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Geodynamic modelling of crustal deformation of the North China block: a preliminary study

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Abstract
The North China block (NCB) has experienced at least two stages of crustal deformation throughout the Mesozoic as revealed by the compressional structural styles before the late Jurassic and the extensional tectonics in the late Mesozoic. The E–W structural trends of the late Triassic Qinling-Dabie and Yinshan-Yanshan orogenic belts, which respectively represent the southern and northern boundaries of the North China block, clearly indicate N–S shortening of the NCB, whereas the widely distributed NNE-trending extensional basins call for E–W-directional crustal stretching during the late Mesozoic. On the basis of the Mesozoic tectonic evolution in the NCB, we employ a mountain-basin evolution system to model these geodynamic processes. The N–S shortening (late Triassic to early late Jurassic) may result from subduction and collision between the North China and South China blocks, along with the collision between the North China–Mongolian and Siberian plates. Horizontal extensional thinning of a previously thickened, unstable lithosphere may have led to the formation of extensional basins as a consequence of so-called strike-slip collapse, which was possibly triggered by the easterly roll-back of the descending subducted slab of the ancient Pacific plate.

Keywords: crustal deformation, geodynamic modelling, lithospheric thinning, North China block

1. Introduction

The North China block (NCB) is one of the oldest continental blocks on Earth with recorded ages of crustal rocks greater than 3.8 Ga (Liu *et al* 1992). It is geographically bounded by the Yinshan-Yanshan orogenic belt in the north and the Qinling-Dabie orogenic belt in the south. The predominant contractional structural features, such as tectonic nappes and thrust-fold belts at the northern and southern margins, suggest N–S shortening before the late Jurassic (Zheng *et al* 1996, 1998, Davis *et al* 1998, 2001, Hacker *et al* 2000), while the widespread development of extensional basins in this block indicates strong crustal extension in the late Mesozoic (Ma 1987, Li and Yang 1987).

The E–W structural trend of the Qinling-Dabie and Yanshanian orogenic belts are believed to result from the collision between the South and North China blocks and the far-field influence of the collision between the North China–Mongolian and Siberian plates (Cong 1996, Zheng *et al* 1996, 1998, Davis *et al* 1998, 2001, Hacker *et al* 2000). The Triassic continental collision between the North China and South China blocks (but not the late Jurassic–early Cretaceous collision between the North China–Mongolian and Siberian plates by the closure of the Mongol-Okhotsk Ocean) can be considered as the driving force for N–S horizontal shortening. In our model, we assume that the Tan-Lu fault acts as the eastern boundary, preventing material from escaping eastwards (figure 1). This is because, at that time, the westward

