EVOLUTION OF THE NORTH CHINA CRATON: A RE-EVALUATION

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Introduction

Traditionally, the North China Craton has been considered to be composed of a relatively uniform Precambrian crystalline basement, partially overlain by a younger cover sequence, and its tectonic history explained using a pre-plate tectonic geosynclinal-style model. Terrane accretion and collisional models have only recently been applied and the craton is still poorly-constrained in terms of tectonic subdivisions and terrane boundaries.

A review of a wide variety of published geological information, including lithological, geochemical, geochronological, structural and metamorphic P–T–t data, combined with our own research in the area, suggests that the basement of the North China Craton can be divided into eastern and western blocks, separated by major terrane boundaries that roughly correspond with the limits of a 100 - 300 km wide zone, named the Trans-North China Orogen (Fig. 1). The

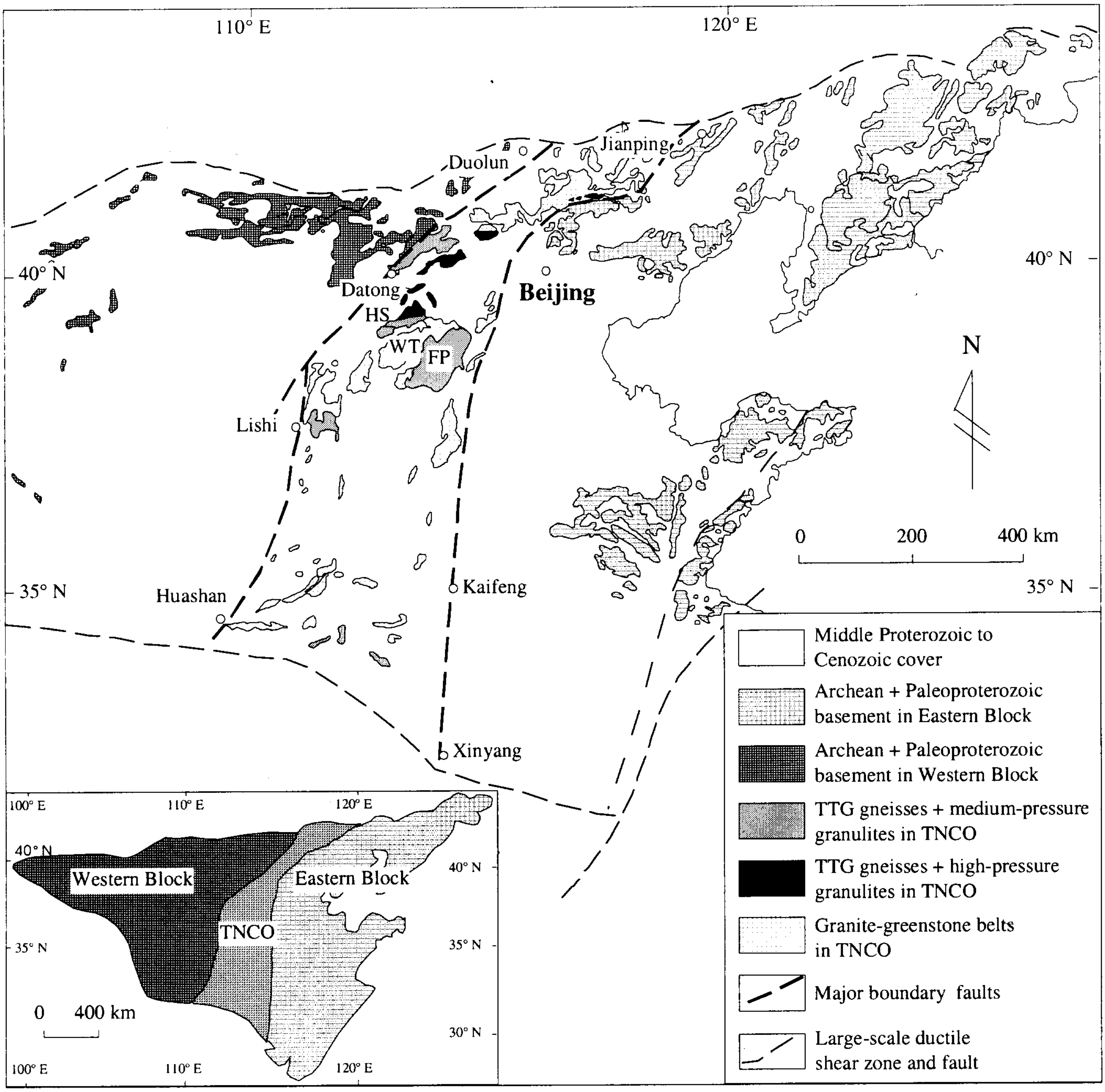

Figure 1. Map of the North China Craton, showing the distribution of the various domains where Precambrian rocks are exposed. The major boundary faults define the Trans-North China Orogen (TNCO). HS = Hengshan Complex, WT = Wutai Complex and FP = Fuping Complex. Inset emphasises the proposed three-fold subdivision of the craton. Modified from Zhao et al. (1999)

