TWO PHASES OF EXTENSION IN NORTH CHINA SINCE MESOZOIC:

A NUMERICAL STUDY

A Thesis

presented to

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at the University of Missouri-Columbia

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

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by

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Dr. Mian Liu Thesis Supervisor

DECEMBER 2013

The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

TWO PHASES OF EXTENSION IN NORTH CHINA SINCE MESOZOIC:

A NUMERICAL STUDY

presented by Feng Lin,

a candidate for the degree of master of science,

and hereby certify that, in their opinion, it is worthy of acceptance.

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Professor Eric Sandvol

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TWO PHASES OF EXTENSION IN NORTH CHINA SINCE THE MESOZOIC: A NUMERICAL STUDY

Feng Lin

Dr. Mian Liu, Thesis Supervisor

ABSTRACT

The North China Craton was formed around 1.8 Ga by collision and amalgamation of the Eastern and Western blocks. It remained tectonically stable since then until the Mesozoic, when its eastern part experienced widely distributed extension and volcanism. This distributed extension waned during the early Cenozoic, and was replaced by localized extension (rifting) in the western part of the North China Craton. I have developed a series of viscoplastic finite element models to investigate the causes of these two phases of different continental extension in North China. My results show that the Mesozoic-early Cenozoic widely distributed extension requires a thin and hot lithosphere, which is probably the result of delamination or thermal erosion of the lithospheric root under the eastern part of the North China Craton. The localized rifting during the late Cenozoic in the western part of the North China Craton indicates a relatively cold and thick lithosphere. Furthermore, preexisting lithospheric weakening is needed to explain the formation of the Late Cenozoic rift zones within the

relatively thick lithospere. These preexisting weakening zones may be inherited from the Paleoprotozoic collision that formed the North China Craton.

Chapter 1. INTRODUCTION

1.1 Continental extension and rifting

Continental extension is a very important tectonic process. It produces most of the sedimentary basins and may lead to continental plate breakup. Continental rifts are defined as regions where continental lithosphere has gone extension.

Continental rifts can be further categorized into wide rift mode and narrow rift mode. Examples of narrow rifts include Rio Grand rift and East Africa rift, where extension is localized in narrow rift valleys. The wide rifts include the Basin and Range Province in western US and the Bohai Bay Basin in eastern north China.

There are numerous reasons why rifting is important(Olsen 1995):

1. Rifting is one of the fundamental tectonic processes affecting the continent.

2. Rifting causes permanent modification of the continental lithosphere.

3. Rifting provides a 'window' for looking into the physical and chemical state of the mantle, through melt generation and volcanism.

4. A variety of natural resources, such as hydrocarbons and mineral deposits, can be associated with a rift tectonic environment.

5. Rifts can be associated with natural hazards such like earthquakes and volcanoes.

1.2 North China Craton and the Mesozoic-Cenozoic North China Extension

A craton is the relatively stable part of a continent formed at Precambrian or even earlier. Usually Craton has very little tectonic activity and attached to a high velocity thick lithospheric mantle root (Kearey et al. 2009).

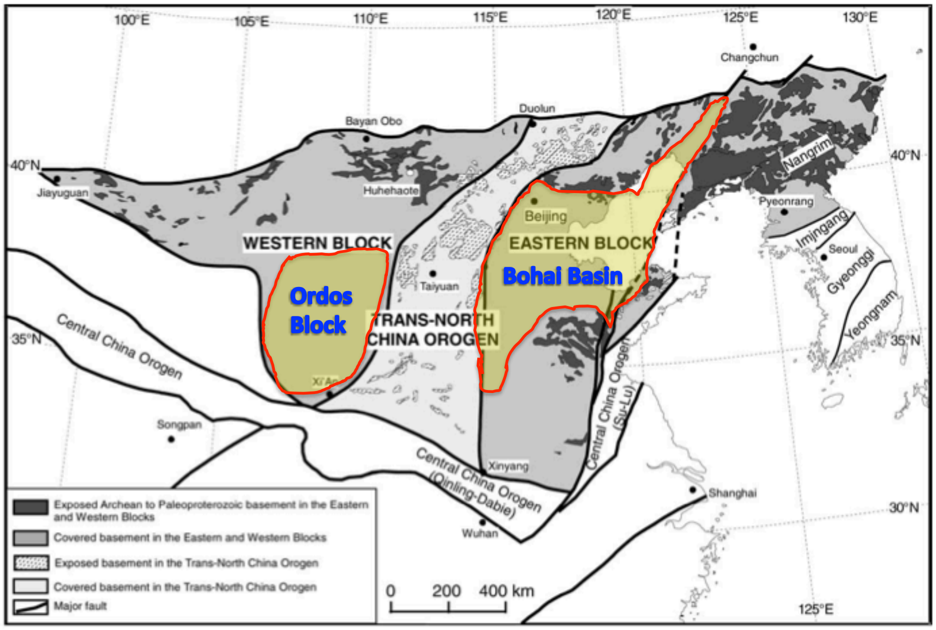


Figure1.1. *Geology Map of North China Craton and it subdivision. The Ordos Block situated in the Western Block and the Bohai Basin situated in the Eastern Block (Zhao et al. 2005).*

The North China Craton was formed around 1.8 Ga by collision and amalgamation of the Eastern and Western blocks. It remained tectonically stable since theMesozoic, when its eastern part experienced widely distributed extension and volcanism. One of the typical examples is the Bohai Bay Basin. Bohai Bay Basin is situated among the eastern side of North China (Figure1.1). It is about 1100km NNE-SSW by 400km WNW-ESE (Allen et al. 1998) and covers most of Eastern North China. It consists of a series of grabens and half grabens formed by ENE-WNW trending normal and strike slip faults(Allen et al. 1998), which indicate that once there was a significant WNW-ESE extension.

Stratigraphic study in the Bohai Bay Basin revealed that Bohai Bay Basin formed as an extensional feature from the early to middle Cenozoic.

This distributed extension waned during the early Cenozoic, and was replaced by localized extension (rifting) in the western part of the North China Craton around the Ordos block (Figure1.2). The later extension around Ordos caused four rifting zones: Shanxi graben, Weihe graben, Yinchuan Graben and Hetao Graben. The width of the rifting systems is less than 100km wide (Zhang et al. 1998).

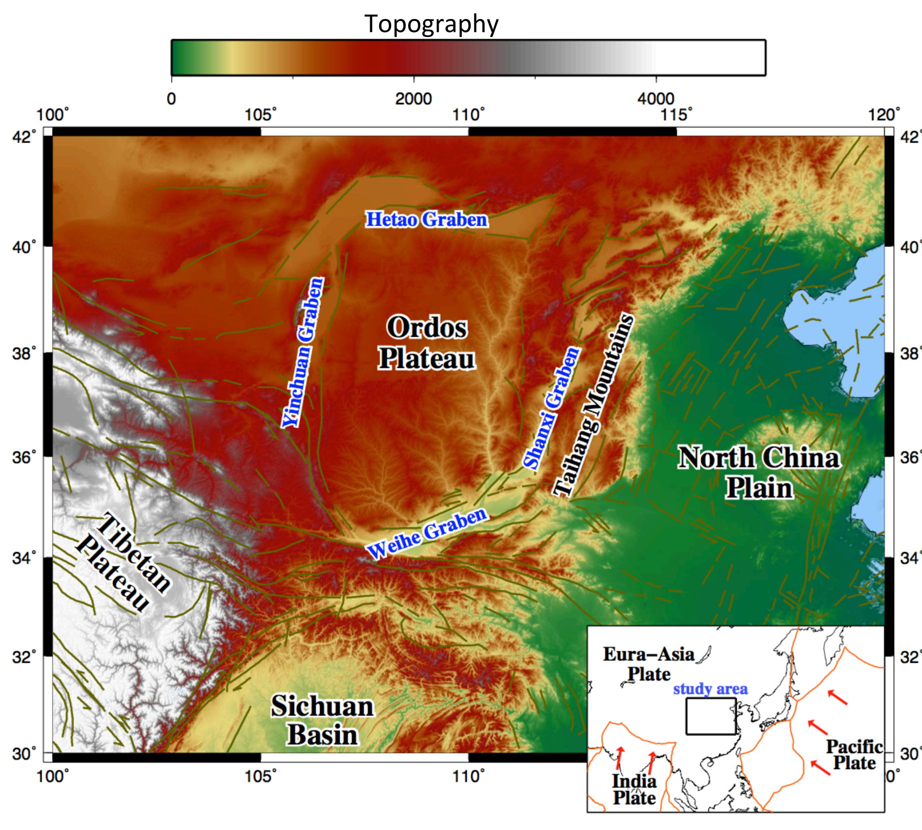


Figure1.2. *Geology map of graben system around Ordos Block. The right bottom corner shows the location and tectonic environment of the study area.*

There are many hypothesizes explaining the extension in North China. These hypothesizes include extrusion of Asian lithospheric blocks driven by the Indo-Asian collision (Tapponnier et al. 1982; Zhang et al. 2003), extensional stress associated with the retreat of Western Pacific subduction zone(Northrup et al. 1995), or the basal shear cause by mantle flow induced by Pacific subduction (Zhao et al. 2011; Lei 2012); however, what cause the two different mode of extension is not well understood. In my study I setup a series of models to investigate the cause of the early distributed extension and later localized extension.

Chapter 2. NUMERICAL METHOD

2.1 Continuum mechanics and basic equations

Long term tectonic evolution of the lithosphere and asthenosphere can be described by the continuum mechanics. This implies that on a macroscale the media does not contain any mass-free voids. We can present different physical properties of a continuum by field variables, such as strain, pressure, and density.

Basically the deformation can be represented as three parts: elastic strain, viscous strain and plastic strain. My thesis is focused on the understanding of the strain localization and evolution of the lithosphere, so the plastic properties are crucial to my models, since the strain localization is likely caused by plasticity. For long term tectonism, strain rate in lithosphere is around $1\times10^{-15}/yr$ and continues for millions of years, so the elastic strain is trivial and negligible. So I considered the whole model domain as visco-plastic material.

