Reconstruction and interpretation of giant mafic dyke swarms: a case study of 1.78 Ga magmatism in the North China craton

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Abstract: Short-lived giant mafic dyke swarms are keys to the interpretation of continental evolution and tectonics, reconstruction of continental palaeogeographical regimes, and petrogenesis of volcanism. The 1.78 Ga Taihang–Lvliang dyke swarm, one of the most significant and best-preserved Precambrian swarms in the central part of the North China craton (NCC), is reviewed and discussed. It is interpreted to have a radiating geometry that is compatible with the Xiong'er triple-junction rift, in which the Xiong'er volcanic province is proposed to be the extrusive counterpart of this swarm. It resulted in significant extension, uplift and magmatic accretion of the NCC, and it is comparable with the Phanerozoic large igneous provinces (LIPs) in areal extent (*c.* 0.3 Mkm^2) and estimated volume (*c.* 0.3 Mkm^3), short lifespan ($<$20 Ma), and intraplate setting. This North China LIP is unique in that it comprises large volumes of both mafic and intermediate components. It could have resulted from extensive mantle–crust interaction, probably driven by a large-scale mantle upwelling. A plume tectonic model is favoured by several lines of supporting evidence (i.e. massive volcanic flows correlated over large areas and a giant fanning dyke swarm with plume-affinitive chemistry). It could responsible for massive sulphide (Pb–Zn) and gold (Au–Ag) ore deposits in the Xiong'er volcanic province. Dismembered remnants of this magmatism in other block(s), with potential candidates in South America, Australia and India, could identify other cratonic blocks that were formerly connected to the North China craton.

There are more than 100 giant mafic dyke swarms that extend for more than 300 km on planet Earth; thus far, the largest recognized is the Mackenzie swarm of the northern Canadian Shield, which extends for $>$2000 km (Ernst & Buchan 2001). Giant dyke swarms provide information on large-scale extension occurring in the continental lithosphere, and thus they are important in interpreting continental evolution and plate or plume tectonics (e.g. Ernst *et al.* 1995; Hanski *et al.* 2006). They serve as conduits transporting large volumes of magma from the mantle and thus contribute to growth of the continental crust. They could be the key to the petrogenesis of an overall magmatic event as they may preserve different and sometimes more primitive magma compositions, less affected by assimilation. They also provide a powerful tool in reconstructing ancient continental palaeogeography because of their large areal extent, well-defined and often short duration, palaeomagnetic record and inherent geometry (e.g. Bleeker & Ernst 2006). However, after their emplacement, dyke swarms may have been overprinted by later tectonothermal events resulting in deformation, metamorphism, displacement and dismemberment, and thus reconstruction is necessary prior to interpretation. Here, a case study on a 1.78 Ga giant dyke swarm in the North China craton is reviewed and discussed.

Geological background

The North China craton (NCC, also known as the Sino-Korean craton; Fig. 1) formed as a result of amalgamation of Archaean blocks either in the late Palaeoproterozoic (*c.* 1.85 Ga; e.g. Zhao, G.-C. *et al.* 2001, 2005; Wilde *et al.* 2002; Guo *et al.* 2005; Kröner *et al.* 2005), or alternatively in the latest Archaean (*c.* 2.5 Ga) followed by Palaeoproterozoic remobilization and recratonization (e.g. rifting, collision and/or uplift) (Li *et al.* 2000, 2002; Zhai *et al.* 2000; Kusky & Li 2003; Zhai & Liu 2003; Kusky *et al*. 2007*a*, *b*; Zhai & Peng 2007). After 1.8 Ga, the NCC stabilized, followed by episodes of rifting (1.8–1.6 Ga and *c.* 0.9 Ga; e.g. Zhu *et al.* 2005; Peng *et al.* 2008*b*) and platform deposition (1.6–1.4 Ga; e.g. Zhao, Z.-P. *et al.* 1993). Whether the NCC was involved in a palaeo-supercontinent (e.g. Nuna) or not, and where it may have been positioned in a global configuration have been widely discussed (e.g. Wilde *et al.* 2002; Zhao, G.-C. *et al.* 2002, 2004, 2010; Peng *et al.* 2005; Hou *et al.* 2008*a*). Many of these major events first shaping and then modifying the NCC were accompanied by mafic dyke swarms; that is, the 2.5 Ga Taipingzhai–Naoyumen dykes, the 2.15 Ga Hengling dykes and sills, the 1.97 Ga Xiwangshan dykes, the 1.96 Ga Xuwujia dykes, the 1.78 Ga Taihang–Lvliang dykes, the 1.76 Ga Beitai dykes, the

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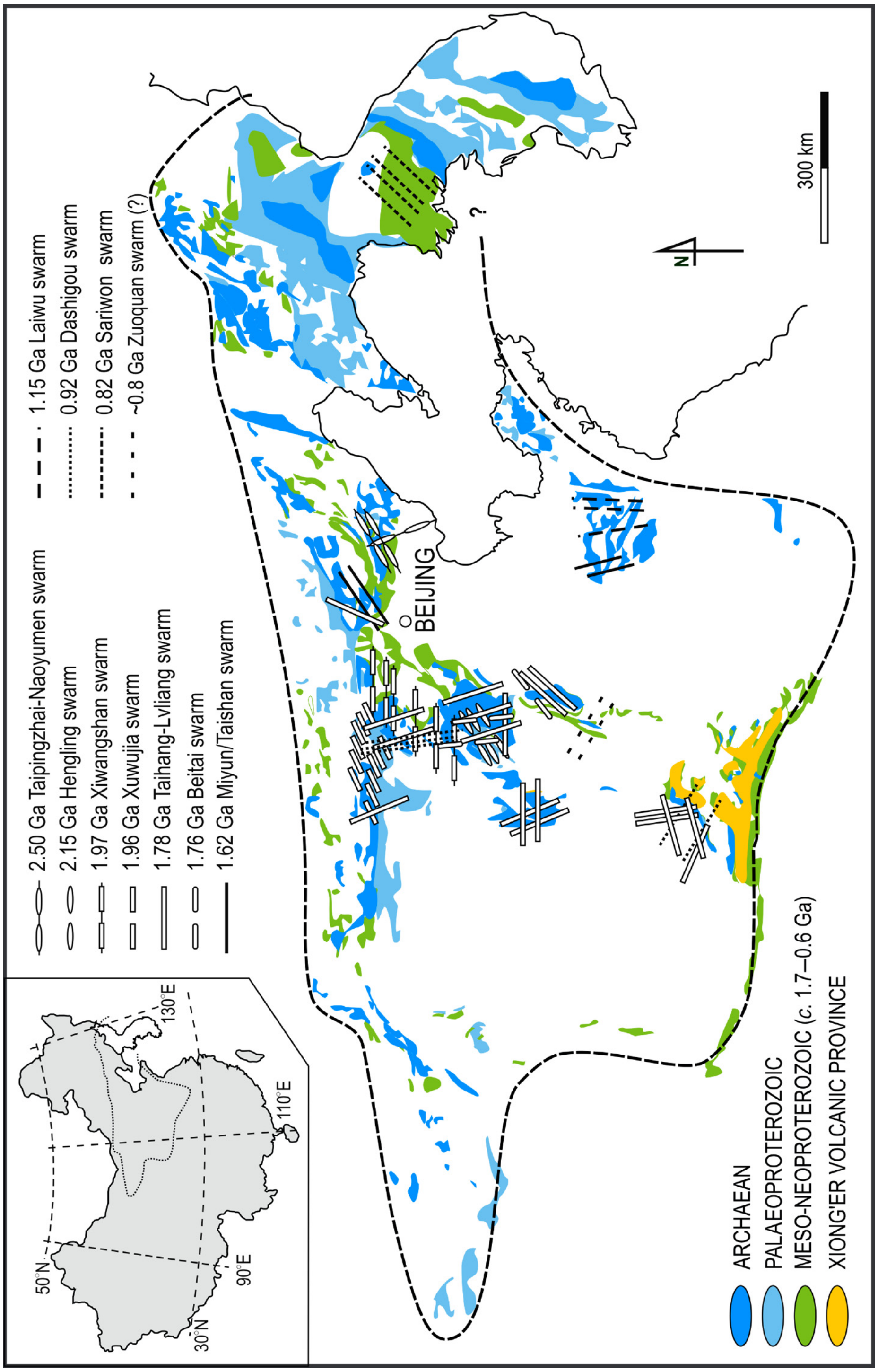