blocks and the orogen can be subdivided into a number of tectonic domains, the boundaries of which are either faults or are obscured by younger rock units. The Trans-North China Orogen is marked by a westward-steepening of the Bouguer gravity anomaly from -10 to -100 mgal (Fig. 2) and other geophysical data confirm a westward deepening of the Moho across the orogen; from 37 km in the east to 42 km in the west (Ren *et al.* 1980). The exact age of the faults bounding the orogen cannot be determined, but geological evidence suggests that their major period of activity was in the Mesozoic (Ren *et al.* 1980). It appears unlikely that these two fault systems actually represent the original terrane boundaries between the crustal blocks; a more likely interpretation is that the faults represent cryptic Late Archaean to Palaeoproterozoic boundaries that were reactivated during the Mesozoic.

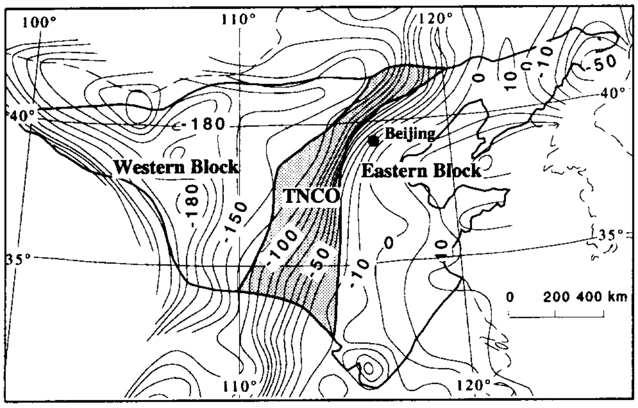

Figure 2. Bouguer gravity map of the North China Craton (based on Ren 1980). Values shown on map in in mgal. TNCO refers to the Trans-North China Orogen.

