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Numerical modelling of lithosphere evolution in the North China Block: Thermal versus tectonic thinning

Ge Lin[a,*], Y. Zhang[b], Feng Guo[a], Yuejun Wang[a], Weiming Fan[a]

[a] *Key Laboratory of Marginal Sea Geology, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Wushan, Guangzhou 510640, PR China*
[b] *CSIRO Exploration and Mining, P.O. Box 1130, Bentley, WA 6151, Australia*

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Abstract

In an attempt to understand the dynamics of lithospheric thinning in the North China Block (NCB), two-dimensional finite-difference numerical models have been constructed to simulate the lithosphere thinning process in the NCB. The models consider the theory of conductive thermal transfer on earth and explore how lithospheric thickness will vary in response to the changes in the thermal conditions of the lithosphere. As a process independent of thermal thinning, the effect of mechanical tectonic extension on lithospheric thickness has been explored by incorporating a constant extensional displacement rate at the lateral edges of the model. The results of a model involving only mechanical extension show that the thinning of the lithosphere is still quite limited to not more than 50 km even under a 25% extension. In contrast, the results of the thermal model quantitatively demonstrate that for a given thermal conductive rate and radioactive heating condition, the increase of the mantle thermal flux at the base of the lithosphere can trigger a great deal of changes in both the thermal state and the lithospheric thickness. The lithospheric thickness in the NCB could be thinned from an original thickness of 200 km to the new thickness of <100 km, when the mantle thermal flux was increased to 35–40 mWm^{-2}. Therefore, thermal perturbation seems to be the predominant mechanism responsible for the significant lithosphere thinning in the NCB. The effects of mechanical tectonic extension may become more profound on lithosphere thinning at a later stage when the lithosphere had already been heterogeneously thinned. A temporary and genetic link between the NCB lithospheric thinning and the Cretaceous global event is put forward to interpret the lithospheric evolution throughout the eastern China in late Mesozoic.

Keywords: Numerical modelling; Thermal thinning; Tectonic thinning; Lithosphere evolution; North China Block

1. Introduction

The lithospheric evolution of the North China Block (NCB) (Fig. 1) has attracted considerable attention over the last two decades due to its dramatic change from a cold and thick (180–220 km) lithosphere in early Paleozoic to a hot and thin (70–80 km) lithospheric mantle in Cenozoic time (e.g., Griffin et al., 1992, 1998; Menzies et al., 1993; Fan et al., 1993, 2000; Xu, 2001). This change requires considerable thinning of the lithosphere during the last 400

* Corresponding author. Tel.: +86 20 85290763; fax: +86 20 85290130.
E-mail address: gelin@gig.ac.cn (G. Lin).

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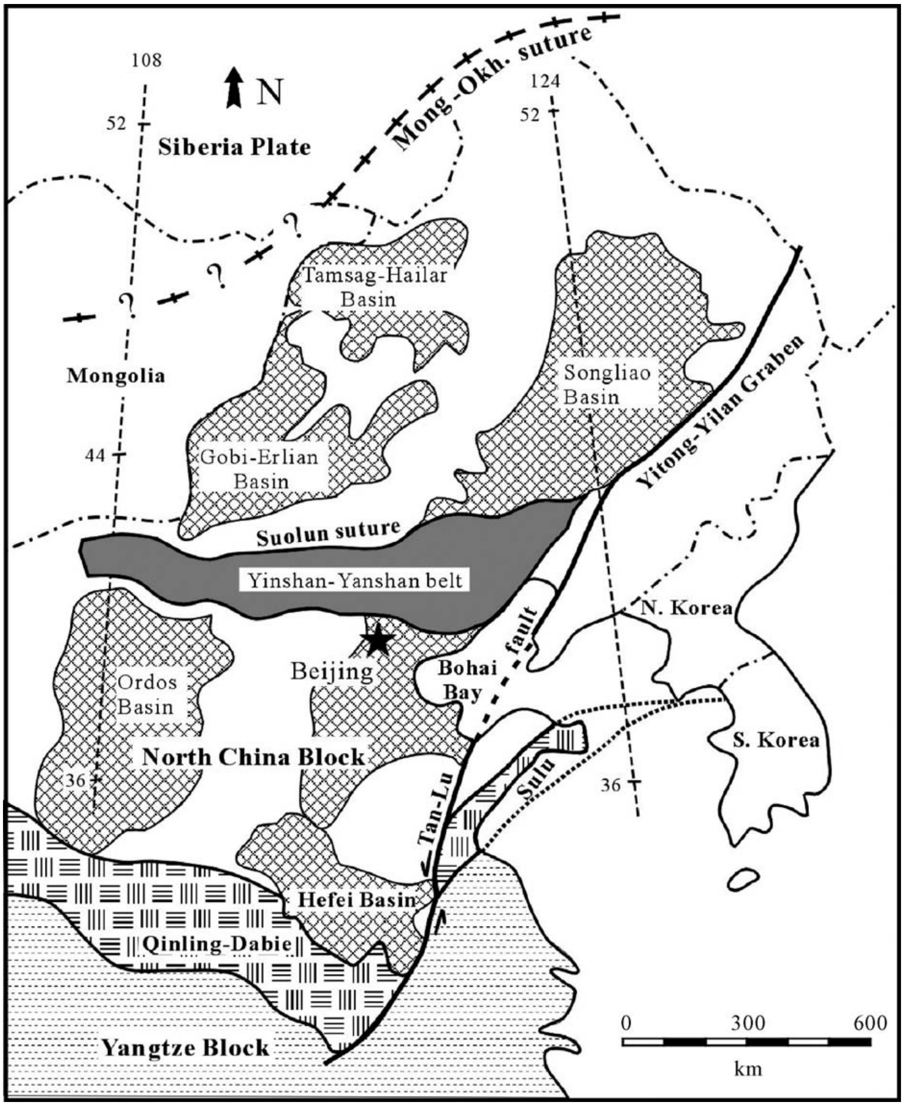

