The collision of the Indian subcontinent with Asia beginning 40 million years ago produced the Himalayan orogenic belt, the largest continental collision belt active today. The foreland fold-and-thrust belt in northern Pakistan consists of the Salt Range-Potwar Plateau area. 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 previous 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 (Davis et al., 1983; Dahlen et al., 1984; Dahlen, 1984), and a later model (Davis and Engelder, 1985) which suggests that fold-and-thrust belts underlain by salt will have: a) narrow (< 1°) cross-sectional tapers, b) larger widths than areas not underlain by salt, c) symmetrical structures, and d) changes in deformational style at the edge of the salt basin.

The section across the eastern Potwar Plateau most closely resembles this latter model, having: a) a taper of 0.8° ± 0.1°, b) a width of 100-150 km, c) thrust faults that verge both to the north and south, and d) 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...
(\tau_0) and the coefficient of internal friction (\mu) are calculated as \tau_0 = 1.33-1.50 \text{ 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, together with the weak evaporite layer, allows the thrust wedge of the southern Potwar Plateau to be pushed over the décollement without undergoing internal deformation. In detail, the Salt Range ramping is caused by a large normal fault in the basement in the central section and the basement upwarp of the Sargodha High in the western section.

The northern Potwar Plateau is strongly folded and faulted, yet the topographic slope remains flat. Although the deformation suggests that salt is not present there, the observed taper in the northern Potwar Plateau is best fitted by the model with salt 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 décollement encountered the Salt Range formation. Between 2 m.y.a. 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.

The success of the mechanical model in predicting the observed features in the Salt Range-Potwar Plateau suggests that salt may lie beneath other fold-and-thrust belts in Pakistan. Two areas, the Sulaiman Lobe and the Karachi Arc, are possible candidates. Although published subsurface information is lacking in these areas, surface observations show that they both: a) extend far across the foreland, b) exhibit low topographic slopes, c) display symmetrical structures, and d) show a change in structural orientation along what is believed to be the edge of the salt basin.
The Mechanics of the Salt Range-Potwar Plateau, Pakistan:
Qualitative and Quantitative Aspects of a Fold-and-Thrust Belt Underlain by Evaporites

by

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A THESIS
submitted to
Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed December 2, 1986
Commencement June 1987
APPROVAL:

Redacted for privacy

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Date thesis is presented December 2, 1986

Typed by Steven C. Jaumé
ACKNOWLEDGEMENTS

I first and foremost would like to thank my parents, Charles and Marilyn Jaumé, without whom none of this would have ever been possible. It was primarily their support and devotion that made me realize my capabilities, and the possibility that I could become something more than just another bump on a cypress log down in the bayous.

My thanks also go out to the chief instigator of this whole mess, my advisor Bob Lillie. It was his tremendous enthusiasm that first got me interested in this project and his guidance that has corralled my (near) intelligence into something productive. I would also like to thank him for showing me that it is possible for even a Tulane graduate to learn how to write, and that even a crazy Cajun can make an impact upon the world of science.

I also want to thank the many people of the faculty and staff of the College of Oceanography and the Department of Geology who have helped me in one way or another during my stay here at O. S. U. On this honor roll are my many instructors and friends among the faculty here: Bill Menke, Dallas Abbott, Randy Jacobson, Dale Bibee, Shaul Levi, Rob Holman, Dick Couch, Vern Kulm, Bob Duncan, Bob Yeats, Bob Lawrence, to name a few. I would also like to acknowledge some of my friends and helpers among the staff here: Deb Jacobson, Marcia Turnbull, Donna Moore, Anne-Marie Fagan, and Anne Poulson. Without the help of these people and many more like I would have never figured out what I was doing here in the first place.

Next come my many friends among the student body. What can I say? With all the wild, decadent parties, ski trips, hiking trips, strange games of D&D and Paranoia, volleyball games, softball games, and general all around weirdness they got me into, it's a wonder that I found the time to work on a thesis at all. There are a few notable personalities that stand out and must be recognized. First, Karen Clemens and her dog Ripple, for pulling me out my office in the afternoons for a hike, and Karen for pulling me out the office in the evenings to go to a movie. Without her I may have had to spend more time in my office (yuck!). I would also like to thank Suzy Leahy for the innumerable pep talks that kept me going when I thought I was about to lose it completely. A special mention goes out to my international cellmates (officemates) in OC-II 168; Michel Poujol, Haraldur Audunsson, and Pordur Arason, for making life very interesting. Also, my many other friends among the Geophysics grad students, Bruce, Fa, Marijke, Bob, Miguel, Osvaldo, Byrdis, and Pierre. A special thanks goes to my friends in both the Geology and Geophysics Departments who worked with me on
the Himalayan foreland project, who often were the first to endure the outburst of some of my wild ideas: Dan Baker, "Leathery" Mike Leathers, Ned(ly) Pennock, and Yannick Duroy.

This study is part of a cooperative project involving Oregon State University and the Geological Survey of Pakistan. I am grateful to the Government of Pakistan and the Oil and Gas Development Corporation of Pakistan for the release of the subsurface data used in this study. I am also grateful to TEXACO, Inc. for the Texaco Fellowship which provided much of my student support while here at Oregon State University. This work was supported by National Science Foundation grants INT-81-18403, INT-86-09914, EAR-83-18194, EAR-86-08224; by the Petroleum Research Fund of the American Chemical Society, grant PRF-17932-G2; and gifts from CONOCO, Inc. and CHEVRON International.
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THE MECHANICS OF THE SALT RANGE-POTWAR PLATEAU, PAKISTAN: QUANTITATIVE AND QUALITATIVE ASPECTS OF A FOLD-AND-THRUST BELT UNDERLAIN BY EVAPORITES

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. This study concentrates on one these fringing belts, the Salt Range-Potwar Plateau area of northern Pakistan (figure 1). 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 Pakistan and from recent quantitative modelling of the mechanics of fold-and-thrust belts by 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 (e.g. Baker, in prep.; Duroy, 1986; McDougall, in prep.; Leathers, in prep.; and Pennock, in prep.) with surface geology, borehole, and gravity data have resulted in cross sections that allow for testing and modification of the mechanical models.

In this study, the mechanics of the Salt Range-Potwar Plateau are examined in the context of the Davis and Engelder (1985) model for a fold-and-thrust belt developed upon an evaporite layer. Also, it is noted from the cross sections that one of the assumptions of the mechanical model, that the basement slope beneath a thrust wedge is linear, is not appropriate throughout this area. A generalization of the model to include a nonlinear basement surface is presented, and its effect on the surface topography of a thrust wedge is tested.

The observed wedge geometry and structure of the Salt Range-Potwar Plateau are found to be generally consistent with the Davis and Engelder (1985) model. It has the
Figure 1 - Tectonic regimes of Pakistan. Shaded area is the foreland fold-and-thrust belt. Note the sinuosity, changes in width, and changes in trend of the fold-and-thrust belts going from northeast to southwest. The lines A through H represent the locations of topographic cross sections in figures 15, 16, 18, and 20. After Kazmi and Rana (1982).
general characteristics of the model: a) a narrow taper, and b) 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: a) there is a lack of surface deformation in the central and western Potwar Plateau where the basement dip (β) is greater than 1°, b) surface deformation is observed in the eastern Potwar Plateau where β < 1°, c) the deformation style of the eastern Potwar Plateau consists of narrow, symmetrical anticlines, and thrusts that verge both north and south, and d) there is a change in the orientation of structural trends at the eastern edge of the salt basin. The seismic sections show that the Salt Range is the result of ramping along a basement normal fault. Although the effects of such features are not considered by Davis and Engelder (1985), their model can be used to show how the low strength evaporites allow the thrust wedge to be pushed over the ramp with very little internal deformation.

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 controls 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. Also, the generalization of the model for a curved basement is seen as a possible way of merging the results of plate flexure models derived from gravity data with mechanical models of thrust belts.
TECTONIC SETTING

From south to north, four major tectonic elements can be defined for the foreland deformation belt of northern Pakistan (figure 2). They are as follows: a) the Jhelum plain, b) the Salt Range and Trans-Indus Salt Range, c) the Potwar-Kohat Plateaus and the Bannu Basin, and d) the Main Boundary Thrust bounding the plateaus to the north (Yeats and Lawrence, 1984). Although this thesis is primarily concerned with the Salt Range-Potwar Plateau area, it is important to briefly examine all these features to enhance the basic understanding of the tectonics of the region.

