Development of the Himalayan frontal thrust zone: Salt Range, Pakistan

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ABSTRACT

The Salt Range is the active frontal thrust zone of the Himalaya in Pakistan. Seismic reflection data show that a 1 km offset of the basement acted as a buttress that caused the central Salt Range-Potwar Plateau thrust sheet to ramp to the surface, exposing Mesozoic and Paleozoic strata. The frontal part of the thrust sheet was folded passively as it overrode the subthrust surface on a ductile layer of Eocambrian salt. Lack of internal deformation of the rear part of the thrust sheet is due to decoupling of sediments from the basement along this salt layer. Early to middle Pliocene (~4.5 Ma) conglomerate deposition in the southern Potwar Plateau, previously interpreted in terms of compressional deformation, may instead document uplift related to basement normal faulting. Stratigraphic evidence, paleomagnetic dating of unconformities, and sediment-accumulation rates suggest that the thrust sheet began to override the basement offset from 2.1 to 1.6 Ma. Cross-section balancing demonstrates at least 20 to 23 km of shortening across the ramp. The rate of Himalayan convergence that can be attributed to underthrusting of Indian basement beneath sediments in the Pakistan foreland is therefore at least 9–14 mm/yr, about 20%–35% of the total plate convergence rate.

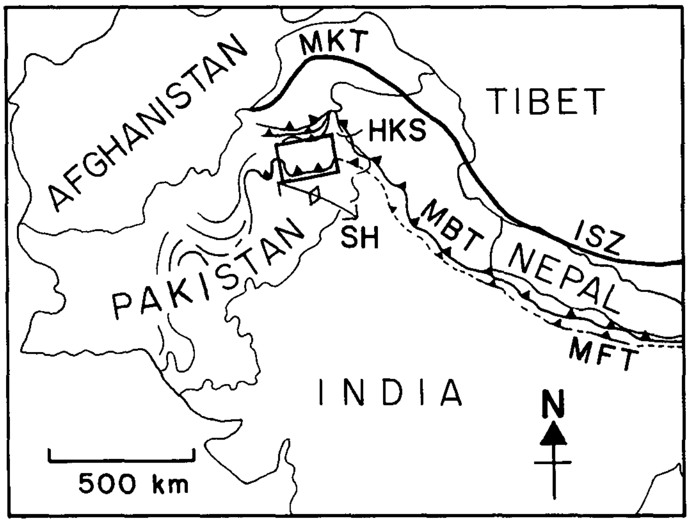

Figure 1. Position of Salt Range thrust front and Potwar Plateau (box) within overall Himalayan trend. HKS = Hazara-Kashmir syntaxis; ISZ = Indus suture zone; MBT = Main Boundary thrust; MFT = Main Frontal thrust (active); MKT = Main Karakoram thrust; SH = Sargodha high. Rectangular box denotes area of Figure 2.

INTRODUCTION

This study is part of an effort to integrate approximately 3000 km of commercial seismic reflection profiles with surface map, drill-hole, and gravity data from the Salt Range–Potwar Plateau area (Lillie et al., 1987). These data have been used to construct a series of balanced cross sections of the foreland fold-thrust belt of the Himalaya in Pakistan (Baker, 1987; Leathers, 1987). Magnetic stratigraphy constrains the timing of deformation and the progression of the deformation front across the foreland basin (Raynolds and Johnson, 1985; Johnson et al., 1986). The rate of shortening at the front of the fold-thrust belt can be determined by using this timing information along with estimates of contraction of the sedimentary cover based on the balanced cross sections. Initiation of ramping in the Salt Range represents a discrete event from which timing and later contraction can be determined. The resulting shortening rate can then be used to infer the part of Indian-Asian plate convergence attributable to underthrusting of the Indian basement beneath sediments at the Salt Range front.