Since I considered the lithosphere and asthenosphere as continuous media and incompressible, the conservation of mass can be written in the continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (1)$$

where ρ is density t is time v is velocity Because density is constant for incompressible media, the continuity equation is simplified as

$$\nabla \cdot \vec{v} = 0 \text{ or } v_{i,i} = 0 \quad (2)$$

Another equation in my models is the momentum equation:

$$\frac{\partial \sigma_{ij}}{\partial x_j} + \rho g_i = \rho a_i \quad (3)$$

where ρ, g, a are density, body force per unit mass, and acceleration, respectively. σ_{ij} is stress and can be further decompose to deviatoric stress (σ'_{ij}) and Pressure (P)

$$\sigma_{ij} = \sigma'_{ij} - P\delta_{ij} \quad (4)$$

For long-term tectonic problems the inertia term is negligible with respect to viscous resistance and gravitational acceleration. So the momentum equation could be simplified as a force balance:

$$\frac{\partial \sigma'_{ij}}{dx_j} - P\delta_{ij} + \rho g_i = 0 \quad (5)$$

2.2 Finite Element Method and the sofeware

2.2.1 FEM and GALE

I solve the partial differential equations for the extensional problems using the Finite Element Method analysis. The Finite Element Method is a numerical calculation method solving a problem described by a series of partial differential equations.

I used the open source code Gale. Gale is a parallel, two or three dimensional finite element code that deals with long term tectonic problems like orogenesis, rifting and subduction. Gale is developed and maintained by the Computational Infrastructure of Geodynamics (www.geodynamics.org).

Gale is perfect for modeling the long-term extension problems since it supports both viscous and plastic properties in the simulation.

2.2.2 Two dimension simplification

The plane strain approximation can reduce complicated three-dimensional problem to two-dimensional problem. It assumes that the strain is only happen on a plane and no strain exists in the direction normal to this plane. Since in continental extension, normally strain in the direction normal to the direction of extension is trivial with respect to other two directions, the approximation is applicable for my problem. In my modeling of extension, I assume no volume change, so extension in one direction must be compensated by shortening in the other dimension. Thus, in the 2-D approximation no area change is produced.

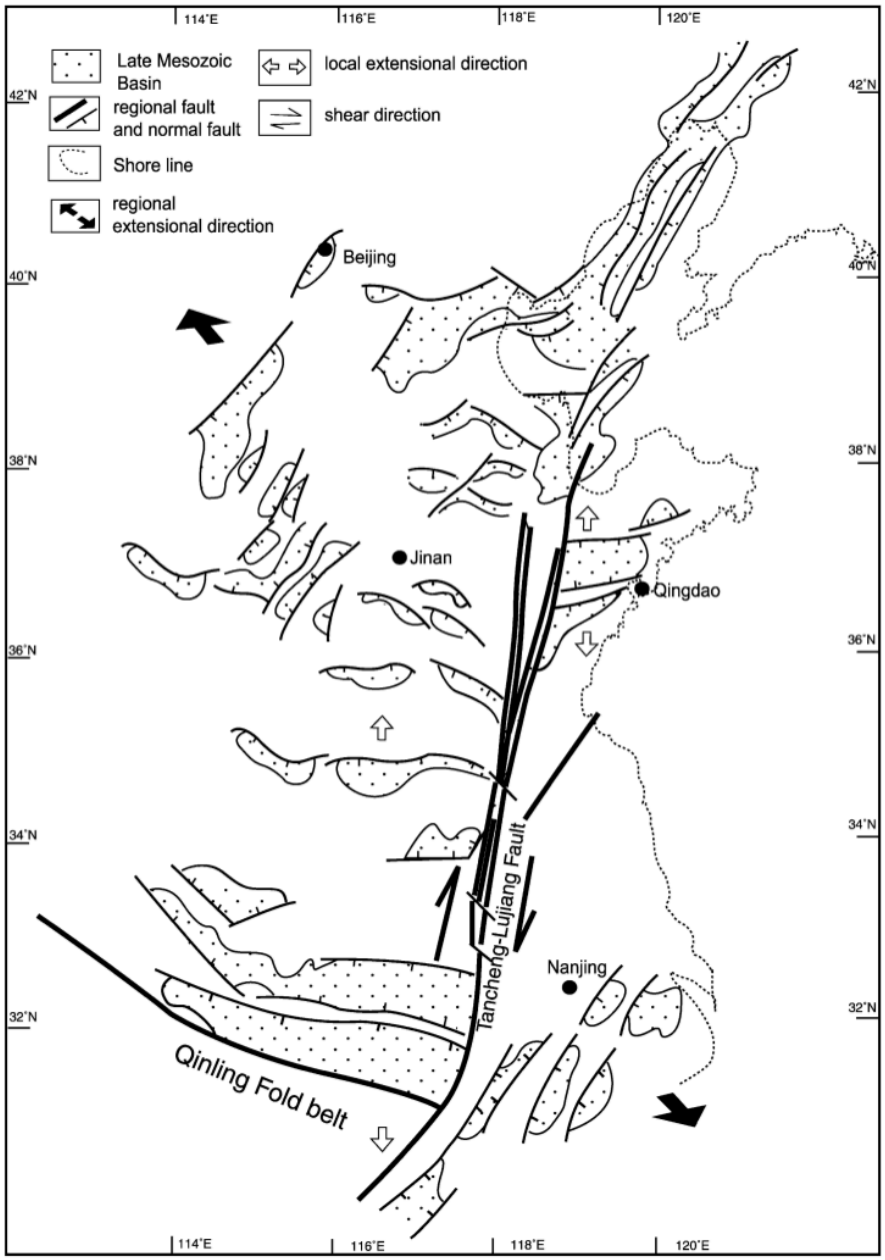
Chapter 3. DIFFUSIVE MESOZOIC - EARLY CENOZOIC RIFTING IN EASTERN NORTH CHINA: A NUMERICAL STUDY

3.1 Introduction

North China has experienced two phases of extensions since Mesozoic: an early extension, which formed the distributed rifting system in Eastern North China, during late Mesozoic-early Cenozoic (Allen et al. 1997; Qi and Yang 2010; Yin 2010), and a later extension, which formed the localized rifting system around the Ordos Block, during late Cenozoic (Xu and Ma 1992; Xu et al. 1993; Zhang et al. 1998).

The early phase of extension in eastern north China is characterized by wide distributed extension (Figure3.1a). One of the typical examples is the Bohai Bay Basin. The Bohai Bay Basin is situated in the eastern side of North China (Figure3.1a). It is about 1100 km long in the NNE-SSW direction and 400-km wide in the WNW-ESE direction (Allen et al. 1998) and covers most of Eastern North China. It consists of a series of grabens and half grabens formed by ENE-WNW trending normal and strike slip faults (Figure3.1b)(Allen et al. 1998), which indicate that once there was a significant WNW-ESE extension. Stratigraphic study in the Bohai Basin revealed that Bohai Bay Basin formed from the early to middle Cenozoic (Allen et al. 1997; Zuo et al. 2011).

a)



b)

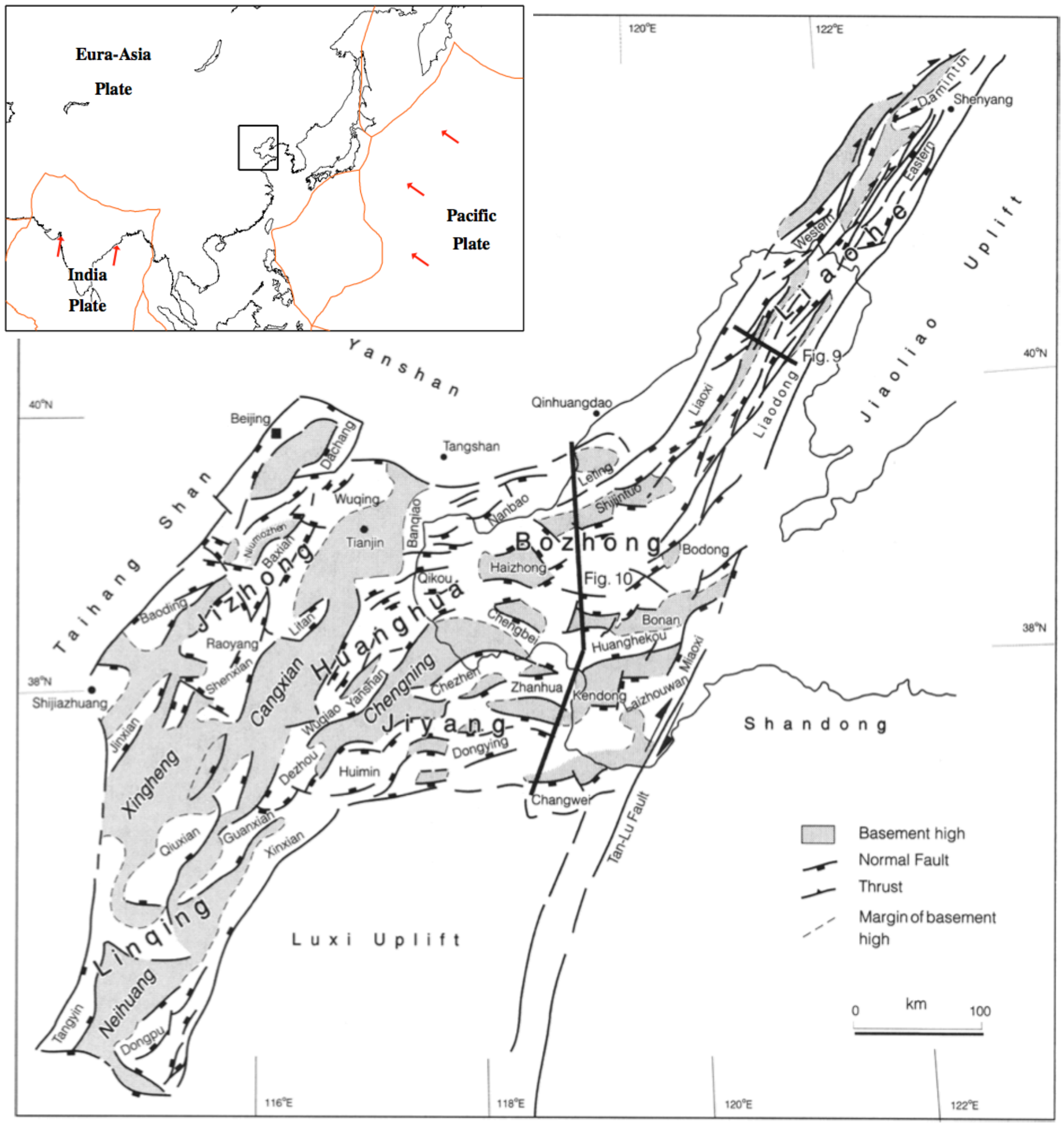


Figure3.1. *Geology map of eastern north China a) Late Mesozoic Basin tectonic map of North China(Ren et al. 2002) b) Structures of the Bohai Basin (Modified from Allen1997). The black box in the top left side subfigure shows the location of the main figure.*

The magnitude of extension across the Bohai Basin are 10% -30%, based on balanced section restoration, comparing the crustal thickness between basin and surrounding area, as well as estimation from tectonic subsidence (Allen et al. 1997).

