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MECHANICS OF THE SALT RANGE–POTWAR PLATEAU, PAKISTAN: A FOLD-AND-THRUST BELT UNDERLAIN BY EVAPORITES

Steven C. Jaumé[1]

College of Oceanography, Oregon State University, Corvallis

Robert J. Lillie

Department of Geology and College of Oceanography, Oregon State University, Corvallis

Abstract. The Salt Range and Potwar Plateau are part of the active foreland fold-and-thrust belt of the Himalaya in northern Pakistan. In this region the distance from the Main Boundary Thrust (MBT) to the front of the fold-and-thrust belt is very wide (100–150 km) because a thick evaporite sequence forms the zone of décollement. Recent studies have combined seismic reflection profiles, petroleum exploration wells, Bouguer gravity anomalies, and surface geology to construct cross sections in the eastern, central, and western Salt Range–Potwar Plateau areas. In this study the sections are compared with a model that considers the mechanics of a fold-and-thrust belt to be analogous to that of a wedge of snow or soil pushed in front of a bulldozer (Chapple, 1978; Davis et al., 1983; Dahlen et al., 1984; Dahlen, 1984). Models which include the effects of evaporites at the base (Chapple, 1978; Davis and Engelder, 1985) suggest that these thrust belts will have (1) narrow (< 1°) cross-sectional tapers, (2) larger widths than areas not underlain by evaporites, (3) symmetrical structures, and (4) changes in deformational style at the edge of the evaporite basin. The section across the eastern Potwar Plateau most closely resembles this latter model, having (1) a taper of 0.8° ± 0.1°, (2) a width of 100–150 km, (3) thrust faults that verge both to the north and south, and (4) structures rotated 30° counterclockwise with respect to the Salt Range. From the observed taper and pore fluid pressures of the eastern Potwar Plateau, estimates of the values for the yield strength of the evaporites (τ_0) and the coefficient of internal friction of the overlying wedge (μ) are calculated as $\tau_0 = 1.33–1.50$ MPa and $\mu = 0.95–1.04$, which are then applied to the other cross sections. In the central and western sections a basement uplift, the Sargodha High, interferes with the front of the fold-and-thrust belt. This feature causes the ramping of the Salt Range Thrust and produces a relatively steep basement slope (2°– 4°) beneath the Potwar Plateau. This dip, in the presence of the weak evaporite décollement, is sufficient to provide critical taper; no topographic slope is necessary, and the thrust wedge of the southern Potwar Plateau is pushed over the décollement without significant internal deformation. The northern Potwar Plateau is strongly folded and faulted, yet the topographic slope remains flat. Although the deformation suggests that evaporites are not present there, the observed taper in the northern Potwar Plateau is best fitted by the model with evaporites at the décollement. Combining this with published paleomagnetic and geologic constraints, a model for the evolution of the northern Potwar Plateau suggests that the area deformed as a steeply tapered (3.5°–5.5°) thrust wedge until approximately 2 million years ago, when the southward propagating décollement encountered the evaporites. Between 2 Ma and the present, the northern Potwar Plateau has been pushed along the salt décollement without deformation, and erosion has reduced its original steep topographic slope to a nearly level surface.

INTRODUCTION

Beginning about 40 million years ago, collision of the Indian subcontinent with Eurasia produced the spectacular Himalayan arc, along with a series of mountain belts to the east and west [Molnar and Tapponier, 1975]. This study concentrates on one of these fringing belts, the Salt Range–Potwar Plateau area of northern Pakistan (Figures 1

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[1] Now at Lamont Doherty Geological Observatory, Palisades, New York.

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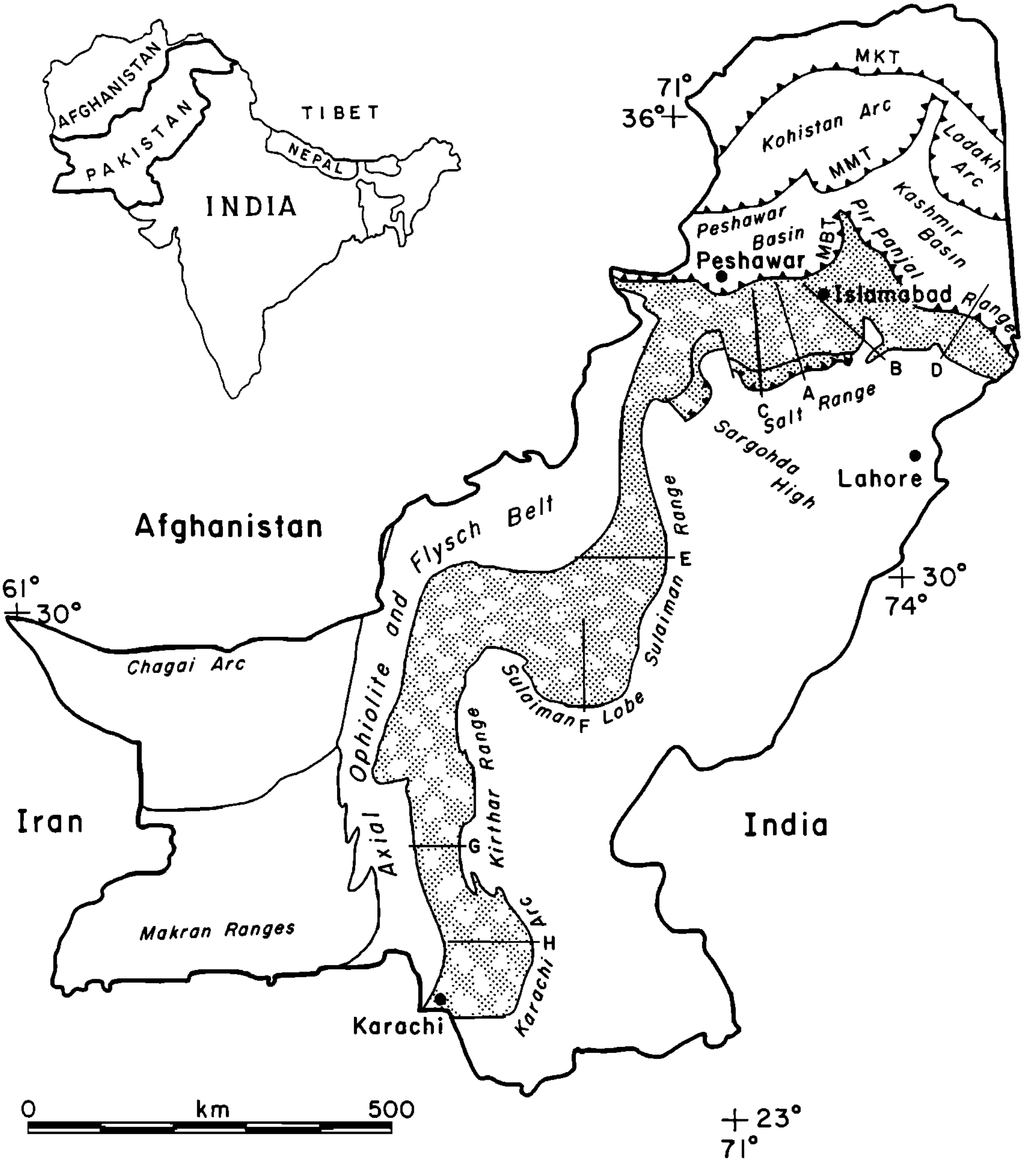

Fig. 1. Tectonic regimes of Pakistan [after Kazmi and Rana, 1982]. Shaded area is the foreland fold-and-thrust belts. Note the sinuosity, changes in width, and changes in trend of these belts going from northeast to southwest. Cross sections A, B, and C shown in Figures 10, 6, and 12, respectively. Topographic profiles for sections A through H are given by Jaumé [1986]. MBT, Main Boundary Thrust. MMT, Main Mantle Thrust. MKT, Main Karakorum Thrust.

and 2). In northern Pakistan the Himalayan arc changes from a northwest-southeast trend to a nearly east-west orientation, bending around the Hazara-Kashmir syntaxis. The Salt Range, the southernmost of these east-west trending ranges, is the active front of deformation. Immediately to the north, the relatively flat Potwar Plateau separates the Salt Range from the main Himalayan ranges of northern Pakistan.

