Geothermal evidence of Meso-Cenozoic lithosphere thinning in the Jiyang sub-basin, Bohai Bay Basin, eastern North China Craton

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A B S T R A C T

The Bohai Bay Basin is at the center of lithosphere destruction and thinning in the eastern North China Craton (NCC). In this paper, the thermal lithospheric thicknesses of the Meso-Cenozoic Jiyang sub-basin in the Bohai Bay Basin were calculated by reconstructing the thermal history of the sedimentary basin using apatite fission track and vitrinite reflectance data. The results show that the Jiyang sub-basin experienced two heat flow peaks in the late Early Cretaceous and in the Middle to Late Paleogene, with heat flow values of 84 ~ 88 mW/m² and 85 ~ 88 mW/m², respectively. The thermal lithosphere thicknesses of the Jiyang sub-basin, calculated from the modeled thermal histories, experienced two thinning stages in the Cretaceous and in the Paleogene. The lithosphere began with an initial thickness of 150 km in the Early Mesozoic and reached a thinning peak of 51 km in the late Early Cretaceous. The thickness then increased to approximately 80 km at the end of the Cretaceous. A second thinning peak occurred in the Middle and Late Paleogene, with a thickness of only 48 km, which corresponds to a rift phase in the Bohai Bay Basin. The lithosphere thinned thereafter and is 78 km at present. The North China Craton now has a thin lithosphere. Our research provides new geothermal evidence for the lithospheric thinning of the NCC.

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1. Introduction

The North China Craton (NCC), which has an evolution history of 3.8 Ga, is located in northern China. Many studies of igneous and metamorphic rocks have been conducted to determine the development and evolution of the NCC during the Precambrian (Wilde et al., 2002; Li et al., 2006; Wan et al., 2006; Zhao et al., 2009; F.Q. Zhang et al., 2011; H.F. Zhang et al., 2011; Tang et al., 2013; Zhang et al., 2013). The NCC was stable for a long period (1.7 ~ 2.0 Ga) (Lu et al., 2005; Yang et al., 2005). During that period, the NCC had a so-called “cool” lithosphere with a thickness of up to ~200 km (Zhang and Yang, 2007; F.Y. Wu et al., 2008). However, the NCC has experienced lithospheric thinning since the late Triassic. The North China lithosphere has decreased in thickness by possibly more than 120 km since the Late Mesozoic (Menzies et al., 1993), which has resulted in mantle transformation, crust reconstruction, magmatic activity, the formation of a Mesozoic basin and plateau-uplift-to-terrain conversion (Gao et al., 2004, 2008; F.Y. Wu et al., 2008; Zhang et al., 2008). Thinning of the North China lithosphere has been confirmed by evidence from the structural geology, mantle xenoliths, magmatic petrology, magmatic geochemistry and geophysics (Chen, 2009; Zhu et al., 2012; Cheng et al., 2013; Xia et al., 2013; Zhao et al., 2013), but debates related to the timing, mechanisms and controlling factors of this thinning remain. There are four main views of the timing of the minimum thickness (or thinning peak) of the North China lithosphere: (1) the Middle Jurassic (Gao et al., 2004), (2) the Early Cretaceous (135 ~ 115 Ma) (F.Y. Wu et al., 2008), (3) the Cretaceous ~ Early Cenozoic (Y.G. Xu et al., 2004; Xu, 2006) and (4) the Cenozoic (Lu et al., 2006). The thinning mechanisms mainly include thermo-chemical erosion of the lithospheric base (Menzies and Xu, 1998; Xu, 2001; Lu et al., 2005; Y.S. Liu et al., 2005; Zheng et al., 2005; Menzies et al., 2007; Zhai et al., 2007) and delamination of the mantle (Gao et al., 2004; Wu et al., 2005b; Xu, 2006; Deng et al., 2007; Gao et al., 2008; Xu et al., 2013).

The formation and evolution of sedimentary basins are the shallow response of deep geodynamic processes. Therefore, the thermal histories of sedimentary basins may provide continuous temporal and spatial evidence that can reveal deep geodynamic processes. Geothermal research plays an important role in continental craton evolution studies (Morgan, 1985; Pollack, 1996; Michaut et al., 2009). To a certain extent, a quantitative study of the tectono-thermal evolution of sedimentary basins may reflect the characteristics of continental dynamics and reveal the thermal background during the lithosphere’s evolution. In addition, the paleo-temperature controls the hydrocarbon generation of
source rocks in the basins. Thus, the thermal evolutions of basins also play an important role in studying the process of hydrocarbon accumulation and quantitative evaluations of oil and gas resources.

