AN ABSTRACT OF THE THESIS OF

Edward S. Pennock for the degree of Master of Science in Geology

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Title: Structural Interpretation of Seismic Reflection Data from the Eastern Salt Range and Potwar Plateau, Pakistan.

Abstract approved: Signature redacted for privacy.

Robert J. Lillie

Approximately 1600 km of seismic reflection profiles from the eastern Salt Range and Potwar Plateau (SR/PP) of Pakistan are integrated with available magnetostratigraphic, surface geologic and well data, to categorize structural styles, determine the timing of deformation and estimate the amount of telescoping of the sedimentary cover. The eastern SR/PP is similar to other fold-and-thrust belts underlain by evaporites in that: 1) it is part of a zone of overthrusting that extends considerably farther over the Himalyan foreland than adjacent areas not underlain by evaporites; 2) the overall thrust wedge has a narrow cross-sectional taper; 3) structures verge toward the hinterland as well as toward the foreland; and, 4) fold trends are long and continuous, consisting of tight, salt-cored anticlines separated by broad synclines.

Disharmonic folding of the sedimentary section relative to the underlying basement is due to effective decoupling along the intervening salt layer. Subsurface mapping on top of a strongly reflective package of Cambrian to Eocene strata reveals that many surface folds are cored by both foreland- and hinterland-dipping, blind thrusts, and some are fault propagation folds. In some cases, intersecting thrusts result in local triangle zones; other surface folds have a pop-up geometry.

The dip of the basement towards the inner part of the fold-and-thrust belt is relatively gentle in the eastern SR/PP (1°-1.5°) compared to the central SR/PP (2°-3°). Mechanical considerations demonstrate that, unlike the relatively undeformed central SR/PP, a broad deformational zone has developed in the eastern SR/PP to provide a surface topographic slope necessary to maintain a critical taper of the thrust wedge. Furthermore, previous paleomagnetic studies indicate that deformation across much of the eastern PP preceded tectonic rotation. This implies that individual structural trends developed perpendicular to the transport direction and were then rotated into their current NE-SW alignment in response to ramping over a basement buttress in the central SR/PP.

Cross-section balancing indicates that approximately 23.1 km of shortening has occurred across the foreland in the eastern SR/PP since 5.5 Ma, 17.8 km in the last 2.5 Ma. The shortening rate of 7 mm/yr for that time interval is roughly 15% of the 40-50 mm/yr convergence rate between the Indian and Eurasian plates.

Structural Interpretation of Seismic Reflection Data from the Eastern Salt Range and Potwar Plateau, Pakistan

by

Edward S. Pennock

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Dean of the Graduate School

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I am grateful to my family, especially my parents, who have always encouraged me to make and pursue my own goals. I am most grateful to my wife, Carol, whose constant support, understanding, and love, have made this thesis a reality.

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INTRODUCTION

The Salt Range and Potwar Plateau (SR/PP) of Pakistan are parts of the Himalayan foreland fold-and-thrust belt, a product of the ongoing collision between the Eurasian and Indian Plates (Figure 1). Deformation throughout the Himalayan foreland is taking place as the Indian shield is overridden by sediments along its northern margin. In the central and western SR/PP this deformation is manifest by south-verging thrusting along the Salt Range thrust. This style contrasts with that of the eastern SR/PP, where deformation is distributed along a broader zone of NE-SW trending, tight to overturned anticlines separated by broader synclines (Figure 2).

The debate concerning the nature of structures in the subsurface of the eastern SR/PP has been largely speculative owing to the sparse amount of data previously available to the academic community. This paper incorporates over 1600 km of multi-channel, seismic reflection lines from the eastern SR/PP released by Amoco and Chevron with the permission of the Ministry of Petroleum and Natural Resources of Pakistan, the Oil and Gas Development Corporation of Pakistan (OGDC), and Pakistan Petroleum Limited (PPL; Figure 3). The seismic lines reveal a variety of structural styles which may be related to several factors, including: 1) changes in distribution and

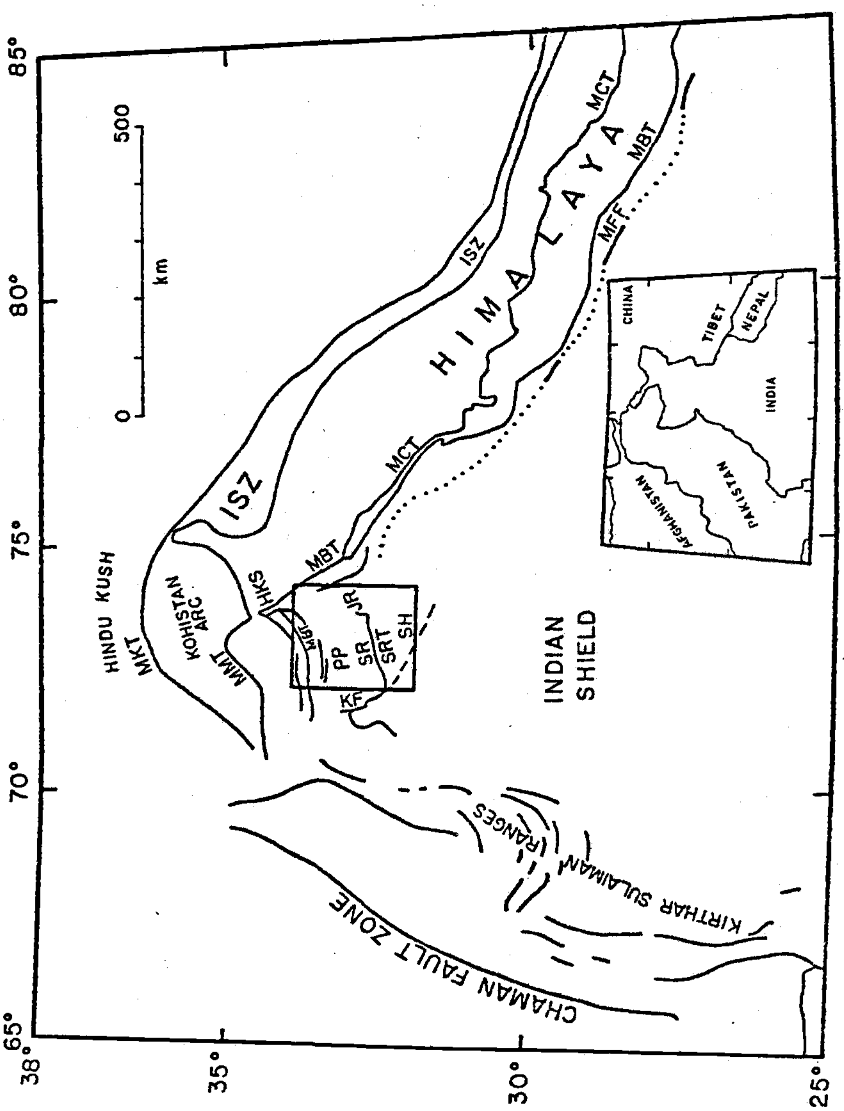
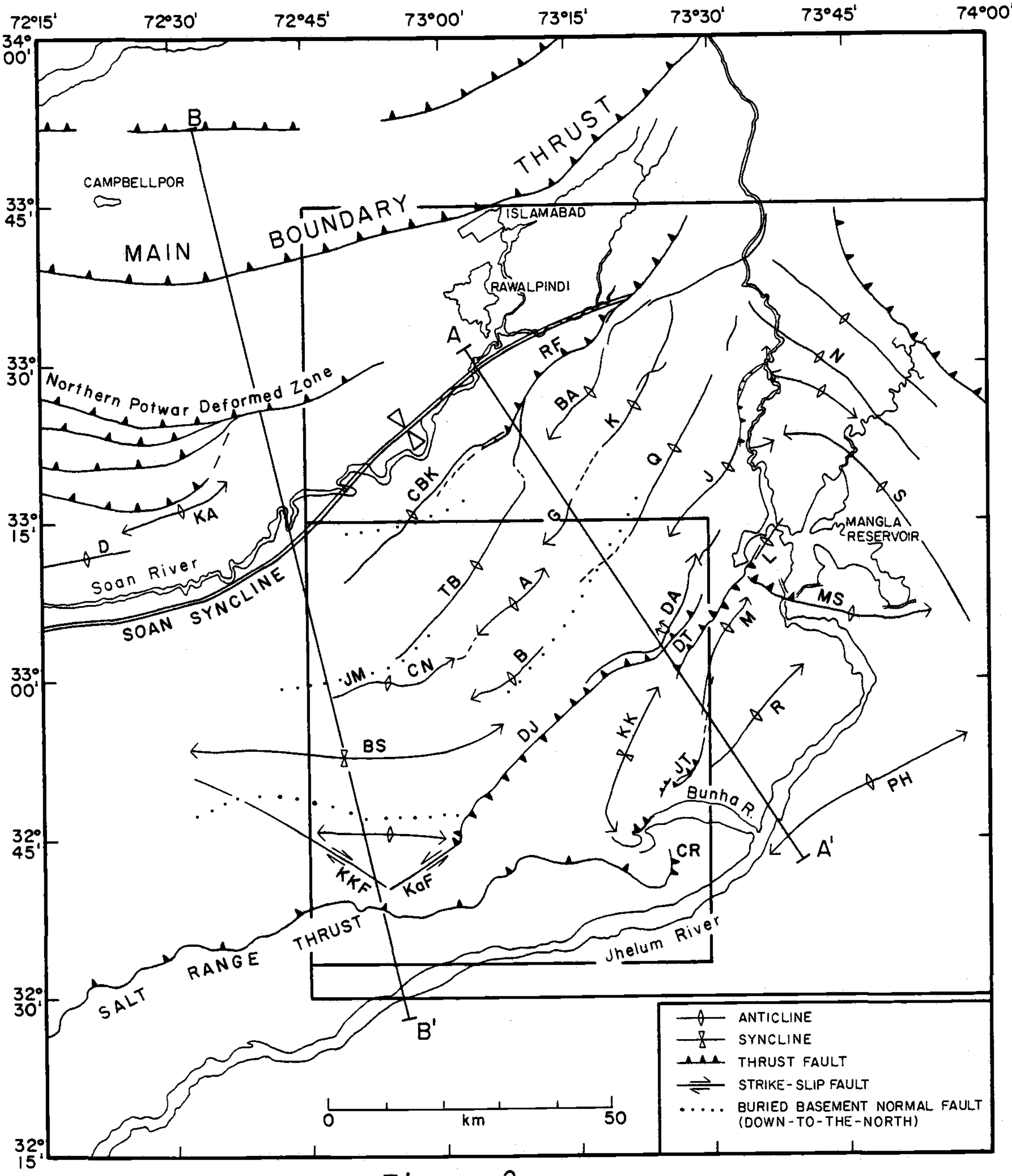


Figure 1. Regional location map showing the proximity of the Salt Range to the main Himalayan trend.

Figure 2. Structural sketch map of the central and eastern SR/PP. Notice the predominance of NE trending folds in the eastern SR/PP. A-A' is the line of the balanced structural cross-section constructed in this paper (Figure 8). B-B' is the line of section of a balanced structural cross-section constructed by Baker (1987) and Baker *et al* (1988; Figure 11). Large bold rectangle shows the area of Figures 3 and 5. Small bold rectangle shows the area of Figure 9. Abbreviations: A=Adhi anticline, B=Bhubar anticline, BA=Buttar anticline, BS=Baun syncline, CBK=Chak Beli Khan anticline, CN=Chak Naurang anticline, CR=Chambal Ridge, D=Dhulian anticline, DA=Domeli anticline,DJ=Dil Jabba thrust, DT=Domeli thrust, G=Gungril anticline, J=Jabbar anticline, JM=Joya Mair anticline, JT=Jogi Tilla anticline, K=Kallar anticline, KA=Khaur anticline, KaF=Karangal fault, KK=Kotal Kund syncline, KKF=Kallar Kahar fault, L=Lehri anticline, M=Mahesian anticline, MBT=Main Boundary thrust, MS=Mangla-Samwal anticline, N=Nar anticline, PH=Pabbi Hills anticline, Q=Qazian anticline, R=Rohtas anticline, RF=Riwat fault, S=Suruh anticline, and TB=Tanwin-Bains anticline.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MAIN BOUNDARY THRUST
CAMPBELLPOR
ISLAMABAD
RAWALPINDI
Northern Potwar Deformed Zone
Soan River
SOAN SYNCLINE
SALT RANGE THRUST
Jhelum River
Bunha R.
MANGLA RESERVOIR
B
B'
A
A'
KA
D
RF
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STRIKE-SLIP FAULT
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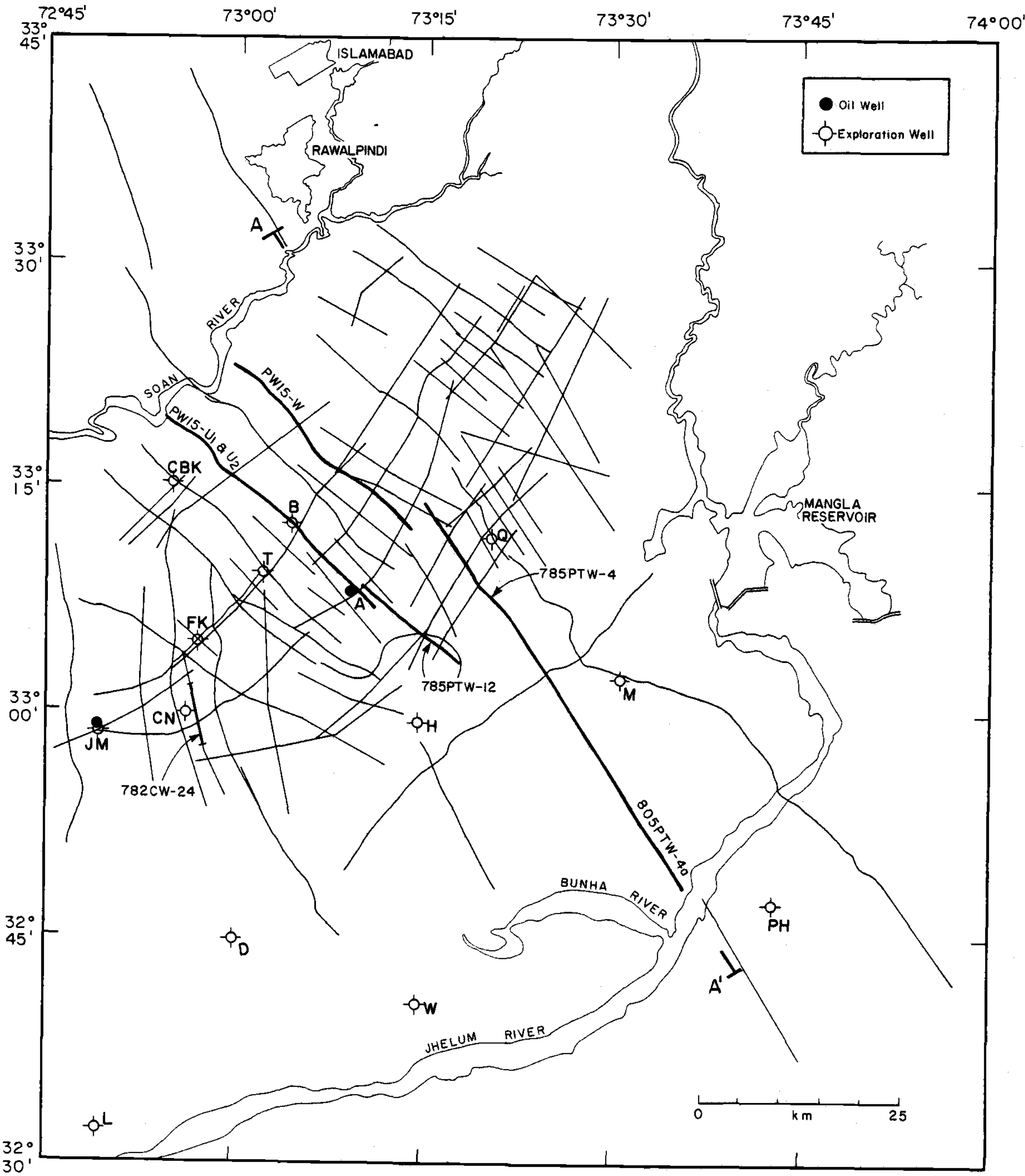
Figure 2.