This study of the mechanics of the Salt Range–Potwar Plateau of Pakistan stems from ongoing work by Oregon State University (OSU) on the geology and geophysics of northern Pakistan and from recent quantitative modelling of the mechanics of fold-and-thrust belts by Chapple [1978], Davis et al. [1983], Dahlen et al. [1984], Dahlen [1984], and Davis and Engelder [1985]. The release of approximately 3000 km of seismic reflection profiles [e.g., Khan et al., 1986] to OSU by the Government of Pakistan has allowed, for the first time, a three-dimensional view of this active fold belt. Integration of these data with surface geology, borehole, and

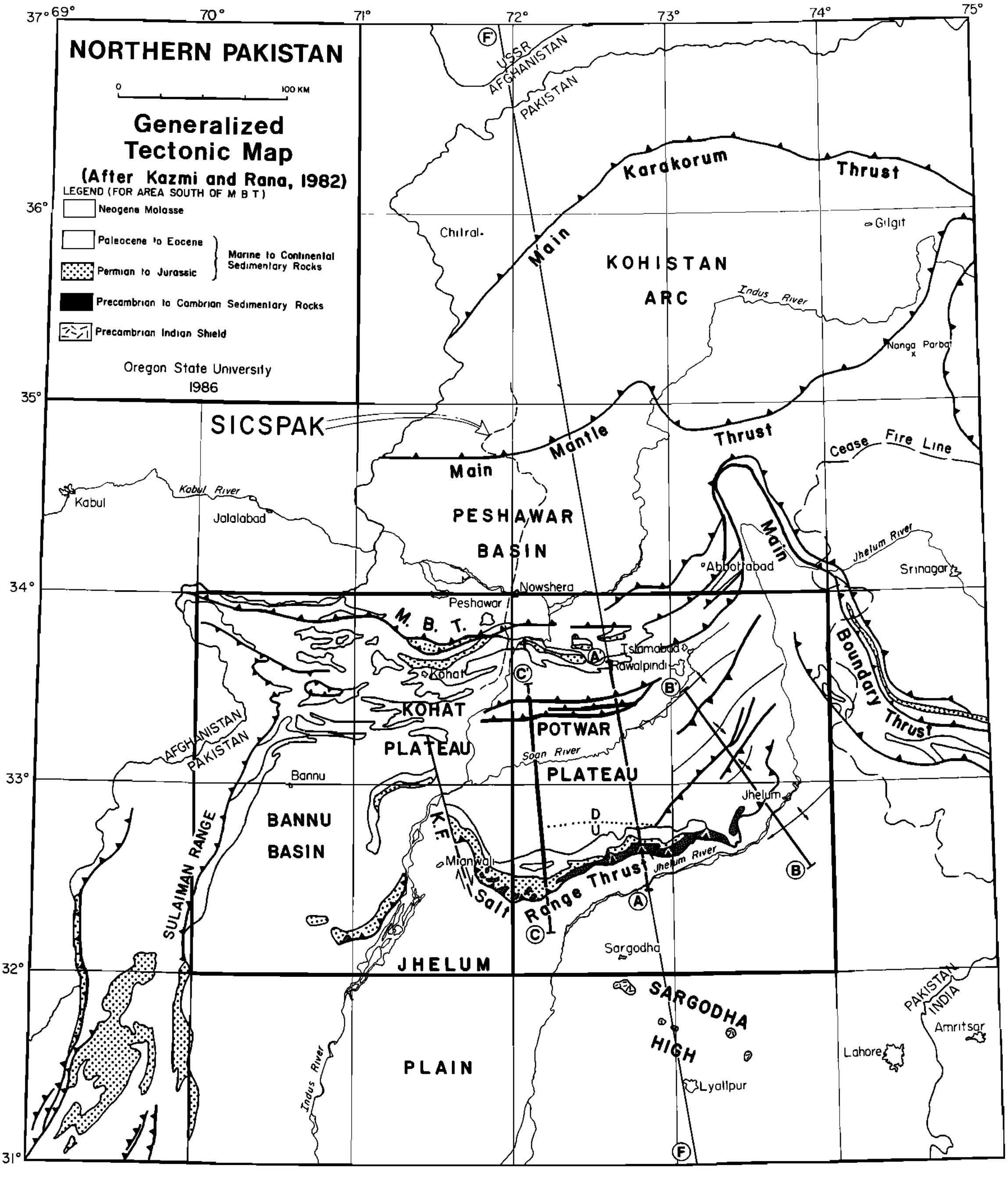

Fig. 2. Generalized tectonic map of northern Pakistan [after Kazmi and Rana, 1982]. A-A', B-B', and C-C' are locations of cross sections interpreted by Baker [1987], N. Pennnock (work in preparation, 1987), and Leathers [1987], and shown in Figures 10, 6, and 12, respectively. F-F' is the line of section for the lithosperic flexure model discussed by Duroy [1986]. KF, Kalabugh Fault. MBT, Main Boundary Thrust. SICSPAK refers to Seismic Investigation of Crustal Structure in Pakistan, a potential deep-crustal reflection traverse [Lillie et al., 1987].

gravity data has resulted in cross sections [Baker, 1987; Baker et al., in press, 1987; Duroy, 1986; Leathers, 1987; N. Pennock, work in preparation] that allow for the application of the mechanical models to an active continental convergent setting.

In this study, the mechanics of the Salt Range–Potwar Plateau are examined mainly in the context of the Davis and Engelder [1985] model for a fold-and-thrust belt developed upon an evaporite layer (commonly salt). The overthrust wedge geometry of the Salt Range–Potwar Plateau is consistent with this model in that it shows these general characteristics: (1) a narrow cross sectional taper; and (2) a broad (100 –150 km) zone of overthrusting. The details of the structure in the Salt Range–Potwar Plateau also agree with the Davis and Engelder [1985] model in that (1) there is a lack of surface deformation in the central and western Potwar Plateau where the basement dip (β) is > 1°, (2) surface deformation is observed in the eastern Potwar Plateau where $\beta < 1°$, (3) the deformation style of the eastern Potwar Plateau consists of narrow, symmetrical anticlines, and thrusts that verge both north and south; and (4) there is a change in the orientation of structural trends at the eastern edge of the salt basin. The seismic sections across the Salt Range further illustrate the importance of basement configuration in the development of structures within the fold-and-thrust belt (e.g., see Wiltschko and Eastman [1983, 1986]); the impingement of the flexural bulge (Sargodha High) with the overthrust wedge in the central and western portions of the Range results in ramping and exposure of the entire stratigraphic section.

Thus this study shows that for a fold-and-thrust belt underlain by salt it is the dip and structure of the underlying basement along with the distribution of the salt, that primarily control the structures developed within the belt. This result should be useful in the study of other fold-and-thrust belts underlain by salt but for which subsurface information is lacking.

TECTONIC SETTING

From south to north, three major tectonic elements can be defined for the active foreland deformation belt of northern Pakistan (Figure 2), as follows: (1) the Jhelum plain, (2) the Salt Range and similar frontal ranges west of the Indus River, and (3) the Potwar-Kohat Plateaus and the Bannu Basin [Yeats and Lawrence, 1984]. The Jhelum Plain is the undeformed foreland south of the Salt Range Thrust. It contains within it the seismically active Sargodha High, a buried basement ridge that trends obliquely to the Salt Range but parallel to the overall Himalayan trend. The Salt Range is the surface expression of the leading edge of the foreland fold-and-thrust belt. On its southern edge, the Salt Range Thrust is anomalous in that it brings pre-Tertiary rocks to the surface at the very front of the fold-and-thrust belt [Crawford, 1974], contrasting sharply with the foreland fold-and-thrust belt in India, where only Tertiary molasse sediments are exposed. Between the Salt Range and the Main Boundary Thrust (MBT) is the Potwar Plateau, which is nearly undeformed south of the Soan River but is deformed on its northern and eastern margins (Figure 2).

