Cratonic reactivation and orogeny: An example from the northern margin of the North China Craton

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A B S T R A C T

Reactivation of cratonic basement involves a number of processes including extension, compression, and/or lithospheric delamination. The northern margin of the North China Craton (NCC), adjacent to the Inner Mongolian Orogenic Belt, was reactivated in the Late Paleozoic to Early Mesozoic. During this period, the northern margin of the NCC underwent magmatism, N-S compression, regional exhumation, and uplift, including the formation of E-W-trending thick-skinned and thin-skinned south-verging folds and south-verging ductile shear zones. Zircon U-Pb SHRIMP ages for mylonite protoliths in shear zones which show ages of 310–290 Ma (mid Carboniferous–Early Permian), constraining the earliest possible age of deformation. Muscovite within carbonate and quartz-feldspar–muscovite mylonites from the Kangbao–Weichang and Fening–Longhua shear zones defines a stretching lineation and gives 40Ar/39Ar ages of 270–250 Ma, 250–230 Ma, 230–210 Ma, and 210–190 Ma. Deformation developed progressively from north to south between the Late Paleozoic and Triassic. Exhumation of lower crustal gneisses, high-pressure granulites, and granites occurred at the cratonic margin during post-ductile shearing (~220–210 Ma). An undeformed Early Jurassic (190–180 Ma) conglomerate overlies the deformed rocks and provides an upper age limit for reactivation and orogenesis. Deformation was induced by convergence between the southern Mongolia and North China cratonic blocks, and the location of this convergent belt controlled later deformation in the Yanshan Tectonic Province. This province formed as older E-W-trending Archean–Proterozoic sequences were reactivated along the northern margin of the NCC. This reactivation has features typical of cratonic basement reactivation: compression, crustal thickening, remelting of the mid to lower crust, and subsequent orogenesis adjacent to the orogenic belt.

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1. Introduction

Lithospheric thinning and reactivation through extension and rifting, and implications on the destruction of cratons have been addressed in several studies (e.g., Menzies et al., 1993; Tappe et al., 2007; Zhang, 2012). Reactivation or re-working along pre-existing structural zones or tectonic belts has also been documented (Holdsworth et al., 1997). Contraction and thickening due to crustal shortening and deformation are also important processes in the reactivation of cratons. In fact, this type of reactivation and orogeny is common and can extend across large areas of a craton. Reactivation and orogenic processes at cratonic margins in actively contracting settings are dominated by crust–mantle interactions. This study aims to determine the processes involved in the reactivation of cratonic basement, and describes orogenic features associated with this process, focusing on a case study from the northern margin of the North China Craton (Fig. 1).

The northern margin of the North China Craton (NCC) has been studied for more than 90 years (e.g., Wong, 1929; Cui and Li, 1983; Cui et al., 1985; Hebei Bureau of Geology and Mineral Resources, 1989; Zhao, 1990; Beijing Bureau of Geology and Mineral Resources, 1991; Wang, 1996; Zhang and Song, 1997; Kusky et al., 2007; Liu et al., 2011). There are contrasting views on the tectonic framework, evolution, and dynamics of development of the northern margin of the NCC. For example, it has been variously termed as an intraplate orogenic belt (Ge, 1989; Zhang and Song, 1997), a reactivated continental platform (Ren et al., 1990), an intracontinental orogenic belt (Wang, 1998), and the Inner Mongolian axis uplift (Ren et al., 1980). Detailed studies have examined the structure, sedimentary, volcanic and metamorphic history of several parts of the northern margin of the NCC (e.g., Bao et al., 1983; Beijing Bureau of Geology and Mineral Resources, 1991; Wang, 1996; Chen, 1998; Davis et al., 2001) as well as along the connected Yanshan Tectonic Belt (Fig. 1B; Wang, 1997; Davis et al., 2001).

Nevertheless, many unresolved problems remain, particularly regarding deformation prior to ~180 Ma (Davis et al., 2001), including the tectonic framework and the evolution of this intracontinental...
tectonic belt before the development of NE–SW-trending deformation at 160–150 Ma (Wang and Li, 2008). The key limitations on our understanding are the absence of (1) isotopic data to constrain the timing of development of the ductile shear zone and associated thrust system; (2) detailed structural evidence to constrain the timing of the deformation; and (3) detailed sedimentary evidence to help constrain the timescale of the evolution of the tectonic province. Furthermore, the transformation from a relatively stable craton to subsequent orogeny has not been clearly characterized.

In this paper, based on field investigations in the Yanshan area and along the southern margin of the Inner Mongolian Orogenic Belt, zircon U–Pb SHRIMP and LA-ICP-MS dating, together with muscovite, biotite,
and K-feldspar $^{40}$Ar/$^{39}$Ar chronology, we analyze the E–W-trending deformation and describe the characteristics and mechanisms of evolution of the northern margin of the NCC.

2. Geological characteristics

2.1. Tectonic setting

The northern margin of the NCC is bound to the south by the Xinglong–Qinglong Fault Zone, with a gradual transition into the stable continental region (Figs. 2 and 4), and to the north by the Kangbao–Weichang Shear Zone between the Inner Mongolian Orogenic Belt (the southern part of the Central Asian Orogenic Belt) and the Yanshan Tectonic Province (YTP). To the west, the craton merges into the Taihang Shan intracontinental mountain belt (TMB), trending NE–SW to NNE–SSW, and continues to connect with the Yinshan Tectonic Belt on the southern margin of the Inner Mongolian Orogenic Belt (Fig. 1). To the east, the reactivated craton forms a NE–SW-trending tectonic belt (Fig. 1).

Between the Inner Mongolian Orogenic Belt and the NCC, at least three distinct geological units are distinguished. From north to south these are: (1) a Late Paleozoic rift depression (?) between the Xilamulong River Fault Zone and the Kangbao–Weichang Shear Zone; (2) a long-lived uplift axis between the Kangbao–Weichang Shear Zone and the Chicheng–Gubeikou Fault Zone; and (3) the Yanshan Tectonic Belt between the Chicheng–Gubeikou Fault Zone and the present North China Craton (Fig. 1).

The Inner Mongolian Orogenic Belt, north of the YTP, began developing in the Early Paleozoic, with the major orogenic climax occurring in the Late Paleozoic. Convergence (Wang, 1996; Xiao et al., 2003, 2009) occurred between the Siberian and North China cratons in the Late Paleozoic–Early Mesozoic, forming E–W-trending ductile shear zones and providing an orogenic framework. The YTP is a transitional region between the Inner Mongolian Orogenic Belt and the NCC, possessing features of both active continental margin and stable craton (Chen and Chen, 1997). The northern margin of the NCC experienced orogenesis from the Late Paleozoic, producing an E–W-trending tectonic framework. This framework evolved further during the Late Paleozoic–Early Mesozoic, with tectonic shortening in the Inner Mongolian Orogenic Belt (discussed below). Although not discussed here, the YTP was also affected by tectonic changes associated with the West Pacific active continental margin, trending E–W in the west and curves round to a NE–SW trend in the east (Figs. 1A, B and 2).

Before the Mid Jurassic, N–S compression controlled the tectonic evolution, while after the Mid–Late Jurassic compression turned to NW–SE (Wang, 1996, 1998; Wang et al., 2011). The Yanshan Tectonic Belt (Fig. 2) is the type locality for the post Mid–Late Jurassic deformation, volcanic eruptions, and magmatism belong to the Yanshanian event (Wong, 1929) (Fig. 3). Given that deformation and tectonics related to the Yanshanian event developed after the Mid Jurassic, there is some confusion in the use of the term ‘Yanshan Belt’, which does not represent a specific deformation period. In this paper we define the Yanshan Tectonic Province (YTP) as the E–W-trending area from the Kangbao–Weichang Shear Zone to the present NCC (Fig. 2), and regard it as part of the northern margin of the NCC. The previously discussed Yanshan Tectonic Belt forms only part of the YTP.

