from NNW to WNW during the Early Cretaceous to Paleogene (Wang et al., 2018).

5.2.1 Early Cretaceous rapid cooling

Early Cretaceous (130-105 Ma) rapid cooling was modelled for chlorine-rich apatites in the northern Sulu orogenic belt of the southern Jiaodong terrane (Fig. 9). A compiled thermochronological dataset from previous studies also shows a few Early Cretaceous AHe and AFT ages in the Jiaodong terrane (Fig. 12a, b, Supplementary Table 3). By contrast, the compiled dataset displays more AHe, AFT and ZFT ages in the Jiaodong (Fig. 12a, b, e) and Luxi terranes (Fig. 12c) during the late Early Cretaceous to middle Late Cretaceous. Moreover, Li and Zhong. (2018) reported Early Cretaceous detrital ZFT age of 134-102 Ma in the Jiyang depression (Bohai Bay Basin) of the Luxi terrane, and Yang et al. (2018a, b) reported a suite of Early Cretaceous (135-120 Ma) intermediate-felsic volcanic rocks in the southern Sulu orogenic belt (Juxian and Junan domains). Thus, we infer that the Early Cretaceous (130-105 Ma) rapid cooling pulse might reflects a regional post-magmatic cooling and exhumation history for the Shandong Peninsula, providing homologous source for the sedimentary sequences in surrounding basins at that time. However, the preservation of this cooling signal in the AFT data is largely dictated by the concentration of Cl in the analyzed apatites of this study.

During the Early Cretaceous, the Paleo-Pacific slab rollback at ~144 Ma resulted in dramatic cratonic mantle thinning during 135-130 Ma and extensive craton destruction at ca. 130-120 Ma (Zheng et al., 2018), and also triggered lithospheric extension, back-arc spreading, asthenospheric upwelling and interaction with lithosphere (Yang et al., 2018a, b, c). Moreover, the eastern NCC underwent a change in tectonic regime from compressional regime at ca. 145 Ma to extension regime at ~115 Ma (Li et al., 2012; Xue et al., 2018). The peak time of craton destruction of the NCC is commonly accepted to be occurred in the Early Cretaceous (Wu et al., 2005; Zhu et al., 2011; Yang et al., 2018a, b, c), and the TLFZ experienced Early Cretaceous sinistral motion with normal faulting and widespread NW-SE extension as a result of the NNW-directed Paleo-Pacific Plate subduction (Chen et al., 1990; Zhu et al., 2010; Wu et al., 2005; Wang et al., 2009; Wang et al., 2018). Thus, we argue that the Early Cretaceous (130-105 Ma) rapid cooling might be response to the sinistral motion of the TLFZ during the Early Cretaceous, and is a record of the thermochronological constraints. Zhu et al. (2012a) indicated that the direction of regional extension in the eastern NCC rotated clockwise from a WNW-ESE-orientation during the earliest-middle Early Cretaceous to a NW-SE-orientation during the latest Early Cretaceous, and before rotating to a N-S-orientation during the Late Cretaceous to Paleogene. Therefore, we could also correlate the Early Cretaceous (130-105 Ma) rapid cooling pulse with the peak time of craton destruction of the NCC associated with the Paleo-Pacific slab rollback, in response to the changing direction of regional extension within a back-arc spreading setting.

5.2.2 Late Cretaceous to Paleogene rapid cooling

Late Cretaceous to Paleogene (85-55 Ma) rapid cooling signal was identified for the southern Sulu Orogenic belt and related domains in the Luxi terrane. Previous thermochronological studies also reported numerous Late Cretaceous AFT, ZFT and AHe ages in the Jiaodong terrane (Fig. 12a, b, e, Supplementary Table 3) and corresponding AFT ages in the Luxi terrane (Fig. 12c, Supplementary Table 3), together with lots of Paleogene AHe and AFT ages for the Jiaodong terrane and Luxi terranes (Fig. 12a, b, c, Supplementary Table 3). By comparison, the Late Cretaceous to Paleogene rapid cooling pulse is likely regarded as the main cooling stage in the Shandong Peninsula, recording rapid cooling multiple thermochronometers.

During the Late Cretaceous to Paleogene, the NCC experienced continuing craton destruction and lithospheric thinning (Wu et al., 2005; Zhu et al., 2010, 2011; Xu et al., 2009; Li et al., 2015; Zhao et al., 2018). A few Late Cretaceous to Paleogene basaltic rocks are exposed in the Shandong Peninsula (~74 Ma) (Yan et al., 2003) and northern Bohai Bay basin (72-23 Ma) (Zhang et al., 2011; Li et al., 2014). Moreover, the Bohai Bay Basin is also considered to have initiated rifting during the Late Cretaceous which continued until the Late Paleogene (Chen et al., 2016; Liu et al., 2016; Zhao et al., 2018).

