Late Mesozoic and Cenozoic thermotectonic evolution along a transect from the north China craton through the Qinling orogen into the Yangtze craton, central China

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1Cretaceous and Cenozoic reactivation of the Triassic Qinling-Dabie orogen between the north China and Yangtze cratons resulted from the combined effects of Pacific subduction–back-arc extension in east China and collisions in west China. We report new apatite fission track and apatite and zircon (U-Th)/He data from east Qinling along a >400-km-long N-S transect from Huashan through the Qinling orogen to Huangling. The ages show a general pattern of younging northward. Three major cooling phases are defined by modeling the multiple thermochronologic data sets. The first phase occurred locally in the North and South Qinling during the late Triassic to early Jurassic, following heating associated with the Triassic Yangtze subduction and exhumation of the Wudang metamorphic core complex on the cratonal edge. A second phase represents regional exhumation between 100 and 60 Ma, coeval with rifting marked by the Late Cretaceous–Eocene (K2–E) red bed deposition in eastern China and possibly indicating a link with Pacific subduction–back-arc extension in eastern China; however, it may also have been superimposed by eastward tectonic escape resulting from the Lhasa–west Burma and Qiangtang-Indochina blocks to the Eurasia continent [Molnar and Tappin, 1975], as well as by the subsequent effects of India-Asia collision at ~50 Ma [Patriat and Achache, 1984; Besse et al., 1984]. This tectonic environment generated various structural features of strike-slip faults, grabens, and folds throughout the eastern Qinling area [Xue et al., 1996a; Tappin and Molnar, 1977; Zhang et al., 1995; Reischmann et al., 1990; Ratschbacher et al., 2003]. The regional geology of the eastern Qinling, as a part of the Qinling-Dabie orogenic belt, has been well documented and correlated with that in the Tongbai-Dabie area by several geologists [Zhang et al., 1989; Xue et al., 1996a; Hacker et al., 1996; Zhai et al., 1998; Meng and Zhang, 2000; Ratschbacher et al., 2003, 2006].

2In some cases, postorogenic dynamics of ancient ranges may record the effects of relatively subtle or far-field tectonic activity, because such high-relief regions are susceptible to subtle changes in erosion rate [Reiners et al., 2003]. The eastern Qinling in central China is an ideal place to investigate the far-field expression of the Indian-Asian collision superimposed on the eastern back-arc extension setting. Apatite fission track (AFT) analysis and apatite and zircon (U-Th)/He (AHe and ZHe, respectively) dating as temperature-sensitive thermochronological techniques, are a powerful tool for constraining the low-temperature history of rocks over a temperature range of ~60–200°C [e.g., Gallagher et al., 1998; Gleadow et al., 2002; Reiners et al., 2003]. Unlike the Tongbai-Dabie area to the east, where several low-temperature thermochronology data sets have been presented [Grimmer et al., 2002; Reiners et al., 2003; Zhou et al., 2003; Xu et al., 2005; Hu et al., 2006], there are only a limited number of studies in the eastern Qinling area. The available low-temperature thermochronology data from the eastern Qinling area are six zircon and apatite fission
track ages without track length measurements at Huashan Mountain in the Lesser Qinling [Yin et al., 2001], and 20 AFT ages with track length measurements in the north Qinling [Enkelmann et al., 2006] as well as 40Ar/39Ar age spectra modeling from 10 K-feldspar grains [Ratschbacher et al., 2003]. Nevertheless, the low-temperature thermal history and postorogenic dynamics of regional eastern Qinling are still poorly understood.

In this contribution, we present new apatite and zircon (U-Th)/He and apatite fission track data along a ∼400 km transect from the Huashan in the north China craton, through the Qinling orogen into the Yangtze craton. These data are combined and modeled to constrain cooling and denudation histories of the Qinling orogen as well as the adjacent cratons. These results allow us to better understand the late Mesozoic–Cenozoic exhumation processes and thermotectonic events for the different tectonic units in the study area. In addition, timing of the main activation of the large strike-slip and normal faults since the late Mesozoic and their linkage to the regional geodynamic evolution are discussed.

2. Background Geology and Tectonic History

The ∼2000-km-long Qinling-Dabie orogenic belt covers a wide area of China. Its western end continues to the Kunlun and Qilian orogens [Deng, 1996] and its eastern end corresponds to the Sulu region as shown in Figure 1. The Qinling-Dabie orogenic belt formed by a Triassic (∼220 Ma) collision of the north China (or Sino-Korean) craton with the Yangtze craton (Figure 1) [Li et al., 1989; Wang, 1989; Zhang et al., 1989; Okay et al., 1993; Hacker et al., 1996, 2000; Ames et al., 1996; Rowley et al., 1997; Ratschbacher et al., 2000, 2006]. After its formation in the Triassic, the Qinling-Dabie orogen was reactivated during the Early Cretaceous by Pacific back-arc extension [Engebretson et al., 1985; Charvet et al., 1994; Yin and Nie, 1996]. Another important aspect of the Early Cretaceous tectonic setting is the eastward, passive escape of the Yangtze craton resulting from the northward accretion of the Lhasa–west Burma and Qiangtang-Indochina blocks to the Eurasia continent [Molnar and Tapponnier, 1975]. Subsequent Cenozoic reactivation of the study area likely resulted from the far-field effects of India-Asia collision at ∼50 Ma [Patriat and Achache, 1984; Besse et al., 1984].