From bottom to top, the stratigraphic section in the Salt Range–Potwar Plateau can be split into four groups: (1) basement complex, (2) Salt Range Formation, (3) platform section, and (4) molasse section [Khan et al., 1986]. The Precambrian basement complex is believed to be similar in lithology to the rocks exposed in the Kirana Hills (part of Sargodha High) south of the Salt Range, consisting of metamorphic and volcanic rocks of the Indian shield [Yeats and Lawrence, 1984]. Although offset by normal faults, thought to be associated with Neogene flexure [Lillie and Yousuf, 1986; Duroy, 1986], the basement beneath the Salt Range and Potwar Plateau is not involved in thrusting. The Eocambrian Salt Range Formation is an evaporitic and sedimentary unit that forms the level of décollement for the fold-and-thrust belt. Although there are a number of facies present (marls, anhydrite, etc.), the dominant facies is halite. The low shear strength of halite makes it the preferred zone of décollement. The platform section consists of Cambrian to Eocene shallow-water sediments with major unconformities at the base of the Permian and at the base of the Paleocene. This part of the section has a high acoustic impedance relative to the surrounding rocks, resulting in a seismic reflection sequence which can be traced throughout the Salt Range–Potwar Plateau region [Khan et al., 1986; Lillie et al., 1987]. There is also an unconformity between the platform sequence and the overlying Miocene to Pleistocene synorogenic molasse section. The molasse section consists of the Rawalpindi and Siwalik Groups, which are over 5000 m thick at the axis of the Soan Syncline (i.e., beneath the Soan River, Figure 2).

MECHANICS OF FOLD-AND-THRUST BELTS

Soon after the recognition of large overthrusts in the 1800s, it was thought impossible for these large, nearly undeformed blocks of rock to have moved tens to hundreds of kilometers. Conventional sliding friction theory required a force greater than the crushing strength of the rocks in order to move a thrust sheet along a horizontal plane [Smoluchowski, 1909]. Early work in thrust mechanics therefore assumed that a body force, gravity, was responsible for the movement of thrust blocks.

Chapple [1978] recognized that all fold-and-thrust belts have several features in common, including (1) a characteristic wedge shape, (2) a basal zone of décollement, below which there is no deformation, and (3) a large amount of horizontal compression above the décollement, primarily at the back of the wedge. He proposed a model in which both the thrust wedge and the weaker basal layer are considered to be perfectly plastic materials yielding in compressive flow. The deformation of such a wedge is considered to be analogous to that of a wedge of snow or soil pushed in front of a bulldozer. The important outcome of this work was that Chapple [1978] showed that horizontal compression is the main driving force in a fold-and-thrust belt and that the necessary condition for the formation of such belts is a weak basal layer, not a surface topographic slope.

Davis et al. [1983] considered a similar model but with a pressure-dependent, noncohesive Coulomb failure criteria and the small angle approximation, $\sin \alpha \approx \alpha$. With this they developed an analytical model relating the critical taper of a fold-and-thrust belt to its basal friction and internal strength. This model is stated mathematically as follows (Figure 3):

$$\alpha + \beta = \frac{\beta + (1 - \lambda_b)\,\mu_b}{1 + (1 - \lambda)\,K} \tag{1}$$

where α is the forward topographic slope of the wedge, β is the backward slope of the basement, λ and λ_b are the Hubbert and Rubey [1959] pore fluid pressure ratios within and at the

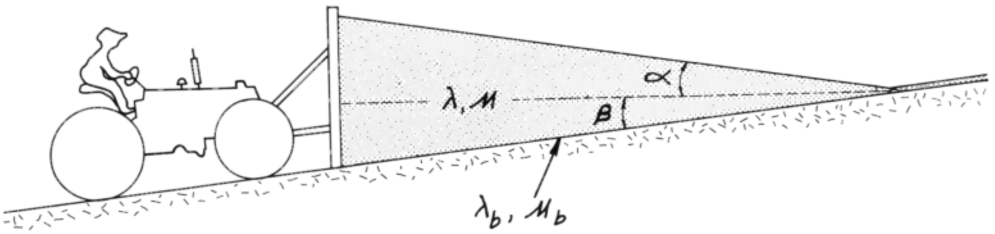

Fig. 3. Davis et al. [1983] model for the mechanics of accretionary wedges and foreland fold-and-thrust belts, considered to be analogous to that of a wedge of snow or soil pushed in front of a bulldozer. Symbols defined in text.

base of the wedge, μ_b is the coefficient of friction at the base of the wedge, and K is a dimensionless number related to the angle of maximum compression and dependent upon μ_b and μ (coefficient of internal friction within the wedge). With their model, Davis et al. [1983], like Chapple [1978], showed that horizontal compressive forces predominate over gravitational forces in a fold-and-thrust belt.

Davis et al. [1983] applied their model to the active fold-and-thrust belt in Taiwan where parameters such as pore fluid pressure ratios ($\lambda \approx 0.675$), basement dip ($\beta \approx 6°$), and topographic slope ($\alpha \approx 2.9°$) are known. Like Chapple [1978], they found the model requires that the basal layer be weaker than the overlying wedge. In terms of the noncohesive Coulomb model, the coefficient of internal friction, μ, within the wedge is about 20% larger than the basal sliding friction μ_b. Davis et al. [1983] used Byerlee's "law" [Byerlee, 1978], $\mu_b \approx 0.85$, and computed a best fitting value for the coefficient of internal friction of $\mu = 1.03$.

Evaporites, especially rock salt, are considerably weaker than other rock types. At depths typical of basal décollement (2–10 km), salt is in the ductile regime. Work by Carter and Hansen [1983] shows that rock salt deforms at shear stresses between 0.5 and 1.5 MPa. This makes the strength of rock salt at typical décollement depths 1 to 2 orders of magnitude less than most other rock types. Chapple [1978] recognized that in the presence of a very weak basal décollement the surface slope of the fold- and-thrust belt will be small and the axis of maximum compressive stress will be nearly parallel to bedding, leading to very symmetrical structures.

Davis and Engelder [1985] extended the model of Davis et al. [1983] to include the presence of salt at the base (Figure 4). Like Chapple [1978], they show that a thrust wedge underlain by salt will have a narrow cross-sectional taper and symmetrical structures (Figure 4a). They also noted that the wedge would be wider than neighboring areas not underlain by salt (Figure 4b) and that drag-related features should develop at

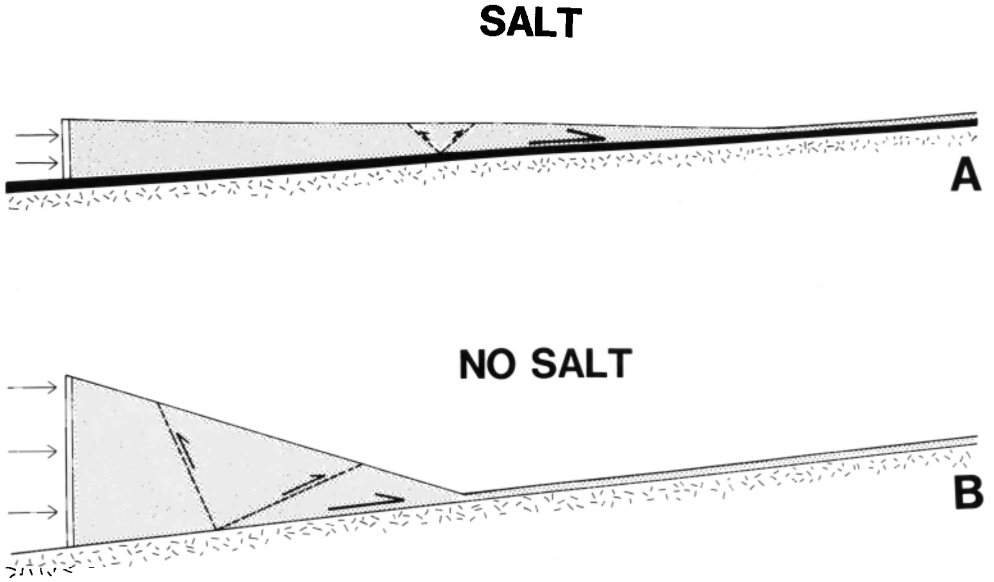

Fig. 4. Cartoons illustrating fold-and-thrust belts underlain by salt verus nonsalt substrate. (a) The thrust belt underlain by salt, shown in black, has a narrower cross-sectional taper, a wider deformational belt, and nearly symmetrical structures, compared to (b) a thrust belt not underlain by salt [after Davis and Engelder, 1985].

