Paleozoic metamorphism in the Qinling orogen, Tongbai Mountains, central China

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ABSTRACT

The collision of the Sino-Korean and Yangtze blocks to form a significant part of China is recorded in the Qinling, Tongbai, and Dabie Mountains. Radiometric ages of the ultrahigh-pressure metamorphic rocks in the South Qinling orogenic belt suggest that subduction and collision took place during the Triassic Period. Our new $^{40}Ar/^{39}Ar$ geochronology of units in the North Qinling orogenic belt confirms that high-grade metamorphism and deformation took place also during the Silurian-Devonian and Carboniferous Periods. These results imply that the amalgamation of eastern China was a multistage process extending over at least 200 m.y.

INTRODUCTION

The Qinling orogen (Fig. 1) extends for over 2000 km across central China, separating the Archean and Proterozoic Sino-Korean block in the north from the Proterozoic Yangtze block in the south. Although the orogen has been recognized as a continental collision zone for some time, the nature, age, and duration of the collision have been the subject of considerable debate (see review in Hacker et al., 1996). The debate has intensified since the recognition of coesite-bearing ultrahigh-pressure rocks in the Dabie region of the South Qinling orogenic belt, which imply subduction of crustal rocks to depths on the order of 100 km. (Wang et al., 1989; Okay et al., 1989). Recent radiometric data suggest that these ultrahigh-pressure rocks formed during Triassic continental subduction (Li et al., 1993; Hacker and Wang, 1995; Ames et al., 1996). However, few reliable radiometric data are available for the North Qinling orogenic belt, and no evidence of Triassic metamorphism has been reported, which is surprising, considering that an orogenic event as significant as ultrahigh-pressure metamorphism was occurring at that time in the Dabie Mountains. Kröner et al. (1993) reported early Paleozoic dates from single zircons in the Tongbai Mountains and Zhai et al. (1995) suggested that the collision zone contains evidence for multiple orogenies. Xue et al. (1996a, 1996b) reported $^{207}Pb/^{206}Pb$ single-zircon dating in the Qinling Mountains and suggested that a 440 Ma (Ordovician–Silurian) intraoceanic arc built on 480 Ma (Ordovician) basement was emplaced onto the southern margin of the Sino-Korean block, and stitched together by 400 Ma post-collisional intrusions. These proposals raise some interesting questions. Why is the high-pressure metamorphism Triassic rather than Devonian, and what happened in the intervening 150 m.y.?

We have studied the North Qinling orogenic belt in the northern Tongbai Mountains and have determined $^{40}Ar/^{39}Ar$ hornblende ages at several key localities. Our results indicate that the main metamorphic event in the North Qinling belt occurred during the Silurian or earliest Devonian and that a Carboniferous metamorphism affected units separating the North and South Qinling belts. Our data do not show significant regional Mesozoic metamorphism in the North Qinling orogenic belt.

TECTONIC BELTS OF THE EASTERN PART OF THE QINLING OROGEN

The North and South Qinling orogenic belts display contrasting styles of metamorphism. The South Qinling belt contains widespread Triassic high pressure/temperature (P/T) metamorphic rocks in the Dabie, south Tongbai, and Wudang regions and very low grade Sinian-Triassic meta-