Figure 3. Map of seismic and well data used in this study. See Khan *et al* (1986), Baker (1987), and Leathers (1987) for locations of additional seismic lines and wells in central and western SR/PP. Bold lines represent seismic lines shown in Figures 6, 7, and 10. A-A' is the line of the balanced structural cross-section constructed in this paper (Figure 8). Well abbreviations: A=Adhi-5, completed in 1978 by Pakistan Petroleum Limited (PPL) and Amoco; B=Bains-2, completed in 1957 by Pakistan Oil Fields Limited (POL); CBK=Chak Beli Khan-3, completed in 1964 by PPL and POL; CN=Chak Naurang, completed in 1953 by PPL; D=Dhariala-1, completed in 1952 by POL; FK=Fim Kasar-1X, completed in 1981 by Gulf and the Oil and Gas Development Corporation of Pakistan (OGDC); H=Hayal-1, completed in 1982 by OGDC; JM=Joya Mair-1 and Joya Mair-3, completed in 1944 and 1947 by Attock Oil Company and POL; L=Lilla-1, completed in 1983 by Shell; M=Mahesian-1, completed in 1960 by POL; PH=Pabbi Hills-1, completed in 1983 by Shell; Q=Qazian-1, completed in 1980 by Gulf and OGDC; T=Tanwin-1, completed in 1962 by POL; and W=Warnali-1, completed in 1983 by Shell.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RAWALPINDI
Oil Well
Exploration Well
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PW15-U1 & U2
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Q
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FK
785PTW-12
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CN
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H
782CW-24
805PTW-4a
MANGLA RESERVOIR
BUNHA RIVER
PH
D
W
JHELUM RIVER
L
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Figure 3.

thickness of a basal evaporite sequence; 2) basement faults and flexures; and, 3) low dip of the basement.

These data, coupled with surface geologic and well data, have been used to construct a balanced structural cross-section of the eastern SR/PP. Specific problems that have been addressed include: 1) why folding predominates over thrusting; 2) how and why structures change trend from generally E-W in the central SR/PP to NE-SW in the eastern SR/PP; 3) the localization of structures and their possible relationship to basement offsets; 4) the amount of shortening of the cover rocks; and 5) the rate of underthrusting of basement beneath sediments in this part of the fold-and-thrust belt. Conclusions are then incorporated into interpretations of the evolution of the Pakistan Himalaya.

The interpretations in this study utilize much of the detailed timing of structural events determined in the SR/PP by Raynolds (1980), Burbank *et al* (1986), and Johnson *et al* (1986). The study also builds on other structural interpretations of the SR/PP by Duroy (1986), Khan *et al* (1986), Jaumé (1986), Baker (1987), Butler *et al* (1987), Leathers (1987), Lillie *et al* (1987), Baker *et al* (1988), and Jaumé and Lillie (in press), by more precisely constraining the subsurface structure and stratigraphy beneath the eastern SR/PP. In this manner, it not only increases the understanding of this part of the Himalayan foreland fold-and-thrust belt, but also provides fundamentally important constraints which are commonly unavailable in ancient collisional mountain belts (e.g., topographic slope, basement slope, detailed timing information).

REGIONAL TECTONIC SETTING

The continent-continent collision responsible for the Himalayan Ranges began in middle-to-late Eocene time (Stoneley, 1974; Stöcklin, 1974; Molnar and Tapponnier, 1975), in association with late-Cretaceous-Cenozoic spreading along the Carlsberg-southeast Indian Ocean Ridge (McKenzie and Sclater, 1971). Since the collision began, seafloor reconstructions indicate that about 2000 km of convergence has occurred between India and Eurasia (Patriat and Achache, 1984).

The collision zone has been studied intensely east of Kashmir, where subdivisions of the Himalaya (from north to south: the Tethyan-Himalaya, High-Himalaya, Lesser-Himalaya, Sub-Himalaya, and Gangetic foredeep) are based on structural, stratigraphic, and morphological criteria (Gansser, 1981). In the central part of the Himalaya, four major structures--the Indus-Tsangpo suture, Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Main Frontal Fault (MFF)--bound these subdivisions (Gansser, 1981). However, these structures and subdivisions are not clearly traceable around the Hazara-Kashmir Syntaxis, where the gently arcuate form characteristic of the ranges throughout India and Nepal gives way in stark contrast to the strongly festooned Pakistani Himalaya (Figure 1).

In northern Pakistan the Himalayan trend has been divided into four major subdivisions (Farah *et al*, 1984; Yeats and Lawrence, 1984; Figure 1). North of the Main Karakoram Thrust (MKT) lie the Karakoram Ranges and Hindu Kush, terranes of Gondwana affinity sutured to Eurasia (the Turan Block) in Late Triassic to Middle Jurassic time (Sengor, 1979). South of the MKT and north of the Main

Mantle Thrust (MMT) lies the Kohistan block, a terrane now believed to have been formed as an island arc (Jan and Asif, 1981; Tahirkheli, 1982; Farah et *al*, 1984) and to have docked with Eurasia in late Cretaceous (Windley, 1983) to early Eocene time (Kennett, 1982). South of the MMT and north of the MBT are the low ranges of Swat, Hazara, and Kashmir, analogous to the Lesser Himalaya of India. The outlying Potwar Plateau and Salt Range, bounded on the south by the Salt Range Thrust, represent the marginal foreland fold-and-thrust belt of the Indo-Pakistan subcontinent, equivalent to the Sub-Himalaya in India (Farah et *al*, 1984). Zeitler et *al* (1982) suggest that the MMT locked approximately 15 Ma, subsequent to rapid uplift north of the fault between 30 and 15 Ma (Zeitler et *al*, 1980). Following the cessation of movement along the MMT, deformation propagated southward to the vicinity of the MBT where unmetamorphosed, Lower Tertiary rocks are thrust over Neogene molasse. In the latest phase in Pakistan, thrusting transferred to the SRT, where deformation as young as 0.4 Ma has been documented (Yeats et *al*, 1984). South of small anticlines in front of the SRT, sediments overlying the Punjab Plain are undeformed; the current foredeep to the Pakistan Himalaya lies in this area.

Approximately 80 km south of the SRT lie the Kirana Hills, composed of ESE trending Precambrian basement rocks of the Indian Shield (Farah et *al*, 1977; Yeats and Lawrence, 1984). These exposures lie along the ESE trending Sargodha High (Figure 1), a topographic ridge which follows a series of gravity highs from India (Aithal et *al*, 1964). Menke and Jacob (1976) recognized a nearly continuous zone of seismicity associated with this feature in India. They, Molnar *et al* (1976), and Duroy (1986) interpreted the ridge and Bouger gravity high as manifestations of a lithospheric flexural bulge related to the northward underthrusting of the Indian plate. Thus, the overall setting of the Himalayan foreland may be thought of as analogous to a modern ocean subduction setting, with the Sargodha High corresponding to the peripheral bulge, the Gangetic/Jhelum foredeep equivalent to the trench, and the Sub-Himalaya/SR/PP thrust belt representing the accretionary wedge.

STRATIGRAPHIC AND STRUCTURAL SETTING

The Pakistani foreland fold-and-thrust belt differs from that of the main Indian/Nepalese Himalaya in several conspicuous ways. In Pakistan, a wide foreland belt (>100 km) and a narrow cross-sectional taper (1°-4°) can be attributed to weak coupling between a low-strength basal evaporite sequence (Eocambrian Salt Range Formation) and the underlying basement (Crawford, 1974; Seeber and Armbruster, 1979; Davis *et al*, 1983; Davis and Engelder, 1985; Jaumé, 1986; Jaumé and Lillie, in press). In contrast, strong coupling between the sediments and basement occurs in India, as evidenced by large earthquakes located beneath the foreland (Quittmeyer *et al*, 1979; Seeber *et al*, 1981), resulting in a narrower deformed foreland belt (< 50 km) and a greater cross-sectional taper (approx. 8°; Acharyya and Ray, 1982).

The Salt Range, trending ENE through northern Pakistan, extends along strike for approximately 160 km. It is bounded on the west by the Kalabagh Reentrant, on the east by the Hazara-Kashmir Syntaxis (Sarwar and DeJong, 1979), and on the south by the undeformed Jhelum Plain (Figure 1). Its southern escarpment, rising 800-900 m above the plains, marks the southernmost extent of significant deformation along the Himalayan fold-and-thrust belt in Pakistan. The northern slope of the Salt Range is gentle, gradually passing into the Potwar Plateau. For centuries, the Salt Range has been a strategic location because it contains large amounts of rock salt (Wynne, 1878). More recently, geologists have recognized that rocks exposed in the Salt Range are older than any others exposed in the ranges that form the southern border of the Himalayan trend (Hemphill and Kidwai, 1973; Meissner *et al*, 1974; Gee, 1980).

The Potwar Plateau is bounded by the Kala Chitta and Margala Hills to the north, the Indus River and Kohat Plateau to the west, and the Jhelum River and the Hazara-Kashmir Syntaxis to the east. Physiographically, it is a surface of low relief, except where dissected by major rivers. The Potwar Plateau has yielded moderate amounts of hydrocarbons, making it an area of considerable economic importance to Pakistan (Khan *et al*, 1986).

Stratigraphy

Detailed surface mapping in the Salt Range (Gee, 1980) and well control across the SR/PP and in the Jhelum plain (Figure 3; Khan *et al*, 1986) have led to an excellent understanding of the stratigraphy in the area (Figure 4). The oldest formation known to lie on top of basement is the Eocambrian Salt Range Formation (Fatmi et al, 1984). Potentially correlative evaporitic deposits in Hazara (Latif, 1973), Multan (Sarwar and DeJong, 1979), the Zagros fold belt of Iran (Ala, 1974; Colman-Sadd, 1978), and in Siberia (Zarkov, 1981) suggest that the initial extent of the evaporite basin may have been quite extensive. More likely, the evaporites were deposited in smaller, isolated, intracratonic basins (Kozary *et al*, 1968).

The overlying Cambrian to Eocene platform rocks in the SR/PP area are similar to those of the rest of peninsular India. In the Salt Range, the base of this sequence is the Lower Cambrian Jhelum

4. Generalized stratigraphic column of the eastern SR/PP. Formation symbols are those used in Figures 5, 7, 9, and 10. Velocities for the stratigraphic section are estimates based on converting stacking velocities from seismic lines to interval velocities. Seismic velocities denote average interval velocities actually used in time-to-depth conversions. Patterns are those used in cross-section A-A' (Figure 8) and B-B' (Figure 11). Cumulative molasse thicknesses (i.e., Rawalpindi and Siwalik Groups) are typically 3000-4000 m. However, as evidenced by well control, individual molasse formations show substantial changes in thickness throughout the SR/PP; therefore, maximum thicknesses are presented. Oil column shows distribution of hydrocarbons in the eastern SR/PP. Stratigraphic section after Gee (1980), Fatmi *et al* (1984), and Khan *et al* (1986).

AGE	FORMATION		SYMB.		VEL.	DESCRIPTION	THICKNESS	OIL
PLEISTOCENE		POTWAR SILT						
PLEISTOCENE	Siwalik Group	SOAN	Qs	QTs	3000 m/s	conglom. & ss and varicolored claystone (Lei Conglometate)	1800+ m	
PLIOCENE	Siwalik Group	DHOK PATHAN	Tdp	QTs	3000 m/s	orange to red clay-stone and grey ss	1000 m	
PLIOCENE	Siwalik Group	NAGRI	Tn	QTs	3000 m/s	green-grey, x-bedded ss & subordinate red to brown clay	1000 m	
PLIOCENE	Siwalik Group	CHINJI	Tc	QTs	3000 m/s	red clay with sub-ordinate grey ss	1500 m	
MIOCENE	Rawalpindi Group	KAMLIAL	Tk	Tr	3300 m/s	red to purple ss & clay with intraformational conglomerates	100-150 m	
MIOCENE	Rawalpindi Group	MURREE	Tm	Tr	3300 m/s	red to purple clay & ss with intraformational & basal conglomerates	approx. 2000 m	yes
EOCENE		BHADRAR	Te	Є - E	4000 m/s	limestone and shale	50-150 m	yes
EOCENE		SAKESAR	Te	Є - E	4000 m/s	limestone	50-150 m	yes
EOCENE		NAMMAL	Te	Є - E	4000 m/s	limestone	50-150 m	
PALEOCENE		PATALA	Tp	Є - E	4000 m/s	shale	20-60 m	
PALEOCENE		LOCKHART	Tp	Є - E	4000 m/s	limestone	20-60 m	yes
PERMIAN		AMB	P	Є - E	4000 m/s	limestone	0-275 m Truncated to the west by an unconformity	yes
PERMIAN		SARDHAI	P	Є - E	4000 m/s	sandy shale, siltstone		
PERMIAN		WARCHHA	P	Є - E	4000 m/s	sandstone		
PERMIAN		DANDOT	P	Є - E	4000 m/s	shale		
PERMIAN		TOBRA	P	Є - E	4000 m/s	conglomerate		yes
CAMBRIAN		BAGHANWALA	Є	Є - E	4000 m/s	shale, salt pseudo.	110-350 m Truncated to the east by an unconformity.	
CAMBRIAN		JUTANA	Є	Є - E	4000 m/s	sandy dolomite		
CAMBRIAN		KUSSAK	Є	Є - E	4000 m/s	sandy shale		
CAMBRIAN		KHEWRA	Є	Є - E	4000 m/s	red brown sandstone		yes
INFRA-CAMBRIAN		SALT RANGE FORMATION	SRF		4400 m/s	red marls and gypsum with interbeds of anhydrite and dolomite and thick seams of massive halite	0 to >2000 m	
PRE-CAMBRIAN		BASEMENT OF INDIAN SHIELD	PЄ		6000 m/s	biotite schist		

Figure 4.

Group consisting of the Khewra, Kussak, Jutana, and Baghanwala Formations (Gee, 1980). The Jhelum Group is disconformably overlain by rocks of Permian to Eocene age, the base of which consists of the Talchir Boulder Beds, of Gondwana affinity. This succession becomes thicker and more complete as one proceeds from east to west (Fatmi *et al*, 1984; Yeats and Hussain, 1987).

The upper part of the stratigraphic section in the SR/PP area comprises the Miocene Rawalpindi Group, and the Plio-Pleistocene Siwalik Group. The Rawalpindi Group consists of the Murree and Kamlial Formations, and the Siwalik Group consists of the Chinji, Nagri, Dhok Pathan, and Soan Formations (Figure 4). These strata are non-marine, time transgressive molassic facies that represent the erosional products of southward advancing Himalayan thrust sheets. They lie on progressively older beds to the south, such that in the Salt Range they lie on early Eocene carbonates, and in the Jhelum plain to the south they are directly on top of Cambrian rocks (Wells, 1984; Yeats and Hussain, 1987).

Johnson *et al* (1979) suggest that the fluvial and fluvio-deltaic Rawalpindi Group deposits indicate the initiation of significant Himalayan uplift. The Siwalik Group records continued uplift of the range. However, while the Lower Siwalik strata are derived from the crystalline and metamorphic terranes of the High Himalaya, Upper Siwalik deposits consist of recycled Lower and Middle Siwalik debris, uplifted and eroded as deformation progressed southward (Keller *et al*, 1977; Abid *et al*, 1983).

Previous attempts to correlate the facies within the molasse have been based on biostratigraphic (Pilgrim, 1913; Pilbeam *et al*, 1977) and lithostratigraphic (Pilgrim, 1910) criteria. More recently, a chronostratigraphic approach, employing magnetostratigraphy and tephrachronology, has permitted age-calibration of individual horizons within the Siwalik Group (e.g., Johnson *et al*, 1979, 1986). By constraining the timing of individual deformational events through the use of detailed chronostratigraphy, these data document the southward advancing deformational front, particularly in the eastern SR/PP.

Due to the recent deformation in the SR/PP, post Siwalik strata are essential for dating deformational events. However, much of these younger deposits have been removed by uplift and erosion. Fortunately, local preservation of the Lei Conglomerate does provide important timing information. The conglomerate, which has a basal age of about 1.9 Ma (Raynolds, 1980), is a valley fill deposit with Eocene clasts. Disregarding the recent alluvial cover, the youngest deposit is the Potwar Silt. Yeats *et al* (1984) suggest that this silt was ponded behind the rising Salt Range. Its age is less than 0.7 Ma (Raynolds, 1980) and may be as young as 170,000 years (J. Shroder, in prep.).

Structure

The earlier works of Wynne (1878), Pinfold (1918), Cotter (1933), Gee (1945, 1947), and Wadia (1945) provide much of the foundation for the modern structural interpretation of the Salt Range and Potwar Plateau. As mapped by Gee (1980), the Salt Range is deformed in several different ways. The stratigraphic section is cut by south-verging, imbricate thrust faults in the central and western portions, giving way westward to right-lateral tear faulting near the Indus River (Kalabagh fault; McDougall, 1985). Voskresenskiy (1978) indicates that north-verging folds are also common.

Beneath the SR/PP lies a shallow-dipping thrust that has carried the entire sedimentary section southwards along a décollement within the Salt Range Formation (Seeber and Armbruster, 1979; Lillie et al, 1987). The Salt Range itself is the topographical expression of this great thrust sheet riding up and over a down-to-the-north, basement normal fault (Lillie and Yousuf, 1986; Baker et al, 1988). However, as one moves eastward, away from the central Salt Range, the prominent topographic expression of the thrust front dies out around the Chambal Ridge (Yeats et al, 1984).

North of the central Salt Range, the intense folding and faulting give way to the asymmetrical Soan syncline, with a gently-dipping south flank and a steeply-dipping north flank. Seismic lines north of the Soan syncline (northern Potwar deformed zone, Figure 2) show a north-dipping imbricate stack (Baker, 1987; Leathers, 1987; Lillie et al, 1987; Baker et al, 1988), similar in many respects to the triangle zone in the Alberta foothills of the Canadian Rockies (Price, 1981, 1986; Jones, 1982).