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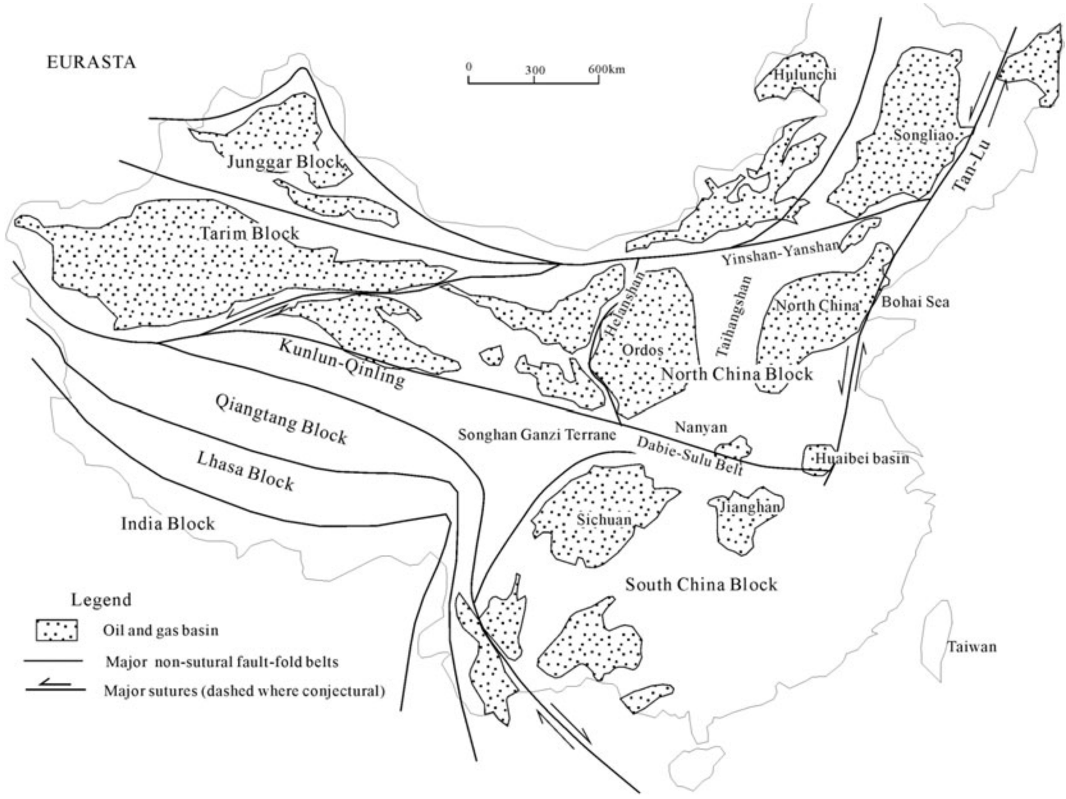

Figure 1. A Schematic tectonic map of China showing the location of the North China block and the major suture zones.

subduction of the Pacific plate underneath the Eurasian plate began to develop. We assume that the heavy material between the subduction zone and the Tan-Lu fault acts as a stress transition zone and, in our model, the Tan-Lu fault acts as a barrier. Therefore, isostatic equilibrium results in crustal thickening mainly in the area west of the Tan-Lu fault. The crustal thickening induced by the N–S shortening east of the Tan-Lu fault is negligible in the following context.

Significant lithospheric thinning might have occured in association with widely distributed basaltic magmatism in the NCB during the late Mesozoic (Menzies *et al* 1993, Griffin *et al* 1998, Fan *et al* 2000, 2001, Zheng *et al* 2001). One of the hypotheses in this paper is that the E–W crustal extension may be mechanically linked to the westerly dipping subduction of the ancient Pacific plate (or Izanagi plate). At that time (late Jurassic–early Cretaceous), the dominant tectonic framework within the NCB changed from an E–W trend to a NE–SW trend. The eastward component of the stress field along the NE–NNE oblique subduction may be the principal contributor to the crustal extension. It is possible that the easterly roll-back of the descending slab provided stress-free space, which triggered the collapse of the thickened crust of the NCB.

In this paper we attempt to model the geodynamic processes responsible for the N–S shortening in the early to mid-Mesozoic and the E–W extensional basin formation in the late Mesozoic using a mountain-basin evolution model (Houseman and England 1986a, Houseman 1996). We assume that the formation of the numerous sedimentary basins in the NCB is the result of the rapid crustal extension of a previously thickened crust. Gravitational collapse of the thickened crust was possibly triggered by the re-orientation of the far-field stress regime or simply by the relaxation of the boundary stress.

2. Tectonic and geophysical background

Previous studies have revealed that in the Mesozoic the Archaean NCB experienced intensive tectono-magmatic activization, which resulted in widespread magmatism and the formation of widely distributed fault-rifted basins (Weng 1927, Chen 1956, Ma 1987).

In the northern margin of the North China block, ductile shear zones in the Yishan-Yanshan orogenic belt formed before the late Triassic and a brittle thrust system developed in the mid-late Jurassic as a consequence of a far-field effect induced by the collision between the North China–Mongolian and Siberian plates (He *et al* 1998, Davis *et al* 1998, 2001, Zheng *et al* 1998). On its southern margin, the ductile shear zones of the Dabie-Qinling orogenic belt were formed during the late Triassic (Li *et al* 1993, 1999, Hacker *et al* 2000) and northerly convergence occurred in the mid-late Jurassic (Ratschbacher *et al* 2000). The widespread development of extensional basins throughout the Mesozoic indicates the continued thinning of the unstable or previously thickened lithosphere with associated extensive magmatism (Menzies and Xu 1998).

