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Crustal structure beneath the Sub-Himalayan fold–thrust belt, Kangra recess, northwest India, from seismic reflection profiling: Implications for Late Paleoproterozoic orogenesis and modern earthquake hazard

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ABSTRACT

Most compressional orogens include salients and recesses along their strike, the age and origin of which can be hard to ascertain. In the Kangra recess in the trace of the Main Boundary Thrust (MBT), the largest such recess within the active Himalayan orogen, the Sub-Himalayan sedimentary fold-thrust belt increases in width to as much as 90 km (the Kangra Basin), but narrows to as little as 10 km in the adjoining Nahan salient of the MBT (the Subathu Basin) to the southeast. New seismic reflection profiling places the Himalayan décollement at 6–8 km depth above thin but reflective Meso- to Neoproterozoic Vindhyan (Lesser Himalayan Series-equivalent) strata. These data show that the Vindhyan sedimentary rocks are thinner in the Kangra recess than further southeast, allowing the hypothesis that the width of the Lesser Himalayan thrust belt, and the existence of the Kangra recess, could be related to the pre-deformation basin thickness. This hypothesis obviates the need for control of the Kangra recess by a lateral ramp in the Main Himalayan Thrust, so making it more likely that the Kangra segment could rupture as part of an earthquake far larger than the devastating 1905 M = 7.8 Kangra earthquake. Below the Proterozoic sedimentary rocks, our reflection data show a west–southwest-dipping reflective fabric spanning a 30 km-crustal thickness, which we infer corresponds to a widespread "Ulleri-Wangtu" orogenic event at c. 1850 Ma affecting a pre-Tethyan Indian continental margin, thickening the basement by c. 20%. The deepest 10 km of this ~50 km-thick crust shows a more horizontal, arguably younger, reflectivity, though the Moho is not clearly marked by strong reflectors.

1. Introduction

The Himalayan orogen that initiated by continental collision between India and Asia at c. 57 Ma (e.g. Leech et al., 2005) conjoins the well-known tectonostratigraphy of the Sub-Himalaya, Lesser Himalaya, Greater Himalaya and Tethyan Himalaya. These zones are separated respectively by the Main Boundary Thrust (MBT), Main Central Thrust (MCT) and South Tibetan Detachment, and together lie between the Main Frontal Thrust (MFT) and the Indus-Tsangpo suture (e.g. DiPietro and Pogue, 2004) (Fig. 1). The thrust faults, both active and inactive, are thought to sole into a single Main Himalayan Thrust (MHT) (Zhao et al., 1993) (inset to Fig. 1). The stratigraphy within the thrust belt extends back into the Proterozoic, and individual faults such as the MCT may have had a pre-Himalayan history of active slip in a Cambro-Ordovician accretionary event (DeCelles et al., 2000; Gehrels et al., 2003).

We use the first deep multi-fold seismic reflection profile in the Sub-Himalaya, and a comparison with published hydrocarbon exploration profiles, to study the underthrust Indian crust of NW India. We address the large-scale geometry of the Himalayan orogenic wedge, including the depth to the MHT, the fault on which great earthquakes occur along the Himalayan front. We identify a reflection fabric characteristic of the underthrust Indian basement that may represent a Paleoproterozoic orogen.

2. Geological setting

In northwest India the crust that is currently being thrust beneath the Himalayan front consists of the Mewar and Bundlekhand Archean nuclei of the North Indian Block (e.g. Mazumder et al., 2000), their linking Paleoproterozoic belts (Aravalli and Delhi fold belts) (e.g. Rajendra Prasad et al., 1998; Rao et al., 2000), and overlying cover sequences (Vindhyan and Marwar Basins) (e.g. Meert et al., 2010; Srivastava et al., 1983) (Fig. 1). Knowledge of the North Indian Block where it is underthrusting is severely limited by the covering fluvial plains of the active foreland basin system, and the tiny number of basement-penetrating wells (Karunakaran and Ranga Rao, 1979;