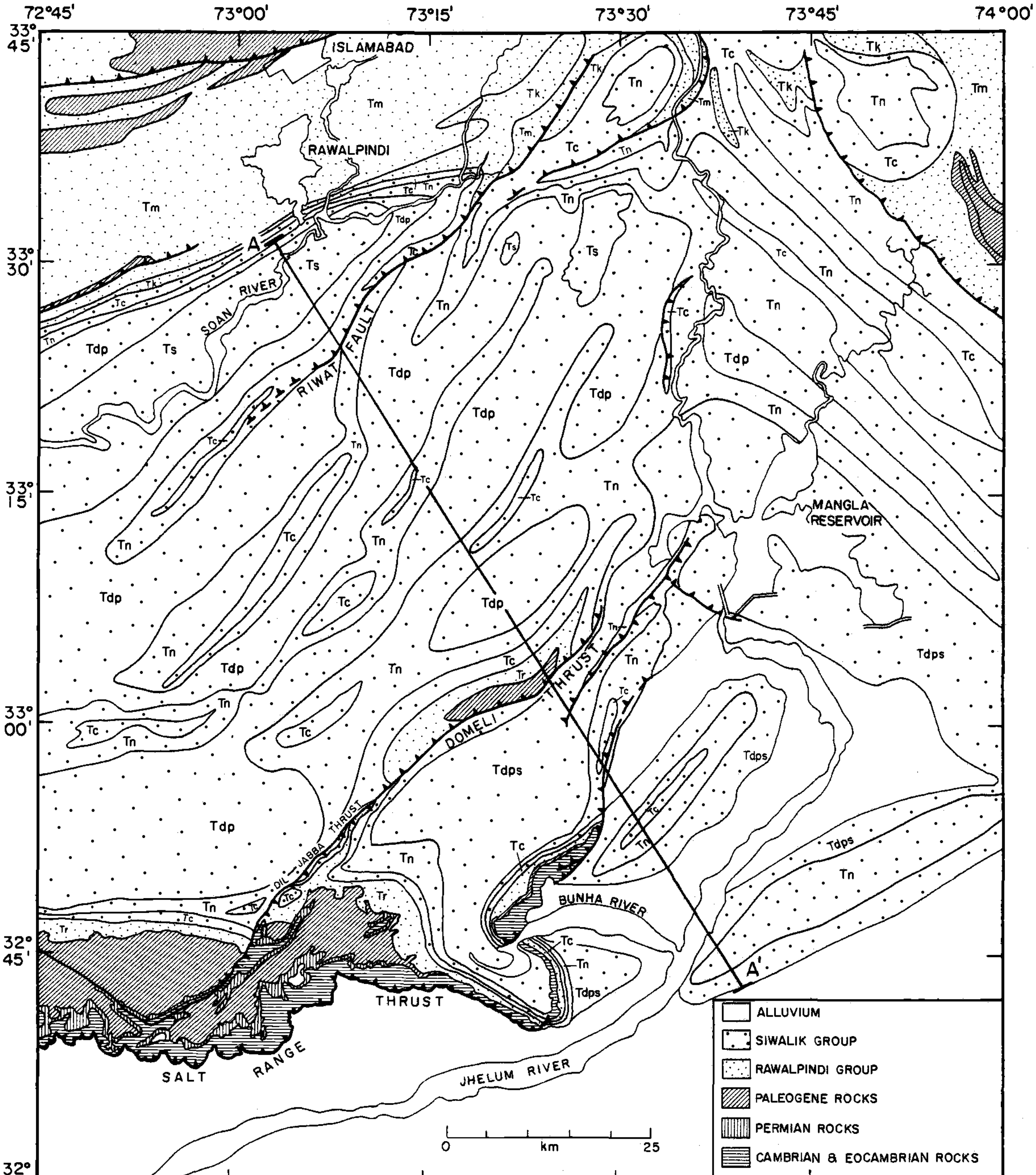
The eastern Salt Range is dominated by folding. Most of the folds in the eastern SR/PP trend NE-SW, in stark contrast to the E-W trending folds in the central SR/PP, and the NW-SE trending folds on the eastern side of the Jhelum Reentrant (Figures 1 and 2). Wavelengths of the folds are typically 10-12 km. Along their lengths, many individual folds gently plunge into saddles; however, overall fold trends are clearly identifiable for distances of 40-60 km. In some instances, the plunging ends of the anticlines coincide with prominent changes in fold trend (e.g., NE end of the Tanwin-Bains anticline; Figure 2).

Folding and erosion of most of the anticlines has exposed rocks of the lower Siwalik Chinji Formation (Figure 5). Although all of the molasse facies rocks are time-transgressive to the south, a nominal age range for the Chinji Formation is 13.1-10.1 Ma (Johnson *et al*, 1982). Stripping of the overlying Nagri, Dhok Pathan, and Soan Formations requires structural relief in excess of 1500 m.

Perhaps most important to a structural interpretation of the eastern SR/PP are that: 1) the anticlines are tight structures, separated by broad, open synclines; 2) dips in the axial zones of most of the anticlines are steep to overturned, as evidenced by both surface and aerial photo mapping (Martin, 1962; Raynolds, 1980); and 3) despite the intense deformation in the cores of the anticlines, surface faulting is comparatively rare. With the exception of the Domeli thrust, those faults which are mapped at the surface display relatively minor displacements.

Johnson *et al* (1986) suggest that the folded structures in the eastern SR/PP are cored by blind, sledrunner thrusts. They suggest that these thrusts cut up-section due to increased basal friction caused by an eastward thinning of salt along the edge of an extensive

Figure 5. Geologic map of the eastern SR/PP. Geology from eastern Salt Range modified from Gee (1980); Mahesian and Lehri anticlines modified from Martin (1962; see Figure 2 for location); northeastern Potwar Plateau compiled from Raynolds (1980) and unpublished 1:100,000 oil company maps; other areas compiled from LANDSAT imagery and unpublished oil company maps. A-A' is the line of the balanced structural cross-section constructed in this paper (Figure 8). See Figure 4 for formation abbreviations. Tdps=undifferentiated Dhok Pathan and Soan Formation. Formation contacts within Siwalik Group and between Siwalik Group and Alluvium are approximated.



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RAWALPINDI
SOAN RIVER
RIWAT FAULT
DOMELI THRUST
DIL JABBA THRUST
MANGLA RESERVOIR
BUNHA RIVER
THRUST
SALT RANGE
JHELUM RIVER
A
A'
0 km 25
ALLUVIUM
SIWALIK GROUP
RAWALPINDI GROUP
PALEOGENE ROCKS
PERMIAN ROCKS
CAMBRIAN & EOCAMBRIAN ROCKS

Figure 5.

Eocambrian salt basin, as predicted by Davis and Engelder (1985). However, Jaumé (1986), and Leathers (1987) suggest that thrusts may cut up-section due primarily to the extremely shallow dip of the basement (<1°), an idea also consistent with the mechanical model developed by Davis and Engelder (1985) for fold-and-thrust belts that have developed over evaporites. More recently, Butler *et al* (1987) have suggested that the structures in the eastern SR/PP decouple within the molasse sediments, not within the Salt Range Formation, but this interpretation is inconsistent with observations from reflection profiles across the region.

STRUCTURAL STYLES IN THE EASTERN SR/PP

The foundation for this study consists of approximately 1600 km of commercial seismic reflection profiles and data from 14 exploration wells, previously unreleased to the academic community (Figure 3). Only a handful of previous interpretations of the SR/PP have used and published commercial well data and seismic reflection profiles (Khan *et al*, 1986; Lillie and Yousuf, 1986; Lillie *et al*, 1987; Baker *et al*, 1988). The profiles from the eastern SR/PP provide crucial subsurface constraints in an area that is structurally unique in the Himalayan foreland of northern Pakistan, and of considerable economic importance in light of recent oil and gas discoveries (Fletcher and Soeparjadi, 1984; Khan *et al*, 1986).

Exploration wells south of the Soan syncline have never drilled repeated section. Due to severe and dangerous overpressures within the molasse, some of these wells never reached the primary Cambrian to Eocene objectives. Other wells, which penetrate the targeted Cambrian to Eocene strata, bottom in the Salt Range Formation, which is generally regarded as economic basement for this part of the fold-and-thrust belt. In one instance, the Hayal well (Figure 3), which was drilled to test a sub-thrust play, reached total depth at 2651 m, after drilling 1700+ m of evaporites. Nevertheless, although duplicated section has never been encountered in drilling, convincing evidence for subsurface thrusting and repetition of beds can be seen on seismic reflection lines (Figures 6 and 7), as shown in both cross-sectional (Figure 8) and plan (Figure 9) view.

Figure 6. (A) Composite seismic line across the eastern SR/PP used for balanced cross-section A-A' (see Figure 3 for location). Line 805PTW-4a is migrated, 12-fold, dynamite source, recorded and processed in 1978 by OGDC. Line 785PTW-4 is 24-fold, 6-32 Hz, Vibroseis™ (CONOCO Inc.) source, recorded in 1978 by O.G.D.C., and processed by Gulf Research and Development Company. Line PW15-W is 12- to 24-fold, 12-40 Hz, Vibroseis™ (CONOCO Inc.) source, recorded in 1976 by Western Geophysical Company and processed by Amoco. Lines are tied along strike; however, there is a difference in horizontal scale between line 785PTW-4 and the line PW15-W.

(B) Generalized interpretation of (A).

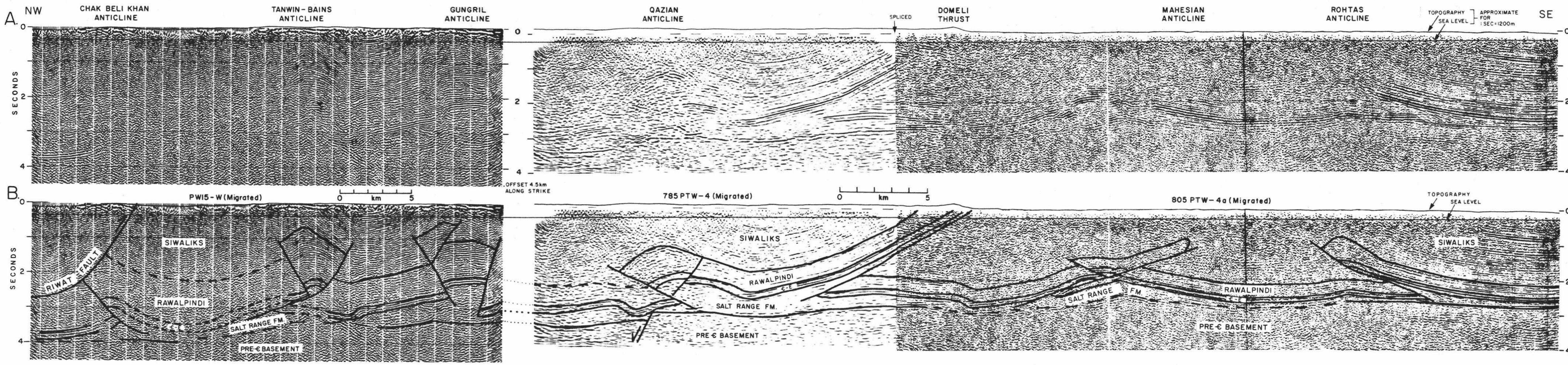
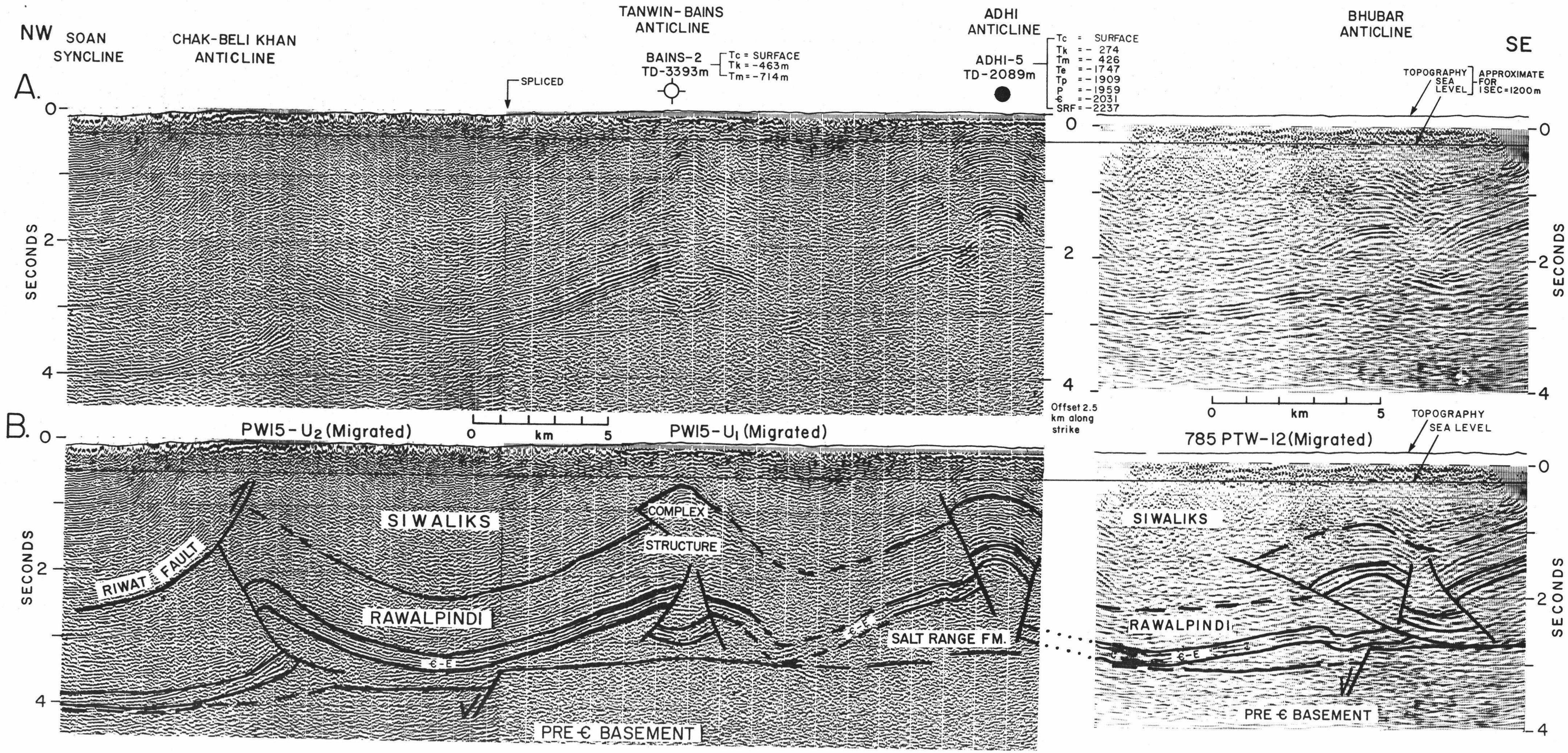

A.
NW
CHAK BELI KHAN ANTICLINE
TANWIN-BAINS ANTICLINE
GUNGRIL ANTICLINE
QAZIAN ANTICLINE
SPLICED
DOMELI THRUST
MAHESIAN ANTICLINE
ROHTAS ANTICLINE
TOPOGRAPHY
SEA LEVEL
APPROXIMATE FOR 1 SEC=1200m
SE
SECONDS
B.
PWI5-W (Migrated)
0 km 5
OFFSET 4.5km ALONG STRIKE
785 PTW-4 (Migrated)
805 PTW-4a (Migrated)
RIWAT FAULT
SIWALIKS
RAWALPINDI
SALT RANGE FM.
PRE-€ BASEMENT

Figure 6.

Figure 7. (A) Composite seismic line across a portion of the eastern SR/PP (see Figure 3 for location). Line 785PTW-12 is migrated, 24-fold, dynamite source, recorded in 1978 by OGDC and processed by Gulf Research and Development Company. Line PW15-U_1 and U_2 are migrated, 24-fold, 12-40 Hz, Vibroseis™ (CONOCO Inc.) source, recorded in 1976 by Western Geophysical Company and processed by Amoco. Lines are tied along strike; however, there is a difference in horizontal scale between line 785PTW-12 and the other two lines. Well information includes tops of formations relative to sea level datum. Abbreviations are the same as for Figure 4.

(B) Generalized interpretation of (A).



NW
SOAN SYNCLINE
CHAK-BELI KHAN ANTICLINE
TANWIN-BAINS ANTICLINE
ADHI ANTICLINE
BHUBAR ANTICLINE
SE
A.
SPLICED
BAINS-2 TD-3393m
Tc = SURFACE
Tk = -463m
Tm = -714m
ADHI-5 TD-2089m
Tc = SURFACE
Tk = - 274
Tm = - 426
Te = -1747
Tp = -1909
P = -1959
€ = -2031
SRF = -2237
TOPOGRAPHY
SEA LEVEL
APPROXIMATE FOR 1SEC=1200m
SECONDS
Offset 2.5 km along strike
B.
PW15-U2 (Migrated)
PW15-U1 (Migrated)
km
785 PTW-12 (Migrated)
TOPOGRAPHY
SEA LEVEL
SIWALIKS
COMPLEX
STRUCTURE
RIWAT FAULT
RAWALPINDI
SALT RANGE FM.
PRE € BASEMENT

Figure 7.