Archaean Crustal Blocks

The eastern block lies to the east of the Jianping-Kaifeng-Xinyang fault system and consists predominantly of Late Archaean tonalitic–trondhjemitic–granodioritic (TTG) dome-like batholiths outlined by anastomosing networks and linear belts of minor volcanic and sedimentary rocks with open to tight synforms. These sequences were intruded by syn-tectonic granites and metamorphosed at greenschist to granulite facies at ~2.5 Ga. They are characterised by anticlockwise P–T paths, interpreted to reflect underplating and intrusion of mantle-derived mafic magmas. Early Archaean basement rocks, which range in age from 3.85 to 3.5 Ga, have been reported from the Eastern Hebei and Anshan–Benxi domains (Liu *et al.* 1992; Song *et al.* 1996) and are composed predominantly of mafic amphibolites, granitic gneisses and sedimentary supracrustal rocks (Jahn *et al.* 1987; Liu *et al.* 1992; Song *et al.* 1996). They may represent microcontinental fragments that became incorporated during a later stage of plate accretion, however, their original extent and tectonic history is unclear, owing to extensive reworking during the 2.5 Ga tectonothermal event. Some Mid-Archaean basement rocks have also been identified in the eastern block and consist mainly of mafic granulites, amphibolites and greenschists, with minor pelitic and granitic gneisses that range in age from 3.5 to 3.0 Ga (Jahn *et al.* 1987). They occur as enclaves, boudins and sheets within the Late Archaean TTG and syn-tectonic granites. These rocks are thought to have experienced a tectonothermal event at *c.* 3.0 Ga (Bai and Dai 1998), but again, the petrographic evidence for this event has been completely obliterated by the intense and widespread reworking during the Late Archaean. There is also a Palaeoproterozoic lithotectonic assemblage, the Liaohe Group, in the eastern block which has been interpreted as representing an intracontinental rift sequence that unconformably overlies the Archaean basement rocks (Bai and Dai 1998).

The western block is delimited along its eastern boundary by the Duolun-Datong-Lishi-Huashan fault system. The basement consists of a 2.7–2.6 Ga TTG suite with minor amounts of mafic igneous rocks and sedimentary rocks, metamorphosed from greenschist to granulite facies at ~2.5 Ga (Liu *et al.* 1993). The structural style and metamorphic history of the rocks are essentially similar to those of the eastern block, although they differ in the absence of Early to Middle Archaean rocks and in being overlain and interleaved by younger khondalite sequences. The Palaeoproterozoic khondalite series consists of graphite-bearing, sillimanite-garnet gneisses, garnet quartzites, calc-silicates and marbles, with minor amounts of felsic gneisses and mafic granulites with a metamorphic age of ~1.8 Ga (Liu *et al.* 1993; Zhao *et al.* 1999). In the khondalites, decompression textures are characterised by cordierite replacing garnet, and cooling textures are characterised by biotite + muscovite ± andalusite replacing an assemblage of cordierite + sillimanite (Liu *et al.* 1993), defining near-isothermal decompressional clockwise P-T paths. Some Archaean mafic granulites and TTG gneisses in the western block adjacent to the boundary with the Trans-North China Orogen (e.g. the Jining domain) also display clockwise P–T paths (Zhao *et al.* 1999), which reflect overprinting of Archaean basement rocks during the Palaeoproterozoic metamorphic event at ~1.8 Ga.

The Archaean mafic granulites in both the eastern and western blocks display three distinct metamorphic stages, denoted M1 to M3 (Zhao *et al.* 1998, 1999). The M1 stage is represented by inclusions of plagioclase + hornblende + quartz ± biotite within hypersthene or garnet grains; the M2 stage is characterised by the growth of hypersthene, clinopyroxene, garnet and plagioclase, whilst the M3 stage is represented by the appearance of garnet + quartz symplectic coronas around the hypersthene, clinopyroxene and plagioclase grains. The change from M1 to M2 reflects an increase in both P and T and the change from M2 to M3 reflects nearly isobaric cooling. A similar three-stage evolution can be recognised in the pelitic gneisses from the eastern block. These features define anticlockwise P–T paths for the Archaean basement rocks in both the eastern and western blocks.

Continental magmatic arc regions have been considered to be the most ideal tectonic regimes in which metamorphism involving an anticlockwise P–T–t path could take place (Bohlen 1991), but it is inappropriate for the North China Craton, and especially for the eastern block since the widths of exposed basement rocks with anticlockwise P–T–t paths are considerably greater than those of modern continental arcs. Moreover, the continental magmatic arc model cannot reasonably explain the extensive exposure of TTG gneiss domes with a width of more than 800 km; the affinities of the mafic granulites to continental tholeiitic basalt; and the occurrence of high-temperature komatiitic rocks in the basement. A continental rift environment is also inappropriate, as it cannot explain the width of the exposed basement rocks (>800 km), dominant domiform structures, and lack of intrusion of alkali rocks commonly associated with rifting. For these reasons, a mantle plume model is favoured to explain the origin and evolution of the Archaean basement rocks in the eastern and western blocks of the North China Craton, supported by the short time span from the primary emplacement of TTG rocks and ultramafic to mafic volcanics until the onset of regional metamorphism.