Fig. 1. Structural outline of the North China Block and neighboring regions.

million years, which may have occurred during Mesozoic–Cenozoic times. Many hypotheses, such as destabilization initiated by the Indo-Eurasian collision (Menzies et al., 1993), replacement by newly accreted mantle (Zheng et al., 2001), lithospheric delamination (Gao et al., 2002) and thermo-chemical erosion (e.g., Xu, 2001) have been proposed to explain the thinning process in the NCB lithosphere. The previous studies have mainly focused on the chemical and isotopic variations of the lithospheric mantle on the basis of detailed description of mafic magmatism and mantle xenoliths. However, whether mechanical processes played an important role in the lithospheric thinning is still unclear.

The boundary between lithosphere and asthenosphere can be considered essentially as a thermal boundary (e.g., McKenzie and Bickle, 1988). Temperature variation across this boundary can lead to the change of lithosphere thickness. In the case of elevated temperatures in a lithospheric layer above 1200 °C, partial melting will begin (Yoder, 1976) and the result of this will be a thinned lithosphere. Thermal state of a lithosphere is mainly controlled by three factors: radioactive heat production, mantle thermal flux and thermal conductivity of rocks (Sandiford and McLaren, 2002; Sandiford et al., 2001, 2002). Each of them are variable along with the evolution of a lithosphere throughout geological history; for example, mantle thermal flux may vary from about 10 to 40 mW m^{-2} among different tectonic terrains

(Sandiford et al., 2002). As a consequence, this will be reflected in the variation of lithospheric thickness. The thermal aspect of lithosphere development has been previously considered in the modelling of plate subduction, convergence and collision (e.g., Andreescu and Demetrescu, 2001; Arnold et al., 2001).

The other mechanism that can thin lithosphere is a tectonic process, mechanical extension. This is essentially a mechanical process dominated by mechanical deformation and material movement/displacement. Stretching during an extension event can also result in a thinner and longer lithosphere. Extensional tectonics has attracted great interests from geoscientists for a long time. Since the original lithospheric stretching model of Artemjev and Artyushkov (1971) and the further modified models by McKenzie (1978), a huge amount of work has been done in the field and can be found in numerous papers (e.g., Wernicke and Burchfiel, 1982; England and McKenzie, 1982; Buck and Toksöz, 1983; England, 1983; Turcotte and Emerman, 1983; England and Houseman, 1985; Cloetingh and Wortel, 1986; Lister et al., 1986; Houseman and England, 1986a, 1986b; Braun and Beaumont, 1987; Lister and Davis, 1989; Govers and Wortel, 1993; Huismans et al., 2001).

The two mechanisms described above are the main reasons why we see large variations in lithospheric thickness spatially across various continents and temporally throughout geological histories. One such area is the NCB that has experienced significant lithosphere thickness changes. While this long period of lithosphere thinning has been broadly attributed to thermo-tectonic changes in the Block since the Palaeozoic (e.g., Griffin et al., 1992, 1998; Menzies et al., 1993; Fan et al., 2000; Xu, 2001), questions still remain as to the quantitative relationship of such huge thinning with thermal evolution and/or tectonic extension in the lithosphere. How does temperature change with the increase of mantle thermal flux in a thermal activation event? Are temperature increases sufficient to lead to significant lithosphere thinning? Is tectonic extension a more efficient mechanism for the lithosphere thinning in the region in comparison with a thermal mechanism?

In this study, we aim to explore these questions using a quantitative numerical modelling approach. The models presented in this paper will follow the sequence: (1) the reconstruction of the geotherm for a cold and thick lithosphere at ca. 460 Ma; (2) lithospheric thinning as a result of elevated mantle thermal flux; (3) lithospheric thinning as a result of tectonic extension (stretching); (4) further thinning of a previously thermally thinned lithosphere by tectonic extension (stretching). It needs to be mentioned that this work does not aim to reproduce precisely, the lithosphere profile through the NCB as predicted by geophysical data. The purpose here is to explore those mechanical–thermal processes significant for lithosphere thinning in the NCB and the possible geodynamic links with the global Cretaceous events.