From north to south, the eastern Qinling is composed of three major tectonic units: north China craton, Qinling orogen, and Yangtze craton (Figure 2). These units were assembled during late Proterozoic–early Mesozoic time and separated by faults as shown by cross section A-A' in Figure 2.

The southern margin of the north China craton, bounded by the Luonan fault to the south (Figure 2), consists of Archean to Proterozoic basement metamorphic rocks (Taihua complex and the Dengfeng greenstone belt) overlain by an uninterrupted 4- to 8-km-thick section of Sinian to Triassic age [Kröner et al., 1988; Regional Geology Survey of Henan, 1989]. This area within our

Figure 1. Topographic relief and simplified tectonic features of China and neighboring regions (modified after Liu et al. [2004]) showing the Cenozoic rifts and the study area.

Figure 2. Generalized geological map of the study area (modified after Zhang et al. [1991], Meng and Zhang [2000], Zhang et al. [2001], and Ratschbacher et al. [2003]). Location of samples used for AFT, AHe, and ZHe analyses are indicated on the geological map. Cross section A-A' shows the crustal structure and the main faults separating geological units in the study area (modified after Meng and Zhang [2000]). The Cenozoic Weihe rift basin stratigraphy and the structural (cross section B-B') and the sedimentation rate [Xing et al., 2005] are shown in the bottom two diagrams.
Figure 2
study region belongs to the northernmost zone of the Qinling Mountains, i.e., the Lesser Qinling.

[8] The north Qinling belt, bounded by the Lonan fault in the north and by the Shangdan fault in the south (Figure 2), contains a series of tectonic units: the Proterozoic-Silurian passive margin or accretionary wedge, represented by Kuanping group [Ratschbacher et al., 2003, 2006]; an Ordovician-Silurian intraoceanic arc ophiolite, including the Erlangping, Danfeng, and Heihe groups [Xue et al., 1996a, 1996b; Li et al., 1990]; the Yangtze basement [Ratschbacher et al., 2006] or a microcontinent [Meng and Zhang, 2000]; and the Liuling group, which is a Paleozoic flysch and the Triassic Yangtze–north China suture is within it [Ratschbacher et al., 2003]. A suite of relatively undeformed late Silurian–early Devonian plutons intrudes the Erlangping, Qinling [Xue et al., 1996a], and Kuanping [Zhai et al., 1998] groups, forming a continental margin arc [Ratschbacher et al., 2003].

[9] The Yangtze craton in our study area includes South Qinling and the Huangling area inside the interior of the Yangtze craton, which is mostly overlain by strata of Sinian to Mesozoic age. Basement outcrops are exposed in the Shennong, Wudang, Yaolinghe, and Huangling areas (as the Wudang, Yaolinghe and Kongling groups) [Hacker et al., 1996]. The Douling group, exposed along the south of the Liuling group, has also been proposed to be a part of the Yangtze basement [Hao et al., 1994]. Meng and Zhang [2000] distinguished the Wudang group as a transitional basement from the crystalline basement of the Yangtze craton, but Ratschbacher et al. [2003] interpreted the Wudang (basement massif) as a metamorphic core complex formed ~230–235 Ma along the northern edge of the Yangtze craton. In the following, we distinguish South Qinling, as being located between the Shangdan and Wudang faults, from the Yangtze craton (Figure 2).

[10] The Triassic orogenic was thermally less significant in the Qinling area than in the Dabie [Hacker et al., 1998, 2000]. \(^{40} \text{Ar}/^{39} \text{Ar}\) K-feldspar spectra from the pre-Mesozoic rocks in the Qinling area indicate deformation temperatures between 100 to 300°C, (locally <400°C) along the shear/fault zones (Lonan, Shangxiang, and Shangdan faults) in the North Qinling between 240 and 200 Ma [Ratschbacher et al., 2003]. The clear Triassic thermal signature in the Wudang blueschists, and the absence of temperatures >300°C farther north imply that the Triassic event involved subduction and exhumation of the Wudang blueschists [Ratschbacher et al., 2003]. The geodynamic setting is associated with the Late Triassic–Middle Jurassic southward thrusting and folding in the foreland basin formed at the northern edge of the Yangtze craton.

[11] Early Cretaceous strike-slip and extensional deformation features in the Qinling area probably correspond to those observed in regional eastern Asia, which are attributed to Pacific back-arc extension [e.g., Engebretson et al., 1985; Charvet et al., 1994; Yin and Nie, 1996]. Widespread Late Cretaceous strike-slip faulting, half graben formation (Late Cretaceous red bed along the faults), and folding throughout the Qinling [Xue et al., 1996b; Tapponnier and Molnar, 1977; Zhang et al., 1995; Reischmann et al., 1990; Ratschbacher et al., 2003] are related to the eastward tectonic escape resulted from the Lhasa–west Burma–Qiangtang-Indochina collision [Tapponnier et al., 1982]. Cretaceous plutons in the Qinling crop out nearly exclusively in the north China craton and the adjacent Kuanping group [Zhang, 1996].