REGIONAL SETTING AND STRUCTURE OF THE SALT RANGE–POTWAR PLATEAU

The southern margin of the Himalayan collision zone in Pakistan is the Salt Range and Kohat–Potwar Plateau, an active foreland fold-thrust belt formed in response to the underthrusting of cratonic India beneath its own Phanerozoic sedimentary cover (Fig. 1). At the Hazara-Kashmir syntaxis, the fold-thrust belt changes trend and broadens in Pakistan. In India, there is strong coupling between sediments and basement; consequently, the zone of underthrusting is narrow and has a high angle of cross-sectional taper (Davis et al., 1983; Davis and Engelder, 1985). In Pakistan, on the west flank of the Hazara-Kashmir syntaxis, low-strength evaporites of late Precambrian to Early Cambrian age constitute the zone of decollement (Crawford, 1974). As a result, and in contrast to India, the zone of underthrusting extends far out over the foreland (Seeber and Armbruster, 1979), more than 100 km south of the Main Boundary thrust, and it has a narrow cross-sectional taper (Jaumé and Lillie, 1987).

At the Salt Range front (Fig. 2), Eocambrian evaporites and overlying strata override synorogenic fan material and alluvium (Yeats et al., 1984). The strongly emergent central Salt Range is located between a weakly emergent thrust front at the Surghar Range and a buried thrust front in the easternmost Salt Range (terminology of Morley, 1986). The right-lateral Kalabagh tear fault terminates the Salt Range to the west (Yeats and Lawrence, 1984). In contrast, the eastern termination of the Salt Range is divided into several fault blocks bounded by forward- and rearward-verging thrusts (Johnson et al., 1986). The Salt Range lies about 80 km outboard of thrusting in the northern Potwar deformed zone (NPDZ); the intervening Soan syncline is relatively undeformed (Fig. 3).

Seismic reflection profiles in the region (Khan et al., 1986; Lillie et al., 1987) show that the Salt Range and southern Potwar Plateau constitute a large slab that is being thrust over the foreland with very little internal deformation.

The northern flank of the central Salt Range is an eroded monocline that flattens northward into the southern limb of the Soan syncline. The monocline is the surface expression of a footwall ramp, identified by reflection profiles as a normal fault with a basement offset of 1 km down-to-the-north (Lillie and Yousuf, 1986; Fig. 4). The most likely hypotheses for the origin of the down-to-the-north basement fault are (1) extension related to Eocambrian rifting that may have accompanied the formation of evaporite basins on the northwestern margin of the Indian subcontinent, or (2) Neogene normal faulting related to flexure as the crust is loaded by thrust sheets from the north (Lillie and Yousuf, 1986; Duroy, 1986). The ramp and the underlying fault are expressed by a local steepening of the Bouguer gravity gradient (Farah et al., 1977). The basement offset apparently acted as a buttress that controlled ramping and emplacement of the Salt Range thrust sheet. The Salt Range, like anticlines of the Potwar Plateau, is underlain by salt, which appears to have flowed from beneath synclines (cf. Davis and Engelder, 1985; Fox, 1983), as suggested by the presence of more than 2 km of allochthonous salt at the bottom of the Dhariala well (Gee, 1983; D in Fig. 2).

TIMING OF BASEMENT FAULTING AND RAMPING

The timing of thrusting is often bracketed by the youngest rocks involved in deformation and the oldest sediments overlapping these deformed strata. Yeats et al. (1984) documented that the Salt Range thrust is young and possibly still active; the initiation of ramping, however, is more difficult to constrain. In the central Salt Range at the Baun locality (Fig. 2), the top of the middle Siwalik molasse, dated as 5.1 Ma or slightly younger (Johnson et al., 1982), is overlain disconformably by upper Siwalik strata. Lower and middle Siwalik beds are tilted northward and truncated above the footwall ramp (Fig. 4), indicating that ramping began later than 5.1 Ma. Initiation of ramping predates deposition of the Potwar silt, which is believed to have been ponded behind the rising Salt Range. Raynolds (1980) found only normal magnetization in the Potwar silt, indicating