Fig. 1. Map showing the distribution of Precambrian mafic dykes and sills in the North China craton.

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1.62 Ga Taishan–Miyun dykes, the 1.15 Ga Laiwu dykes, the 0.9 Ga Dashigou dykes, and the 0.9–0.8 Ga Sariwon and Zuoquan dykes (Fig. 1; Table 1). Each of these dyke swarms may provide important insights into the tectonothermal evolution of the Precambrian lithosphere of the NCC, and the possible palaeo-linkage(s) between the NCC and other craton(s). The 1.78 Ga Taihang–Lvliang swarm has a extent of *c.* 1000 km, and is the largest, most prominent and best-preserved Precambrian swarm in the NCC (e.g. Qian & Chen 1987; Halls *et al.* 2000; Hou *et al.* 2000, 2005, 2008*a*; Peng *et al.* 2004, 2007; Wang *et al.* 2004, 2008).

Brief introduction to the 1.78 Ga Taihang–Lvliang swarm

The Taihang–Lvliang dyke swarm (TLS) consists of NNW–SSE-trending (315°–345°) dykes evenly distributed throughout the central NCC, as well as a few NE–SW-(20–40°) and east–west-trending (250–290°) dykes (Fig. 2). It was followed by a younger NNW–SSE-trending swarm with distinct compositions (the Beitai swarm, 1765 Ma: Wang *et al.* 2004; Peng *et al.* 2006; Fig. 3a). The NE–SW-trending dykes occur mainly in the South Taihang Mountains. The east–west dykes are restricted to the Lvliang, southern Taihang, Huoshan and Zhongtiao Mountains, and they locally cut or branch off the NNW–SSE dykes. The east–west dykes can be further distinguished into two groups, one trending between 250° and 270° (mainly in the Lvliang and Taihang Mts) and another group trending 270–290° (mainly in the Zhongtiao and Huoshan Mts) (Fig. 2).

The TLS dykes are up to 60 km long and up to 100 m wide, with a typical width being *c.* 15 m. The dykes are vertical to subvertical and show sharp, chilled contacts with the country rocks. The systematic northward branching of the dykes indicates a magma flow direction from south to north (e.g. see Rickwood 1990). Mean ^{206}Pb–^{207}Pb ages reported for the TLS dykes are 1769 ± 3 Ma (zircon thermal ionization mass spectrometry (TIMS), Halls *et al.* 2000), 1778 ± 3 Ma [zircon sensitive high-resolution ion microprobe (SHRIMP), Peng *et al.* 2005], 1777 ± 3 Ma (zircon plus baddeleyite TIMS), and 1789 ± 28 Ma (baddeleyite TIMS) (Peng *et al.* 2006). An Ar–Ar age of about 1780 Ma is also available (Wang *et al.* 2004). The TLS dykes are composed of gabbro and dolerite, with a mineralogy dominated by plagioclase and clinopyroxene. They are tholeiitic in composition, varying from basalt to andesite, with minor occurrences of dacite and rhyolite. Peng *et al.* (2004, 2007) chemically divided the TLS dykes into three groups, followed by a fourth group, now identified as the Beitai swarm (Fig. 3a, b). It needs to be clarified that Wang *et al.* (2004) have also divided the dykes in South Taihang Mountains into three groups, on the basis of their chemistry, with their group 1 being compositionally similar to the NW group of the TLS dykes, their group 2 being similar to the Beitai swarm, and their group 3 being distinct, possibly another swarm.

Geometrical reconstruction of the Taihang–Lvliang swarm

Because the orientations of the TLS dykes have been modified after their intrusion [for instance, the Taihangshan Block has recorded a *c.* 15° anticlockwise rotation relative to the Ordos Block in the Mesozoic–Cenozoic (Fig. 2; e.g. Zhang *et al.* 2003; Huang *et al.* 2005)] the geometry of the dykes in these blocks needs to be reconstructed. In Figure 4a, the original orientations of dykes in the Taihang, South Taihang, Lvliang, Huoshan, Zhongtiao and Xiong'er Mountains are shown together with reconstructed orientations suggested by palaeomagnetic data (Zhang, Y.-Q. *et al.* 2003; Huang *et al.* 2005). Figure 4b shows the presumed dyke tracks after restoration of the rotations. The dykes constitute a radiating pattern, which could fit the geometry of the Xiong'er triple-rift (the Xiong'er volcanic province); that is, the majority are consistent with the rift arm extending into the central NCC. The other two groups of east–west-trending dykes are parallel to other two arms of this rift. Qian & Chen (1987) and Hou *et al.* (2000) suggested that the east–west dykes are late intrusions that were emplaced in a different stress field. However, these east–west dykes are distribute only in the areas with lower exposure depths. Peng *et al.* (2008*a*) argued for two groups of dykes intruding into coeval fissures, either in a changing stress regime such as from plume-generated uplift to the onset of rifting and breakup, or in a single stress field with two groups of conjugate fissures at the uppermost crustal level, based on the observation of NNW–SSE- and east–west-trending dykes in a reticular fissure system. Also, the local crosscutting relationships (east–west dykes cutting NNW–SSE dykes) would have arisen during continuous intrusion and uplift.

