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Key Points:
- We reveal the lithospheric deformation mode of the intracontinental Qinling orogeny, central China
- The ∼40 km lithospheric thickening was likely balanced by >130 km thin-skinned crustal shortening
- The long-distance strain-transfer décollement plays a vital role in accommodating the crustal shortening and lithospheric thickening

Supporting Information:
Supporting Information may be found in the online version of this article.

Correspondence to:
S. Dong and H. Wang, swdong@nju.edu.cn; hyanwhy@163.com

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Zhang, Y., Dong, S., Wang, H., Feng, M., Thybo, H., Li, J., et al. (2022). Coupled lithospheric deformation in the Qinling Orogen, central China: Insights From Seismic Reflection and Surface-Wave Tomography.

Abstract We combine a ∼485 km-long seismic reflection profile and a S-wave speed transect from surface-wave tomography, to reveal the lithospheric deformation mode of the intracontinental Qinling orogeny, central China. We observe a thick lithosphere keel in the convergence zone between the Yangtze Block and the North China Craton (NCC) and a shallow-crustal (8–15 km depth) décollement that extends into the lower crust of the Qinling Orogen. Combining with surface structural geology and magmatism, we interpret these seismic findings as kinematically linked features formed by renewed intracontinental convergence between the NCC and the Yangtze Block in the late Mesozoic. We highlight that the ∼40 km lithospheric thickening in the convergence zone was likely balanced by > 130 km thin-skinned crustal shortening along a crustal-scale strain-transfer décollement, and was responsible for the occurrence of late Mesozoic magmatism (∼160–100 Ma) at the southern edge of the NCC.

Plain Language Summary Here we reveal the lithospheric deformation mode of the intracontinental Qinling orogeny, central China, through a seismic reflection profile and a S-wave speed transect from surface-wave tomography. Our results suggest a thick lithosphere keel in the convergence zone between the Yangtze Block and the North China Craton (NCC), and a shallow-crustal (8–15 km depth) décollement that extends into the lower crust of the Qinling Orogen. Coupled with published surface data, we suggest that these seismic findings document the lithospheric deformation induced by late Mesozoic intracontinental convergence between the NCC and the Yangtze Block. It appears that the ∼40 km lithospheric thickening was balanced by >130 km thin-skinned crustal shortening along a long-distance strain-transfer décollement.

1. Introduction

The processes involved in continental deformation as a response to plate collisions have been controversial since the acceptance of the plate-tectonic theory (e.g., Cawood & Buchan, 2007; Molnar & Tapponnier, 1975). The intracontinental orogeny generally occurs at far distances from convergent boundaries, but forms an integral part of plate tectonics on Earth, as exemplified by the Cenozoic Tian Shan and Mongolia-Altai orogeny (Avouac et al., 1993; Cunningham, 2005; Raimondo et al., 2014), the Laramide orogeny in North America (English & Johnston, 2004), and the sub-Andes (Beck & Zandt, 2002). A vital issue for understanding the intra-plate tectonic processes is the mode of lithospheric shortening and, in particular, the mass balance of material transfer during the intracontinental orogeny (DeCelles et al., 2009; Houser & Molnar, 2001; Tapponnier et al., 2001).

The Qinling Orogen in the heart of China (Figure 1) preserves the largest tract of Triassic ultrahigh-pressure rocks along its eastern Dabie-Hong'an segment formed by the collision between the North China Craton (NCC) and the Yangtze Block (e.g., Enkin et al., 1992; Hacker et al., 2000; Yin & Nie, 1993; Zhao & Coe, 1987). It was intensively rejuvenated in the Middle-Late Jurassic, resulting in significant crustal shortening, extensive magmatism and Mo-Au polymetallic mineralization (Dong et al., 2013; Li et al., 2015; Mao et al., 2011). This study shows the lithospheric architecture across the Qinling orogen based on the crustal structure along a ∼485 km long deep seismic reflection profile and a coincident S-wave speed transect derived by surface-wave tomography (Figure 1).
These seismic findings reveal the crustal and lithospheric deformation modes to accommodate the convergence between the NCC and the Yangtze Block. We propose a new tectonic model in which the crustal shortening and the lithospheric thickening were mutually balanced and linked by a crust-penetrating décollement.

2. Tectonic Setting

The Qinling orogen is part of the Central Orogenic Belt in China with a long-lasting evolutionary history (Mattauer et al., 1985). Following the scissor-like closure of the Paleo-Tethys ocean (Zhao & Coe, 1987), the collision of the NCC and the Yangtze Craton (Dong et al., 2011) gave rise to the Triassic Qinling orogeny. Deep continental subduction of the Yangtze Block beneath the NCC occurred along the eastern segment and gave rise to the UHP metamorphic rocks in the Tongbai-Dabie orogen (Hacker et al., 2000; Ratschbacher et al., 2003). The Jurassic convergence between the NCC and the Yangtze Craton resulted in crustal shortening across the Daba Shan foreland thrust-fold belt in South Qinling (Dong et al., 2013; Li et al., 2015).