The widely distributed normal faults are recognized all around the Bohai Basin. The cross section along the middle of the Bohai Basin shows that the extension formed a distributed rifting system and the spacing between the normal faults is approximately tens of kilometers (Figre3.2)(Allen et al. 1998).

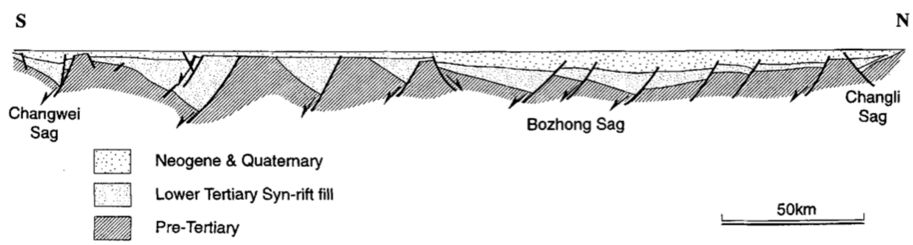


Figure3.2. *North South Cross section of the black line in Figure3.1 of Bohai Bay Basin(Allen et al. 1998).*

Late Mesozoic-early Cenozoic basalts were widely distributed within Eastern North China (Figure3.3) (Wu et al. 2005; Xu and Zhao 2009). The heat flow during the early Cenozoic was very high $(\sim 80mW/m^2)$, which is inferred from Cenozoic xenolith brought by alkali basalt to the surface (Xu 2001). The voluminous early Tertiary basalts and high heat flow during the early Cenozoic reflect a significantly thinned lithosphere (Xu 2001)(Figure3.4).

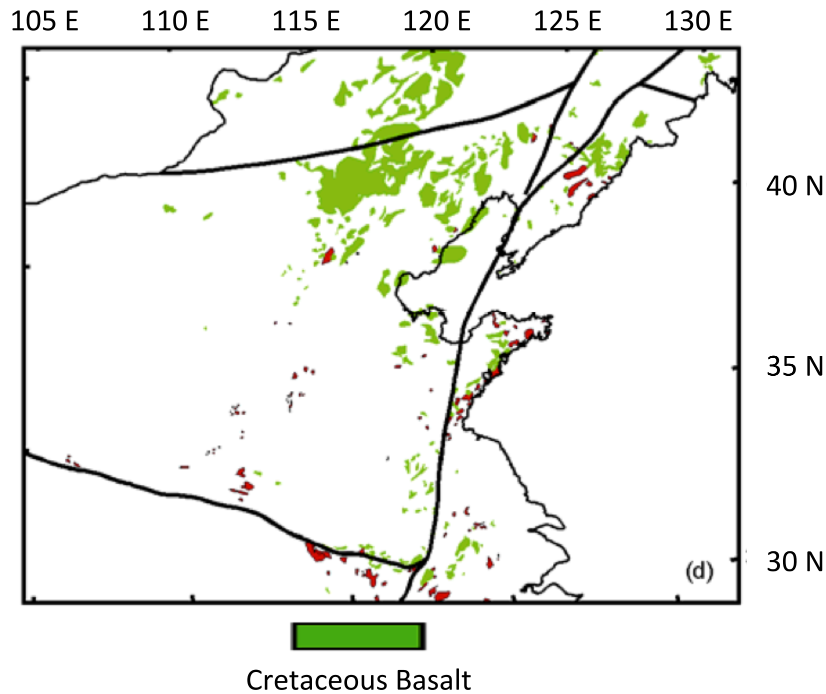


Figure3.3 *Distribution of Cretaceous Basalt in North China(Xu et al. 2009)*

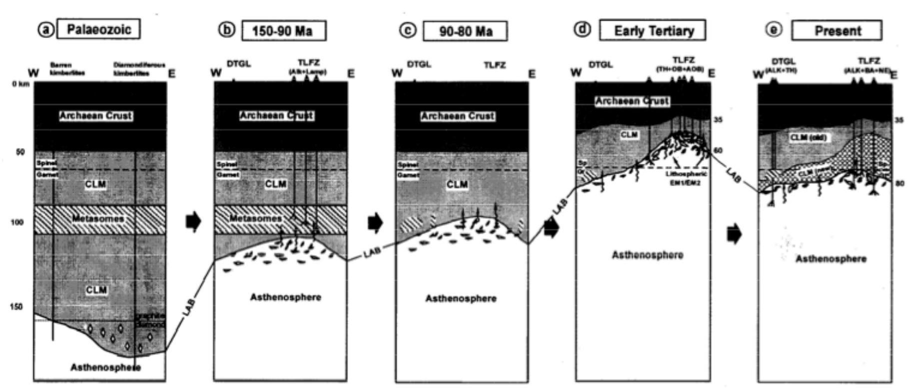


Figure3.4. *Schematic picture illustrating the lithosphere evolution beneath Eastern North China Craton (Xu 2001). Notice that the lithosphere under the Eastern North China Craton is significantly thinned during the later Mesozoic and early Cenozoic.*

Although previous studies has given us a good understanding about the structure and extension history about the early North China (Allen et al. 1997; Allen et al. 1998; Qi and Yang 2010; Zuo et al. 2011), the cause of the wide distributed rifting system is still not clear.

In this section I setup a series of numerical models to investigate what caused the distributed extension in eastern North China in Late Mesozoic early Cenozoic.

3.2 Method

My numerical calculations were carried out using the finite element code Gale, described in Chapter 2. Gale is an open source code developed and maintained by Computational Infrastructure of Geodynamics (www.geodynamics.org). Gale supports visco-plastic properties and could deal with problems relate to the long-term deformation, such like continental rifting, subduction and mountain building processes.

3.2.1 Governing equation:

Basically, Gale solves a conservation equation for momentum:

$$\tau_{ij,j} - P_{,i} = f_i \qquad (1)$$

subject to the continuity equation:

$$v_{i,i} = 0 \qquad (2)$$

in both 2- or 3- dimension. Where τ is the deviatoric stress, p is pressure and f is the body force such as gravity(ρg), v is the velocity.

I set up a series of 2D visco-plastic numerical models to simulate the extension process and see how rheological structure affects extension.

3.2.2 Plasticity

My goal is to determine what controls the extension mode, i.e., distributed extension versus localized rifting. Plasticity is very important for my modeling, because plasticity is needed to simulate strain localization during extension.

I applied Von Mises yielding criterion to approximate the plastic behavior of the lithosphere, which could be expressed by equation:

$$\sqrt{J_2} = C' \tag{3}$$

Where J_2 is the second invariant of deviatoric stress and C' is cohesion, in this case it is simply the yielding stress of the crust or lithosphere.

I integrated a linear strain softening as following (Figure 3.5)

$$C' = (1-\alpha) \cdot C_{initial} + \alpha \cdot C_{final} \tag{4}$$

Where α is defined as $\alpha = \min(1, \varepsilon / \varepsilon_0)$, ε is the finite strain and ε_0 is the saturate strain beyond which no more softening takes place.

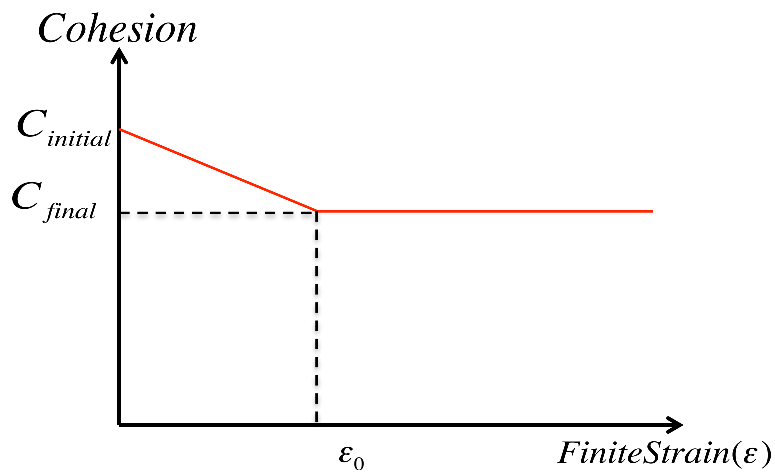


Figure3.5. *A curve shows the strain softening applied in this study. Details are described in the text.*

3.2.3 Geometry and boundary conditions

My model domains are set as $500km \times 200km$ box including lithosphere (brittle upper crust, ductile lower crust and brittle lithospheric mantle) and ductile asthenosphere (Table3.1).