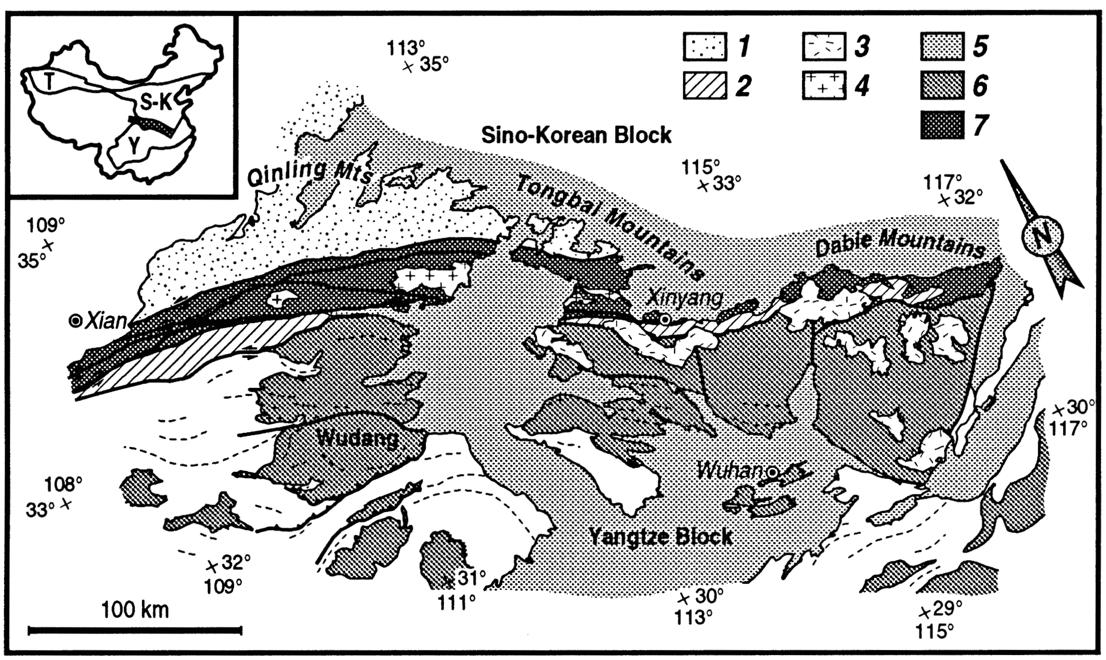

Figure 1. Index map of Qinling orogen. Inset shows Tarim (T), Sino-Korean (S-K), and Yangtze (Y) blocks and location of the Qinling orogen (pattern). Beginning in the north, Unit 1 shows undifferentiated Paleozoic and older rocks of Sino-Korean block. North Qinling orogenic belt (unit 7) contains Kuanping, Erlangping, and Qinling Groups, as well as pre-Cretaceous cover rocks. It is separated from South Qinling orogenic belt by "flysch" (unit 2) known in Tongbai region as Xinyang Group. South Qinling orogenic belt includes deformed basement (unit 6), including high *P/T* metamorphic rocks, and low-grade or unmetamorphosed cover (no pattern) of Yangtze block. These lithotectonic belts are overlain by undifferentiated Cretaceous and younger sedimentary rocks (unit 5) and intruded by Paleozoic (unit 3) and Mesozoic granitoid plutons (unit 4). Bold lines indicate regionally extensive fault zones, and dashed lines show trends of fold hinge lines.

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sedimentary rocks farther west in the Qinling Mountains proper (Fig. 1). In the Dabie area and eastern parts of the south Tongbai region (Fig. 1), this high *P*/*T* terrane contains the ultrahigh-pressure mineral coesite. The North Qinling orogenic belt, in contrast, is a medium *P*/*T* metamorphic belt that is separated from the southern belt by metasedimentary and metavolcanic rocks of the Xinyang Group, which continue westward to the Qinling Mountains proper as a "Devonian trough" (Mattauer et al., 1985) or "flysch nappe" (Hsü et al., 1987).

Four fault-bounded tectonic units are recognized in the north Tongbai Mountains region of the North Qinling orogenic belt (Fig. 2). The northernmost unit comprises mica schists, quartzites, marbles, and amphibolites similar to the Kuanping Group in the Qinling Mountains This metasedimentary and metavolcanic assemblage is thought to have been deposited at the southern margin of the Sino-Korean block during the Late Proterozoic and corresponds to rocks farther west described as mobilized cover of the Sino-Korean block (Hsü et al., 1987). On the basis of preliminary isotopic ages, the Kuanping Group has been considered to have been metamorphosed during Late Proterozoic or Paleozoic times (Zhang, 1990; Zhang et al., 1991; Zhang et al., 1994). The Huanggang diorite complex comprises intermediate and silicic intrusions, intrudes the Kuanping rocks to the north and is bounded in the south by a major shear zone (Ma, 1989; Zhai, 1989; Okay et al., 1993). Preliminary data suggest K-Ar ages of 375–400 Ma and a U-Pb zircon age of ca. 400 Ma (Kröner et al., 1993; Zhai, 1989).

The Erlangping Group is a metavolcanic complex consisting of abundant upper greenschist facies to amphibolite facies rocks, the protoliths of which may have been mafic to intermediate volcanic rocks and hypabyssal dikes. The Erlangping Group in the Qinling Mountains contains Paleozoic fossils (Niu et al., 1993). The age of metamorphism has been considered to be early Paleozoic, based on poorly documented isotopic data (Zhang et al., 1989).