[12] Cenozoic tectonics in continental China is characterized by contrasting contraction in the west and extension in the east [Molnar and Tapponnier, 1975; Peltzer et al., 1985; Deng, 1996; Yin and Harrison, 2000]. The North China Plain rift system (see Figure 1) in the east was reactivated in the Eocene along a series of major Mesozoic-originated NNE and/or NE faults, and widespread post-early Miocene subsidence occurred over the area [Allen et al., 1997; Liu et al., 2004]. Some of the rifts developed after the Indo-Asia collision at ~50 Ma [Patiat and Achache, 1984; Besse et al., 1984] and some, such as the Yinchuan-Hetao rift in the west and the Shanxi (Fen-Wei) rift system in the northernmost part of our study area are still active [Bellier et al., 1988; Zhang et al., 1998, 1999]. The cross section and estimated sedimentation rates of the Cenozoic Weihe graben are shown along profile A-A’ in Figure 2 [Xing et al., 2005]. Bellier et al. [1988] and Zhang et al. [1998, 1999] studied the Weihe graben along the southeastern margin of the Ordos block and established three successive extensional regimes: approximately WNW-ESW during the Paleogene, approximately NE-SW during the Neogene, and approximately NW-SE during the Pliocene-Quaternary. The widespread Eocene sedimentation in half graben basins and related offset of pre-Cenozoic markers indicate that the Paleogene was the major period of sinistral strike-slip and rifting in eastern Qinling. The latest Cenozoic deformation in the Qinling involves normal slip on ENE striking, graben-bounding faults, dextral slip along NNE trending faults, and mostly sinistral slip along east to ESE trending faults.

3. Sampling Strategy and Methodology

3.1. Sampling Strategy

[13] Thirty six samples, weighing ~1–2 kg each, were collected from all the major tectonic and stratigraphic units of the study area along a N-S linear transect from the Huashan in the north China craton, through the Qinling orogen into the Huangling anticline in the Yangtze craton (Figure 2). Most of the samples are basement metamorphic rocks, including blueschist, quartzite, gneiss and greenschist-grade metasedimentary rocks in the Liuling group (Figure 2). Samples were also collected from deformed (Paleozoic or older) or undeformed (early Cretaceous) granites and granodiorites (Table 1).

[14] Although samples were taken over a range of elevations (160–1700 m), they do not fulfill the requirements for a strict vertical fission track profile approach [e.g., Fitzgerald et al., 1999; Raab et al., 2005], because the high-density fault network made it difficult to sample a nondisrupted vertical profile within a tectonic unit. However, the distribution of samples along the transect allows
Table 1. Apatite Fission Track Analyses Results Along the Transect From Huanshan to Huangling\textsuperscript{a}

<table>
<thead>
<tr>
<th>Sample</th>
<th>Group(Gr)</th>
<th>Batholith</th>
<th>Latitude, °S</th>
<th>Longitude, °E</th>
<th>Elevation, m</th>
<th>Number of Grains</th>
<th>Standard Track Density\textsuperscript{b} (100 cm\textsuperscript{2})</th>
<th>Fossil Track Density\textsuperscript{b} (105 cm\textsuperscript{2})</th>
<th>Induced Track Density\textsuperscript{b} (106 cm\textsuperscript{2})</th>
<th>U, ppm</th>
<th>Chi Square Probability, %</th>
<th>FT Age, Ma</th>
<th>Mean Track Length ± Error,\textsuperscript{c} µm</th>
<th>SD, µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>QL-12</td>
<td>K granite</td>
<td>34°30.20</td>
<td>109°57.46</td>
<td>1600</td>
<td>10</td>
<td>0.8881(3132)</td>
<td>0.1031(64)</td>
<td>0.2916(181)</td>
<td>4.1</td>
<td>85.5</td>
<td>30 ± 4.1</td>
<td>13.1 ± 0.17(87)</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>QL-13</td>
<td>Taihua Gr</td>
<td>34°26.53</td>
<td>109°56.86</td>
<td>1700</td>
<td>20</td>
<td>0.9032(3132)</td>
<td>0.3635(456)</td>
<td>1.7260(2165)</td>
<td>23.9</td>
<td>72.7</td>
<td>34 ± 2</td>
<td>13.1 ± 0.16(90)</td>
<td>1.55</td>
<td></td>
</tr>
<tr>
<td>QL-14</td>
<td>Gaoshanhe</td>
<td>34°20.33</td>
<td>110°2.69</td>
<td>1200</td>
<td>7</td>
<td>0.9183(3132)</td>
<td>0.8601(240)</td>
<td>2.1576(602)</td>
<td>29.4</td>
<td>72.7</td>
<td>65 ± 5</td>
<td>12.8 ± 0.19(41)</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{a}Standard and induced track densities measured on mica external detectors (g = 0.5) and fossil track densities on internal mica surfaces. Ages calculated using the zeta method [Hurford and Green, 1982] (a zeta value of 357 ± 4.8 Ma for all the samples). All ages are pooled ages [Galbraith and Laslett, 1993]. Gr, group.

\textsuperscript{b}Parentheses show number of tracks actually counted.

\textsuperscript{c}Number of track measurements reported in parentheses.
the evaluation of differential possible cooling histories across the main faults traversed.

3.2. Laboratory Processing

[15] AFT analyses were performed at School of Earth Sciences, Melbourne University. Sample preparation and experimental methods used followed those reported by Kohn et al. [1995] with the exception that neutron thermal fluences were monitored using muscovite attached to the CN-5 standard glass [Bellemans et al., 1995]. Briefly, neutron irradiation was carried out in the well-thermalized X-7 facility of the HIFAR reactor, Australia. Ages were measured using the external detector method with Brazil Ruby muscovite detectors to record induced track densities. In order to detect possible flux gradients, apatites were packed between two standard glasses during irradiation. Fission tracks in each mount were counted in transmitted light using a dry objective at a magnification of $\times 1250$. A total of 20 individual crystals were analyzed where possible and only fully etched and horizontal "confined tracks" were measured in grains with polished surfaces parallel to prismatic crystal faces. Suitable track lengths were measured using a projection tube and a digitizing tablet calibrated using a stage micrometer. For this procedure, the same magnification as for counting was applied, and where possible, 100 horizontal confined track lengths were measured per sample. Ages were calculated using the zeta calibration method, and are expressed as pooled ages (essentially a weighted mean age) [Galbraith and Laslett, 1993]. Errors were calculated using the conventional method [Green, 1981] and are expressed at the $\pm 1\sigma$ standard deviation level.