A prominent element in the Jhelum plain is the Sargodha High, a basement ridge that trends obliquely to the Salt Range, but parallel to the overall Himalayan trend. Its trend is defined both by exposed basement rocks of the Kirana Hills and by a series of positive gravity anomalies that extend from the foot of the Trans-Indus Salt Range (Khisor Range) to at least the Pakistan-India border (Farah et al., 1977). There are three basic interpretations for the Sargodha High: 1) it is caused by flexure due to the Tertiary underthrusting of the Indian plate beneath Eurasia, similar to an outer trench swell in oceanic settings (Yeats and Lawrence, 1984), 2) it is an older basement feature similar to the Aravalli Range of India (Farah et al. 1977), and 3) it is an expression of a recently activated intracontinental thrust (Lefort, 1975). Seeber et al. (1981) have shown that the Sargodha High is seismically active, which supports the hypothesis that it is a young feature associated with continental collision, but observed strike-slip focal mechanisms leave unanswered the question of its origin (see Duroy, 1986).

The Salt Range and Trans-Indus Salt Range are the southernmost expression of thrusting in northern Pakistan. They are anomalous in that they bring pre-Tertiary rocks to the surface at the foreland edge of the thrust belt (the Eocambrian Salt Range Formation in the Salt Range, Gee, 1980; Permian rocks in the Surghar Range, Meissner et al., 1974; and the Cambrian Jhelum Group in the Khisor Range, Hemphill and Kidwai, 1973). This contrasts sharply with the foreland fold-and-thrust belt in India, where only Tertiary molasse sediments (Siwalik and Rawalpindi Groups) are exposed.

The central Potwar Plateau can be split into two regions: a) the asymmetric Soan Syncline occupying the southern part of the Potwar Plateau, and b) a more deformed zone to the north. The Soan Syncline has a very gentle southern limb, but the northern limb is turned up sharply where it meets the first fault of the northern Potwar. In the northern Potwar Plateau, Tertiary and older rocks are deformed as a classic fold-and-
Figure 2 - Generalized tectonic map of northern Pakistan. A-A', B-B', and C-C' are locations of cross sections interpreted by Baker (in prep.), Pennock (in prep.), and Leathers (in prep.), respectively. F-F' is the line of section for the flexure model discussed in Duroy (1986). K.F.-Kalabugh Fault, M.B.T.-Main Boundary Thrust. After Kazmi and Rana (1982).
thrust belt, but even with this more intense deformation the overall topography is as flat as the less-deformed southern half of the plateau.

West of the Indus River the Kohat Plateau and Bannu Basin correspond structurally to the northern and southern Potwar Plateau, respectively. The topography of the Bannu Basin is flat; there is no apparent deformation at the surface and only gentle folding is observed in the subsurface (Khan et al., 1986). Although the Kohat Plateau is as deformed as the northern Potwar Plateau, a major difference is that there is significant topographic relief in the Kohat Plateau. This difference is at least in part due to the presence in the Kohat Plateau of Eocene evaporites and shales that form an upper level of detachment and commonly form the cores of anticlines. The rocks in the Kohat Plateau are strongly folded and faulted, and the topographic relief suggests that the deformation is recent and may still be occurring.

The Hill Ranges rise sharply along the north side of the Potwar and Kohat Plateaus. Along the southern edge of these ranges, thrust faults bring deformed Tertiary, Cretaceous, Jurassic and Triassic rocks to the surface. In the northern part of the ranges Paleozoic and Precambrian rocks are exposed. The thrusts of the Hill Ranges have been correlated with the Main Boundary Thrust (MBT) in the Himalaya, (Yeats and Lawrence, 1984). It has been suggested by R. D. Lawrence (pers. comm., 1986) that the Hill Ranges are the surface expression of a basement ramp.

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 south of the Salt Range, consisting of metamorphic and volcanic rocks of the Indian shield (Yeats and Lawrence, 1984). Although offset by normal faults associated with flexure (Lillie and Yousuf, 1986; Duroy, 1986), the basement beneath the Salt Range and Potwar Plateau is apparently not involved in thrusting. The Eocambrian Salt Range Formation is an evaporitic and sedimentary unit that includes 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., in press, 1986). 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.

The timing of deformation is constrained by paleomagnetic and fission-track dating information collected in the eastern and central Potwar Plateau (Johnson et al., in press, 1986). These data record rotation and deformation in the southern Potwar Plateau 4.5-3.0 m.y.a. In the eastern Potwar Plateau, deformation concurrent with counterclockwise rotation started 3.4 m.y.a. on the northern flank of the Soan Syncline. This deformation progressed southeastward across the eastern Potwar Plateau to the Kharian (Pabbi Hills) anticline, which developed surface expression less than 0.4 m.y.a. In the central Potwar Plateau the data record the uplift of the northern flank of the Soan Syncline at 2.1-1.9 MyrBP. Based on the timing information from the eastern Potwar Plateau, Johnson et al. (in press, 1986) date the ramping of the Salt Range as occurring between 2.2-1.5 MyrBP.

Three cross sections are being constructed, one each in the western (Leathers, in prep.), central (Baker, in prep.), and eastern (Pennock, in prep.) Salt Range-Potwar Plateau. These interpretations, especially the shape of the décollement surface, the variation in thickness of the Salt Range Formation, and the change in thickness of the overlying wedge, provide important parameters used in this mechanical modeling study. Bouguer gravity anomaly data provide further constraints on the dip and shape of the basement surface (Duroy, 1986).
MECHANICS OF FOLD-AND-THRUST BELTS

Early work in mechanics of fold-and-thrust belts

Large overtrusts were first recognized in Europe during the early 1800's and were soon proven to have displacements of tens to hundreds of kilometers. The existence of large, nearly undeformed thrust blocks that have moved great distances proved to be a mechanical paradox. Smoluchowski (1909) pointed out that a rectangular block of granite requires a force exceeding its crushing strength to overcome friction at its base and move over a horizontal plane; he therefore suggested that the bottom of a thrust block may be weaker than the rest of the block, or that it may have been on an inclined plane at the time of movement.

The problem of overcoming friction at the base of a thrust block without exceeding the crushing strength of the rock led to the suggestion that a body force, gravity, was responsible for the movement of thrust blocks. This led to the development of two theories, gravity sliding and gravity spreading, in an attempt to solve the mechanical problem posed by overthrusting. The theory of gravity sliding proposes that the thrust sheet slides down a foreland-dipping regional slope under the influence of gravity (Smoluchowski, 1909). Gravity spreading proposes that some type of orogenic uplift was created, and that a fold-and-thrust belt forms when this mass collapsed due to its own weight and spread out in a visco-elastic manner (Bucher, 1956; 1962). Both of these theories require some sort of pre-existing orogenic uplift to supply a topographic gradient.

A problem with the gravity sliding hypothesis is that it is still necessary to overcome the sliding friction along the base of the thrust block. Hubbert and Rubey (1959) in their classic paper considered this problem and suggested that abnormal pore fluid pressures could act to reduce the friction along the base of the thrust block. In their paper they considered a rectangular two-dimensional thrust block having the Mohr-Coulomb failure criteria

\[ \tau = S_0 + \sigma_n \tan \phi \]  

where \( \tau \) is the shear stress at the base of the block, \( S_0 \) is the cohesive strength of the rock, \( \sigma_n \) is the normal stress, \( \phi \) is the angle of internal friction (related to the coefficient
of internal friction, \( \mu \), by \( \mu = \tan \phi \). Hubbert and Rubey (1959) considered a case where a fracture already existed at the base of the block and the basal cohesion is \( S_0 = 0 \). They showed that in the presence of pore fluid pressure in the rock that the normal stress across a plane is

\[
\sigma = (\sigma_n - p_f)
\]

(2)

where \( \sigma_n \) is the lithostatic pressure and \( p_f \) is the pore fluid pressure, i.e., that pore fluid pressure reduces the normal stress across the plane. They introduce a dimensionless number, \( \lambda \), as the ratio of the pore fluid pressure to the lithostatic pressure

\[
\lambda = \frac{p_f}{\sigma_n}.
\]

(3)

With this the Mohr-Coulomb failure criteria can be rewritten as

\[
\tau = (1 - \lambda) \sigma_n \tan \phi.
\]

(4)

From (4) an equation for the maximum length of an overthrust block of a given thickness along a horizontal plane can be derived. In the presence of a highly overpressured basal surface (\( \lambda = 0.90 \)) and a block over 5 km thick, overthrust lengths over 100 km were predicted (see Table I in Hubbert and Rubey, 1959).