A thermal lithosphere is a type of lithosphere dominated by heat conduction (Morgan, 1984; Rudnick et al., 1998), and a thermal lithosphere's thickness is defined by the base of the thermal lithosphere as the intersection of a geotherm with a mantle adiabat $T_m = 1300$°C (Rudnick et al., 1998; Artemieva and Mooney, 2001). Thinning of the North China lithosphere mainly occurred in the eastern block of the NCC, and the Bohai Bay Basin is located at the center of the cratonic destruction. In this study, the thermal history of the Jiyang sub-basin, a sub-basin in the Bohai Bay Basin, was reconstructed using vitrinite reflectance and apatite fission track data. The thermal lithosphere thicknesses during the Meso-Cenozoic were then calculated based on the thermal history and thermal conductive theory, considering the lithosphere a conductive layer overlying the convective adiabatic mantle. This work may provide new evidence for the lithospheric thinning of the NCC.

2. Geologic setting

The Jiyang sub-basin is an oil-rich region in the Bohai Bay Basin, which is located in the eastern block of the NCC and is the center of the lithospheric thinning and destruction of the NCC (Fig. 1). This Meso-Cenozoic basin developed on an Archean–Paleoproterozoic crystalline basement. The basin experienced a stable depositional phase from the Middle to Late Proterozoic to the end of the Paleozoic (Tian et al., 2000; Hou et al., 2001). The Mesozoic was an important tectonic transition period in the Bohai Bay Basin, with basin formation and magmatic–thermal activities occurring. The basin experienced extensive erosion; thus basal metamorphic rocks were exposed on the surface in most regions of the Bohai Bay Basin due to long-term uplift during the Mesozoic. The Triassic strata are dominated by sandstone, shale and interbedded carbonaceous mudstone. Their thickness is 106 – 900 m and are mainly distributed in the Linqing, Huanghua and Jizhong sub-basins (Zhang et al., 2009). Jurassic sedimentary rocks are widely distributed in the Bohai Bay Basin. The Middle and Lower Jurassic strata consist of shale, sandstone, interbedded carbonaceous mudstone and thin coal seams, and the maximum thickness (400 m) is in the Jizhong sub-basin (Zhang et al., 2009). The Upper Jurassic strata are dominated by intermediate-acidic volcanic rocks, lacustrine sandstone and shale. The Lower Cretaceous succession widely developed volcanic rocks, and the Upper Cretaceous consists of red clastic rock, interbedded igneous rock or pyroclastic rock in the Jiyang sub-basin (Xu et al., 2006; Zhang et al., 2009).

The Jiyang sub-basin developed a rift phase again at the end of the Cretaceous. The sub-basin was filled with a thick Cenozoic lacustrine deposition with a thickness of up to 8000 m in the deep sags. This rift phase can also be divided into four sub-stages (Li, 2003): the initial development of the rift sub-stage from the end of the Cretaceous to the Early Paleogene (74 – 53 Ma), the lateral EW extension sub-stage from 53 Ma to 48 Ma, the strong rift sub-stage from 48 Ma to 37 Ma, and the lateral compression and uplift sub-stage from 37 Ma to 24.6 Ma. The Jiyang sub-basin deposited the Kongdian, Shahejie and Dongying formations during the Paleogene. The sub-basin changed from an extensional stress environment to an extrusion stress environment in the Neogene, and it was mainly filled with plain-fluvial sediments, with a thickness of 1000 ~ 2500 m.

3. Thermal history modeling

3.1. Analytical methods and thermal indicator parameters

Apatite fission track and vitrinite reflectance data were used as thermal indicators to reconstruct the thermal history in this study. To reconstruct the Mesozoic thermal history of the basin, it is important to obtain paleothermal indicators that could reliably record Mesozoic thermal information. Our samples were collected from oil exploration boreholes.