The Qinling Group includes felsic and mafic granulites, amphibolites, granitoid gneisses, marbles, and subordinate metapelites. Although a shear zone separates the Qinling and Erlangping Groups, metamorphic grade decreases without major discontinuity across the contact, from granulite facies in the Qinling Group, through amphibolite facies to upper greenschist facies in the Erlangping unit. Some workers have considered the Qinling Group to be Precambrian and have interpreted the unit as an allochthonous nappe of the Sino-Korean basement (e.g., Liu and Hao, 1989). However, recent $^{207}Pb/^{206}Pb$ zircon evaporation ages of 434–475 Ma suggest a significant Paleozoic history for these rocks (Kröner et al., 1993).

In the Tongbai area (Fig. 2), the North Qinling belt is separated from the high *P*/*T* metamorphic terrane in the South Qinling orogenic belt by the Xinyang Group, which contains amphibolite and kyanite mica schist. The metamorphism and associated deformation of the Xinyang Group are considered to be either Paleozoic (Mattauer et al., 1985; Zhang et al., 1987; Zhang et al., 1989) or Mesozoic (Hsü et al., 1987).

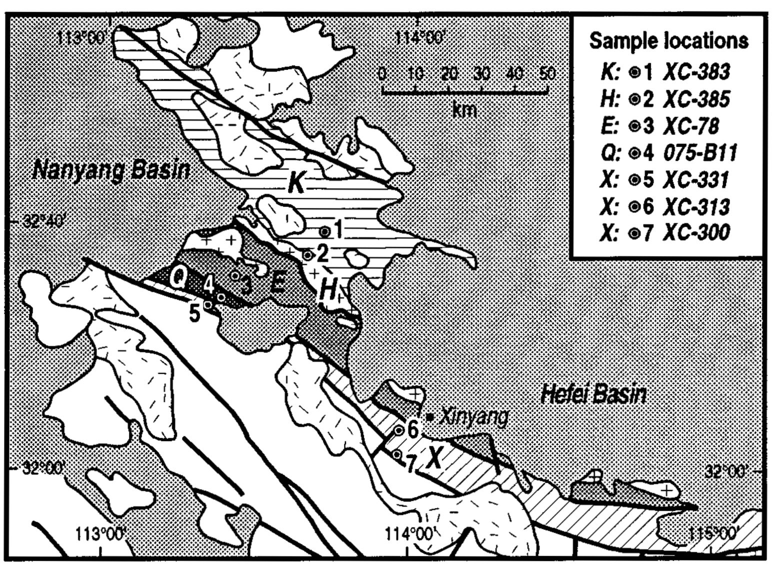

Figure 2. Geologic map of Tongbai Mountains. Abbreviations in ruled and dark dot patterns: E—Erlangping Group; H—Huanggang diorite complex; K—Kuanping Group; Q—Qinling Group; X—Xinyang Group. Light dot pattern—undifferentiated Cretaceous and younger sedimentary rocks; crosses—Paleozoic(?) granitoid intrusions; random line pattern—Mesozoic granitoid intrusions; no pattern—undifferentiated rocks of Sino-Korean Block to north and South Qinling orogenic belt to south. Numbers show sample localities. Bold lines show major fault zones.

NEW ARGON DATA

In the North Tongbai Mountains, the granulite- and amphibolite-facies sialic basement of the Qinling Group is overlain by the lower-grade Erlangping volcanic arc. The metamorphism and deformation of this complex, the Kuanping continental-margin assemblage to the north, and the Xinyang Group to the south reflect the major thermal and tectonic events during which the orogen formed. In order to constrain the age of these events, we analysed $^{40}Ar/^{39}Ar$ in hornblende from sixteen amphibolites using step-heating methods described by Hacker et al. (1997). The release spectra of nine samples were too disturbed to be interpreted unambiguously and are not presented here (Zhai, 1996). The $^{40}Ar/^{39}Ar$ analyses of the remaining seven samples (loc. 1–7, Fig. 2) demonstrate that the age of the main metamorphism in these tectonic units is Paleozoic (Appendix).[1]

Hornblende that defines the foliation in an amphibolite from the Kuanping Group (loc. 1, Fig. 2) gave a $^{40}Ar/^{39}Ar$ plateau age of 434 ± 2 Ma (Fig. 3A). Hornblende from an intrusive diorite in the nearby Huanggang complex (Loc. 2, Fig., 2) also gave a plateau age of 433 ± 2 Ma (Fig. 3B).