Although it is difficult to reconstruct the possible coeval dykes in other parts of the NCC (e.g. the Taishan Mts, Hou *et al.* 2008*b*), this fanning geometry clearly indicates a stress field radiating from a magma centre as a result of uplift; that is, not simply compression or extension (e.g. a north–south compression; Hou *et al.* 2006). It is revealed that the dykes were uplifted and exhumed from crustal levels up to 20 km, mainly deep in the

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Table 1. *Precambrian mafic dyke swarms of the North China craton*

Swarm	Present orientation(s)	Rocks	Series	Distribution	Scale (km)	Ages
Taipingzhai–Naoyumen	NW–SE and ENE–WSW	Gabbro	Both tholeiitic and alkaline	Eastern Hebei	>100	2504 ± 11 Ma, 2516 ± 26 Ma (zircon U–Pb), Li *et al*. (2010)
Hengling	Deformed	Metagabbro (amphibolite schist)	Tholeiitic	Wutai Mts.	*c*. 100	2147 ± 5 Ma (zircon U–Pb), Peng *et al*. (2005)
Xiwangshan	Deformed (ENE–WSW to east–west)	Metagabbro (high-pressure granulite)	Tholeiitic	Sanggan River	*c*. 200–300	1973 ± 4 Ma (zircon U–Pb), Peng *et al*. (2005)
Xuwujia	Deformed (ENE–WSW)	Metagabbro (high-temperature granulite)	Tholeiitic	Liangcheng–Tuguiwula (Yinshan Mts.)	*c*. 200	1960 ± 4 Ma (zircon U–Pb), author's own unpublished data
Hengshan	Deformed (ENE–WSW)	Metagabbro (high-pressure granulite)	Tholeiitic	Hengshan Mts.	*c*. 100?	1914 ± 2 Ma, 1915 ± 4 Ma (zircon U–Pb), Kröner *et al*. (2006)
Taihang–Lvliang	NNW–SSE and east–west	Gabbro, dolerite	Tholeiitic	Central NCC and possibly other parts	*c*. 1000	1780–1770 Ma (present study)
Beitai	NNW–SSE to north–south	Gabbro	Tholeiitic	Hengshan–Taihang–South Taihang	>200	1765 ± 1 Ma (Ar–Ar whole rock), Wang *et al*. (2004)
Miyun	NE–SW	Gabbro, dolerite	Tholeiitic	Miyun–Chengde	*c*. 100	1620 Ma (zircon U–Pb), author's own unpublished data
Taishan	NNW–SSE to NE–SW	Gabbro, dolerite	Tholeiitic	Taishan Mts.	*c*. 200?	1619 ± 16 Ma (baddeleyite Pb–Pb), Li, H.-M., *et al*. pers. comm.
Dashigou	NNW–SSE	Gabbro	Alkaline	Hengshan–Wutaishan Mts.	*c*. 300?	917 ± 7 Ma (baddeleyite Pb–Pb), author's unpublished data
Sariwon	ENE–WSW to east–west	Gabbro, dolerite	Tholeiitic	Pyongnam Basin, North Korea	*c*. 150	816 ± 34 Ma (zircon U–Pb); 884 ± 15 Ma (baddeleyite Pb–Pb), Peng *et al*. (2008*b*) and author's own unpublished data
Zuoquan	NW–SE	Gabbro, dolerite	Tholeiitic	Zuoquan and adjacent area	Unknown	Neoproterozoic, according to geological relationship