Hence, the Late Cretaceous to Paleogene rapid cooling can be related to the timing of basaltic magmatism in the eastern NCC that is linked with craton destruction and lithosphere thinning as a result of asthenosphere upwelling and lithosphere thermal structure modification (Xu et al., 2009). The cooling ages (85-55 Ma) are also contemporaneous with the timing of rifting and the associated exhumation history of Bohai Bay and adjacent basins. In addition, the TLFZ underwent continued sinistral strike-slip motion induced by the NNW-directed Pacific subduction at 65-55 Ma. The sinistral motion ceased at ~55 Ma caused by the far-field effect of the NNE-directed India-Eurasia collision. Subsequently, the subduction direction of the Pacific Plate changed from NNW to WNW which destroyed the stress balance on the TLFZ kept with the former NNW-directed Pacific subduction and far-field effect of the India-Eurasia collision, eventually resulting in dextral motion during 48-42 Ma (Wang et al., 2018). Accordingly, the Late Cretaceous to Paleogene (85-55 Ma) rapid cooling might record the evolution process of the sinistral strike-slip motion of the TLFZ during the Paleogene. Although our obtained AFT data only report the rapid cooling stage during 85-55 Ma, previous studies also revealed Eocene-Oligocene (50-30 Ma) rapid cooling in the Jiaobei uplift (Zhao et al., 2018) and multiple rapid cooling periods of 62-53 and 44-37 Ma (Li et al., 2007) for the Luxi terrane. Therefore, we interpret that the Late Cretaceous rapid cooling response to continuing craton destruction triggered by the NNW-directed Pacific Plate subduction, while the Paleogene interval multiple rapid cooling might relate the dextral motion of the TLFZ derived by the Pacific Plate subduction when the subduction direction changed from NNW to WNW and/or due to the far-field effect of the India-Eurasia collision.

5.3 Comparison with neighbouring tectonic units

The eastern Dabie orogenic belt, located in the southern Shandong Peninsula, underwent sequential tectonic evolution including subduction, exhumation, and uplift, which originated during the subduction of the Yangtze Craton at 240-220 Ma, followed by two rapid exhumation events at 220-200 Ma and 180-170 Ma, and eventual uplift (Ratschbacher et al., 2000; Li et al., 2005; Liu et al., 2009), in response to the collision and subduction of the Yangtze Craton beneath NCC during the Late Triassic to Early Jurassic (Xu et al., 1992; Chen et al., 2000). Previous studies on low-temperature thermochronology of the Dabie orogenic belt show a range of AFT from 160 to 66 Ma (Fig. 12h), with other thermochronometers (ZFT, Ar-Ar, ZHe and AHe) characterized by peaks at 208 Ma for ZFT ages, at 124 Ma for biotite/muscovite/amphibole Ar-Ar ages, at 104 Ma for ZHe ages, and at 36 Ma for AHe ages (Fig. 12g, i, j, k). Thus, the eastern Dabie orogenic belt experienced gradual tectono-thermal evolution from Late Triassic to Paleogene in response to the sequential tectonic evolution of subduction, exhumation and uplift of the Dabie orogenic belt.

Previous thermochronological investigations show several peaks at 40 Ma for AHe ages, at 80 Ma for AFT ages, at 88 Ma for ZFT ages for Jiaodong terrane, at 36 Ma for AFT ages for Luxi terrane, and two peaks at 124 and 208

Ma for biotite/muscovite/amphibole Ar-Ar ages for Shandong Peninsula (Fig. 12a, b, c, e, f). The AFT ages obtained in this study mainly concentrate at Late Cretaceous to Early Paleogene (100-58 Ma) (Fig. 12d). By contrast, the peaks of multiple thermochronometers from Shandong Peninsula (Jiaodong and Luxi terranes) and eastern Dabie orogenic belt are almost consistent (Fig. 12). Furthermore, the Taihang Mountains nearby the western Shandong Peninsula also display ZFT ages of 68-52 Ma, AFT ages of 52-18 Ma, ZHe ages of 80-70 Ma, and AHe ages of 27-15 Ma (Zhang et al., 2002b; Chang et al., 2019; Wu et al., 2019), and identify multiple rapid cooling stages of 100-45 Ma, 38-30 Ma and after ~20 Ma (Chang et al., 2019) or of ~100 Ma, 50-40 Ma and 27 Ma (Wu et al., 2019). The Bohai Bay Basin within interior of the northern Shandong Peninsula also shows AFT ages of 97-60 Ma and AHe ages of 75-21 Ma and three rapid cooling periods of 130-90 Ma, 62-53 and 44-19 Ma (Li et al., 2007; Chang et al., 2018). Therefore, we infer that the eastern China underwent similar tectono-thermal evolution history during the Meso-Cenozoic, with multiple cooling events during the Early Cretaceous, Late Cretaceous, Paleogene and Neogene, induced by the successive westward subduction of the Paleo-Pacific Plate and Pacific Plate together with far-field effect of the India-Eurasia collision (Grimmer et al., 2002; Chang et al., 2018, 2019; Wu et al., 2019).