![Fig. 1. Sketch map of structural unit divisions in the Bohai Bay Basin and the study wells used for thermal history reconstruction in the Jiyang sub-basin. Thermal conductivity of each stratum is shown in the stratigraphic column as mean value ± SD from Gong et al. (2003a), where SD is standard deviation. NCC = North China Craton.](image-url)
There are thousands of meters of Cenozoic strata in most sags of the Jiyang sub-basin. Most of the Mesozoic strata have been deeply buried, resulting in the resetting of apatite fission track (AFT) ages and preventing the application of these indicators in the reconstruction of the Mesozoic thermal history. Although the partial annealing zone (PAZ) of apatite could be obtained in some wells in the sags, ideally, we would have been able to select Mesozoic thermal indicators from wells where significant erosion occurred at the end of the Mesozoic and/or Cenozoic due to tectonic uplift. In these cases, the thermal indicators may retain their recorded thermal information and reveal the Mesozoic thermal history (Fig. 2). Based on these tectonic exhumation conditions, some wells in the uplift structural units were selected for sampling to obtain the vitrinite reflectance and apatite fission track data (Fig. 1).

Mudstone samples were selected to test the vitrinite reflectance, and the measurement results are listed in Table 1. The organic matter of the Paleogene samples is mostly types I and II based on Rock-Eval analysis data and has TOC values of 2.5% – 7.96% (Li, 2003). However, the Mesozoic and Paleozoic mudstone samples are types II2 and III based on the measurement results are listed in Table 1. The organic matter of the Rock-AFT information and Ro data. In our modeling, 1000 thermal paths were developed using the Monte Carlo inverse modeling method; the best-temperature path model identified the thermal history of the sample. Additional attempted path simulations would have provided a better thermal interpretation; however, 1000 simulations are considered sufficient to obtain a reasonably well-constrained interpretation. A temperature path was regarded as the effective thermal history of a sample when the difference between the calculated and measured thermal indicator values arrived at a minimum. The timing of tectonic thermal events and temperature paths, and possibly the burial history of the sample, could be constrained from AFT data. Therefore, an average paleothermal gradient (Gt) from the top of the unit to the sample depth could be calculated from the modeled paleotemperature (Tt) and the corresponding paleo-burial depth (Zt) of the investigated samples (e.g., Gt = (Tt − Tsurface)/Zt). The paleoburial depth of a sample could be obtained from the burial histories. This paleothermal gradient was an average value over the depth interval from the paleoburial depth to the surface. Finally, the paleo-heat flow values were modeled based on paleothermal gradient and burial depth.

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**Table 1**

<table>
<thead>
<tr>
<th>Well no.</th>
<th>Z (m)</th>
<th>Strata</th>
<th>R0 (%)</th>
<th>Well no.</th>
<th>Z (m)</th>
<th>Strata</th>
<th>R0 (%)</th>
</tr>
</thead>
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<td>2175</td>
<td>Eocene</td>
<td>0.60</td>
<td>Y135</td>
<td>3018</td>
<td>Eocene</td>
<td>0.79</td>
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<tr>
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<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>2194</td>
<td>Eocene</td>
<td>0.60</td>
<td>2175</td>
<td>Eocene</td>
<td>0.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2195</td>
<td>Eocene</td>
<td>0.60</td>
<td>2176</td>
<td>Eocene</td>
<td>0.79</td>
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<td></td>
</tr>
</tbody>
</table>

---

Fig. 2. The validity of thermal indicators (shaded areas) to record paleo-temperature information. a. Thermal indicators may retain their recorded thermal information with significant erosion at the end of the Mesozoic and/or Cenozoic. b. Thermal indicators are reset by higher temperature at the later period. The \( \checkmark \) means that the thermal indicators are valid and \( \times \) represents invalid.
on the paleothermal gradient and thermal conductivities of individual strata.

3.2. Basic geological data

The parameters in the thermal history simulation include thermal indicators and basic geological data. The basic geological data include lithological parameters, present-day surface temperatures, geothermal gradients, heat flows, and information on strata. The lithological data include thermal conductivity, heat production, rock densities, the compaction factor and the original porosity. The present-day temperatures and thermo-physical rock properties were those of Gong et al. (2003a). The compaction factor and original porosity data of rocks were obtained from well-logging data based on Sclater and Christie's P3.