Figure 8. Balanced and restored structural cross-section of the eastern SR/PP (line A-A', Figure 2). A) Post Rawalpindi, pre-Siwalik restoration (approx. 12-13 Ma). B) Balanced cross-section showing present structure. In particular, notice: 1) the distribution of deformation across the breadth of the section; 2) the lack of a dominant sense of vergence; and 3) the shallow dip of the basement. Also note that the northern end of A-A' differs from line PW15-W (Figure 6). Due to the change in strike along the northern end of the Tanwin-Bains anticline (Figure 2), the Tanwin-Bains anticline lies just south of the Riwat fault.

EASTERN POTWAR PLATEAU

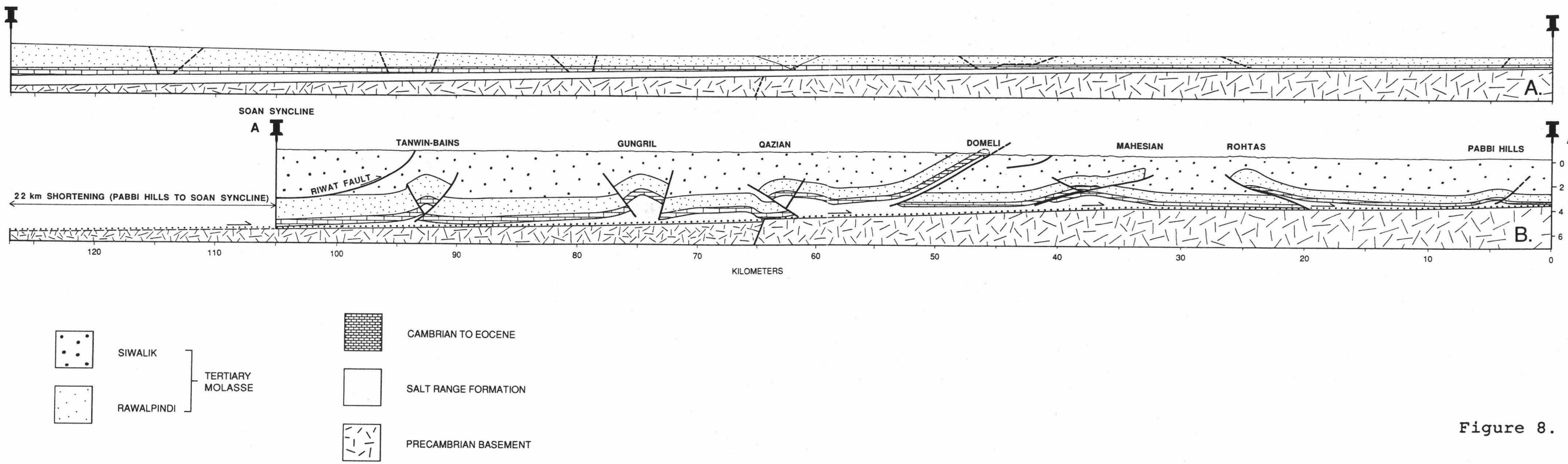
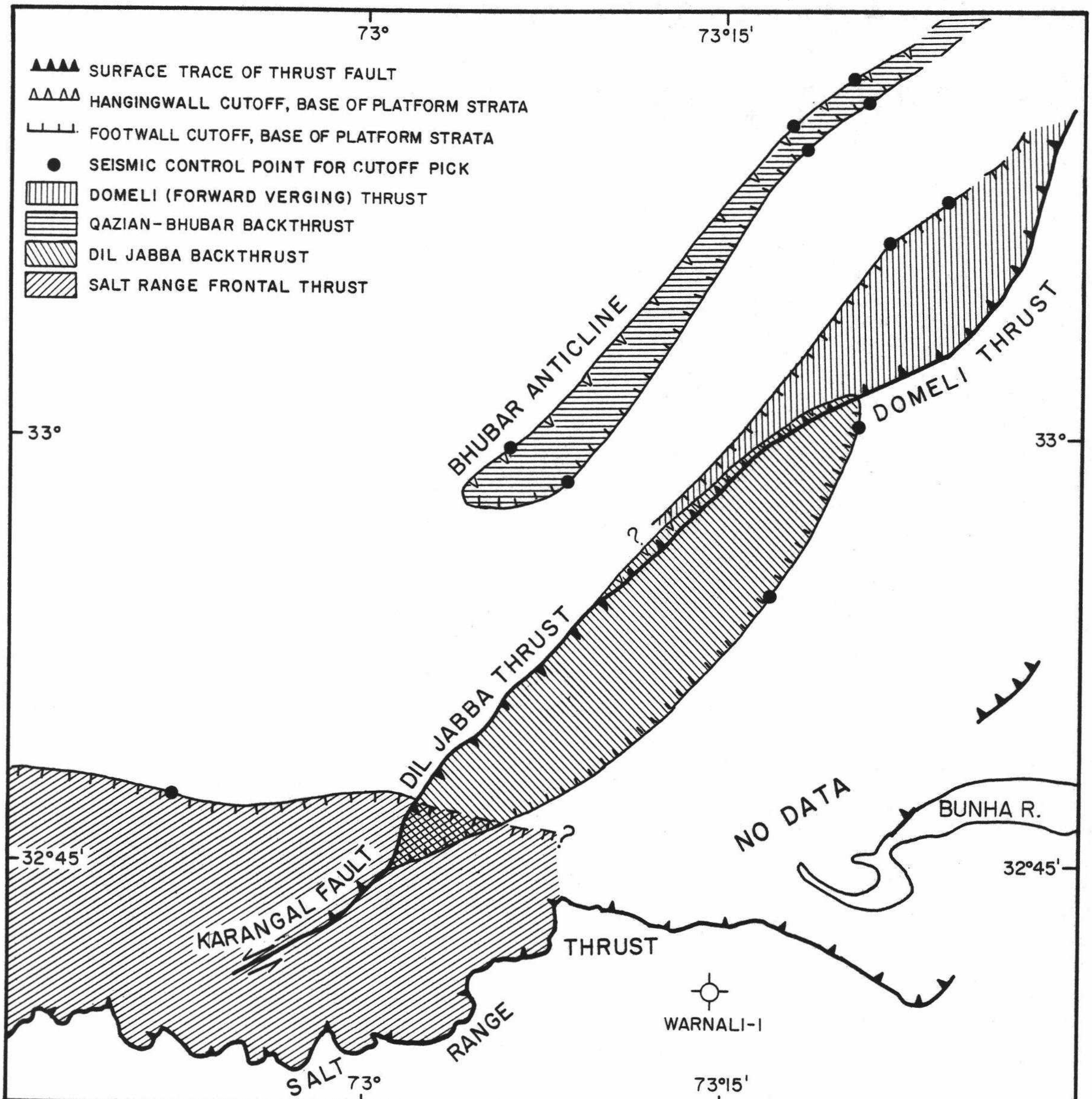


Figure 8.

Figure 9. Map demonstrating areas of duplicated Cambrian to Eocene platform strata in the southwestern portion of the eastern SR/PP. Duplicated zones (shaded areas) are determined by mapping the separation of matching hanging wall-footwall cutoffs. Small zone of triplicated strata beneath the Bhubar anticline is not depicted. Cutoffs and zones of repetition constrained by seismic reflection data. Salt Range thrust sheet footwall cutoff from Baker (1987). With the exception of Precambrian basement encountered in the Warnali well, no well in the SR/PP has penetrated below the Salt Range Formation. The assumption made during drilling was that the Salt Range Formation was the economic basement, below which no hydrocarbons would be found. As this figure demonstrates, overthrust structures in the eastern SR/PP have caused the platform section to be duplicated in some areas, leaving numerous sub-thrust plays untested for hydrocarbons. The figure also demonstrates: 1) the complex nature of thrusting (overlapping thrust sheets) associated with the Domeli-Dil Jabba thrusts; and, 2) that the decrease in amount of shortening on the Salt Range thrust to the east (Baker, 1987) is compensated for by an increase in deformation along the Domeli-Dil Jabba thrusts.



73°
73°15'
SURFACE TRACE OF THRUST FAULT
HANGINGWALL CUTOFF, BASE OF PLATFORM STRATA
FOOTWALL CUTOFF, BASE OF PLATFORM STRATA
SEISMIC CONTROL POINT FOR CUTOFF PICK
DOMELI (FORWARD VERGING) THRUST
QAZIAN-BHUBAR BACKTHRUST
DIL JABBA BACKTHRUST
SALT RANGE FRONTAL THRUST
BHUBAR ANTICLINE
DOMELI THRUST
33°
33°
DIL JABBA THRUST
NO DATA
BUNHA R.
32°45'
32°45'
KARANGAL FAULT
THRUST
WARNALI-1
SALT RANGE
73°
73°15'

Figure 9.

Synthetic seismograms were made available by Shell for the Pabbi Hills, Lilla, and Warnali wells (Figure 3). Where synthetics were not provided, interval velocities, which were derived from stacking velocities, were used to tie the seismic data to the wells. Once tied, the seismic expression of the different lithologies could be characterized. In general, the stratigraphic column can be broken down into four divisions based on seismic signatures (Figure 4). The molasse is typified by semi-continuous, parallel reflections of moderate amplitude (Figures 6 and 7). Below the molasse are a series of strong, parallel, continuous reflections of moderate to high amplitude. These reflections represent the Cambrian to Eocene platform sequence, and can be easily recognized throughout the SR/PP, except where data quality diminishes due to structural and/or topographical complexities. Below the platform sequence is a seismically transparent zone corresponding to the Salt Range Formation evaporites. Locally this zone gives way to semi-continuous reflections that may represent either bedded evaporites or the actual décollement plane. Finally comes a locally continuous, flat to sub-horizontal, strong reflection from the top of basement. The relatively consistent seismic signature of the different packages of rock throughout the region increases the confidence of the interpretation, even in areas where synthetic and velocity control are lacking.

Seismic lines across the eastern SR/PP reveal several important characteristics which can be summarized as follows (Figures 6 and 7):

1) Disharmonic folding and thrusting of all strata above the gently north-dipping basement indicate that the regional décollement in the eastern SR/PP lies within the Salt Range Formation (Raynolds, 1980; Davis and Engelder, 1985; Lillie *et al*, 1987); the décollement has not cut up-section into the molasse, as suggested by Butler *et al* (1987).
2) Surface folds are cored by both foreland- and hinterland-dipping, blind thrusts.
3) Salt has flowed away from beneath synclines into the cores of adjacent anticlines.
4) Basement offsets appear to localize thrusting in some instances.
5) Fault-propagation folds (Suppe and Medwedeff, 1984; Suppe, 1985), and triangle zones and pop-up structures (Butler, 1982) are all common deformational styles.

Many of these features are similar to those interpreted from seismic profiles across the Parry Island fold belt in the Canadian Arctic (Fox, 1983), as noted by Davis and Engelder (1985).

Basement Offsets

Seismic reflection data reveal numerous undulations and offsets of the basement reflection in the eastern SR/PP (Figures 6 and 7), suggesting that the top of basement may not be a smooth, north-dipping feature. Lateral velocity changes can explain some, but not all, of these features on the time sections. Beneath the

Rohtas anticline and Domeli thrust, the basement reflection abruptly steepens (line 805 PTW-4a, Figure 6). In both cases, reflections above the basement show the same deviation. Surface geology reveals that the Domeli thrust, which brings high-velocity, Eocene carbonates to the surface, crops out immediately above the time offset. In the case of the Rohtas anticline, the hanging wall cutoff of the carbonate section is interpreted to lie directly over the time offset.

The apparent offsets of the basement in these two examples may be nothing more than velocity artifacts; there is no reason to interpret actual basement offsets. Using the velocities in Figure 4, replacing 1500 m of slow Siwalik molasse with evaporites (100 m), carbonates (400 m), and Rawalpindi molasse (1000 m) yields a time difference of 0.148 sec. Thus, the majority of the 0.2 sec time sag is explained by overthrusting and duplication of the faster rocks. The remaining velocity sag is best accounted for by assuming local velocity anomalies, which are different than the velocities used in the simplified model (Figure 4).

However, velocity effects do not explain all of the offset basement reflections in the eastern SR/PP. Basement faults similar to the one beneath the central SR/PP (i.e., Baker, 1987; Lillie et *al*, 1987; Baker et *al*, 1988) are interpreted to exist beneath the Joya Mair-Chak Naurang anticlines, the Qazian-Bhubar anticlinal trend, and the Chak Beli Khan anticline (Figure 2). In all cases, the faults appear to be down-to-the-north. However, based on seismic data alone, the direction of dip of the fault plane is equivocal; it is, therefore, not clear whether the faults have normal or reverse sense of offset.

In the central Salt Range, interpretations for the origin of the large basement fault (dotted line south of the Baun syncline, Figure 2) include: 1) normal faulting related to either an Eocambrian or Mesozoic rifting event; 2) reverse faulting related to either latest Cretaceous to Paleocene compression in the Attock-Cherat Range or to the current compressional regime (Yeats and Hussain, 1987); and 3) normal faulting related to flexural loading of the basement by southward advancing thrust sheets (Lillie and Yousuf, 1986; Lillie *et al*, 1987; Duroy *et al*, in review). Stratigraphic and sedimentological evidence indicates that the flexural loading model is the most likely interpretation and suggests that normal faulting in the central SR/PP occurred approximately 4.5 Ma (Baker, 1987; Baker *et al*, 1988), as evidenced by unroofed Eocene clasts deposited 4.5 Ma in the Baun syncline (Johnson *et al*, 1986; Burbank and Raynolds, in prep.). By analogy, most of the basement faults in the eastern SR/PP are also interpreted to be down-to-the-north, normal faults. Although a lack of stratigraphic and sedimentological evidence in the eastern SR/PP precludes an estimation of the timing of basement faulting, in this interpretation they are inferred to predate Neogene thrusting.

In the northeastern-most part of the SR/PP, a few N-S trending basement faults are interpreted from seismic data to have reverse offset. Possible explanations for the origin of reverse faulting may lie within a more fundamental understanding of the origin of the

Jhelum Reentrant and its northern extension, the Hazara-Kashmir Syntaxis. Reverse faults may represent strain related to the bending of the mountain chain around a "tongue-like projection" of the Indian shield (Wadia, 1931). Alternatively, reverse faulting could either be related to, or actually accommodate, strike-slip faulting within the Jhelum Reentrant. Strike-slip faulting could be a mirror image of the right-lateral Kalabagh tear fault in the western SR/PP (McDougall, 1985).

Fault-Propagation Folds

Structures that develop above a thick salt décollement commonly show a strong sense of symmetry (Davis and Engelder, 1985). Although this is generally true for the eastern SR/PP, there are some folds that are asymmetrical and overturned. Colman-Sadd (1978) observed that most structures in the Zagros Fold Belt of Iran are southward (foreland) verging. He attributed this sense of vergence to the relative depletion of salt from beneath synclines. This consequence would produce imperfect decoupling beneath the syncline, thus retarding the development of the back limb and resulting in the observed asymmetry. This process may play a role in the eastern SR/PP, where salt has clearly flowed from beneath synclines.

Fault-propagation folding (Suppe and Medwedeff, 1984; Suppe, 1985) also provides a good explanation for the steep to overturned limbs characteristic of many of the folds and the lack of major thrust faults recognized at the surface. These structures are asymmetric, hanging wall folds which develop immediately in front of the tip line of a thrust fault (Suppe and Medwedeff, 1984; Mitra, 1986). Propagation of the thrust tip may be either a consequence of folding or the catalyst for folding (see Williams and Chapman, 1983). In either event, the decrease in fault displacement up-section is balanced by an increase in fold-related shortening.

Chak Naurang Anticline -- An excellent example of a fault-propagation fold can be seen beneath the Chak Naurang anticline (Figure 10). It is a southward-verging anticline with a steeply-dipping southern limb and a moderately-dipping northern limb. No fault has been mapped at the surface. Reflection data show a strong, north-dipping basement reflection, overlain by a thick evaporite section. The evaporites thicken from 0.63 sec of two-way travel time (approx. 1400 m) at the southern end of line 782CW-24 to 1.12 sec (approx. 2450 m) in the hanging wall of the fault. Above the evaporites, the strongly reflective platform sequence is offset, and the fault appears to lose displacement up-section in the Rawalpindi and Siwalik Formations.

The thickened salt beneath the Chak Naurang anticline may represent layer-parallel thickening formed in response to compressive stresses associated with buttressing at the Salt Range normal fault (Baker, 1987; Baker et *al*, 1988). In this respect the basement offset created a sticking point on the décollement surface. Similarly, the salt-thickened cores of anticlines farther to the east may represent layer-parallel thickening associated with sticking along the décollement surface (e.g., Fischer and Coward,

Figure 10. (A) Seismic line across the Chak Naurang anticline showing a fault-propagation fold (see Figure 3 for location). Line 782CW-24 is 12-fold, migrated, dynamite source, recorded in 1978 by OGDC, and processed by Gulf Research and Development Company. The Chak Naurang well is located 1.5 km west of seismic line along strike. Well information includes tops of formations relative to sea level datum. Abbreviations are the same as in Figure 4.

