

# A preliminary study on the lithospheric thermal-rheological structure of the East Qinling orogenic belt

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**Abstract** This paper considers the lithospheric rheological structure of the East Qinling orogenic belt to explore its geodynamics. The lithospheric rheological structure was calculated by the constraints of the lithospheric temperature structure. The thermal-rheological stratification structures of the lithosphere in the East Qinling orogenic belt present different features from each other within different tectonic units. The hinterland fault-bounded fold zone (HLZ) and the North Qinling thick-skinned imbricated thrust zone (NQL) in the northern half part of the Qinling orogen, with a temperature of 305°C for the Moho boundary, are characterized by “cold” geotherm, thickened lithosphere and the model C for rheological stratification structure. The South Qinling tectonic zone (SQL), with a mean temperature of 642°C and a high temperature of 826°C for the Moho boundary, has obvious features with the model H of “hot” geotherm, thinned lithosphere and intensive rheological behavior within moderate-lower crust and top of the upper mantle. During post-orogenesis, the NQL, being the convergent frontal region of continental subduction beneath the Qinling orogen by both the North China craton (NC) and Yangtze craton (YZ), is in a coexistence period of a dominantly thickened lithosphere and an initial delamination, and the SQL, probably under pluming, has been developing new delamination and underplating and partial melting within the crust in its axial area and recycling for mass and energy (in the forms of heat transfer and convection) between the crust and mantle.

**Keywords** Qinling orogenic belt, rheological structure of the lithosphere, delamination, continental dynamics

In April 2003, a white paper entitled, *New Departures in Structural Geology and Tectonics*, was published by the

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National Science Foundation of America (The Tectonics Program, Earth Science Division, and National Science Foundation (GEO/EAR), 2003)<sup>1</sup>. Four new study directions for the next decade in the areas of structural geology and tectonics were advanced. Specific emphasis was placed on “Beyond plate tectonics: Rheology and orogenesis of the continents”. Lithospheric rheology, therefore, has become one of the new frontiers for probing continental dynamics (Ranalli and Murphy, 1987; Ranalli, 1995; Zang et al., 2002; Liu et al., 2004).

The Qinling orogenic belt (QL), as a major component of the Central Orogenic System (COS), is a critical segment for exploring the interaction of subduction, collision and matching between the North China and Yangtze continents, their vertical and lateral tectonic coupling/uncoupling, and dynamic driving mechanisms. A thorough study from geology, geophysics and geochemistry subsidized by the NSF indicates that the Qinling orogenic belt consisting of three plates (the southern margin of North China, Qinling and the northern margin of Yangtze) and two sutures (Shangdan and Mianlue sutures), underwent Caledonian plate subduction in the Early Paleozoic and finally collision orogenesis from the Hercynian to Indo-Chinese epochs, and afterwards superimposed and composite extensive intracontinental orogenesis. A 3D tectonic model has been created (Zhang et al., 1996a, b, 2001). Based on the lithospheric electrical structure in the Qinling orogenic belt detected by magnetotelluric sounding (MTs), a uniformly dynamic model for western and eastern segments has also been created and features between the two segments compared (Cheng et al., 2003, 2004). However, after delamination in the Mesozoic under the framework of the 3D “flyover” model, what characteristics and implications for continental dynamics does the detailed lithospheric thermal-rheological structure for various tectonic units have? To counter geo-transection of the East Qinling orogen (Yuan et al., 1994, 2002; Liu et al., 1995; Li et al., 1998; Cheng et al., 2004), combined geological data and lithospheric

<sup>1</sup>The Tectonics Program, Earth Science Division, and National Science Foundation (GEO/EAR) (2003). *New Departures in Structural Geology and Tectonics*. <http://www.Pangea.Stanford.Edu/~Dpollard/NSF>

thermal-rheological structure in different tectonic units are calculated and deep level dynamic background for formation and evolution has further been explored.

## 1 Rheology of lithospheric materials

Silicate polycrystals exhibit rheological properties that change as a function of temperature and pressure and therefore depth. At low to moderate  $p$  and  $T$  conditions, yielding is by fracture or sliding along pre-existing fracture planes. Linear frictional failure criteria (Sibson, 1974) can be applied

$$\sigma_1 - \sigma_3 \geq \beta \rho g z (1 - \lambda) = \sigma_b \quad (1)$$

where  $\sigma_1$  and  $\sigma_3$  are maximum and minimum compressive stresses, respectively;  $\beta$  is a parameter depending on type of faulting, with values of 3.0, 0.75 and 1.2 for thrust, strike-slip, and normal faulting, respectively (3.0 adopted in this paper due to thrusting);  $\rho$  is the density of material;  $g$  is acceleration of gravity;  $z$  is depth, and  $\lambda$  is the pore fluid factor (ratio of pore fluid pressure to overburden pressure). Formula (1) shows that linear frictional failure in the brittle domain strongly depends on pressure rather than temperature.