The main interest of Hubbert and Rubey (1959) was to determine if gravity sliding is possible in the presence of high pore fluid pressures; they did not present a detailed examination of horizontal compression. The bulk of their paper is concerned with proving the feasibility of gravity sliding.

Hsü (1969) studied the same case as Hubbert and Rubey (1959) except that he considered the cohesive strength of the rock, \( S_0 \), to be non-negligible in a moving thrust sheet. He derived an equation for the maximum length of a thrust block moving down a slope, similar to that of Hubbert and Rubey (1959), but with a cohesive strength of 20 MPa along the base (Handin et al., 1963). Hsü (1969) found that very long (>100 km) thrusts are not possible without a push from the rear. He concluded that thrust blocks cannot glide downslope due only to the influence of gravity, except when the cohesive strength of the décollement is very low.

Forristal (1972) made a re-evaluation of the maximum length of an overthrust
block using elasticity theory to determine the state of stress within the thrust block. He suggested that the maximum length of the thrust block can only be one half of that calculated by Hubbert and Rubey (1959) and Hsu (1969), due to stress concentrations that will cause rupture of the block.

Kehle (1970) used a different approach to the problem by considering viscous flow of a weak zone (décollement) between two higher viscosity layers. Kehle (1970) notes that many decollements are in evaporites, thin shales, and limestones where pore fluid pressures would be unimportant. The movement of the thrust block in this model is due to deformation of the lowest viscosity zone and there is no deformation in the overlying block as long as its viscosity is one or more orders of magnitude larger than the low viscosity zone.

The main objections to the idea of gravity sliding were from field workers (e.g. Price and Mountjoy, 1970), based upon observations of the geology of thrust belts. These workers noted the lack of a basement slope dipping towards the foreland and the lack of the predicted "tectonic gap" where the block broke from the main mountain mass. In fact, it was often found that the detachment along which the thrust sheet moved dips towards the hinterland and not the foreland, and that the thrust sheets formed a fairly continuous mass without any breaks. This led some workers to revive the gravity spreading hypothesis (Price, 1971), but without quantitative evaluation.

Elliot (1976) considered the driving force of thrust sheets to be the topographic slope of the sheet itself (this is similar to the gravity spreading hypothesis). He avoided the need for a foreland dipping basement slope by saying the fold-and-thrust belt should move in the direction of the topographic surface slope, $\alpha$, regardless of the basement slope. An important assumption of this model is a pre-existing topographic slope. His equation for the shear stress caused by the topographic slope is

$$\tau = \rho g H \alpha$$

(5)

where $\tau$ is the shear stress, $\rho$ is the density of the wedge, $g$ is the acceleration of gravity, $H$ is the thickness of the thrust sheet, and $\alpha$ is the topographic slope. He related the influence of horizontal vs. gravitational tectonic forces by the magnitude of a dimensionless number $k$ defined by

$$\left(\frac{\tau_m}{\rho g H \cos \alpha}\right)^2 = \left(\frac{k}{2}\right) + \left[\tan \alpha + k \left(\frac{H}{L}\right)\right]^2$$

(6)
where \( \tau_m \) is the strength of the wedge (taken to be 20 MPa) and \( L \) is the length of the thrust sheet. He found that \( k \) is far less than 1 for thrust belts, and concludes that gravitational forces dominate in the movement of thrust sheets.

Recent work in mechanics of fold-and-thrust belts

Chapple (1978) recognized that fold-and-thrust belts share several features in common, including: a) a characteristic wedge shape, b) a surface of detachment below which there is no deformation, and c) a large amount of horizontal compression above this level, especially at the back of the wedge. He proposed a model in which both the thrust wedge and a weaker basal layer are considered to be perfectly plastic materials yielding in compressive flow. One 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 surface topography is the result and not the cause of the deformation. This conclusion regarding the surface topography is opposite to the result obtained by Elliot (1976). Chapple (1978) suggests that a weak basal layer is a necessary factor in the development of a fold-and-thrust belt. His relationship between the strength of the basal layer and the overlying wedge is

\[
\tau = \chi \kappa
\]

where \( \tau \) is the basal shear strength, \( \kappa \) is the strength of the overlying wedge, and \( \chi \) is the ratio of the two strengths. Chapple (1978) states that it is this strength ratio that determines the taper of the wedge.

Stockmal (1983) also used perfectly plastic rheology in a study of accretionary wedge mechanics. He chose a model in which he assumed a range of yield strengths for the accretionary wedge and then solved for the basal properties. From the observed wedge geometry, uplift rates, and rates of tilting he calculated the instantaneous stress and velocity fields of the Sunda accretionary wedge. Like Chapple (1978) he found that a weak basal layer is required by the wedge geometry. He noted that variations in topography and uplift rates indicate variations in basal shear stress.

One problem with models that assume a plastic rheology to describe the mechanics of fold-and-thrust belts and accretionary wedges is that the magnitude of the wedge yield
strength is not well constrained, as noted by Stockmal (1983). Another problem is that the observed deformation style in fold-and-thrust belts is usually brittle-elastic, i.e. deformation by thrusting and folding. Plastic flow generally does not occur in rocks above the typical brittle-ductile transition (10-15 km for continental crust), with the exception of such rocks as evaporites and possibly some shales. The Mohr-Coulomb failure criteria may therefore be a better method of describing the mechanics of most fold-and-thrust belts.

Davis et al. (1983) proposed a model in which fold-and-thrust belts are considered to be analogous to wedges of soil or snow pushed in front of a moving bulldozer (figure 3). Like Hubbert and Rubey (1959), the model was based upon the wedge deforming according to the Coulomb failure criteria (1). Davis et al. (1983) find that such wedges deform internally until reaching a critical taper, and then slide forward stably. Following Hubert and Rubey (1959), Davis et al. (1983) considered a thrust wedge where the cohesion was considered to be negligible. They developed an analytical model relating the critical taper of fold-and-thrust belts and accretionary wedges to the friction at the base of the wedge, the pore fluid pressure ratio, the slope of the basement surface, and the coefficient of internal friction within the wedge. This model can be stated for a fold-and-thrust belt as follows:

\[
\frac{\beta + (1 - \lambda_b) \mu_b}{\alpha + \beta} = \frac{1 + (1 - \lambda) K}{1 + (1 - \lambda) K}
\]

where \( \alpha \) is the forward topographic slope of the wedge, \( \beta \) is the backward slope of the basement, \( \lambda \) and \( \lambda_b \) are the Hubbert and Rubey (1959) pore fluid pressure ratios within and at the base of the wedge, \( \mu_b \) is the coefficient of friction at the base of the wedge, and \( K \) is a dimensionless quantity related to the direction of maximum compression and dependent upon \( \mu_b \) and \( \mu \) (coefficient of internal friction). An analytical approximation for \( K \) given by Davis et al. (1983) is

\[
K = \frac{\sin \phi}{1 - \sin \phi} + \frac{\sin^2 \phi_b + \cos \phi_b (\sin^2 \phi - \sin^2 \phi_b)^{1/2}}{\cos^2 \phi_b - \cos \phi_b (\sin^2 \phi - \sin^2 \phi_b)^{1/2}}
\]
Figure 3 - Davis et al. (1983) model for the mechanics of accretionary wedges and foreland fold-and-thrust belts. The mechanics of a fold-and-thrust belt is considered to be analogous to that of a wedge of snow or soil pushed in front of a bulldozer. Symbols defined in text.
where $\phi$ is the angle of internal friction within the wedge and $\phi_b$ is the corresponding term for the basal friction ($\mu_b = \tan \phi_b$). 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.