Concomitant with the Mesozoic Qinling orogeny are two phases of magmatic flare-ups separated by an Early-Middle Jurassic magmatic quiescence (Figure S1 in Supporting Information S1) (Dong et al., 2011). The Triassic (240-210 Ma) syn-collisional granitoids, peaking at 220-215 Ma, are mainly I- and S-type, with their distributions limited to west of 110°E in South Qinling; zircon Hf(t) and whole rock Nd isotopes suggest mixing of crust- and mantle-derived magma sources (Dong et al., 2011) (Figure S1 in Supporting Information S1). The Late Jurassic-Early Cretaceous magmatic activity shifted N-ward, primarily distributed in North Qinling and the southern margin of the NCC (Lesser Qinling). The magmatism is featured by two magmatic flare-ups at 160-135 Ma and 135-100 Ma, formed by melting of a thickened ancient crust with mixing of mantle-derived magma (Mao et al., 2011).
3. Seismic Findings

We acquired a composite, ∼485 km long, deep seismic reflection profile through the SINOPROBE project (Figure 2). It crosses the northern Sichuan basin and the Daba Shan foreland fold-thrust belt, and the northern section across the north Qinling, the Cenozoic Weihe graben, and the Ordos basin (Li et al., 2017). Data acquisition and processing are given in Appendix 1 of Supporting Information S1.

3.1. Moho

The Moho is clearly observed in the whole section with a laterally variable depth of ∼45 km or 15–16 s two-way travel time (TWT) in the Yangtze Craton, ∼38–42 km (13–14 s TWT) in the Qinling Orogen, and ∼42 km (∼14 s TWT) in the NCC. It displays an overall upward-arching rise below the Qinling Orogen, consistent with seismic results from broad-band receiver functions (Feng et al., 2017).

A remarkable discontinuity at the Moho occurs at point A, where gently north-dipping reflections from the mantle imply northward underthrusting of the Yangtze Craton beneath the Qinling Orogen. The upwarping Moho between points A and B accords with the observed uplift of the Qinling orogenic belt. The northern frontal fault that bounds the Cenozoic Weihe graben to the south slightly offsets the Moho, and indicates Cenozoic modification of the Moho.

3.2. The Qinling Décollement

The most spectacular feature of the seismic profile is a crust-penetrating décollement (the Qinling décollement) that extends from ∼4 s depth beneath the Daba Shan, northward to ∼14 s depth beneath the North Qinling Orogen (marked II in Figure 2). Details regarding its southern part were interpreted by Li et al. (2015). It is observed as a set of SW-vergent branch thrusts across the North Daba Shan between the Chengkou and Ankang Faults, and fault-related folds across the South Daba Shan; they merge at a depth of 12–15 km (4–5 s TWT) to a quasi-flat, sole décollement. An array of moderately north-dipping reflectors (marked I in Figure 2) merges upward with the main décollement. The crust of Qinling shows a strongly reflective character at both the footwall and the hangingwall of the Qinling décollement. Below the seismically-transparent Triassic pluton domain (numbered 1 in Figure 2), we interpret several high-amplitude, gently-dipping reflectors as foliated migmatites that are locally exposed at the surface in the South Qinling. South-dipping reflections are prominent in the lower crust in zone number 2 (Figure 2).
The North Qinling frontal fault, controlling Cenozoic subsidence of the Weihe graben, is observed as a steeply north-dipping normal fault. Conjugate sets of shallow-level normal faults vanish in the less-reflective middle crust, and Cenozoic sediments within the Weihe graben are imaged as subhorizontal, high-amplitude reflections.

3.3. Lithospheric S-Wave Speed

The lithospheric mantle structure is imaged by surface-wave tomography using data from 477 portable and permanent broadband seismic stations in the study region. Appendix 2 in the Supporting Information S1 provides details of data, method, and model evaluation. Figure 3 shows the resulting S-wave speed (vs.) transect parallel to our reflection seismic profile across the Sichuan Basin, the Qinling Orogen, and the Ordos Basin. The Moho estimated from the Versus model shows a similar variation from thicker crust beneath Dabashan to thinner crust beneath Qinling (Figure 2), and a broad rise beneath the Weihe graben and the Ordos basin. The mantle lithosphere beneath the Yangtze Block and the NCC has very high velocity (>4.5 km/s). We interpret the lithosphere-asthenosphere boundary as a maximal decrease in vertical for seismic velocities. It is generally observed at a depth of ca. 150 km in both the Yangtze Block and the NCC with minor variations. Still, it deepens abruptly to ∼200 km beneath the Weihe graben, indicating a convergent zone with a thickened lithosphere keel below the southern margin of the Ordos Basin. The velocities in the convergent zone are less than 4.5 km/s.