[16] Single grain (U-Th)/He analyses were performed at Yale University. Euhedral zircon and apatite grains were hand-picked from sample separates, and their physical dimensions were measured with a stereomicroscope. The selected zircon and apatite grains were individually wrapped in Nb foil and Pt tubes, respectively. Each aliquot was placed in a $\sim$3-mm-deep pits in a copper planchet, then heated using a focused Nd:YAG laser beam for fifteen minutes (zircon) or three minutes (apatite). To completely heated using a focused Nd:YAG laser beam for fifteen in Nb foil and Pt tubes, respectively. Each aliquot was selected zircon and apatite grains were individually wrapped dimensions were measured with a stereomicroscope. The hand-picked from sample separates, and their physical

3.3. Thermochronology and Thermal History Modeling

[18] The length reduction of confined fission tracks within an apatite grain leads to a reduction of its AFT age, and the length distribution of the confined tracks reflects the thermal history subsequent to the last time it cooled below $\sim$110°C [e.g., Gallagher et al., 1998; Gleadow et al., 2002]. Thus the AFT system is ideal for determining the timing of denudation in response to cooling of upper crustal rocks [Gleadow and Brown, 2000]. In this study the AFT data have mainly been interpreted using the system response [Green et al., 1989] based on an empirical kinetic description of laboratory annealing data in Durango apatite described by Laslett et al. [1987]. Useful summaries of fission track dating and annealing are given by Gallagher et al. [1998], Dumitru [2000] and Gleadow et al. [2002].

[19] The recently revived (U-Th)/He methods can also provide useful constraints on low-temperature thermal histories, particularly in the temperature range of $\sim$70–200°C [Farley, 2002]. The most common target minerals are apatite and zircon which have different He diffusion properties. The He closure temperature of apatite is estimated as $\sim$70°C ($\sim$2 km at a geothermal gradient of 25°C/km) for a cooling rate of $\sim$10°C/Myr and grain radius of $\sim$100 μm [Wolf et al., 1996; Farley, 2002]. For zircon, a closure temperature of 180 ± 20°C is commonly accepted at a cooling rate of 10°C/Myr and a crystal radius of 60 μm [Reiners and Spell, 2002; Reiners et al., 2004].

[20] The combined use of AFT, AHe and ZHe data allow for the determination of denudation rates for various tectonic units in the study area in order to further elucidate regional deformation and uplift histories. The application HeFTy, was employed for simultaneous calculations of multiple thermochronometric systems [Ketcham, 2005].

4. Results

4.1. AFT Age and Length and Their Implication

[21] Twenty-six samples yielded AFT central ages ranging from 30 ± 4.1 (QL-13) to 121 ± 7 Ma (QL-19) (Table 1) and generally increase from north to south. Mean track lengths vary between 11.6 ± 0.23 and 13.1 ± 0.16 μm (Table 1). The youngest AFT ages (30–34 Ma) are observed at Huashan in the Lesser Qinling of the north China craton, these ages are slightly older than the ages (18–41 Ma) reported by Yin et al. [2001] for a local vertical profile on Huashan Mountain sampled between 580 and 2160 m. AFT ages for the North Qinling range from 57 to 73 Ma, which is comparable with the data from the Tongbai-Dabie area [Grimmer et al., 2002; Reiners et al., 2003; Hu et al., 2006]. AFT ages for the South Qinling
(80–129 Ma) are similar to those for Huangling anticline area in the Yangtze craton (87–102 Ma). In terms of the track length distribution (Figure 3), all samples show a unimodal distribution, but those from the Qinling orogen or near the Shanddan fault have a tail of shorter lengths, suggesting a complex thermal history involving either a prolonged residence in the AFT partial annealing zone (PAZ) or a reheating event.

[22] There is generally no simple relationship observed between elevation and AFT age, except for the vertical profile from Huashan Mountain previously reported by Yin et al. [2001] (see Figure 4a). This pattern indicates multiple denudation events [Fitzgerald and Stump, 1997], or differ-
ential movement and denudation between individual fault-bounded sub-tectonic units along the transect. Other factors however, may also perturb the age versus elevation relationship. The annealing properties of fission tracks in apatite [Gleadow and Duddy, 1981; Green et al., 1985; Barbarand et al., 2003] and mineralogical properties [Carlson et al., 1999]. The total annealing temperature for chlorine-rich apatites for example, occur at higher temperatures ~110–150°C compared to that in the more common fluorine-rich apatites ~90–100°C [e.g., Green et al., 1985; Burtner et al., 1994, O’Sullivan and Parrish, 1995]. Although chlorine

Figure 3. Apparent AFT ages, distribution of confined track lengths and radial plots for samples collected along the N-S transect. In radial plots [Galbraith, 1990], the slope of a straight line from the origin (0) passing through an individual grain age is equivalent to the fission track age read off the radial scale around the perimeter of the plot. The X value and the percent relative error are a measure of the precision of each grain age. The farther a point plots to the right of the origin, the more precise the individual grain age measurement. If all grains belong to a single age population, they should scatter within the ±2σ age range about the central age (outlined by the shaded horizontal rectangle) which is read by extrapolating a straight line from the origin (0) at the left of the plot to intercept the radial scale around the perimeter of the plot shown on the Y axis.
substitution probably exerts the most important effect on annealing, the possible influence of other trace elements (including rare earths) has also been noted [Barbarand et al., 2003].