Late Jurassic E–W trending fold-and-thrust belts and tectonic nappes are prevalent in the southern and northern margins, especially in the Yanshanian and Dabie-North Huaiyang orogenic belts (Davis *et al* 1998, 2001, Zheng *et al* 1998, Ratschbacher *et al* 2000): this contractional deformation is both spatially and temporally associated with the emplacement of plutons and was followed in many places by early Cretaceous extension (Davis *et al* 1996). The crustal deformation has been regarded traditionally as the Yanshanian orogeny. These Jurassic compressional structural styles suggest the extensive N–S shortening of the NCB (Yin and Nie 1996). Following the late Jurassic N–S shortening, E–W extension was predominant in the early Cretaceous in southern Liaoning and Yunmengshan regions (Davis *et al* 1996), and NE–SW extension in western Inner Mongolia (Zheng 1999, Zheng *et al* 2001). This extensional event marked the collapse of the previously thickened lithosphere, followed by the formation of numerous Cretaceous extensional basins in the NCB.

Studies of peridotites from mantle xenoliths indicate that from the late Mesozoic to Cenozoic, the lithosphere beneath the NCB has been thinned significantly from ∼200 km to ∼140 km (Griffin *et al* 1998, Fan *et al* 2000, Xu *et al* 2001). At the same time, the tectonic framework changed from a compressional regime to an extensional one (Zhao *et al* 1994, Shao *et al* 2000). A regional compressional stress field with a near N–S trend was predominant during the Indosinian period as a result of continental collision between the South and North China blocks and that between the North China–Mongolian and Siberian plates (Davis *et al* 1998, 2001, Wan 1999). From the late Jurassic, there developed widespread NE-trending structures in eastern China when it rotated clockwise by 45°: these include a series of NE–SW trending strike-slip folds and thrust faults as well as basin-and-range tectonics.

Heat-flow data show a marked contrast between the fault basins around the Bohai Sea and the surrounding mountains (Xie *et al* 1980, Zhang *et al* 1982). Compared to the mountainous areas, the thermal gradients in the basins are much higher, suggesting warmer crust and upper mantle (Ye *et al* 1985). Besides, seismic data reveal that the crustal thickness gradually increases from about 30 km beneath the fault basins to 45 km in western areas, such as the Ordos basin (Feng and Teng 1983). The crust beneath the fault basins around the Bohai Sea is significantly thinner than in the surrounding regions (Zhang *et al* 2002).

Gravity surveys indicate that the entire region is generally in isostatic equilibrium except for the basins around the Bohai Sea, where small positive Bouger anomalies (20–30 mGals) are observed (Ma *et al* 1987). Since gravity compensation is usually ascribed to variation in crustal thickness, these gravity data probably indicate that the depth to the Moho discontinuity is roughly 10–15 km shallower in the centre of the rifting basins than in the surrounding mountainous areas.

3. Geodynamic modelling

In order to account for the mechanism of basin formation in the NCB, we employ a geodynamic model as follows.

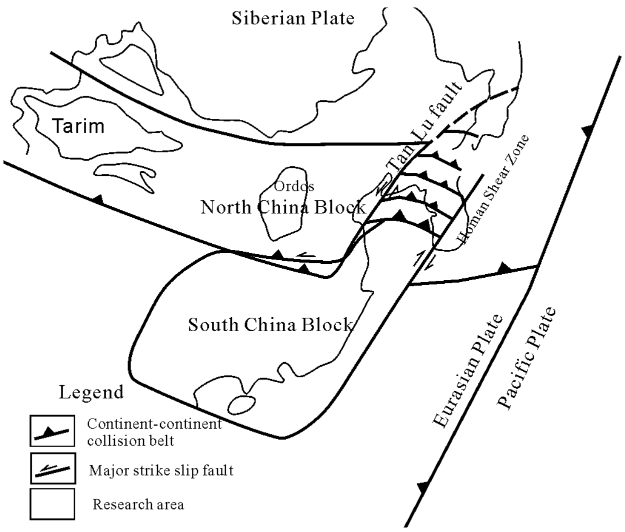

Figure 2. The Triassic continental collision between the North and South China blocks (following Yin and Nie (1993, 1996)).