2.2. Sedimentary, magmatic, and metamorphic rocks

Several rock types of different ages are exposed within the YTP, including uplifted Archean and Paleoproterozoic mid- and lower-crustal gneiss and granulite, and Paleozoic and Mesozoic sediments intruded by Late Paleozoic–Early Mesozoic granites. The older structures are covered mainly by Mesozoic volcanic rocks (Fig. 3).

At the northern margin of the NCC, E–W-trending Late Paleozoic–Early Mesozoic sedimentary rocks are exposed. These rocks show...
a transition from marine sedimentation in the rifted depression of the Inner Mongolian Orogenic Belt, to continental sedimentation (Fig. 3). The northern part of the YTP contains marine sediments related to those in the Inner Mongolian Orogenic Belt. From the Late Permian to the Mid Triassic, continental red-bed sedimentary facies were deposited contemporaneously with similar deposits in the Inner Mongolian Orogenic Belt. There is a disconformity between the Lower–Mid Triassic and the Upper Triassic–Lower Jurassic systems. Molasse-type sediments occur along the mountain front, consisting of pebbles derived from crystalline basement, indicating that Mesozoic deformation caused erosion of likely elevated areas and uplift of pre-Cambrian sediments and metamorphic rocks as part of the orogenic process which formed the YTP. Upper Triassic–Early Jurassic conglomerates contain pebbles of gneiss and granulite, whereas conglomerates in Lower and Mid Triassic strata contain no gneiss pebbles. An unconformable cover of Upper Triassic–Lower Jurassic conglomerate sediments rests on ductile shear zones, and on folded rocks and older sediments of various ages, indicating that the shear zones and fold structures were formed prior to the Late Triassic. U–Pb zircon dating of the sediments using LA-ICP-MS suggests that they were deposited after ~197 Ma (Liu et al., 2007, 2012).

Most of the outcrops consist of gneiss, granulite, granite, and granodiorite of various ages, together with some Meso-Neoproterozoic and Lower Jurassic sedimentary rocks. The gneisses and granulites are distributed throughout the YTP and are cut by several E–W ductile shear zones; e.g., the Fengning–Longhua ductile Shear Zone. Sedimentary strata of Meso-Neoproterozoic to Early Cretaceous age cover the Archean–Paleoproterozoic crystalline basement. Archean–Paleoproterozoic gneiss and granulite are exposed between the Kangbao–Weichang Shear Zone and the Damiao–Niangniangmiao Shear Zone (Fig. 4). Mesoproterozoic–Cambrian sedimentary rocks occur on the southern side of the Damiao–Niangniangmiao Shear Zone, and cover the entire NCC. Granodiorites formed in the north between 320 and 290 Ma (Fig. 4; Zhang et al., 2007, this study), and granites were intruded between 240 and 210 Ma at the southern margin of the YTP (Ma et al., 2007). The E–W-trending Nandaling Formation is composed of basalt erupted in the Mid Jurassic (~174 Ma; Zhao et al., 2006).
3. Structural framework

Prior to the Mid Carboniferous, there was little deformation in the Yanshan area and in the NCC, except for some uplift (Wang et al., 2010, and references therein). After this time, marine sedimentation decreased and coal-bearing sediments were deposited. Deformation in the YTP commenced during the Late Permian–Early Triassic. Three main ductile shear zones formed progressively from north to south, and folds developed. The YTP, which is divided from north to south by the shear zones into magmatic–volcanic provinces, includes a high-temperature region, a ductile shear region, and a folded region with northwards-inclined fold axial planes. The southern margin of the YTP is transitional between the YTP and the relatively stable North China Craton.

3.1. E–W-trending ductile shear zones

Ductile shear zones in the YTP, from north to south, are the Kangbao–Weichang, the Fengning–Longhua, the Damiao–Niangniangmiao, and the Chicheng–Fengning zones (Figs. 2 and 3). These have an E–W trend and dip to the north at 40°–85°. Shear fabrics within the shear zones have a top-to-the-south shear sense (Figs. 4–7). Microstructures include imbrication, mica fish, S–C fabric, and pressure shadows. Shearing lineations plunge to the north (350°–000°) at angles of 15°–80°. Shear bands occur parallel to the axial planes of shear folds, also indicating a top-to-the-south sense of shear. Ductile shear zones are identified by mylonitic gneiss, mylonitic granite, and quartz–feldspar–muscovite and carbonate mylonites. Their protoliths are mainly Archean–Proterozoic gneiss, and Paleozoic granite and metasediments.

3.1.1. Kangbao–Weichang ductile shear zone

This structural zone is also termed the northern marginal belt of the Inner Mongolia axis (Ren et al., 1980). It extends along approximately N42° longitude, and west into the Yinshan Tectonic Belt. The shear zone, where exposed, consists of granitic mylonite, quartz–feldspar–muscovite mylonite, and carbonate mylonite. The width of the zone varies from several meters to 3 km, and it is mostly covered by Tertiary–Quaternary sediments (Fig. 4A). The mylonitic foliation...
dips toward 350°–010°, at angles of 45°–60° (Figs. 5A, 6, 7A and B). Deformation structures, including S–C fabrics, inclined and recumbent folds, and sigma-type rotated potassium feldspar porphyroclasts show a top-to-the-south sense of shear. The shear zone cuts through gneiss, Proterozoic schist, granodiorite, and Neoproterozoic diorite (Fig. 7C). New growth of muscovite aggregates is elongated parallel to the stretching lineation.

3.1.2. Fengning–Longhua ductile shear zone

This shear zone has developed predominantly within gneisses and granulites, and cuts through a 320–290 Ma granodiorite and diorite (Figs. 4B, 5B and E). The foliation is vertical and stretching lineations plunge northwards at a high angle. Mylonite commonly contains muscovite and chlorite, indicating its formation during retrograde metamorphism of gneiss and other high-grade metamorphic rocks. Muscovite aggregates are abundant and elongated to define a stretching lineation. In mylonite, lineations and foliations are generally steep, but towards the north and south of the shear zone, foliation in the proto-mylonites has a lower angle of dip (30°–50°) and a stretching lineation plunges to the north.

S–C fabrics, shear folds, and rotated porphyroclasts show a top-to-the-south shear sense across the belt. In some areas, such as the Chicheng region, mylonite is covered by Mid–Early Jurassic coal-bearing sedimentary rocks. Along the shear zone, no strike-slip motion has occurred, but the rocks are cut by high-angle normal faults (Fig. 7G). Between the Kangbao–Weichang and Fengning–Longhua shear zones, there are several post-Mid Jurassic granitic plutons, but no E–W-trending shear zones with a top-to-the-south sense of shear.

3.1.3. Damiao–Niangniangmiao ductile shear zone

This structural zone is oriented sub-parallel to the Fengning–Longhua ductile shear zone. Proterozoic gabbro and diabase are exposed along the belt. These rocks are mylonitized and contain rotated hornblende and pyroxene porphyroclasts. The ductile shear zone cuts through gneiss and granulite, including a ~290 Ma granodiorite (this study), forming mylonitic granite, mylonitic gneiss, and quartz–feldspar mylonite (Figs. 6 and 7H–J). Typical microtectonic features are microfaults transecting feldspar porphyroclasts, oriented parallel to the lineation defined by aligned aggregates in granitic mylonite and recrystallized quartz ribbons (Fig. 7H–J). The dip of northward-dipping mylonitic foliation varies in different structural cross-sections, but

![Fig. 4 (continued).]
strectching lineations are of consistent orientation. Towards the west, the Damiao–Niangniangmiao shear zone is cut by the Chicheng–Fengning ductile shear zone, obscuring its further extension (Fig. 2). Mid–Early Jurassic coal-bearing sedimentary rocks cover the mylonite.