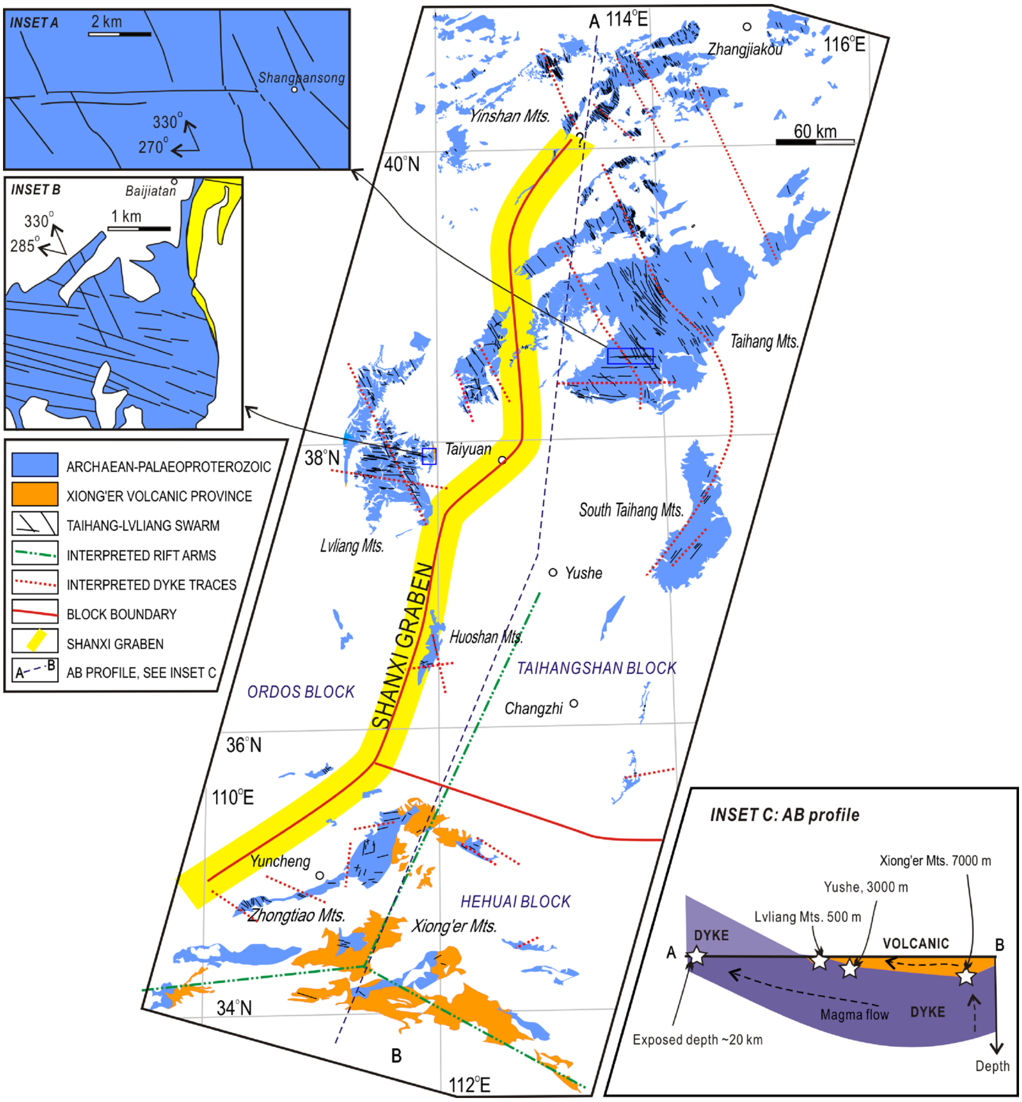

Fig. 2. Map showing the distribution of the Taihang–Lvliang swarm and Xiong'er volcanic province in the central NCC (after Peng *et al.* 2008*a*, with some younger dyke swarms, now dated and known to be unrelated, removed). Insets A and B show enlarged maps of local areas, and inset C is a profile of the study area based on the available geophysical (Wang 1995), geological (Peng *et al.* 2007) and palaeomagnetic data (Hou *et al.* 2000).

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northern but shallow in the central study area according to the palaeomagnetic data (Hou *et al.* 2000) and a P–T–t path (Peng *et al.* 2007). A north to south profile of the study area (Line AB in Fig. 2, inset c) can be constructed after incorporating seismic data in the south (e.g. Wang 1995). The increased uplift in the north of the study area could be partly responsible for the regional orientation changes of the dykes in the northern part of the central NCC (Fig. 4b); that is, the events resulting in this regional tilt could have distorted the orientations of the dykes in the northern part. Figure 4c shows an idealized image of the possible geometry of the TLS dykes and Xiong'er rift system at 1.78 Ga.

The Xiong'er volcanic province: extrusive counterpart of the Taihang–Lvliang swarm?

The Xiong'er volcanic province (XVP) has been thought to have no genetic relationship with the

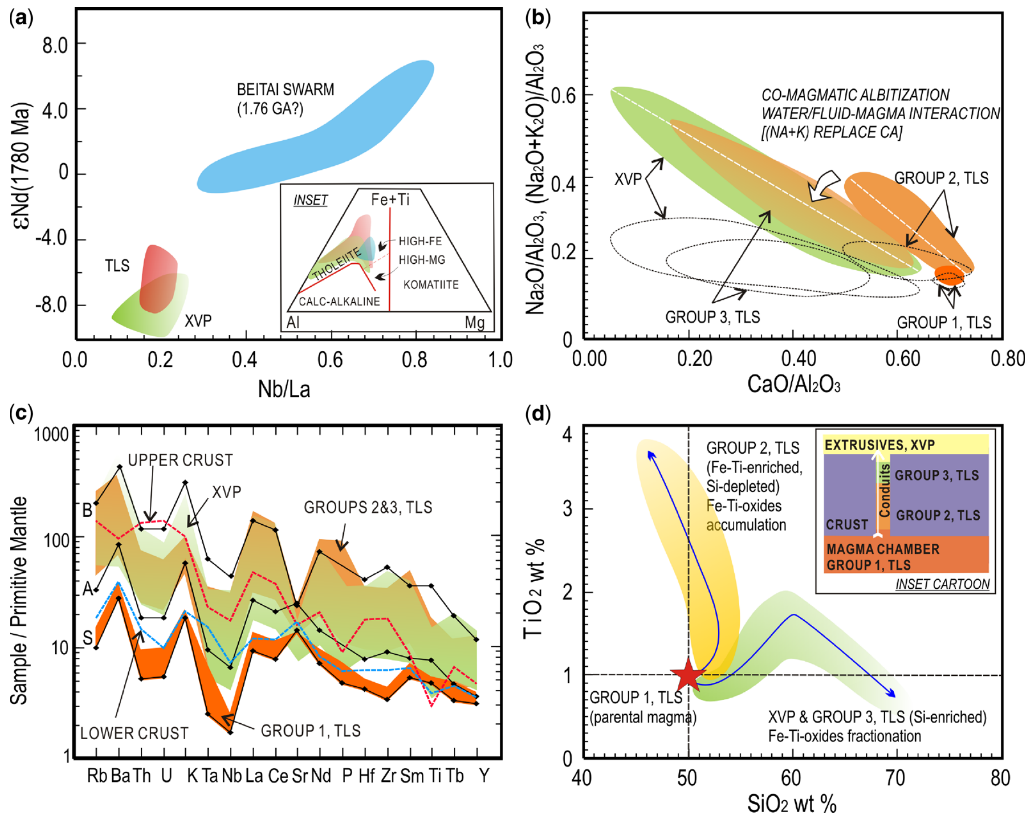

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Fig. 3. (**a**) εNd (1780 Ma) v. Nb/La plot. Inset: Fe + Ti v. Al v. Mg (mol) diagram (after Peng *et al.* 2007). (**b**) Na_2O/Al_2O_3 (open fields) and $(Na_2O + K_2O)/Al_2O_3$ (coloured fields) v. CaO/Al_2O_3 plot. (**c**) Primitive mantle-normalized trace element spidergram of the Taihang–Lvliang dykes (TLS) and Xiong'er volcanic rocks (XVP): labelled curves refer to calculated liquid compositions after *in situ* crystallization (A) and fractional crystallization (B) from the starting composition (S) (after Peng *et al.* 2007). Primitive mantle-normalized values are after Sun & McDonough (1989). Data for the upper and lower crusts are after Rudnick & Gao (2001). (**d**) TiO_2 (wt%) v. SiO_2 (wt%) plot: the arrowed dashed lines show the differentiation trend, and the inset schematic illustration shows the relative differentiation depths of the TLS and XVP in the crust. Here Groups 1, 2 and 3 of TLS refer to the LT, NW and EW groups of Peng *et al.* (2007), respectively. Database is after Peng *et al.* (2008*a*).