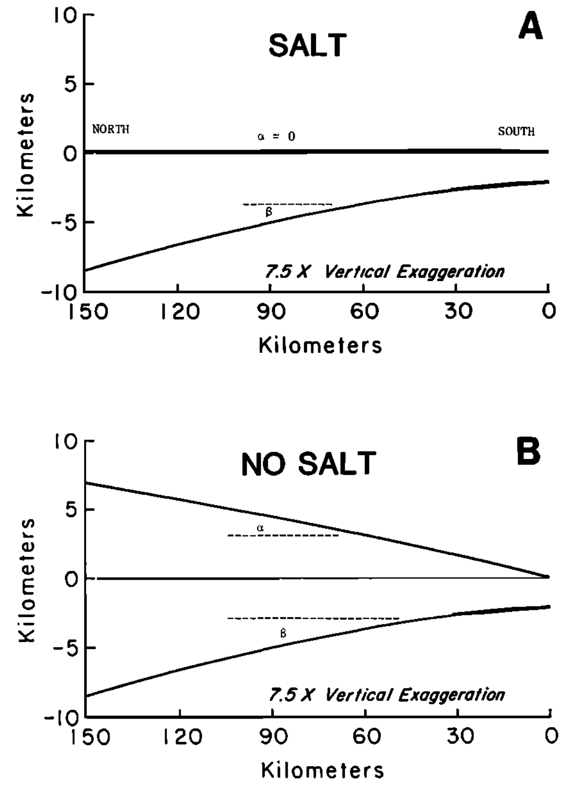

Fig. 5. (a) Model of a noncohesive Coulomb wedge underlain by a layer of salt, developed on top of a curved basement surface. Model derived using the critical taper equation of Davis and Engelder [1985] modified for β increasing from south to north, as in the central Salt Range-Potwar Plateau [Jaumé, 1986]. Note that the topographic slope is slight at the front of the wedge and that it becomes flat as the basement dip steepens and the thickness of the wedge increases. (b) Model with same basement slope as in Figure 5a, but with a strong basal décollement (Davis et al. [1983], as modified by Jaumé [1986] to account for the curved basement). Unlike the Salt Range-Potwar Plateau region, a significant topographic slope ($\alpha \approx 2.5°$) is predicted for this region.

the edges of the salt basin. This model is mathematically stated as

$$\alpha+\beta = \frac{\beta + (\tau_0/\rho g H)}{1 + (1 - \lambda)(2 / [\csc\phi - 1])} \qquad (2)$$

where τ_0 is the yield stress of the salt, $\phi = \tan^{-1}\mu$ is the angle of internal friction, ρ is the average density of the wedge, g is the acceleration of gravity, H is the thickness of the wedge, and the other variables are as defined in (1). At yield stresses appropriate for rock salt (~ 1 MPa) this means that very small taper (~1°) is required for the wedge to be pushed over the foreland [Davis and Engelder, 1985].

Owing to lithospheric flexure, the basement beneath the Himalayan foreland shows a curved, rather than linear, surface [Karner and Watts, 1983; Lyon-Caen and Molnar, 1983; 1985; Duroy, 1986]. The mechanical models [Chapple, 1978; Davis et al., 1983; Dahlen et al., 1984; Davis and Engelder, 1985] were therefore modified slightly to allow for β to vary along lines of cross section [see Jaumé, 1986]. Figure 5 shows the application of the previously derived salt and no salt décollement models for the south to north increase in β observed in the central Salt Range–Potwar Plateau region. The discussion below shows that the salt décollement case (Figure 5a) is applicable for the region and that east-to-west changes in α and in internal deformation are primarily due to east-to-west changes in β.

MECHANICS OF THE SALT RANGE–POTWAR PLATEAU, PAKISTAN

Eastern Potwar Plateau (B-B')

The frontal (southernmost) 100 km of the eastern Potwar Plateau fold belt (Figure 6) most closely resembles the salt décollement model of Davis and Engelder [1985]. The thrust wedge has a narrow cross-sectional taper ($\alpha + \beta < 1°$), and internally there is no consistent direction of thrusting; thrusts verge both to the northwest and the southeast. Also, anticlines are cored by ductilly thickened salt and are separated by broad synclines underlain by thin salt.

In map view (Figure 7), a change in structural strike between the Salt Range and the structures of the eastern Potwar Plateau is evident. The Davis and Engelder [1985] model predicts a change in deformational style at the edge of the salt basin. This is consistent with the hypothesis that the salt facies thins eastward [Seeber et al., 1981] and that the eastern Potwar Plateau fold belt is developed at the edge of the Eocambrian salt basin. A thinning of the Salt Range Formation to the southeast is evident in B-B' (Figure 6). A change in deformational style in the eastern Potwar Plateau is supported by the paleomagnetic work of Opdyke et al. [1982], which suggests that the eastern Potwar Plateau is rotated 30° relative to the Salt Range and the central and western Potwar Plateau.

The parameters necessary to define the mechanics of the thrust wedge using equation (2) are the critical taper ($\alpha + \beta$), the yield strength of the evaporites (τ_0), the pore fluid pressure ratio (λ), coefficient of internal friction ($\mu = \tan\phi$), density (ρ), and thickness (H) of the wedge. Two of these parameters, ϕ and τ_0, are not available for the eastern Potwar Plateau; an attempt is made below to define the best constrained estimates for these parameters.

The topography in the eastern Potwar Plateau rises to the north-northwest at a gentle slope of 0.2° for the first 100 km (Figure 6). The basement dip (β) along section B-B' is 0.6° ± 0.1° for the same distance. This gives a critical taper of only 0.8° ± 0.1°, less than 1°, as predicted by Davis and Engelder [1985]. Seismic reflection profiles north of the Soan River indicate that the basement slope steepens in the north, but interpretation of these data has not proceeded to the point where an accurate measure of β can be taken. The topography north of the Soan River to the foot of the Hill Ranges (i.e., near Islamabad, Figure 2) is very flat ($\alpha < 0.1°$).

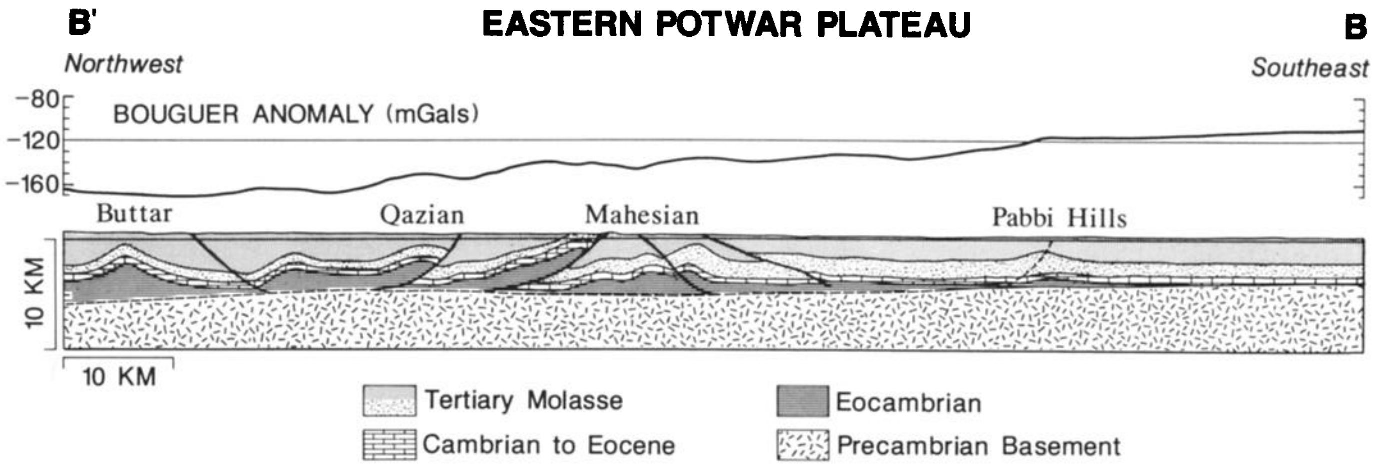

Fig. 6. Interpreted cross section B-B' across the eastern Potwar Plateau [after Leathers, 1987]. Seismic profiles and the gentle Bouguer gravity gradient suggest a basement slope (β) of < 1°. The observed topographic slope (α) is about 0.2°.