2. Tectonic settings

The general geology of the North China Block (NCB) has been widely covered in the literature (e.g., Griffin et al., 1998; Fan et al., 2000; Guo et al., 2001, 2003; Zhang et al., 2003; Zheng et al., 2001). It is one of the oldest cratons in the Earth, composed of early Archaean and Proterozoic metamorphic rocks with the oldest recorded crustal ages >3.8 Ga (e.g., Liu et al., 1992). It is separated from the Yangtze Block by the Triassic Qinling–Dabie–Sulu collisional belt in the south and from the Mongolian Block by late Paleozoic–Triassic Yinshan–Yanshan–Liaoxi orogenic belt in the north (see Fig. 1). The early Paleozoic diamondiferous character for some of the kimberlite pipes (ca. 460 Ma) suggests that the early Paleozoic lithosphere was thick and stable to depths within the diamond stability field (i.e., 180–200 km) with a low thermal flux <40 mW m^{-2} (Chi and Lu, 1996; Menzies et al., 1993). In contrast, the Cenozoic lithosphere was thin (<80 km) and Cenozoic lithospheric mantle was mainly composed of chemically fertile spinel peridotites of low Sr and high Nd isotopic compositions, as is revealed by basalt-borne mantle xenoliths (e.g., Fan et al., 2000; Griffin et al., 1992, 1998). Nevertheless, *P*–*T* estimation of asthenosphere-derived tholeiitic basalts around the Bohai Bay indicated that the lithospheric thickness in the NCB was the thinnest in early Cenozoic, up to about 55–60 km (Xu et al., 1995).

The late Mesozoic geology of the NCB is characterized by strong tectono-magmatic activities, which led to the extensive emplacement of magmas and the subsequent formation of NE to NNE-trending fault-rift basins. Such a tectonic event required voluminous heat supply and tectonic extension. For this reason, this evolution stage has been widely considered as an important lithospheric thinning period, during which the cratonic lithosphere was destroyed and thinned (e.g., Guo et al., 2001, 2003; Zhang et al., 2003; Xu, 2001; Gao et al., 2002).

Compared with the results derived from petrological and geochemical studies, data from geophysical surveys show that the present-day thinness of the lithosphere ranges from ∼70 km at the center of Bohai Bay in the eastern NCB

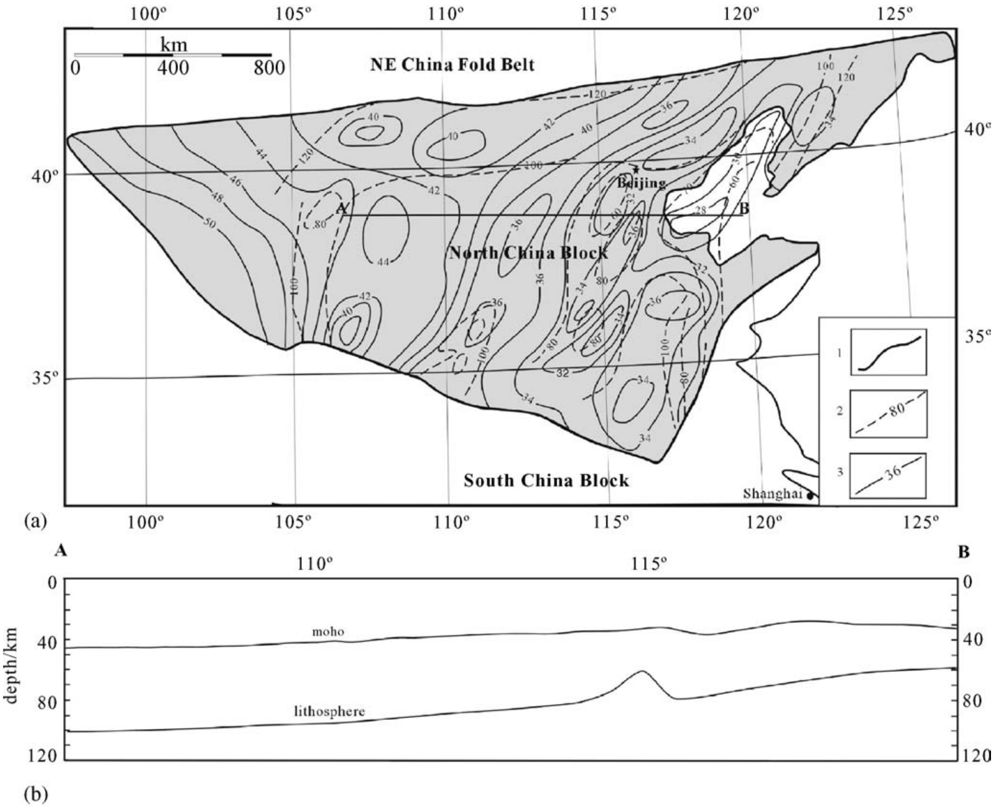

Fig. 2. (a) Contours of present-day crust and lithosphere thickness in the North China Block (after Ma, 2002). (b) Variations of crust and lithosphere thickness along profile A–B (see a). (1) The boundary of the NCB; (2) lithosphere thickness; and (3) crust thickness.

to 120 km in the Erdos basin from the western NCB (Fig. 2) (Yuan, 1996; Fang et al., 2001; Ma, 2002). Similarly, the crustal thickness is the thinnest at the center of Bohai Bay around 26 km and increases to 45 km in the Erdos basin. Such variation trends suggest that the lithospheric thinning was inhomogeneous across the NCB, i.e., the extent of lithospheric thinning is stronger in the eastern than that in the western NCB, with the strongest in the Bohai Bay.