We envisage independent large plume heads uplifting the mantle lithosphere and overlying continental crust and causing lithospheric stretching, leading to extensive eruption of ultramafic to mafic volcanism (komatiites and basalts). At the same time, the heat transfer from the plumes to the upper mantle or lower crust resulted in extensive partial melting of basaltic or amphibolitic rocks and formed large volumes of TTG magma, which became unstable at the base of the crust and rose diapirically into the lower and upper crust, forming the domes. The relief associated with the diapiric intrusion of the TTG plutons led to local erosion and sedimentation, forming minor amounts of Late Archaean sedimentary supracrustal rocks in the two blocks. Heat transfer from the plumes to the crust also led to regional metamorphism. At first, the relatively cooler plume head heated the crust, causing prograde metamorphism (M1). At the same time, large volumes of magma were added to the base of the crust and some intruded to higher levels, resulting in crustal thickening. Subsequently, the hot plume "tail" continued to rise upward and heated the crust, causing peak metamorphism (M2) at amphibolite to granulite facies, depending on the distance from the plume. It also resulted in widespread anatexis of TTG gneisses, resulting in the production of syn-tectonic charnockites and quartz monzonites. Finally, the heated crust experienced near-isobaric cooling (M3) when the effect of heating ceased through the termination of plume activity. This tectonothermal process is consistent with the counterclockwise P–T paths determined from the basement rocks in the eastern and western blocks of the North China Craton.

Trans-North China Orogen

The Trans-North China Orogen lies between the two Archaean crustal blocks, bounded by two major fault systems (Fig. 1). The orogen is composed of a series of greenschist to granulite facies metamorphic terrains containing re-worked Archaean basement components derived from the western and eastern blocks, together with juvenile Late Archaean to Palaeoproterozoic igneous and sedimentary rocks. The supracrustal rocks include voluminous thick-layered marbles and calc-silicates that are in general absent in the eastern and western blocks. In addition, ~1.8 Ga syn-tectonic S-type granites, commonly containing sillimanite and/or garnet, are ubiquitous in the high-grade domains of the Trans-North China Orogen, but rare in the eastern block.

The metamorphic history of these rocks contrasts with that determined for the eastern and western blocks. The mafic granulites, amphibolites and pelitic gneisses in the Trans-North China Orogen (and the khondalite series in the western block) exhibit decompression and then cooling-retrogression textures following peak metamorphism. Most garnetiferous mafic granulites display two-stage symplectic coronas on garnet, formed after the peak metamorphic mineral assemblage (M1) of orthopyroxene + clinopyroxene + garnet + plagioclase + quartz ± hornblende ± biotite. The early stage symplectic coronas (M2) are represented by worm-like hypersthene + plagioclase + magnetite symplectites or clinopyroxene + orthopyroxene + plagioclase coronas around garnet grains. The second stage of symplectic corona (M3) is represented by hornblende + plagioclase + magnetite symplectites around garnet grains or by retrograded hornblende rims on pyroxene grains. Locally, symplectic pyroxenes are replaced by symplectic hornblendes. The pyroxene + plagioclase symplectic coronas formed in response to decompression, with minor cooling following peak metamorphism, whereas the hornblende + plagioclase symplectic coronas formed as a result of cooling and some retrogression. These features define clockwise P–T paths in the granulites and similar patterns are evident in the amphibolites. All these textural relations define clockwise P–T paths for the basement rocks in the Trans-North China Orogen where the metamorphism has been dated at ~1.8 Ga, similar to the khondalite series in the western block.