(1) The Mesozoic tectonic evolution in the NCB is divided into two stages. The first stage is dominated by the N–S shortening (220–208 Ma), and the second stage by the E–W extension (130–120 Ma);
(2) Physically, the NCB is assumed to be a relatively weak zone except for the Ordos basin, which has a relatively higher viscosity than the surrounding regions.

3.1. *Initial conditions of N–S shortening*

The late Triassic collisional suture between the South and North China blocks is shown in figure 2 (Yin and Nie 1993). We use this tectonic model as the initial model for numerical modelling.

In this model, the southern margin of the NCB was a straight northward dipping subduction zone, whereas the northern margin of the South China block was irregular with its eastern part extending 550 km farther north than its western counterpart. The collision of South and North China blocks started in late Permian between the Tan-Lu fault and the Honam shear zone due to indentation of the northeastern part of the South China block. Thrusts, folds, and related foreland basins developed near the collision zone. Volcanism is expected to be continuous east of the Tan-Lu fault and west of the Honam shear zone. Sediments eroded from the collision zone were deposited on both sides of the South China block.

Due to the irregularity of the northern margin of the South China block, the ocean in the eastern part of the future Dabie belt closed first in the mid to late Triassic. In response to this diachronous closure of the ocean, volcanism related to subduction systematically shut down westward from the Tan-Lu fault along the suture zone. Parts of the earlier flysch deposits were subducted underneath the NCB during the closure of the ocean between the two blocks. The irregular geometry of the northern margin of the South China block may also have produced left-slip faults west of the Tan-Lu fault along the suture zone. Triassic clastic sediments were deposited over a wide area of North China.

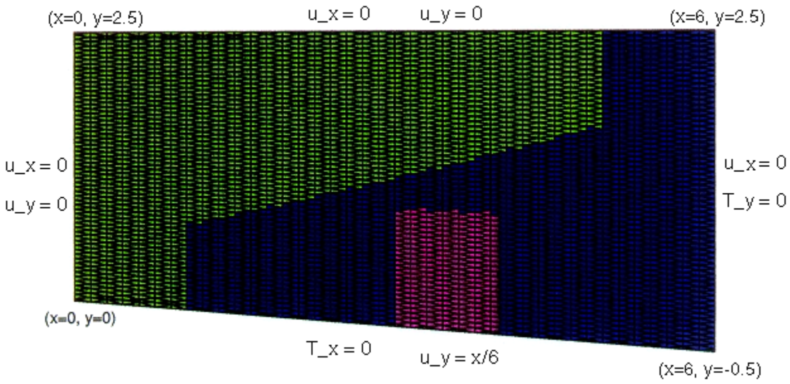

Figure 3. The initial setup of the numerical simulation showing the conditions at the boundaries.

During the early Jurassic, indentation of the irregular northern margin of the South China block caused left-slip motion along the suture zone. The Tan-Lu fault propagated northward and offset the northern boundary of the Sino-Korean craton. Based on the description above, the initial state of the numerical simulation is shown in figure 3, in which the size of the four edges is W : N : E : S = 2.5 : 6 : 3 : 6. The boundary conditions used in the numerical computation are as follows:

(i) the west boundary ($X = 0$) is fixed, i.e., $U_x = 0$ and $U_y = 0$;
(ii) the north boundary ($Y = 2.5$) is also fixed, i.e., $U_x = 0$ and $U_y = 0$;
(iii) east boundary ($X = 6$): $T_y = 0$, $U_x = 0$; and
(iv) south boundary ($Y = -X/12$): $U_y = (X/6)U_0$, $T_x = 0$;

where T_x and T_y are the traction components.