(B) Generalized interpretation of (A).

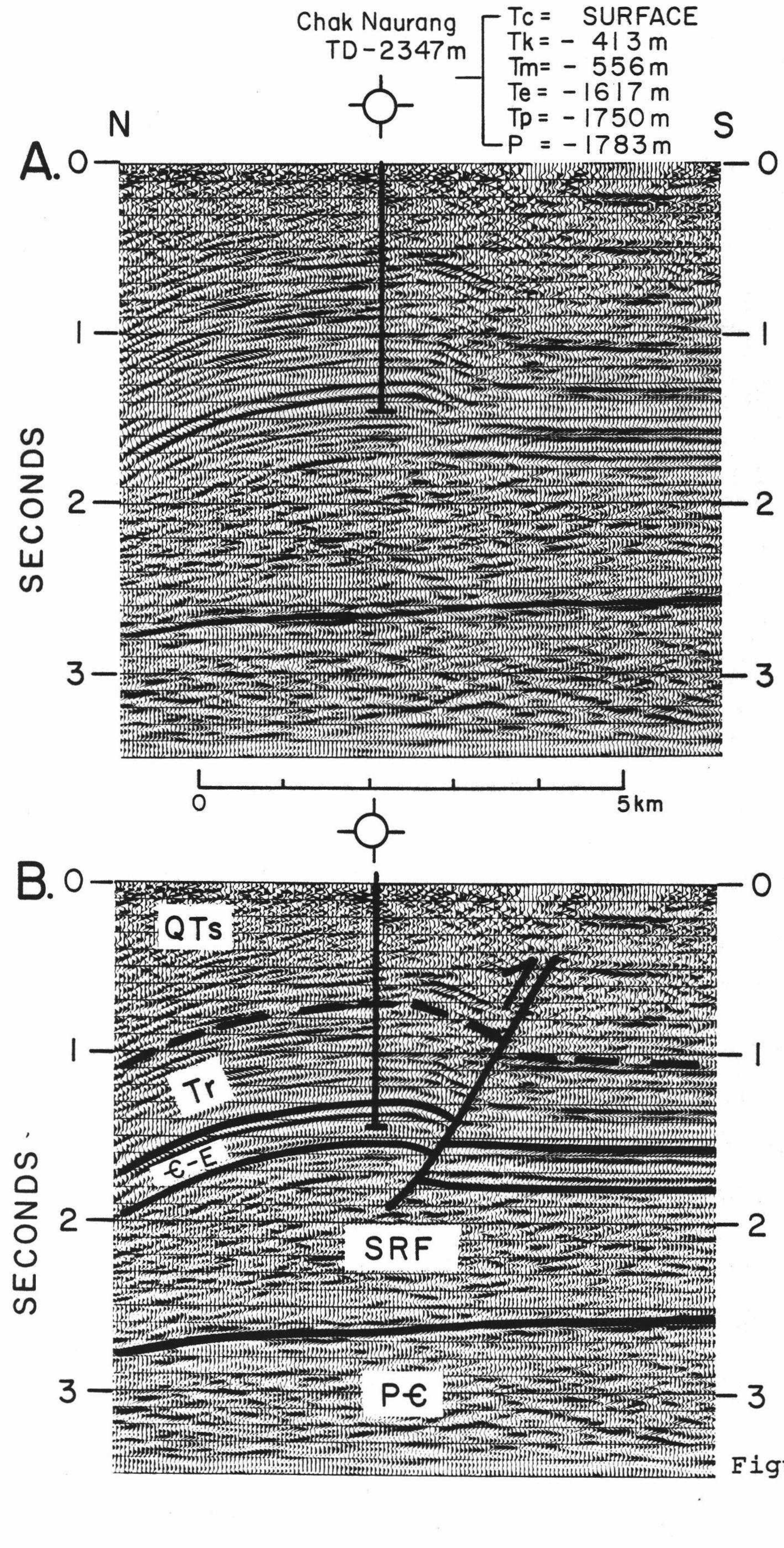

Chak Naurang
TD-2347m
Tc = SURFACE
Tk= - 413 m
Tm= - 556 m
Te = -1617 m
Tp = -1750 m
P = -1783 m
N
S
A.
0
1
2
3
SECONDS
0
5 km
B.
QTs
Tr
Є-E
SRF
P-Є

Figure 10.

1982; Coward and McClay, 1983). Chapman and Williams (1984) explain this as a result of the thrust propagation rate being much slower than the thrust slip rate. In the eastern SR/PP, this relationship is best explained by the ability of the evaporites to flow into the cores of the anticlines, thus accommodating the shortening (slip) during the initial stages of folding. At a certain stage, perhaps related to either rock competency contrasts (William and Chapman, 1983) or the limited availability of the evaporites to flow into the core of the fold, a fracture may nucleate. This sequence of events has been demonstrated in experiments using multilayered plasticene models (Dubey and Behzadi, 1981).

The Chak Naurang fault propagation fold appears to have frozen while still in the initial stages of development. Its excellent seismic expression (Figure 10) is indicative of its relative lack of deformation. Unfortunately, much of the seismic data farther to the east are less clear because deformation is much greater. However, surface data do suggest that several eastern SR/PP folds may be fault propagation folds.

Mahesian Anticline -- The Mahesian anticline, which exposes Chinji rocks in its core, is bent near the town of Mahesian into a more southerly direction (Figure 5). The fold is cut by two small faults, neither of which shows surface displacements of more than a few meters (Martin, 1962). The southern end of the fold, which is crossed by line 805PTW-4a (Figure 6), has an overturned eastern limb (60°-75°) and a moderately-dipping western limb (30°-40°).

The subsurface structure of the Mahesian anticline is peculiar (Figure 6). Five to six km north of the mapped surface exposure of the fold, at a two-way travel time of 2.0 sec (approximately 3200 m), lies a salt cored structure similar to the "opposed dip complex" of Butler *et al* (1987). This structure is interpreted as a fault-propagation fold which has developed a small pop-up backthrust. This interpretation explains the apparent offset between the surface and subsurface positions of the structure and the observed overturning and asymmetry of the beds at the surface.

Triangle Zones and Pop-Up Structures

Isolated pop-up and triangle zones (terminology of Butler, 1982) and low amplitude folds are characteristic of broad regions of low deformation. These structures are well-developed in the Appalachian fold belt of West Virginia, Pennsylvania, and New York (Gwinn, 1964; Root, 1973; Wiltschko and Chapple, 1977). Butler (1982) and Morley (1986) suggest that triangle and pop-up zones are caused by stick-slip movement on the sole thrust, analogous to the mechanism for fault-propagation folds (Fischer and Coward, 1982; Coward and McClay, 1983).

Adhi-Gungril Anticlines -- The Adhi and Gungril anticlines are relatively symmetrical structures. Their crestal regions are gently dipping (generally < 20°) compared to their flanks which are moderately dipping (30°-60°). Seismic reflection data (Figures 6 and 7) suggest that the Adhi-Gungril structure is a salt-cored pop-up bounded by steeply-dipping thrusts to the NW and SE. The strong, semi-continuous reflections recorded across the crest of the structure indicate relatively little hanging wall deformation. The Adhi-5 well confirms the presence of salt in the core of the fold at the relatively shallow depth of 1516 m (sub-sea). The salt is thick in the core of the fold (about 1.4 sec = 3080 m) and thins to nearly zero beneath the adjacent synclines. Like other pop-up structures, much of the shortening on Adhi-Gungril is accommodated through vertical displacements. This has certainly been influenced by the thick, buoyant evaporite core, and results in the steeply dipping bounding thrusts, and little deformed crestal zone. It is interesting to note that the Adhi field is one of the few producing fields south of the Soan syncline. Its productivity may be related to the relative lack of hanging wall deformation.

Tanwin-Bains Anticline -- The Tanwin-Bains anticline also shows a salt-thickened core (Figure 7). However, strong reflections, similar in seismic character to the platform sequence, appear to be overridden by thrusts both to the NW and SE. This geometry is interpreted as an incipient triangle zone (e.g., Butler, 1982) and is analogous to the axial depressed zone of anticlinal cores in the Appalachian Plateau Province (Gwinn, 1964).

This triangle zone can be mapped a minimum of 9 km to the SW (as far as line PW15-AI). However, only 9 km to the NE the Tanwin-Bains fold is interpreted to be cored by a southwest verging thrust which has developed a small pop-up backthrust (see line PW15-W, Figure 6). This peculiar "reversal" in structural style along strike requires that the displacement on the faults within the triangle zone must diminish to zero at some point between the triangle zone and the southward-verging thrust. Indeed, line PW15-V, a dip line which crosses the Tanwin-Bains structure between Figures 6 and 7, reveals that a salt pillow cores the fold; no thrusting is evident. This example demonstrates how significant changes in subsurface structural style can occur along strike, even without an apparent surface manifestation.

Domeli-Dil Jabba Thrusts -- Several aspects of the Domeli thrust (Figure 2) make it one of the most important structures in the eastern SR/PP. It is a foreland-verging fault that shows a significant amount of shortening (approximately 8.8 km, Table 1). It is one of the few emergent thrusts in the eastern SR/PP and is the only thrust along cross-section A-A' which carries Eocene rocks to the surface (Figure 5). To the southwest, progressively younger rocks are exposed along the fault trace. However, the fault flips polarity, such that Cambrian rocks are brought to the surface on the south side of the fault at Dil Jabba (Figure 5).

Seismic lines north of the Domeli thrust clearly show the footwall cutoff of the Cambrian to Eocene platform sequence (Figure 6). The amount of shortening along the Domeli thrust, determined by measuring the hanging wall-footwall separation, decreases to the southwest (Figure 9). This decrease in shortening is partially compensated for by an increase in shortening on a backthrust beneath the Qazian-Bhubar anticline trend. South of the Domeli thrust, seismic data reveal a duplicated Cambrian to Eocene platform

Table 1. Summary of structural styles, timing of deformation, and rotations in the eastern SR/PP. Blank boxes indicate that no data are available. Note general north-to-south progression of deformation, although out-of-sequence deformation is also apparent. Superscripts refer to sources as follows: 1) Burbank and Raynolds (in prep.); 2) Burbank *et al* (in press); 3) Johnson *et al* (1986); 4) Yeats *et al* (1984); 5) Johnson *et al* (1982); 6) Opdyke *et al* (1982); 7) Raynolds (1980); 8) Opdyke *et al* (1979); 9) Johnson *et al* (1979); 10) Keller *et al* (1977).

Table 1.

Structure	Initial Def. (Ma)	Surface Expression (Ma)	Counter-clockwise Rotation	Structural style	Estimated Shortening (km)		
					struc.	total	
Soan Syncline	2.1-1.9[3]		40° ±10°[2]				NORTH
Riwat Fault		3.4-2.7[3]		Out-of-the-syncline thrust			
Buttar	< 5.5[3]			Salt cored pop-up			
Chak Beli Khan				Fault-propagation fold above a backthrust			
Tanwin-Bains		Pre- Riwat Fault[7]		Fault-propagation fold complicated by triangle zone	1.9	23.1	
Adhi/Gungril				Salt-cored pop-up	1.3	21.2	
Qazian/Bhubar				Hanging wall fold above a backthrust; pop-up to NE	2.1	19.9	
Jabbar		< 3.0[3,5]					
Domeli		2.5[3,5]		Forethrust, possibly ramping above a basement normal fault	8.8	17.8	
Mahesian/Lehri	2.3[3,5]		9°[1]	Fault-propagation fold above a forethrust	4.2	9.0	
Rohtas	1.7[9]	by 0.4[3,9]	0°[8]	Fault-propagation fold above a backthrust	4.5	4.8	
Chambal Ridge	< 2.4[9]	< 0.7[9]	10°[6]				
Pabbi Hills	1.2[9]	0.4[4,9,10]		Fault-propagation fold above a forethrust.	0.3	0.3	SOUTH

sequence. These repeated strata can be traced to the Dil Jabba backthrust. Thus, the flipping of the polarity along the Domeli-Dil Jabba thrust trace is explained by overlapping traces of different thrust sheets. The opposed dips of the intersecting thrusts produce a triangle zone geometry.

Out-of-the-Syncline Thrusts

South of the Hill Ranges, folding and thrusting expose Eocene and younger strata in the northern Potwar deformed zone (NPDZ of Baker, 1987, and Leathers, 1987). In light of seismic reflection and well data, Baker (1987), Leathers (1987), and Lillie *et al* (1987), interpret much of this area as a triangle zone (see NPDZ, Figure 11). Similar structures are found associated with mountain fronts around the world (Bally *et al*, 1966; Price, 1981; Jones, 1982, 1987; Vann *et al*, 1986). Recently, Banks and Warburton (1986) have called a similar structure in the Kirthar and Sulaiman Ranges of Pakistan a passive roof duplex. The development of hanging-wall folds formed by the stacking of ramp anticlines within a duplex involves significant amounts of shortening. The geometry also produces out-of-the-syncline thrusts that typically lie in front of, and develop during, the formation of the major steep zone (Banks and Warburton, 1986; Jones, 1987).

The Soan syncline marks the southern boundary of the NPDZ. South of the Soan syncline, in the eastern PP, the first major structure is the Riwat fault, interpreted here to be an out-of-the-

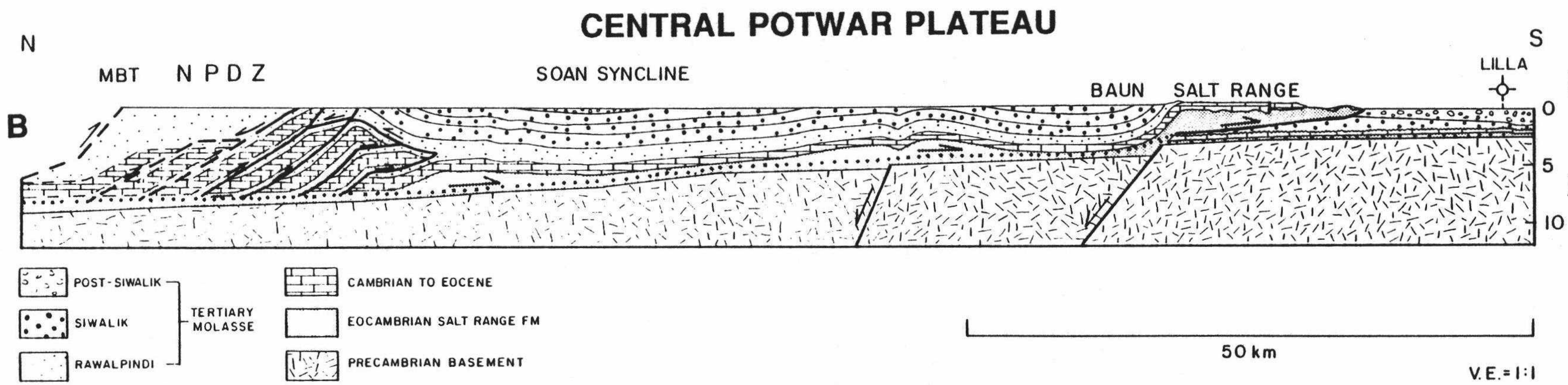


Figure 11. Balanced structural cross-section of the central SR/PP (after Baker, 1987; line B-B', fig. 2). Note the lack of internal deformation of the thrust sheet between the Salt Range and the northern Potwar deformed zone (NPDZ), and that virtually all of the shortening (approx. 22 km) has been concentrated at the range front along the Salt Range thrust.

syncline thrust. As such, the timing of deformation along the Riwat fault should be contemporaneous with deformation within the NPDZ, and the fault plane should not sole out into the master décollement in front of the triangle zone.

As mapped by Raynolds (1980), the Riwat fault is a southward verging thrust that juxtaposes Lower Siwalik sediments with Middle Siwalik deposits (Figure 5). At its southwestern terminus, it is shown dying out along the southeastern flank of the Chak Beli Khan anticline. To the northeast, it dies out near the axis of the Soan syncline. Magnetostratigraphic data from Kas Dovac (Raynolds, 1980) suggest that the Riwat fault uplifted the southeast flank of the Soan syncline between 3.4-2.7 Ma, and that by 2.6 Ma the fault had largely ceased to move (Table 1). Truncation of the Dhok Pathan Formation on the northern limb of the Soan syncline indicates that deformation in the NPDZ is at least as young as 5.1 Ma (Johnson *et al*, 1982), while folding of the Soan syncline between 2.1 and 1.8 Ma is thought to record the latest deformation within the NPDZ (Raynolds and Johnson, 1985; Johnson *et al*, 1986). Thus, the timing of thrusting along the Riwat fault appears to be contemporaneous with deformation within the NPDZ.

The Riwat fault crops out near the northern end of line PW15-W (Figure 6). The fault is traced into the subsurface by the juxtaposition of generally flat-lying reflections with north-dipping reflections at a two-way travel time of 2.4 sec (approximately 3500 m) along the fault trace. Although migration edge effects on the end of the line tend to mask the reflections, the fault is interpreted to become bedding-parallel north of this point so that it does not sole into the master décollement within the Salt Range Formation. Unfortunately, much of the available reflection data across and to the north of this portion of the Riwat fault are of poor quality and do not help to further delimit the geometry of the fault.