![Fig. 3. Vitrinite reflectance in different structural layers in some wells of the Jiyang sub-basin.](image)

Table 2

<table>
<thead>
<tr>
<th>Well no.</th>
<th>Z (m)</th>
<th>Stratum</th>
<th>$\rho_s$ ($10^5$/cm) (Ns)</th>
<th>$\rho_i$ ($10^5$/cm) (Ni)</th>
<th>P ($\chi^2$) (%)</th>
<th>T (Ma) (±1σ)</th>
<th>L (μm) (±1σ) (N)</th>
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<td>Y8</td>
<td>1725.3</td>
<td>Es$^3$</td>
<td>2.446 (316)</td>
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<td>76.75</td>
<td>67.0 ± 4.2</td>
<td>12.2 ± 1.5 (105)</td>
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<td>2316.3</td>
<td>Es$^4$</td>
<td>3.823 (295)</td>
<td>9.862 (761)</td>
<td>0.01</td>
<td>72.6 ± 1.0</td>
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<td>2589.5</td>
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<td>1.845 (202)</td>
<td>9.899 (1084)</td>
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<td>50.9 ± 6.9</td>
<td>9.9 ± 1.8 (106)</td>
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<td>2990</td>
<td>Es$^4$</td>
<td>0.97 (107)</td>
<td>13.27 (1464)</td>
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<td>6.9 ± 4.6</td>
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<td>20.42 (1564)</td>
<td>0.0</td>
<td>9.3 ± 2.6</td>
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<td>2.652 (395)</td>
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<td>5.71 (1146)</td>
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<tr>
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<td>Ng</td>
<td>2.7 (323)</td>
<td>9.4 (1140)</td>
<td>73.9</td>
<td>53.1 ± 1.9</td>
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<td>7.0 (1034)</td>
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<td>93.6 ± 3.0</td>
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<td>6.7 (306)</td>
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<td>9.2 (1294)</td>
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<td>2.3 (295)</td>
<td>7.4 (959)</td>
<td>98.2</td>
<td>57.2 ± 2.3</td>
<td>11.3 ± 2.3 (74)</td>
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<td>5.3 (734)</td>
<td>97.3</td>
<td>61.1 ± 2.9</td>
<td>11.2 ± 1.4 (101)</td>
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<td>727.0</td>
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<td>5.0 (792)</td>
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<td>Ng</td>
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<td>100</td>
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<td>3.7 (1299)</td>
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<td>Mz</td>
<td>17.60 (2163)</td>
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<td>1761.6</td>
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<td>16.5</td>
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<td>12.5 ± 1.4 (73)</td>
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<td>84.0 ± 6.0</td>
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<td>1.32 (538)</td>
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<td>56.0 ± 5.0</td>
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<td>Mz</td>
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<td>0.0</td>
<td>3.1 ± 0.8</td>
<td>N.D.</td>
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<tr>
<td>1809.9</td>
<td>Mz</td>
<td>11.89 (5004)</td>
<td>2.92 (1230)</td>
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<td>73.0 ± 7.0</td>
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<tr>
<td>1818.2</td>
<td>Mz</td>
<td>11.12 (5026)</td>
<td>1.81 (818)</td>
<td>0.0</td>
<td>48.0 ± 5.0</td>
<td>13.0 ± 1.8 (107)</td>
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<tr>
<td>1825.2</td>
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<td>22.87 (4249)</td>
<td>5.33 (992)</td>
<td>0.0</td>
<td>74.0 ± 6.0</td>
<td>11.6 ± 1.4 (91)</td>
<td></td>
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</tbody>
</table>

$\rho_s$ = spontaneous track density; $\rho_i$ = induced track density. All track densities are $10^5$/cm$^2$. Ns and Ni are the number of spontaneous and induced track, respectively. Ages calculated using a zeta of 322.1 ± 3.6 for dosimeter glass CN5 for apatite. The $\lambda_b$ is 1.55 × 10$^{-10}$/year and $g = 0.5$ in this measurement. $P(x^2) = \chi^2$-square probability, which is a measure of probability that individual grains counted in a sample are from a single population; ages were determined using average age when values of $P(x^2) > 5\%$, which are generally taken to indicate that multiple age populations are present. However, ages were determined using assembled age with the values of $P(x^2)$ > 5%. Mean track lengths (L) are corrected for length bias. N is number of tracks counted. N.D. = not determined. The samples were tested by the Institute of High Energy Physics, Chinese Academy of Sciences.
(1980) model. The stratigraphic data come from the drilled values and the strata bottom ages were taken from the Editorial Committee of “Petroleum Geology of China” (1987) as follows: the age of the bottom of the Pingyuan Formation of the Quaternary (Qn) is 2.0 Ma; the Minhuazhen Formation of the Neogene (Nm) is 12 Ma; the Guantao Formation of the Neogene (Ng) is 24.6 Ma; the Dongying Formation (E0) is 32.8 Ma; the 1st Member of the Shahejie Formation (E1) is 36 Ma; the 2nd Member of the Shahejie Formation (E2) is 38 Ma; the 3rd Member of the Shahejie Formation (E3) is 42 Ma; the 4th Member of the Shahejie Formation (E4) is 50.5 Ma; the Kongdian Formation (E5) is 65 Ma; the Cretaceous (K) is 145 Ma; the Jurassic (J) is 208 Ma; and the Triassic (Tr) is 245 Ma (Fig. 1). The surface temperature was set at 15 °C for the entire geological time in our simulation.