This model was then applied to the active fold-and-thrust belt in Taiwan where parameters such as pore fluid pressure ratios ($\lambda = 0.675$), basement dip ($\beta = 6^\circ$), and topographic slope ($\alpha \approx 2.9^\circ$) are known. For the basal friction of the wedge Davis et al. (1983) used Byerlee's "law" (Byerlee, 1978), $\mu_b = 0.85$, which describes the sliding friction of many types of crustal rocks above the brittle-ductile transition. With this they were able to compute a best fitting value for the coefficient of internal friction of $\mu = 1.03$, about 20% larger than the assumed laboratory value for the base (Davis et al., 1983). They interpret this to mean that the wedge is not so internally fractured that slip planes of all possible orientations exist, and that fracturing and slip along suboptimally oriented surfaces must occur for deformation to proceed. They also conclude that no extraordinary properties, such as very weak basal layers or extremely high basal pore fluid pressures, are necessary for the formation of fold-and-thrust belts. Davis et al. (1983) applied this model to other active thrust belts and accretionary wedges using the rock properties $\mu_b = 0.85$ and $\mu = 1.03$ and the observed topographic (or bathymetric) and basement slopes to predict pore fluid pressure ratios. The agreement with available fluid pressure data was found to be good, suggesting that this model has a general application.

Dahlen (1984) took the theory of noncohesive Coulomb wedges and found an exact relation between the critical taper $\alpha + \beta$ and the parameters $\mu$, $\mu_b$, $\lambda$, and $\lambda_b$. This is written as

$$\alpha + \beta = \psi_b - \psi_o$$

(10)

with

$$\psi_b = 1/2 \arcsin (\sin \phi_b' / \sin \phi) - 1/2 \phi_b'$$

(11)

$$\psi_o = 1/2 \arcsin (\sin \alpha' / \sin \phi) - 1/2 \alpha'$$

(12)
\[ \alpha' = \arctan \left[ \frac{1}{1 - \lambda} \tan \alpha \right] \quad (13) \]

and

\[ \mu'_b = \mu_b \left[ \frac{1 - \lambda_b}{1 - \lambda} \right]. \quad (14) \]

With this more exact theory Dahien (1984) recalculated the best fitting value for the internal coefficient of friction for the Taiwan fold-and-thrust belt and found \( \mu = 1.10 \), about 6\% larger than that calculated by Davis et al. (1983). Dahlen (1984) stated that this is not unreasonable in view of the approximate theory used by Davis et al. (1983).

Dahlen et al. (1984) also considered the same model but with the effects of cohesion taken into account, similar to the work of Hsu (1969) on the model of Hubbert and Rubey (1959). For this analysis they redefined the geometry of the wedge in cylindrical coordinates as opposed to the Cartesian coordinates used in Davis et al. (1983). The model with the effects of finite cohesion is as follows:

\[ \beta + (1 - \lambda_b) \mu_b - Q \left( \frac{S_0}{\rho g r} \right) \cot \phi \]

\[ \alpha + \beta = \frac{\beta + (1 - \lambda_b) \mu_b - Q \left( \frac{S_0}{\rho g r} \right) \cot \phi}{1 + (1 - \lambda) K} \quad (15) \]

where \( S_0 \) is the cohesion, \( \rho \) is the density of the wedge, \( g \) is the acceleration of gravity, \( r \) is the radial distance from the front of the wedge, \( \phi \) is the angle of internal friction, \( Q \) is a constant defined similar to \( K \), and all of the other variables are the same as in (8). Dahlen et al. (1984) find that \( K \) and \( Q \) can be approximated for the case of a very weak basal layer by

\[ K = Q = 2 / (\csc \phi - 1). \quad (16) \]

It was found by Dahlen et al. (1984) that the effect of cohesion is to decrease the critical taper in the vicinity of the wedge toe, and that the critical taper asymptotically approaches the noncohesive value far from the toe, giving the topographic surface a concave upward shape. Following Davis et al. (1983), this model was applied to the active fold-and-thrust belt of western Taiwan. The best fitting values for the wedge
cohesion and the coefficient of internal friction for western Taiwan were $S_o = 5-20$ MPa and $\mu = 0.9-1.0$. Similar to the results of Davis et al. (1983), no extreme rock properties were necessary to produce the observed thrust wedge.

Evaporites, especially rock salt, are considerably weaker than other rock types. At depths typical of basal detachments (2-10 km), salt is in the ductile regime and cannot be accurately modelled by the Coulomb criteria (1). Work by Carter and Hansen (1983) show that rock salt deforms at shear stresses between 0.5 MPa and 1.5 MPa. Davis and Engelder (1985) find it more appropriate to write

$$\tau = \tau_o \leq 1 \text{ MPa}$$

(17)

as the failure law for an evaporite basal layer in a fold-and-thrust belt instead of the Mohr-Coulomb law. This makes the strength of rock salt at depths typical of basal detachments one to two orders of magnitude less than that of most other rocks. Davis and Engelder (1985) developed a model for the formation of fold-and-thrust belts that are developed on top of salt-dominated detachments (figure 4). This model is mathematically stated as:

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

(18)

where $\tau_o$ is the yield stress along the basal detachment, $\phi = \tan^{-1}\mu$ is the angle of internal friction, $\rho$ is the average rock 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 (8) and (15). At yield stresses appropriate for rock salt (~1 MPa) this means that essentially no taper (~1°) is required for the wedge to be pushed over the foreland. A thrust belt with salt at its base can therefore be pushed forward without internal deformation if the basement dip is greater than $= 1^\circ$.

The model proposed by Davis and Engelder (1985) has several important implications (figure 4). Fold-and-thrust belts developed upon a basal salt layer should be narrowly tapered and occur over a very wide belt. As the salt thins at the edges of the basin, the greater shear traction should lead to the development of drag-related features. The strength of the décollement also controls $\phi_b$, the angle at which the axis of maximum
Figure 4 - A fold-and-thrust belt underlain by salt vs. non-salt substrate. The thrust belt underlain by salt has a narrower cross sectional taper, a wider deformational belt, and has nearly symmetrical structures developed in it than the non-salt thrust belt. After Davis and Engelder (1985).
compressive stress dips toward the foreland with respect to the basal dip. In the presence
of salt, $\phi_b$ is only about 1°, leading to slip planes (i.e. forward and back thrusts) having
nearly equal dips. This stress orientation leads to the development of symmetrical
structures above the salt layer. The mobility of salt allows it to flow into salt-cored
anticlines that may continue to grow, due to gravitational instability caused by the salt
having a lower density than the overlying sediments.

Another development in the mechanics of fold-and-thrust belts was a study by
Wiltschko and Eastman (1983; in press, 1986) on the effect of basement warps and
faults in localizing thrust ramps. They used a two-dimensional photoelastic model to
look at stress concentrations in the material above a décollement in the presence of
basement warps and faults. Wiltschko and Eastman (1983; in press, 1986) found that the
basement structures act to concentrate stress in the section above, and thus facilitate
failure. Analysis of the stress field predicts natural-looking fault orientations. This work
showed that the positioning of faults in a fold-and-thrust belt may not be haphazard, but
may be controlled by inhomogeneities in the underlying basement.

A problem with the theory developed by Davis et al. (1983), Dahlen et al. (1984),
and Davis and Engelder (1985) is that they used an idealized thrust wedge cross section
that assumes a linear basement slope. Observations of structures within the basement
beneath the décollement show that this is often not the case (e.g. Lillie and Yousuf,
1986). It has been found that the loading of a lithospheric plate by thrust sheets causes
the plate to be flexed downward, resulting in a convex upward basement surface (Karner
and Watts, 1983). In the next section, an attempt will be made to generalize the model
for the case where the surface of the underthrusting plate is curved.

New work in mechanics of fold-and-thrust belts

Davis et al. (1983) show that there is a linear relationship between the basement
and topographic slopes of fold-and-thrust belts that can be expressed in the form:

$$\alpha + R\beta = F$$  \hspace{1cm} (19)

This applies to any of the equations for the taper of a fold-and-thrust belt developed by
Davis et al. (1983), Dahlen et al. (1984), and Davis and Engelder (1985). In their
models they considered only the case where the basement surface was defined by a uniformly dipping slope.

Equation (19) can be important when one considers the response of a lithospheric plate to either loading by thrust sheets (Karner and Watts, 1983) or subduction beneath another plate. It has been found that the lithosphere behaves very much like a thin elastic plate overlying an inviscid fluid (Walcott, 1970). Thus the curvature of a plate in a convergent setting can be defined by using elastic plate theory. If the basement underneath a fold-and-thrust belt is curved according to elastic theory, it may be possible to use this curvature in the mechanical models of thrusting, instead of a linear approximation of the basement slope.