4. Discussion: A Long-Distance Strain-Transfer Model of the Qinling Intra-Continental Orogeny

Our seismic reflection and surface-wave topography data show the following first-order observations: (a) a fossil, thickened lithospheric keel at the amalgamation zone between the Yangtze Block and the NCC; (b) a thin-skinned thrust-fold zone accommodating a total amount of ∼130 km of shortening in the upper crust of Yangtze; and (c) a crust-penetrating, north-dipping décollement extending from the shallow crust of the Yangtze Block to the deep crust in the Qinling Orogen. Although surface tectono-magmatic observations largely document Triassic
collisional orogeny, we argue that these seismic findings represent relicts of the intra-continental orogeny during the Middle-Late Jurassic, based on three following arguments. First, the youngest strata involved in the Daba Shan foreland is of Early-Middle Jurassic in age (Li et al., 2015). Second, 40Ar-39Ar dating of syntectonic sericite collected from sheared rocks along the Chengkou Fault yields a cooling age of ∼143 Ma (Li et al., 2010). Third, the paleomagnetic study in the Daba Shan foreland thrust-fold belt demonstrates significant chemical remagnetization related to fluid migration driven by the Middle-Late Jurassic orogeny (Zhang et al., 2020).

Our seismic findings across the Qinling Orogen, coupled with published structural and magmatic data (Figure S1 in Supporting Information S1), allow us to clarify a two-stage tectonic evolution for the Mesozoic Qinling Orogen (Figures 4a and 4b). Northward subduction of the Yangtze Block and subsequent collision with the NCC resulted in crustal shortening, melting, and plutonism, which created the Triassic South Qinling Orogen (e.g., Meng & Zhang, 2000; Ratschbacher et al., 2003). After a ∼40 Myr tectonic quiescence, Mid-Late Jurassic convergence between the NCC and the Yangtze Block lead to the intracontinental orogeny, during which the Yangtze Block indented NCC and thickened the southern marginal zone of the North China cratonic lithosphere. Lithospheric deformation is partitioned between lithospheric thickening in the convergence zone and crustal shortening across the Daba Shan foreland thrust-fold zone. The two elements are linked via a north-dipping, crustal penetrating décollement that propagated toward the Sichuan basin.

**Figure 4.** A new model for Mesozoic tectonic evolution of the East Qinling orogenic belt. (a) The collision of the Yangtze Block with the North China Craton (NCC) resulted in the formation of the Triassic (240-200 Ma) Qinling Orogen with widespread plutonism in South Qinling. (b) Renewed convergence between the Yangtze Block and the NCC in Late Jurassic to Early Cretaceous (160-100 Ma) led to the intracontinental orogeny, during which the Yangtze Block indented NCC and thickened the southern marginal zone of the North China cratonic lithosphere. Lithospheric deformation is partitioned between lithospheric thickening in the convergence zone and crustal shortening across the Daba Shan foreland thrust-fold zone. The two elements are linked via a north-dipping, crustal penetrating décollement that propagated toward the Sichuan basin.
Lesser Qinling zone. This thickening compensated >130 km crustal shortening above the Qinling décollement (Figure 4b).

The northern part of the intracontinental orogenic lithosphere underwent extensional overprinting during Cenozoic time, as evidenced by significant normal faulting and subsidence in the Weihe graben and surface uplift of the Qinling Orogen (Zhang et al., 2019). Due to negligible or minor Cenozoic tectonism, the central and southern parts of the syn-orogenic lithospheric structure could be preserved and is imaged by seismic reflection profiling (Figures 2 and 3). In contrast to the vertically coherent lithospheric deformation (i.e., the thin viscous sheet hypothesis, England & Houseman, 1986), the loci of crustal shortening and lithospheric thickening are laterally offset by at least 100 km (Figure 4b). This lithospheric deformation pattern requires significant horizontal shear and/or lateral strength variations to link the crustal shortening with lithospheric thickening. In contrast to the TVS model, we invoke a crustal-scale strain-transfer model based on seismic imaging of the large-scale, crust-penetrating décollement. This décollement, extending from beneath the foreland downward to beneath the orogenic root (Figure 4b), could have accommodated the strain transfer between the crust and the lithospheric mantle. This model predicts long-distance tectonic coupling of lithospheric deformation, in which ~40 km lithospheric thickening was balanced by > 130 km amount of crustal shortening due to the accommodation of a long-distance strain-transfer décollement. This model may explain the occurrence of the late Mesozoic magmatism (~160–100 Ma) and Mo-Cu mineralization, which are confined to the North and Lesser Qinling zones directly above the convergent zone. This well-defined spatial association between the late Mesozoic magmatism and the lithospheric thickening implies a potential geodynamic relationship between the magma generation and the localized lithospheric thickening and melting during the intracontinental orogeny. However, due to Cenozoic extensional overprinting, detailed geodynamic processes associated with intracontinental orogeny at the convergent zone need to be further clarified by numerical modeling and tectonic studies.

Data Availability Statement
Data supporting this article are available from the following database: https://zenodo.org/record/6370064#.YjXgC1NGr3Q.

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