3.1.4. Chicheng–Fengning ductile shear zone
This ductile shear zone occurs mostly within gneiss, Archean high-temperature metamorphic rocks, and late Paleozoic magmatic rocks (Fig. 5F–G). Rotated hornblende porphyroclasts are apparent, and muscovite aggregates define a stretching lineation. Quartz–feldspar–muscovite mylonite contains aligned K-feldspar porphyroclasts that define a stretching lineation. The foliation in the mylonite dips northwards at 45°–60° (Fig. 7D–F). Drilling data in the Chicheng area, as well as profile sections from geophysical and surface investigations, show that the ductile shear zones extend towards the north as low-angle ductile shear planes (Wang, 1996).

3.2. E–W-trending folding at the northern margin of the NCC
Folds occur in layered sediments deposited since the Neoproterozoic; mylonites or ductile shear zones do not cross layered sediments (Fig. 6). Folds in older sediments (e.g., Meso–Neoproterozoic age) and metamorphic units (Archean and Paleoproterozoic age; e.g., Shi et al., 2012) are inclined to recumbent, and the axial planes are parallel to the mylonite.
foliation (Fig. 7K–L). In the Upper Cambrian to Triassic sandstone, limestone and shale, the folds are box-folds and have inclined axial planes. Few thrust faults occur in the fold belt. Generally, since the Triassic, Cambrian–Triassic strata were deformed only by folds with cleavage parallel to their axial planes. This is similar to folds found in the ductile shear zones, suggesting that the two sets of folds formed under similar kinematics. The characteristics of the folds vary with depth and from north to south. The southern part of the YTP (in the Chicheng, Chengde, and Xinglong areas) contains box-folds and folds with southward-dipping axial planes (Fig. 6).

Mesoproterozoic–Triassic strata were involved in shear deformation-related folding. Fold axes trend at approximately 270°. Below Ordovician strata, cleavage is parallel to fold axial planes, and flow cleavage is developed within Meso-Neoproterozoic strata. The cleavage dips towards 350°, at angles of 50°–60°. Most of the folds are south-vergent and have steep axial planes. Some small-scale inclined and recumbent folds also occur within the strata layers. Folding deformation decreases in intensity from north to south, and then is lost in the interior of the North China Craton. Mesoscopic folding is spectacularly exposed within Meso-Neoproterozoic strata, and may involve Cambrian–Triassic strata. Towards the south, in the eastern YTP, E–W-trending open folds have dominantly vertical axial surfaces. Folds are accompanied by small-scale thrust faults within beds and along flexural slip planes. Box-folds occur only in the southern part of the YTP.

3.3. Deformation characteristics

Ductile shear zones cut through Archean and Paleoproterozoic metamorphic rocks such as granulites, gneisses, and migmatites, and some Carboniferous–Early Permian (320–290 Ma) granites and granitoids. Triassic (240–210 Ma) granites in the southern YTP are not deformed (Figs. 4–6). Other mylonites are developed in mica granite with hornblende porphyroclasts. Retrograde metamorphism occurred where ductile shear zones cut through gneiss, while mylonites are surrounded by metamorphic rocks. In some thin-sections, hornblende and K-feldspar occur as rotated porphyroclasts, while muscovite, biotite, chlorite, and quartz occur as newly crystallized minerals. The textures of quartz and feldspar (Fig. 7A and B) indicate that deformation occurred at temperatures of >420–450 °C (e.g., Passchier and Trouw, 2005). The mylonitized rocks are assigned to the upper greenschist facies, indicating temperatures of >400–450 °C. Granites and gneisses in the YTP occur as lenses surrounded by mylonites, indicating that the crystalline basement of the North China Craton was involved to some extent in ductile shearing and orogenic deformation, and was cut by shear zones only when deformation resulted in mechanical instability. Fluid circulation caused recrystallization, leading to ductile behavior and crystallization of hydrous minerals such as muscovite and chlorite. The basement was involved in deformation only as unaltered blocks transported passively along the ductile shear zones. Folds in the cover layers of Paleozoic–Mesozoic strata are unrelated to those within the ductile shear zones, and differ in their fold style.

Newly crystallized, elongated muscovite flakes in mylonites define a stretching lineation in the shear zones, which plunges steeply to the north. However, muscovite was not part of the original mineral composition of the protolith granite, diorite, and gneiss, suggesting that it formed during ductile shear deformation and mylonitization.

4. Isotope geochronology

4.1. Sampling and analytical methods

The U–Pb zircon ages of the granite and granodiorite protoliths, together with 40Ar/39Ar dating of muscovite in mylonites, can help constrain the timing of formation of the ductile shear zones. We selected 22 samples from the northern margin of the NCC for zircon U–Pb SHRIMP and LA-ICP-MS analysis, and to obtain muscovite, biotite and K-feldspar 40Ar/39Ar plateau ages (the sample locations are shown in Fig. 4). Zircon U–Pb SHRIMP and 40Ar/39Ar dating methods used in
this study are described by Wang (2006) and Wang and Li (2008). The samples were analyzed at the Tianjin Institute of Geology and Resources, and Beijing SHRIMP Center, China, using LA-ICP-MS and SHRIMP to obtain zircon U–Pb ages. Cathodoluminescence (CL) images of zircons were obtained before performing geochronological analyses. LA-ICP-MS analyses and laboratory procedures followed Liu et al. (2004). LA-ICP-MS zircon U–Th–Pb measurements used spot sizes of ~35 μm on single grains. The zircon standard TEMORA was analyzed every 5 analyses as an external control for age calculations, and NIST SRM610 was analyzed twice every 20 analyses for calculations of U, Th, and Pb concentrations for the LA-ICP-MS dating. Ages were calculated using ISOPLOT 2.31 (Ludwig, 2000).

Fig. 7. Structures and microstructures in the Yanshan Tectonic Province. (A) Mylonitized granite with north-dipping foliation. Rotated feldspar porphyroclasts and recrystallized quartz show top-to-the-south sense of shear in the Kangbao–Weichang ductile shear zone, from where sample wys-52 was collected. (B) Microstructures with recrystallized quartz and newly formed muscovite that is elongated and aligned to define a stretching lineation. The section is cut parallel to the aggregate lineation and normal to the foliation. These structures are from the same thin-section as shown in (A). (C) Strongly deformed Proterozoic mica-schist from an area of south-vergent ductile shearing. Mica kink-bands show dextral shear, as also seen for the Kangbao–Weichang ductile shear zone. Sample wys-61 was collected from this locality. (D) Granite and quartz–feldspar mylonite, with north-dipping foliations. Rotated feldspar porphyroclasts from the Chicheng–Fengning ductile shear zone indicate a top-to-the-south shear sense. Sample wys-32 was collected from this locality. (E) Rotated feldspar surrounded by quartz and muscovite in the same thin-section as that shown in (D). The section has been cut parallel to the aggregate lineation and normal to the foliation. (F) Sub-vertical stretching lineations within mylonitized granite. The lineations plunge northwards. In thin-section, biotite and elongate recrystallized muscovite flakes define the stretching lineation. Along the Chicheng–Fengning and Fengning–Longhua ductile shear zones, the stretching lineation plunges at a high angle and the foliation dips to the north. Sample wys-27 was collected at this locality (the Chicheng–Fengning shear zone). (G) Recrystallized quartz bands and neoblasts of sericite defining the stretching lineations with sinistral shear sense. The sample is from the Damiao–Niangniangmiao ductile shear zone. Sample wys-181 was collected at the same site. (K) Recumbent folds involving Paleoproterozoic schist and gneissic rocks on the footwall of the south-vergent Fengning–Longhua ductile shear zone. (L) Inclined folds involving Meso–Neoproterozoic sedimentary rocks. The axial surfaces of the folds dip to north on the south side of the ductile shear zone, close to the North China Craton interior.
SHRIMP and LA-ICP-MS U–Pb and ⁴⁰Ar/³⁹Ar data are listed in Supplementary materials 1 and 2, and summarized in Table 1. U–Pb concordia and part of ⁴⁰Ar/³⁹Ar plateau ages are shown in Figs. 8 and 9.