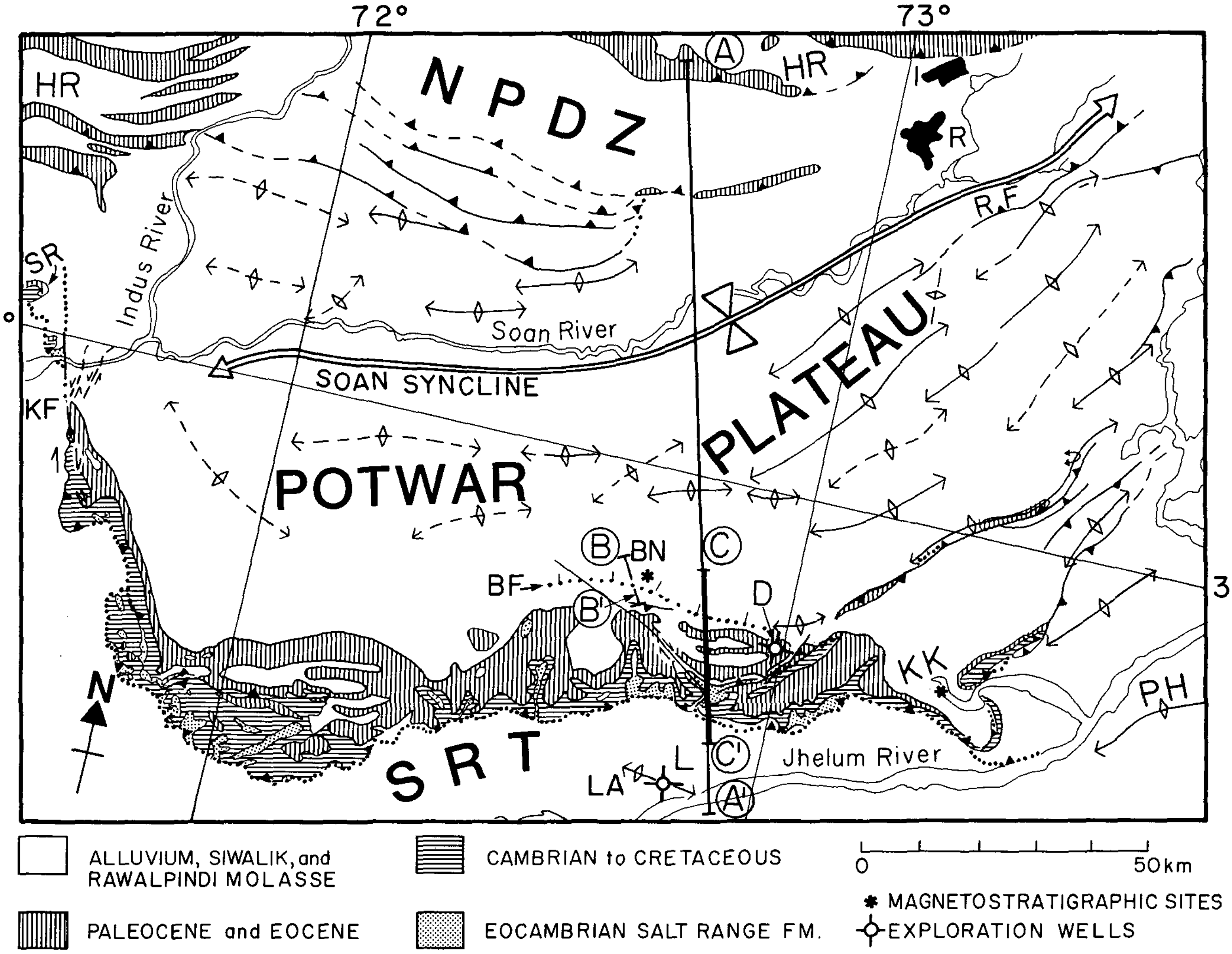

Figure 2. Geologic map showing locations of structural features mentioned in text (after Gee, 1980). BF = basement fault; HR = Hill Ranges; KF = Kalabagh fault; LA = Lilla anticline; NPDZ = northern Potwar deformed zone; PH = Pabbi Hills anticline; RF = Riwat fault; SR = Surghar Range; SRT = Salt Range thrust. Cities: I = Islamabad; R = Rawalpindi. Exploration wells: D = Dhariala; L = Lilla. Cross-section traces (circled letters): A–A' (see Fig. 3); C–C' (see Fig. 5); seismic line: B–B' (see Fig. 4). Magnetostratigraphic sample locations (Johnson et al., 1982): BN = Baun; KK = Kotal Kund. Solid lines represent structures mapped from Landsat photographs, dashed lines indicate less prominent features, and dotted lines denote buried structures.

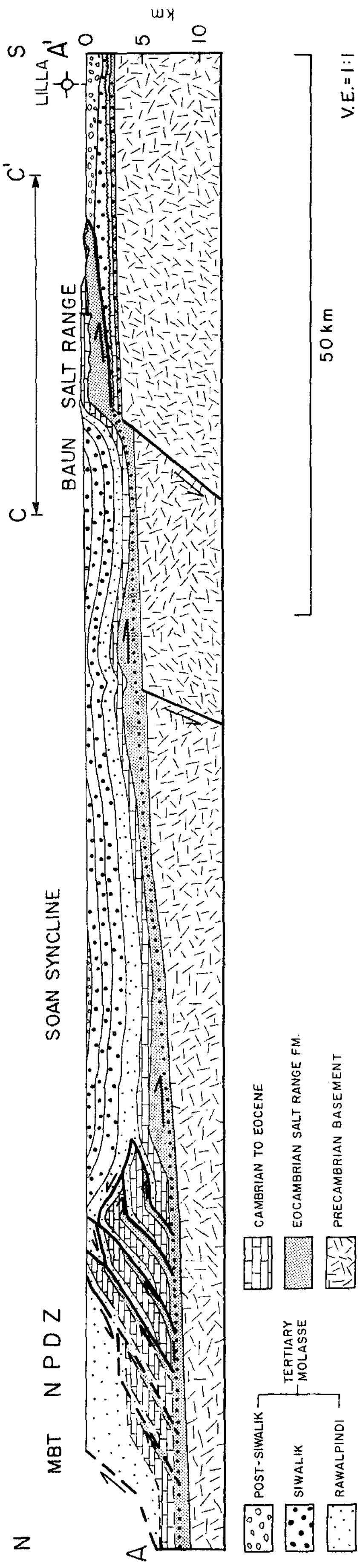

Figure 3. Balanced cross section A–A' of Himalayan foreland fold-thrust belt in Pakistan (see Lillie et al., 1987, for example of seismic profiles used to construct section). MBT = Main Boundary thrust; NPDZ = northern Potwar deformed zone. See Figure 2 for location and Figure 5 for restoration of C–C'.

a Brunhes age of less than 0.7 Ma, and Shroder et al. (in prep.) suggest that the silt may only be as old as 0.17 Ma on the basis of thermoluminescence data.

An upper Siwalik conglomerate bed, deposited about 4.5 Ma at the Baun locality, contains clasts of Eocene carbonates and recycled Precambrian granitic clasts from the Permian Tobra Formation (Johnson et al., 1986; Burbank and Raynolds, 1987). These clasts are important stratigraphic evidence constraining the timing of ramping and basement faulting. If the source area of upper Siwalik clasts is the upper thrust plate of the Salt Range, then conglomerate deposition may indicate incipient Salt Range thrusting by 4.5 Ma (Johnson et al., 1986; Burbank and Raynolds, 1987). However, Gee (1980) showed that Paleozoic strata in the upper thrust plate were covered by Eocene beds at the time of upper Siwalik conglomerate deposition and were not available as a source of sediment for northward transport to Baun.