[23] The chlorine content of the dated apatite grains dated was analyzed by electron microprobe analysis for three representative samples and the data are plotted in Figure 4b. These come from a gneiss of the Taihua group (QL-13) in the north China craton, a gneiss of the Douling group (QL-8) in the North Qinling, and a gneiss of the Kongling group (QL-29). Out of the 63 grains analyzed more than 70% was F apatite with Cl concentrations ranging between \( <0.01 \) and \( <0.4 \) wt % Cl. However, sample QL-8 contained grains with slightly higher concentrations ranging between \( <0.5 \) and \( <0.8 \) wt % Cl. The majority of these Cl concentrations are less than or equal to that for Durango apatite (\( <0.4 \) wt % Cl) as confirmed by a qualitative consideration of apatite solubility for other samples in that the track etching rate and etch pit size are known to broadly correlate with chlorine content [Donelick, 1993; Barbarand et al., 2003]. Hence paleotemperatures determined by applying the Laslett et al. [1987] model for track annealing are interpreted to be reasonable estimates. However, if the average chlorine content for samples is slightly higher than the Durango apatite value, it would suggest that paleotemperatures reconstructed on this basis may be too low in some cases, possibly by as much as \( <10-20 \)°C, but are unlikely to be too high.

[24] The large spread in AFT ages and track length distributions imply a complex temperature-time history along the sampled transect. Figure 5 shows AFT ages plotted against mean track lengths, in a so-called boomerang plot. If the samples experienced a single-stage cooling related to a discrete phase of fast denudation, then the plot should form a distinctive boomerang-like pattern [Green et al., 1989; Gallagher et al., 1998]. The samples along the Huashan to Huangling transect do not show such a trend, suggesting a more complex cooling history. AFT data from the Huashan near the Cenozoic Fenwei graben (QL-13 together with the six young ages from the vertical profile on the Huashan reported by Yin et al. [2001] record a young cooling (uplift/denudation) event related to the rifting.

Oligocene to Quaternary sediments in the Weihe graben attain a thickness of \( <7 \) km (Figure 2), indicative of strong erosion processes operating at that time in the Lesser Qinling [Xing et al., 2005]. AFT ages from the Qinling orogen are significantly younger than those from the South Qinling and Yangtze craton, which indicates Cenozoic reactivation along preexisted faults, such as the Lonan and Shangdan [Ratschbacher et al., 2003]. One relatively old AFT age for sample QL-8 is attributed to its higher chlorine content (see Figure 4b).

4.2. ZHe and AHe Ages

[25] Sixteen samples yielded reproducible ZHe ages in the range of 38.3 to 293 Ma (Table 2). Most of the ages correspond to Middle Triassic–Late Cretaceous although there are two exceptionally young (QL-12 in the Huashan, 38.3 Ma) and old (QL-32 in the Huangling, 293 Ma) ages. The new ages show a wider range than but are generally consistent with the ZHe ages reported from the Dabie Shan...
area (\(~90–140\) Ma) [Reiners et al., 2003]. Ages from the north China craton range from 38.3 to 116.3 Ma (mean of 77.3 ± 55 Ma); ages from the Huashan (38.3 Ma) are consistent with the zircon fission track ages (38–68.3 Ma) previously reported by Yin et al. [2001]. Ages from the North Qinling range between 65.7 and 197.5 Ma (mean of 119.7 ± 45 Ma), the south Qinling and Huangling areas in the Yangtze craton show a similar ZHe age pattern ranging between 107.3 and 293 Ma (mean of 182.9 ± 58 Ma). In summary, ZHe ages generally increase from north to south.

5. Thermal History: Combined Modeling

[27] Cooling paths of individual samples were modeled using HeFTy program [Ketcham, 2005]. The annealing model of Laslett et al. [1987] was employed for AFT analyses, and the diffusion data of Reiners et al. [2004] and Wolf et al. [1996] were used for ZHe and AHe, respectively. The new AFT, ZHe and AHe data were combined with previously reported K-Ar and 40Ar-39Ar age standards used to calibrate ages. This approach was because this most closely resembles the mean length in the starting point of our time-temperature path calculations.

5.1. Huangling Anticline, Yangtze Craton

[28] All the Yangtze craton samples are from the Huangling Anticline which consists of the Precambrian Kongling group and the Huangling granitic batholith in the core of the anticline. The seven AFT ages range between 87 and 102 Ma (Table 1) and the average track lengths are close to 12.5 \(\mu\)m without obvious short tracks (<10 \(\mu\)m) tail (see Figure 3), indicating a moderate rate of cooling through the PAZ. K-Ar biotite and muscovite ages from the granitic batholith are in the range of 687–799 Ma [Li et al., 2002]. Combined modeling reveals that the Huangling Anticline most likely experienced a long period of slow cooling over the temperature range of 250° to 150° C at a rate of ~0.5°C/Myr until ~100 Ma, followed by an increased cooling rate of ~2.5°C/Myr between ~100 and 40 Ma. Detailed cooling histories modeled for two representative samples (QL-29, 34) are shown in Figures 6a and 6b. QL-34 shows an especially prolonged cooling history characterized the location close the Yangtze River gorge.