TLS as it is compositionally dominated by intermediate rather than mafic volcanic rocks (e.g. Pirajno & Chen 2005; He *et al.* 2008, 2009, and references therein). The XVP is located in the south of the NCC, and has three branches: two branches along the southern margin of the NCC and a third one extending northward into the interior of the NCC (Fig. 2). The XVP has a thickness of 3–7 km (Zhao, T.-P. *et al.* 2002) and is dominated by thick and continuous lava flows, with rare, thin, sedimentary and volcaniclastic interlayers. There are also minor pillow lavas. The XVP is composed of diabasic and porphyritic rock. It is chemically tholeiitic and varies from basalt to andesite, dacite and rhyolite, with andesitic compositions being dominant; thus the XVP does not resemble a bimodal association. It consists of two volcanic cycles, both varying from mafic–intermediate to more silicic compositions; the age gap between the two cycles is not known. There are also some ultramafic bodies in the province, with associated Ni–Cu– PGE (platinum group elements) deposits, which are probably related to the XVP (Zhou *et al.* 2002). Ages of *c.* 1780–1770 Ma have been reported for the XVP (Zhao, T.-P. *et al.* 2004, 2005; Xu *et al.* 2007; He *et al.* 2009); however, some significantly younger ages have also been reported (He *et al.* 2009) but it remains unclear how these relate to the main XVP sequence.

The XVP is a host of important massive sulphide (Pb–Zn) and gold (Au–Ag) ore deposits in China, and there is evidence that the mineralization

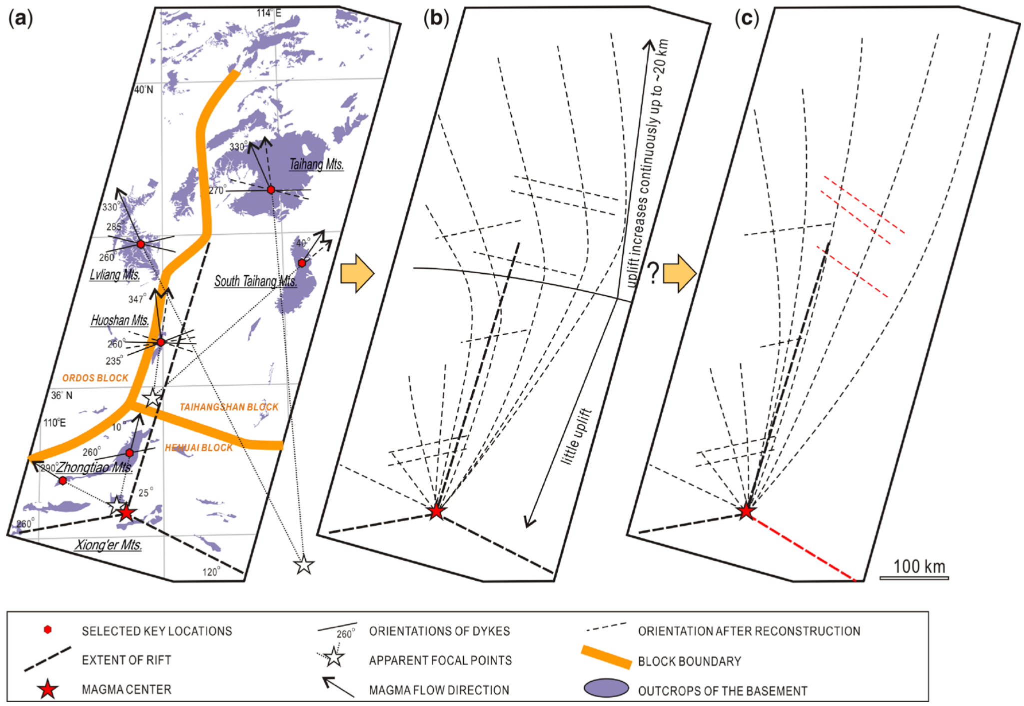

Fig. 4. Geometry of the TLS and XVP: (**a**) orientations of the dykes and apparent magmatic focal points in the selected locations, and the extent of the rifts; (**b**) presumed geometry of the dykes after reconstruction in relation to the configuration of the rift; (**c**) idealized geometry of the dykes and the rifts based on model discussed in text.

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could be associated with the volcanism. Some may have formed by (magmatic) fluid–rock interaction during the late stages of volcanism (e.g. Zhao, J.-N. *et al.* 2002; Hou *et al.* 2003; Ren *et al.* 2003; Zhang, H.-C. *et al.* 2003; Weng *et al.* 2006; Cao *et al.* 2008), especially in some fissures and vent complexes (Pei *et al.* 2007). This water (fluid)–rock interaction also caused albitization of feldspar, as well as alteration of the whole-rock chemistry, resulting in a spilite–keratophyre-type affinity in some of the XVP rocks (Peng *et al.* 2008*a*).

A cogenetic relationship between the XVP and TLS is favoured (i.e. the XVP is the extrusive counterpart of the TLS), because of the following observations: (1) the feeder dykes of the XVP have similar ages and compositions to the dykes of the TLS; (2) the geometries of the TLS (radiating fan) and XVP (triple-junction) are compatible with each other, and they share the same magmatic centre (Fig. 4b); (3) the exposure depths of the TLS and XVP are spatially correlated with the exhumation of the central NCC (Fig. 2, inset c); (4) they share similar petrographic characteristics, chemical variations (e.g. SiO_2 contents of the TLS and XVP vary from 45 to 68 wt% and from 45 to 78 wt%, respectively), trace element patterns and isotopic compositions (Peng *et al.* 2008*a*). Further support for a cogenetic relationship comes from the observation that both the XVP rocks and a few of the TLS dykes have experienced co-magmatic albitization, resulted in the variations of certain major and trace elements (e.g. Na, Ca, K, Sr, Rb, etc., Peng *et al.* 2008*a*).

Thus the same parental magma, with varied degrees of differentiation and/or assimilation, can explain the petrogenesis of both the TLS and XVP. Figure 3c shows one possible model, which began with *in situ* crystallization, followed by assimilation and fractional crystallization, with an assemblage composed of plagioclase, clinopyroxene and olivine (Peng *et al.* 2008*a*). This model successfully interprets the variations of most trace elements and partly those of some major elements, excluding those altered by albitization. However, to explain the variations of some other elements (e.g. Fe and Ti) fractionation of Fe–Ti-oxides should be considered (Fig. 3d).

