

AN ABSTRACT OF THE THESIS OF

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Title: Crustal Shortening and Tectonic Evolution of the Salt Range in Northwest Himalaya, Pakistan.

Abstract approved: _____ Signature redacted for privacy.

Dr. Robert D. Lawrence

The Salt Range is clearly the active participant in the scenario of the progressive southward migration of the Himalayan thrust front. It extends approximately 180 km ENE along strike and is underlain by salt. This is manifested by its very narrow ($<1^\circ$) cross-sectional taper and great (150 km) width. Integration of approximately 450 km of seismic reflection data with available surface geologic, magnetostratigraphic, and exploration well data help in delineating different tectonic features in the Salt Range. These studies reveal a concealed duplex structure under the roof sequence, help to determine the footwall and hangingwall geometries of the leading edge at different successive evolutionary stages, estimate the lateral extent of a basement normal fault, constrain the ages of different structural features, and define lateral variations in the deformational style within the leading edge. The above mentioned features have been synthesized to document an out-of-sequence evolutionary model of the Salt Range.

The newly recognized, concealed duplex structure extends more than 40 km along the strike and gradually progrades southward along a décollement that first ramps within the Salt Range Formation and then across the platform sequence and follows the shaley horizons of overlying Murree Formation near the contact. This duplex structure is terminated along the two lateral ramps in the east and west.

The northern ramp in the footwall of the roof sequence is localized by a basement normal fault in the central Salt Range, and changes its position and characteristics in the eastern and western Salt Range. In the western Salt Range, it is located 15 km farther south and is entirely within the sedimentary sequence. These two segments are linked by a lateral ramp that developed over the western culmination wall of the lateral ramp associated with the underlying duplex structure. In the eastern Salt Range, however, the northern

ramp first continues within the sedimentary sequence beyond the end of the basement normal fault and farther east it changes into an oblique ramp. This oblique ramp is truncated by another N-S trending lateral ramp farther to the east. The monoclinical structure of the Chambal Ridge marks the southernmost extension of this lateral ramp. Along this lateral ramp the roof sequence steps down and joins the basal décollement.

Due to the down stepping of the roof sequence the structural style also changes from fault-bend fold to fault propagated fold geometry. Because in fault-bend fold geometry the major component of shortening was accommodated across the northern ramp, very little shortening occurred within the roof sequence. In contrast, all the shortening in the east has been distributed over a region in a prograde fashion. Therefore, the thrust wedge is internally deformed into a fault propagated fold geometry to provide a surface topographic slope necessary to maintain a critical taper.

The concealed duplex structure is the earliest structure of the Himalayan thrust front that was formed during 9-7 m.y., and further suggests that out of sequence thrusting has occurred over a region of 150 km during the past 9 m.y. Due to the development of a basement normal fault at 7 m.y., the thrust acquired a high friction front and was unable to move forward. Crustal shortening was then taken up by the Main Boundary Thrust zone in the north, which was quite active during this time. Between 5-6 m.y., the thrust wedge started to ramp over the basement normal fault, facilitated by the development of a thick salt pad on the down-thrown side, during 7-6 m.y. The newly built topography due to the ramping of the thrust wedge resisted the southwards propagation of the roof sequence and caused further out-of-sequence thrusting in the north but was not sufficient to stop its southward progradation. It was followed by the major horizontal translation of the roof sequence over the roof sequence flat. This study also suggests that 13° counter clockwise rotation has occurred along the northern ramp and the concealed duplex structure.

Recognition of the concealed duplex structure and better understanding of the footwall geometry of the roof sequence also generates new prospects of oil exploration in the Salt Range.