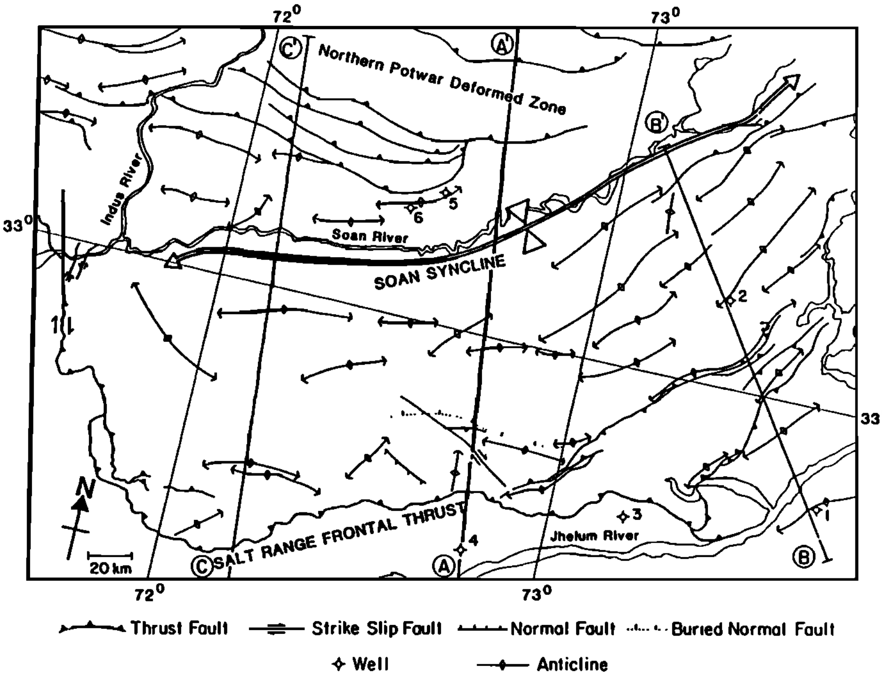

Fig. 7. Structural map of the Salt Range and the Potwar Plateau, including locations of wells cited in text. The wells are (1) Pabbi Hills, (2) Qazian, (3) Warnali, (4) Lilla, (5) Dhurnal, and (6) Khaur. A-A', B-B', and C-C' are the same as in Figure 2. Note that the structures in the eastern Potwar Plateau are rotated about 30° counterclockwise from the strike if the Salt Range [after Baker, 1987].

An estimate of the pore fluid pressure ratio for the southeastern Potwar Plateau is available from drilling mud densities in the Pabbi Hills-1 well and the Qazian-1X well (Figure 8; locations in Figure 7). The data show a hydrostatically pressured surficial unit (Pabbi Hills: 0–750 m; Qazian: 0–560 m), with the formation pressures increasing rapidly below this level. In the Qazian well the formation pressures decrease slightly in the lower part of the section (below ~1600 m) but still remain well above hydrostatic. An average value of $\lambda = 0.82$ for the overpressured section was calculated for the Pabbi Hills well from the drilling mud densities and sediment densities estimated from sonic logs. The average pore fluid pressure ratio for the Qazian well is also $\lambda = 0.82$, calculated using the same method as for the Pabbi Hills well. An average value for the density of the sediments overlying the Salt Range Formation is $\rho = 2330$ kg/m^3, estimated from gravity modelling studies of the Potwar Plateau [Duroy, 1986].

With two unknowns (μ and τ_0) in (2), it is not possible to uniquely solve for either one. Fortunately, there are some experimental and observational data from other sources that help constrain these parameters. Carter et al. [1982] find that differential stresses in some samples of naturally deformed halite are in the range $\tau_0 = 0.5$–1.1 MPa. Carter and Hansen [1983] state that the yield strength (τ_0) of halite is in the range 0.5–1.5 MPa. Davis and Engelder [1985] adopted a range of 0.1–1.0 MPa for τ_0 in their discussion.

The coefficient of internal friction, μ, is harder to constrain. Handin [1969] states that it should be considered only as the slope of the Mohr envelope for an intact material. Davis et al. [1983], Dahlen et al. [1984], Dahlen [1984], Davis and Engelder [1985], and Zhao et al. [1986] use μ as a value to help quantify the internal strength of a thrust wedge. As such, the only values available to constrain μ are those calculated by Davis et al. [1983], Dahlen et al. [1984], and Dahlen [1984]. Davis et al. [1983] found $\mu = 1.03$ as their best fitting value for the Taiwan fold-and-thrust belt using the approximate noncohesive Coulomb theory. Later, Dahlen [1984] revised this to $\mu = 1.10$ with an exact noncohesive Coulomb theory. Dahlen et al. [1984] found a best fitting value of $\mu = 0.95$ using cohesive Coulomb theory and a value of 5–20 MPa for the cohesion of the Taiwan wedge.

A tradeoff curve between μ and τ_0 can be computed using (2) to find the ranges of the parameters that fit the theory and that are comparable with those cited above (Figure 9). Since the Davis and Engelder [1985] model was developed for a noncohesive Coulomb wedge, the best fitting value for μ can be expected to be near the value calculated by Davis et al. [1983] and larger than that calculated by Dahlen et al. [1984]. From Figure 9 we feel the best fitting values of μ and τ_0 lie in the range $\mu = 0.95$–1.04 and $\tau_0 = 1.33$–1.50 MPa. Following Davis et al. [1983], 1.03 will be adopted for μ, and correspondingly 1.48 MPa for τ_0. This relatively high value of τ_0 is not surprising if the eastern Potwar Plateau is believed to lie at the edge of the salt basin. Although the interpretations of the seismic data imply that the Salt Range Formation is still relatively thick underneath the eastern Potwar Plateau, there may be inclusions of facies other than

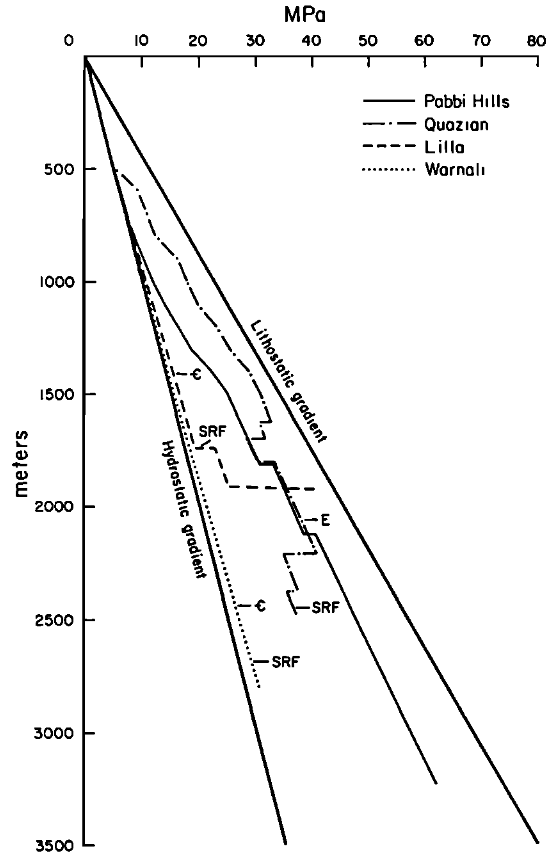

Fig. 8. Pore fluid pressures in some petroleum exploration wells in the Salt Range-Potwar Plateau. E, top of Eocene, C, top of Cambrian, SRF, top of Salt Range Formation. The section drilled in the Pabbi Hills well lies entirely in the Neogene molasse. Note that in the Lilla well the fluid pressure remains nearly hydrostatic until reaching the Salt Range Formation. The Pabbi Hills and Qazian wells have a hydrostatically pressured surface layer and then become overpressured with depth.

halite near the edge of the basin that would tend to increase the strength of the décollement.

