by Guowei Zhang, Liwen Xiang and Qingren Meng

The Qinling orogen and intracontinental orogen mechanisms

The Qinling orogen is a composite continental orogen with a complex evolutionary history. During the Early and Middle Proterozoic, it was a continental rift; in the late Proterozoic, it began to be part of a plate tectonic regime; from the Palaeozoic to Early Mesozoic, it was involved in subduction-collision between three plates; and in the Mesozoic and Cenozoic, it was affected by intracontinental postorogenic tectonism. The Qinling orogen has a flyover-shaped, 3-D lithospheric architecture.

Introduction

The Qinling orogen extends from east to west in the middle of the China continent. Linking the Dabie Mountains in the east and the Qilian and Kunlun mountains in the west, it is in a geotectonically important position. It is now believed to be a unique composite continental orogen with a complicated composition and structure. It has undergone evolution under different tectonic regimes during its long developmental history, constrained by different tectono-dynamic systems of the palaeo-Pacific, Tethys, Laurasia and Gondwanaland.

Main tectonic units and evolutionary stages

The main tectonic units of the Qinling orogenic belt are shown in Figure 1. Primarily, the belt is composed of three distinct tectono-lithostratigraphic units, which possess different crustal compositions and textures, and which evolved under different tectonic regimes in three stages. The lower unit represents two kinds of orogenic basement. One is a Late Archaean–Early Proterozoic metamorphic crystalline complex, now dispersed in the orogenic belt making it very hard to reconstruct the early history. The other is a widely outcropping Middle Proterozoic sedimentary–volcanic low-grade metamorphosed succession, which is actually a sort of transitional basement formed in extensional tectonic settings. It is evident that intense rifting occurred at 800–1000 Ma and the succession was produced in a mosaic rift valley and small ocean basin environment (Zhang, 1988). The middle unit is a Late Proterozoic–Middle Triassic succession, consisting of depositional sequences developed at both active and passive continental margins; subduction-related ophiolites, and collisional granites. All these demonstrate a plate tectonic regime at this stage (Li et al., 1978; Mattauer et al., 1985; Hsu et al., 1987; Zhang, 1988; Xu et al., 1986; Ren, 1991). In addition, widespread basement uplift also implies subcrustal underplating and vertical accretion (Platt, 1993; Michard, 1993). The upper unit is made up of both intrusive granites and sediments deposited in foreland-, hinterland-, and postorogenic-rifted basins. The Meso-Cenozoic intracontinental rift faulting, tectono-magmatism and tectonic deformation indicate an intracontinental orogenesis following the main period of strong orogenic movement. The Qinling orogen was actually a branch of the northern flank of palaeo-Tethys from the Late Proterozoic to the

Palaeozoic. Two limited oceans originated during this time and the Qinling microplate was then separated from the north China plate and the Yangtze plate. Subduction of oceanic crust took place in the Early and Middle Palaeozoic, accompanied by coeval vertical underplating and accretion. Continent–continent collision occurred from the Carboniferous to the Middle Triassic in an oblique and diachronous fashion, creating two major suture zones, that is, the northern Shangdan suture zone and the southern Mianlue suture zone. Intense Mesozoic–Cenozoic intracontinent orogeny brought about rapid uplift and eventually formed the present-day Qinling.

Processes in, and the characteristics of, the main Qinling orogeny

The main phase of the Qinling orogeny was in the Late Proterozoic–Early Mesozoic. The processes operating and characteristics of the orogeny can be summarised as follows.

Breakup of the Late Proterozoic Qinling lithosphere and change in the tectonic regime

A preliminarily united Yangtze Block formed as a result of complex integration of segments of crystalline basement during the Jinningian (1000–800 Ma), but the Qinling, (the northern margin of the Yangtze Block at that time) was still suffering extension and breakup. Rifting-related volcanism was intense along the Shangdan fault and Shangxian fault from the Late Proterozoic to the Early Palaeozoic. A Qinling proto-ocean was initiated by continuous rifting in the pre-Sinian period and caused the north China plate to become separated from the Yangtze plate.