3.3. Thermal history modeling results

There have been many documents on the present-day heat flow (Chen, 1988; Wang, 1996; Gong et al., 2003a,b) and the thermal state of this basin’s lithosphere (Wang, 1987, 1996; He et al., 2001; Zang et al., 2002; Fu et al., 2004; S.W. Liu et al., 2005; Hu et al., 2007; Q.B. Wu et al., 2008). Previous studies of the thermal history of the basin have mainly focused on the thermal evolution since the Eocene (Hu et al., 2001; Qiu et al., 2004; Lü, 2006; Qiu et al., 2006, 2007; Ding et al., 2008; Qiu et al., 2010), and the results have shown a cooling process. There have been few studies on the Mesozoic thermal history of the basin (Hu et al., 2007).

Fig. 4 presents the results of the thermal history reconstruction of well Y155 in the Jiyang sub-basin. Well Y155 has thermal indicators of the relatively high present-day heat flow value (52 ± 5 mW/m2) during the Early Cretaceous, which is consistent with evidence from the tectonic evolution, magmatic petrology and geochemistry (Wu et al., 2005b; Zhai et al., 2005; Zbu et al., 2008). The heat flow has gradually decreased since then to 68 mW/m2 during the Late Cretaceous. In this paper, the Mesozoic thermal histories of 5 wells (e.g., wells Y135, Y155, D43, ZB3 and Z11) were reconstructed. The denudation thickness during the Mesozoic is listed in Table 3.

The Ro data in well Y155 did not provide enough information for the Late Cretaceous. Due to the extensional rift phase in the Paleogene, the heat flow increased again. The Jiyang sub-basin experienced a second heat flow peak of 85 – 88 mW/m2 during the Middle and Late Paleogene. The heat flow decreased again after the basin entered a thermal subsidence phase. At present, the heat flow is only 60 – 68 mW/m2 (Fig. 7).

4. Thermal lithospheric thickness calculations

It is possible to estimate the temperature–depth curve within a lithospheric depth interval at different geologic periods based on the paleo-surface heat flow values and the equation of one-dimensional heat conduction (Eq. (1)). The depth of the intersection between the temperature–depth curve and the mantle adiabatic or dry basalt solidus line indicates the thermal lithospheric thickness (Fig. 8):

$$T_z = T_0 + \left(\frac{q \times Z}{K - \left(A \times Z^2\right)^{1/2}}\right),$$

where $T_0$ is the temperature at the Earth’s surface, taken as the annual average ground temperature of 15 °C in the Jiyang sub-basin; q is the measured surface heat flow (mW/m2); A is the heat production of crustal rock (μW/m3); Z is the depth scaling parameter for the heat-producing layer (km); and K is the thermal conductivity of rocks (W/m · K).

The thermal lithospheric thickness can be calculated by the single discrimination criterion (Rudnick et al., 1998; Hu and Wang, 2000) or by two adiabatic lines that define the upper limit (Tz) and lower limit (T1) of the bottom temperature of the thermal lithosphere (Artemieva and Mooney, 2001; Zang et al., 2002):

$$T_1 = 1200^\circ C + 0.5^\circ C/km \times Z/km$$

$$T_2 = 1300^\circ C + 0.4^\circ C/km \times Z/km.$$  

In our study, the thermal lithospheric thickness is the average value of these two calculation results from the above adiabatic lines. The error for the thermal lithospheric thickness in this calculation method is approximately 15% (Pasquale et al., 1990).