Due to the linear relationship between the basement and topographic slopes, a basement topographic surface defined by a curve can be used in place of a linear slope, as long as a local basement slope can be defined. Consider a basement surface defined by a continuous function \( f(x) \). The slope of this function can be found at any \( x \) by taking the derivative of the function \( f(x) \). The angle of the slope is:

\[
\beta(x) = \arctan \left[ f'(x) \right].
\] (20)

In the presence of a curved basement surface underlying a fold-and-thrust belt, a continuous function for the topographic slope can be defined as:

\[
\alpha(x) = F - R\beta(x)
\] (21)

The value of \( \alpha(x) \) can then be found either analytically or numerically.

To test the applicability of this equation to the analysis of fold-and-thrust belts, three computer models were generated by the author, using the critical taper equations of 1) Davis et al. (1983) for a noncohesive Coulomb wedge; 2) Dahlen et al. (1984) for a cohesive Coulomb wedge; and 3) Davis and Engelder (1985) for a noncohesive Coulomb wedge underlain by evaporites. A simple basement slope function, \( \beta(x) = 1.0^\circ + 0.2^\circ x, x = 0 - 150 \text{ km} \), was used, giving a change of basement slope from \( 1^\circ \) at 0 km to \( 4^\circ \) at 150 km. This approximates the basement curvature seen across the central Salt Range-Potwar Plateau area (Baker, in prep.; Duroy, 1986; Jaume' et al., 1985).

Model 1 was computed by modifying the critical taper equation of Davis et al. (1983). Following Davis et al. (1983), \( \mu \) and \( \mu_b \) were chosen as 1.03 and 0.85.
respectively. \( \lambda = \lambda_b \) was arbitrarily chosen as 0.90. The resulting topography shows an upward convexity similar to, but not as prominent as that of the basement (figure 5). Subsequent modeling showed that the curvature of the topographic surface can be increased not only by increasing the basement curvature, but also by decreasing \( \lambda \).

Model 2 was calculated by modifying the critical taper equation of Dahlen et al. (1984). Following Dahlen et al. (1984), \( \mu \) was chosen as 0.95, with \( \beta(x) \), \( \mu_b \), \( \lambda \), and \( \lambda_b \) being the same as in Model 1. A value of 10 MPa was chosen for the cohesion \( (S_0) \). The shape of the resulting wedge is essentially the same as that predicted by Dahlen et al. (1984) (figure 6). The frontal portion of the wedge is concave upwards and the slope approaches a constant value. The topographic slope of Model 2 equals that of Model 1 (to within 0.1°) between \( x = 128 \) km and \( x = 150 \) km.

Model 3 was created using the critical taper equation of Davis and Engelder (1985), modified for a curved basement surface. Following Davis and Engelder (1985), \( \tau_0 \) was chosen as 1MPa, with the remaining parameters being the same as in Model 1. The results show a small positive topographic slope for the first 33 km of the wedge (figure 7). Beyond \( x = 35 \) km the wedge becomes supercritically tapered (i.e., the wedge taper is larger than the critical taper).

Visually, the results of these simple models suggest that a curved décollement surface has the most influence on a noncohesive critical Coulomb wedge (Model 1, figure 5). But numerically, the largest change in \( \alpha \) occurs in the first 30 km of Model 3. This change is 0.015°/km in Model 3; in Model 1 it is only 0.006°/km. In all three models the critical taper of the thrust wedge increases as the basement slope increases. As long as the internal strength of the wedge is greater than that of the décollement, the critical taper will increase more slowly than the basement slope. It is the difference in strength between the décollement and the thrust wedge that controls the magnitude of this change. The larger the strength difference between the décollement and the wedge, the smaller the change in the critical taper, and therefore the larger the change in topographic slope. The largest strength difference occurs when salt is present at the décollement, and therefore the largest changes in topographic slope.

A complete review of the effects of a curved basement surface and its application to several fold-and-thrust belts is beyond the scope of this study. As shown in the next section, application to the mechanical study of the Salt Range-Potwar Plateau is somewhat limited. The refined modeling does appear to explain the general topographic characteristics of the area; deformation at the front of the fold-and-thrust belt (the Salt
Figure 5 - Model 1 of a non-cohesive Coulomb wedge on top of a curved basement surface. Model derived using the modified critical taper equation of Davis et al. (1983) to account for the curved basement.
Figure 6 - Model 2 of a cohesive Coulomb wedge on top of a curved basement surface. Model derived using the modified critical taper equation of Dahlen et al. (1984).
Figure 7 - Model 3 of a non-cohesive Coulomb wedge underlain by a layer of salt developed on top of a curved basement surface. Model derived using the modified critical taper equation of Davis and Engelder (1985). Note that the topographic slope is low at the front of the wedge and that it becomes level as the basement dip steepens and the thickness of the wedge increases.
Range) and no deformation deeper into the belt (the southern Potwar Plateau). But in detail, the Salt Range is observed to be due to smaller scale obstructions in the basement that the thrust plate has overridden (i.e. basement offset along a normal fault). In the eastern Potwar Plateau there is more potential for an application of this idea. There is a topographic slope similar to that of Model 3 in the frontal 100 km of the fold belt, and then the topography becomes level again. Unfortunately the available seismic coverage is not extensive enough to see significant curvature of the basement surface.
MECHANICS OF THE SALT RANGE-POTWAR PLATEAU: PAKISTAN

The mechanics of the Salt Range-Potwar Plateau was studied along three cross sections interpreted from seismic reflection profiles, surface geology, and well data. These interpreted sections are from Baker (in prep.) and Lillie et al. (in press, 1986) for the central Salt Range-Potwar Plateau (A-A'), Leathers (in prep.) and Pennock (in prep.) for the eastern Potwar Plateau (B-B'), and Leathers (in prep.) for the western Salt Range-Potwar Plateau (C-C'). The observed taper of the thrust belt, its structure, and pore fluid pressure ratios are examined in the light of the mechanical models of Davis et al. (1983), Dahlen et al. (1984), and Davis and Engelder (1985).

Eastern Potwar Plateau (B-B')

The frontal (southernmost) 100 km of the eastern Potwar Plateau fold belt (figure 8) most closely resembles the salt décollement model of Davis and Engelder (1985). The thrust wedge has a narrow cross sectional taper ($\alpha + \beta < 1^\circ$), and internally there is no consistent direction of thrusting; thrusts verge both to the northwest and the southeast (figure 8). Also, the anticlines developed in the eastern Potwar Plateau, where not cut by thrust faults, tend to be symmetrical and separated by fairly wide synclines.

In map view (figure 9), 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 the eastern Potwar Plateau fold belt is developed at the edge of the Infracambrian salt basin. A thinning of the Salt Range Formation to the southeast is evident in B-B'. A change in deformational style in the eastern Potwar Plateau is supported by the paleomagnetic work of Opdyke et al. (1982), that shows the eastern Potwar Plateau is differentially rotated 30° relative to the Salt Range and the central and western Potwar Plateau. Note, however, that the Kharian (Pabbi Hills) structure at the southernmost end of the eastern Potwar Plateau is rotated only about 10° relative to the Salt Range. Johnson et al. (in press, 1986) show that the Kharian anticline first had its surface expression only 0.4 MyrBP. This suggests that it may still be active, and has not yet completed its rotation.

A problem with interpreting the mechanics of thrusting along this cross section is
Figure 8 - B-B'. Preliminary interpreted cross section across the eastern Potwar Plateau.
After Leathers, in prep.
Figure 9 - Structural map of the Potwar Plateau, including locations of wells cited in text. The wells are: 1) Pabbi Hills, 2) Qazian, 3) Warna, 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 of the Salt Range. After Baker (in prep.).
that, although the cross section is approximately perpendicular to structural strike, it is
not perpendicular to the presumed direction of transport of the thrust wedge. 
Unfortunately, available seismic coverage is not able to delineate the basement slope in 
the direction of transport in the eastern Potwar Plateau. But examination of Bouguer 
gravity anomalies (Farah et al., 1977) and total sediment isopachs (Khan et al., 1986) 
suggest that there may be little difference in basement slope between the two directions. 
Therefore, the taper of the thrust wedge observed in cross section B-B' will be used as 
the critical taper of the eastern Potwar Plateau fold belt. It is noted, however, that a 
different critical taper will change the numerical results.