The structural styles and clockwise P–T–t paths of Late Archaean to Palaeoproterozoic basement rocks in the Trans-North China Orogen and the Palaeoproterozoic khondalite series from the western block of the North China Craton reflect tectonothermal processes characterised by initial crustal thickening, subsequent nearly isothermal exhumation and final cooling, a sequence of tectonic events consistent with continent-continent collisional environments. Considering the spatial and timing relationships between these rocks and those of the basement in the eastern and western blocks, this collision is most likely related to the accretion and amalgamation of these two blocks during the Late Palaeoproterozoic.

Terrane Assembly

Evidence concerning the nature of the collisional process can be sought in the various domains that make up the Trans-North China Orogen (Fig. 1). The largest of these is the composite Hengshan-Fuping-Wutai Domain and this has been studied in detail by the authors. This area reveals a cross-section through a complex Late Archaean arc. The high-grade Hengshan and Fuping gneisses represent deep crustal portions of the arc, whereas the lower grade Wutai Complex represents the upper crustal component, dominated by calc-alkaline volcanism. The oldest components are 2.8 - 2.7 Ga inherited zircons incorporated in gneisses of the Fuping Complex and in the Lanzhishan Granite within the Wutai Complex. These zircon ages are interpreted to be either the result of contamination or to reflect the protolith age of granitoids which evolved at the eastern margin of the eastern block. A suite of older granitoids, with emplacement ages ranging from 2555 to 2545 Ma (and including the Lanzhishan Granite), are in tectonic contact with the volcanogenic succession of the Wutai Complex, for which ages of ~2525 Ma has been determined from the felsic volcanic components (Wilde *et al.* 1997). Geochemical data support derivation of the felsic volcanic rocks by partial melting of a common enriched mantle source within an island arc of intermediate maturity. Another suite of granitoids evolved coeval with the volcanism and these have crystallisation ages of 2530-2520 Ma. It is considered that the older granitoids evolved at an Andean-type continental margin, representing the eastern margin of the eastern crustal block, and that this evolved to become an active margin bordered by island arcs by ~2530 Ma. There is also evidence for the development of back arc basins with some mafic volcanics, tectonically interleaved with the felsic components of the Wutai Complex, showing N-MORB signatures.

It would appear that subduction had ceased by the close of the Archaean. Early Palaeoproterozoic carbonates and clastic sediments were deposited on the eastern block between 2.3 and 2.1 Ga (the Hutou Group and sediments within the Fuping Complex) and this is also considered to be the age of deposition of the khondalite series in the western block (Wu *et al.* 1997), whose location with respect to the eastern block at this time is unknown. There is also evidence within the Wutai Complex of a subsequent period of local granite plutonism, with the Dawaliang and pink phase of the Wangjiahui Granite recording Palaeoproterozoic ages of ~2170 Ma and ~2120 Ma, respectively. These granitoids are potassic and were most likely derived by local partial melting of continental crust.

There was then a renewal of plate movement, corresponding with the global 2.0-1.8 Ga collisional event. This resulted in the progressive closure of an ocean separating the eastern and western blocks and led to their ultimate collision, with formation of the Trans-North China Orogen. The various segments of the Late Archaean arc at the edge of the eastern block were dismembered and tectonically interleaved during the Palaeoproterozoic as a result of this collision. This is particularly evident in the Wutai Complex where felsic volcanics, earlier granitoids and mafic components of the original back-arc basin became complexly interleaved. The deeper segments underwent multiple phases of compressional deformation and peak high-pressure metamorphism, as revealed in the Hengshan Complex. This event is recording by ~1.8 Ga overgrowths on Late Archaean zircons and by new zircon growth, widely recognised in both the Hengshan and Fuping Complexes. This was followed by rapid exhumation during the Late Palaeoproterozoic. It is this collision between the eastern and western blocks that resulted in the final amalgamation of the North China Craton.