At temperatures sufficiently high for steady-state flow, many experiments have indicated that creep dislocation of all crust and upper mantle rocks is a strong function of temperature, which agrees with steady-state power-law creep (Kirby, 1983; Tsenn and Carter, 1987) and can be written as

$$\sigma_d = (\dot{\epsilon}/A)^{1/n} \exp(Q/nRT) \quad (2)$$

where  $\dot{\epsilon}$  is the ductile strain rate ( $1.0 \times 10^{-14} \text{ s}^{-1}$  in this paper following Ranalli and Murphy (1987));  $A$ ,  $n$  and  $Q$  are material parameters, which are approximately stress- and temperature-independent in the range of interest;  $R$  is the gas constant, and  $T$  is the absolute temperature.

Rheological stratification of the lithosphere is determined by a comparison between deviatoric stress  $\sigma_b$  required for brittle deformation and deviatoric stress  $\sigma_d$  required for ductile deformation. When  $\sigma_b < \sigma_d$  at the relevant depth, brittle frictional slipping will occur and otherwise ductile creep (Ranalli and Murphy, 1987) will take place. And the relevant depth for  $\sigma_b = \sigma_d$  is a transition zone from brittle to ductile behavior of rocks in the lithosphere, corresponding deviatoric stress is known as flow stress. Thus the depth from brittle to ductile deformation is determined according to the envelope line of yielding stress that begins to flow in the rheological strength profile and the 'strength' at any given depth is the lower of the brittle and ductile stress difference

$$\sigma_y = \min(\sigma_b, \sigma_d) \quad (3)$$

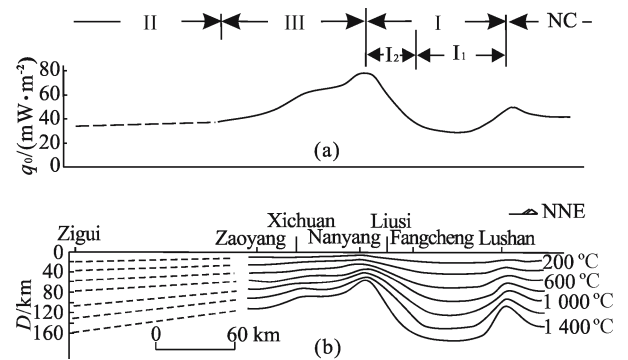
## 2 Characteristics of thermal-rheological stratification structure in the lithosphere

Based on the velocity and electrical structure from the seismic reflection, MT and seismic tomography profiles from

Yexian in Henan Province to Nanzhang in Hubei Province, we carried out further stratification for the lithospheric section, taking thermal flow data from Hu et al. (2001) (Fig. 1a) and theoretical model equations from Wang et al. (2001). Thermal conductivity of the lithosphere, as a function of temperatures, is expressed as

$$k(T, z) = k_0 / (1 + \alpha T_0)$$

where  $k_0$  is 3.0, 2.3 and 2.5 W/(m·K) for upper crust, lower crust and lithospheric mantle, respectively;  $\alpha$  is temperature gradient, taken to be 0.001, 0.0 and  $-0.0025$ , respectively, and  $T_0$  is mean temperature per year, taken to be 14°C. The lithospheric temperature section calculated is shown in Fig. 1b. A lithospheric petrologic model is obtained based on comprehensive study (Wang et al., 1995; Gao et al., 1999a, b). Quartz and/or granite, quartz-diorite and olivine represent compositions in the upper crust, moderate and lower crust and lithospheric mantle, respectively, corresponding to material parameters listed in Table 1.