The parameters necessary to define the mechanics of this wedge using equation 18 
(Davis and Engelder, 1985) are the critical taper (α + β), the yield strength of the 
evaporites (τ₀), the pore fluid pressure ratio (λ), coefficient of internal friction (μ = tan 
φ), density (ρ), and thickness (H) of the wedge. Two of these parameters, φ and τ₀, are 
not available for the eastern Potwar Plateau, and an attempt will be made 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. 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 is very flat (α < ± 
0.1°).

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 10; locations in figure 9). The data show a normally pressured surficial unit 
(Pabbi Hills-1: 0-750 meters; Qazian-1X: 0-560 meters) with the formation pressures 
increasing rapidly below this level. In the Qazian-1X well the formation pressures 
decrease slightly in the platform section (below ~1500 meters), but still remain well 
above hydrostatic. An average value of λ = 0.82 for the overpressured section was 
calculated using equation (3) for the Pabbi Hills-1 well from the drilling mud densities 
and sediment densities estimated from sonic logs. The average pore fluid pressure ratio 
for the Qazian-1X well is also λ = 0.82, calculated using the same method as the Pabbi 
Hills-1 well. An average value for the density of the sediments overlying the Salt Range
Figure 10 - 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. Note that in the Lilla well the fluid pressure remains hydrostatic until reaching the Salt Range Formation. The Pabbi Hills and Qazian wells have a hydrostatically pressured surface layer and then becomes overpressured with depth. The section drilled in the Pabbi Hills well lies entirely in the molasse.
Formation is $\rho = 2330 \text{ kg/m}^3$, taken from model densities for the Potwar Plateau (Duroy, 1986).

With two unknowns ($\mu$ and $\tau_0$) in equation 18 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 ($\tau_0$) of halite is believed to lie in the range $\tau_0 = 0.5-1.5$ MPa. Davis and Engelder (1985) adopted a range of 0.1-1.0 MPa for $\tau_0$ in their discussion.

The coefficient of internal friction, $\mu$, 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 $\mu$ as a value to help quantify the internal strength of a thrust wedge. As such, the only values available to constrain $\mu$ 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 $\mu$ and $\tau_0$ can be computed using equation 18 to find the ranges of the parameters that fit the theory and that are comparable with those cited above (figure 11). Since the Davis and Engelder (1985) model was developed for a noncohesive Coulomb wedge, the best fitting value for $\mu$ 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 13 the best fitting values of $\mu$ and $\tau_0$ 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 $\mu$, and correspondingly 1.48 MPa for $\tau_0$. This rather high value of $\tau_0$ 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 halite near the edge of the basin that would tend to increase the strength of the décollement.
Figure 11 - Tradeoff curve between coefficient of internal friction and evaporite yield strength for the eastern Potwar Plateau. Best fitting parameters are $\mu = 1.03$ and $\tau_0 = 1.48$ MPa (dotted lines).
Central Salt Range-Potwar Plateau (A-A')

Several differences are readily apparent between this section (figure 12, A-A', Baker, in prep.; Lillie et al., in press, 1986) and the one across the eastern Potwar Plateau (figure 8). The most apparent feature is a large normal fault (throw = 1 km) 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., in press, 1986; Duroy, 1986). Another important difference is the lack of major deformation in the southern Potwar Plateau (Soan Syncline). The surface of the central Potwar Plateau between the north flank of the Salt Range and the Hill Ranges is essentially flat (α < 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. This drastic change in basement slope 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 12), but is 4 km in front of the Kharian (Pabbi Hills) anticline (figure 8).

For ease of discussion this cross section will be divided into three units; a) the Salt Range (SR), including the entire section south of the basement normal fault, b) the Southern Potwar Plateau (SPP), including the section between the basement normal fault and the first thrust fault north of the Soan River, and c) 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 (\( > 10° \)) normal fault. But by redefining equation 18 to be

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

(18')
Figure 12 – A-A'. Preliminary interpreted cross section across the central Salt Range-Potwar Plateau. After Baker (in prep); Lillie et al. (in press); and Duroy (1986).
an estimate of the critical taper needed to push a wedge up the fault surface can be made. The coefficient of internal friction, yield strength of the salt, and sediment density are taken from the eastern Potwar Plateau values \((\mu = 1.03; \tau_0 = 1.48 \text{ MPa}, \rho = 2330 \text{ kg/m}^3)\). The sediment thickness \((H)\) is taken as 3250 m, the average over the ramp. The angle at which the thrust wedge goes up the ramp \((\beta = 25^\circ)\) is used as the basement dip. Unfortunately there are no available pore fluid pressure data in the SR. If the pore fluid pressure ratio for the eastern Potwar Plateau, \(\lambda = 0.82\), is used, the predicted critical taper is 13°, which would allow for a topographic slope \(\alpha = -12^\circ\). It is found that as long as \(\lambda < 0.98\), there will be no deformation within the thrust wedge as it overrides the ramp. Thus the thrust plate is easily able to slide up the ramp with its topographic slope of \(\alpha = -1.0^\circ\) (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; Baker, in prep.) with high angle (normal?) or stike-slip faults common in the central portion (Baker, in prep.). 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 12). Lillie et al. (in press, 1986) have interpreted that this is cored by a "sledrunner" thrust (i.e. a southward extension of the main décollement). This interpretation is supported by well 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 10), suggesting compression at that level.

The southern Potwar Plateau (SPP) is remarkable in that, although it has been pushed at least 16 km southward (Baker, in prep.; Leathers, in prep.), it has undergone little or 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 \(\beta\) (1.9°–3.6° in the central Potwar as opposed to 0.6° in the eastern Potwar). This lack of deformation suggests that the taper of the SPP is either at or greater than the necessary critical taper. The basement slope \((\beta)\) is sufficient to provide the critical taper; no topographic slope is necessary.
A test of this hypothesis is to solve equation 18 for $\lambda$ 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 (pers. comm., 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 unlike the consistently high pressures found in the fold-and-thrust belt of Taiwan (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 18 was solved for $\lambda$ at two points in the SPP, one just north of the basement normal fault ($\beta = 1.9^\circ$, $H = 3000$ meters) and the other at the axis of the Soan syncline ($\beta = 3.6^\circ$, $H = 6000$ meters). The topographic slope was taken as $\alpha = 0^\circ$ and the eastern Potwar Plateau values were taken for $\mu$ and $\phi$. The pore fluid pressure ratios calculated for a thrust wedge at critical taper were $\lambda = 0.87$ and $\lambda = 0.97$ 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 surface topography is flat. 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 (pers. comm., 1986) notes that there has been considerable uplift and erosion in the NPP. Yet the lack of a surface topographic slope suggests that the NPP is underlain by salt, like the SPP.

By applying both equation 8 and equation 18, the best fitting model (salt or no salt) can be chosen for the NPP. A pore fluid pressure ratio for the NPP is available from Hubbert and Rubey (1959) for the Khaur well (figure 9). They find that $\lambda = 0.93 \pm 0.01$, larger than the eastern Potwar Plateau values but less than that calculated for the northern part of the SPP (see above). Given the value of $\lambda$ from the Khaur well, equations 8 and 18 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 8) parameters used are $\mu = 1.03$, $\mu_b = 0.85$, $\lambda = 0.93$, and $\beta = 3.6^\circ$. The critical taper calculated in this case is $\alpha + \beta = 5.3^\circ$, predicting a
topographic slope of $\alpha = 1.7^\circ$. Clearly the NPP has no such topographic slope. For the salt case, applying equation 18 and solving for the critical taper (using $\tau_0 = 1.48$ MPa and $H = 6000$ meters) gives $\alpha + \beta = 3.1^\circ$, predicting a topographic slope of $\alpha = -0.5^\circ$ (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 9) 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., in press, 1986) show that the northern flank of the Soan Syncline was upturned about 2.1 m.y.a. and deformation ceased by 1.9 m.y.a., as evidenced by the flat-lying Lei Conglomerate. Deformation then apparently transferred to the Salt Range. Baker (in prep.) and Leathers (in prep.) report that there has been at least 16 km of movement along the Salt Range Thrust. Because very little shortening has occurred within the intervening SPP, it is suggested that the NPP has been translated at least 16 km across the original northern edge of the salt basin in the past 2.1–1.9 m.y.a. (figure 13). 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. 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 removable 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.