TECTONIC SHORTENING

Balanced Cross-Section

Reliable estimates of tectonic shortening can be obtained from balanced structural cross-sections. The use of balanced sections has a rich history in the oil and gas industry (Bally *et al*, 1966; Dahlstrom, 1969, 1970; Royse *et al*, 1975; Lamerson, 1982), and has been employed in several foreland fold-and-thrust belts around the world (Western Cordillera--Price, 1981; Alps--Butler, 1983; Appalachians--Roeder and Witherspoon, 1978). More recently, the technique has been used in the Himalayan foreland of northern Pakistan to determine the amount of contraction of the sedimentary cover and aid in the interpretation of structural timing (Coward and Butler, 1985; Butler *et al*, 1987; Leathers, 1987; Yeats and Hussain, 1987; Baker *et al*, 1988).

Complex deformation in the eastern SR/PP reduces seismic data quality in a number of locations. The line of section for the regional balanced cross-section (A-A', Figure 2) was chosen to maximize the potential of the seismic coverage. The southern 70 km of the balanced section either directly overlie seismic control, or require only slight (<1 km) projections onto the line of section. The northern 35 km trend obliquely to PW15-W (Figure 6) and cross several other seismic lines. Where appropriate, structure and well data were projected onto the line of section along the northern portion of the line.

Two different balancing techniques were employed to construct the balanced section across the eastern SR/PP. Because it is competent, the Cambrian to Eocene platform sequence has not thickened or thinned in response to deformation; well data showing a gradual thickening to the north can be interpreted simply in terms of stratigraphic thickening. Therefore, these strata could be balanced using bedlengths alone (Dahlstrom, 1969). However, the evaporite sequence has been deformed by ductile flow. Because bed thickness has not been conserved during deformation, this zone was balanced using the area method (Dahlstrom, 1969).

The highly variable thickness of molasse formations, as evidenced by well data, prompts additional section balancing considerations. The Bains-2 well (Figures 5 and 7) reached total depth in the Murree Formation after drilling 2401 m of Rawalpindi molasse. A strong set of intra-molasse reflections can be seen starting at 0.6 sec in the axial part of the fold (Figure 7). These reflections dip steeply to the north and south, away from the fold axis, and are strongly disharmonic with respect to underlying reflections. The intra-molasse reflections become parallel to the platform reflections approximately 2 km down-dip from the fold axis. This is particularly clear on the north limb of the structure. Additionally, the reflections between the strong intra-molasse reflections and the platform reflections are highly discontinuous and relatively incoherent, implying complex deformation. This is supported by surface geologic data which shows steep to overturned beds in the core of the fold. Similar relationships can be seen on line PW15-R (a dip line which crosses the Tanwin-1 well, which bottomed in molasse after drilling 2715 m of Rawalpindi Group).

The Adhi-5 well (Figures 5 and 7), located 12 km SE of the Bains-2 well, penetrated only 1473 m of Rawalpindi molasse. The seismic character of this structure is distinctly different from that of the Tanwin-Bains anticline (Figure 7). Most notable are the coherency, continuity, and parallelism of the reflections in the axial region of the fold. Gentler surface dips in the Adhi anticline also indicate this difference. These differences provide strong arguments in support of tectonic thickening of molasse in the Tanwin-Bains anticline.

Tectonic thickening of the molasse has important implications concerning both balancing and estimated values of shortening. Although the molasse has not flowed like the evaporites, complex deformation that is unresolvable by seismic data alone has required area balancing of the molasse. Tectonic thickening has also yielded unnaturally high thicknesses of molasse as recorded in wells. Therefore, the predeformed stratigraphic model is not derived strictly from well data; it also takes into account outcrop and seismic reflection constraints.

Balancing requires that pin lines be placed in zones of little or no interstratal slip. These zones correspond to the undeformed foreland to the south and to the axis of the Soan syncline to the north. Another requirement for a section to be rigorously balanced is that the line of section must be oriented parallel to the transport direction. Yeats *et al* (1984) suggest that the transport direction in the SR/PP is S15°E. However, the structures in the eastern SR/PP trend from approximately N40°E to N55°E. To facilitate the projection of surface, seismic, and well data, the regional balanced section (Figure 8) was drawn oblique to the transport direction, along a line trending N35°W. The calculated amount of shortening was then corrected to the transport direction using the methods of Cooper (1983).

Palinspastic Restoration

The amount of tectonic shortening is determined by comparing the position of points in the deformed section with their counterparts in the undeformed section. This shortening amounts to approximately 22 km along cross-section A-A' the eastern SR/PP (Figure 12). When corrected to the transport direction using the methods of Cooper (1983), a shortening value of 23.1 km (or 19% of the restored length of 127 km) is obtained. Table 1 shows the approximate amounts of shortening associated with individual structures. The overall value compares to estimates of approximately 20 km by Johnson *et al* (1986), 35-40 km by Butler *et al* (1987), and 13 km by Leathers (1987).

In general, estimates of shortening determined from balanced cross-sections are considered to be minimum values. They cannot, for example, account for eroded portions of thrust fronts. Although this problem does not play a significant role in the southern portion of the eastern SR/PP where the thrust tip line is buried, it may affect the amount of shortening estimated from emergent thrusts (e.g., the Domeli thrust). The correct matching of hanging-wall and footwall cutoffs is also crucial for an accurate depiction of shortening. Seismic constraints have, in general, reduced this error. However, in seismically transparent or disturbed zones, where the correct pairing may not always be made, ramp cutoffs have been consistently drawn to minimize shortening values.

A precise restoration of the deformed section across the eastern SR/PP is complicated by several factors. These circumstances include: 1) molasse facies are time-transgressive to the south; 2) due to tectonic thickening, the thickness of the molasse formations indicated by well data are not always representative of the original stratigraphic thickness; 3) the amount of movement on the Riwat fault is unknown; 4) the salt at the base of the sedimentary sequence has flowed; 5) timing of salt flow has not been constrained; 6) timing of the basement faulting is not well constrained.

To account for these complexities, the palinspastically restored model is based on several assumptions. The horizon chosen for the restoration is the top of the Rawalpindi, approximately 12-13 Ma. This horizon was chosen because it definitely precedes the southward advancing deformational front across the eastern SR/PP (Table 1), and because formations older than 13 Ma are less time-transgressive than younger formations (Leathers, 1987). Reflections on seismic lines also appear to show this Rawalpindi/Siwalik contact more noticeably than intra-Siwalik contacts, thus allowing a better estimation of the true stratigraphic thickness of the Rawalpindi molasse compared to the Siwalik molasse.

As previously mentioned, pin lines are supposed to be placed in zones of little or no interstratal slip. However, the northern pin line is located in the Soan syncline, which is deformed by the Riwat fault. Because the Riwat fault is interpreted to be an out-of-sequence, out-of-the-syncline thrust (accommodating shortening farther north in the NPDZ), it does not affect the amount of shortening determined on the basal décollement south of the pin line.

To accommodate salt flow, the following assumptions have been made: 1) the predeformed shape of the evaporites was a northward thickening wedge; 2) the evaporites have not flowed in or out of the plane of the section; and 3) the area of the evaporites in the plane of the section has not increased significantly due to southward flow from beneath the NPDZ and the Soan syncline, although some amount of southward flow has probably occurred (Gee, 1983). Restoration of the evaporite wedge, assuming conservation of area, yields a southern thickness of 150 m and a northern thickness of 830 m. The restored model also assumes that the deformation of salt by ductile flow did not occur until after the deposition of the Rawalpindi Group; however, it is possible that salt flow had already began by this time.

The basement normal fault beneath the Qazian anticline is interpreted as a Neogene feature associated with flexure of the top surface of the basement. With the absence of precise timing information, the restored section assumes that the basement fault occurred after Rawalpindi deposition; presumably it was contemporaneous with Siwalik deposition. The dip of the basement on the restored model was determined by assuming a 0.2° topographic slope (equal to the present-day topographic slope). Using this value, the intervening strata were restored sequentially from top to bottom, yielding a paleo-basement dip of 0.9°.

Times and Rate of Deformation

Although magnetostratigraphic studies provide an excellent record of the timing of deformation for parts of the eastern SR/PP (Table 1), significant gaps of data still preclude a complete understanding of the timing and rate of deformation. Spacially, the most widely separated deformational events in the eastern SR/PP are the folding of the Soan syncline and the Pabbi Hills anticline. However, folding of the Soan syncline between 2.1 and 1.8 Ma marks a major out-of-sequence event (Burbank and Raynolds, in prep.). The Riwat fault, active 3.4-2.7 Ma (Raynolds, 1980; Johnson et *al*, 1986), truncates the northeastern axis of the Tanwin-Bains anticline, again indicating out-of-sequence deformation.

The northernmost structure that does not appear to form out of sequence, and for which timing information is available, is the Domeli thrust. Raynolds (1980) dates surface expression of the thrust at approximately 2.5 Ma. This indicates that the deformational front has propagated at an average rate of about 27 mm/yr since 2.5 Ma. This is in close agreement with a 30 mm/yr facies migration rate for the same area (Raynolds and Johnson, 1985).

The amount of shortening that takes place along and to the south of the Domeli thrust is approximately 17.8 km (Table 1). Therefore, over the last 2.5 Ma, the average rate of frontal shortening in the eastern SR/PP is 7.1 mm/yr. This value compares with estimates of 9-14 mm/yr in the central SR/PP (Baker *et al*, 1988), 13 mm/yr in the western SR/PP (Leathers, 1987), and 10-15 mm/yr beneath the central Himalaya in India (Lyon-Caen and Molnar, 1985). The 7 mm/yr convergence rate for the eastern SR/PP may be lower than the others due to out-of-sequence deformation farther to the north.

The amount of frontal shortening in the eastern SR/PP represents only about 15% of the average plate convergence rate of 40-50 mm/yr between the Indian and Asian plates (LeFort, 1975; Minster and Jordan, 1978). The additional shortening is manifested by further shortening of the sedimentary sequence north of the PP (e.g., Johnson *et al*, 1986), uplift and internal deformation (lithospheric imbrication) within the Himalayan collision zone (e.g., Yeats and Lawrence, 1984) and escape-block tectonics within the Eurasian plate (e.g., Tapponnier *et al*, 1982; Baranowski *et al*, 1984).

Tectonic Rotations

Paleomagnetic studies throughout the SR/PP have documented aberrant paleopole positions for Cambrian and Permian rocks (Crawford, 1974; Klootwijk, 1979), as well as for Tertiary molasse (Opdyke *et al*, 1979, 1982; Burbank and Raynolds, in prep.; Burbank *et al*, in press). In general, they have been explained as a consequence of counterclockwise rotations which have accompanied overthrusting of the Salt Range thrust sheet. However, variable and seemingly contradictory rotational data indicate that rotation has involved complex mechanisms not yet fully understood.

Regional counterclockwise rotation of the Salt Range thrust sheet during ramping implies that total shortening will increase monotonically from east to west for the same period of time (R.S. Yeats, personal comm.). Taken at face value, the estimated 34 km of shortening in the western SR/PP (Leathers, 1987), 19-24 km of shortening in the central SR/PP (Baker, 1987; Baker *et al*, 1988), and 17 km of shortening south of the Domeli thrust along section A-A' suggest the possibility of regional rotation during ramping. However, Leathers (1987) addresses the fact that footwall cutoffs are not visible on all seismic lines and that shortening values may have been overestimated in the western SR/PP. In fact, Baker (1987) found no systematic increase in shortening along a series of N-S sections across the central SR.

Ramping of the Salt Range thrust sheet over the basement normal fault in the central SR/PP is interpreted to have occurred betwen 2.1-1.6 Ma (Baker, 1987; Baker *et al*, 1988). Therefore, rotation should also be restricted to this period of time. This appears to be the case along a paleomagnetic transect that crosses the Soan syncline south of Rawalpindi. On the basis of sampled sediments ranging in age from 9 to less than 0.7 Ma, Burbank *et al* (in press) have interpreted three phases of rotation lasting from approximately 9-2.5 Ma, 2.5-1.8 Ma, and 1.8-0.7 Ma. During the first phase, 10-20° of counterclockwise rotation took place, representing both Indian plate rotation and regional rotation away from the Hazara Kashmir syntaxis. The second phase was marked by little or no rotation. However, an additional 20-25° of counterclockwise rotation took place during the third phase of rotation. This indicates that a significant amount of rotation was roughly coeval with ramping. Burbank *et al* (in press) interpret this late-stage rotation as part of a regional rotation, above the décollement surface, in response to differential shearing along the Jhelum Reentrant.

However, a transect in the Baun syncline yields conflicting results. There, Opdyke *et al* (1982) have interpreted the 35° of counterclockwise rotation to have occurred prior to deposition of Upper Siwalik beds tentatively correlated with the Gilbert chron (3.3-4.5 Ma) by Opdyke *et al* (1979). These and other paleomagnetic data (Table 1) support the Opdyke *et al* (1982) interpretation that rotation above the décollement has occurred at different times in response to segmentation of the thrust sheet.

DISCUSSION

Telescoping vs. Translation

In the central and western SR/PP the Salt Range thrust sheet, whose trailing edge is marked by the northern limb of the Soan syncline, has been transported southward as a coherent slab, undergoing little internal deformation (Figure 11). Balanced cross-sections through these regions indicate that less than 1 km of the shortening occurs between the Salt Range and NPDZ (Baker, 1987; Leathers, 1987; Baker et *al*, 1988). Thus, south of the NPDZ, most of the shortening in the central and western SR/PP is without internal strain, and is manifested by overthrusting of the entire southern PP and SR (translation) as a coherent slab along the Salt Range thrust. This differs significantly from the corresponding areas in the eastern SR/PP where deformation has been distributed (telescoped) across the breadth of the foreland (Figures 6 and 8).

Butler et *al* (1987) have recently reported that the contrasting structural styles between the eastern and central SR/PP can be attributed to a different level of décollement within the sedimentary pile. They suggest that the folds in the eastern SR/PP have formed in response to increased basal traction as the décollement surface has risen into the molasse. Their transect (see Butler et *al*, 1987, their Figures 6 and 10), which is a few kilometers east of regional section A-A' (Figure 8), shows the following: 1) the décollement has progressively cut higher up into the molasse section in the direction of tectonic transport; 2) the platform sequence is thicker than the Rawalpindi molasse; 3) the Riwat fault has involved thrusting of the Cambrian to Eocene platform sequence; 4) the Domeli thrust has not offset any Cambrian to Eocene rocks; and, 5) thrusting south of the Domeli thrust involves only Siwalik strata. These interpretations are contradicted by the seismic and well data presented in this paper. The corresponding estimates of shortening derived from the restoration of Butler *et al* (1987) are too high.

Disharmonic folding above the basal evaporite sequence is clearly evident along the entire length of the composite seismic line (Figure 6). At the northern end of the line, the folds are cored by blind thrusts that have formed pop-up or triangle zones (e.g., the Tanwin-Bains and Adhi-Gungril anticlines). The Domeli thrust, which at the surface exposes Eocene carbonates in the overturned hanging wall (Figure 5), soles out into the Salt Range Formation. Southwards, the "opposed dip complex" of Butler *et al* (1987) can be seen just north of the Mahesian anticline. The seismic character of the core of this structure suggests that it is cored by salt, and that the deformation is not solely within Siwalik strata (Figure 6). The Mahesian well (Figure 3), which bottoms in the Salt Range Formation, confirms this. A strong basement reflection beneath the Rohtas anticline is overlain by a 0.2-0.3 sec sequence of chaotic reflections. The seismic character suggests that this is an evaporite sequence that has, in this case, influenced the location of a backthrust. The Pabbi Hills anticline, which marks the southernmost deformation in the eastern SR/PP, also appears to be cored by a thickened evaporite sequence. These relations can be seen on seismic line 781PTW-1 that is located approximately 20 km to the east of line 805PTW-4a (Figure 3).

Davis and Engelder (1985) suggest that abrupt changes in deformational style may occur along the edges of salt basins. Citing work in the Appalachian Plateau by Rodgers (1963) and in the Mackenzie Mountains by Aitken *et al* (1982), they concluded that both the wavelength and trend of the folds in the eastern SR/PP could be explained by faults cutting up-section in response to increased basal traction as the salt thins to the east. In the central SR/PP the average salt thickness is about 1.3 km (Baker, 1987), and in the eastern SR/PP the average salt thickness is about 0.5 km. Thus, a comparison of average salt thicknesses indicates that the salt does thin to the east.

However, when compared to other salt-floored fold-and-thrust belts, it would appear that the evaporite zone in the eastern SR/PP should be thick enough to act as an effective décollement zone. For example, Rodgers (1963) indicates that the average thickness of the Upper Silurian Salina Group through parts of Tioga County, Pennsylvania is approximately 305 m. Prucha (1968) and Jacoby and Dellwig (1974) give estimates of 282 m and 221-244 m, respectively, for its thickness through central New York. Davis and Engelder (1985) provide an average thickness of 100 m for the Triassic evaporites which form the zone of décollement in the Jura, and 200 m for the Cambrian Saline River Formation beneath the Franklin Mountains of northwestern Canada. These data suggest that a 100-300 m thick evaporitic sequence will act as an effective zone of décollement.