The velocity, U_y, of the south boundary increases linearly from 0 ($X = 0$) to 1 ($X = 6$) following the tectonic model given in Yin and Nie (1993). This model can be summarized as follows: the North and South China collision started first in the eastern Shandong Province in the late early Permian and propagated westward to the Dabie region in the mid to late Triassic and to the Qinling in the late Triassic to early Jurassic.

Justification for the conditions on the east boundary follows the tectonic model in figure 2, given by Yin and Nie (1993).

3.2. Relative viscosity

The NCB consists of metamorphic basement rocks as old as the early Archaean (>3800 Ma) (Liu *et al* 1992). However, despite its ancient basement, the NCB cannot be considered as a rigid block and, as pointed out by Sengor and Natal'in (1996), can hardly be described as a 'craton' when one attempts to reconstruct its late Precambrian–end Mesozoic palaeotectonics.

The Ordos basin is of high elevation and viscosity. There is little deformation in evidence.

The non-dimensionalized strength of the NCB is set at $B = 0.2$, in contrast to the background strength $B = 1$. Within the NCB, a region with strength $B = 2$ represents the Ordos area.

The numerical simulation of crustal thickening and subsequent horizontal extension uses a two-dimensional thermo-mechanical finite element modelling approach (England and Houseman 1986, Houseman and England 1986b, 1996), and the thin viscous sheet model of continental deformation (England and McKenzie 1982, England and Houseman 1985, Bird 1998).

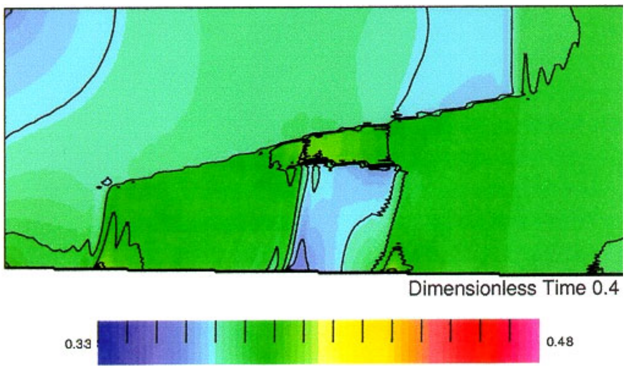

Figure 4. The N–S shortening at dimensionless time 0.4. The colour scale represents non-dimensionalized thickness. At this time, the weaker region (the North China block) is thickening, but the thickness of the strong region (the Ordos) does not change.

3.3. N–S shortening

Figure 4 depicts the progress of the N–S shortening. The scale represents the non-dimensionalized thickness. At dimensionless time $t = 0.4$, the weaker region (the NCB) is thickening, but the thickness of the strong region (the Ordos) has not changed.

At time $t = 0.9$ (figure 5), the whole weak region, including the inner strong region, has thickened. Significantly, the eastern portion has thickened by about 30%.

3.4. E–W extension

The boundary conditions at the second stage (the E–W extension) are set as follows:

(i) the west boundary is still fixed, unchanged from the previous stage;
(ii) the north boundary is set to be a shear friction boundary $T_x = -cU_x$, with $U_y = 0$;

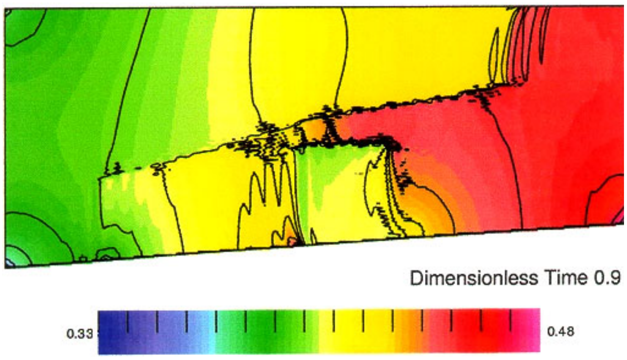

Figure 5. The N–S shortening at dimensionless time 0.9. The whole of the weak region, including the inner strong region, has been thickened. Significantly, the eastern portion has been thickened by about 30%. This is then used as the initial state in modelling subsequent E–W extension.