Also of interest in this mechanical study is the structural development at the transition zone between the SPP and the NPP (i.e. the north flank of the Soan syncline). The observed structure is similar to the "triangle zone" recognized by Jones (1982) in the foothills of the Canadian Rocky Mountains in Alberta. He also reports similar structures in other parts of the world, including the Nittany Anticlinorium in the western
Pre-2 m.y.a.: The northern Potwar Plateau is actively deforming as a fold-and-thrust belt and has not yet encountered the Salt Range Formation. The normal fault beneath the future Salt Range forms.

2 m.y.a.: The deformation front reaches the northern edge of the salt basin and the "triangle zone" structure is formed. Uplift of the Salt Range begins.

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 at the Salt Range Front.

Figure 13 - Cartoon showing possible structural evolution of the northern Potwar Plateau. This is one explanation of the apparent paradox of the strong internal deformation and the low topographic slope in the northern Potwar Plateau.
Appalachians, the Molasse Basin in Switzerland, and the eastern Carpathian Foothills in Romania. In these last three areas Davis and Engelder (1985) report them as fold-and-thrust belts developed on top of a layer of salt. Although these observations are inconclusive, it is here suggested that there may be a causal relationship between the development of "triangle zone" structures and the propagation of a fold-and-thrust belt onto a salt-dominated detachment.

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

The western Salt Range-Potwar Plateau section (C-C', figure 14, Leathers, in prep.) is similar to the central Salt Range-Potwar Plateau section (A-A'). These sections can be readily divided into the same three units: the Salt Range (SR), the Southern Potwar Plateau (SPP), and the Northern Potwar Plateau (NPP). In almost all 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, in prep.). Using the same parameters as in the central SR, but with \( H = 2000 \) meters and \( \beta = 22^\circ \), the angle at which the thrust wedge is ramped upwards, a surface topographic slope of \( \alpha = -10^\circ \) is predicted using equation 18'. The upper thrust plate therefore slides just as easily over the ramp in the western SR as does in the central SR.

Another difference between the central and western SR is the lack of "sledrunner" thrusts in front of the Salt Range. Examination of Bouguer anomalies (Farah et al., 1977) shows that part of the Sargodha Gravity High underthrusts the front of the Salt Range in the west. 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.

In the west the SPP is very similar to the SPP in the central section. Internal deformation of the thrust plate is minor and consists of gentle folds. The dip of the underthrusting basement is \( \beta = 3.4^\circ \) just north of the Salt Range ramp and \( \beta = 2.2^\circ \)
Figure 14 - C-C'. Preliminary interpreted cross section across the western Potwar Plateau. After Leathers, in prep.
under the Soan Syncline. Solutions of equation 18 yield values of $\lambda = 0.91$ and $\lambda = 0.94$ 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 $1.3^\circ$. Duroy (1986) finds that a shallowing of the basement dip in the NPP is supported by Bouguer gravity anomalies. Using equation 8, the critical taper estimated for the no salt case is $\alpha + \beta = 3.6^\circ$, giving $\alpha = 2.3^\circ$. For the salt case, equation 18 gives $\alpha + \beta = 1.35^\circ$. This suggests that the western NPP is near its critical taper. This also leads to the interpretation that the observed high pore fluid pressures in the NPP are being maintained by tectonic compression. Also, examination of seismic profiles in the northeast Potwar Plateau suggest $\beta = 1.2^\circ$. From this the preferred interpretation for the entire NPP is a thrust wedge is presently near its critical taper and the high pore fluid pressures are a result of continued tectonic compression.
COMPARISON WITH OTHER FOLD BELTS OF PAKISTAN

The Salt Range has been described as an "anomaly" (Crawford, 1974) in the tectonics of the Himalayas. As discussed above, the interaction of a weak detachment and basement topography provide a plausible explanation for the position of the Salt Range so far south of the MBT, and the exposure of Paleozoic rocks at the very front of the orogenic belt. It is instructive, therefore, to compare the Salt Range-Potwar Plateau with nearby regions of the Himalaya.

Several authors (e.g. Sarwar and DeJong, 1979) have commented upon the system of lobes and re-entrants in the foreland fold-and-thrust belt of Pakistan (figure 1). Two explanations for these features have been put forward: a) that the lobes and re-entrants are controlled by features on the underthrusting Indian shield (Wadia, 1953), and b) that they are related to the distribution of salt in the subsurface (Sarwar and DeJong, 1979). Davis and Engelder (1985) show that the surface topography, the width of the thrust belt, and the style of deformation of a fold-and-thrust belt are sensitive to the presence of salt at depth. With the exception of the Salt Range-Potwar Plateau area, subsurface data for Pakistan are generally not available, but surface topography and geology are. A Landsat mosaic (R. D. Lawrence, unpubl. data) is also available for analysis. The brief discussion of these data may provide some clues as to the role of salt in other portions of the Pakistan foreland fold-and-thrust belt.

Salt Range-Potwar Plateau vs. Kashmir Himalaya

The most apparent difference between the Kashmir Himalaya and the Salt Range-Potwar Plateau is the topography. While in the Salt Range-Potwar Plateau $\alpha < 1.0^\circ$ (figure 15), the foreland thrust belt in Kashmir has $\alpha = 2.1^\circ$ (figure 16; Burbank et al., in press, 1986). Another readily apparent difference is the width of the thrust belt. The distance between the Salt Range Thrust and the MBT is 100–150 km, whereas in Kashmir, the distance between the deformation front and the MBT is only 40–60 km (figure 1).

Seeber and Armbruster (1981) report the dip of the décollement along the Himalayan front varies between 1.5°–3.0°. This is consistent with plate flexure models of Lyon-Caen and Molnar (1983, 1985), derived from gravity data, that show the dip of the Indian plate to be about 3.0° beneath the Lesser Himalaya. This gives a taper $\alpha + \beta =$
Figure 15 - Topography of the Salt Range-Potwar Plateau area. Data is from Army Map Service (AMS) 1:250,000 topographic maps of India and Pakistan. Dotted lines are sea level and deformation fronts are at 0 km. Sections correspond to A, B, and C in figure 1.
Figure 16 - Topography of the Kashmir Himalaya. Data is from AMS 1:250,000 topographic maps of India and Pakistan. Dotted line is sea level and deformation front is at 0 km. Section corresponds to D in figure 1.
5.0° for the Kashmir Himalaya, compared with eastern Potwar Plateau where \( \alpha + \beta < 1.0° \).

Seeber and Armbruster (1981) conclude, mainly from earthquake data, that the thick salt of the Salt Range Formation is lacking east of the Potwar Plateau. They argue that the lack of major earthquakes in the Salt Range-Potwar Plateau area is due to lubricating effect of the salt, while the 1905 Kangra earthquake (\( M_S = 8 \)) that occurred about 100 km southwest of section D (figure 1) suggests greater coupling along the detachment there. In addition, the fairly large (5.0°) taper and narrow width of the thrust belt in Kashmir support this conclusion. Following Davis et al. (1983), the pore fluid pressure ratio for the thrust wedge in Kashmir is estimated at \( \lambda = 0.92 \). Note that this differs from \( \lambda = 0.76 \) estimated by Davis et al. (1983) for the Nepal Himalaya, due to the larger taper of the thrust wedge in Nepal (\( \alpha + \beta = 7.0° \)). Unfortunately, no pore fluid pressure data are available to confirm these estimates.

**Sulaiman Lobe vs. Sulaiman Range**

One of the most striking features of the foreland fold-and-thrust belt in Pakistan is the Sulaiman Lobe (figure 1). Like the Salt Range-Potwar Plateau, it extends far out of the foreland when compared to nearby mountain belts. Examination of figure 1 shows that the foreland fold-and-thrust belt of the Sulaiman Lobe is very wide when compared with the Sulaiman Range.