Alternatively, if the Eocene and Permian clasts were eroded from the upthrown basement fault block underlying the Salt Range, then the clasts may have been derived from the south, when this part of the crust was at the crest or along the northern flank of the peripheral bulge formed by crustal loading of Himalayan thrust sheets; this bulge now underlies the Sargodha high (Fig. 1; see Duroy, 1986; Baker, 1987). This interpretation is supported by the Shell #1 Lilla well (L in Fig. 2), which penetrated Cambrian rocks directly beneath Siwalik molasse. Erosion of intervening strata, including Eocene carbonates and the Lower Permian Tobra Formation, is therefore demonstrated in the buried block south of the basement offset. If upper Siwalik conglomerates preserved at Baun were derived from the upthrown basement fault block to the south, then the down-to-the-north basement offset (Figs. 4 and 5) was formed or enhanced by Neogene faulting related to flexure, as suggested by Lillie and Yousuf (1986; Duroy, 1986).

The timing of the onset of ramping is also constrained by information from the eastern margin of the Salt Range–Potwar Plateau, where the progressive south-southeastward onset of deformation can be traced from the Riwat fault to the Pabbi Hills anticline (Johnson et al., 1986; Fig. 2). Johnson et al. (1986) interpreted the ramping of the Salt Range thrust sheet as having begun between 2.1 and 1.6 Ma, as the thrust sheet began to override the basement offset. The timing of this major structural event is suggested by the abrupt termination of folding in the NPDZ at about 1.9

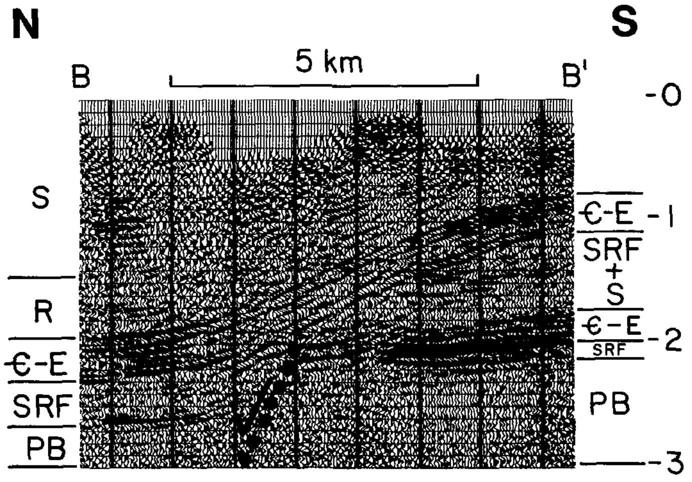

Figure 4. Seismic profile of ramp region (see Fig. 2 for location). Note down-to-north basement offset, general form of prominent reflectors (Є–E) across ramp and flat-lying, prominent reflectors beneath allochthon. S = Siwaliks; R = Rawalpindi Group; Є–E = Cambrian to Eocene; SRF = Salt Range Formation; PB = Precambrian basement. Vertical scale is two-way traveltime in seconds.