Figure 6. (left) Combined thermal models for representative samples along the transect from Huashan to Huangling indicate multiple-stage cooling as signified by the gray shaded areas, involving (1) an early cooling period during the Late Triassic to Early Jurassic (~240–200 Ma) in the North and South Qinling, (2) regional cooling between 100 and ~60 Ma, and (3) a later cooling phase initiated at ~45 Ma along the southern margin of the Weihe graben in Lesser Qinling and in the North Qinling. See text for more detailed discussion. Dark lines are "good (GOF > = 0.5)" fits, light lines are "acceptable (GOF = 0.05–0.5)" fits. (right) Low-temperature thermochronology parameters for those both measured and predicted for best fit. GOF is the goodness of fit between the data measured and that predicted by the model. Cooling paths of individual samples were modeled using HeFTy program [Ketcham, 2005]. The annealing model of Laslett et al. [1987] was employed for AFT analyses, and the diffusion data of Reiners et al. [2004] and Wolf et al. [1996] were used for ZHe and AHe, respectively.

5.2. Wudang Core Complex, South Qinling

[30] Well-documented muscovite and hornblende samples from the Wudang basement yielded 40Ar/39Ar ages of 237–232 Ma [Ratschbacher et al., 2003]. One sample from Wudang (QL-21) yielded ZHe ages of 222–230 Ma and an AFT age of 80 Ma (Tables 1 and 2). Modeling shows that the Wudang basement massif experienced two major cooling episodes since the Late Triassic: (1) moderately rapid cooling ~9°C/Myr during Middle to Late Triassic time and (2) a less rapid cooling period of ~3.5°C/Myr during 80–60 Ma. The timing of the first cooling event corresponds to the development of the Wudang metamorphic core complex which ended at ~220 Ma. After this time from ~200 Ma, the cooling rate of the Wudang area significantly decreased (~1°C/Myr) and reduced to nearly isothermal (<0.5°C/Myr) until ~80 Ma (Figure 6c).

[31] 40Ar/39Ar data suggest that the Douling group in the north Wudang blueschist had never been heated above ~300°C since its formation in Proterozoic [Ratschbacher et al., 2003]. Our modeling based on AFT and AHe data reveal similar later thermal paths between the Wudang basement (QL-21) and the Douling group (QL-8 in Figure 6d) since the Early Cretaceous. The cooling path for the earlier history is not well constrained because no AHe data are available so only the 40Ar/39Ar muscovite age [Ratschbacher et al., 2003] has been used as a constraint for the higher temperatures.
Figure 6
5.3. North Qinling

[32] All samples covering this area are from the metamorphic Qinling group (QL-1, -2, -4, -5, -9, -11, see Figure 2), and from the Paleozoic (QL-16) and Cretaceous (QL-15) granitoids. A $^{40}$Ar/$^{39}$Ar hornblende age spectrum from the North Qinling indicates a thermal event at 420 ± 30 Ma [Ratschbacher et al., 2003], and a number of K-Ar biotite, muscovite and whole rock ages vary between 354 and 432 Ma [Regional Geology Survey of Henan, 1989; Zhang et al., 1991]. Ratschbacher et al. [2003] presented two K-feldspar samples from the Qinling group (their sample location is close to our QL-2) for $^{40}$Ar/$^{39}$Ar age spectra modeling. One sample yielded almost linear cooling from 300°C at ~300 Ma to 160°C at ~250 Ma (~3°C/Myr), followed by very slow cooling to 150°C by ~200 Ma (0.2°C/Myr), (this sample may have cooled through 250°C as early as 300 Ma). Such a cooling rate decrease is also detected from their second sample: linear and fast cooling from 300 to 180°C between 270 and 240 Ma (4°C/Myr), followed by nearly isothermal cooling by 200 Ma. Ratschbacher et al. [2003] also modeled age spectra from two K-feldspar samples in the Shangdan fault zone of the northern Liuling group (close to our QL-17 location). One sample shows evidence of low-T ductility (~300°C) overprinting a high-T fabric (~500°C). The sample reveals a spectacular age gradient between 1200 and 220 Ma. Models allowing reheating show a thermal history at 300°C between 600 and 300 Ma followed by cooling to 200°C by 200 Ma. These data have been used in our model as a higher temperature constraint.

[33] Modeling of the QL-17 (sample location close to the Shangdan fault zone) data suggests three cooling stages: (1) Triassic cooling from ~300°C around 250 Ma to 150°C at 220 Ma; (2) very slow cooling (~0.3°C/Myr) to 110°C by 80 Ma; and (3) cooling from 110°C at ~80 Ma to 50°C at ~40 Ma (Figure 6e). QL-8 is a metamorphic sample from the Qinling group located between the Shangxian and Shandang faults and yielded ZHe and AFT ages systematically younger than those for QL-17. These results suggest similar cooling patterns for QL-8 and QL-17, but the former experienced a slower cooling in the Late Triassic (Figure 6f). Sample QL-15 is from a Cretaceous pluton (K-Ar biotite age 135 Ma) [Zhang et al., 1991], which intruded in the Kuaping group south to the Lounan fault. Modeling of the available data also revealed three cooling stages: (1) rapid cooling of the pluton from 300°C to ~160°C at ~100 Ma; (2) very slow cooling to 150°C by ~60 Ma; and (3) rapid cooling from 150°C to the surface between 60 and 40 Ma (Figure 6g). Compared with the later cooling event of QL-8 and QL-21 in the South Qinling, the later cooling for QL-17 and QL-2 was prolonged by ~20 Ma, but that for QL-15, close to Lounan fault, was later, at ~60–40 Ma, which may suggest a different reactivation history of the strike-slip faults during Late Cretaceous–early Tertiary time.