Central Salt Range-Potwar Plateau (A-A')

Several differences are readily apparent between this section (Figure 10) [Baker, 1987; Lillie et al., 1987] and the section across the eastern Potwar Plateau (Figure 6). The most apparent feature is a large normal fault (throw ≈ 1 km) in the basement beneath the north flank of the Salt Range that causes the ramping of the entire section. This basement normal fault has been interpreted as being due to flexure of the Indian plate [Lillie and Yousuf, 1986; Lillie et al., 1987; Duroy, 1986]. Another important difference is the lack of major deformation in the southern Potwar Plateau and Soan Syncline. The surface of the central Potwar Plateau between the north flank of the Salt Range and the Hill Ranges is essentially flat ($\alpha < 0.1°$); the Salt Range itself is the only appreciable topography in the area. The basement slope in the central region is larger than in the east, being 1.3° in front of and underneath the Salt Range, 1.9° just north of the basement normal fault, and 3.6° under the central and northern Potwar Plateau. The change in basement slope is confirmed by the reflection profiles [Lillie et al., 1987; Leathers, 1987] as well as by a steeper Bouguer gravity gradient in the central region (Figure 10) as compared to the east (Figure 6). This drastic change in β is due to impingement of the Sargodha High, a basement uplift south of the Salt Range (Figure 2). Note that the depth to basement in front of the central Salt Range is less than 2 km (Figure 10) but is 4 km in front of the Kharian (Pabbi Hills) anticline (Figure 6).

For ease of discussion, cross section A-A' (as well as C-C' to the west) is divided into three units: (1) the Salt Range (SR), including the entire section south of the basement normal fault; (2) the Southern Potwar Plateau (SPP), including the section between the basement normal fault and the first thrust fault north of the Soan River, and (3) the Northern Potwar Plateau (NPP), including the remainder of the section.

The most important features of the SR are the basement normal fault and the Salt Range Thrust. None of the models of Davis et al. [1983], Dahlen et al. [1984], Dahlen [1984], and Davis and Engelder [1985] include the effect of basement structures upon the taper of fold-and-thrust belts. The small angle approximation $\sin \alpha = \alpha$ used in the Davis and Engelder [1985] model is inappropriate for a thrust wedge pushed up a high-angle (> 10°) basement offset. Yet it appears that Davis and Engelder's [1985] conclusion that there will be no topographic slope if $\beta > 1°$ is valid. The thrust sheet is overriding a steep ramp ($\beta \approx 25°$) with only slight internal deformation. In fact, the thrust plate is sliding up the ramp with a topographic slope of $\alpha \approx -1.0°$ (i.e., 1° northward).

The Salt Range overthrust appears to move as a fairly coherent block, cut only by numerous small faults. Compressional structures (mainly folds) appear common at the front of the range [Yeats et al., 1984] with high-angle (normal?) or strike-slip faults common in the central portion

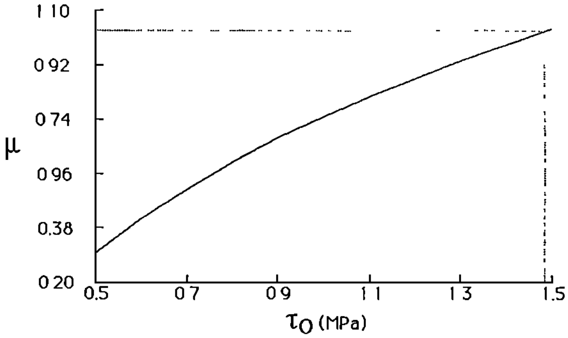

Fig. 9. Tradeoff curve between coefficient of internal friction and evaporite yield strength for the eastern Potwar Plateau. Best fitting parameters are μ = 1.03 and τ_0 = 1.48 MPa (dotted lines).

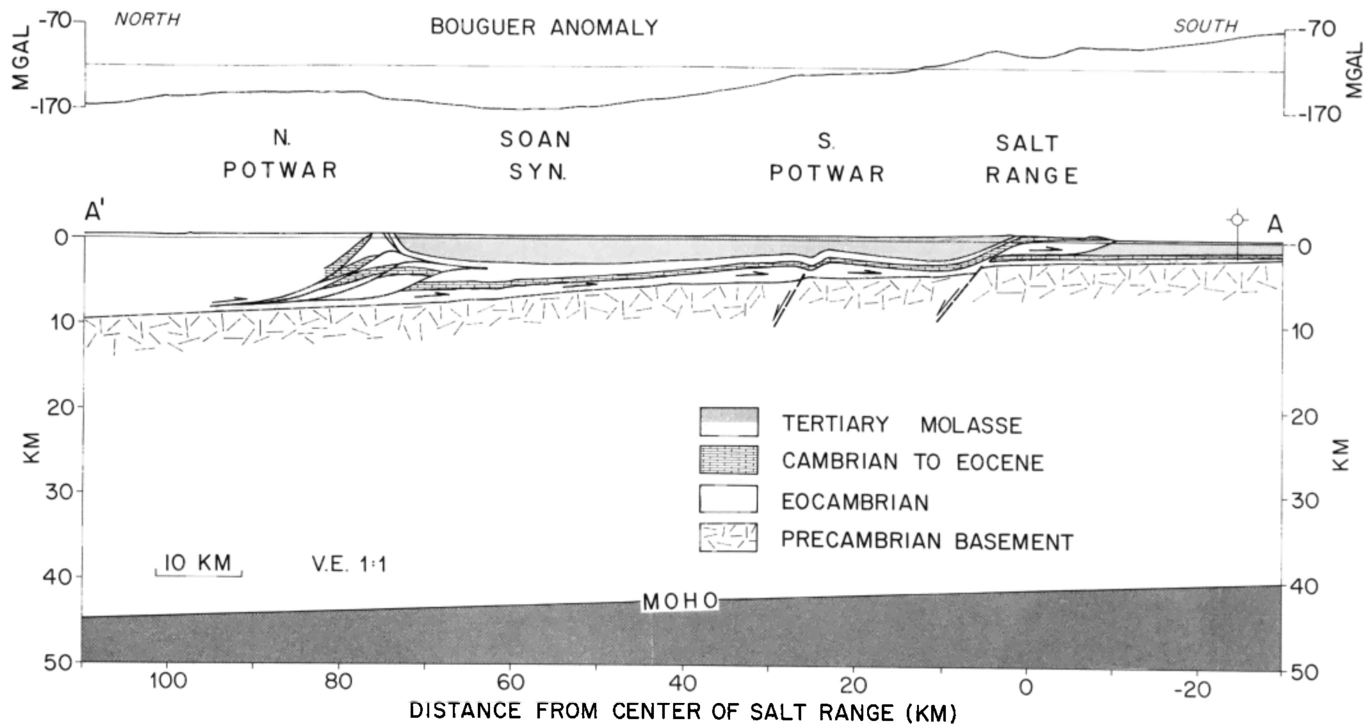

Fig. 10. Interpreted cross section A-A' across the central Salt Range–Potwar Plateau. From Baker [1987] and Lillie et al. [1987]. Gravity modeling by Duroy [1986] suggests that the south to north Bouguer gradient is due to the moho and the top of the basement dipping northward at about the same angle. Seismic profiles and the moderate Bouguer gradient suggest basement slopes (β) between 1° and 4°. The topographic slope (α) is essentially zero.