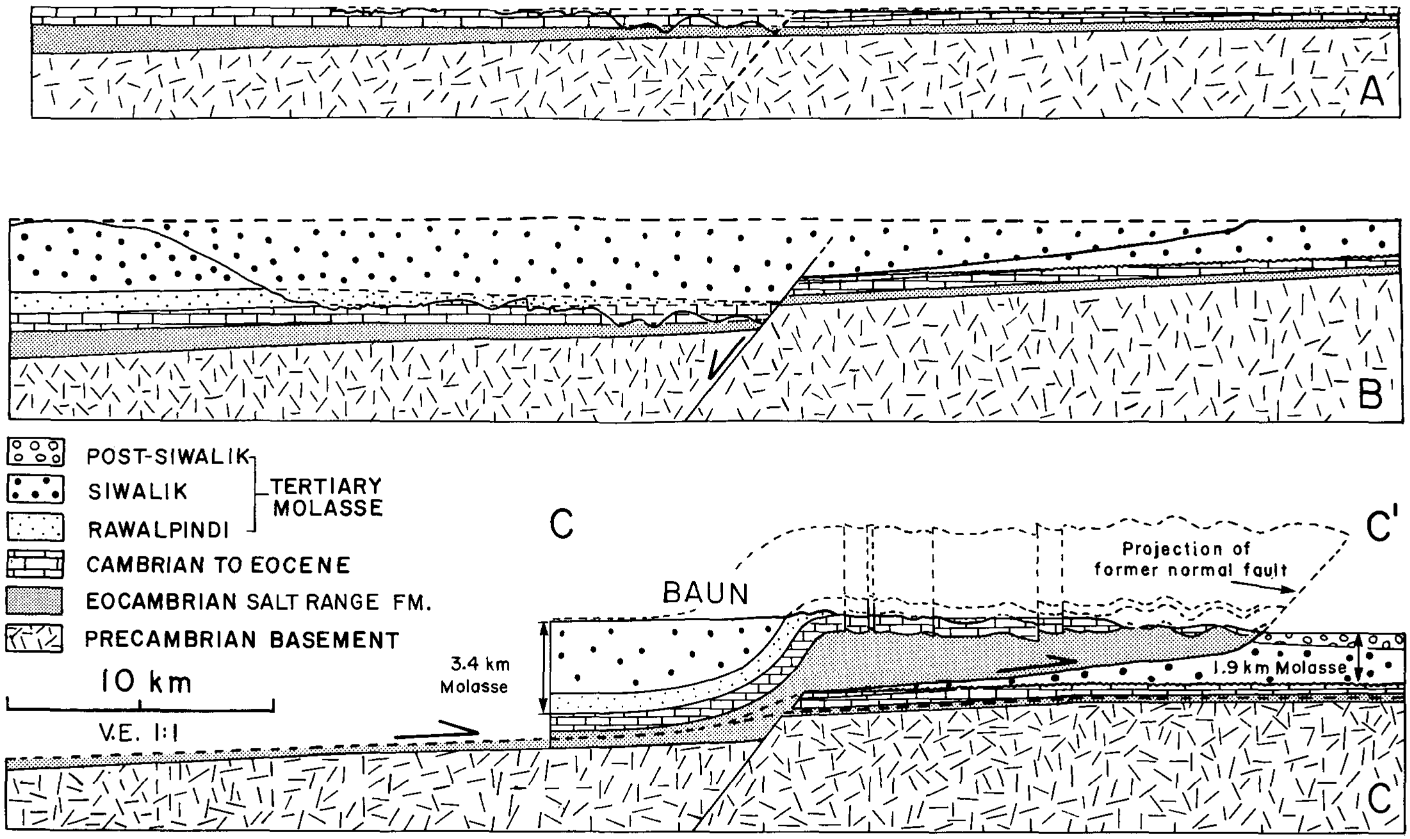

Figure 5. Balanced cross section and restorations demonstrating possible mode of origin of Salt Range. Formation contacts are dashed above upward limit of preserved strata. A: Stratigraphic sequence at end of platform deposition and prior to molasse deposition (ca. 35 Ma). Thinner Cambrian to Eocene sequence south of future basement offset is interpreted to result from erosion during subsequent basement faulting. B: Restoration after normal faulting and associated erosion of platform strata south of basement offset, prior to compressional deformation (ca. 2 Ma). Note that Neogene molasse thickens across normal fault. C: Present configuration. Thrust sheet encountered basement offset and ramped above thickening layer of salt. Salt has flowed into section from north. Molasse removed from autochthon during thrusting is not shown. Dashed detachment surface is schematic. Vertical faults were mapped as "normal or probably normal" by Gee (1980).

Ma, termination of sedimentation over folds in the eastern Potwar, cessation of sedimentation in the Kotal Kund region at 1.6 Ma (Johnson et al., 1986), and rapid rotation of the Soan syncline after 2.1 Ma (Burbank and Raynolds, 1987). Initiation of ramping between 2.1 and 1.6 Ma also fits the chronology of the south-southeastward–propagating deformation front, when the position of the central Salt Range ramp is projected along strike to the east. During this time span, there was a transfer of strain release from the NPDZ to the Salt Range ramp, implying that the Soan syncline–Salt Range region began to move as one coherent thrust sheet.