Model	Upper Crust Viscosity/yielding stress	Lower crust Viscosity	Mantle Lithosphere Viscosity/yielding stress	Asthenosphere Viscosity	Weakening Strain
Crème brûlée	$1\times10^{25}Pa\cdot s/1\times10^{7}Pa$	N/A	N/A	$1\times10^{21}Pa\cdot s$	0.5
Jelly sandwich coupled	$1\times10^{25}Pa\cdot s/1\times10^{7}Pa$	N/A	$5\times10^{23}Pa\cdot s/2\times10^{8}Pa$	$1\times10^{21}Pa\cdot s$	0.5
Jelly sandwich decoupled	$1\times10^{25}Pa\cdot s/1\times10^{7}Pa$	$5\times10^{21}Pa\cdot s$	$5\times10^{23}Pa\cdot s/2\times10^{8}Pa$	$1\times10^{21}Pa\cdot s$	0.5

Table3.1. Parameters of the three models. In the Crème brûlée I didn't set the lower crust and mantle lithosphere layer; while in the Coupled Jelly sandwich model I did't set the lower crust.

The boundary condition is set as in the Figure3.6: the extension is driven by a constant velocity boundary at right hand side. The left hand side is set as a horizontally fixed $(V_x = 0)$ and vertically free-slip boundary. The bottom is set as horizontal free slip boundary $(V_y = 0)$. The top of the box is set as a free boundary, which means neither horizontal nor vertical is fixed.

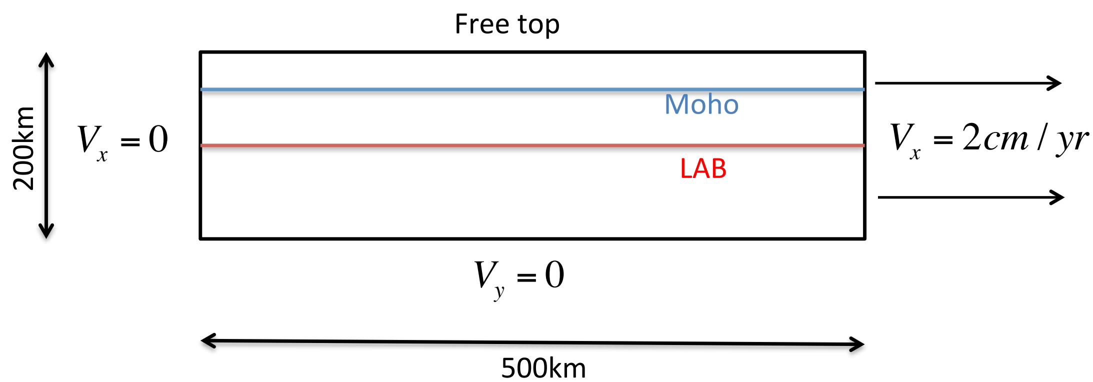


Figure3.6. *Velocity boundary conditions of the model*

3.2.4 Rheology structure

I divided the models into two groups:

The Crème brûlée model(Jackson 2002): The crust is lying over a weak lithospheric mantle reflecting the hot continent (Figure3.7).

Jelly sandwich model: The crust is lying over the Strong lithospheric mantle corresponding to a cold continent.

The Jelly sandwich model can be further divided as coupled Jelly sandwich and decoupled Jelly sandwich depend on whether it has a weak low crust (Figure 3.7).

The Crème brûlée model and Jelly sandwich model are tested by a series of viscosity of $1\times10^{24}\sim1\times10^{27}\,Pa\cdot s$ for crust and $1\times10^{20}\sim5\times10^{23}\,Pa\cdot s$ for the mantle in both of the groups.

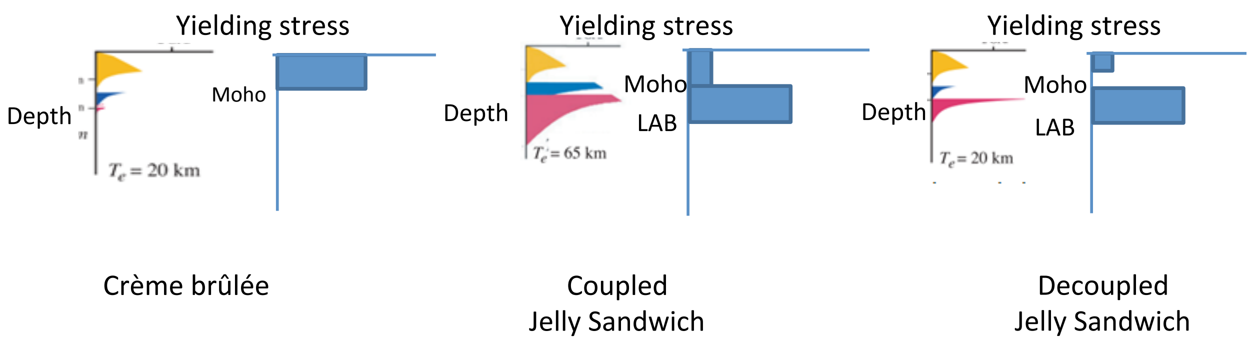


Figure3.7 *Rheology structure of the three models. The left side of each subset figure is the schematic picture illustrating different rheology model. And the right side of each subset figure is the simplified lithosphere strength in my calculation.*

3.3 Results

Figure 3.8 shows the results of about 5% extension assuming the " Crème brûlée model" of lithospheric rheology (Table 3.1). The results show a widely distributed rifting system (Figure 3.8). The rifting spacing is related to the thickness of the brittle lithosphere/crust. The interval of the rift is tens of kilometers, which is comparable with the structure observed in Eastern North China (Figure3.2).

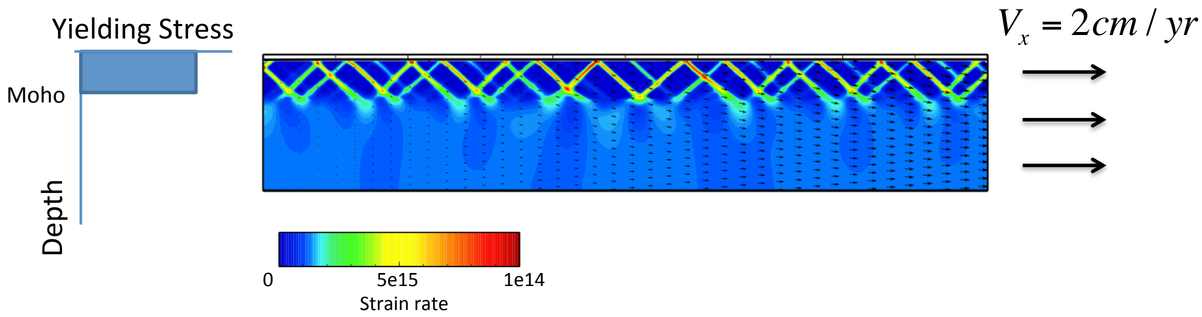


Figure3.8. *Strain rate pattern of the Crème brûlée model lithosphere after 5% extension of. The left diagram is the strength model I used in this case.*

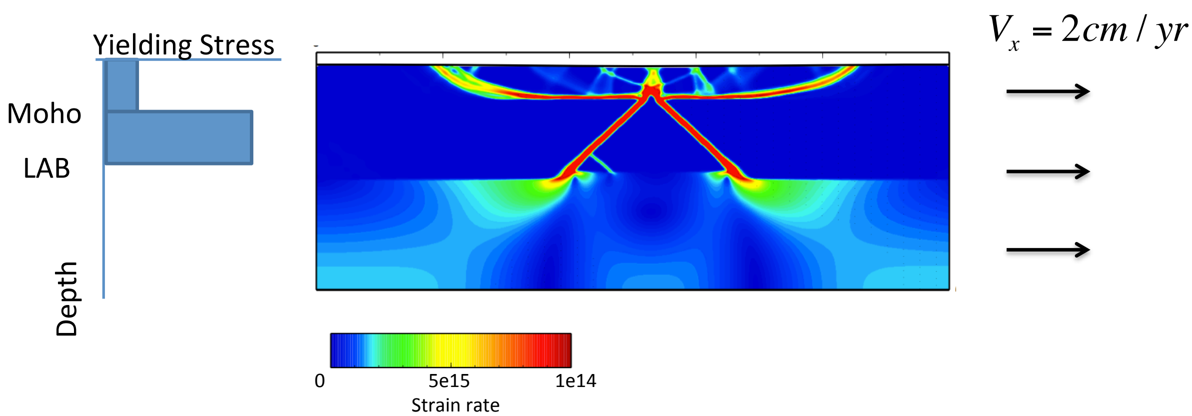


Figure3.9. *Strain rate pattern of the coupled jelly sandwich model lithosphere after 5% extension of. The left diagram is the strength model I used in this case.*

After about 5% extension the coupled Jelly sandwich model predicted a highly localized zone in the mantle and crust and with a pair of detachment faults (Figure3.9). This pattern is very different from what we observed in the Eastern North China.

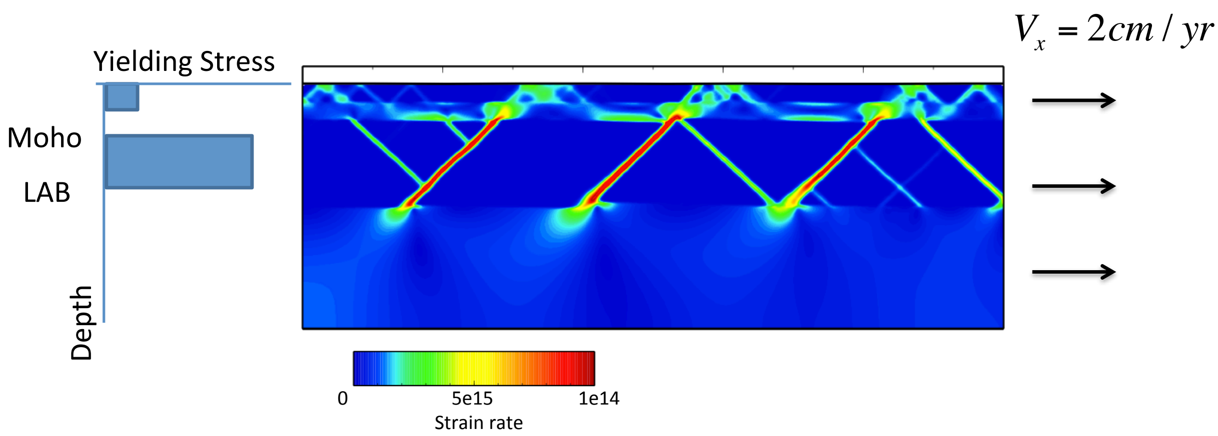


Figure3.10. *Strain rate pattern of the decoupled jelly sandwich model lithosphere after 6% extension of. The left diagram is the strength model I used in this case.*

After about 6% extension the decoupled Jelly sandwich model predicted a relatively localized rifting system (Figure3.10). Since the lithospheric mantle is strong, the strain is mainly localized in the lithospheric mantle and makes the rifting spacing relatively wider than the Crème brûlée model. The interval between rifting system is controlled by the thickness of lithosphere and is about 100-200km. Although the rifting system is distributed in the crust, the spacing is one order of magnitude larger than we observed in Eastern North China.