4.2. Results of zircon U–Pb SHRIMP dating

Sample WYS-27, collected from mylonitized granite along the Chicheng–Fengning shear zone, contains zircons that, based on cathodoluminescence (CL) imaging, do not exhibit significant sector zoning. Core and rim analyses of single zircons yield contrasting ages. One older spot age of 1092 Ma represents inherited zircon. Sixteen of the 20 analyses of this sample yielded a single age group that spreads slightly along the concordia, yielding a mean ²⁰⁶Pb/²³⁸U age of 291 ± 5 Ma (Early Permian), interpreted the age of the granitic intrusion.

Sample WYS-181, a biotite–granite mylonite collected from the Damiao–Niangniangmiao shear zone, yields zircons with oscillatory zoning. The contact between the rim and core is not sharp for some individual grains, and we obtained a rim-weighted-mean ²⁰⁶Pb/²³⁸U age of 227 ± 1 Ma (Late Triassic) and a core weighted ²⁰⁶Pb/²³⁸U mean age of ~1983 Ma. Another sample, wys-443, was collected from an E–W-trending granitic porphyry dyke, oriented parallel to fold axial planes. The zircons are complex, with several grains showing oscillatory zoning and others with no zoning features. Four zircon grains yielded a ²⁰⁶Pb/²³⁸U apparent age of...
4.4. Results of $^{40}$Ar/$^{39}$Ar dating

4.4.1. Ductile shearing and syn-kinematic muscovite along the Kangbao–Weichang shear zone

Five muscovite samples wys-48, -51, -53, -59, and -61, were collected from mylonitized granite and carbonate mylonite in the E–W-trending Kangbao–Weichang shear zone. Elongated mica crystals define a stretching lineation. Samples wys-48, -51, and -53, from a mylonitized granite and a quartz-feldspar mylonite, gave weighted mean plateau ages (WMPA) of 269 ± 1 Ma, 264 ± 1 Ma, and 265 ± 1 Ma (Mid Permian), respectively. These ages are within error of their isochron age. Sample wys-59, separated from deformed quartz schist within the Kangbao–Weichang ductile shear zone (with feldspar–quartz–muscovite muscovite), yielded a WMPA age of 263 ± 1 Ma, similar to the isochron age of 265 ± 3 Ma. Sample WYS-61, collected from a carbonate mylonite in the eastern extension of the shear zone, gave a WMPA of 255 ± 1 Ma and an isochron age of 255 ± 3 Ma (Late Permian).

4.4.2. Syn-kinematic muscovite along the Fengning–Longhua ductile shear zone

We collected six samples of syn-kinematic muscovite from two locations along the Fengning–Longhua ductile shear zone. Three muscovite samples, wys-8, -10, and -11, from mylonite and proto-mylonite, yield WMPA ages of 243 ± 1 Ma, 249 ± 1 Ma, and 252 ± 1 Ma, respectively. These ages are identical, within error, as isochron ages of 244 ± 1 Ma, 251 ± 3 Ma and 250 ± 2 Ma, respectively. Another three muscovite samples, wys-82, -83, and -84, were collected in the eastern segment of the Fengning–Longhua ductile shear zone, from mylonite and proto-mylonite with a foliation dipping at a moderate angle and a top-to-the-south shear sense. These samples yielded WMPA ages of 252 ± 1 Ma, 248 ± 1 Ma, and 251 ± 1 Ma (Late Permian–Early Triassic), respectively, similar to their isochron ages of 250 ± 2 Ma, 248 ± 10 Ma, and 250 ± 0.4 Ma (Early Triassic).

Another two muscovite samples, wys-6 and wys-24, were collected from muscovite–quartz dykes located in the footwall of the Fengning–Longhua ductile shear zone, at 200–500 m away from the shear zone itself. These yield a WMPA age of 277 ± 1 Ma and a preferred age (PA) of 287 ± 1 Ma (Early Permian), consistent with the isochron ages. We interpret these two ages as the cooling ages of the muscovite–quartz dykes, constraining the exhumation of the crystalline basement from the northern margin of the North China Craton.

4.4.3. Syn-kinematic muscovite and magmatic biotite in the Chicheng–Fengning ductile shear zone, and K-feldspar from post-deformation cooling

Three samples of syn-kinematic muscovite were collected from a mylonitized granite in the Chicheng–Fengning ductile shear zone. Sample wys-32Mus, collected near Chicheng Town, yielded a WMPA age of 234 ± 1 Ma (Mid Triassic), which is similar to its isochron age of 233 ± 1 Ma, and yields a $^{40}$Ar/$^{36}$Ar intercept of 296 ± 19. One K-feldspar sample, wys-32K (from the same hand sample as wys-32Mus), from mylonitized granite yields a plateau age at high-temperature steps (~48% $^{39}$Ar released) of 180 ± 1 Ma. The $^{40}$Ar/$^{36}$Ar intercept is lower than 295.5, indicating argon loss. Thus, we interpret 180 ± 1 Ma (Early Jurassic) as a cooling age. Samples wys-4Mus and -5Mus, collected close to each other east of Fengning Town, have sub-vertical stretching lineations and yield WMPA ages of 235 ± 1 Ma and 237 ± 1 Ma, respectively, which are within error of their isochron ages. One K-feldspar sample, wys-4K, yielded serially increasing ages. The data do not define a flat plateau, and >70% $^{39}$Ar released from moderate- to high-temperature steps yields apparent ages from 135 to 150 Ma (Late Jurassic–Early Cretaceous). We interpret these K-feldspar spectra as a plateau age disturbed after ductile shearing.

One biotite sample from the Chicheng–Fengning ductile shear zone, wys-27Bio, was collected from granitic mylonite with a NE–SW-striking foliation and a N–S-trending lineation. This sample yields internally discordant step ages and shows a PA age of 240 ± 2 Ma, similar to its isochron age of 239 ± 3 Ma. The country rock is
mylonitized granodiorite; we therefore assume the PA is an estimate for the cooling age of the mylonite.

4.4.4. Age constraints for folding in the Yanshan Tectonic Province

On the southern side of the Xinglong Fault, and at the eastern and western extensions of the fault, open folds with inclined axial planes are developed. These folds formed between 220 and 200 Ma (Late Triassic; muscovite 40Ar/39Ar dating) in the West Hills of Beijing (this area represents the western extension of the YTP; Wang et al., 2011). To the southwest of the Xinglong Fault, Late Triassic granitic plutons with zircon U–Pb SHRIMP ages of ~210 Ma (Ma et al., 2007) intruded folded Proterozoic strata. Two muscovite samples, D04-02 and D04-04, collected from the contact between metamorphic rocks and unmetamorphosed limestone, yielded identical PA and WMPA ages of 207 ± 1 Ma (Late Triassic), within error of isochron ages. We interpret the age of 207 ± 1 Ma as a contact-metamorphism cooling age, constraining the upper age limit for the folding. On the northern side of the Xinglong Fault, granitic and granitic porphyry dykes, oriented parallel to fold axial planes, intruded an area with south-vergent inclined folds. These dykes yield zircon U–Pb

Fig. 8. U–Pb zircon SHRIMP ages of mylonite protoliths and LA-ICP-MS ages of granite and granitic porphyry dykes in the Yanshan Tectonic Province. (1) Sample WYS-27, (2) sample WYS-181, (3) sample wys-454, and (4) sample wys-443. Inset photos are selected zircon CL images.