4.1. Basic parameters

The parameters for calculating thermal lithospheric thicknesses include the crust thickness, erosion data, surface heat flows, surface temperatures and the thermal properties of rocks. The crustal structures at different geological times were modified from several references (Fig. 9) (Chen, 1988; Ren et al., 2002; Li et al., 2004; Y.G. Xu et al., 2005; Lu et al., 2005; Shao et al., 2005; Wu et al., 2005a,b; Zhai et al., 2005; Cai et al., 2007; Zhu et al., 2008; Xu and Zhao, 2009). The thermal physical parameters of rocks mainly include radiogenic heat production (A) and thermal conductivity (K). The radiogenic heat production values of the sediments were adopted from Hu et al. (2007). The radiogenic heat production of the upper crust is calculated using the exponential decay model:

$$A = A_0 \exp\left(-Z/D\right)$$

where D is the depth of the radioactive element-enriched layer or the depth scaling parameter for the heat-producing layer and A0 is the heat production of near-surface rocks, which is 1.24 μW/m3 (S.W. Liu et al., 2005). However, Ketcham (1996) stated that this model cannot be used throughout the crust because the heat production of the middle and upper crust would be underestimated. Therefore, we assume that the exponential model of the radiogenic heat production distribution can be used only in the upper crust, and the heat production values for the middle and lower crust are constant (S.W. Liu et al., 2005). The mantle heat production rate is also constant (Rudnick et al., 1998). The thermal conductivity values of the sediments were also taken...
from Hu et al. (2007). The thermal conductivity values for the mid-lower crust and the lithospheric mantle were taken from Pollack and Chapman (1977) and Morgan (1984). The radiogenic heat production and thermal conductivity of each structural layer in the Jiyang sub-basin are listed in Table 4.

4.2. Thermal lithospheric thickness calculation

The thicknesses of the thermal lithosphere of the Jiyang sub-basin were calculated for every 5 Ma since the Mesozoic (Fig. 10). Here, the average heat flow value of the modeled thermal histories in Fig. 7 is used in our calculation. The lithosphere experienced two thinning...
Fig. 5. Modeled thermal history of samples in Wells D43 and DB3 based on AFT data. 1000 thermal paths were generated using the Monte Carlo inverse modeling method. The green lines are the accepted paths and the thick blue line is the "best fit" temperature path in the left figures. The modeled and measured AFT length histograms are shown in the right figures. GOF = goodness of fit.

Fig. 6. Thermal history simulation of Well Y8 in the Jiyang sub-basin based on the Ro and AFT data. a. Burial and thermal histories. b. Fitting between measured (black dots) and modeled Ro values (dashed line). c–e. Modeled and measured AFT length histograms of three samples.
stages during the Cretaceous and the Paleogene. The Jiyang sub-basin had the characteristics of a craton basin in the Early Mesozoic, and its lithosphere was relatively thick (up to approximately 150 km) based on this study and references (Hu et al., 2007; Xu and Zhao, 2009). Thereafter, the lithosphere began to thin, and reached a thinning peak in the late Early Cretaceous of ~51 km. The thickness then increased to approximately 80 km at the end of the Cretaceous, corresponding to the basin's tectonic depression. With the development of a rift phase in the Bohai Bay Basin, the lithosphere experienced a second thinning peak in the Middle and Late Paleogene of 48 km. The lithosphere thickened thereafter and is 78 km at present (Fig. 11). This thickness can be compared with those from the seismic observations of 70 ~ 90 km (Chen, 2009; Chen et al., 2009; Huang and Zhao, 2009; Tian et al., 2009), which confirm the reliability of this geothermal calculation.

5. Discussion

The period of large-scale magmatic activity in the Early Cretaceous is in accordance with the formation time of the pull-apart basin (Shao et al., 2005), which indicates that the Bohai Bay Basin was an extensional tectonic environment. The lithosphere thinned due to the extensional regime, and the asthenosphere contributed more heat energy to the lithosphere due to upwelling, which led to an increase in the lithosphere's geothermal gradient and surface heat flow. This analysis is consistent with the Mesozoic thermal history simulation of the Bohai Bay Basin. The heat flow of the Jiyang sub-basin was low in the Early Mesozoic and then reached a maximum in the Late Mesozoic, followed by a gradual decrease in the Cenozoic. The lithosphere of the Bohai Bay Basin thinned during the Jurassic, and evidence of this can be found in the sporadic magmatic activity (W.L. Xu et al., 2004; Jiang et al., 2005; Zhang et al., 2005). The thinning reached a peak in the Cretaceous. In general, the lithospheric thinning had a long history and began in the Mesozoic. Different structural units may display different thinning rates, which will be further examined in another work with more sub-basin studies of the Bohai Bay Basin.