3. Model description

Numerical thermal modelling has been conducted using the finite difference computer code FLAC (Fast Lagrangian Analysis of Continua; Itasca, 2000). The code simulates a geological entity in terms of a 2D mesh comprising quadrilateral elements, and is capable of modelling conductive thermal transfer and geological deformation. The code has been successfully applied to studies of various structural geological and tectonic problems (Vermeer and de Borst, 1984; Hobbs et al., 1990; Patino Douce et al., 1990; Zhang et al., 1994, 1996, 1998, 2000; Strayer et al., 2001).

Modelling of conductive heat transfer in the current models follows Fourier's Law, which assumes a linear relationship between heat flow and temperature gradient (Ranalli, 1987; Itasca, 2000). The model considers internal heat production, basal thermal flux and a surface temperature of 25 °C as internal and boundary thermal constraints. Thermal conductivity is the major thermal parameter controlling thermal transport through the thermally isotropic medium. When thermal computation is coupled with mechanical modelling, temperature distributions in the model are also modified according to geometrical changes caused by mechanical deformation.

Mohr–Coulomb elastic–plastic constitutive laws (Vermeer and de Borst, 1984; Jaeger and Cook, 1979; Ord, 1991; Itasca, 2000) are employed to model mechanical deformation in crust. Under this rheology, rocks, loaded by stress or displacement rates (velocities), behave initially elastically until the maximum shear stress reaches a critical value (yield stress), and then deform plastically to large strain; yielding follows the Mohr–Coulomb yield criterion so that

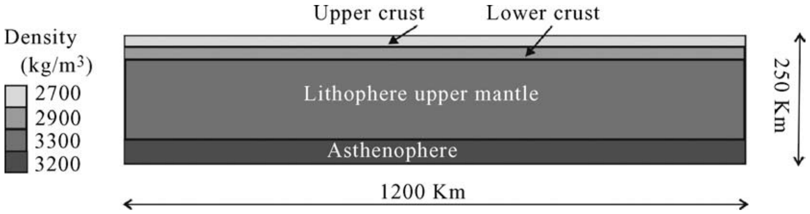

Fig. 3. Initial geometry of the current numerical models.

Table 1
Mechanical and thermal parameters of the models

Layer	ρ (kg m^3)	G ($\times 10^{10}$ Pa)	K ($\times 10^{10}$ Pa)	C ($\times 10^6$ Pa)	T ($\times 10^6$ Pa)	ϕ (°)	ψ (°)	η (Pa S)	κ (Wm^{-1} k^{-1})	q (μW m^{-3})
Upper crust	2700	1.6	2.667	12	6	25	2		2.0	2.0
Lower crust	2900	2.8	4.666	20	10	25	2		3.0	0.20
Lithospheric upper mantle	3300							1×10^{21}	4.0	0.02
Asthenosphere	3210							1×10^{20}	4.0	0.02

ρ: Density; G: shear modulus; K: bulk modulus; C: cohesion; T: tensile strength; ϕ: friction angle; ψ: dilation angle; η: viscosity; κ: thermal conductivity; q: heat production rate.

the flow stresses are strongly pressure dependent. The deformation of the lithospheric upper mantle and asthenosphere units follows a linear viscous rheology (Jaeger and Cook, 1979; Turcotte and Schubert, 1982; Itasca, 2000), which assumes a linear relationship between stress and strain rate (controlled by viscosity). In this model, the material can flow in a manner of viscous-creep under small stress and strain rate.

The construction of a lithosphere-scale thermal model requires the specification of geometry structure, density, specific heat, thermal conductivity, radioactive heat production and mantle thermal flux. Mechanical deformation models require the specification of density, bulk modulus, shear modulus, cohesion, tensile strength, friction angle and dilation angle for the Mohr–Coulomb elastic–plastic materials, and density and viscosity for the linear viscous materials. The geometry of our conceptual cross-section is determined based on our understanding of the geological structures and petrological data of the region (see Figs. 1 and 2). This conceptual model (Fig. 3) simulates a cross-section column of 1200 km long and 250 km deep, including upper crust (20 km thick), lower crust (25 km), lithospheric upper mantle (155 km) and asthenosphere (50 km). The rock mechanical and thermal parameters for the different layers of the model are given in Table 1 (Fowler et al., 1988; Andreescu and Demetrescu, 2001).

Three sets of models have been explored: (1) lithospheric thinning due to tectonic extension (stretching); (2) lithosphere thinning as a result of elevated mantle thermal flux; and (3) tectonic extension of an already thermally thinned lithosphere. We have adopted the view that the boundary between lithosphere and asthenosphere represents a thermal boundary, temperature is 1200 °C (the solidus) (Yoder, 1976), and therefore, temperature variation across this boundary can change lithosphere thickness, which is reflected in the change of the depth of the 1200 °C isotherm boundary. In the case of elevated temperatures in the lithosphere above 1200 °C, it is assumed that the situation of a thinned lithosphere occurs.