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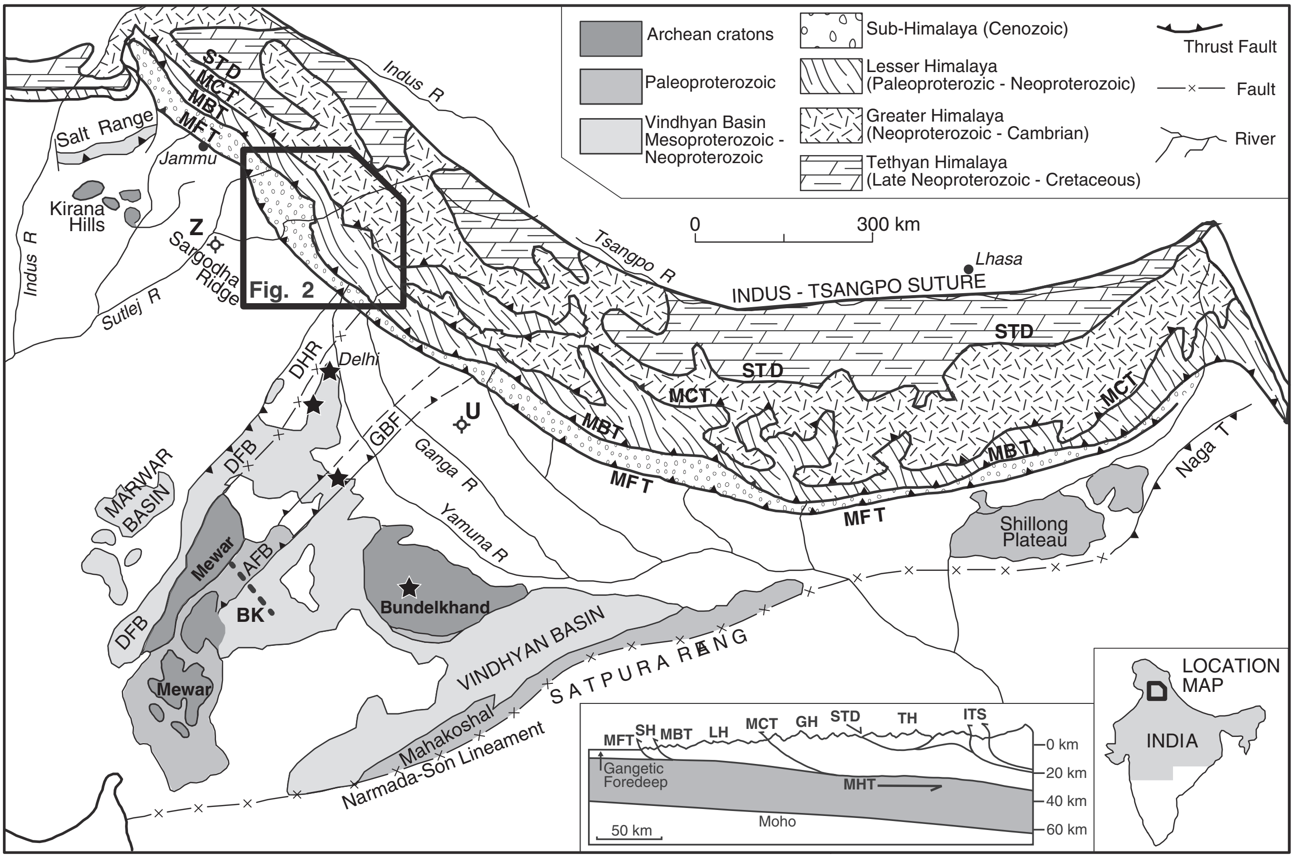

Fig. 1. Generalized geological map of northern India and Himalaya (after Valdiya, 1995) and (inset) schematic crustal cross-section SW–NE across NW Himalaya. Heavy box marks location of Fig. 2. Precambrian structures: GBF—Great Boundary Fault; AFB—Aravalli Fold Belt; DFB—Delhi Fold Belt; DHR—Delhi—Hardwar Ridge. Cenozoic (Himalayan) structures: MFT—Main Frontal Thrust; MBT—Main Boundary Thrust; MCT—Main Central Thrust; STD—South Tibetan Detachment; ITS: Indus-Tsangpo Suture. Himalayan terranes: SH: Sub-Himalaya; LH: Lesser Himalaya; GH: Greater Himalaya; TH: Tethyan Himalaya. Exploration wells: U—Uhjani; Z—Zira. Bundi-Kunjer reflection profile: BK (Rajendra Prasad and Vijaya Rao, 2006). Stars: locations of crustal thickness estimates (Jagadeesh and Rai, 2008).