The evidence for this important transition from a continental rift regime in the Middle Proterozoic to a plate tectonic regime in the Late Proterozoic includes the following:

- The Yangtze-type Sinian is developed only to the south of the Shangdan fault and has never been found to the north.
- Different kinds of ophiolitic and volcanic rocks (983 Ma; 357–402 Ma) are preserved within or beside the Shangdan zone (Zhang et al., 1994; Li et al., 1989).
- There are also subductional and collisional granites (382–440 Ma; 323–210 Ma) (Zhang et al., 1992; Zhang et al., 1994).
- The northern margin of the Yangtze plate shows geological features of a passive continental margin, while the southern margin of the north China plate has the character of an active margin.

Subduction–collision from the Palaeozoic to the Early Mesozoic

Following the establishment of the north China plate and Yangtze plate in the Late Proterozoic, the continuing evolution of the Qinling was not simply a response to the interaction and lateral movement of these two plates. Further extension of palaeo-Tethys led to the formation of a rifted zone along the present-day Mianlue fault (SF₂, Figure 1) during the interval from the Devonian to the Carboniferous. This rift was a new branch of the northern flank of palaeo-Tethys, separating the Qinling plate from the Yangtze plate, and

Figure 1 Major tectonic units of the Qinling Orogenic Belt.

I	South margin of North China Block	III ₂	northern part of south Qinling Late Palaeozoic uplifted zone in the southern part of south Qinling	F ₄	Huangtai-Waxuezi thrust zone	2	Foping
I ₁	hinderland thrust-fold zone			F ₅	Shangxian-Xiaguan thrust fault	3	Xiaomoling
I ₂	thick-skinned imbricated thrust zone	SF ₁	Shangdan suture zone	F ₆	Shanyan-Fengzhen thrust fault	4	Douling
II	Northern margin of Yangtze Block	SF ₂	Mianlue suture zone			5	Tongbai
			Major faults:	F ₇	Shiyan fault	6	Dabie
II ₁	foreland thrust-fold zone	F ₁	Northern boundary fault of Qinling	F ₈	Shiquan-Ankang thrust fault	Transitional basement blocks:	
II ₂	large-scale frontal thrust zone on the south margin of Bashan-Dabie Mountains	F ₂	Shimen-Machaoying thrust fault	F ₉	Hongchuenban-Pingli fault	7	Hongan
				F ₁₀	Yangpingguan-Bashanhu-southern Dabie thrust fault	8	Suixian
				F ₁₁	Longmenshan thrust zone	9	Wudang
III	Qinling microplate	F ₃	Luonan-Luanchuan thrust fault	F ₁₂	Huayingshan thrust zone.	10	Pingli
III ₁	Late Palaeozoic rifted zone in the				Blocks of Precambrian basement:	11	Niushan-Fenghuangshan.
				1	Yudongzi	Solid black: ultramafic rocks	

gradually becoming another suture zone (the southern suture zone, SF₂) with the features of subduction and collision. The western segment of this suture zone is marked by a typical ophiolitic melange but the eastern segment was buried due to large-scale southward thrusting along the Bashan fault and the southern edge of the Dabie Mountains (Figure 1) in the Mesozoic. Nevertheless, some remnants of the Mianlue suture zone can still be traced in Zhenba, southern Suizhou, and the southern Dabie Mountains. The Mianlue suture zone is strongly modified and less exposed, but it is apparently connected with the Kunlun orogen to the west by the Huashixia suture zone in Qinghai. It is clear that the Qinling, including most of the Dabie Mountains, became an independent lithospheric plate in the Devonian and was located between the northern and southern suture zones. However, it has an Early-Middle Proterozoic basement similar to that of the Yangtze plate and a passive continental margin sedimentary sequence (Sinian-Early Palaeozoic) which belongs to the north margin of the plate. So, the Qinling was part of the Yangtze plate during the Early Palaeozoic, and began its own development in the Devonian.

The evidence shows that the Qinling was built up by subduction and collision between three plates along two suture zones and that the orogeny was further complicated by the presence, between the plates, of a number of continental fragments. The Qinling orogeny is too complicated to be explained by simple Caledonian or Indosinian

subduction and collision processes. Rather, it developed along the lines of the following:

- 1 Lithospheric breakup led to the initiation of the Qinling proto-ocean and the establishment of both the north China plate and Yangtze plate in the early Late Proterozoic (1000–700 Ma).
- 2 The Qinling proto-ocean continued to develop and the north China plate, Yangtze plate, and, from the Sinian to Cambrian (700–500 Ma), numerous rifted continental blocks moved laterally.
- 3 Subduction of the Yangtze plate beneath the north China plate took place, resulting in Early Palaeozoic (Caledonian) magmatism, and two distinct continental margins, active and passive, were involved in the Ordovician-Silurian (500–400 Ma).
- 4 The southern rifted zone was initiated in the Devonian, and the Qinling plate broke away from the Yangtze plate. Convergence continued in the Shangdan suture zone.
- 5 The Qinling proto-ocean at the Shangdan zone was diminishing and became isolated remnants because of irregularity of the continental margin during the initial collision in the Late Devonian and Carboniferous (370–290 Ma).
- 6 The residual Qinling proto-ocean was filled up and became a marsh indicating eventual diminishment of the Qinling proto-ocean in the Carboniferous and Permian. The final intense continent-continent oblique collision occurred in the Middle Triassic

between the north China plate and Qinling plate, and was followed by the closure of the Mianlue proto-ocean and collision between the Qinling plate and Yangtze plate. Intracontinental tectonism has predominated in the late development of the Qinling since then (290–200 Ma).

Lateral and vertical accretion

The Qinling orogeny was not only initiated by lateral motion, with consequent breakup, collision and integration of three plates and microcontinental fragments, but was also greatly influenced by the coeval vertical uplift of crystalline basements and the accompanying magmatism and metamorphism. The Foping dome may serve as a good example. It is ellipsoid-shaped and has an Early Proterozoic complex core which is in fault (shear zone) contact with the overlying Sinian–Devonian sequences. The Foping dome represents not only a centre of magmatic complex, implying a deep-seated hot magmatic source, but also a thermal centre for metamorphism. This is well demonstrated by a decrease in metamorphic grade from the centre outwards. The dome was not only formed by lateral plate motion and crustal extension but also to a great extent controlled by mantle upwelling. This inference is supported by the occurrence of an alkaline mafic and ultramafic crypto-volcanic complex (431 Ma) with inclusions (900–700 Ma) of deep origin (Huang, 1993) in the south part of the Qinling. Vertical accretion and growth of the Qinling lithosphere could be a direct response to mantle fluid movement and magmatic diapiring. Clearly, the unique characteristics of Qinling orogen are a consequence of combined lateral and vertical tectonic activity.

Postorogenic intracontinental tectonism and mechanisms

After the Middle Triassic collision, the Qinling orogen entered a postorogenic phase when the intracontinental tectonism was still active and intense.

Intracontinental features

Block collapse, strike-slip faulting and thrusting were dominant in the Early Mesozoic. Block faulting and subsidence were induced by rapid uplift due to continuous subduction within the continental lithosphere, and most basins took the form of half grabens filled with Upper Triassic–Lower Cretaceous red beds. Oblique subduction led to pronounced strike-slip faulting and the formation of some small-scale pull-apart basins along the Shangdan suture zone. In general, the Qinling was in a compressive tectonic setting and was marked by large-scale multi-layered thrusting and granitic magmatism. In contrast, the southern margin of the north China plate was subducted southward in the zone (F_2) to the north of the Shangdan fault, causing northward thrusting. As a result, the whole Qinling structural profile is asymmetrically fan-shaped from north to south.

The Late Mesozoic development of the Qinling was characterized by intense crustal extension, rapid uplift, and large-scale granitic magmatism and mineralisation, suggesting an important thermo-tectonic event. The Qinling has been elevated over 10 km since the Late Cretaceous. Large-scale and widespread sialic magmatic intrusion and mineralisation occurred around 100 Ma, while sedimentary layers in the Late Triassic–Early Cretaceous fault-bounded basins were deformed and slightly metamorphosed.

Two north–south-trending belts of gravity gradient have appeared in the China continent since the Mesozoic, marking a series of north–south fault-bounded basins in west Henan and at the boundary between Shaanxi and Gansu provinces, respectively. These two belts divide the Qinling into three segments, which are, from west to east, the west Qinling, the east Qinling and the Dabie Mountains. The segments have been elevated at different rates and eroded to differ-

ent depths, so they are now often treated as three new distinct tectonic elements. This implies a tendency of breakup of the Qinling–Dabie orogen.