5.4 Implications for lithospheric destruction

The destruction process of the NCC is also reflected in the compiled low-temperature multiple thermochronological ages in the range from Late Triassic to Neogene (Fig. 12), suggesting that the Meso-Cenozoic NCC underwent multiple stages of thermo-tectonic reactivation. However, there is no consensus for the timing of termination of craton destruction. Wang et al. (2009) proposed that the Late Cretaceous eastern NCC was experiencing continued regional extension and differential uplift, indicating that lithospheric thinning of the NCC continued in the Late Cretaceous. In general, the crustal uplift and regional extension represents the shallow response to lithospheric thinning (England and Houseman, 1989; Meissner and Mooney, 1998; Wang et al., 2009). Combining the Cretaceous to Paleogene rapid cooling history revealed in this study with previous studies related Paleogene rapid uplift in the Shandong Peninsula (Li et al., 2007; Zhao et al., 2018), we support that the timing of cessation of craton destruction of Shandong Peninsula likely occurred during the Early Paleogene, not prior to the Late Cretaceous.

During the Meso-Cenozoic, the NCC experienced lithospheric destruction characterized by the eastward lithospheric thinning trend from 200-250 km in the western NCC through 100-150 km in the central NCC to less than 60 km in the eastern NCC (Shandong Peninsula) (Zhu et al., 2011; Zheng et al., 2018; Yang et al., 2018a, b, 2019). Yang et al. (2018b) argued that multiple tectonic events surrounding the NCC during the Paleozoic to Cenozoic jointly resulted in lithospheric thinning and craton destruction of the NCC, while the westward subduction of Paleo-Pacific Plate since the Late Triassic was generally accepted as the main tectonic mechanism responsible for lithospheric thinning of the NCC. This is almost consistent with the initial timing of craton destruction of the NCC during the Middle-Late Triassic as a result of the collision between the NCC and Yangtze Craton (Yang and Wu, 2009; Yang et al., 2010; Zhang et al., 2014). Excluding the Precambrian AUPb ages in this study associated with Paleoproterozoic crustal growth events in the NCC, the other Mesozoic AUPb ages in the range of 162-112 Ma record temporal process of lithospheric destruction of the eastern NCC. Moreover, coupled with newly obtained low temperature thermochronological data which yielded two group AFT central ages of 122-113 Ma and 98-59 Ma together with two rapid cooling stages of 130-105 Ma and 85-55 Ma, we further conclude that the Early Cretaceous marks the peak timing of craton destruction of the NCC driven by the Paleo-Pacific slab rollback, while the Late Cretaceous to Paleogene events might represent the terminational craton destruction of Shandong Peninsula triggered by the Pacific Plate subduction and/or due to the far-field effect of the India-Eurasia collision. Eventually, we argue that multiple tectonic thermal events during the Meso-Cenozoic collectively contributed to the lithospheric destruction of the eastern NCC.

6. Conclusions

1) The newly obtained Precambrian apatite U-Pb ages show peaks at ~2.3, ~2.0 and ~1.8 Ga, and the Mesozoic AUPb ages are in the range of 162-112

Ma, representing their crystallization age.

2) The Mesozoic AUPb ages of 162-112 Ma overlap with published zircon ages of these rocks (161-115 Ma), suggesting rapid post-magmatic cooling during the Late Jurassic to Early Cretaceous.

3) The AFT dating yields two groups of AFT central ages of 122-113 Ma and 98-59 Ma, and corresponding thermal history models reveal two rapid cooling stages of 130-105 Ma and 85-55 Ma for Shandong Peninsula.

4) The Early Cretaceous rapid cooling, mainly preserved in chlorine-rich apatite, is correlated with the peak time for lithospheric destruction in the eastern NCC.

5) The Late Cretaceous rapid cooling is interpreted as a response to continued lithosphere thinning, whereas the corresponding Paleogene likely representing the termination of craton destruction of Shandong Peninsula.