All analyzed amphiboles from the Erlangping Group yielded disturbed spectra and isotopic ratios indicating excess ^{40}Ar (Zhai, 1996). The only sample presented here (XC-78, loc. 3, Fig. 2) yielded a saddle-shaped spectrum (Fig. 4A) typical of hornblende with excess ^{40}Ar (Harrison and McDougall, 1981). Twelve contiguous steps, containing 69% of the total ^{39}Ar released, define a linear array on an inverse-correlation plot of $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ (Fig. 4B). Although the scatter about the best linear fit to the array is larger than that expected from analytical uncertainty alone, the data imply an isochron age of 404 ± 5 Ma with a trapped $^{40}Ar/^{36}Ar$ ratio of 1019, significantly higher than the atmospheric value (295.5). This date is consistent with a plateau age from the neighboring Qinling Group and is interpreted as a reliable cooling age for the hornblende.

Hornblende from a felsic, garnet–two-pyroxene granulite in the Qinling Group (O75-B11, loc. 4, Fig. 2) yielded a plateau age of 404 ± 2 Ma (Fig. 3C). Hornblende separates from a clinopyroxene-bearing amphibolite and another granulite in the Qinling Group gave disturbed spectra with excess ^{40}Ar and are not presented here (Zhai, 1996).

Two amphibolites from the Xinyang Group yielded younger, late Paleozoic ages. Hornblende from amphibolite XC-313 (loc. 6, Fig. 2) gave a plateau age of 316 ± 1 Ma (Fig. 3D). Hornblende from an amphibolite in the western Xinyang Group (Loc. 5, Fig. 2) produced a dis-

[1]GSA Data Repository item 9842, analyses of argon in hornblende, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

turbed spectrum (Fig. 4C) with an isochron age of 304 ± 14 Ma and a trapped $^{40}Ar/^{36}Ar$ ratio of 5026 (Fig. 4D). A third amphibolite from the Xinyang Group (loc. 7, Fig 2) has a plateau age of 130 ± 1 Ma (Fig. 3E). The sample locality lies in the contact aureole of a Cretaceous granitoid pluton, near a major fault zone (loc. 7, Fig. 2).

DISCUSSION

The ages presented here imply that the main metamorphic events in the North Qinling belt occurred during the Paleozoic. There is no evidence preserved in these data for earlier, i.e., Precambrian, metamorphism (e.g., Zhang et al., 1994) or for Mesozoic regional metamorphism, as might be expected from the Triassic metamorphism in the nearby Dabie and South Tongbai regions. Indeed, if the high *P*/*T* metamorphism in those regions was associated with a Triassic continental collision, it is puzzling that there is no record of such in our data. Contrary to the suggestions of Hsü et al. (1987), evidence of early Paleozoic deformation and metamorphism has not been obliterated by Mesozoic deformation, and there is no evidence that the Paleozoic ages are reset or partially reset Precambrian ages. The presence of excess ^{40}Ar in many of our samples (e.g., Fig 4; see also Zhai, 1996) shows that previously reported K-Ar ages from this region should be treated with caution.

Our $^{40}Ar/^{39}Ar$ ages in the Tongbai region are cooling ages, although some of the ages from lower grade amphibolites may approximate the times of peak metamorphism. The ages young systematically across fault-bounded terranes, from 434 Ma in the north to about 300 Ma in the south, and it is improbable that they record extended cooling from a single tectonic and/or metamorphic event. The ages from the Kuanping, Erlangping, and Qinling Groups range from 434 to 404 Ma and are consistent with either one long or two discrete metamorphic events during Silurian to earliest Devonian time. The older ages may reflect cooling following intrusion of tonalite and granodiorite at 435 Ma or earlier (Kröner et al., 1993; Lerch et al., 1995). The 300 Ma ages from the Xinyang Group suggest a previously unrecognized episode of Carboniferous metamorphism.