Raiverman, 2002) (Fig. 2). Aeromagnetic data support the extension of northeast trends, exposed on the shield, beneath the Gangetic foredeep orthogonal to the Himalaya, including the Delhi-Hardwar Ridge (DHR in Fig. 1) (Karunakaran and Ranga Rao, 1979; Raiverman, 2002; Valdiya, 1976). Although limited seismicity data have been used to argue that some NE–SW faults remain active (Verma et al., 1995), any basement ridges were apparently peneplaned before deposition of the Himalayan foreland basin, as depth contours on basement beneath the Indo-Gangetic plains continue smoothly across the Precambrian trends (Karunakaran and Ranga Rao, 1979; Raiverman et al., 1983; Sengupta, 1996). The western edge of the Delhi-Hardwar Ridge projects into the Himalaya close to the modern location of the drainage divide between the Indus (Sutlej) and Ganges (Yamuna) river systems (Fig. 1). The spatial coincidence between the postulated basement ridge and the drainage divide has been suggested to imply a profound influence of the Precambrian Aravalli-Delhi fold belt on the tectonics of the Himalaya (Raiverman, 2002; Valdiya, 1976), but if so this influence can only have been felt after a major drainage re-organization of the western Himalayan river systems and c. 500 km eastward migration of the drainage divide since 5 Ma (Clift and Blusztajn, 2005). Alternatively, the DHR may become parallel to the Himalayan trend (Rao, 1973) like the Sargodha Ridge (Fig. 1).

Above these possible ridges in the crystalline basement is the overlying Meso- to Neoproterozic Vindhyan Supergroup and Neoproterozoic Marwar Supergroup (or "Trans-Aravalli Vindhyans") (e.g. Meert et al., 2010; Srivastava et al., 1983). The Lesser Himalaya Series (LHS) from NW India to Nepal contains a presumably equivalent stratigraphy of 1.8 to 0.5 Ga low-grade meta-sedimentary rocks, locally up to 10 km thick (DeCelles et al., 2001), and high-grade orthogneisses (Richards et al., 2005), including the Wangtu granitic orthogneiss (1866 ± 10 Ma) and metarhyodacites (1840 ± 16 Ma) (Miller et al., 2000) in the Chail–Jutogh nappes of NW India (Fig. 2). These orthogneisses have been interpreted as shallow intrusions (Kohn et al., 2010) or as the LHS basement (Célérier et al., 2009), and are part of a belt that stretches from Pakistan (Kotla, Shang and Iskere orthogneisses) through Nepal and Sikkim (Ulleri granitic orthogneiss) to NE India (Sharma and Rashid, 2001), recently interpreted as part of a 2.0–1.8 Ga anorogenic belt (Singh et al., 2009) or as a 1780–1880 Ma continental arc along the margin of the Columbia super-continent (Kohn et al., 2010).

The Sub-Himalaya is separated from the modern foreland basin by the active MFT, and from the Proterozoic LHS by the MBT that formed at about 11 Ma (Meigs et al., 1995). The Sub-Himalaya forms the frontal part of the fold–thrust belt in which marine to fluvial Paleogene to Miocene stratigraphy is repeated across numerous northeast-dipping thrusts (Najman et al., 2004; Powers et al., 1998). This uplifted foreland basin has been divided into sub-basins, including the Kangra sub-basin (Kangra recess) in which the mapped surface expressions of the MBT and MFT are separated by nearly 100 km, and the adjoining Subathu sub-basin (Nahan salient) in which the mapped surface expressions of the MBT and MFT approach as close as 10 km (Fig. 2). Here we follow local terminology that uses the terms recess and salient to describe changes in the shape of the trace of the MBT rather than arcuate sections of the Himalayan thrust belt as a whole; and that uses the term sub-basin to describe segments of the Sub-Himalaya with different widths and not necessarily regions of separate facies development, isopach patterns or paleodispersal patterns. The MFT is almost straight across this region, and the Kangra