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Figure captions

Figure 1. Tectonic framework of the NCC and surrounding orogens (modified after Zhao et al., 2005; Santosh, 2010), showing the exposure major crustal blocks, fault systems and study area. Abbreviations of metamorphic complexes:

CD, Chengde; NH, Northern Hebei; EH, Eastern Hebei; XH, Xuanhua; HA, Huai’an; HS, Hengshan; WT, Wutai; FP, Fuping; LL, Lüliang; ZH, Zanhuang; ZT, Zhongtiao; DF, Dengfeng; TH, Taihua; WB, Western Block; TNCO, Trans-North China Orogen; EB, Eastern Block; IMSZ, Inner Mongolia Suture Zone; JLJB, Jiao-Liao-Ji Belt.

Figure 2. Geological map of Shandong Peninsula (modified after BGMRSP, 1991), showing different magmatic units and sampling locations.

Figure 3. Representative field photographs of igneous rocks from Shandong Peninsula in this study. (a) Sample SD-1; (b) Sample SD-2; (c) Sample SD-12; (d) Sample SD-14; (e) Sample SD-4; (f) Sample SD-6; (g) Sample SD-9; (h) Sample SD-10; (i) Sample SD-11.

Figure 4. Representative photomicrographs of igneous rocks from Shandong Peninsula in this study showing their texture. (a) Sample SD-1; (b) Sample SD-2; (c) Sample SD-3; (d) Sample SD-12; (e) Sample SD-14; (f) Sample SD-15; (g) and (h) Sample SD-4; (i) Sample SD-6; (j) Sample SD-9; (k) Sample SD-10; (l) Sample SD-11. Mineral abbreviations: Pl, plagioclase; Kfs, K-feldspar; Bt, biotite; Qtz, quartz; Ol, olivine, Px, pyroxene; Amp, amphibole.

Figure 5. Apatite U-Pb Terra-Wasserburg Concordia plots and corresponding

weighted mean ^{207}Pb corrected ^{206}Pb/^{238}U ages for Precambrian intrusive samples from Luxi terrane.

Figure 6. Apatite U-Pb Terra-Wasserburg Concordia plots and corresponding weighted mean ^{207}Pb corrected ^{206}Pb/^{238}U ages for Mesozoic igneous samples from Jiaodong terrane.

Figure 7. Radial plots with D_{par} values as color scale and track length histograms of AFT age for Precambrian intrusive samples from Luxi terrane. MTL represents mean track length.

Figure 8. Radial plots with D_{par} values as color scale and track length histograms of AFT age for Mesozoic igneous samples from Jiaodong terrane.

Figure 9. Thermal history models calculated by the QTQt (5.6.0) based on the AFT data in this study. Details are in the Supplementary Figure 1. Note that the samples with dashed tT paths are poorly constrained models, and thus some caution is required for further interpretation.

Figure 10. Comparison published zircon U-Pb age data with apatite U-Pb age data obtained in this study. Data are from Dong et al. (2017) and Gao et al. (2018) for Precambrian zircon ages, and compiled Mesozoic zircon ages figure

(a) is modified after Yang et al. (2018a).

Figure 11. (a) AFT age versus MTL for boomerang plots, and (b) AFT age versus Chlorine concentration in this study. Pink shadow illustrates changing trends of MTL and Cl with the increase of AFT ages.

Figure 12. Histograms of different age data on thermochronology from Shandong Peninsula and eastern Dabie orogenic belt. Abbreviations: AHe, apatite [U-Th-Sm]/He); ZFT, zircon fission track; ZHe, zircon [U-Th-Sm]/He). Data are from Supplementary Table 3. Data sources: Wang et al. (2007), Liu et al. (2010), Zhao et al. (2018), Deng et al. (2015), Wu et al. (2016, 2018) and references therein.

Supplementary Figure 1. Thermal history models in this study retaining relative probability distributions illustrated by colored lines and histograms showing details of statistical fits between observed and predicted data generated in the QTQt (5.6.0).

Table captions

Table 1. Locations and details of the samples taken from Shandong Peninsula in this study.

Table 2. AFT age and corresponding apatite U-Pb age data for the samples taken from Shandong Peninsula in this study.

Supplementary Table 1. LA-ICP-MS apatite U-Pb age data for the samples taken from Shandong Peninsula in this study.

Supplementary Table 2. Individual apatite grain data of AFT age and associated chemical data for the samples taken from Shandong Peninsula in this study.

Supplementary Table 3. Compilation of published different age data on thermochronology from Shandong Peninsula and eastern Dabie orogenic belt.