The assemblages of metamorphic minerals and *P-T* estimates suggest that these metamorphic events occurred in a substantially thickened crust. Staurolite-kyanite mica schists in the Xinyang, Qinling, Erlangping, and Kuanping Groups (Zhang, 1990) suggest medium pressure metamorphism, and thermobarometric studies of hornblende granulites in the Qinling Group indicate pressures of 5.5–7 kbar at minimum temperatures of 600–700 °C (Zhai, 1996; cf. also Zhai, 1989; Kröner et al., 1993). These metamorphic conditions are similar to those found in collisional orogens.

The nature and age of metamorphism in the Qinling, Erlangping, and Kuanping Groups in the North Tongbai Mountains are consistent with recent suggestions that an early Paleozoic intra-

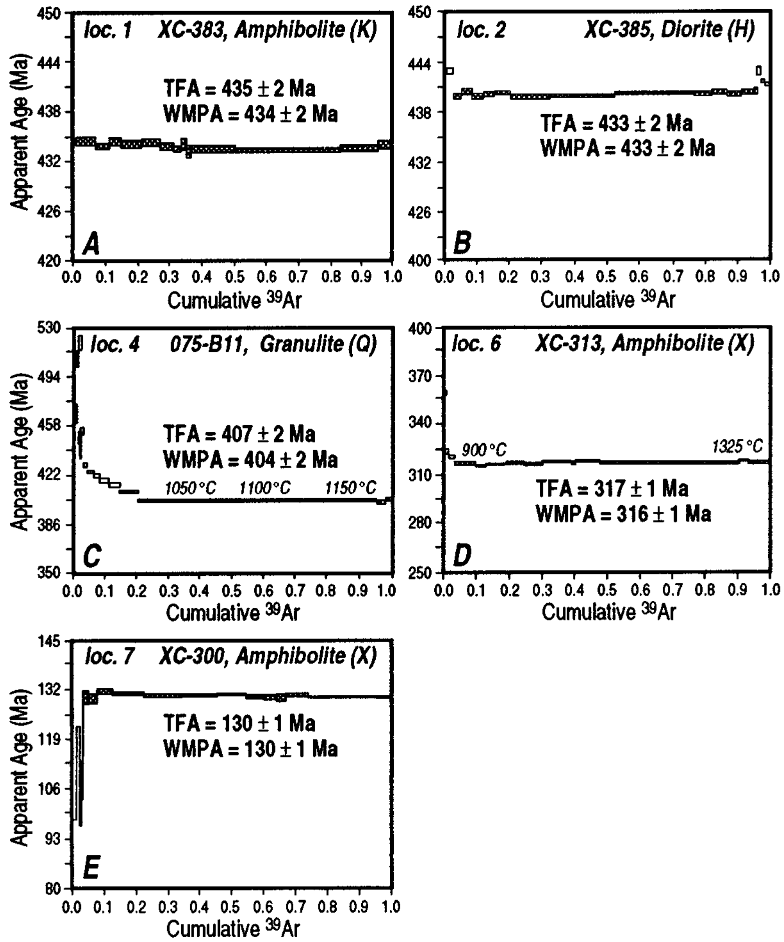

Figure 3. $^{40}Ar/^{39}Ar$ **plateau spectra for hornblende samples located in Figure 2. Abbreviations: TFA—total fusion age; WMPA—weighted mean plateau age; other abbreviations as in Figure 2. A: Locality 1. Plateau age of 434 Ma is composed of 14 heating steps that contain 98% of the** ^{39}Ar **released. B: Locality 2. Plateau age of 433 Ma is defined by 14 heating steps that contain over 93% of** ^{39}Ar **released. C: Locality 4. Plateau age of 404 Ma consists of 5 high-temperature steps that contain 80% of** ^{39}Ar **released. D: Locality 6. Plateau yields age of 316 Ma with over 95% of** ^{39}Ar **released contained in 15 steps; corresponding inverse isochron gives equivalent age with trapped** $^{40}Ar/^{36}Ar$ **ratio of 310 ± 10, close to accepted atmospheric value. E: Locality 7. Plateau consisting of 12 steps with 96% of** ^{39}Ar **released defines age of 130 Ma.**

oceanic arc collided with the continental margin of the Sino-Korean block during Silurian-Devonian time (Okay et al., 1993; Kröner et al., 1993; Zhai et al., 1995; Xue et al., 1996a). Our isotopic data provide the first direct and unambiguous evidence of cooling at 404–434 Ma, following metamorphism of the volcanic arc, its basement, and the adjacent Kuanping continental margin assemblage. Postcollisional and arc-related granitoids in the Qinling Mountains to the west yield U-Pb zircon ages of 401 to 422 Ma and $^{207}Pb/^{206}Pb$ zircon evaporation ages ranging from 470 to 487 Ma (Lerch et al., 1995; Xue et al., 1996a). Our metamorphic ages correspond most closely with the ages of the postcollisional granites and suggest that the characteristic metamorphism of these units was associated with cooling of this postcollisional continental arc.