3.4 Discussion and Conclusions

3.4.1 Strain softening

I tested a series of strain softening scenarios, which increases the strain rate at the bands of high strain rates and affect the pattern of extension at some level; however, it does not fundamentally change the model results. The model with high strain softening effect formed a pair of localized strain bend in the mantle and a region with localized strain in the crust within 3% extension (figure3.11b). While the model with a low strain softening effect didn't form significant stain localization after 9% of extension (figure 3.11c).

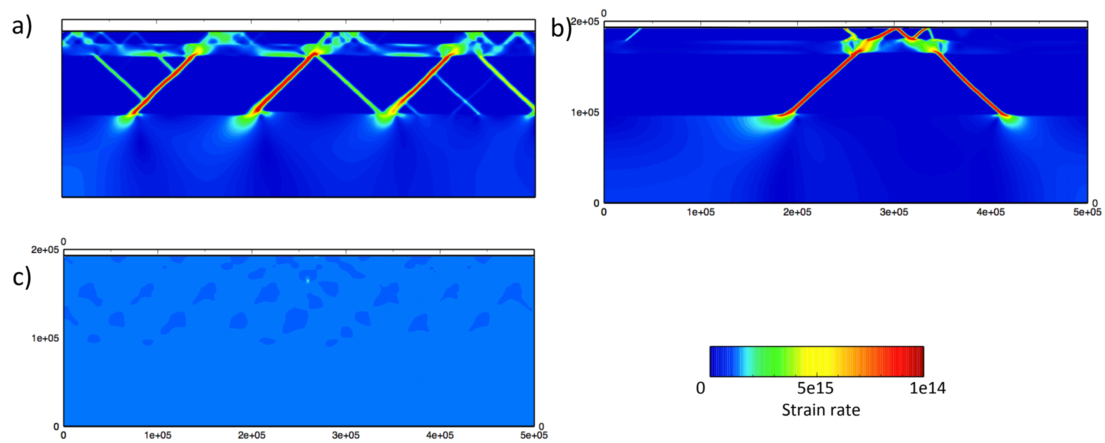


Figure3.11. *Comparison of different strain softening* a) a moderate strain softening effect, the yielding stress is reduced to 1/2 of the starting yielding stress. b) a high strain softening effect, the yielding stress is reduced to 1/10 of the starting yielding stress. c) a low strain softening effect, the yielding stress is reduced to 8/10 of the starting yielding stress.

3.4.2 Comparison with Basin and range

Diffusive crustal extension is not limited to North China. The Basin and Range province has the same type of extension, about 50-100% since Mid-Cenozoic (Hamilton and Myers 1966; Wernicke 1992). Similar to North China, the lithosphere in Basin and range is as thin as about 65 km based on seismology results (Smith et al. 1989; Benz et al. 1990). Surface heat flux is as high as

~$90mW/m^2$ (Lachenbruch and Sass 1978), and the upper mantle is hot, indicated by the gravity (Eaton 1978) and seismic attenuation (Romanowicz 1979; Smith et al. 1989). Also a significant mantle upwelling since mid-Miocene is indicated by widespread volcanism accompanied extension. Liu(Liu and Shen 1998) suggested that there possibly existed a mantle upwelling even before the basin and range extension.

3.4.3 The caused of the thin and weak lithosphere

The thinned lithosphere during the Mesozoic-early Cenozoic in eastern North China could be caused by various mechanisms delamination, thermal erosion. Zhu (Zhu et al. 2011) concluded that the Pacific subduction could produce localized mantle convection cells associated with the downgoing slab and thus cause either delamination and thermal erosion or both. Both of the mechanism would remove the strong lithosphere and replace it with weaker asthenosphere.

3.4.4 Conclusions

From my study I can draw the following conclusion: The diffuse rifting system formed by the Mesozoic-early Cenozoic extension in Eastern North China is a result of extending a weak and thin lithosphere, which was possibly produced by delamination and/or thermal erosion process associated with the subduction of the Pacific Plate under eastern Asian continent.

Chapter 4. WHAT CAUSED THE SHANXI RIFT?

4.1 Introduction

The Shanxi rifting system or Shanxi graben is a northeast-southwest oriented rifting system, about 500 km long and 40 km wide, and is situated between the Ordos block and the Taihang Mountains within North China Craton (Figure4.1). Comparing to the age of North China craton, Shanxi rifting system is relatively young, initiated since the Pliocene (Xu and Ma 1992; Xu et al. 1993; Zhang et al. 1998). The Shanxi rifting system is still active in present. More than 30 earthquakes of magnitude larger than 6 have occurred during the last 2000 years in Shanxi Rifting system.

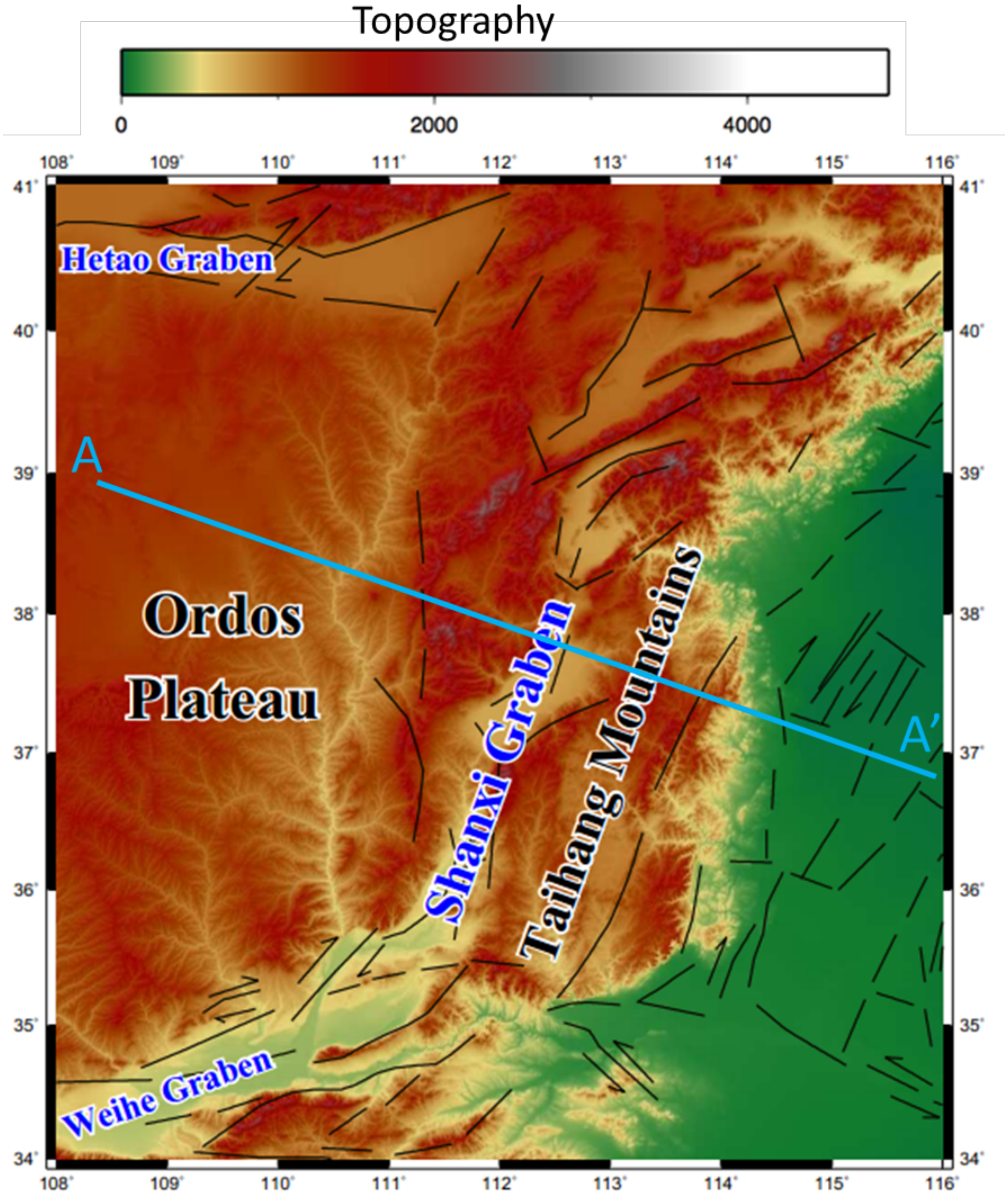
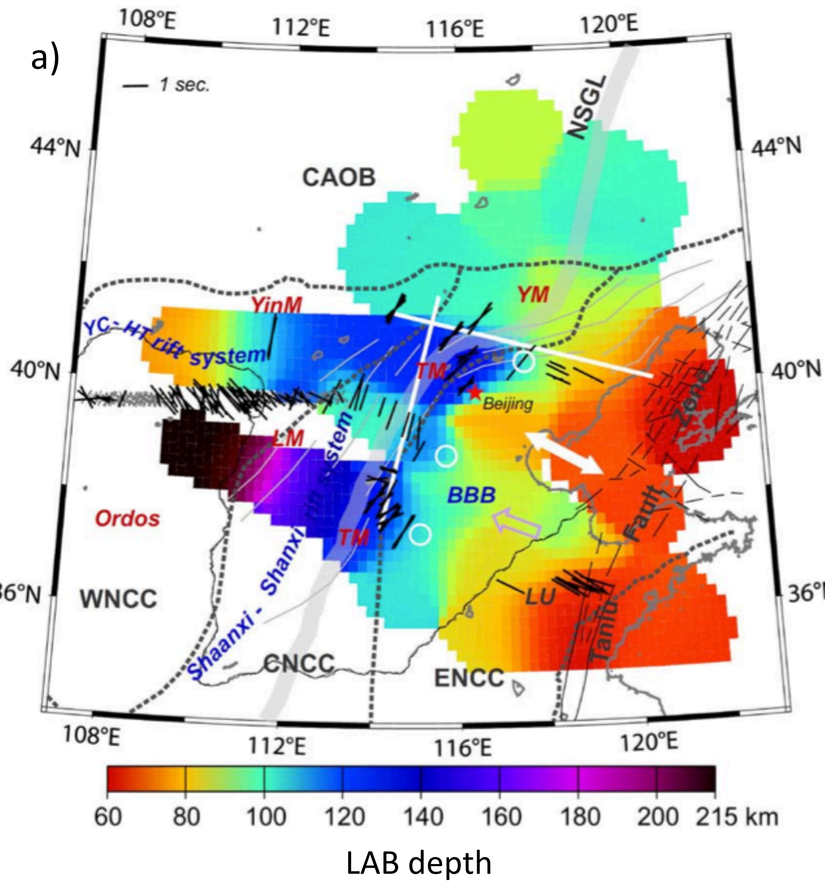