How then can we explain the apparent difference in dominant chemistry; that is, mafic (TLS) v.

intermediate (XVP)? The TLS is chemically divided into three groups: group 1 is minor and proposed as the parental magma composition of this magmatism; group 3 is intermediate-dominated and similar to the XVP; whereas group 2 forms most of the TLS and has very similar trace element patterns but partly distinguishable concentrations as compared with the XVP, especially for major elements (Table 2; Fig. 3c, d). The group 2 rocks show an Fe–Ti-enriched trend (Si-depleted), whereas the XVP rocks (and group 3) present a Si-enriched trend (Fig. 3d). It has been suggested that the liquid would have Fe–Ti enrichment when it differentiated in a closed system at a relatively low oxidation state, whereas it would be Si-enriched when it interacted with the oxidized and hydrated surroundings (Brooks *et al.* 1991). As the group 2 dykes are commonly exposed from greater depth than the group 3 dykes and the XVP (Peng *et al.* 2007), it is reasonable to propose that the corresponding liquid has evolved from being more mafic in the deeper crust to being more silicic at shallower depth (Fig. 3d). Also, as the iron-rich liquid is more dense and more difficult to erupt (e.g. Brooks *et al.* 1991), this more mafic liquid would crystallize along the margins of the dyke conduits, forming the mafic rocks (e.g. group 2). In the mean time, the remaining relatively more Si-rich liquid and also the fractionated liquid would interact and be incorporated with more oxidized and hydrated crust, fractionating more Fe–Ti-oxides, and produce more Si-rich liquid, forming the intermediate-dominated rocks (e.g. XVP and group 3) (Fig. 3d). Thus the differentiation of Fe–Ti-enriched liquid at great depth, as well as the continuous assimilation and fractionation (of plagioclase, clinopyroxene and olivine) during ascent, could be responsible for the average composition gap between the TLS and XVP (Table 2).

Another point is that some would argue that the XVP belongs to a calc-alkaline series, which makes it different from the tholeiitic TLS rocks (e.g. He *et al.* 2008, 2009, and references therein). However, this point of debate could be largely explained by the recognition of widespread albitization in the XVP and some of the TLS dykes (Han *et al.* 2006; Peng *et al.* 2008*a*; Fig. 3b). In this case, discrimination based on elements influenced by albitization (e.g. Na, K, Rb, Sr and Ca) should be avoided. In an Fe + Ti–Al–Mg diagram (Fig. 3a inset), both XVP and TLS samples plot in the tholeiitic field instead of the calc-alkaline field. It should be noted that most of the XVP samples, as well as many of the TLS samples, plot in the calc-alkaline field in a Th–Co diagram suitable for altered rocks (Zhao *et al.* 2009). However, this diagram is based on island arc rocks (Hastie *et al.* 2007), and has not yet been tested for continental volcanic rocks, especially those with high Th content.

A large igneous province: lines of evidence and particularities

Large igneous provinces (LIPs) are considered to be massive crustal and intraplate emplacements of predominantly mafic extrusive and intrusive rocks that originated via processes other than 'normal' seafloor spreading (Coffin & Eldholm 1994, 2001). This definition has been extended to silicic provinces (Bryan *et al.* 2002; Sheth 2007; Bryan & **Q3** Ernst 2008). Bryan & Ernst (2008) renewed this definition as those 'magmatic provinces with areal extents >0.1 Mkm^2, igneous volumes >0.1 Mkm^3 and maximum lifespans of *c.* 50 Ma that have intraplate tectonic settings or geochemical affinities, and are characterized by igneous pulse(s) of short duration (*c.* 1–5 Ma), during which a large proportion ($>75\%$) of the total igneous volume is emplaced'. It should be noted that a minimal areal extent of 0.05 Mkm^2 (Sheth 2007) or 1 Mkm^2 (Courtillot & Renne 2003), and a lifespan of *c.* 1 Ma (e.g. Courtillot & Renne 2003) or ≥ 40 Ma (e.g. Birkhold *et al.* 1999; Revillon *et al.* 2000) have been proposed.

Here, the area encompassed by Figure 2 is considered the estimated areal extent of the TLS, at *c.* 0.3 Mkm^2. The XVP is continuous over a north–south extent of 500 km and an east–west extent of 360 km (Fig. 2; Wang 1995; Zhao *et al.* **Q4** 2002; Xu *et al.* 2007); thus its areal extent can be **Q5** calculated as $\frac{1}{2} \times 500$ km $\times$ 360 km $= 0.09$ Mkm^2, considering its triangular distribution. For the exposed areas, the areal extents are approximately 0.1 Mkm^2 and 0.02 Mkm^2 for the TLS and XVP, respectively (Fig. 2). The estimated magmatic volume of the TLS is calculated as: V (volume) $=$ a (areal extent) $\times$ h (average height of the dykes) $\times$ λ (extension ratio). A height of 20 km is estimated based on an exposed depth (Peng *et al.* 2007) and the palaeomagnetic data (Hou *et al.* 2000). Although extension ratios ranging from 0.28 to 0.48% are available (Hou *et al.* 2006), three well-exposed profiles are further checked. These profiles, including the 25 km long Jvlebu–Zhangxiaocun (Datong), the 20 km long Hongqicun–Jiulongwan (Fengzhen) and the 50 km Doucun–Shengtangbu (Wutai) profiles, give extension ratios at 1.0%, 1.27% and 0.72%, respectively. The variation could be a result of uneven distribution and/or miscount. Here 1.0% is taken as the average extension ratio. Thus the estimated volume would be $V = 0.3$ (a, Mkm^2) $\times$ 20 (h, km) $\times$ 1.0% (λ) $= 0.06$ Mkm^3, and the estimated exposed volume would be $V = 0.1$ (exposed area, Mkm^2) $\times$ 20 (h, km) $\times$ 1.0% (λ) $= 0.02$ Mkm^3. The volcanic volume of

Table 2. *Average compositions of the Taihang–Lvliang swarm (TLS) and the Xiong'er volcanic province (XVP), and the upper and lower crust*

Contents (wt%)	Parental magma (Group 1, TLS)*	Group 2 (TLS) average*	Group 3 (TLS) TLS average*	TLS average*	XVP average*	TLS & XVP total average†	Lower crust‡	Upper crust‡
SiO_2	50.09	50.29	56.66	51.55	57.69	56.27	53.40	66.60
TiO_2	1.02	2.57	1.40	2.20	1.20	1.43	0.82	0.64
Al_2O_3	14.85	13.00	14.23	13.41	14.11	13.95	16.90	15.40
Fe_2O_3(total iron)	13.31	15.47	10.18	14.22	9.39	10.50	8.57	5.04
MnO	0.19	0.20	0.14	0.19	0.14	0.15	0.10	0.10
MgO	6.99	4.02	3.62	4.20	3.49	3.65	7.24	2.48
CaO	10.31	7.45	5.69	7.35	4.58	5.22	9.59	3.59
Na_2O	2.27	2.65	2.45	2.58	2.92	2.84	2.65	3.27
K_2O	0.61	2.28	3.06	2.29	3.30	3.07	0.61	2.80
P_2O_5	0.14	1.08	0.52	0.89	0.36	0.48	0.10	0.15
Total	99.76	99.01	97.95	98.86	97.17	97.56	99.98	100.07