**Fig. 1** Heat flow and temperature profile of the lithosphere in the East Qinling orogenic belt

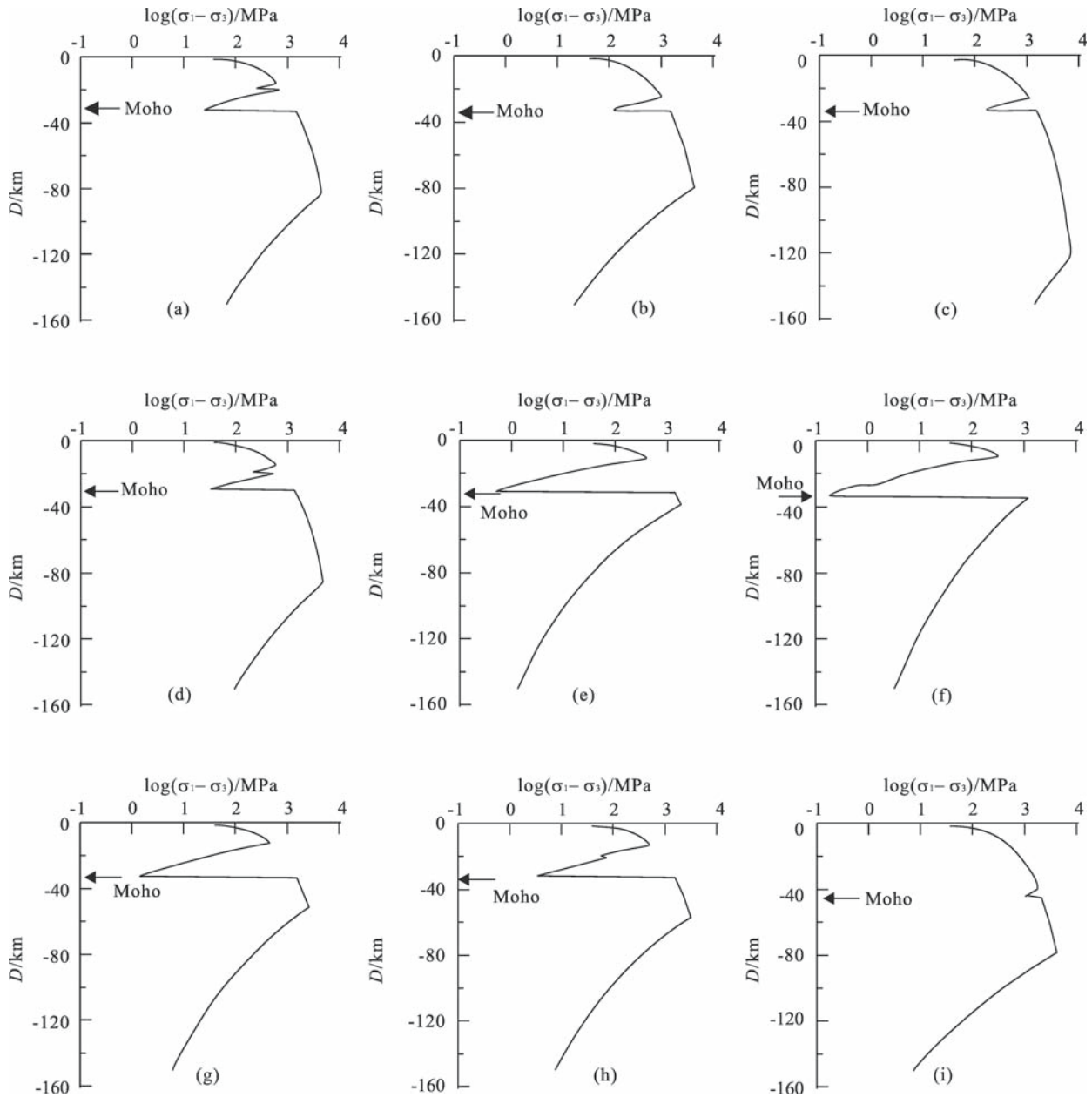
(a) Heat flow profile; (b) temperature distribution of the lithosphere. NC. North China block; I. southern part of North China block; I<sub>1</sub>. hinterland thrust bounded fold zone; I<sub>2</sub>. North Qinling thick-skinned imbricated thrust zone; II. northern margin of Yangtze block; III. South Qinling tectonic zone (Qinling tiny block)

**Table 1** Rheological parameters used by the model

Materials	$A/(\text{MPa}^{-n} \cdot \text{s}^{-1})$	$Q/(\text{kJ} \cdot \text{mol}^{-1})$	$n$
Quartz (dry)	$5.0 \times 10^{-6}$	190	3.0
Quartz-diorite	$1.3 \times 10^{-3}$	219	2.4
Olivine	$1.9 \times 10^3$	420	3.0

The rheological profiles in the East Qinling orogenic belt (Fig. 2) show that rheological stratification and creep strength in the lithosphere depending on depth vary with different tectonic units. They reflect vertical and horizontal anisotropic characteristics of composition, temperature structure and dynamic driving mechanism after undergoing long term tectonic evolution.