Figure 4.1. *Topography map of Shanxi graben and surrounding region. The blue line A-A' is the profile in Figure4.2. The inset shows the location of North China Craton.*

Seismic results suggest a thick lithosphere (>150km) under the Ordos block to the west of the Shanxi graben and a thin (<100km) lithosphere under the North China Plain to east of Shanxi graben (Huang and Zhao 2006; An et al. 2009; Chen et al. 2009; Huang et al. 2009)(An 2009, Chen 2009, Huang 2009, Huang 2006).

An S-receiver function method was used to study the lithosphere thickness under the North China (Chen et al. 2009). The results shows that lithosphere is about 200 km thick under the Ordos block and gradually changed to about 80 km under the North China Plain (Figure4.2a,b), and the Shanxi rifting system is situated in the lithosphere transition zone where the lithosphere changed from thick to thin(Figure4.2c). Other methods, such as Surface wave tomography and P-wave tomography, are used to study the lithosphere thickness under the North China and show similar results with a S-receiver function (Huang et al. 2009; Xu and Zhao 2009). Although the exact numbers are different (Table4.1), all the results indicate a thick lithosphere under the Ordos block, a thin lithosphere under North China Plain and the lithosphere is gradually changed from Ordos to North China Plain.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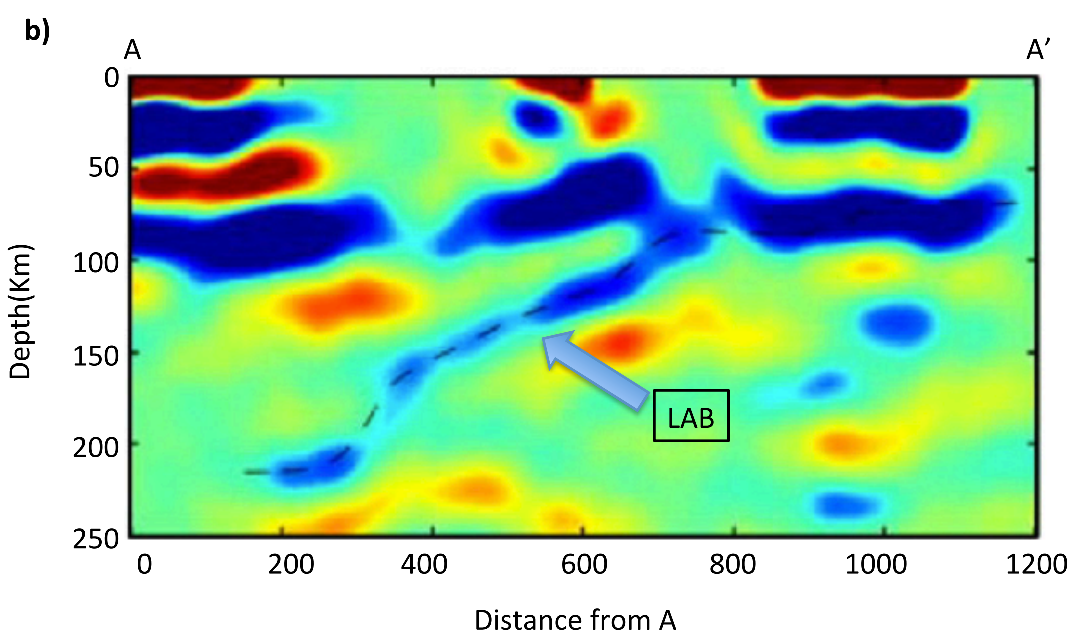
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c)

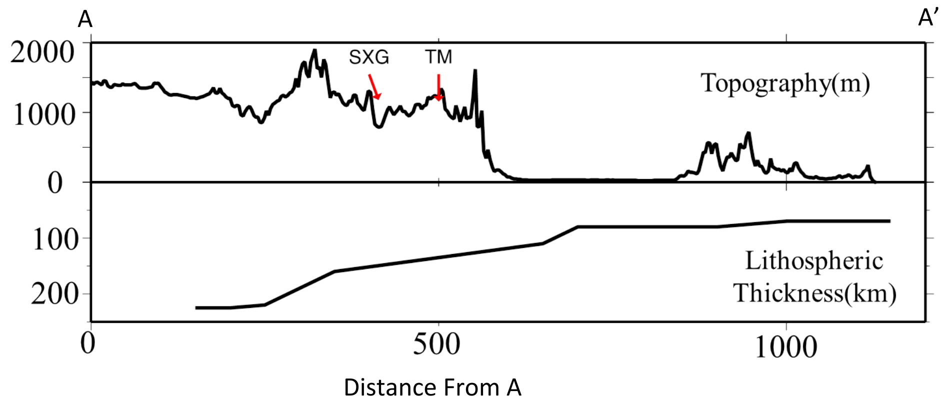

Figure 4.2. *Lithosphere thickness in North China craton. a) The depth of Lithosphere Asthenosphere Boundary (LAB) in the North China region(Chen et al. 2008).The color map in figure shows the depth of LAB in North China b) Receiver function result profile along the line AA’ in figure4.1(Chen et al. 2009). The dashed line in the figure shows the LAB as interpreted by Chen. c) Cross-section of lithosphere (modified from figure4.2b) and topography along the line AA’ line in figure4.1.*

Method	Ordos	North China Plain	Ref
S-wave receiver function	210 km	90 km	(Chen et al. 2009)
Surface wave tomography	160 km	70 km	(Huang et al. 2009)
P wave tomography	220 km	80 km	(Xu and Zhao 2009)

Table4.1. *Lithosphere thickness under north China Craton revealed by different study.*

Many models have been proposed to explain what caused the Shanxi rifting system. These models include: 1) extrusion of Asian lithospheric blocks driven by the Indo-Asian collision (Tapponnier et al. 1982; Zhang et al. 2003), 2) extentional stress associated with the retreat of Western Pacific subduction slab (Northrup et al. 1995), or 3) the basal shear cause by mantle flow induced by Pacific subduction (Zhao et al. 2011; Lei 2012).

These models cannot explain why Shanxi rifting system formed between the Ordos block and Taihang Mountains instead of at the foothill of the Taihang

Mountain (east wedge of Taihang Mountains) where the thin lithosphere replaces the thick lithosphere leading to tectonic deformation within the thin lithosphere.

In this study, I setup a series of 2-D visco-plastic model to investigate the possible cause of the Shanxi rifting system.

4.2 Model settings

The proposed models for the formation of the Shanxi rift could be categorized into two groups: The farfield extensional forces related to trench retreat, and extrusion or basal shear caused distributed extension.

I set up a series of 2D visco-plastic numerical models to simulate the extension process and investigate the effect of geometry of lithosphere and velocity boundary conditions on strain localization. I built a $2000km \times 200km$ box to simulate the east-west intersection across the Shanxi graben. Considering the change of lithospheric thickness, I assumed a gradually thinned lithosphere from west to east, based on the seismic results (Chen et al. 2009; Huang et al. 2009; Xu and Zhao 2009). The lithosphere is set as a viscoplastic layer while the asthenosphere is set as a viscous layer (Figure4.3).

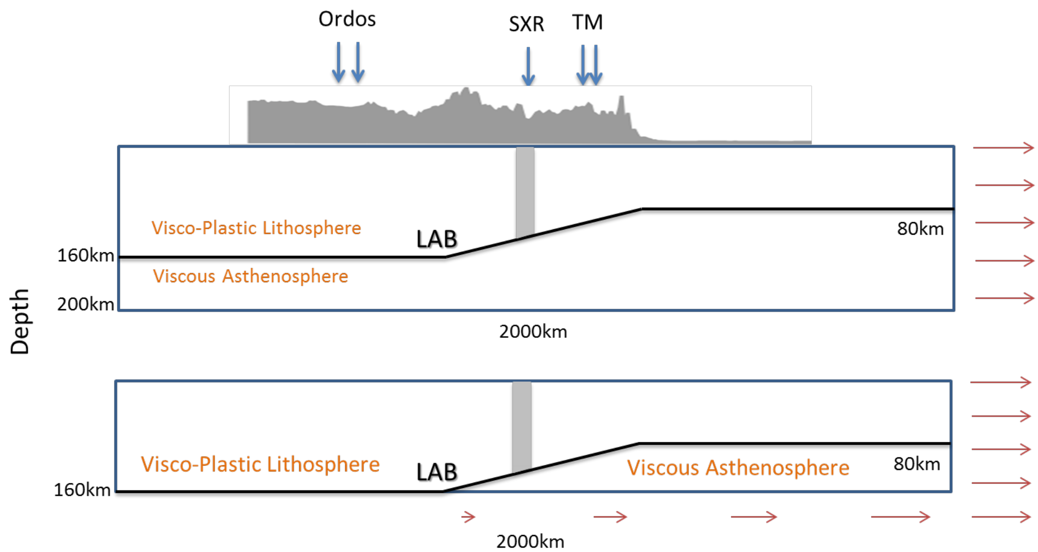

Figure 4.3. *Model geometry and the velocity boundary conditions*

I tested a range of viscosity between $10^{21} \sim 10^{24}\ Pa \cdot s$ for the brittle lithospheric and $10^{19} \sim 10^{21}\ Pa \cdot s$ for the viscous asthenosphere. In my models, I applied Von Misses yielding criteria to simulate the plastic behavior, which can be expressed as

$$\sqrt{J_2} = C' \qquad (3)$$

where J_2 is the second invariant of deviatoric stress and C' is cohesion, in this case it is simply the yielding stress.