Fig. 9. Two muscovite 40Ar/39Ar plateau ages. Other muscovite, biotite, and K-feldspar plateau and isochron ages are available from Supplementary material 2. M, muscovite; WMPA, weighted mean plateau age.
LA-ICP-MS ages of 203 ± 8 Ma and 227 ± 1 Ma, suggesting that the folds were formed at or prior to ~203 Ma.

4.5. Sequence of events in the Yanshan Tectonic Province

4.5.1. Age interpretations

We can distinguish overprinting mylonite and ductile shear zones from pre-existing mylonite in the gneiss and granulite. Newly formed mylonite has clear, recrystallized quartz, mica-fish, recrystallized quartz ribbons, and muscovite oriented parallel to the stretching lineation, regardless of the orientation of the foliation. These features show that the mylonite was formed in the mid to upper crust (greenschist facies), rather than deep crustal levels, during ductile shearing. In the pre-existing mylonite, there is no new growth of muscovite, the quartz has undergone recovery and no lineation is apparent. In the gneiss mylonite, there is a high rate of recovery in quartz grains, indicating static recrystallization. Striped gneiss, composed of alternating layers of recrystallized feldspar and quartz ribbons, may have developed during formation of the craton basement. Some quartz ribbons comprise single crystals oriented parallel to the gneissic schistosity, but not to the ductile shear foliation or the lineation defined by aligned muscovite grains. The mylonite occurs as muscovite–quartz–feldspar mylonite, granitic mylonite, and carbonate mylonite along ductile shear zones at the northern margin of the North China Craton. Mylonite protoliths are gneiss, granite, granodiorite, and carbonate or marble. The ductile shear zones cut through Archean (Wang, 1996); (2) convergence in the Okhotsk Sea in Far East Asia between the Siberian and North China (or Sino-Korean) plates (Davis et al., 2001); and (3) compression and magmatic upwelling (Davis et al., 2001; Zhang et al., 2010; Wang et al., 2011). Compression associated with the formation of the YTP has been explained in terms of: (1) formation of the Inner Mongolian Orogenic Belt and collision between the Siberian and North China (or Sino-Korean) plates (Wang, 1996); (2) convergence in the Okhotsk Sea in Far East Asia (Davis et al., 2001); and (3) compression and magmatic upwelling in the Inner Mongolian Orogenic Belt. None of these hypotheses provides a satisfactory explanation for the intracontinental YTP, given the overprinting of the E–W-trending tectonic framework by a later event.

4.5.2. Timing of reactivation and orogeny along the northern margin of the NCC

The age data from zircon, muscovite, biotite, and K-feldspar suggest that the northern margin of the NCC was deformed by E–W-trending shear zones, intruded by granites, and crystalline basement was exhumed between 310 Ma and 180 Ma (Late Carboniferous to Early Jurassic) (Fig. 10). Zircon U–Pb SHRIMP dating shows that the deformed granodiorite and diorite were intruded between 310 and 290 Ma (Late Carboniferous–Early Permian). This age constrains the lower limit of the timing of E–W-trending, south-vergent folds, and mylonitization. Muscovite crystals that define stretching lineations yield 40Ar/39Ar ages of 270–210 Ma (Mid Permian–Late Triassic), becoming younger from north to south. This result indicates that the four ductile shear zones, Kangbao–Weichang, Fengning–Longhua, Damiao–Niangniangmiao and Chicheng–Fengning, have formed progressively from north to south, at 265–255 Ma, 250–245 Ma, and 235–230 Ma, and the folding deformation occurred prior to ~203 Ma (Fig. 11A). The K-feldspar cooling age of ~180 Ma shows that the mylonite and the crystalline basement were exhumed and uplifted after 200 Ma. Mylonites and gneiss were unconformably overlain by ~190 Ma Late Triassic–Early Jurassic sedimentary rocks (Hebei Bureau of Geology and Mineral Resources, 1989; Liu et al., 2007, 2012), and by 180–175 Ma basaltic lavas (e.g. Zhao et al., 2006). After ~180 Ma, a tectonic trend change from E–W to NE–SW affected eastern part of the tectonic belt (Fig. 2). These findings indicate that exhumation of the YTP occurred prior to ~180 Ma.

5. Discussion

The origin and evolution of the YTP remain controversial (e.g., Ren et al., 1990; Zhang et al., 2010; Wang et al., 2011). Compression associated with the formation of the YTP has been explained in terms of: (1) formation of the Inner Mongolian Orogenic Belt and collision between the Siberian and North China (or Sino-Korean) plates (Wang, 1996); (2) convergence in the Okhotsk Sea in Far East Asia (Davis et al., 2001); and (3) compression and magmatic upwelling in the Inner Mongolian Orogenic Belt. None of these hypotheses provides a satisfactory explanation for the intracontinental YTP, given the overprinting of the E–W-trending tectonic framework by a later event.

![Fig. 10](image-url). Summary of U–Pb zircon and 40Ar/39Ar plateau ages, showing timing sequences of granitic intrusions, deformation, cooling and erosion.
NE–SW structural trend that formed later than the Mid Jurassic (Ren et al., 1990; Zhao et al., 1994; Wang, 1996; Wang and Li, 2008; Wang et al., 2011). Any model for the formation of the YTP has to account for more regional tectonic changes, such as the tectonic evolution of the Inner Mongolian Orogenic Belt, the evolution of the West Pacific Plate, and the related tectonics of the active continental margin in eastern China (discussed in detail in a forthcoming contribution). In the YTP, both thick- and thin-skinned deformation occurred together, with both controlled by N–S directed compression.

As a transitional region between the Inner Mongolian Orogenic Belt and the NCC (Fig. 11), the YTP is different from other collisional zones or subduction-related orogenic belts (e.g., Coward and Ries, 1986). The structural geometry of the YTP is not consistent with simple thin-skinned or thick-skinned deformation, and we regard the YTP as the reactivated margin of the North China Craton.

5.1. Reactivation and orogenesis of the northern margin of the NCC

The reactivation of the NCC occurred during the formation of an orogenic belt with south-vergent, north-dipping folding and thrusting in a ductile shear system with contemporaneous uplift of crystalline basement and crustal erosion (Table 2).

Significant granite and granodiorite magmatism occurred in the area between ~320 and 290 Ma, resulting in intrusive bodies being emplaced into the northern margin of the NCC; this magmatism also remelted and weakened the basement crystalline rocks through thermal and fluid input. During and after the extensive deformation and south-vergent compression in the region, another suite of granite and granitic dikes was emplaced between ~240 and 205 Ma; these dikes were not deformed during the ductile shearing event, but are folded, especially in the southern part of the YTP, which was subjected to thin-skinned deformation.