Figure 17 compares the topography of the Sulaiman Lobe and the Sulaiman Range. A difference in topography, although not as drastic as between the Salt Range-Potwar Plateau and the Kashmir Himalaya, is apparent. In both areas the topography rises to a level of a plateau about 1.0–1.5 km above sea level; the difference is that the Sulaiman Range reaches this level much more quickly. The topographic slope for the Sulaiman Lobe is \( \alpha = 0.6° \), and that of the Sulaiman Range is much larger, \( \alpha = 1.7° \).

The structures in the Sulaiman Lobe, from Landsat photos and surface geology (Khan, unpubl. data), consist of broad, gentle anticlines that bend at both the eastern and western ends (figure 18). This is consistent with the Davis and Engelder (1985) model as to the type of structures to be expected in a fold-and-thrust belt developed on salt. Taken together with the low (< 1°) surface slope and the wide (100 km) thrust belt, it
Figure 17 - Topography of the Sulaiman Range and Sulaiman Lobe. Data is from AMS 1:250,000 topographic maps of India and Pakistan. Dotted lines are sea level and deformation fronts are at 0 km. Sections correspond to E and F in figure 1.
Figure 18 - Structural map of the Sulaiman Lobe. Structural trends are taken from Landsat photos, and map units simplified from Kazmi and Rana (1982). Rock units are: no pattern-Quaternary alluvium, gravel pattern-Neogene molasse, dot pattern-Jurassic to Oligocene marine and continental sedimentary rocks. Note changes in structural orientation at the east and west edges of the belt.
suggests the presence of salt along the basal décollement, as proposed by Sarwar and DeJong (1979).

Unfortunately very little published subsurface data are available in the Sulaiman region. Tainsh (1959) reports on some gas exploration wells in the frontal portion of the Sulaiman Lobe. These wells did not penetrate deep enough to reach the décollement surface, but Tainsh (1959) does report on fluid pressures. Analysis of the data shows the pore fluid pressure ratio, in at least the upper part of the thrust wedge, to be approximately hydrostatic ($\lambda = 0.45$).

With only the surface slope $\alpha$ and only partial pore fluid pressure data, there is no way to uniquely determine whether or not a weak décollement zone (e.g. salt) is present beneath the Sulaiman Lobe thrust belt. More data, especially as to the depth of the décollement, is needed. The low surface slope, large width of the fold-and-thrust belt, and the gentle folding at the front of the Sulaiman Lobe suggest the presence of salt at depth, but cannot uniquely determine it.

**Kirthar Range vs. Karachi Arc**

The Karachi Arc (Sarwar and DeJong, 1979) is a less spectacular feature than the Sulaiman Lobe, but shares many similar features with it (figure 1). Like the Sulaiman Lobe, it is wide when compared to the Kirthar Range to the north (100 km vs. 40 km). Topographically it is even more subdued (figure 19), the surface slope being only $\alpha = 0.2^\circ$. The surface slope of the frontal thrust belt of the Kirthar Range is $\alpha = 1.1^\circ$. R. D. Lawrence (pers. comm., 1986) reports that the structures of the Karachi Arc, while prominent in Landsat photos (figure 20), are quite subdued; the limbs of the anticlines dip very gently. Sarwar and DeJong (1979) report that there is a strong change in the orientation of the structures at the southern edge of the Karachi Arc. There is no available subsurface information for either the Karachi Arc or the Kirthar Range, making it impossible to determine whether or not salt is present at depth. But like in the Sulaiman Lobe, a combination of surface features suggests that it is.

**Summary of Lobes and Re-entrants in Pakistan**

The observations outlined above suggest that the sinuous outline of the foreland fold-and-thrust belts in Pakistan is due mainly to the distribution of salt in the
Figure 19 - Topography of the Kirthar Range and the Karachi Arc. Data is from AMS 1:250,000 topographic maps of India and Pakistan. Dotted lines are sea level and deformation fronts are at 0 km. Sections correspond to G and H in figure 1.
Figure 20 - Structural map of the Karachi Arc. Structural trends are taken from Landsat photos, and map units simplified from Kazmi and Rana (1982). Rock units are: no pattern-Quaternary alluvium, gravel pattern-Neogene molasse, dot pattern-Jurassic to Miocene marine and continental sedimentary rocks. Note the strong change in structural orientation at the south edge of the arc and the narrowing of the fold-and-thrust belt to the north.
subsurface. Besides being in the Salt Range-Potwar Plateau area, salt is also known to lie in the subsurface south of the Sargodha High near Multan (Cento, 1972, as referenced by Sarwar and DeJong, 1979). It is possible that the Salt Range Formation could extend to the south and west far enough to be present in other thrust belts. It is only the presence of the basement ramp in the Salt Range-Potwar Plateau area that brings the Salt Range Formation to the surface. A fold-and-thrust belt with a relatively smooth basement surface, similar to the eastern Potwar Plateau, may not expose the underlying salt at the surface.
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 provide a three dimensional view of this thrust belt that gives the necessary constraints to allow an application of the model.

The model is successful in explaining almost all of the observed 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 changes in the underlying basement. The deformation of the eastern Potwar Plateau represents an interaction of a shallow basement dip (β < 1°) 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, allow the estimation of values for the yield strength of the evaporites (τ₀ = 1.48 MPa) and the coefficient of internal friction (µ = 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, the Salt Range is due to a thrust ramp caused by a basement normal fault in the central Salt Range, and to a 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, in prep.; Leathers, in prep.). The Sargodha Ridge also creates a steeper basement slope (β = 2°−4°) beneath the central and western 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 deformation. This interpretation is consistent with the undeformed nature of the southern Potwar Plateau.

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., in press, 1986), the deformation in the northern Potwar Plateau stopped about 2 m.y.a. In this study it is proposed that the northern Potwar Plateau existed as a strongly tapered
fold-and-thrust belt prior to 2 m.y.a., and it has since overridden the north edge of the salt basin and erosion has removed its former topographic slope.

The discrete offset of the basement beneath the central Salt Range and the general non-linearity of the basement slope beneath the Salt Range-Potwar Plateau are not adequately covered by the Davis and Engelder (1985) model. They do not directly conflict with the model; the model has not been sufficiently generalized to deal with them. All of the models considered by Davis et al. (1983), Dahlen et al. (1984), Davis and Engelder (1985), and Zhao et al. (1986) assume that the basement is not offset and has a linear slope. The effect of a basement offset beneath a fold-and-thrust belt has been considered by Wiltschko and Eastman (1983; in press, 1986), although not for the case of a salt décollement. It is suggested here that, due to the presence of salt, the thrust sheet can override the normal fault beneath the Salt Range with little internal deformation. The effect of basement offsets might be further studied by the continued use of the "sandbox" model of Davis et al. (1983), together with a "fault" placed along the bottom surface of the box. To address the second deviation (basement curvature), a generalization of the Davis et al. (1983) model is proposed here where the basement surface follows a continuous function, such that the slope can be derived at any point. This is considered as a way to possibly integrate basement surfaces of underthrusting slabs derived from plate flexure models (e.g. Lyon-Caen and Molnar, 1983; 1985) together with mechanical models of thrusting.

Another point not adequately discussed by Davis and Engelder (1985) is the nature of the changes in structural style when a salt/no-salt boundary is encountered. A "triangle zone" structure is seen in the northern Potwar Plateau; it is considered to have originally developed at the northern end of the salt basin. The occurrence of structures of this type elsewhere (Jones, 1982) often coincide with the presence of salt at the base of a fold-and-thrust belt (Davis and Engelder, 1985). It is suggested here that there may be a causal relationship between the existence of "triangle zones" and a décollement that propagates into a salt basin.

With the success of the Davis and Engelder (1985) model in predicting many of the features in the Salt Range-Potwar Plateau area, a brief look is taken at the rest of the active fold-and-thrust belt in Pakistan to see if some of these features are present elsewhere. The Sulaiman Lobe and the Karachi Arc are seen to exhibit several of the features predicted by the model, including: a) low topographic slopes, b) wide thrust belts, c) symmetrical structures, and d) changes in structural strike at the edges. Note
that one of these areas, the Sulaiman Lobe, was considered in an earlier paper (Sarwar and DeJong, 1979) to be underlain by the Salt Range Formation. From this it is suggested that the sinuous form of the mountain belts in Pakistan is mainly controlled by the distribution of salt in the subsurface, as opposed to basement highs in the underthrusting Indian plate.


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