In order to test the mechanical consequence of the two groups of models, I applied 2 sets of velocity boundary conditions in my models as shown in Figure4.3.

In one group, I applied a $10 \sim 100\ mm/yr$ boundary velocity on the right side of the box to simulate the far field stretching (Figure4.3a). As the west side of Ordos block is relatively stable , it is set as a horizontally fixed ($V_x = 0$). Both left and right sides are vertically free-slip. The bottom is a horizontally free slip boundary ($V_y = 0$) and the top is a free boundary, which means neither horizontal nor vertical is fixed.

In the other group, I applied a graduate increased velocity at the bottom of the lithosphere to simulate the distributed extension (Figure4.3b). The top and left velocity boundary is the same with the far field stretching models. The right side of the lithosphere is moving with the asthenosphere at a same velocity.

4.3 Results

As a reference model, I set the viscosity as $1\times10^{23}\,Pa\cdot s$ and $1\times10^{20}\,Pa\cdot s$ for the lithosphere and asthenosphere, respectively. I also set a yielding stress of $2\times10^{8}\,Pa$ for the whole lithosphere.

After 10% of extension of far-field stretching, the strain is localized at the foothill of the Taihang Mountain (the edge of the lithosphere thickness transition zone), not under the Shanxi rifting system (Figure 4.4a). It denotes that a rifting system would be produced in the foothill of Taihang Mountain, rather than the location of the Shanxi rift. Although the result from distributed extension model (Figure 4.4b) has some trivial differences from the farfield stretching model

(Figure 4.4a), the major pattern of the strain field is the same: the strain is localized in the east side of the Taihang Mountain, where the lithosphere changed from 160km to 80km. Obviously, the variations of lithospheric thickness controls the distribution of strain. Assuming constant lithospheric properties, the rifting system is predicted to initiate in the foothill of Taihang Mountain, instead of the location of Shanxi rifting system.

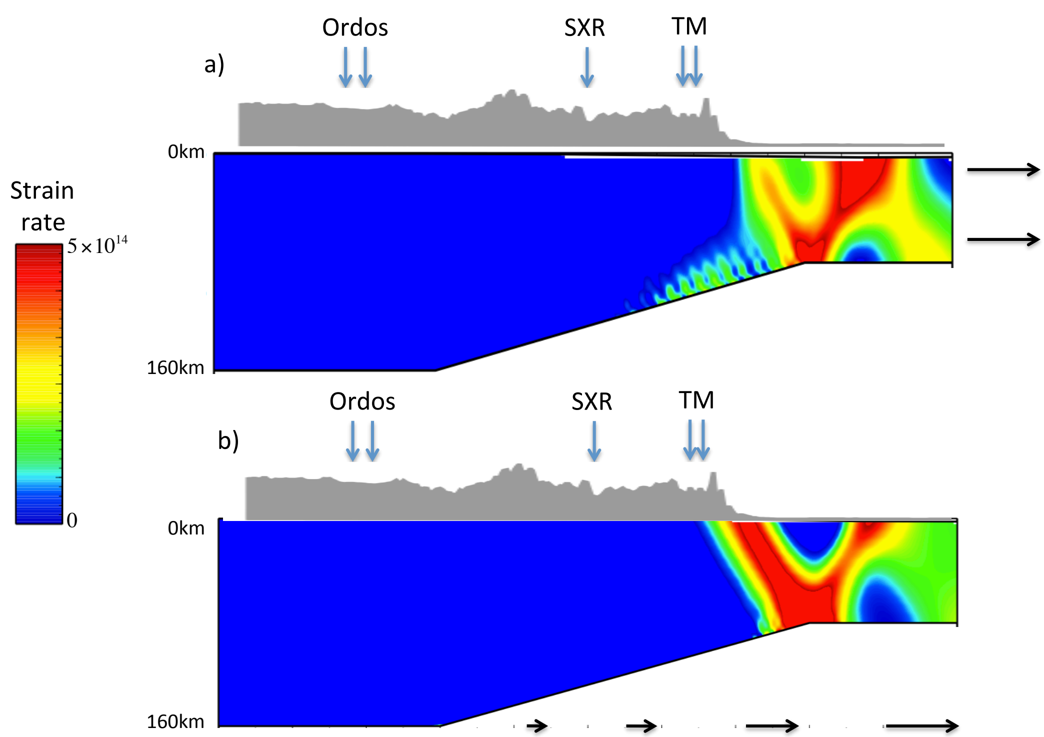

Figure 4.4. *The strain rate pattern of the lithosphere in different models. a) result of the farfield stretching model. b) result of distributed extension model. The top grey part of both figure a) and b) show the topography along the profile and The arrows over the topography figure show the location of Shanxi rifting system, ordos block and Taihang Mountain. SXR: Shanxi rifting system (Shanxi Graben); TM: Taihang Mountain*

Since both mechanisms predict the rifting in the foothill of Taihang Mountain and do not produce a rifting in Shanxi Graben, a preexisting weak zone under the Shanxi Graben is needed to cause rifting under the location of Shanxi rifting system. I set up another set of models with preexisting weak zone under Shanxi rifting system to compare with the models without preexisting weak zone. The weak zone is set as a region with a lower yielding stress (grey zone in Figure4.3).

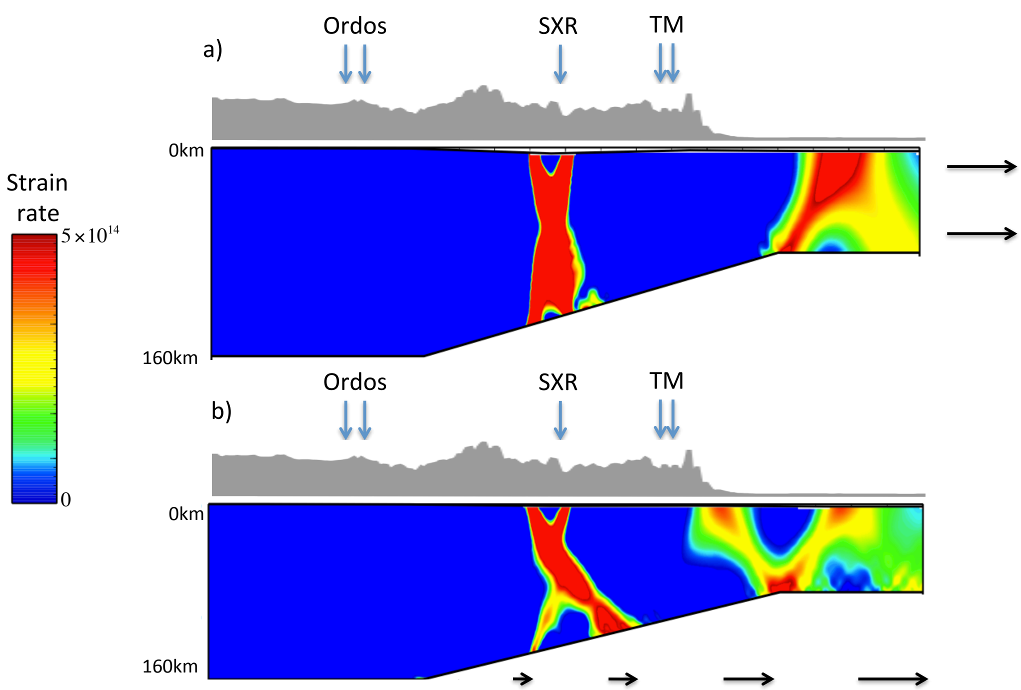

Figure 4.5. *The strain rate pattern of the lithosphere in different models with preexisting weak zone. a) result of the farfield stretching model. b) result of distributed extension model. The top grey part of both figure a) and b) show the topography along the profile and The arrows over the topography figure show the location of Shanxi rifting system, ordos block and Taihang Mountain. SXR: Shanxi rifting system (Shanxi Graben); TM: Taihang Mountain*

From the second strain rate invariants after 10% of extension of far-field stretching, we can easily notice that the strain is localized in the preexisting weakzone under the Shanxi rifting system. Again, for the distributed extension model (figure 4.5b), although the result has some trivial differences from the far-field model (Figure 4.5a), the major pattern is the same with the farfield extension: that there is significant strain localization predicted under the Shanxi graben. Comparing with the result from models without preexisting weakzone, the models with preexisting weakzone shows that introducing a weakzone would cause the strain localization under Shanxi rifting system.

4.4 Discussion and Conclusions

The preexisting weakening is possibly related to the ancient collision between Eastern and Western North China block as an old scar (Zhao et al. 2005; Zheng 2009), although we could not observe the weak zone physically.

Figure 4.6 shows that the location of Yinchuan-Hetao rifting is identical with the Khonodalite Belt (Zhao et al. 1999; Kusky 2011), which formed during Northen Western North China Block and Southern Wesern North China Block collision even earlier than Eastern and Western North China Block Collision (Figure4.6) (Zhao et al. 2005).

Moreover, seismic result review that there is even not much thickness change of lithosphere across the north and west of the Ordos Block, which means that without introducing a preexisting weakening it will be even harder to explain why there is riftings in the Yinchuan and Hetao rifting system and what caused the rifting. Also this kind of process, that rifting from the old collision, could be found in the close and reopen of the Atlantic Ocean, which is known as the famous Wilson Cycle (Wilson 1966).