DISCUSSION

Ramping

In Figure 5, the Salt Range is interpreted as a fault-bend fold. The shape of this anticline differs from the fault-bend fold of Suppe (1983) because of its lack of a frontal, forward-dipping limb and the ductile behavior of salt at the base of the thrust sheet. Loading by the thick molasse sequence within the Soan syncline is believed to have caused ductile flow of salt toward the south (Gee, 1983), which may have resulted in a salt buildup against the basement buttress. The work of Wiltschko and Eastman (1983) on potential thrust-fault orientations associated with basement faults suggested that the normal-fault plane would likely be reactivated during compression in strata overlying the basement (Fig. 5). As salt growth continued, Cambrian and younger strata on the north side of the fault would be lifted until they could be pushed across the basement offset. This mechanism explains the source of thickened salt in the allochthon (e.g., Dhariala well; Gee, 1983) while avoiding an unreasonably sharp initial interlimb ramp angle. Therefore, the southern flank of the central Salt Range is not only an eroded thrust-fault scarp (Yeats et al., 1984) but also the preserved part of the downthrown normal-fault block (Fig. 5).

Due to its limited lateral extent (Fig. 2), the basement offset does not satisfactorily explain the emplacement of the entire Salt Range. A thrust-fault surface may propagate along strike into areas where there is no other mechanical cause for failure (Wiltschko and Eastman, 1983). In the western Salt Range, ramping may have been facilitated by a basement warp interpreted by Leathers (1987) as the northeast flank of the Sargodha basement ridge converging with the overthrust belt. In the eastern Salt Range, a southward thinning of the decollement-zone salt facies may have aided thrust ramping. Therefore, it appears that a combination of ramping mechanisms was responsible for the emplacement of the entire Salt Range.

Calculation of Shortening Rate

In the western Himalaya at long 73°E, the northward motion of the Indian plate relative to the Asian plate is calculated as 42 mm/yr (Minster and Jordan, 1978). Convergence is taken up by (1) shortening of sedimentary strata in the foreland as India underthrusts its cover rocks; (2) contraction within the collision zone by uplift in the high Himalaya and reactivation of interior thrust faults; and (3) crustal shortening via thickening of the crust and escape-block tectonics along strike-slip faults to the north of the collision zone (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977).

Balanced sections through the central Salt Range suggest at least 20 to 23 km of horizontal shortening of the competent Cambrian through Eocene section (e.g., Fig. 5; Baker, 1987). The calculated shortening is a minimum because erosion of the hanging wall at the Salt Range front has not been accounted for. If it is assumed that the thrust sheet overrode the ramp between 2.1 and 1.6 Ma, the minimum rate of shortening between the Indian basement and the Phanerozoic sedimentary cover is between 9 and 14 mm/yr. These rates are comparable to the 10–15 mm/yr convergence absorbed by underthrusting as estimated by Lyon-Caen and Molnar (1985) for the Himalayan foreland in India. Balanced cross section A–A′ (Fig. 3) indicates 20% shortening for a 90 km length of the fold-thrust belt between the Lilla anticline and intense deformation in the NPDZ. This is a relatively low degree of shortening compared to values obtained in other fold-thrust belts around the world, probably because the thrust front only recently jumped the large distance from the NPDZ to the Salt Range.

Our estimate of the shortening rate represents about 20%–35% of the convergence rate between the Indian and Asian plates. The calculated rate would indicate that most convergence is absorbed north of the frontal thrust zone by contraction within the collision zone and escape-block tectonics. The calculated rate and percentage of shortening should be compared to those of the Indian part of the Himalayan foreland fold-thrust belt, where a salt decollement zone is lacking. A comparison of results could be used to evaluate the decoupling effects of salt and the origin of the Hazara-Kashmir syntaxis.

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