Jaumé (1987) and Jaumé and Lillie (in press) suggest that a shallower northward dip of the basement is primarily responsible for both the frequency of structures and the difference in structural style between the eastern and central SR/PP. When compared to a mechanical model that considers a fold-and-thrust belt to be analogous to a wedge of snow or soil pushed in front of a bulldozer (see Chapple, 1978; Davis et *al*, 1983; Dahlen et *al*, 1984; Dahlen, 1984), the decreasing dip of the basement in the eastern SR/PP reduces the cross-sectional taper of the overthrusting wedge. (The cross-sectional taper is defined as the sum of the basal slope along the lowermost thrust surface and the overall surface topographic slope. Because the décollement zone in the SR/PP is within the basal evaporite sequence, the basal slope is essentially equal to the slope of the top of basement.) The model predicts that as long as critical taper is maintained (that is, the wedge taper that exists when the entire thrust belt is on the verge of horizontal compressive failure), an overthrusting wedge will be able to be pushed forward without undergoing additional internal deformation. However, if the cross-sectional taper is too narrow, it will not slide along its basal décollement; rather, it will deform and thicken, increasing the topographic slope until critical taper is re-established.

Seismic lines (Figures 6 and 7) and the balanced cross-section (Figure 8) indicate that the dip of the basement beneath the eastern

SR/PP is shallow. The depth to basement on the southern end of the regional cross-section is 3350 m. At the northern end, beneath the Soan syncline, the top of basement is at a depth of 5900 m. The average dip over this interval is, therefore, 1.4°. The topography along the same transect increases from an elevation of approximately 200 m in the south to 550 m in the north, giving an overall topographic slope of 0.2°.

Davis and Engelder (1985) have shown that the critical taper for areas underlain by evaporites is approximately 1°. Although the values along section A-A' are in excess of the 1° estimate, the basement dip farther to the east becomes even shallower--about 0.8°. Apparently, the basement along section A-A' is transitional between the steeper central SR/PP and the very shallow eastern-most SR/PP. In this manner, the structures in the eastern SR/PP are viewed as a response to a too narrowly tapered wedge (Jaumé, 1987; Jaumé and Lillie, in press). That is, the basal thrust has periodically had to cut up-section to increase the topographic slope, thereby increasing the taper of the thrust wedge and allowing further southward movement along the salt décollement. Thus, whereas thinner salt may increase basal traction, mechanical considerations suggest that a shallow dip of the basement is sufficient to create stick-slip movement along the décollement.

North of the basement fault in the central SR/PP, the basement dips northward at about 1.9°, increasing to 3.6° beneath the northern PP (Baker, 1987). Here, the basement slope alone provides enough cross-sectional taper to allow the thrust sheet to slide without undergoing internal deformation. It is interesting to note that the topographic slope in the central SR/PP is essentially 0°. This would appear to support the mechanical model.

Effects of Basement Offsets

Although the relationships are not clear, basement offsets and warps in the eastern PP may have controlled and localized thrust ramps (e.g., Wiltschko and Eastman, 1983), similar to interpretations of the central Salt Range (Lillie and Yousuf, 1986; Lillie *et al*, 1987; Baker *et al*, 1988) and other fold-and-thrust belts (Appalachians--Harris and Milici, 1977; Wyoming Cordillera--Blackstone, 1979; French Alps--Davies, 1982; Bavarian Alps--Bachmann *et al*, 1982).

The hanging-wall cutoff of the Domeli thrust restores to a position approximately 2.5 km south of the interpreted basement fault that now underlies the Qazian anticline (Figure 8). However, the restored section assumes a minimum amount of shortening of 8.8 km on the Domeli thrust. If there was actually a greater amount of displacement along the Domeli thrust that has since been eroded, the hanging-wall cutoff would restore closer to the basement normal fault, implying that ramping of the Domeli thrust was facilitated by a basement offset. The basement normal fault trends parallel to the Domeli/Dil Jabba thrusts, and can be mapped in the subsurface for over 25 km to the southwest (Figure 2). Although seismic data gaps preclude a definite relationship, this NE-SW trending basement fault may connect with the large basement normal fault beneath the central SR/PP.

Orientation of Structural Trends

The Davis and Engelder (1985) model of differential rotation along the edge of a salt basin may explain changes in structural trend between the central and eastern SR/PP. However, their model implies that tectonic rotations will be contemporaneous with deformation. This is not consistent with some rotational data from the eastern PP (Table 1).

Ramping of the central Salt Range thrust sheet over the basement normal fault (Figure 2) occurred approximately 2.1-1.6 Ma (Baker, 1987; Baker et *al*, 1988). This was immediately preceded by deformation of the Soan syncline 2.1-1.9 Ma, as documented by the youngest folded molasse sediments and the oldest, undeformed overlying strata, the Lei Conglomerate (Raynolds and Johnson, 1985). In the eastern SR/PP, deformation as far south as the Mahesian anticline was roughly coeval with deformation of the Soan syncline in the central SR/PP. Thus, whereas deformation in the eastern SR/PP has propagated progressively over the foreland, basement buttressing in the central SR apparently caused the thrust tip to stick.

Burbank et *al* (in press) have shown that a significant amount of rotation occurred along the previously mentioned transect that crosses the Soan syncline south of Rawalpindi, contemporaneous with thrust ramping in the central SR/PP. However, this rotation post-dates deformation in the eastern SR/PP as far south as the Mahesian anticline. This suggests that many of the folds in the eastern PP may have formed roughly perpendicular to the transport direction, S15°E, and were then rotated into their current alignment in response to rotation associated with ramping over the basement buttress in the central SR/PP. If this is the case, drag may play a less important role regarding the current structural strike in the eastern SR/PP. Rather, the basement buttress, which undoubtedly controlled the rapid thrust propagation rates in the central SR, has played a primary role in rotating the structures into their current alignment.

This model predicts that rotation of the folds in the eastern PP should be generally confined in time to the period during which overthrusting in the central Salt Range occurred. Unfortunately, rotations for many of the folds have not been determined. The model also predicts that structures in the eastern SR/PP that started to form after overthrusting began in the central Salt Range should show less rotation. Data from the Mahesian and Rohtas anticlines (Table 1) and from the undeformed foreland near Jalapur (Opdyke et *al*, 1979) indicate that this is the case.

CONCLUSIONS

The data presented in this study place important constraints on the structure and evolution of the eastern SR/PP. The important conclusions can be summarized as follows:

1) Seismic reflection profiles reveal that the NE-SW trending folds are cored by both foreland- and hinterland- verging blind thrusts. Fault-propagation folds explain the asymmetry and overturning of many of the structures as well as the relative lack of emergent thrusts. Triangle and pop-up zones have been influenced by the distribution of evaporites which form the basal décollement zone. All three structures are interpreted to have formed due to stick-slip movement along the décollement surface.

2) Palinspastic restoration indicates that approximately 23 km of shortening have occurred in the eastern SR/PP since 5.5 Ma. Average shortening rates over the last 2.5 Ma are estimated to be 7 mm/yr. This corresponds to roughly 15% of the 40-50 mm/yr convergence rate between the Indian and Eurasian plates.

3) Several factors may influence the change in deformational style (translation vs. telescoping) between the central and eastern SR/PP. Data in this study support the work of Jaumé (1987) and Jaumé and Lillie (in press), suggesting that the reduced dip of the basement increases the amount of internal deformation required for the thrust sheet to maintain critical taper. Data also indicate

that the salt wedge does thin to the east, a factor which may increase basal traction and influence internal deformation (Davis and Engelder, 1985; Johnson *et al*, 1986); however, this mechanism is not required given the shallow dip of the basement. Finally, a few of the structures may be localized by the presence of basement offsets, similar to the intepretation beneath the central SR (Lillie and Yousuf, 1986; Baker, 1987; Baker *et al*, 1988). The data contradict the interpretation of Butler *et al* (1987) that the increased deformation is a result of the level of décollement rising up into the molasse.

4) The alignment of the structural trends into a NE-SW configuration may be explained in part by drag-induced rotation (Davis and Engelder, 1985). However, the timing of deformation and rotation suggest that folds in the eastern PP may have formed roughly perpendicular to the transport direction. Rotation accompanying ramping in the central SR/PP between 2.1 and 1.6 Ma may have shifted the structures into their present alignment.

REFERENCES

Abid, I. A., I. A. Abbasi, and M. T. Shah, 1983, Petrography and geochemistry of the Siwalik sandstone and its relationship to the Himalayan orogeny: Geological Bulletin of the University of Peshawar, v. 16, p. 65-83.

Acharyya, S. K., and K. K. Ray, 1982, Hydrocarbon possibilities of concealed Mesozoic-Paleogene sediments below Himalayan nappes - reappraisal: AAPG Bulletin, v. 66, p. 57-70.

Aithal, V. S., G. Gopalakrishnan, P. Nath, Y. K. Murty, B. Nandra, and D. Das, 1964, Gravity and magnetic surveys in the Plains of Punjab: 22nd International Geological Congress, New Delhi, sec. 2, pt. 2, p. 179-188.

Aitken, J. D., D. G. Cook, and C. J. Yorath, 1982, Upper Ramparts River (106G) and Sans Sault Rapids (106H) map areas, District of Mackenzie: Geological Survey of Canada, Memoir 388.

Ala, M. A., 1974, Salt diapirism in southern Iran: AAPG Bulletin, v. 58, p. 1758-1770.

Bachman, G. H., G. Dohr, and M. Müller, 1982, Exploration in a classic thrust belt and its foreland: Bavarian Alps, Germany: AAPG Bulletin, v. 66, p. 2529-2542.

Baker, D. M., 1987, Evolution, shortening, and deformation style of the central Salt Range and Potwar Plateau, Pakistan: M. S. thesis, Oregon State University, Corvallis, Oregon, 120 pp.

Baker, D. M., R. J. Lillie, R. S. Yeats, G. D. Johnson, M. Yousuf, and A. S. H. Zamin, 1988, Development of the Himalayan frontal thrust zone: Salt Range, Pakistan: Geology, v. 16, p. 3-7.

Bally, A. W., P. L. Gordy, and G. A. Stewart, 1966, Structure, seismic data and orogenic evolution of southern Canadian Rocky Mountains: Bulletin of the Canadian Petroleum Society, v. 14, p. 337-381

Banks, C. J., and J. Warburton, 1986, 'Passive-roof' duplex geometry in the frontal structures of the Kirthar and Sulaiman mountain belts, Pakistan: Journal of Structural Geology, v. 8, p. 229-238.

Baranowski, J., J. Armbruster, and L. Seeber, 1984, Focal depths and fault plane solutions of earthquakes and active tectonics of the Himalaya: Journal of Geophysical Research, v. 89, p 6918-6928.

Bird, P., 1978, Initiation of intracontinental subduction in the Himalaya: Journal of Geophysical Research, v. 83, p. 4975-4987.

Blackstone, D. L., Jr., 1979, Geometry of the Prospect-Darby and La Barge faults at their junction with the La Barge Platform, Lincoln and Sublette Counties, Wyoming: Geological Survey of Wyoming Report Investigation 18, 34 pp.

Burbank, D. W., R. G. H. Raynolds, and G. D. Johnson, 1986, Late Cenozoic tectonics and sedimentation in the northwestern Himalayan foredeep: II. Eastern limb of the northwest syntaxis and regional synthesis: *in* P. Allen and P. Homewood, eds., Foreland Basins: International Association of Sedimentologists Special Publication 8, p. 293-306.

Burbank, D. W., and R. G. H. Raynolds, in prep., Stratigraphic keys to the timing of deformation: an example from the northwestern Himalayan foredeep.

Burbank, D. W., R. G. H. Raynolds, and D. P. Whistler, in press, Detailed chronologies of tectonic rotations: new insights from magnetostratigraphic studies in Pakistan and along the Garlock fault.

Butler, R. W. H., 1982, The terminology of structures in thrust belts: Journal of Structural Geology, v. 4, p. 239-245.

Butler, R. W. H., 1983, Balanced cross-sections and their implications for the deep structure of the northwest Alps: Journal of Structural Geology, v. 5, p. 125-137.

Butler, R. W. H., M. P. Coward, G. M. Harwood, and R. J. Knipe, 1987, Salt, its control on thrust geometry, structural style and gravitational collapse along the Himalayan mountain front in the Salt Range of northern Pakistan: *in* I. Lerche and J. J. O'Brien eds., Dynamical Geology of Salt and Related Structures, Academic Press Inc., p. 339-418.

Chapman, T. J., and G. D. Williams, 1984, Displacement-distance methods in the analysis of fold-thrust structures and linked-fault systems: Journal of the Geological Society of London, v. 141, p. 121-128.

Chapple, W. M., 1978, Mechanics of thin-skinned fold-and-thrust belts: GSA Bulletin, v. 89, p. 1189-1198.

Colman-Sadd, S. P., 1978, Fold development in Zagros simply folded belt, southwest Iran: AAPG Bulletin, v. 62, p. 984-1003.

Cooper, M. A., 1983, The calculation of bulk strain in oblique and inclined balanced cross-sections: Journal of Structural Geology, v. 5, p. 161-165.

Cotter, G., 1933, The geology of the part of the Attock District west of Longitude 72°45'E: Geological Survey of India Memoirs, v. 55, p. 63-161.

Coward, M. P., and K. McClay, 1983, Thrust tectonics of south Devon: Journal of the Geological Society of London, v. 140, p. 215-228.

Coward, M. P. and R. W. H. Butler, 1985, Thrust tectonics and the deep structure of the Pakistan Himalaya: Geology, v. 13, p. 247-256.

Crawford, A. R., 1974, The Salt Range, the Kashmir Syntaxis and the Pamir Arc: Earth and Planetary Science Letters, v. 22, p. 371-379.

Dahlen, F. A., 1984, Noncohesive critical Coulomb wedges: an exact solution: Journal of Geophysical Research, v. 89, p. 10125-10133.

Dahlen, F. A., J. Suppe, and D. Davis, 1984, Mechanics of fold-and-thrust belts and accretionary wedges: Cohesive Coulomb theory: Journal of Geophysical Research, v. 89, p. 10087-10101.

Dahlstrom, C. D. A., 1969, Balanced cross sections: Canadian Journal of Earth Science, v. 6, p. 743-757.

Dahlstrom, C. D. A., 1970, Structural geology in the eastern margin of the Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geology, v. 18, p. 332-406.

Davies, V. M., 1982, Interaction of thrusts and basement faults in the French external Alps: Tectonophysics, v. 88, p. 325-331.

Davis, D. M. , J. Suppe, and F. A. Dahlen, 1983, Mechanics of fold-and-thrust belts and accretionary wedges: Journal of Geophysical Research, v. 88, p. 1153-1172.

Davis, D. M. and T. Engelder, 1985, The role of salt in fold-and-thrust belts: Tectonophysics, v. 119, p. 67-88.

Dubey, A. K., and H. Behzadi, 1981, Development of flexural slip folds, overlapping boudins and extensional faults in multilayered materials: field evidence and experimental model: Journal of the Geological Society of India, v. 22, p. 274-284.

Duroy, Y., 1986, Subsurface densities and lithospheric flexure of the Himalayan foreland in Pakistan interpreted from gravity: M. S. thesis, Oregon State University, Corvallis, Oregon, 74 pp.

Duroy, Y., A. Farah, and R. J. Lillie, in review, Reinterpretation of the gravity field in the Himalayan foreland of Pakistan: *in* L. L. Malinconico and R. J. Lillie, eds., Tectonics and Geophysics of the Western Himalaya, GSA Special Paper.

Farah, A., M. A. Mirza, M. A. Ahmad, and M. H. Butt, 1977, Gravity field of the buried shield in the Punjab Plain, Pakistan: GSA Bulletin, v. 88, p. 1147-1155.

Farah, A., R. D. Lawrence, and K. A. DeJong, 1984, An overview of the tectonics of Pakistan: *in* B. U. Haq and J. D. Milliman, eds., Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan, p. 161-176.

Fatmi, A. N., M. Akhtar, G. S. Alam, and I. Hussain, 1984, Guide book to geology of the Salt Range: Geological Survey of Pakistan, First Pakistan Geological Congress, Lahore, 14 pp.

Fischer, M. W., and M. P. Coward, 1982, Strains and folds within thrust sheets: an analysis of the Heilam Sheet: Tectonophysics, v. 88, p. 291-312.

Fletcher, G. L., and R. A. Soeparjadi, 1984, Oil and gas developments in Far East in 1983: AAPG Bulletin, v. 68, p. 1622-1675.

Fox, F. G., 1983, Structure sections across the Parry Island fold belt, and Vesey Hamilton Salt Wall, Arctic Archipelago, Canada: *in* A. W. Bally, ed., Seismic Expression of Structural Styles, AAPG Studies in Geology #15, v. 3, p. 3.4.1-54 - 3.4.1-72.

Gansser, A., 1981, The geodynamic history of the Himalaya: *in* H. K. Gupta and F. Delany, eds., Zagros-Hindu Kush-Himalaya Geodynamic Evolution, American Geophysical Union, Series 3, p. 111-112.

Gee, E. R., 1945, The age of the Saline Series of the Punjab and Kohat: Proceedings to the National Academy of Science, India, v. 14, p. 269-312.