4. Modelling results

4.1. Reconstruction of the geotherm for the NCB at 460 Ma

The thermal state of the NCB at 460 Ma reflects a stable and cold lithosphere with low thermal flux input from deep mantle. A series of models involving different thermal parameters has been explored to establish these conditions (Fig. 4). The results show that the thermal state of the lithosphere in the NCB at 460 Ma can be approximately reconstructed by assuming a mantle thermal flux of 13 mWm^{-2}, heat productions of 2.0, 0.2 and 0.02 μW m^{-3}, and thermal conductivities of 2.0, 3.0 and 4.0 W m^{-1} K^{-1}, respectively, for the upper crust, lower crust and upper mantle; these parameters are consistent with published data (Fowler et al., 1988; Andreescu and Demetrescu, 2001). At thermal equilibrium, the base of the lithosphere at the 200 km depth in the model has a temperature of about 1200 °C, compatible

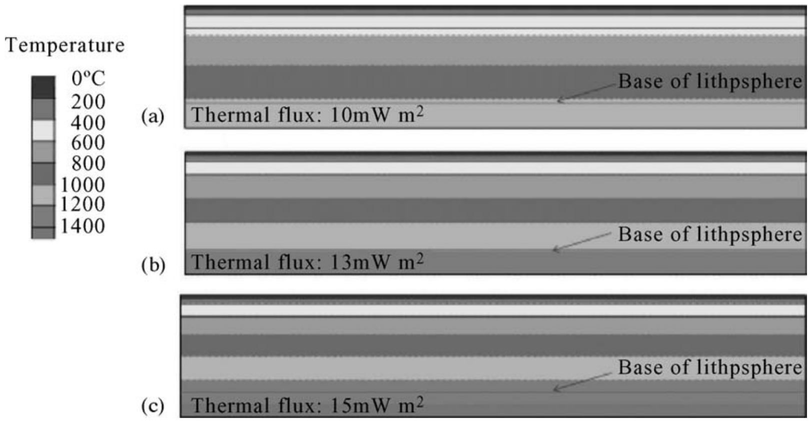

Fig. 4. The final equilibrium geothermal gradients of three thermal models with three different mantle thermal flux rates: (a) 10 mW m^2; (b) 13 mW m^2; and (c) 15 mW m^2.

with the solidus temperature (Yoder, 1976). The equilibrium thermal state of this model has been used in the following models to investigate the influence of increasing mantle thermal flux in thermal activation stages.

4.2. Lithospheric thinning due to tectonic extension

One of the possible mechanisms for lithospheric thinning in the NCB is tectonic extension (stretching). The basic model is shown in Fig. 3. We have explored this scenario by incorporating a constant extensional displacement rate at the lateral edges of the model to show the process of the mechanical extensional lithospheric thinning. The displacement field in this case essentially reflects lateral material movements associated with horizontal extension. It is noted that by a bulk extension of 6.25%, the lithospheric thickness would be thinned to 189 km from the initial thickness of 200 km, that is, the decrease of the thickness of the lithosphere is only 11 km (Fig. 5). Even by the stage of 25% bulk extension, at which the lithosphere slab would become much longer, the thickness of the lithosphere still ranges from 147 to 171 km. The extent of lithospheric thinning is still very limited (less than 53 km), far less than the amount of the lithosphere thinning known for the NCB. Similar to the deformation of the lithospheric mantle, the crust shows inhomogeneous stretching as illustrated in Fig. 5. The locations of the highest extensional strain within the crust correspond to that of the thinnest parts along the lithosphere, favorable sites for the development of shear zones and reactivation of pre-existing major faults. In summary, the modelling results show that the tectonic extension would cause limited thinning

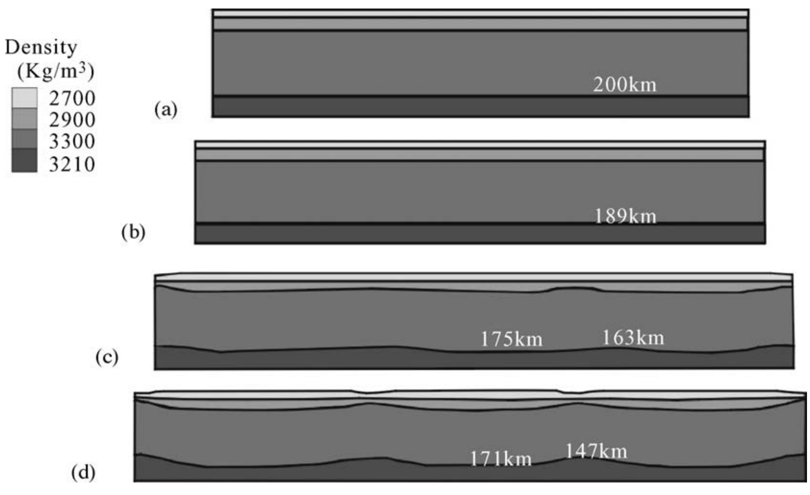

Fig. 5. The variations of the lithosphere thickness in a model with only mechanical tectonic extension (stretching) for different extension stages: (a) 0%; (b) 6.25%; (c) 18.75%; and (d) 25%.