[Gee, 1980; Baker, 1987]. The level or precise orientation of the décollement underneath the Salt Range is not known; it may be that there is no single shear zone. In any case the frontal topographic slope of the Salt Range appears to be controlled mainly by erosion of the upper thrust plate rather than by compressional tectonics.

South of the Salt Range there is a small salt-cored anticline (Figure 10). Lillie et al. [1987] have interpreted that this anticline is underlain by a "sledrunner" thrust (i.e., a southward extension of the main décollement). This interpretation is supported by pressures in the Lilla-1 well. The molasse section overlying the Salt Range Formation is at normal (hydrostatic) pressure, but the pressure jumps to almost lithostatic below 1700 meters (within the Salt Range Formation, Figure 8), suggesting there may be compression at that level.

The southern Potwar Plateau (SPP) is remarkable in that although it has been pushed at least 20 km southward [Baker, 1987; Leathers, 1987], it has undergone almost no internal deformation. What deformation there is consists of broad, gently folded anticlines [Khan et al., 1986]. This is due both to the weak evaporite layer and to the increase in β (1.9°–3.6° in the central Potwar as opposed to 0.6° in the eastern Potwar). A test of this hypothesis is to solve (2) for the pore fluid pressure ratio within the wedge (λ) in the SPP. No pore fluid pressures are available in the SPP, but Khan et al. [1986] report alternating excessive and low formation pressures in the Tertiary molasse section and M. Yousuf (personal communication, 1985) reports that normal (hydrostatic) pressures are again encountered in the platform (Cambrian to Eocene) section. The alternating high and low fluid pressures are similar to those encountered in areas of high sedimentation, like the U. S. Gulf coast [Jones, 1969], and are unlike the consistently high pressures found in the fold-and-thrust belt of Taiwan [Suppe and Wittke, 1977; Davis et al., 1983]. This suggests that the average pore fluid pressure ratios in the SPP may be less than those encountered in the eastern Potwar Plateau.

Equation (2) was solved for λ at two points in the SPP, one just north of the basement normal fault (β = 1.9°, H = 3000 m) and the other at the axis of the Soan syncline (β = 3.6°, H = 6000 m). The topographic slope was taken as α = 0°, and the eastern Potwar Plateau values were taken for μ and ϕ. The pore fluid pressure ratios calculated for a thrust wedge at critical taper were $\lambda = 0.87$ and 0.97, respectively, both in excess of the eastern Potwar Plateau values. It is concluded here that the SPP is a supercritically tapered thrust wedge (i.e., $\alpha + \beta$ is larger than necessary and the wedge can be pushed forward without internal deformation).

The northern Potwar Plateau (NPP) is radically different in its structural style when compared to the SPP. It is complexly folded and faulted, with Miocene and older rocks exposed at the surface. It does share one feature in common with the SPP; the overall surface topography is flat (i.e., $\alpha \approx 0$). These two features suggest conflicting ideas as to the nature of the mechanics of the NPP. The intense deformation suggests stronger coupling at the décollement than is observed to the south. R. S. Yeats (personal communication, 1986) notes that there has been considerable uplift and erosion in the NPP. Yet the lack of a surface topographic slope might suggest that the NPP is underlain by salt, like the SPP.

By applying both (1) and (2) the best fitting model (salt or no salt) can be chosen for the NPP (e.g., Figure 5). A pore fluid pressure ratio for the NPP is available from Hubbert and Rubey [1959] for the Khaur well (Figure 7). They find that $\lambda = 0.93 \pm 0.01$, larger than the eastern Potwar Plateau values but slightly less than that calculated for the northern part of the SPP (see above). Given the value of λ from the Khaur well, (1) and (2) can be solved for the critical taper of the wedge, and the best fitting model matched to the observations.

In the non-salt case (equation (1)) parameters used are μ = 1.03, μ_b = 0.85, λ = 0.93, and β = 3.6°. The critical taper calculated in this case is $\alpha + \beta$ = 5.3°, predicting a topographic slope of α = 1.7°. Clearly the NPP has no such topographic slope. For the salt case, applying (2) and solving for the critical taper (using τ_0 = 1.48 MPa and H = 6000 m) gives $\alpha + \beta$ = 3.1°, predicting a topographic slope of α = –0.5° (i.e. 0.5° northward). The salt case is in much closer agreement with the observations, suggesting that the salt continues northward beneath the NPP. This conclusion is partially supported by a well in the NPP (Dhurnal, Figure 7) that reached salt within the Salt Range Formation in the core of an anticline just north of the Soan River.

The intense deformation in the NPP can be reconciled with the existence of salt at depth when considering the recent geologic history of the NPP. Paleomagnetic studies of the sedimentation history in the Salt Range–Potwar Plateau area [Johnson et al., 1986] show that the northern flank of the Soan Syncline was upturned about 2.1 Ma and deformation ceased by 1.9 Ma, as evidenced by the flat-lying Lei Conglomerate. Deformation then abruptly transferred to the Salt Range Thrust, along which Baker [1987] and Leathers [1987] calculate that there has been at least 20 km of southward movement relative to the basement complex. Because very little internal shortening has occurred within the intervening SPP, it is suggested that the NPP has also been translated at least 20 km across the original northern edge of the salt basin in the past 2.1–1.9 m.y. [Baker, 1987] (Figure 11). The intense deformation evident in the NPP was a result of its original development upon a décollement dominated by frictional sliding instead of salt, probably somewhere in the vicinity of the foot of the present Hill Ranges (i.e., MBT zone, Figure 2). The present lack of a surface topographic slope is due to the NPP being translated onto the salt-dominated décollement. Its original topographic slope (here estimated at 1.7°) was no longer necessary, and erosion has subsequently reduced the topography to its present level surface. The denudation rate necessary for the removal of the topography is estimated at 125 mg/cm^2/yr. This lies between the present denudation rate of Asia (33 mg/cm^2/yr [Garrels and Mackenzie, 1971]) and the denudation rate in the central mountains of Taiwan (1365 mg/cm^2/yr [Li, 1976]), the highest known in the world. It is the same order of magnitude as that of the Alpine Rhine region in Europe (133 mg/cm^2/yr [Li and Erni, 1974]), showing that the removal of the topographic slope in the NPP is physically plausible.

Western Salt Range-Potwar Plateau (C-C')

The western Salt Range–Potwar Plateau section (Figure 12) [Leathers, 1987] is similar to the central Salt Range–Potwar Plateau section (Figure 10). In almost all

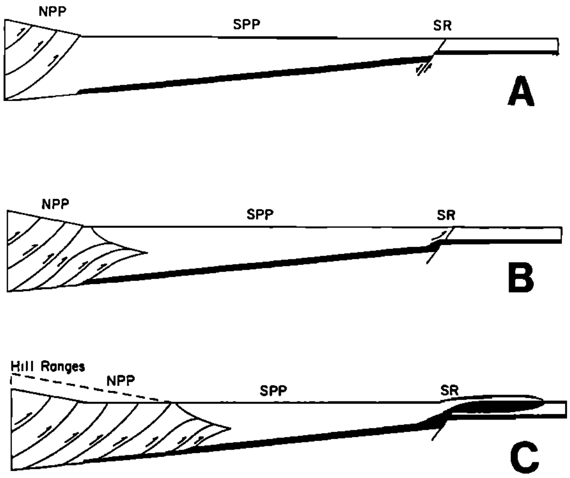

Fig. 11. Cartoon showing one explanation of the apparent paradox of the strong internal deformation and the low topographic slope in the northern Potwar Plateau (NPP). (a) Pre-2 Ma. The NPP is actively deforming as a fold-and-thrust belt and has not yet encountered evaporites of the Salt Range Formation (shown in black). Significant topographic slope is necessary to maintain critical taper. The normal fault beneath the future Salt Range (SR) also forms at this time. (b) 2 Ma. The deformation front reaches the northern edge of the salt basin and a "triangle zone" structure is formed. Uplift of the SR begins as the décollement extends southward within the Salt Range Formation. (c) Present. The northern Potwar Plateau has overridden the northern edge of the salt basin, and a large critical taper is no longer needed. Erosion has reduced the topography to its present nearly level surface. Shortening is being taken up at the Salt Range Front.

respects, the results of the mechanical studies from the central section can be applied equally well to the section in the west.