The YTP was extensively deformed from the Late Paleozoic onwards (Figs. 12–13). The kinematics of E–W-trending ductile shear systems, with top-to-the-south shear senses, are similar to those in the southern segment of the Inner Mongolian Orogenic Belt, although the tectonic framework of the belts differs (e.g., Wang, 1996). Similar to the northern margin of the NCC, which underwent southward-inclined folding and thrusting (Fig. 11B), the southern segment of the Inner Mongolian Orogenic Belt trends E–W and is southward-inclined (Figs. 1B, 11B, and Table 2; Wang, 1996, and references therein), although the two areas differ in terms of the degree of shortening-related tectonic stress and tectonic evolution. However, given these similarities, we strongly suggest that the thick-skinned, and some of the thin-skinned, deformation in the YTP during the Triassic and Early Jurassic was related to coeval deformation in the Inner Mongolian Orogenic Belt.

Ductile shearing took place in the YTP between 270 and 210 Ma, with folding between ~220 and 200 Ma (this study; Wang et al., 2011), with K-feldspar cooling ages from mylonites indicating exhumation between 200 and 180 Ma. Undeformed Late Triassic–Early Jurassic sedimentary basins (e.g., Liu et al., 2007, 2012, and references therein) constrain the upper age limit of this exhumation to before ~180 Ma (Fig. 12). During ductile shearing and folding that produced E–W and later NE–SW-trending structures, Archean–Palaeoproterozoic high-grade metamorphic rocks (e.g., Zhai and Liu, 2003; Kusky et al., 2007) were uplifted and exhumed on the northern margin of the

Table 2

Processes of cratonic reactivation and orogeny of the Northern margin of the North China Craton.

<table>
<thead>
<tr>
<th>series</th>
<th>Isotopic ages</th>
<th>Deformation/magmatism/sedimentation</th>
<th>Contributions to the cratonic reactivation and subsequent orogeny</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>320–290 Ma (U–Pb)</td>
<td>Granitic and granodioritic intrusions</td>
<td>Thermal softening</td>
</tr>
<tr>
<td>2</td>
<td>270–210 Ma (40Ar–39Ar)</td>
<td>Ductile shear zones with a 'top-to-the-south' shear sense, deformation developed progressively from north to south</td>
<td>Crustal shortening and thickening</td>
</tr>
<tr>
<td>4</td>
<td>240–210 Ma (U–Pb)</td>
<td>Granitic intrusions</td>
<td>Syn- and post-orogeny thermal event</td>
</tr>
<tr>
<td>5</td>
<td>210–180 Ma (40Ar–39Ar)</td>
<td>Erosion and sedimentation</td>
<td>Exhumation, end of cratonic reactivation</td>
</tr>
</tbody>
</table>

In the table, U–Pb data are from Zhang et al. (2010) (240–210 Ma), Liu et al. (2006) (210–180 Ma), Ma et al. (2007) (210 Ma), and this study.
NCC. This exhumation of basement along E–W-trending structures was directly related to top-to-the-south ductile shear deformation and shallow south-vergent folding, confirming that ductile shearing was a major control on the exhumation and uplift of cratonic crystalline basement during orogenesis. Exhumation of high-grade metamorphic rocks is spatially variable in the YTP, and occurred as part of the late Paleozoic–Mesozoic tectonic evolution of the area; granulites are exposed in regions where NE-SW-trending structures developed after ~180 Ma, overprinting E–W-trending structures. Within both E–W and NE–SW-trending structural belts, basement metamorphic rocks retain an E–W-trending lineation and gneissic banding (Fig. 2).

In the YTP, deformation was dominated by ductile shearing, but post-shearing and post-extensional magmatism also significantly influenced the structural evolution of the region. In this area, Late Triassic–Early Jurassic sedimentary basins discordantly overlie folded rocks, dominantly in synclines and faulted basins, and basinal conglomerate deposits are dominated by gneissic and mylonitic pebbles derived from the underlying basement. In addition, basaltic magmas erupted during the Mid–Early Jurassic along the southern margin of the YTP (e.g., Zhao et al., 2006), with the subsequent deposition of coal-bearing sediments in basins formed above the basalts. These coal-bearing sediments were deposited along the southern margin of the Inner Mongolian Orogenic Belt, in the core of the YTP, and throughout the northern part of eastern China. The deposition of coal-bearing sediments during the Middle–Early Jurassic marks the end of the Inner Mongolian Orogeny, and also the end of cratonic reactivation and orogeny at the northern margin of the NCC.

The YTP formed a transitional tectonic belt between the continental margin and interior during Late Paleozoic–Late Triassic reactivation of the craton, thereby forming part of an orogenic belt. Geophysical and geochemical data indicate that the YTP forms a transition zone between the Inner Mongolian Orogenic Belt and the NCC (e.g., Ma et al., 1991; Bai et al., 1993; Wang, 1996; Chen and Chen, 1997).

In summary, the main orogenic features of the reactivated northern margin of the NCC are as follows. (1) The relatively stable crystalline basement was reactivated between the Late Permian and Early Jurassic to form an E–W-trending tectonic belt in response to south-vergent, north-dipping ductile shearing of the crystalline basement. This belt formed at the same time as the Inner Mongolian Orogenic Belt, which was controlled by Late Paleozoic convergence between the southern Mongolia and North China cratonic blocks. This tectonic evolution is not typical of foreland deformation or intraplate orogeny, but here is...
defined as a craton-margin orogeny. (2) Basement metamorphic rocks and sedimentary cover were deformed together between the Late Permian and Triassic. E–W-trending structures, such as ductile shear zones, folds, and basins, developed on the continental margin and formed an E–W-trending tectonic framework. These structures and features of basement deformation are different from those formed in an intraplate environment (e.g., Chase et al., 1993; Evans, 1993; Narr, 1993; Schmidt et al., 1993). (3) Voluminous granitic and granodiorite magmatism occurred prior to extensive south-vergent ductile deformation and folding; syn- and post-deformation granites and granitic dykes were also emplaced along the E–W-trending tectonic belt. After deformation and magmatism, exhumation and crustal uplift occurred along the entire YTP.

5.2. Mechanical constraints on reactivation and orogeny of the northern margin of the NCC

The Qinling–Dabie Orogenic Belt is separated from the YTP by the North China cratonic block (Fig. 1A) and underwent collisional tectonics during the Mesozoic (240–190 Ma; e.g., Ratschbacher et al., 2000, 2003). It should be noted that contemporaneous deformation and sedimentation in the YTP were not related to this collision. Initial subduction of the West Pacific Plate at >1200 km from the YTP also occurred after ~180 Ma (Bartolini and Larson, 2001; Wang and Li, 2008) and strongly influenced the eastern extension of the northern margin of the NCC during the Mid Jurassic to Late Cretaceous (e.g., Davis et al., 2001; Wang and Li, 2008; Zhu et al., 2011).

To determine the formation mechanism of the E–W-trending tectonic framework of the YTP between 270 and 210 Ma, it is necessary to establish the origin of regional compression. The N–S compression and extension that formed E–W-trending structures were due to convergence between the southern Mongolia and North China cratonic blocks, resulting in formation of the Inner Mongolian Orogenic Belt during the Late Paleozoic–Early Mesozoic (Wang, 1996; Xiao et al., 2003). Between 270 and 210 Ma, both the Inner Mongolia Orogenic Belt and the northern margin of the North China Craton underwent voluminous granite intrusive magmatism that initiated in the north and progressed south (e.g., Chen et al., 2009; Zhang et al., 2010) (Fig. 13). During this period, the Inner Mongolia area underwent intercontinental deformation and contraction that progressed from north to south; i.e., from the orogenic belt to the cratonic margin, causing significant metamorphism and magmatism. The focus of deformation moved...
from the margin to the interior of the craton between 270 and 210 Ma, and granite plutons were intruded between 250 and 205 Ma (Ma et al., 2007; Zhang et al., 2010). The formation of the Inner Mongolian Orogenic Belt can be related to convergence between the southern Mongolia and North China cratonic blocks, with features later overprinted by those associated with the subduction of the West Pacific Plate (Davis et al., 2001; Wang and Li, 2008). Tectonic transmission may have involved syn-tectonic magmatic flow (Zhou and Wang, 2012) or ductile shearing that progressed from north to south, and from the convergent zone to the continental margin or interior was responsible for the reactivation and orogenesis of the northern margin of the NCC between 320 and 210 Ma (Fig. 12 and Table 2; based on U–Pb zircon dating of magmatic rocks).