(1) The lithosphere in the southern margin of the North China craton (NC) shows an overall brittle, ductile and brittle "sandwich" structure (Fig. 2a). The moderate and upper crust



**Fig. 2** The rheological structural profiles of tectonic units in the East Qinling orogenic belt

(a) North China block; (b) northern part of the hinterland thrust and fold zone; (c) southern part of the hinterland thrust and fold zone; (d) North Qinling thick-skinned imbricated thrust zone; (e) northern part of South Qinling tectonic zone (nearby Shangdan suture zone); (f) central part of South Qinling tectonic zone (Tanghe–Dengxian); (g) southern part of South Qinling; (h) southern margin of South Qinling (Zaoyang–Xiangfan); (i) northern margin of Yangtze block (Zigui)

is characterized by brittle deformation, and the average brittle-ductile transition depth is located at 17 km. The thickness of the thin brittle layer between the moderate and lower crust and the Moho boundary is 8–16 km. Obvious ductile deformation occurs below 90 km and creep strength (i.e., deviatoric stress) decreases with increasing depth. The rheology stratification structure, except for a thicker ductile layer and lower creep strength in the moderate and lower crust, is very similar to model C for Precambrian cold geotherm tectonic province proposed by Ranalli and Murphy (1987).

(2) The rheology stratification structure of the northern part of the hinterland fault-bounded fold zone (HLZ) within the Qinling orogenic belt shows as three layers (Fig. 2b). The moderate and upper crust also displays a brittle and brittle-ductile transition depth at 20 km, and ductile layer thickness in the lower crust is only 12 km but creep strength is higher ( $> 100$  MPa). The temperature at the base of the Moho boundary is  $305^{\circ}\text{C}$ . Creep strength increases with increasing depth and rocks show brittle behavior from the Moho boundary down to 80 km (within upper mantle). The lithosphere in

the southern part of the HLZ of the Qinling orogenic belt is much thicker (220 km) (Li et al., 1998), with heat flow  $32.1 \text{ mW/m}^2$ , compared with 150 km for the cold geotherm lithosphere that is given by Ranalli and Murphy (1987) and Ranalli (1995), with the exception of occurrence of about 10 km ductile deformational trend (creep strength  $> 100 \text{ MPa}$ ) in the lower crust and a very thick brittle layer in the uppermost mantle (Fig. 2c). In general, rheology stratification structure in the HLZ is approximate to model C of the cold geotherm for the Precambrian tectonic province, and the main difference between them is that the HLZ has a thicker, colder lithosphere.

(3) The southern part of the North Qinling thick-skinned imbricated thrust zone (NQL) shows a “sandwich” rheological structure in the form of brittle, ductile and brittle, due to its proximity to the South Qinling tectonic zone (SQL). Its creep strength is more than that of the southern part of the NC but less than that of the HLZ. From north toward south its rheological behavior increases and the depth of brittle-ductile transition within the moderate-upper crust gradually shallows, varying from 16 to 14 km, and brittle layer thickness of the uppermost mantle also varies from 57 to 18 km. Its present rheological stratification structure is also similar to the model C corresponding to cold geotherm for Precambrian tectonic province.

(4) In the Shangdan and the SQL, thickness of the ductile layer is the greatest and flow stress in the crust and upper mantle is the lowest of the lithospheric ductile domain of the whole East Qinling orogenic belt. In the northern and southern parts of the SQL, with the exception of brittle behavior occurring within 10 km in the uppermost crust, the ductile domain from 10 km down to the Moho boundary is dominant, the thickness of the creep layer within the crust is 20 km and flow stress near the Moho interface quickly decreases to  $< 1 \text{ MPa}$ . There is a little obvious brittle layer but only small undulations within the moderate crust (Fig. 2e, g). The thickness of the brittle domain in the uppermost mantle is only 8 km and flow stress beneath that rapidly decreases to less than 1 MPa with increasing depth. The thickness of the upper crustal brittle layer in the central part of the SQL (between Tanghe to Dengxian) is only 9 km and the remaining part of the lithosphere shows ductile domain (Fig. 2f), besides creep strength above and under the Moho boundary, jumping due to compositional differences. The creep strength of the southern margin of the SQL, near the Xiangguang fault, increases and the brittle layer in the upper mantle thickens (Fig. 2h).

To sum up, the rheological stratification structure of the SQL is, as a whole, similar to the model H that is relevant to hot geotherm for a continental extensional province or an intra- or inter-plate strike-slip province; possibly, also to the “core zone” of some Mesozoic-Cenozoic orogenic belts (Ranalli and Murphy, 1987; Ranalli, 1995). On the other hand, depths starting to flow within the crust and upper mantle in the SQL show prominently to be deepened, and creep strength also increases from the central axis towards the south and north, the minimum value, located between Tanghe and

Dengxian, is less than one order than that of both the southern and northern sides.