We mentioned the timing of the two thinning stages as the Cretaceous and the Paleocene based on the heat flow history. The heat flow retrieved here is the surface heat flow of the basin as mentioned in Eq. 1. The thinning mainly occurred in the deep lithosphere, which would result in a high surface heat flow in the basin. However, the thinning occurred simultaneously with the high surface heat flow in our study, which is similar to McKenzie's (1978) instantaneous extension model. Theoretically, some time may be necessary to transfer energy from the deep thinning of the lithosphere to the basin surface. We agree that the thermal relaxation time of the lithosphere should be taken into account when constraining the timing of the lithospheric thinning and the timing of the lithospheric thinning is earlier than the timing of heat flow peak. However, the timing of the heat transfer or thermal relaxation time of the lithosphere depends on the thermophysical characteristics of lithosphere (e.g. the thermal conductivity of rocks), the lithospheric rheology (He, 2002), etc.

5.1. Influence of erosion thickness and heat flow on the lithosphere thickness

The surface paleoheat flow and the amount of erosion are the most important parameters for calculating the thermal lithospheric thickness. The Mesozoic erosion thickness of the Bohai Bay Basin has been studied by stratigraphic correlation, the deposition rate, log, the paleothermal gradient, and fission tracks (Li and Liao, 2001; Fu et al., 2004; Li et al., 2005; Zhao et al., 2005; Ji et al., 2006). In our study, the modeled erosion is between 1880 and 2095 m for the Upper Jurassic and Lower Cretaceous, but it can be up to 3786 ~ 3980 m for the Middle and Upper Triassic (Table 3). In thermal modeling, varying erosion or
heat flow values will result in matching of the measured and calculated $R_p$ values. Generally, increasing the amount of erosion and decreasing the heat flow will result in the same $R_p$ value. As shown in Fig. 12, the differential thermal lithospheric thickness is the result of different heat flow and erosion values. If the surface heat flow decreases from 97 mW/m² to 82 mW/m² and erosion increases by 500 m, the thermal lithospheric thickness may increase markedly from 35 km to 55 km. The lithospheric thickness varies markedly when the heat flow changes and the amount of erosion remains the same; by contrast, the lithospheric thickness is affected only slightly when the amount of erosion varies and the heat flow is constant (Fig. 13).

5.2. Petrological evidence of lithospheric thinning in the Mid–Late Mesozoic

Two large-scale magmatic events occurred in the Jurassic and Early Cretaceous in the Bohai Bay Basin due to the Yanshan movement (Y.G. Xu et al., 2004; Wu et al., 2005a,b). The Yanshan movement generally resulted in intense tectono-magmatic activity and resulted in numerous faults in the base and lithosphere, which contributed to magmatic and volcanic activity. The geodynamic regime for granite formation in the Jurassic is still debated. Li et al. (2004) considered it to be the result of intraplate extension, whereas Wu et al. (2005b) thought it was a consequence of the thickening and melting of the crust after the subsidence of the Paleo-Pacific plate. At that time, granite magmatic activity extended in a NNE direction and was dominated by adakitic granite, with a lack of basic magma. An investigation of the isotopic composition showed that the source of the paleo-crust originated in the transitional type I-S in terms of the petrochemistry. The zirconium saturation temperature of the Jurassic granite is ~750 °C, which is significantly lower than the granite formation temperature of the Cretaceous (Wu et al., 2007). Thus, the Jurassic granite may be related to subsidence of the Paleo-Pacific plate (Wu et al., 2005b, 2007). Recent studies have supplied new evidence for thinning of the North China lithosphere in the Jurassic (Shao et al., 2005). A basic lamprophyre swarm of 155 Ma distributed in the Huaziyu of the Liaodong Peninsula came from the enriched lithospheric mantle (Jiang et al., 2005), which suggests that the asthenosphere pushed up in parts of North China (Xu and Zhao, 2009). In addition, the geochemical properties of the orthoclase of the Early Jurassic copper complex body in the North China hinterland are similar to Oceanic Island Basalt (OIB), so the complex body may be the melting product of the mantle from the asthenosphere base. In this area, the orthoclase of the copper complex body in the early stage (185 Ma) came from parts of the melting product of mantle in the asthenosphere (Zhang et al., 2005), whereas the adamellite in the late stage (177 Ma) came from the ancient lower mantle (Shao et al., 2005). All these studies indicate that the lithosphere of North China thinned in the Jurassic, and the transformation of magma properties is consistent with the thermal energy transfer from the mantle to the crust during the thinning process, which led to an increase in the surface heat flow.