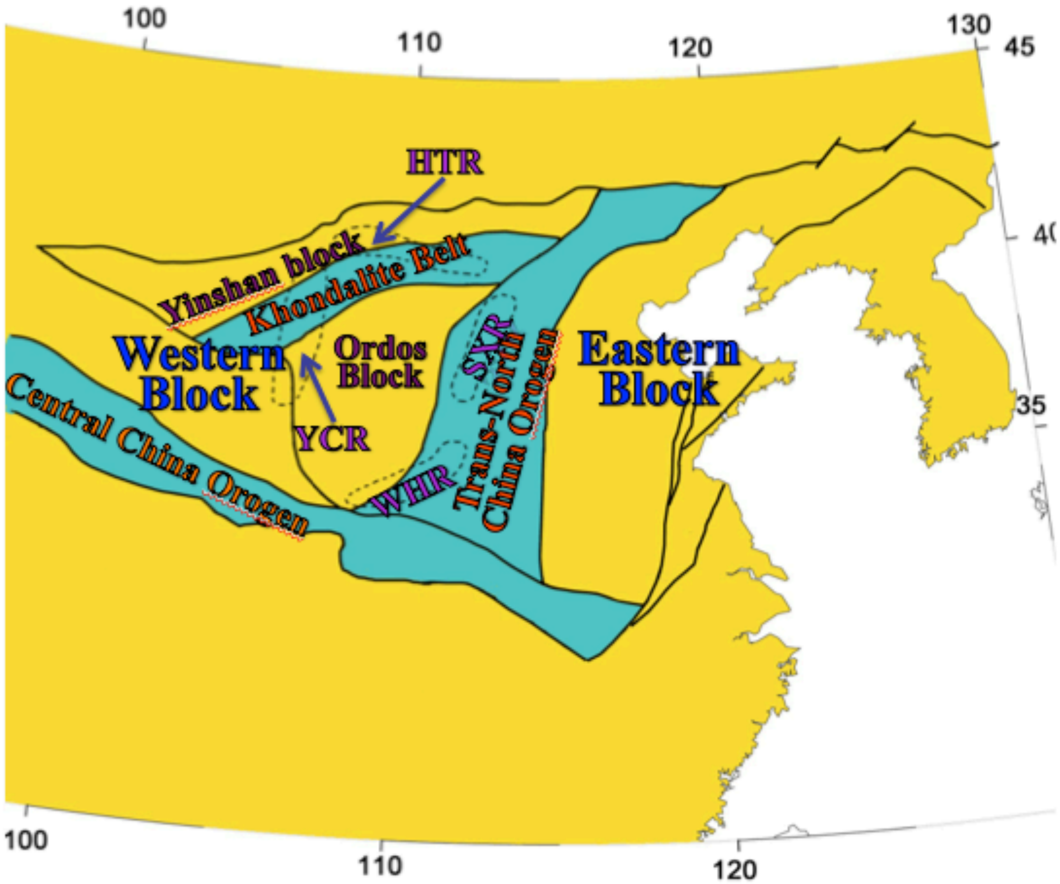

Figure 4.6. *Tectonic subdivision of North China, followed (Zhao et al. 2005). The green regions are the collision belts in North China and the region bounded by dashed line are rifting systems in north China. SXR: Shanxi Rift; WHR: Weihe Rift; HTR: Hetao Rift; YCR: Yinchuan Rift*

In my study, I chose a series of viscosity for the lithosphere and asthenosphere to test the consequence of the extension. I tested a model with separated crust and lithospheric mantle. I divided the brittle lithosphere into two layers: one brittle crust with lower brittle yielding stress $(1 \times 10^{7} Pa)$ and a brittle lithospheric mantle with higher yielding stress $(2 \times 10^{8} Pa)$ (Figure4.7). The result shows that the two-layer lithosphere could introduce some detachment on the Moho and forms a slightly different strain pattern in the lithosphere. However, although the detailed pattern is somewhat different from the one-layer lithosphere, the major feature is the same (Figure 4.8). Without the preexisting weakening the strain localized in the foothill of Taihang Mountain, since the strain localization is controlled by the lithosphere shape. And by introducing a preexisting weakzone, the strain is localized in the Shanxi Graben.

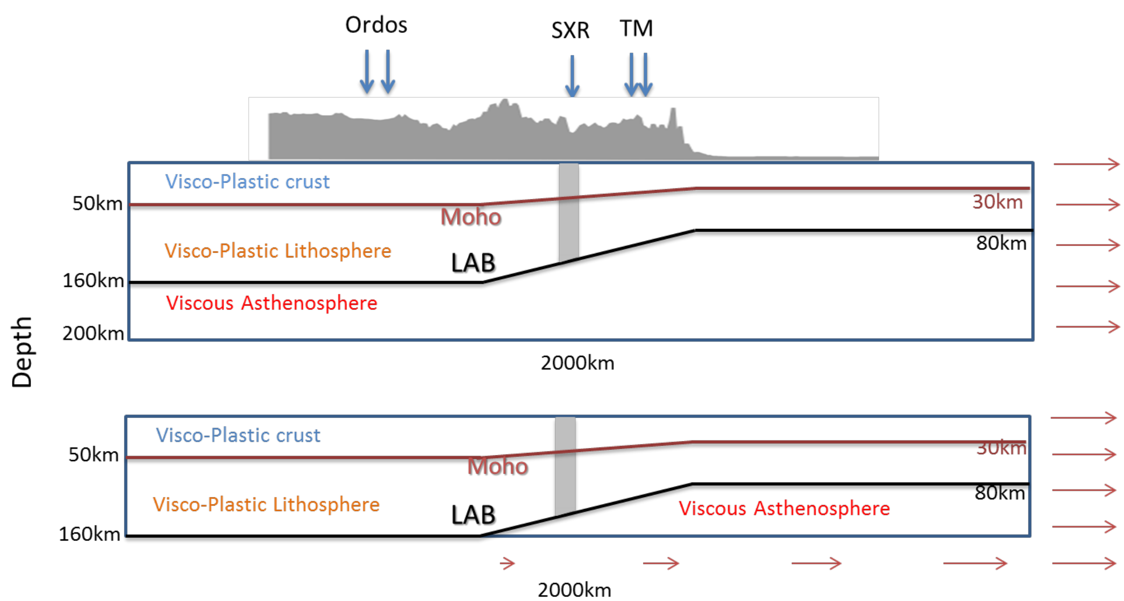

Figure4.7. *Geometry and the velocity boundary condition for two layer lithosphere models*

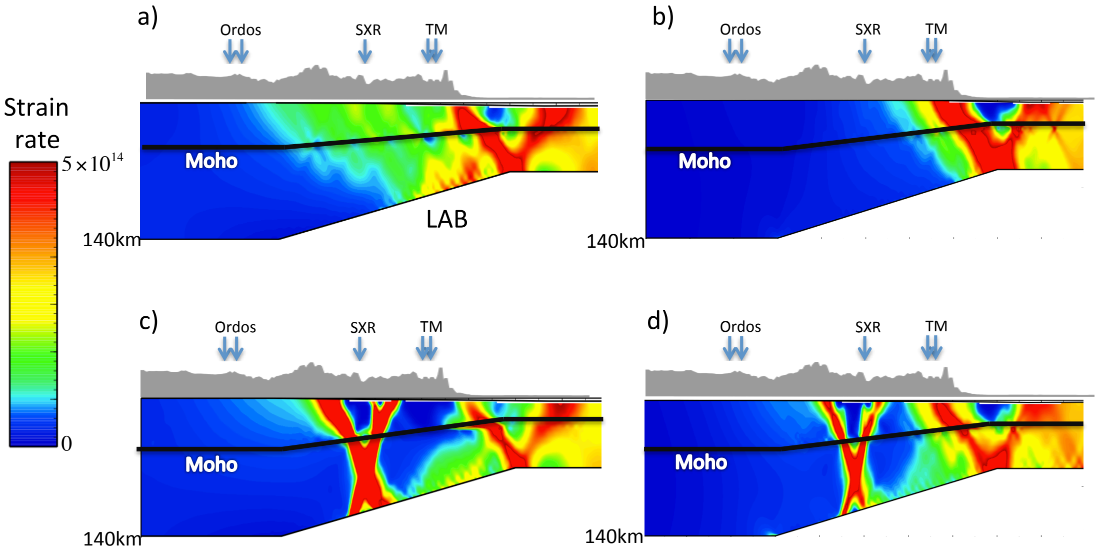

Figure4.8. *The strain rate pattern of the lithosphere in different models with layered lithosphere. a) result of the farfield stretching model without weak zone. b) result of distributed extension model without weakzone. c) result of the farfield stretching model with weak zone. d) result of distributed extension model with weakzone. SXR: Shanxi rifting system(Shanxi Graben); TM: Taihang Mountain*

From all the results and discussions I can draw to following conclusions: 1) the preexisting weak zone is required to form the Shanxi rifting system at the place we observed today; 2) those preexisting weak zone is possibly the collision belt formed during the amalgamation of the North China Craton; 3) the preexisting weak zone is one of the controlling factors of initiating the continental rifting system.

Chapter 5. CONCLUSIONS

By discussing North China the two-phase extension as specific examples, I studied the control of rheology structure and the preexisting weak zone of the lithosphere on continental extension. My study reveals that:

1) Mesozoic-early Cenozoic wide-distributed extension requires a thin and hot lithosphere, which is probably the result of delamination or thermal erosion of the lithospheric root under the eastern part of the North China Craton.

2) The localized rifting during the late Cenozoic in the western part of the North China Craton indicates a relatively cold and thick lithosphere. Furthermore, preexisting lithospheric weakening is needed to explain the formation of the Late Cenozoic rift zones within the relatively thick lithospere. These preexisting weakening zones may be inherited from the Paleoprotozoic collision that formed the North China Craton.

3) The ancient tectonic collision event which occurred billions of years ago can still affect the recent tectonic activity.

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