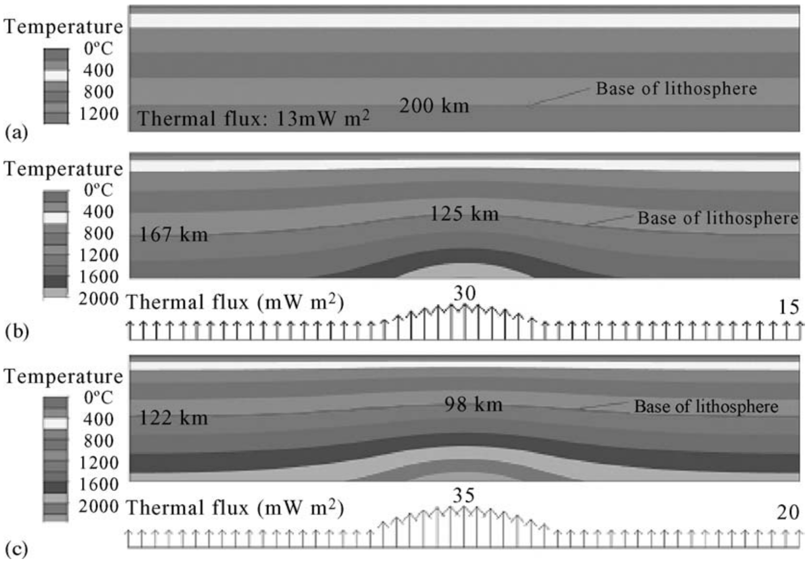

Fig. 6. The results of thermal models simulating the influence of an increase in mantle thermal flux on lithosphere geotherm and thickness. (a) The starting thermal state of the models before elevation of thermal flux (this is the final equilibrium geothermal state of a thermal model with a uniform thermal flux of 13 mW m^2; also see Fig. 4b. (b) Final geothermal state and lithosphere thickness of a model with the elevation of thermal flux to the range of 15–30 mW m^2. (c) Final geothermal state and lithosphere thickness of a model with the elevation of thermal flux to the range of 20–35 mW m^2. In (b) and (c), the lengths of arrows at the bottom of the diagrams illustrate the variations of flux rates along the base of the model.

of the lithosphere, at the same time, it would result in localized crustal stretching and the formation of fault-rifting basins.

4.3. Lithosphere thinning under the increase of mantle thermal flux

Onset of a thermal activation event manifested at lithosphere levels can be considered as the result of intensified upward heat transport, which is fundamentally controlled by core–mantle interactions and the formation of mantle plume and convection cells. An important aspect of this process is the increase of thermal flux from deep mantle into the shallower lithosphere–asthenosphere domain. To simulate thermal and lithospheric structural change in the NCB since the Precambrian, an increase in mantle thermal flux is considered in the following models, based on the geotherm established above for a cold and thick lithosphere revealed by the geochemical analyses of early Paleozoic kimberlites and their diamond inclusions.

The mantle thermal flux distribution at the base of the lithosphere can be inhomogeneous. Our approach here is to use the reconstructed geothermal state for the thick lithosphere before thinning (Fig. 6a) as the initial state, and increase thermal flux along the central segment of the model base to simulate an elevated thermal flux situation; the inhomogeneous rates of the increased thermal flux follow profiles as illustrated in Fig. 6b and c. In the first model (Fig. 6b), thermal flux increase takes such a profile that it varies from 15 to 30 mW m^{-2}, with the maximum flux rate the central location of the model. At equilibrium, the 1200 °C temperature envelope sits at much shallower depth levels ranging from 125 to 167 km. By assuming partial melting and probably also mineralogy phase changes at/above 1200 °C (Yoder, 1976), the portion of the original lithosphere below these depth levels now becomes part of asthenosphere. This indicates that an increase in mantle thermal flux at such a scale can lead to a maximum lithosphere thinning of 75 km, a very efficient thinning mechanism. In the second model (Fig. 6c), mantle thermal flux is further increased to 20–35 mW m^{-2}. The resultant 1200 °C temperature envelope is now located at 98–122 km depth levels. This represents a maximum lithosphere thinning of 102 km and a minimum lithosphere thickness of 98 km for the NCB. Continuing to increase thermal flux along this line will lead to even more thinning and a thinner lithosphere. For example, a thermal flux profile with a maximum value of 40 mW m^{-2} can result in a minimum lithosphere thickness of less than 90 km. These results demonstrate that the mechanism of thermal thinning alone is sufficient to modify the lithosphere thickness

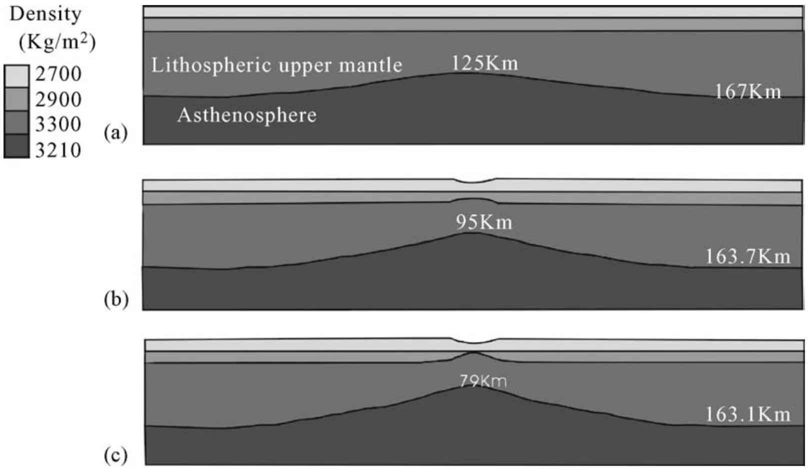

Fig. 7. The development of displacement fields for a coupled mechanical and thermal model simulating the influence of mechanical extension on an already thermally thinned lithosphere. (a) The initial geometry of a model, which is the final state of a thermal-thinning model with a thermal flux of 15–30 mW m^2 (see Fig. 6b). (b) and (c) The distributions of displacement vectors at the stage of 2.7 and 4.5% bulk extension, respectively.