5.4. Cretaceous Huashan Granitoids, North China Craton

[34] The Huashan Granitoid is a Cretaceous pluton intruding the Taihua group in the north China craton, and also forms Huashan Mountain. The Cenozoic Weihe graben (Shanxi rift) is located at the northern foot of the mountain. The granitoid has a $^{40}$Ar/$^{39}$Ar biotite age of 121 Ma [Zhang et al., 1991] and zircon FT ages of 38–68 Ma for elevations between 580 and 2160 m [Yin et al., 2001]. Sample QL-12 from this granitoid yields a ZHe age of 38.3 Ma, a AHe age of 25.8 Ma and an AFT age of 29.6 Ma. Modeling indicates cooling from 300 to 210°C by ~45 Ma followed by monotonic and cooling at a rate of ~8°C/Myr to the surface by ~15 Ma (Figure 6h). This cooling rate, corresponding to an exhumation rate of ~0.3 km/Myr (assuming a paleo-temperature gradient of 25°C/km) is temporally consistent with the Eocene to Miocene sedimentary record in the Weihe graben. Thickness of the sedimentary units in the graben reached up to 6.9 km and the apparent deposition rates (without compaction correction) are in the range of 0.06–0.7 km/Myr. The apparent deposition rate appears to increase during 3.4–2.6 Ma (see cross section A-A’ in Figure 2) indicating that active erosion processes continued in the footwall of the graben-bounding normal fault of the Weihe graben, but the eroded area changed to the higher mountain area farther away from the graben boundary, and the erosion in the sampled low elevation area closer to the graben boundary became weak, which is the reason why the modeled sample shows a stable time period from 15 Ma to the present.

[35] Ratschbacher et al. [2003] reported K-feldspar data from two Early Cretaceous granitoids, ~150 km to the southeast of Huashan Mountain in the North China craton. Their modeling results are however, not in agreement with the cooling path obtained from the QL-12. Under the assumption of monotonic cooling, one indicates linear cooling from 300°C at 112 Ma to ~100°C at 103 Ma; the other shows an age spectrum that climbs from 55 to 85 Ma with a flat segment at 73 Ma. The modeled spectrum indicates slow cooling from ~280 to 260°C between 73 and 63 Ma and faster cooling to 150°C by 55 Ma. If reheating is allowed, cooling follows a thermal spike at 85 Ma. The difference of cooling histories between the Cretaceous plutons at different locations implies that the Cenozoic rifting has direct impact on the rapid exhumation of Huashan Mountain.

6. Discussion

[36] The cooling phases as recorded by the thermochronological data can be linked to the Mesozoic-Cenozoic deformation history of the region. The subduction-related deformation and reactivation induced by regional tectonic setting resulted in local and regional exhumation/cooling.

[37] Subduction of the Yangtze plate under the north China craton imposed dextral transpressive slip onto preexisting shear/fault zones (Loran, Shangxian, Shangdan) in the North Qinling between 200 and 240 Ma [Ratschbacher et al., 2003]. This event induced significant heating of the Erlangping, Qinling, Liuling, and Douling groups by up to 300°C [Ratschbacher et al., 2003] and resulted in a later (220–200 Ma) cooling event in the North Qinling (see Figures 6c, 6e, and 6f). Synconvergence, extensional exhu-
mation of the subducted northern Yangtze craton formed the Wudang metamorphic core complex at ~230–235 Ma. During this period, significant exhumation (≥0.6 km/Myr) occurred reducing the crustal thickness to <20 km [Ratschbacher et al., 2003]. Our modeling, combining ZHe and AFT data for samples north of Wudang, together with ⁴⁰Ar/³⁹Ar biotite ages [Ratschbacher et al., 2003] indicated that the exhumation related to the Wudang core complex development was probably active to the late Triassic (∼220 Ma) and that exhumation during 220 to ~200 Ma decreased significantly. This decreased exhumation can probably be considered as a static “adjustment” period after the rapid exhumation (see Figure 6c). Several basement domes in the northern Yangtze craton (Wugong Shan, Jiuling Shan and the Lu Shan) formed during the Triassic extension [Faure et al., 1996; Lin et al., 2000, 2001]. Basement rocks exposed in the interior of the Yangtze craton were under a nearly isothermal temperature state of ~160–250°C, or at depths of 8–10 km, during this time (Figures 6a and 6b).

[36] Minor deformation and sedimentation are observed in the Qinling area during Jurassic to Early Cretaceous time [Zhang et al., 1989]. Reactivation of the eastern Qinling during the Cretaceous is evidenced by the transition of the cooling rate: from the stable cooling (Jurassic—Early Cretaceous) to the regional pronounced cooling episodes in the interior of Yangtze craton between 100 and 60 Ma (Figures 6a and 6b), in the South and North Qinling between 80 and 60 Ma (Figures 6c–6g) and in the granite body of the Kuaping group during the Early Cretaceous (Figure 6g). The relatively rapid cooling histories observed over a relatively wide area are interpreted as corresponding to an episode of major regional exhumation, whose products formed widespread Late Cretaceous (K₂) to Eocene red bed deposits in eastern China. The regional dextral wrenching, which was active within a NE-SW extensional regime between ~60 and 100 Ma [Xue et al., 1996b; Zhang et al., 1995; Reischmann et al., 1990; Ratschbacher et al., 2003], caused rapid exhumation. Ratschbacher et al. [2000] suggested that widespread Cretaceous strike-slip and extensional deformation in eastern Asia, coeval with that reported in the Qinling-Dabie belt [Hacker et al., 2000; Ratschbacher et al., 2000], resulted from the combined effects of the Siberia-Mongolia–Sino-Korean collisions, Lhasa–west Burma–Qiangtang-Indochina collisions, and Pacific subduction and its related arc magmatism. This regional tectonic setting reactivated the preexisting low-angle faults in the study area through strike-slip faulting. Exhumation/colling happened when the movements were not horizontal.