Even though deformation of the YTP was driven by convergence between the Mongolian arc (or micro-block) and the North China cratonic block (Wang, 1996; Xiao et al., 2009), foreland molasse basins have not been found in the northern YTP, which most likely represents a palaeo-active continental margin (Bachmann et al., 1987; Baby et al., 1992). This indicates that the northern margin of the NCC was not directly linked to a collisional or subduction zone, but instead may have been influenced by far-field stress related to arc–continent collision between the North China and Siberian plates (Fig. 13).

5.3. Tectonic evolution from craton to orogeny: the northern margin of the NCC

The recent studies indicate that lithospheric thinning or cratonic separation was responsible for craton reactivation (Holdsworth et al., 1997; Tappe et al., 2007); however, this is only part of the cratonic reactivation process, as contractional deformation and orogenesis of cratonic basement rocks are also important processes that can drive craton reactivation or destruction. The basic features of cratonic reactivation include a cratonic margin or interior with orogenic features in the middle and/or upper crust, with thick-skinned deformation followed by magmatism and exhumation of cratonic basement. This indicates that, in order for cratonal lithosphere to be reactivated, the deep roots of the northern margin of the NCC must have been removed or remobilized.

Between 320 and 290 Ma, the North China cratonic margin was intruded by southward-flowing granodiorite and diorite magmas (Zhang et al., 2007; Zhou and Wang, 2012). Partial melting of the basement occurred, resulting in local lithospheric weakness that enabled contractual ductile shearing and folding; this contraction occurred progressively from the cratonic margin towards the interior, uplifting the basement and exhuming the northern margin of the NCC. Post-exhumation erosion and sedimentation (Liu et al., 2007, 2012), with significant alkaline magmatic activity (230–210 Ma; Zhang et al., 2010), occurred from the Inner Mongolia Orogenic Belt to the margin of the North China Craton. In addition, the lower crustal layer of the northern margin of the North China Craton underwent thermal softening and weakening between 320 and 200 Ma by partial re-melting, ductile shearing, and extensive folding. All of these processes are indicative of crustal shortening and thickening. The basement was then exhumed and eroded, followed by sedimentation and basin formation, and further alkaline magmatism, representing ongoing extension and lithospheric thinning. This sequence of events is typical of the processes that occur during cratonic reactivation and subsequent orogenesis. In summary, cratonic reactivation of the northern margin of the NCC and subsequent orogenesis involved: (1) thermal softening; (2) crustal shortening and thickening; and (3) exhumation with local extension (Fig. 12).

The dominant structural features of the YTP suggest that the type and extent of deformation in this time period differed between the lower and upper crust, probably due to the different nature of the crystalline basement and sedimentary cover sequences in the Yanshan crust. This is evidenced by folding of the Cambrian–Permian and Triassic sedimentary cover, whereas ductile shearing with minor folding is present in the deformed crystalline basement. The deformation between the southern and northern boundaries of the YTP is, in general, different from the deformation style observed within other orogenic belts or intraplate deformation zones. In the YTP, deformed layers are predominantly found in the upper (3–10 km depth) and middle–upper (16–22 km) crust; these sections of the crust were susceptible to ductile shearing and indicate progressive development of the tectonic province from north to south and from deeper to shallower. Ductile shearing was accompanied by folding caused by the incorporation of basement rocks at the continental margin, and is unique to the YTP.

The following features are typical of reactivation and orogenic processes in the northern margin of the NCC. (1) The craton was reactivated by destruction of the Inner Mongolian Orogenic Belt to the north of the North China Craton. The crystalline basement of the craton was deformed and uplifted, with deformation and magmatism suggesting that the craton changed from relatively stable to a region undergoing orogenesis by thermal softening, crustal shortening, and thickening, followed by exhumation. (2) No foreland basins or relic ophiolites exist along the cratonic margin, and the spatial and temporal distribution of deformation suggests vergence and evolution from north to south, from the crystalline basement to sedimentary cover, and from the cratonic margin to the interior.

5.4. Typical cratonic reactivation and subsequent orogeny at a cratonic margin

Cratons are considered to be the stable nuclei of continents and represent regions of the earth’s crust over 2.5 billion years old, with low geothermal gradients (De Wit et al., 1992). Deformation of cratonic crust has been termed as reworking, or reactivation (Holdsworth et al., 1997, 2001). Reactivation includes deformation, magmatism, or metamorphism along pre-existing orogenic belts (Holdsworth et al., 1997; Stewart et al., 1997; Hand and Sandiford, 1999; Ross and Eaton, 1999) or structural zones, such as those involved in the reworking of the Gawler Craton (Dutch, 2009). In general, both tectono-thermal evolution and deformation are important processes during cratonic reactivation or destabilization (Holdsworth et al., 1997, 2001; Ligeos et al., 2012). Reactivation of cratonic basement rocks would change lithospheric mantle conditions and therefore affect the tectono-thermal evolution of a region.

The current definition is that reworking or reactivation of a craton along pre-existing structures or existing orogenic belts occurs at the time when continental lithosphere is modified by the repeated focusing of deformation or magmatism and metamorphism in the same area (Holdsworth et al., 1997), with some reworking or reactivation occurring in either the core of the craton or in surrounding areas (van der Pluijm et al., 1997; Harman et al., 1998; de Boisgrollier et al., 2009). Continental reworking or reactivation is intrinsically linked with two significantly different processes: ductile shearing and deformation at depth, and magmatism related to melting of the middle to lower crust or the cratonic crystalline basement. In some cases, reactivation is related to extension or thinning of the lithosphere, for example during faulting or shear movement with differing displacements along pre-existing structures (Holdsworth et al., 1997; Tappe et al., 2007). These features typify reactivation, for example during displacement of the South American and Africa continents around ~130 Ma (Harman et al., 1998), extension of the Basin and Range Province in the west of the North American Craton (Colgan et al., 2006), and intracontinental or intraplate deformation, for example within the Australian (Hand and Sandiford, 1999) and eastern European cratons (Nikishin et al., 1996), although such features were not formed during reactivation of the Siberian craton adjacent to the Central Asian Orogenic Belt (CAOB; De Boisgrollier et al., 2009).
Table 3
Summary of the features developed during, and processes associated with, reactivation and subsequent orogeny of a craton, and comparison with features that formed during the development of reactivated fault zones or cratonic reactivation associated with extension and lithospheric thinning.