of the NCB to the levels reported in previous studies from geophysical and geochemical observations (Griffin et al., 1992; Menzies et al., 1993; Menzies and Xu, 1998).

4.4. Effect of tectonic extension

In this model, we simulate the effects of mechanical tectonic extension on a lithosphere that is already thinned by the thermal process. The final configuration of a thermally thinned lithosphere in the model with the elevated mantle thermal flux of 15–30 mW m^{-2} (Fig. 7) is adopted as the initial state of the current model and a constant extensional displacement rate is applied to the lateral edges. The lithospheric thickness would be thinned to 79 km from the initial 125 km in the middle of the model and from 167 to 163 km near both lateral edges of the model when the amount of extension is only 4.5%, with decrease of the thickness of the lithosphere by 46 km. This indicates that the tectonic extension of an already thermally thinned lithosphere could lead to a maximum lithosphere thinning of 120 km. The modelling results indicate that the effect of mechanical tectonic extension on lithosphere thinning is much greater while the extension begin with the activity of the mantle thermal flux, in comparison with the cases with mechanical extension only or thermal process only. In this case, bulk extension is dominantly localized at the segment of the lithosphere with the maximum thermal thinning, and a few percent bulk extension can generate much greater thinning (about 120 km) at such locations.

5. Discussion and conclusions

The modelling results above suggest that both the increase of mantle heat flux and tectonic extension (or stretching) are effective means for thinning of the NCB lithosphere. One of the most important aspects in applying the numerical modelling results to geological models is whether the parameters of the numerical model (e.g., thermal perturbation for heat flux increase, extensional styles for crustal stretching) can be comparable with the geological observations. For this purpose, we will firstly find the evidence for both kinds of mechanisms that occurred since the Mesozoic time, and discuss the possible geodynamic model for the lithospheric evolution in the NCB.

5.1. Evidence for thermal perturbation beneath the NCB

The direct manifestation for increase in mantle heat flux (thermal thinning) through the lithosphere is reflected by the partial melting of lithosphere or underlying asthenosphere. In the NCB, the extensive melting of the lithospheric mantle in the interior of the NCB and its margins (e.g., the Dabie–Sulu orogen on its south and the Yinshan–Yanshan belt on its north) suggests either the occurrence of abrupt thinning of the lithosphere that marks asthenospheric upwelling and thermal elevation, or a major impact from an abnormally hot plume that caused the widespread emplacement of mafic–ultramafic magmas. Geochemical investigations on late Mesozoic mafic magmatism in both the interior and margins of the NCB suggest that few asthenosphere-derived magmas were present and most of them were derived from long-term LILE- and LREE-enriched mantle sources (e.g., Guo et al., 2001, 2003; Fan et al., 2001, 2003; Zhang et al., 2003), arguing against the existence of plume impact on the base of the lithosphere.

On the other hand, the interaction between the East Asian continental margin and the Pacific plate caused the large-scale displacement of lithosphere-scale faults, e.g., the Tan-Lu wrench fault system (e.g., Xu et al., 1987). Along the fault distribute numerous shoshonitic volcanic rocks and plutons, and high-Mg basalts in the fault-rifting basins around the Bohai Bay. A favorable interpretation for the occurrence of contemporaneous shoshonitic magmas is that the strike-slipping movement of the Tan-Lu Fault triggered the extensive shearing of the deep lithosphere, which is a potential drive for causing the crustal deformation and thermal perturbation of the thickened lithosphere. Based on detailed petrological and mineralogical studies on the Cenozoic basalt-hosted peridotite xenoliths along the Tan-Lu fault, Xu et al. (1996) suggested that the recrystallized and sheared peridotite xenoliths had higher equilibrium temperature than prophyroclastic ones, representing the sign for the occurrence of thermal perturbation in the lithospheric mantle. On a global scale, the contemporaneous accretion of oceanic crust had attained its highest level, also indicating that the global mantle convection was active for a hotter earth during this period (e.g., Larson, 1991).

In summary, despite the absence of an abnormally hot plume beneath the NCB, the thermal perturbation of the lithosphere is a potential cause for basaltic generation in the NCB, indicative of thermal thinning during the Mesozoic lithospheric evolution.