One of the few differences between the two sections is the lack of a large basement normal fault acting as a ramp for the Salt Range thrust in the west. Some sort of ramp exists, as evidenced by the westward continuation of the Salt Range, but the basement appears to be gently flexed rather than abruptly faulted [Leathers, 1987]. Examination of Bouguer anomalies [Farah et al., 1977] shows that part of the Sargodha basement high underthrusts the front of the Salt Range in the west; the gentle basement flexure on section C-C' is therefore the northeast flank of this high (Figure 2) [Leathers, 1987]. A seismic profile that crosses the Sargodha High near Mianwali shows basement and pre-Miocene strata truncated and unconformably overlain by younger strata. It is possible that the Salt Range Formation has been eroded away just south of the Salt Range in the western SR and the décollement is unable to continue southward.

As in the central area, the SPP in the west shows only minor internal deformation consisting of gentle folds. The dip of the underthrusting basement is $\beta = 3.4^\circ$ just north of the Salt Range ramp and $\beta = 2.2^\circ$ under the Soan Syncline. Solutions of (2) yield values of $\lambda = 0.91$ and 0.94, respectively, similar to the central SPP values. The interpretation is that the western SPP, like the central SPP, is an overtapered (supercritical) thrust wedge.

The interpreted basement slope under the western part of the NPP is considerably less than in the central NPP, only 1.3°. Using (1), the critical taper estimated for the no salt case is $\alpha + \beta = 3.6^\circ$, giving $\alpha = 2.3^\circ$. For the salt case, (2) gives $\alpha + \beta = 1.35^\circ$, implying a negligible α. This suggests that the western NPP is near its critical taper. Also, examination of seismic profiles in the northeast Potwar Plateau suggests $\beta = 1.2^\circ$. Thus, it appears that the entire NPP is a thrust wedge near its critical taper, suggesting that observed high pore fluid pressures are a result of continued tectonic compression.

CONCLUSIONS

The Salt Range–Potwar Plateau area of Pakistan provides a good test for the Davis and Engelder [1985] model, in that it is an active fold-and-thrust belt underlain by salt. The seismic reflection profiles, Bouguer gravity anomalies, and well data provided by the Government of Pakistan give the necessary constraints to allow an application of the model.

The model is successful in explaining most of the gross features of the Salt Range–Potwar Plateau. The differences in topography and surface structure across the Salt Range–Potwar Plateau are mainly due to the response of the fold-and-thrust belt to a weak evaporite layer at the base and to changes in the underlying basement surface. The deformation of the eastern Potwar Plateau represents an interaction of a shallow basement dip ($\beta < 1^\circ$) with drag along the eastern edge of the salt basin. The taper of the wedge, together with pore fluid pressure ratios from petroleum exploration wells, allows the estimation of values for the yield strength of the evaporites ($\tau = 1.48$ MPa) and the coefficient of internal friction ($\mu = 1.03$) of the overlying wedge. These values fall within expected ranges derived from other sources.

In the central and western Salt Range–Potwar Plateau the Sargodha High, a basement uplift in the Indian plate, interferes with the fold-and-thrust belt, causing the ramping of the décollement. Specifically, ramping is controlled by a basement normal fault in the central Salt Range and by a less abrupt, basement upwarp in the western Salt Range. The weak evaporite layer, together with the relative steepness of the ramp, allow the thrust wedge to override the ramp with only minor deformation. This coincides with the interpretation that the Salt Range remains a coherent slab [Baker, 1987; Leathers, 1987]. The Sargodha High also creates a steeper basement slope ($\beta \approx 2^\circ$ to 4°) beneath the central and western as compared to the eastern, Potwar Plateau. This relatively steep slope provides more than the necessary taper for the southern Potwar Plateau, allowing it to be pushed across the foreland without internal deformation.

The northern Potwar Plateau is a strongly deformed thrust wedge, yet it has essentially no topographic slope. This apparent contradiction is resolved when considering the timing of deformation. Based on paleomagnetic data [Johnson et al., 1986], the deformation in the northern Potwar Plateau stopped about 2 Ma. In this study it is proposed that the northern Potwar Plateau existed as a strongly tapered fold-and-thrust belt prior to 2 Ma; it has since overridden the north edge of

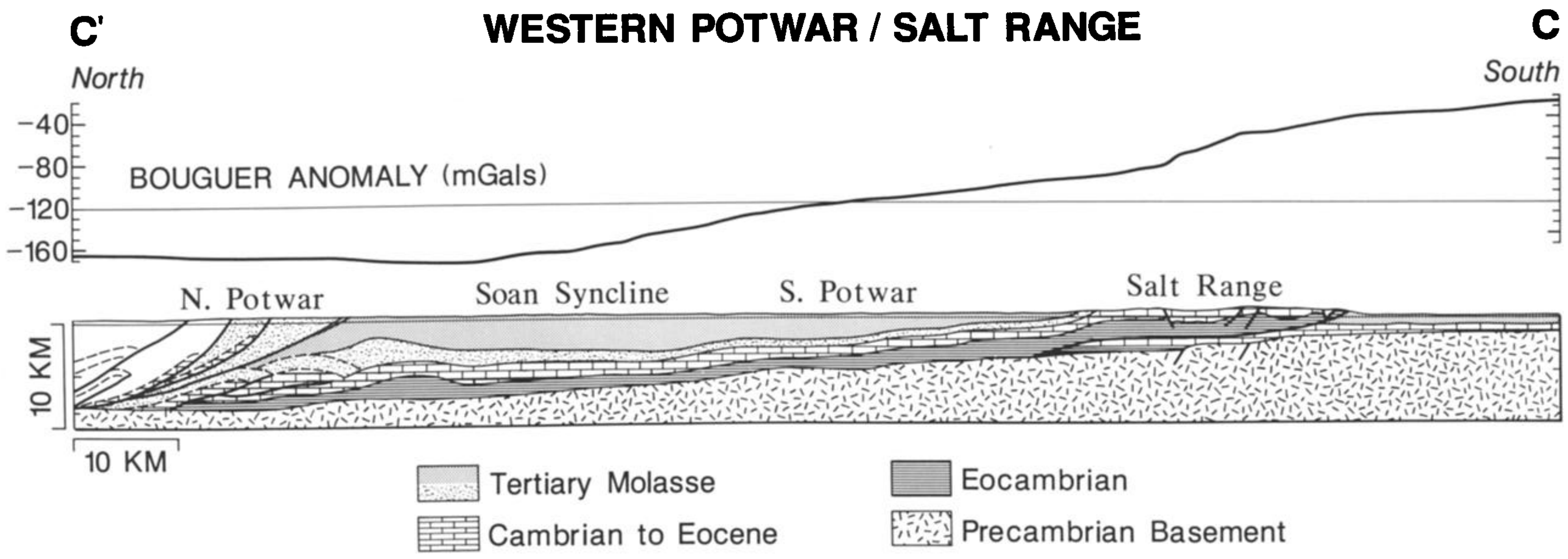

Fig. 12. Interpreted cross section C-C' across the western Salt Range–Potwar Plateau [after Leathers, 1987]. Seismic profiles and a steep Bouguer gravity gradient show northeast flank of the Sargodha basement high underthrusting the Salt Range and the southern Potwar Plateau. Except in the Salt Range, the topographic slope (α) is essentially zero.

the salt basin and erosion has removed its former topographic slope.

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S. C. Jaumé, Lamont Doherty Geological Observatory, Palisades, NY 10964.

R. J. Lillie, Department of Geology, Oregon State University, Corvallis, OR 97331.

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