<table>
<thead>
<tr>
<th>Features of cratonic reactivation</th>
<th>Classification of cratonic reactivation</th>
<th>Reactivation and subsequent orogeny</th>
<th>Cratonic separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation</td>
<td>Deep-level ductile shearing, thrust faulting and folding with orogenic vergence</td>
<td>Ductile shearing or faulting along pre-existing fault zones</td>
<td>Intraplate orogeny</td>
</tr>
<tr>
<td>Deformation features and kinematics</td>
<td>Crustal thickening and shortening, with widespread orogenic features from margin to interior</td>
<td>Compression</td>
<td>Extension</td>
</tr>
<tr>
<td>Mechanism</td>
<td>Compression</td>
<td>Compression, extension, or shearing</td>
<td>Extension</td>
</tr>
<tr>
<td>Magmatism</td>
<td>Mid-lower crustal melting, forming granitic magmas, etc.</td>
<td>Small magmatic intrusions</td>
<td>Volcanic eruptions</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>Retrograde metamorphism of crystalline basement rocks</td>
<td>Metamorphism along tectonic belts</td>
<td>No characteristic metamorphism</td>
</tr>
<tr>
<td>Probable magmatic source</td>
<td>Of orogenic thermal transmission, magmatic flow</td>
<td>Upper mantle or tectono-thermal heating</td>
<td>Upper mantle</td>
</tr>
<tr>
<td>Changing of cratonic features</td>
<td>From stable to active, complete change in cratonic stability</td>
<td>No change to previous cratonic features</td>
<td>Cratonic separation, from large to small segments of cratonic crust</td>
</tr>
<tr>
<td>Post-reactivation tectonic evolution</td>
<td>Subsequent orogeny, uplift, exhumation of the crystalline basement</td>
<td>Local erosion and uplift of the crystalline basement</td>
<td>Small-scale local erosion</td>
</tr>
<tr>
<td>Timing and spatial relationship to marginal orogeny</td>
<td>Marginal orogeny along cratonic margins</td>
<td>No marginal orogeny</td>
<td>Marginal orogeny in part along cratonic margins</td>
</tr>
<tr>
<td>Surrounding tectonic settings</td>
<td>Adjacent to orogenic belts or related to far-field stress from plate subduction or collision</td>
<td>Far-field stress due to plate subduction</td>
<td>Far-field stress due to plate subduction</td>
</tr>
<tr>
<td>Relationship with plate tectonics</td>
<td>Changes in plate tectonic stress North China Craton</td>
<td>Changes in plate tectonic stress Australia</td>
<td>Changes in direction of plate movement Basin-and-Range province in North America, opening of Atlantic between South America and Africa</td>
</tr>
</tbody>
</table>

However, no matter what the definition of reworking or reactivation, these terms are not suggestive of compressional deformation, thickening of cratonic crust, and subsequent orogenesis or magmatism along either cratonic margins or the interior of cratonic regions (Table 3). In the case of the northern margin of the NCC, there is no evidence to show that magmatism, metamorphism, and deformation occurred along pre-existing structural features. In addition, south-vergent deformation and melting of both cover and crystalline basement by tectono-thermal fluids suggest that the craton reactivated within an orogenic regime, with significant reactivation concentrated along the northern margin of the NCC. Tectonic events are spatially focused along the craton margins; the orogenic activity occurring in Inner Mongolia focused tectono-thermal thickening of the crust and de-root (delamination) of the crystalline basement along the northern margin of the NCC, which significantly decreased the stability of the craton. This meant that, after the magmatism and deformation between 320 and 210 Ma, the northern margin of the North China Craton was orogenic in nature rather than cratonic.

In most cases, craton reactivation is caused by a change in the tectonic setting of regions surrounding the craton; for example, reactivation of the northern Brazil craton was induced by marginal plate tectonics (Harman et al., 1998). These typical reactivation events are affected by and involved with orogenic cycles. Several large cratons are currently known to have undergone reactivation, for example the North American, Siberian, South American, and West African cratons (e.g., Holdsworth et al., 1997; Harman et al., 1998; Colgan et al., 2006; De Boisgrollier et al., 2009; Igeos et al., 2012). All of these have similar features that relate to the plate tectonics of the surrounding region; i.e., orogenic belt development along the craton followed by reactivation of the continental margin or cratonic interior. In other areas, changes in the regional stress field or direction of plate motion have caused craton reactivation and reworking, for example in the Atlantic, South America, and Africa regions (Harman et al., 1998) and the northern margin of the North China Craton. The Australia intraplate orogenic event was also related to changes at the plate margin (Hand and Sandiford, 1999), as was deformation and associated development of the west Canada craton (Brandley et al., 1996; Ross and Eaton, 1999). This suggests that it does not matter whether the reactivation is caused by deformation along existing structures or is in response to large-scale tectonic changes that can change the tectono-thermal lithospheric regime and provide another mechanism for reactivation, as the result will be the same: basement reactivation, magmatism and deformation across different lithospheric levels.

The broad coincidence between the timing of plate margin movement, orogenic vergence, and the timing of cratonic deformation indicates that reactivation of the northern margin of the NCC was directly related to the formation of the Inner Mongolia Orogenic Belt; in addition, the NE of Brazil has similar characteristics (Harman et al., 1998). These areas have similar relationships between the tectonic evolution of the interior of the continental area and the surrounding oceanic basins. For Australia and other regions, deformation and magmatism in intracratonic areas or continental extension appear to be related to far-field stresses, with basement reactivation due to changes in the tectono-thermal regime or lithospheric mantle, but linked with the tectonics of the surrounding plates (Hand and Sandiford, 1999). Crustal thickening is another characteristic feature of the northern margin of the NCC, with marginal mobile belts (as with the North China Craton) being derived from changes in the regional stress field related to adjacent plates, such as the North America craton (Van der Pluijm et al., 1997; Foley, 2008), the Eastern European craton (Nikishin et al., 1996), or the Siberian craton (De Boisgrollier et al., 2009).

Thus, the northern margin of the NCC reactivation produced a number of features related to orogeny: south-vergent ductile shearing and thrusting and folding, pre- or syn-deformation magmatism, and post-orogenic exhumation and denudation. The formation of the orogenic belt relates to either changes in plate motion or convergence, and was contemporaneous with reactivation of the craton. This reactivation is not related to intraplate or intracontinental deformation, regardless of whether the features generated by this reworking are thick- or thin-skinned. Furthermore, the reactivation and subsequent orogenesis of the NCC are not due to a simple tectonic superposition or reactivation of pre-existing basement structures, but...
a change in the entire characteristics of the craton: from stable to un-stable, and from low heat flow and deep cratonic roots to features more typical of orogenic belts. Put simply, the tectonic features of the region are transformed from cratonic to orogenic. Consequently, we can say that the reworking of the northern margin of the NCC is a typical cratonic reactivation, or, more specifically, a typical marginal reactivation (Table 3).

6. Conclusions

The reactivation and subsequent orogeny of the northern margin of the North China Craton were initiated in the Late Paleozoic, with significant deformation during the Mesozoic, forming E–W-trending structures (e.g., ductile shear zones) between 270 and 210 Ma. Exhumation of the basement occurred between 210 and 180 Ma, as constrained by U–Pb SHRIMP and LA-ICP-MS dating of zircon, and 40Ar/39Ar isotopic dating of muscovite, biotite, and K-feldspar. The northern areas of cratonic basement were deformed in E–W-trending shear zones, indicating that deformation in these segments of the YTP was thick-skinned, whereas E–W-trending folds in the south indicate the dominance of thin-skinned tectonics. This indicates that the YTP is not an intraplate tectonic belt, nor an orogenic belt on an active continental margin, but formed as a result of the reactivation and subsequent orogeny of the craton between 320 and 210 Ma. N–S compression, resulting from convergence between the southern Mongolia and North China cratonic block, shaped and controlled E–W-trending structures, with this compression also forming the Inner Mongolian Orogenic Belt. After the Mid–Late Jurassic, the West Pacific stress regime controlled the tectonic evolution of the YTP. This cratonic reactivation and subsequent orogeny is commonly observed elsewhere, with compression, adjacent to an orogenic belt, and involving extensive deformation and exhumation of the cratonic basement.

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Appendix A. Supplementary data

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