

Geomorphic response of an active metamorphic core-complex in a collisional orogen: Example from the Lunggar Shan, Southern Tibet

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Abstract. We present structural and neotectonic mapping from the Lunggar Shan rift in southern Tibet. The Lunggar Shan is a N-trending mountain range ~70 km long N-S and up to 40 km wide E-W. The Lunggar Shan is bounded on its east side by a low-angle (<40°) east-dipping detachment fault that juxtaposes mylonitic gneiss and variably deformed granites in its footwall against alluvial fans and Neogene gravels in its hangingwall. Foliations in the mylonitic footwall dip <40° east and stretching lineations are east plunging. The range front detachment is presently inactive as indicated by undisturbed moraines and Quaternary sediments that overlie it. However, we consider the Lunggar Shan detachment to be an active structure, as inferred by range parallel fault scarps cutting Quaternary alluvium located 4-5 km into the hangingwall basin, with >40 m of throw on individual scarps. An intriguing observation is that an intrabasinal topographic high is actively developing near areas of inferred maximum extension, with lacustrine sediments being uplifted and eroded. This observation indicates that the rift basin initially developed as a typical half-graben system that underwent a transition from deposition, to uplift and erosion perhaps as a result of isostatic rebound of the footwall at depth, warping the overlying hangingwall basin. If correct, the Lunggar Shan may represent a modern analogue to the supradetachment basin model.

1. Introduction

It has long been speculated and predicted from geodynamic models that the development of low-angle normal fault (detachment) systems and extensional metamorphic core complexes is favored in high-elevation regions characterized by hot, thick crust [1, 2, 3, 4, 5]. Furthermore, the presence of a weak mid-crustal layer, decoupled from the upper crust and capable of flow, has been invoked to explain some geometric aspects of core complex activation of slip on detachments in the brittle upper crust [6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. Despite these widely held views, geological evidence demonstrating a direct linkage between the "core complex" mode of extension and thickened crust is scarce because the best studied detachment fault systems that are proposed to be presently active are located at low elevations and characterized by thin crust (e.g., in Papua New Guinea, Baja California, Salton Trough, Death Valley, Mediterranean) [16, 17, 18, 19, 20, 21, 22, 23, 24]. The only well documented exception, to our knowledge, is the Cordillera Blanca detachment fault system within the Peruvian

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Andes, which is anomalous in that its formation is attributed to the combined affects of thickened crust and the subduction of a buoyant oceanic ridge [25, 26].

The ideal natural laboratory to investigate the mode of extension within the *hinterlands* of collisional orogens characterized by anomalously hot and thick crust is in southern Tibet where ~N-trending rifts are actively developing above an extremely thick crust (65-85 km) [27, 28, 29] that arguably includes a fluid-bearing mid-crustal layer capable of flow [30, 31, 32, 33, 34, 35, 36, 37, 38]. Our understanding of the history of deformation and basin development associated with rifts in Tibet remains infant, yet recent studies reveal some common observations. First, Tibetan rifts are widely spaced (~100-300 km) [39], which may reflect mantle involvement, yet characterized by narrow-width rift flank uplifts (30-40 km) and basins (<10-15 km), consistent with isostatic compensation occurring in a low-viscosity lower crust [40]. Nascent rifts that have accommodated minimal (a few km's) extension are characterized by range-bounding high-angle normal faults and basins that show minimum basin elevations and depocenters in the central part of the rift [41]. In contrast, Tibetan rifts with more than ~15km of extension appear to be characterized by range-bounding, low-angle normal faults, structurally underlying extensional shear zones, and intrabasin topographic highs where basin fill is actively being uplifted, incised and which correspond to areas of inferred maximum extension [41]. Our hypothesized kinematic history calls upon an evolving breakaway fault system that leads to active slip on detachment faults in the uppermost crust and uplift and erosion of rift basin fill above the detachments in response to tectonic unloading and associated isostatic rebound of the footwall at depth. In contrast to North American Cordilleran detachment fault systems, extension is localized near rift-bounding faults (i.e., the hanging wall remains unextended outside of rift).

2. Active Deformation in Central Tibet

The Himalayan-Tibetan orogen is the archetype example of an active continent-continent collision zone and has served as the premier natural laboratory for investigating how the continental lithosphere deforms and high-elevation plateaus develop during collisional orogenesis. It has been known for decades that much of Tibet is currently undergoing ~E-W extension [42, 43, 44, 45, 46, 47, 48]. This extensional system is impressive in spatial extent, relief (locally >2 km), and rate (~2 cm/yr, one half the rate of Indo-Asian convergence). Numerous models have attempted to explain the tectonic significance of this syncollisional extension, generally calling upon one or some combination of the following: gravitational collapse due to crustal thickening or following removal of mantle lithosphere [49, 50], oblique convergence at the Himalayan front and growth of the Himalayan arc [46, 47, 51], eastward lateral extrusion of central Tibet with respect to southern Tibet [52-54], distributed eastward extrusion of crustal wedges [55, 56], and basal shear tractions related to underthrusting of Indian lithosphere [57]. Several studies have sought to constrain the initiation age of extension to test the aforementioned models or to date when Tibet supposedly achieved its maximum sustainable elevation [58, 59, 60, 61, 62, 63, 64, 65, 66].