*The TLS and XVP averages are based on a database from Peng *et al.* (2008*a*) (Groups 1, 2 and 3 correspond to the LT, NW and EW groups therein, respectively), and Group 1 (TLS) is proposed to represent the parental magma compositions.
†Total TLS and XVP average is calculated taking the estimated magma volumes as their weight.
‡The lower and upper crustal compositions are after Rudnick & Gao (2001).

the XVP is calculated using V (volume) $= a$ (areal extent) $\times\ h$ (average thickness of the volcanic rocks). Assuming the original XVP extrusive extent as a triangular pyramid and taking the maximum exposed thickness of 7 km as an overall maximum, the volume would be $V = \frac{1}{3} \times 0.09$ (a, Mkm^2) $\times$ 7 (h, km) $\approx 0.2\ Mkm^3$, and the exposed volume would be $V = 0.02$ (exposed area, Mkm^2) $\times$ 5 (average thickness, km) $= 0.1\ Mkm^3$. Collectively, the TLS and XVP have a estimated total areal extent of *c.* 0.3 Mkm^2, a volume of about 0.3 Mkm^3, an exposed area of *c.* 0.1 Mkm^2, and an exposed volume of *c.* 0.1 Mkm^3. All these estimates could be doubled or even tripled if remnants in other parts of the NCC are confirmed, especially for the TLS.

The TLS and XVP postdate the regional granulite-facies metamorphism and amphibolite-facies retrograde metamorphism at 1790–1780 Ma (e.g. Wang *et al.* 1995; Zhang *et al.* 2006). They are followed by 1.75–1.73 Ga post-magmatic sye- Q6 nitic intrusions (Ren *et al.* 2000) and the 1.76 Ga Beitai swarm (Peng *et al.* 2008*a*). Thus the lifespan and duration of TLS and XVP magmatism is roughly bracketed to 1780–1760 Ma (i.e. about 20 Ma), even if the Beitai swarm is included. However, the duration of the major pulse is unknown. Undoubtedly, the magmatism has an intraplate tectonic affinity as it occurs largely within the NCC undergoing extension, and has within-plate compositional characteristics (see Bryan & Ernst 2008).

In summary, the 1.78 Ga magmatism including the TLS and XVP fits the LIP definition except for not knowing the duration of the major pulse (e.g. Bryan & Ernst 2008). There are several schemes for classification of LIPs; for instance, oceanic v. continental (Coffin & Eldholm 2001), mafic v. silicic (Bryan & Ernst 2008), and volcanic v. pluto- Q3 nic (Sheth 2007). It may be noted that most LIPs (both silicic and mafic dominated) are compositionally bimodal, and may also show a spectrum of compositions from basalt to high-silica rhyolite Q3 (e.g. Sheth 2007; Bryan & Ernst 2008). However, this North China LIP is characterized by more intermediate rocks than mafic rocks (with very few silicic components). The mafic portions are about 85% and 20% for the TLS and XVP, respectively (based on a database given by Peng *et al.* 2008*a*). The total mafic portion (p) could be $p_{total} = V_{mafic}/V_{total} = (p_{TLS} \times V_{TLS} + p_{XVP} \times V_{XVP})/(V_{TLS} + V_{XVP}) \approx 35$ vol.%. In contrast, the intermediate portion could be *c.* 65 vol.%, as there are few other components. It should be mentioned that this mafic portion may be a minimum estimation, as the volume of TLS could be substantially underestimated.

Table 2 shows the average compositions of the TLS and XVP, their estimated total average, and their comparison with the average crust. Both the TLS and XVP averages, as well as their total average, show distinct characteristics from a potential melt from the lower or upper crust; for example, it would be the difficult for the low Al_2O_3 content but high TiO_2 content to originate from the crust (Table 2, Fig. 3c). However, the total average of TLS and XVP is intermediate in composition (Table 2), which makes them in somewhat different from mantle-derived associations. In this case, incorporation of crustal melts in the parental magma (chamber) could be possible. However, it is still hard to evaluate this, as there is a possibility of underestimating the volume of TLS and thus the mafic weight in the total average. Nevertheless, some characteristics of the XVP, for example, slightly lower Nb and Ta but higher Th, U and Nd contents, as well as distinct higher Si concentration, compared with the TLS counterparts, could be partly inherited from the upper crust (e.g. Table 2; Fig. 3c). Thus it is reasonable to suggest that there are volumes of crustal melts incorporated into the magma during its ascent, especially for the late-stage differentiates (XVP).

Constraints on regional evolution and geodynamics

Reconstruction of the 1.78 Ga magmatism in the NCC (the TLS and XVP) increases its importance for the regional evolution and geodynamics. It indicates a broad rigid block undergoing significant extension and uplift at 1.78 Ga. It suggests that this rigid NCC block had basically ceased basement evolution from 1.78 Ga until the Mesozoic–Cenozoic, when the geometry of the TLS was distorted (Fig. 4). This implies a major magmatic accretion event at 1.78 Ga in the NCC, consistent with results from some *c.* 1.8 Ga mantle xenoliths (e.g. Gao *et al.* 2002).

Such reconstruction can also constrain the tectonic settings of the NCC at 1.78 Ga, as various alternatives have been proposed; that is, synorogenic (post-collisional uplift in the central NCC and Andean-style collision along its southern margin) (Fig. 5a; e.g. Zhao, G.-C. *et al.* 1998, Q7 2010; Wang *et al.* 2004, 2008; He *et al.* 2008, 2009) or non-orogenic (Fig. 5b, c; e.g. Li *et al.* 2000; Zhai *et al.* 2000; Kusky & Li 2003; Hou *et al.* 2006, 2008*a*; Kusky *et al.* 2007*b*; Peng *et al.* 2004, 2008*a*). The synorogenic hypothesis is mainly based on the subduction-influenced geochemistry (e.g. depletion in high field strength elements) of both the TLS and XVP rocks, and Andean-style calc-alkaline volcanism. Nevertheless, the chemistry could alternatively be interpreted as affected by assimilation of the continental crust, or inherited from a fertilized mantle region. Also,