The lithospheric architecture

Deep-seated structures

Geophysical studies (Yuan, 1991), have shown that the Qinling lithosphere is markedly inhomogeneous. It is vertically layered and laterally segmented. The upper surface of the asthenosphere is at a depth of some 110 km in the southern Qinling, but deepens to 250 km in the area to the north of the Shangdan suture zone and along the Bashan zone. This difference in depth is up to about 150 km and must be of great dynamic significance. The crustal thickness also varies. East of longitude 108° E, the crust is about 32 km thick and the Moho is flat, indicating the absence of a mountain root; west of it, the crustal thickness reaches 56 km. There is a strong, flat seismic reflection in the middle crust, which is now proved to be a low-velocity, highly conductive layer. The Qinling is an area with high heat flow, which may be related to partial melting in the middle crust. This inference comes from study of granites which originated at depths of 15–20 km. Evidently, the middle crust as well as the upper part of the lower crust in the Qinling represents a rheological soft stratification and is also an intracrustal dynamic layer. CT studies of the Qinling region demonstrate that the lower lithosphere, below the depth of 20–40 km, shows spaced north–south-trending zones with different tectono-geophysical states, while the upper, above 20 km, is dominated by east–west-trending structural lineaments. A flat deformation zone lies between the lower and upper lithosphere. The 3-D geometrical pattern of the Qinling region is much like a flyover and is one of the remarkable features of the Qinling structure.

Upper crustal structures of the present Qinling

The Qinling is connected in the east with the Dabie Mountains. Different tectonic levels of the crust have been exposed by denudation from east to west. The orogenic root zone crops out in the Dabie Mountains; both deep and middle levels are exposed in the east Qinling; while the west Qinling is dominated by sedimentary cover with less outcrop of crystalline basement. The denudation of ultrapressure root zone on the Dabie Mountains implies much stronger shrinking and uplifting of the crust than in the Qinling. The Qinling north–south-trending profile is fan-shaped due to northward subduction and final collision. The southern part is marked by southward thrusts and the northern part shows opposite vergence. The northern part of the Qinling is the orogenic core and is characterised by thick-skinned southward imbricated thrusts (Figure 1). In the southern Qinling, structural vergence represents lateral variations along the strike, that is, the vergence changes on the east and west sides of the Foping dome. The thrusting is southward on the east and northward on the west, and a transfer zone exists in between. The present complex structural pattern of the Qinling has come about by the superposition of vertical accretion at depth and large-scale thrusting in the upper crust.

Dynamic analysis

Any analysis of the mechanism of Mesozoic–Cenozoic intracontinental orogeny and 3-D geometrical pattern of the Qinling should take into account the following.

- The present 3-D framework of the Qinling was established during the main orogeny, but some early structures can still be traced and the Mesozoic–Cenozoic reformation is much more manifest. The deep-seated structures reflect the state of recent tectonic readjustment.
- The Mesozoic–Cenozoic intracontinental orogeny was mainly controlled by the Asian continent, Pacific and Indian plates. The east part of the Qinling was much more influenced by the Pacific plate, resulting in dynamic and kinetic adjustment of the Qinling lithosphere. The deep-seated rheological adjust-

ment led to the north-south-trending tectonophysical and textural zonation in the Qinling lithospheric mantle. In contrast, ancient east-west-trending structures may be preserved because they have been hardened during the postorogenic period and have not yet been fully modified. The middle and lower crust is in a transitional position, where the orogenic root was erased due to the rheological flattening. The flyover-shaped 3-D framework of the Qinling lithosphere was thus created. The middle and lower crust, as a soft rheological stratification in the lithosphere, can not only absorb strain and energy of mantle tectonic adjustment, but also controls material exchange and structural deformation of the upper crust (Ranalli and Murphy, 1987; Quinlan, 1993). Therefore, deep-seated mantle adjustment and the middle-lower crustal rheological state were important dynamic mechanism for the intense intracontinental Qinling orogeny in the Mesozoic and Cenozoic.

- Deep geophysical studies reveal that the asthenosphere, under the main body of the Qinling, strongly upwelled to depths of 60–80 km and the lithosphere sharply thinned accordingly. There are two mechanisms for this upwelling. One is the large-scale lateral migration of material in the rheological layer; the other is that some parts of the lithosphere melted away by the rising asthenosphere. Intense extension occurred in the Mesozoic, especially in the Late Cretaceous, resulting in rapid crustal uplift and large-scale magmatic activity. Lithospheric mantle delamination (Kay and Kay, 1993; Sacks, 1993) and asthenospheric upwelling are believed to be the main dynamic causes of the Mesozoic–Cenozoic intracontinental orogeny of the Qinling.

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