3. Structural Geology of the Lunggar Rift

The N-trending Lunggar Range parallels a rift valley in the northern Lhasa terrane of west-central Tibet. The Lunggar Rift valley is ~70 km long and ~5-10 km wide [41]. The central part of the Lunggar Rift is bounded on its western flank by a <40° E-dipping normal fault that juxtaposes variably deformed biotite granite, leucogranite, and mylonitic gneiss in the footwall against Paleozoic strata and Neogene alluvial fan, fluvial and lacustrine rocks in the hanging wall. The proximal footwall includes chloritized breccia, cataclasites, and mylonitic gneisses with foliations subparallel to the normal fault and E-plunging stretching lineations and S-C fabrics indicating top-to-the-east sense-of-shear. We refer to this relatively low-angle normal fault with mylonitic rocks in the footwall as the "Lunggar detachment" [41]. Neogene gravels in the proximal hanging wall record the unroofing of the Lunggar Range as indicated by growth strata with clasts of both footwall and hanging wall lithologies. In turn, these gravels are cut by numerous N-striking, brittle normal faults. The brittle hanging-wall

normal faults are both W- and E-dipping, and fault striae and sense-of-shear indicators indicate dominantly top-to-the-E displacement [41].

Presently, the Lunggar detachment is inactive at the surface as indicated by undisturbed moraines and alluvial fans that unconformably overlie it. However, ~4 km east of the inactive range front, *active* range-parallel E-dipping normal faults cut Quaternary alluvium within the rift basin. One example of active faulting in the central Lunggar basin is a flight of fluvial terrace risers developed along an E-flowing drainage that records the progressive incision of the river and associated abandonment of the higher terrace levels. At least five levels of terrace development record successive incision by the E-flowing stream. North-striking normal faults cut the terrace risers providing estimates of net throw that ranges from ~1m for the youngest surfaces to >35m for the oldest cumulative fault scarps. The central Lunggar Rift basin is bounded on its eastern margin by a system of high-angle W-dipping normal faults with Cretaceous strata in the footwall. Gently to moderately E-dipping rift basin fill occurs in the hanging wall and is well exposed due to recent incision. It consists of ~200 m of lacustrine mudstone capped by conglomerates derived from the Lunggar Range, based on abundant granitic and gneissic clasts [41].

The northern and southern Lunggar Rift is bounded on its western flank by high-angle E-dipping normal faults. Footwall rocks to the south include orthogneisses, although our preliminary studies suggest that the gneissic fabric predates normal faulting, whereas those to the north consist mainly of Paleozoic strata showing no any evidence of penetrative deformation. An intriguing observation is that normal fault scarps cutting Quaternary deposits in the northern and southern part of the Lunggar Rift are located along or within hundreds of meters of the range front, in contrast to the central part of the range where fault scarps are located kilometers from the range front. Preliminary apatite (U-Th)/He data from the central low-angle normal fault of the Lunggar Range footwall suggest the range underwent significant and rapid exhumation in response to low-angle extensional faulting in Plio-Pleistocene time. Ages cluster between 0.5-1.5 Ma [41].

4. Geomorphic Response of an Active Metamorphic Core-complex.

For the Lunggar Rift we investigated the spatial along-strike geomorphic response of the footwall and hanging wall by analyzing stream channel profiles. Because of the effects of lithologic and structural controls on stream channel profiles, we limited our analysis to the central region of the Lunggar Rift because of the uniform lithology and structural relationships. We subdivide individual along channel profiles into three regions based on the following geomorphic indices; an upper glacial dominated reach, an intermediate reach characterized by debris flow dominated incision with low channel concavity, and a downstream fluvial dominated reach with higher channel concavity. We observe channel concavities to increase (i.e., channel profile steepness decreases) southward along the central part of the Lunggar Range, with channel profiles to the north dominated by debris flow and glacial dominated reaches. These preliminary observations suggest that the Lunggar Range is likely a transient landscape responding to along-strike variations in fault geometry and magnitude of fault slip.

Another intriguing observation of the landscape is that a drainage divide occurs in the central part of the Lunggar Rift valley in the region of maximum inferred extension. To understand the spatial relationship between the hanging wall drainage divide and the footwall, rift parallel topographic swath profiles were generated by digitizing a polygon defined by the extent of Quaternary sediments in the basin, and a 4km swath spanning the crest of the Lunggar Range. The topographic data are then collapsed onto rift parallel profiles. When comparing elevation versus distance relative to the region of inferred maximum extension, we observe maximum basin elevations that coincide with the region of inferred maximum slip for the Lunggar detachment. This is in contrast to Tibet rifts with smaller magnitudes of displacement (< 5km's) which have minimum elevations occurring in the middle of the rift, consistent with a typical half graben geometry.

These observations led to the development of the following hypothesis for the evolution of the Tibetan grabens, where the rifts initiate with development of a breakaway fault as a typical half graben system with internally drained conditions located in the central region of the rift basin. As extension

increases, the breakaway fault gets back rotated to a low angle, becomes abandoned and a new breakaway fault is initiated. With further tectonic unloading of the footwall at depth, the footwall undergoes isostatic rebound, resulting in upwarping of the detachment and uplift of the hanging wall basin and migration of the active depocenters toward the rift tips. With further extension, mylonitic rocks get exhumed to the surface and locally, the locus of active faulting steps basinward, resulting in basin cannibalism, and narrowing of the rift valley with progressive extension.

5. References

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