Gee, E. R., 1947, Further note on the age of the Saline Series of the Pujab and of Kohat: Proceedings to the National Academy of Science, India, v. 16, p. 95-116.

Gee, E. R., 1980, Salt Range series geological maps, 1:50,000, 6 sheets: Directorate of Overseas Surveys, United Kingdom, for Government of Pakistan and Pakistan Geological Survey.

Gee, E. R., 1983, Tectonic problems of the Sub-Himalayan region of Pakistan: Kashmir Journal of Geology, v. 1, p. 11-18.

Gwinn, V. E., 1964, Thin-skinned tectonics in the Plateau and northwestern Valley and Ridge Province of the Appalachians: GSA Bulletin, v. 75, p. 863-900.

Harris, L. D. and R. C. Milici, 1977, Characteristics of thin-skinned style of deformation in the southern Appalachians, and potential hydrocarbon traps: USGS Professional Paper 1018, 40 pp.

Hemphill, W. R., and A. H. Kidwai, 1973, Stratigraphy of the Bannu and Dera Ismail Khan areas, Pakistan: USGS Professional Paper, 716b, 36 pp.

Jacoby, C. H., and L. F. Dellwig, 1974, Appalachian foreland thrusting in Salina Salt, Watkins Glenn, New York: *in* A. H. Coogan, ed., Fourth Symposium on Salt, Northern Ohio Geological Society, v. 1, p. 227-233.

Jan, M. Q. and M. Asif, 1981, A speculative tectonic model for the evolution of NW Himalaya and Karakoram: Geological Bulletin of the University of Peshawar, v. 14, p. 199-201.

Jaumé, S. C., 1986, The Salt Range-Potwar Plateau, Pakistan: Quantitative and qualitative aspects of fold-and-thrust belt underlain by evaporites: M. S. thesis, Oregon State University Corvallis, Oregon, 58 pp.

Jaumé, S. C., and R. J. Lillie, in press, Mechanics of the Salt Range-Potwar Plateau, Pakistan: a fold-and-thrust belt underlain by evaporites: Tectonics.

Johnson, G. D., N. M. Johnson, N. D. Opdyke, and R. A. K. Tahirkheli, 1979, Magnetic reversal stratigraphy and sedimentary tectonic history of the upper Siwalik Group, eastern Salt Range and southwestern Kashmir: *in* A. Farah and K. A. DeJong, eds., Geodynamics of Pakistan, Geological Survey of Pakistan, Quetta, p. 149-165.

Johnson, G. D., R. G. Raynolds, and D. W. Burbank, 1986, Late Cenozoic tectonics and sedimentation in the northwestern Himalaya foredeep: I. Thrust ramping and associated deformation in the Potwar region: *in* P. Allen, and P. Homewood, eds., Foreland Basins: International Association of Sedimentologists Special Publication 8, p. 273-291.

Johnson, N. M., N. D. Opdyke, G. D. Johnson, E. H. Lindsay, and R. A. K. Tahirkheli, 1982, Magnetic polarity stratigraphy and ages of the Siwalik Group rocks of the Potwar Plateau, Pakistan: Palaeogeology, Palaeoclimatology, Palaeoecology, v. 37, p. 17-42.

Jones, P. B., 1982, Oil and gas beneath east-dipping underthrust faults in the Alberta foothills: Rocky Mountain Association of Geology Guidebook, Denver, CO, p. 61-74.

Jones, P. B., 1987, Quantitative geometry of thrust and fold belt structures: AAPG Methods in Exploration Series No. 6, 26 pp.

Keller, H. M., R. A. K. Tahirkheli, M. A. Mirza, G. D. Johnson, N. M. Johnson, and N. D. Opdyke, 1977, Magnetic polarity stratigraphy of the Upper Siwalik deposits, Pabbi Hills, Pakistan: Earth and Planetary Science Letters, v. 36, p. 187-201.

Kennett, J., 1982, Marine Geology: Prentice-Hall, Inc., Englewood Cliffs, N.J., 813 pp.

Khan, M. A., R. Ahmed, H. A. Raza, and A. Kemal, 1986, Geology of petroleum in Kohat-Potwar depression, Pakistan: AAPG Bulletin, v. 70, p. 396-414.

Klootwijk, C. T., 1979, A summary of paleomagnetic data from peninsular IndoPakistan and south central Asia: implications for collisional tectonics: *in* P. S. Saklani, ed., Structural Geology of the Himalaya, Today and Tomorrow Printers and Publishers, New Delhi, p. 307-360.

Kozary, M. T., J. C. Dunlap, and W. E. Humphrey, 1968, Incidence of saline deposits in geologic time: GSA Special Paper no. 88, p. 43-57.

Lamerson, P. R., 1982, The Fossil Basin area and its relationship to the Absaroka thrust fault system: *in* R. B. Power, ed., Geologic Studies of the Cordilleran Thrust Belt, Rocky Mountain Association of Geologists, p. 279-340.

Latif, M. A., 1973, Partial extension of the evaporite facies of the Salt Range to Hazara, Pakistan: Nature, v. 244, p. 124-125.

Leathers, M., 1987, Balanced structural cross-section of the western Salt Range and Potwar Plateau: Deformation near the strike-slip terminus of an overthrust sheet: M. S. thesis, Oregon State University, Corvallis, Oregon, 271 pp.

Lefort, P., 1975, Himalayas: the collided range. Present knowledge of the continental arc: American Journal of Science, v. 275-A, p. 1-44.

Lillie, R. J., and M. Yousuf, 1986, Modern analogs for some midcrustal reflections observed beneath collisional mountain belts: *in* M. Barazangi and L. Brown, eds., Reflection Seismology: the Continental Crust, American Geophysical Union, Geodynamic Series, v. 14, p. 55-65.

Lillie, R. J., G. D. Johnson, M. Yousuf, A. S. H. Zamin, and R. S. Yeats, 1987, Structural development within the Himalayan foreland fold-and-thrust belt of Pakistan: *in* C. Beaumont and A. J. Tankard, eds., Sedimentary Basins and Basin-Forming Mechanisms, Canadian Society of Petroleum Geologists, Memoir 12, p. 379-392.

Lyon-Caen, H., and P. Molnar, 1985, Gravity anomalies, flexure of the Indian plate, and the structure, support and evolution of the Himalaya and Ganga basin: Tectonics, v. 4, p. 513-538.

McDougall, J., 1985, Strike-slip faulting in a foreland fold-thrust belt, western Salt Range, central Pakistan: GSA Abstract with Programs, p. 658.

McKenzie, D. P. and J. G. Sclater, 1971, The evolution of the Indian Ocean since the Late Cretaceous: Geophysical Journal, v. 25, p. 437-528.

Martin, N. R., 1962, Tectonic style in the Potwar, West Pakistan: Punjab University Geological Bulletin, v. 2, p. 39-50.

Meissner, C. R., J. M. Master, M. A. Rashid, and M. Hussain, 1974, Stratigraphy of the Kohat Quadrangle, Pakistan: USGS Professional Paper 716d, 30 pp.

Menke, W. H. and J. H. Jacob, 1976, Seismicity patterns in Pakistan and northwest India associated with continental collision: Seismological Society of America Bulletin, v. 66, p. 1695-1711.

Minster, J. B., and T. H. Jordan, 1978, Present day plate motions: Journal of Geophysical Research, v. 83, p. 5331-5354.

Mitra, S., 1986, Duplex structures and imbricate thrust systems: geometry, structural position, and hydrocarbon potential: AAPG Bulletin, v. 70, p. 1087-1112.

Molnar, P., and P. Tapponnier, 1975, Cenozoic tectonics of Asia: effects of a continental collision: Science, v. 189, p. 419-426.

Molnar, P., W. P. Chen, T. J. Fitch, P. Tapponier, W. E. K. Warsi, and F. T. Wu, 1976, Structure and tectonics of the Himalaya: a brief summary of relevant geophysical observations: *Colloques International du Centre National de la Recherch Scientific, no. 268, p. 269-294.*

Morley, C. K., 1986, A classification of thrust fronts: AAPG Bulletin, v. 70, p. 12-25.

Opdyke, N. D., E. Lindsay, G. D. Johnson, N. M. Johnson, R. A. K. Tahirkheli, and M. A. Mirza, 1979, Magnetic polarity stratigraphy and vertabrate paleontology of the Upper Siwalik subgroup of northern Pakistan: Palaeogeology, Palaeoclimatology, and Palaeoecology, v. 27, p. 1-34.

Opdyke, N. D., N. M. Johnson, G. D. Johnson, E. H. Lindsay, and R. A. K. Tahirkheli, 1982, Paleomagnetism of the Middle Siwalik Formations of northern Pakistan and rotation of the Salt Range décollement: Palaeogeology, Palaeoclimatology, and Palaeoecology, v. 37, p. 1-15.

Patriat, P., and J. Achache, 1984, Collision chronology and its implications for crustal shortening and the driving mechanisms of plates. India-Eurasia: Nature, v. 311, p. 615-621.

Pilbeam, D., J. Barry, G. E. Meyer, S. M. I. Shah, M. H. L. Pickford, W. W. Bishop, H. Thomas, and L. L. Jacobs, 1977, Geology and paleontology of Neogene strata of Pakistan: Nature, v. 270, p. 684-689.

Pilgrim, G. E., 1910, Preliminary notes on a revised classification of the Tertiary freshwater deposits of India: Records of the Geological Survey of India, v. 40, p. 185-205.

Pilgrim, G. E., 1913, The correlations of the Siwaliks with mammal horizons of Europe: Records of the Geological Survey of India v. 43, p. 264-326.

Pinfold, E. S., 1918, Notes on structure and stratigraphy in the North-west Punjab: Records of the Geological Survey of India, v. 49, p. 137-159.

Price, R. A., 1981, The Cordilleran foreland thrust and fold belt in the southern Canadian Rocky Mountains: *in* J. R. McClay and N. J. Price, eds., Thrust and Nappe Tectonics, Geological Society of London, Blackwell Scientific Pub., p. 427-448.

Price, R. A., 1986, The southeastern Canadian Cordillera: thrust faulting, tectonic wedging, and delamination of the lithosphere: Journal of Structural Geology, v. 8, p. 239-254.

Prucha, J. J., 1968, Salt deformation and décollement in the Firtree Point anticline of Central New York: Tectonophysics, v. 6, p. 273-299.

Quittmeyer, R. C., A. Farah, and K. H. Jacob, 1979, The seismicity of Pakistan and its relation to surface faults: *in* A. Farah and K. A. DeJong, eds., Geodynamics of Pakistan, Geological Survey of Pakistan, Quetta, p. 271-284.

Raynolds, R. G., 1980, The Plio-Pleistocene structural and stratigraphic evolution of the eastern Potwar Plateau, Pakistan: Ph.D. thesis, Dartmouth College, Hanover, New Hampshire, 265 pp.

Raynolds, R. G., and G. D. Johnson, 1985, Rates of Neogene depositional and deformational processes, northwest Himalayan foredeep margin, Pakistan: *in* N. J. Snelling, ed., The Chronology and the Geological Record, Geological Society of London, Memoir 10, p. 297-311.

Rodgers, J., 1963, Mechanics of Appalachian foreland folding in Pennsylvania and West Virginia: AAPG Bulletin, v. 47, p. 1527-1536.

Roeder, D., and W. Witherspoon, 1978, Palinspastic map of east Tennessee: American Journal of Science, v. 278, p. 543-550.

Root, S. I., 1973, Structure, basin development and tectogenesis in the Pennsylvanian portion of the folded Appalachians: *in* K. A. DeJong and R. Scholten, eds., Gravity and Tectonics, New York, Wiley, p. 343-360.

Royse, F., Jr., M. A. Warner, and D. L. Reese, 1975, Thrust belt structural geometry and related stratigraphic problems, Wyoming-Idaho-Northern Utah: *in* Rocky Mountain Association of Geology, Symposium on Deep Drilling Frontiers in central Rocky Mountains, p. 4-54.

Sarwar, G. and K. A. DeJong, 1979, Arcs, oroclines, syntaxes: the curvature of mountain belts in Pakistan: *in* A. Farah and K. A. DeJong, eds., Geodynamics of Pakistan, Geological Survey of Pakistan, Quetta, p. 341-350.

Seeber, L., and J. Armbruster, 1979, Seismicity of the Hazara Arc in northern Pakistan: décollement vs. basement faulting: *in* A. Farah and K. A. DeJong, eds., Geodynamics of Pakistan, Geological Survey of Pakistan, Quetta, p. 131-142.

Seeber, L., J. G. Armbruster, and R. C. Quittmeyer, 1981, Seismicity and continental subduction in the Himalayan Arc: *in* H. K. Gupta and F. M. Delany, eds., Zagros-Hindu Kush-Himalaya Geodynamic Evolution, American Geophysical Union, Geodynamics Series v. 3, p. 215-242.

Sengor, A. M. C., 1979, Mid-Mesozoic closure of Permo-Triassic Tethys and its implications: Nature, v. 279, p. 590-593.

Shroder, J. F., in prep., Quaternary history of middle and upper Indus and surrounding valleys, northern Pakistan.

Stöcklin, J., 1974, Possible ancient continental margin in Iran: *in* C. L. Drake and C. A. Burke, eds., The geology of continental margins, New York, Springer-Verlag, p. 873-887.

Stoneley, R., 1974, Evolution of the continental margin bounding a former Tethys: *in* C. L. Drake and C. A. Burke, eds., The geology of continental margins, New York, Springer-Verlag, p. 889-903.

Suppe, J., 1985, Principles of structural geology: Englewood Cliffs, N. J., Prentice-Hall, 537 pp.

Suppe, J., and D. A. Medwedeff, 1984, Fault-propagation folding: GSA Abstracts with Programs, v. 16, p. 670.

Tahirkheli, R. A. K., 1982, Geology of the Himalaya, Karakoram, and Hindu-Kush in Pakistan: Special Issue of the Geological Bulletin of the University of Peshawar, v. 15, p. 51.

Tapponnier, P., G. Peltzer, A. Y. LeDain, R. Armijo, and P. Cobbold, 1982, Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticene: Geology, v. 10, p. 611-616.

Vann, I. R., R. H. Graham, and A. B. Hayward, 1986, The structures of mountain fronts: Journal of Structural Geology, v. 8, p. 215-228.

Voskresenskiy, I. A., 1978, Structure of the Potwar Highlands and the Salt Range as an indication of horizontal movement of the Hindustan Platform: Geotectonics, v. 12, p. 70-75.

Wadia, D. N., 1931, The syntaxis of the northwest Himalaya: its rocks, tectonics and orogeny: Records of the Geological Survey of India, p. 189.

Wadia, D. N., 1945, A note on the repeated ovethrusts of the Cambrian rocks on the Eocene in the north-eastern part of the Salt Range: Proceedings to the National Academy of Science, India, sec. A, v. 14, p. 214-221.

Wells, N. A., 1984, Marine and continental sedimentation in the early Cenozoic Kohat Basin and adjacent northwestern Pakistan: Ph.D. Thesis, University of Michigan, Ann Arbor, 465 pp.

Williams, C., and T. Chapman, 1983, Strains developed in the hanging-walls of thrusts due to their slip/propagation rate: a dislocation model: Journal of Structural Geology, v. 5, p. 563-571.

Wiltschko, D. V., and W. M. Chapple, 1977, Flow of weak rocks in Appalachian Plateau folds: AAPG Bulletin, v. 61, p. 653-670.

Wiltschko, D. V., and D. Eastman, 1983, Role of basement warps and faults in localizing thrust fault ramps: *in* Hatcher, R. D., H. Williams, and I. Zietz, eds., Contributions to the Tectonics and Geophysics of Mountain Chains, GSA Memoir 158, p. 177-190.

Windley, B. F., 1983, Metamorphism and tectonics of the Himalaya: Journal of the Geological Society of London, v. 140, p. 849-865.

Wynne, A. B., 1878, On the geology of the Salt Range in the Punjab: Geological Survey of India, Memoirs, v. 14, 312 p.

Yeats, R. S., S. H. Khan, and M. Akhtar, 1984, Late Quaternary deformation of the Salt Range of Pakistan: GSA Bulletin, v. 95, p. 958-966.

Yeats, R. S., and R. D. Lawrence, 1984, Tectonics of the Himalayan thrust belt in northern Pakistan: *in* B. U. Haq and J. D. Milliman, eds., Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan, p. 177-198.

Yeats, R. S., and A. Hussain, 1987, Timing of structural events in the Himalayan foothills of northwestern Pakistan: GSA Bulletin., v. 99, p. 161-176.

Zarkov, M. A., 1981, History of Paleozoic salt accumulation: Springer-Verlag, New York, 308 pp.

Zeitler, P. K., R. A. K. Tahirkheli, C. W. Naeser, N. M. Johnson, and L. B. Lyons, 1980, Tectonic interpretation and fission-track ages from the Lesser Himalayas, northern Pakistan: EOS, v. 61, p. 359.

Zeitler, P. K., R. A. K. Tahirkheli, C. W. Naeser, and N. M. Johnson, 1982, Unroofing history of a suture zone in the Himalaya of Pakistan by means of fission-track annealing ages: Earth and Planetary Science Letters, v. 57, p. 227-240.