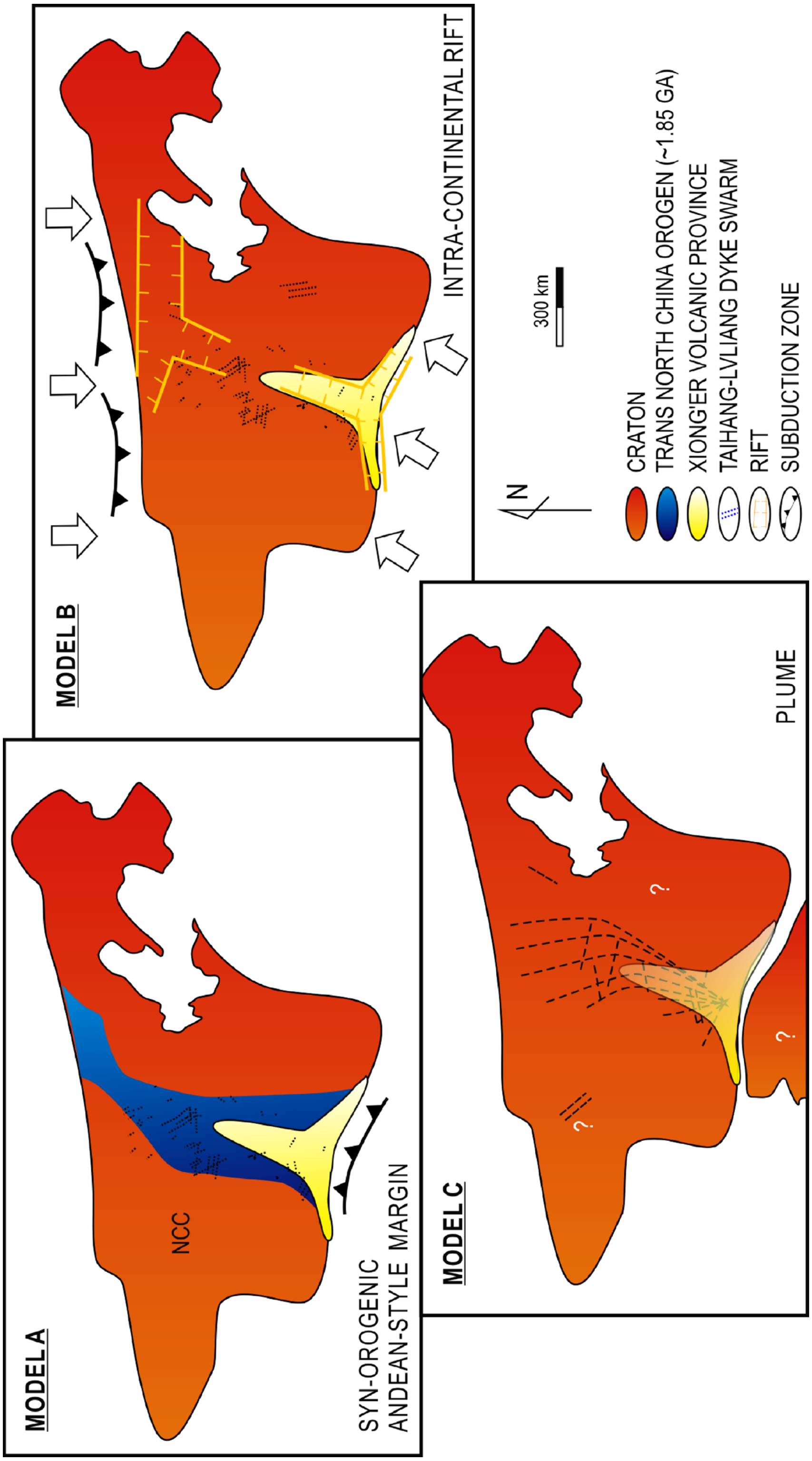

Fig. 5. Schematic illustrations showing tectonic models for the NCC at 1.78 Ga.

Colour online/ mono hardcopy

alteration and widespread albitization could explain a resemblance of the XVP to an Andean-style calc-alkaline association (in fact, it is tholeiitic, see details given by Peng *et al.* 2008*a*). As the TLS dykes have a radiating geometry (e.g. Fahrig 1987) and are very large scales (e.g. Ernst *et al.* 1995), they differ from synorogenic dykes; also, as the XVP developed in a rift with triple-junction geometry, with river–lake-facies sedimentary interlayers, it is less compatible with a continental margin environment.

However, instead of an intra-continental rift model (Fig. 5b), a plume model (Fig. 5c) with magma originating from a rifting centre is preferred here because it meets four out of five criteria suggested by Campbell (2001) to distinguish plume-associated volcanism: (1) uplift prior to volcanism (recorded by the 1.80–1.78 Ga regional P–T–t paths and extensional deformation; e.g. Zhao, G.-C. *et al.* 2005; Guo *et al.* 2005; Zhang *et al.* 2006, 2007); (2) a radiating dyke swarm geometry; (3) massive volcanic flows correlated over a large area (>0.09 Mkm^2) and a long distance (>500 km); (4) plume-associated chemistry (an enriched magma source followed shortly by a depleted source with OIB affinity: Peng *et al.* 2007). This plume possibly could have responded to a massive mantle–crust interaction to produce volumes of both mafic and intermediate igneous rocks of the North China LIP, as well as widespread polymetallic mineralization in this area.

It should be addressed that this 1.78 Ga magmatism is centred in the southern most part of the NCC, and thus it is reasonable to predict missing parts of the TLS and/or XVP outside the NCC (Fig. 5c). According to a database of Ernst & Buchan (2001), roughly coeval (*c.* 1780 Ma) large mafic magmatic events are reported in South America (e.g. Uruguayan dykes in Rio de Plata craton, Halls *et al.* 2001; Avanavero dykes in Guyana shield, Norcross *et al.* 2000; Crepori gabbro–dolerite sills and dykes, Santos *et al.* 2002), Australia (e.g. Harts Range volcanic rocks and sills and Eastern Creek volcanic series, Sun 1997; Tewinga volcanic series, Page 1988; Mount Isa dykes, Parker *et al.* 1987; Hart doleritic sills, Page & Hoatson 2000), and possibly others (e.g. India: Dharwar dykes, Srivastava & Singh 2004). All the above units are potential candidates for the missing part(s) of the TLS and/or XVP, providing clues to which blocks may have been connected with the NCC.

Conclusions

Reconstruction and interpretation of ancient giant mafic dyke swarms could be a potential way to constrain ancient continental evolution and geodynamics. As a case study, a radiating geometry is reconstructed for the 1.78 Ga giant Taihang–Lvliang swarm of the NCC. It can match the geometry of the Xiong'er triple-junction rift, in which the Xiong'er volcanic province is specified as the extrusive counterpart of this swarm. This giant radiating dyke swarm clearly indicates significant extension, uplift, and magmatic accretion in the NCC. Also, it could provide clues to potential linkages between the NCC and other ancient block(s). This dyke swarm, as well as the volcanic counterpart, show affinities to Phanerozoic LIPs, and could be the remnants of an ancient North China LIP. However, this LIP is unique in that it is characterized by large volumes of both mafic (*c.* 35 vol.%) and intermediate (*c.* 65 vol.%) components, which suggests extensive mantle–crust interaction and notable differentiation in this ancient plume setting.

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