Conclusions

On the basis of the data presented here, our conclusion is that by the end of the Archaean, two continental nuclei, the eastern and western blocks, had formed through the interaction of mantle plumes with pre-existing lithosphere in what were subsequently to become the eastern and western parts of the North China Craton. We propose the following tectonic scenario for the final stages of assembly of the North China Craton:

1. In the Late Archaean, the eastern block had an active-type continental margin on which first continental arcs, and then island arcs and back-arc basins, developed. There is no evidence for activity on the western block at this time.

2. In the Early Palaeoproterozoic, the eastern block became a passive margin on which stable shelf sediments evolved, with local generation of granitoids as the result of intra-crustal melting. The western block also had a passive-type continental margin at this time on which stable continental margin sediments were deposited, forming the protoliths of the khondalitic rocks. Separating the two blocks was an ancient ocean.

3. At around 2000-1800 Ma, the onset of a new cycle of plate tectonic activity led to subduction of this oceanic floor beneath the western margin of the eastern continental block. Ultimately, the old ocean between the two blocks completely disappeared and led to the collision of the eastern and western blocks and the formation of the Trans-North China Orogen. The collision caused folding, thrusting and thickening, and resulted in peak metamorphism.

4. Following peak metamorphism, the thickened crust underwent exhumation, resulting in decompression metamorphism and the development of asymmetric upright folds.

5. Finally, retrogressive metamorphism took place when the crust was exhumed to shallow levels.

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References

Bai, J. and Dai, F.Y., 1998. Archaean crust of China. In: Ma, X.Y. and Bai, J. (Eds.) Precambrian crustal evolution of China. Springer–Geological Publishing House, 15–86, Beijing.

Bohlen, S.R., 1991. On the formation of granulites. Journal of Metamorphic Geology, 9: 223–229.

Jahn, B.M., Auvray, B., Cornichet, J., Bai, Y.D., Shen, Q.H. and Liu, D.Y., 1987. 3.5 Ga old amphibolites from eastern Hebei Province, China: field occurrence, petrography, Sm–Nd isochron age and REE geochemistry. Precambrian Research, 34: 311–346.

Liu, D.Y., Nutman, A.P., Compston, W., Wu, J.S. and Shen, Q.H., 1992. Remnants of 3800 crust in the Chinese Part of the Sino-Korean craton. Geology, 20: 339–342.

Liu, X.S., Jin, W., Li, S.X. and Xu, X.C., 1993. Two types of Precambrian high-grade metamorphism, Inner Mongolia, China. Journal of Metamorphic Geology, 11: 499–510.

Ren, J.S., 1980. Tectonics and evolution of China. Science Press, 64–75, Beijing.

Song, B., Nutman, A.P., Liu, D.Y. and Wu, J.S., 1996. 3800 to 2500 Ma crustal evolution in Anshan area of Liaoning Province, Northeastern China. Precambrian Research, 78: 79–94.

Wilde, S.A., Cawood, P. and Wang, K.Y., 1997. The relationship and timing of granitoid evolution with respect to felsic volcanism in the Wutai Complex, North China Craton. In: Qian, X.G., You, Z.D. and Halls, H.C. (Eds.) Proceedings of the 30th IGC: Precambrian Geology and Metamorphic Petrology, VSP, 17: 75–88, Utrecht.

Wu, C.H., Zhong, C.T. and Chen, Q.A., 1997. Ages of khondalites in the Jin-Ji-Meng high-grade terrains, North China Craton. Acta Petrologica Sinica, 13: 289–302 (in Chinese).

Zhao, G.C., Wilde, S.A., Cawood, P.A. and Lu, L.Z., 1998. Thermal evolution of Archaean basement rocks from the eastern part of the North China craton and its bearing on tectonic setting. International Geology Review, 40: 706–721.

Zhao, G.C., Wilde, S.A., Cawood, P.A. and Lu, L.Z., 1999. Tectonothermal history of the basement rocks in the western zone of the North China Craton and its tectonic implications. Tectonophysics, 310: 223–240.