[39] Major cooling in the North Qinling was initiated at ~80 Ma and continued until mid to late Cenozoic time (Figures 6c–6g), probably indicating a relatively prolonged period of strike-slip activity in this area compared to the South Qinling. We link this period of cooling or exhumation with Late Cretaceous–Eocene sedimentation in the half graben basins as well as strike-slip and normal faults pervasive in the north Qinling [Zhang et al., 1998, 1999; Xue et al., 1996a; Ratschbacher et al., 2003]. The Early Cretaceous Huashan Granitoids in the Lesser Qinling of the north China craton experienced pronounced cooling between ~45 and 15 Ma and this can be associated with unroofing related to periodic movements of normal faults on the southern boundary of the Cenozoic Weihe graben (Figure 6h). The ~7-km-thick Oligocene-Quaternary sediments in the Weihe Graben are also considered indicative of strong erosion processes during this period [Xing et al., 2005]. An Eocene event (~45 Ma) has been recognized in the Dabie area to the east [Grimmer et al., 2002; Hu et al., 2006], whereas late Oligocene to Miocene cooling event was reported in association with the development of the large-scale compressive structures throughout north Tibet to the west [Jolivet et al., 2001; Enkelmann et al., 2006]. In addition, the late Cenozoic extension direction (NW-SE) observed in the Qinling area is essentially indistinguishable from the extension direction imposed by the India-Asia collision [Ratschbacher et al., 2003]. Taken together these may suggest a possible link between the exhumation initiated at ~45 Ma in the Qinling and the eastward tectonic escape imposed by the India-Asia collision at ~50 Ma [Patriat and Achache, 1984; Besse et al., 1984; Tapponnier and Molnar, 1977; Liu et al., 2004; Enkelmann et al., 2006].

7. Conclusions

[40] Low temperature thermal histories of the major tectonic units (north China craton, Qinling orogen, Yangtze craton) along a transect in central China have been investigated using ZHe, AFT and AHe thermochronology, and these results have been combined with existing ⁴⁰Ar/³⁹Ar and K-Ar (biotite and K-feldspar) data to identify the regional pattern of tectonothermal events.

[41] The first phase can be defined as a Late Triassic to Early Jurassic (240–200 Ma) cooling episode which followed heating events in the North Qinling associated with dextral transpressive slip onto preexisting shear/fault zones (Lonian, Shangxian, Shangdan). Such reactivation is probably due to (1) Triassic subduction of the Yangtze craton and (2) exhumation of the cratonal edge in a dominantly pure shear extensional setting at ~230–235 Ma forming the Wudang metamorphic core complex [Ratschbacher et al., 2003].

[42] The second phase is a regional cooling or exhumation event initiated during the early Late Cretaceous (~100 Ma in Yangtze craton and ~80 Ma in the South and North Qinling), and continued to earliest Cenozoic time (~60 Ma) in the Yangtze craton and South Qinling, consistent with the cooling in the ultrahigh-pressure metamorphic belt [Hu et al., 2006]. During this phase, the regional dextral wrenching was active within a NE-SW extensional regime in the east China [Ratschbacher et al., 2003]. In the North Qinling, the cooling or exhumation event continued to Eocene (~40 Ma) indicating prolonged reactivation of strike-slip activity in this area, similar with that nearby the Tanlu fault [Grimmer et al., 2002; Hu et al., 2006]. Regional cooling during the early second phase is coeval with the deposition of the Late Cretaceous–Eocene red bed sequences in eastern China suggesting a causative link with the Pacific subduction–back-arc extension in eastern China, but it may be superposed by the eastward tectonic escape.
resulted from the Lhasa–west Burma–Qiangtang-Indochina collision [Tapponnier et al., 1982].

[45] The third phase is characterized by enhanced local cooling between ~45 and 15 Ma mainly in the Lesser Qinling (southern bank of the Cenozoic Weihe graben) of the north China craton. This phase probably resulted from periodic movements of the normal fault defining the southern boundary of the Cenozoic Weihe Graben, and related sedimentation (~7 km in thickness) near Huashan Mountain during Oligocene-Quaternary time. Such pronounced cooling has also been reported throughout north Tibet, further west of the study area, during an almost identical period (late Oligocene–Miocene) [Jolivet et al., 2001; Enkelmann et al., 2006]. This temporal correlation suggests that the third cooling/deflation phase in the Lesser Qinling may be related to the India-Asia collision at ~50 Ma [Patrì and Achathe, 1984; Besse et al., 1984; Yin and Harrison, 2000].

[44] This work is a preliminary reconnaissance along a 400-km-long transect across the Qinling orogenic belt.

Acquisition of more low-temperature data will complement the existing data set and could potentially provide further information about the India-Asia collision-related deflation. Further, the thermal history modeling assumed a generally monotonic cooling because our low-temperature dating are cooling ages and we are dealing with crystalline basement or plutons that has never been buried quite deep by a sedimentary cover during the postorogenic evolution, reheating may be included in the modeling if it can be well constrained when more data available.

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