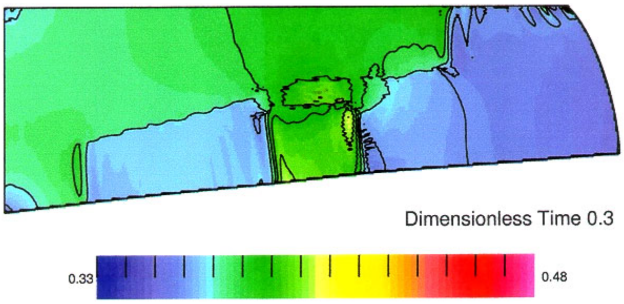

Figure 6. The E–W extension at time $t = 0.3$. The previously thickened area has been thinned, but the strongest region (the Ordos) and its northern portion are thicker than that in the surrounding region.

(iii) the east boundary is set to be lithostatic, i.e., $T_x = 0$, $T_y = 0$; and
(iv) south boundary: $U_y = 0$, $T_x = 0$.

The Huabei basin (which refers here to the area between the Ordos and the Tan-Lu fault) is a NNE-trending, pull-apart basin formed during the late Jurassic to early Cretaceous, an important tectonic transformation period for the NCB (e.g., the structural trend changed from E–W to NE at this time). The Huabei basin is a typical example of a basin system formed in the strike-slip environment. We believe that it resulted from the eastward component of the NE strike-slip of the Pacific subduction zone. However, the easterly roll-back of the descending slab could also provide stress-free space that would trigger the collapse of the thickened unstable lithosphere of NCB.

The strike-slip collapse of the thickened crust is depicted in figure 6. We use figure 5 as the initial model ($t = 0$) of the progress of the E–W extension. At time $t = 0.3$ the whole of the thickened area has been thinned, but the strongest region (the Ordos) and its northern portion are thicker than the surrounding region.

Two significant features in figure 6 are the narrow N–S-trending thicker striped zones on the western and eastern boundaries of the Ordos, despite the Ordos being a relatively steady block. The western boundary corresponds to the Helanshan-Liupanshan orogenic belt and the eastern boundary to the Taihangshan-Luliangshan palaeo-rift zone.

In the Taihangshan belt, deep layer compression and NE-trending ductile shear zones were developed at 163 Ma and uplifted at 108 Ma (Wang 1998). This locality lies on the North-South Gravity Lineament, which divides the NCB into two geophysical areas.

4. Discussion and conclusions

Our numerical calculation, based on the thin viscous sheet model, has simulated the tectonic evolution of the NCB and approximately reproduced its large-scale features. The crust thickened due to the Triassic–Jurassic N–S shortening but when the far-field stress changed its orientation or magnitude, the previously thickened crust collapsed immediately. This E–W stretching eventually produced the extensional basins in the NCB.

The thinning process is complex but the numerical experiment described in the previous section is only a very simple model for only a short period of geological time. This is because a rapid stretching of continental lithosphere produces thinning and meanwhile, the passive upwelling of hot asthenosphere (McKenzie 1978a, 1978b). Here, therefore, the strong thinning of the NCB is not only caused by extension: such extension in this experiment accounts for only 30% thinning in the NCB. The thinning of more than 100 km must also be attributable to other effects, such as heat transform (Menzies *et al* 1993).

The widespread occurrence of late Mesozoic lamprophyres, basaltic lavas and mafic intrusives of enriched Sr–Nd isotopic composition in the NCB suggest that the Archaean enriched lithospheric mantle played an important role in the generation of mafic magmas (Guo *et al* 2001). Decompressional melting of such an enriched lithospheric mantle and the induced upwelling of the hot asthenosphere would certainly result in lithospheric thinning. It seems that the Archaean lithospheric keel was removed mainly through partial melting during the magma generation.

In summary, the Mesozoic–Cenozoic evolution of the NCB was a very complex process: the numerical modelling of this evolution described here has provided only preliminary results.

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