The Carboniferous metamorphism of the Xinyang Group probably represents a separate tectonic event. The Xinyang Group is reported to contain Devonian fossils (Gao and Liu, 1990; Shan et al., 1992), and our hornblende dates (304–316 Ma) suggest that the medium-pressure metamorphism of the Xinyang Group took place during the Carboniferous Period. Metasedimentary rocks in the Qinling Mountains to the west, which are equivalent to the Xinyang Group, yield a $^{40}Ar/^{39}Ar$ biotite age of 314 Ma and contain ultramafic, mafic, and gabbroic pebbles similar to the Erlangping-Qinling volcanic complex (Mattauer et al., 1985).

CONCLUSIONS

Our data from the North Qinling orogenic belt contain no evidence of Mesozoic metamorphism. Instead, the main metamorphism and deformation of the major lithotectonic belts in the North Tongbai Mountains occurred during the Silurian to earliest Devonian, broadly coincident with the construction of a magmatic arc at or near the southern margin of the Sino-Korean Block. The

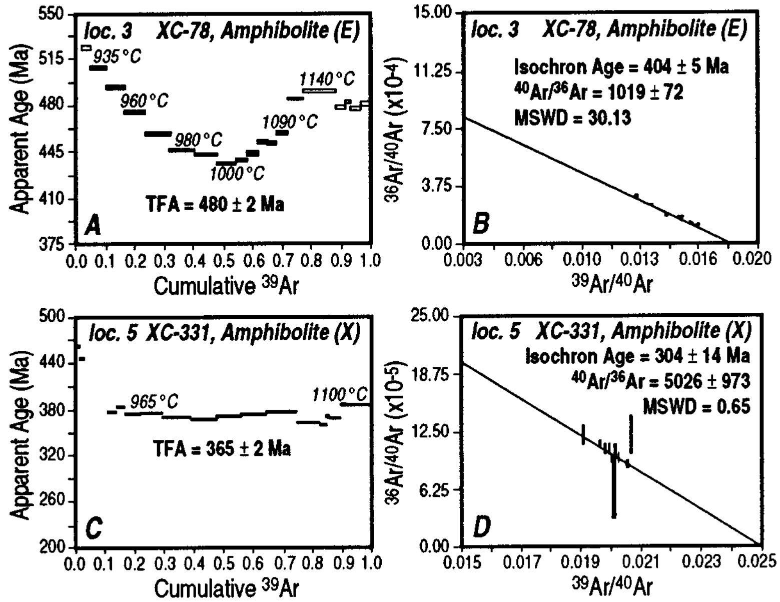

Figure 4. Disturbed spectra and inverse correlation diagrams. Abbreviations: MSWD—mean squared weighted deviations; others as in Figure 3. A: Locality 3. Saddle-shaped hornblende spectrum from Erlangping amphibolite. B: Locality 3. Inverse correlation diagram yielding isochron age of 404 Ma; the trapped component has $^{40}Ar/^{36}Ar$ = 1019, significantly higher than the atmospheric value of 295.5. C: Locality 5. Disturbed spectrum yields only a total fusion age of 365 ± 2 Ma. D: Locality 5. Inverse correlation diagram defines isochron age of 304 Ma with $^{40}Ar/^{36}Ar$ ratio of 5026.

Carboniferous metamorphism observed in the Xinyang Group suggests a second Paleozoic orogenic event that may be important in understanding the long history of collision and plate interaction in the Qinling orogen, but its significance remains an open question. The main phase of metamorphism in the high *P*/*T* metamorphic terrane in the Tongbai and Dabie regions occurred at about 200 Ma, about 100 m.y. later than the Carboniferous metamorphism in the Xinyang Group. Thus, the Qinling orogen contains a record of at least three major metamorphic and deformational events extending over at least a 200 m.y. interval during the Paleozoic and Mesozoic.

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