(5) For comparison, a rheological structural profile in the northern margin of the Yangtze craton (YZ) has been calculated by heat flow ( $35.42 \text{ mW/m}^2$ ) measured at nearby Zigui (Fig. 2i). The result indicates that a brittle-ductile transition zone occurs at a depth of about 79 km, except for creep strength jump ( $\sim 1000 \text{ MPa}$  and creep layer thickness being only 4 km) at the Moho interface. Lithospheric thickness by MT is 140–150 km. In general, rheological stratification structure in the northern margin of the YZ is very similar to the model C with cold geotherm for Precambrian tectonic province.

### 3 Conclusions

Due to different levels of the lithosphere (i.e., shallow, moderate and deep) in the Qinling orogenic belt being likely in different tectonic stress regimes, decoupling between different orientational structural layers might be developed. An extensional stress trending S-N in the moderate-upper crust produces E-W strike rifting basins, which are superimposed on the orogenic belt. The moderate-lower crust and lithospheric mantle, because of intracontinental subduction by both the NC southward and the YZ northward, are in an S-N strike compressive regime. The asthenospheric mantle being in NNW-SSE directional extensional stress may bring about a regional heat material upwelling from the asthenosphere approximately along the S-N strike.

(1) The rheological structure in the southern margin of the NC has a cold geotherm and quartz/diorite intermediate crust. Its differences when compared to the models from Ranalli and Murphy (1987) and Ranalli (1995) are related to superpositions that derive from intracontinental subduction by the NC southward since the Late Cretaceous period and rifting along NNE-SSW strike caused by the deep mantle dynamics of the western Pacific Ocean. These indicate that the lithospheres in the southern margin of the NC and the northern part of the HLZ still have reserved partial properties of stable craton although remoulded during the post orogenic period.

(2) Thickened lithospheric root detected by MT in the southern part of the HLZ and northern part of the NQL occurs at present. Its creep strength is not only more than one order than that of the SQL but also more than that of the south margin of the NC.

The rheological structure in the HLZ and the NQL not only has lithospheric thickened process but also possesses the conditions of the lower crustal convective instability (Jull and Kelemen, 2001). Therefore, we infer that the thickened lithospheric root in the HLZ and northern part of the NQL is an indication from the Mesozoic hot lithosphere to evolve a “cold” and thick one today, and mainly has a reflected deformation regime of the lithosphere after the Late Cretaceous period, particularly by intracontinental deformation mechanism in the late to recent era (Cheng et al., 2003). The

rheological structure in this paper confirms the findings by MT and supports the above-mentioned inference from another side. Thus, delamination in the HLZ and the northern part of the NQL is not a dominant factor but is in an initial period (or “prelude” stage) (Cheng et al., 2003).

(3) The SQL between the Shangdan suture and Xiangfan, as one of the main tectonic units consisting of the Qinling orogenic belt, which had been matched in the Indo-Chinese epoch, is characterized by hot geotherm, thinned lithosphere and rheological structure similar to the core of the Mesozoic-Cenozoic orogenic belt and intra-plate extension and/or, inter-plate strike-slip (Ranalli and Murphy, 1987; Ranalli, 1995). The creep strength of the moderate-lower crust in the SQL is shown as 10–1 MPa (with minimum value less than 1 MPa) with developing horizontal rheological layer, which agrees with findings that have been detected by magnetotelluric sounding (Li et al., 1998), for example, lithospheric thickness of 68 km between Nanyang-Dengxian, development of eclogite-bearing peridotites and partial melting body within the lower crust and the top of the upper mantle.

(4) The northern margin of the YZ (along Zigui E-W strike), as a component part of the foreland basin in the Qinling orogenic belt, accepts continuous sediments during  $T_3$ –J. With starting uplift from the Cretaceous until today its crustal thickness is 44–46 km and lithospheric thickness of about 155 km, which belongs to properties of cold geotherm and thick crust. The rheological structure suggests that the uppermost of the lithosphere chiefly shows brittle, the creep strength jumping between crust and mantle is not clear and brittle-ductile transition depth in the upper mantle is located at 79 km. These results confirm that distinct stress-strain relaxation does not take place in the Moho boundary along with continuous intracontinental subduction by the YZ northward in the post-orogenic period. Therefore, there is mountain root and higher coupling degree between the crust and the mantle. Loading of above sea level and mass excess within the crust are supported by topographical undulation of the Moho interface and elastic flexure of the lithosphere. Their isostatic compensation is mainly accomplished by mass to flow within the asthenosphere.

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