5.2. *Evidence for extensional thinning of the NCB lithosphere*

In the NCB, extensional deformation styles are widely distributed in both the interiors and its margins, particularly the formation of fault-rift basins around the Bohai Bay (e.g., from north to south are the Xialaiohe, Jizhong, Huanghua, Jiyang and Laiyang basins), the extensive emplacement of early Cretaceous granitoid plutons (e.g., Ma et al., 1998; Wang et al., 1998) and the uplifting of metamorphic core complexes (e.g., Davis et al., 2001). The amount of extension attained its highest level in early Tertiary with the opening of the Bohai Bay and eruption of tholeiitic basalts in the area. Xu et al. (1995) reported that the lithospheric thickness of the NCB was about 55–60 km at this period.

It remains argumentative about the relationship between magmatism and extension. This is crucial for interpreting the results of the model that incorporates lateral displacement in an already thinned lithosphere, in the context of the geology and tectonics of the NCB. This model suggests that as an efficient thinning scenario, thermal thinning may be prior to extensional tectonics, i.e., at the earlier stage thermal perturbation was predominant whereas tectonic extension played an important role at the later stage. In the NCB, despite the existence of numerous basins throughout the Mesozoic time, most of them mainly show compressional deformation styles before the beginning of the Cretaceous; even some early Cretaceous sedimentary basins show such features. The formation of the basins may be a consequence of crustal doming and uplifting, and was probably resulted from the associated magma emplacement. The extension became stronger from late Cretaceous to early Tertiary, when a series of NE- to NEE-trending rift basins formed. The strongest crustal stretching and shearing ultimately led to the opening of the Bohai Bay. On the other hand, although the thinnest lithosphere (55–60 km) or the maximum thinning scale was recorded by early Tertiary tholeiitic basalts around the Bohai Bay, the scale of magmatism including the voluminous emplacement of ultramafic–mafic magmas and granitoid plutons, the eruption of basalts and intermediate-felsic lavas had attained the highest level during early Cretaceous (135–120 Ma). This means that the strongest magmatic activity in the NCB was prior to the highest amount of crustal extension, consistent with the suggestion of our current model.

5.3. *Implications for the geodynamics of NE China*

One of the most concerning issues for geologists working in China is the existence of late Mesozoic NE-trending tectono-magmatic belt with a length of 5000 km from the northeastern China across the NCB and finally to the offshore areas in the southeastern China, which constitutes the largest belt in the NE Asian continental margin. Previous studies have been attributed the formation of this belt to the NW-directional subduction of the paleo-Pacific Ocean, but this hypothesis is inconsistent with the data derived from the geophysical survey of the Pacific plate, include the Kula, Fallanon and Izanagi plates, which suggested that the beginning of the NW-dipping subduction toward the NE

Asian continental margin is not earlier than 100 Ma (Engebretson et al., 1985). If so, such a large-scale of tectono-magmatic activity should require a new geodynamic model to account for the lithospheric evolution in the NE Asia. Previous hypotheses generally gave emphases on the Triassic collision between the NCB and the Yangtze block and the middle-late Jurassic collision between the North China-Mongolian Block and the Siberian Plate (e.g., Zhang et al., 2003; Fan et al., 2003), or a combined effect resulted from the surrounding plate interactions (e.g., Guo et al., 2003). Nevertheless, for a lithosphere with a normal thermal gradient, it seems unlikely to ascribe the extensive tectono-magmatic event in eastern China to the theoretical convective thinning or chemo-thermal erosion of the lithosphere. Despite the predominant intermediate-felsic compositions in the belt, the total area of late Mesozoic igneous rocks in the belt exceeds 4,000,000 km^2, an eruption scale defined by any of the large igneous provinces. Thus, we speculate that beneath the eastern China existed a hotter convective mantle, which was possibly resulted from the stronger intensity of deeper mantle perturbation or more active core–mantle interaction in late Mesozoic.

During this period, the production of the oceanic crust had attained the highest level, and this defined a long Cretaceous normal magnetic time from 125 to 90 Ma, consistent with the eruption episodes of the largest Ontong-Java large igneous province in the southwestern Pacific Ocean. Larson (1991) proposed a superplume hypothesis to interpret the global Cretaceous event, and Filatova (1998) suggested that the formation of Cretaceous active continental margins was correlated with this event. Considering the geological observations on the lithospheric evolution of the NCB and other blocks in eastern China, and our modelling results that highlight the importance of higher mantle heat fluxes at the base of lithosphere, we thus conclude that the lithospheric thinning in the NCB and the extensive tectono-magmatic activities all over the eastern China may reflect the thermo-tectonic response to the global Cretaceous event.

6. Conclusions

Numerical modelling results of this study provide information about the possible effects of both the thermal and tectonic extensional impact on the NCB lithosphere. It seems likely that the increase of mantle heat flux is a main thinning mechanism to account for the lithospheric thinning of >100 km, whereas mechanical tectonic extension may be subordinate. Considering the geological history of the NCB since early Palaeozoic (e.g., from ca. 460 Ma, when diamond-hosting kimberlites were extruded), especially from early Cretaceous to early Tertiary, a thermal perturbation at the base of the lithosphere before intensive tectonic extension is probably responsible for the widespread magmatism in early Cretaceous and the subsequent formation of fault-rift basins in this block. The results of this study favour a temporary and genetic link between the lithospheric evolution of the NCB and the global Cretaceous event. The latter was likely related to broad active core–mantle interaction and provided necessary thermal conditions for a high mantle heat flux beneath the NCB.

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