The magmatic activity of the Cretaceous was more significant than that of the Jurassic in terms of both scale and intensity. Basic and acidic magma appeared simultaneously, and more mantle material was involved in the Cretaceous magmatism, of which the granite belonged to the type I-A (Yang et al., 2005). The period of large-scale magmatic activity of the Early Cretaceous is consistent with that of the pull-apart
basin formation (Shao et al., 2005), which implies that the Bohai Bay Basin was in an extensional tectonic setting when the lithosphere thinned, with upwelling of asthenosphere material due to the extension. F.Q. Zhang et al. (2011) recently proposed that Early Cretaceous volcanism occurred in an extensional back arc setting associated with the subduction of the Paleo-Pacific plate, large-scale upwelling of the asthenosphere, and intensive lithospheric thinning of the eastern continental margin of NE China. This process may have lasted until

Fig. 10. Thermal lithospheric thickness of the Jiyang sub-basin at different Geological stages. The thicknesses for every 5 Ma were calculated based on the thermal histories. a. Slow thinning period during the 240 ~ 145 Ma with a thinning rate of 0.48 km/Ma and rapid thinning period during 145 ~ 110 Ma with a thinning rate of 1.49 km/Ma. b. Thickening period during the 110 ~ 65 Ma with a thinning rate of ~0.62 km/Ma. c. Rapid thickening period during 65 ~ 40 Ma with a thinning rate of 1.28 km/Ma. d. Thickening period during 40 ~ 0 Ma with a thinning rate of ~0.80 km/Ma. The thinning rate is calculated from the thinning amount of the lithosphere and the corresponding time intervals.

Fig. 11. Thermal thickness evolution of the Meso-Cenozoic lithosphere in the Jiyang sub-basin.
ca. 109 Ma. The convection asthenosphere contributed more heat to the lithosphere by heat conduction, which led to an increase in the geothermal gradient of the lithosphere and surface heat flow. This result coincides with the simulated Mesozoic thermal history of the Jiyang sub-basin. The Mesozoic thermal history of the Jiyang sub-basin was complex, with a low heat flow in the early Mesozoic, a peak in the Late Mesozoic, and a subsequent decrease (Fig. 7). The lithosphere thinned to some degree in the Jurassic, which might be reflected in the scattered magmatic activity (W.L. Xu et al., 2004; Jiang et al., 2005; Zhang et al., 2005). The lithosphere thinning was most intensive in the Early Cretaceous. Generally speaking, the lithospheric thinning of the Bohai Bay Basin was not transient; rather, it began in the Mesozoic with different thinning rates in different tectonic units. Overall, the thinning rate was low in the Triassic and increased in the Jurassic, reaching a peak in the Cretaceous. These studies not only provide evidence in the magmatic rock petrology but also confirm that the Early Cretaceous was the lithosphere thinning peak of the Bohai Bay Basin in the Mesozoic.

5.3. Lithospheric thinning in the Paleogene

Although two notable lithospheric thinning stages in the NCC are proposed based only on the case study of the Jiyang sub-basin, one
6. Conclusions

The Meso-Cenozoic thermal history shows that the Jiyang sub-basin experienced two periods of heat flow peaks, in the late Early Cretaceous and in the Middle to Late Paleogene. The sub-basin experienced a low heat flow of ~53 mW/m² during the Early Mesozoic. The heat flow then gradually increased until it reached the first heat flow peak of 84 – 88 mW/m² during the late Early Cretaceous. The heat flow then gradually decreased to 69 – 72 mW/m² in the Late Cretaceous. Due to the extensional rift phase in the Paleogene, the heat flow increased again. The Jiyang sub-basin experienced its second heat flow peak of 85 – 88 mW/m² during the Middle and Late Paleogene. The heat flow then decreased after the basin entered the thermal subsidence phase. At present, the heat flow is 60 – 68 mW/m². The thicknesses of the thermal lithosphere of the Jiyang sub-basin in the Meso-Cenozoic were calculated using the modeled thermal histories. The results indicate that the lithosphere experienced two thinning stages in the Cretaceous and the Paleogene. The lithospheric thickness began to thin from 150 km in the Early Mesozoic and reached a thinning peak in the late Early Cretaceous with a thickness of only 51 km; it then increased to approximately 80 km at the end of the Cretaceous. The lithosphere experienced a second thinning peak in the Middle and Late Paleogene, with a thickness of only 48 km, which corresponds to the rift phase in the Bohai Bay Basin. The lithosphere was thickened again thereafter and is 78 km at present. Thus, this thermal history study may provide evidence revealing the time, process and stages of lithospheric thinning in the NCC.

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References


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