**Crustal Shortening and Tectonic Evolution of the Salt Range
in
Northwest Himalaya, Pakistan**

**by
Mazhar Qayyum**

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To my Late Father

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CRUSTAL SHORTENING AND TECTONIC EVOLUTION OF THE SALT RANGE IN NORTHWEST HIMALAYA, P A K I S T A N

INTRODUCTION

Thin skinned tectonics are now recognized in the forelands of most, if not all, orogenic belts of the world, both ancient and modern. Low-angle thrusts with detachment surfaces in rocks of low yield strength, especially shales and evaporites are characteristic features of these orogens [*e.g.*, Caledonian-Appalachians-Ouachita-Marathon fold belt (Morley, 1986; Rich, 1934; Harris, 1970; Harris & Milici, 1977; Cook *et al.*, 1979, 1980; Mitra, 1988; Wickham *et al.*, 1976; Lillie, et al., 1983, 1985), the Alpine-Himalayan belt (Argand, 1916; Pierce, 1966; Laubscher, 1971, 1972, 1975; Rybach et al., 1980; Wadia, 1957; Gansser, 1964; Molnar, 1984; Coward & Butler, 1985, Brunel, 1986) and the Cordilleran belt (Mingramm *et al.*, 1979; Price, 1981)]. Older thin-skinned orogenic belts, such as the Appalachians, the Caledonides, and the Urals, have been inactive long enough that erosion has substantially removed most of the syn-orogenic strata and has exposed the deeper levels of these belts. However, syn-orogenic strata are well preserved in modern orogenic belts, such as the Cordilleran-Andean belt and the Alpine-Himalayan orogen. These two are the best known examples of orogenic belts that resulted from the collision of plates. Both document a very detailed history for the most recently developed structures; analogous features have been removed by erosion elsewhere. However, the degree of complexity of the leading edge of the foreland fold-and-thrust belt is more apparent in the Alpine-Himalayan orogen where the deformation is continuing.

Our current understanding of the geometric development of foreland systems is strongly influenced by modern mechanical wedge models (Chapple, 1978; Davis *et al.*, 1983; Davis and Engelder, 1895) and balanced cross-sections of important thrust belts (Boyer and Elliot, 1982). They have developed a model with general forward progradation of thrusts, motion under critical taper, and out-of-sequence faults to maintain taper. Active orogenic belts contain important information very critical in evaluating these models of foreland thrusting. Three critical parameters of the analytical model for thrusting (Davis *et al.*, 1983) are: (1) the forward topographic slope of the deforming wedge; (2) the ratio of pore fluid pressure to vertical normal traction exerted by the lithospheric overburden within and at the base of the wedge respectively; and (3) the regional dip of the basal décollement towards the inner portion of the orogen. In ancient foreland fold-and-thrust belts these parameters are generally obscure, but in the active Himalayan fold-and-thrust belt they are directly and accurately measurable. In particular, the current geometry of the Himalayan wedge is the geometry that produces thrust motion, so mechanical ideas can be directly tested.

The Salt Range, a part of the Himalayan foreland fold-and-thrust belt, marks the southernmost position of the thrust front in the northwest Himalaya of Pakistan (Fig. 1). Tectonically the Salt Range is the Himalayan equivalent of the Jura Mountains in the Alps and the Pine Mountains of the Appalachians. It is bordered by the Potwar Plateau in the north and Punjab plain in the south. The Potwar Plateau is the Himalayan equivalent of the Molasse Basin of the Alps, a raised topographic plateau between the main mountains and the outlying Juras. Some of the advantages of studies of the thrust front in the Salt Range/Potwar Plateau of Pakistan are as follows: (1) the current configuration of the basement and surface topography reflect active thrust motion; (2) normal faults, probably produced by lithospheric flexure, have a demonstrated major role in localizing thrust ramps; (3) since isostatic rebound has not yet altered the slope of the basement, ideas on

Figure 1: Regional Tectonic setting of Himalayas showing main sutures and major thrusts. 1) Himalayan foreland fold-and-thrust-belt, 2) Quaternary filled foreland basins (modified after Gansser, 1964; Mattauer, 1986). Note that the width of the fold belt widens in the northwest and the Indus Tsangpo Suture Zone bifurcates into two sutures: **MKT**, Main Karakoram Thrust; **MMT**, Main Mantle Thrust that bound the Kohistan (**K**) and Ladakh (**L**) Arcs. **MBT**, Main Boundary Thrust, **MFT**, Main Frontal Thrust; **SRT**, Salt Range Thrust; **P**, Pamirs; **T**, Turan Block; **PP**, Potwar Plateau; **CF**, Chaman Fault; **H**, Helmand Basin.

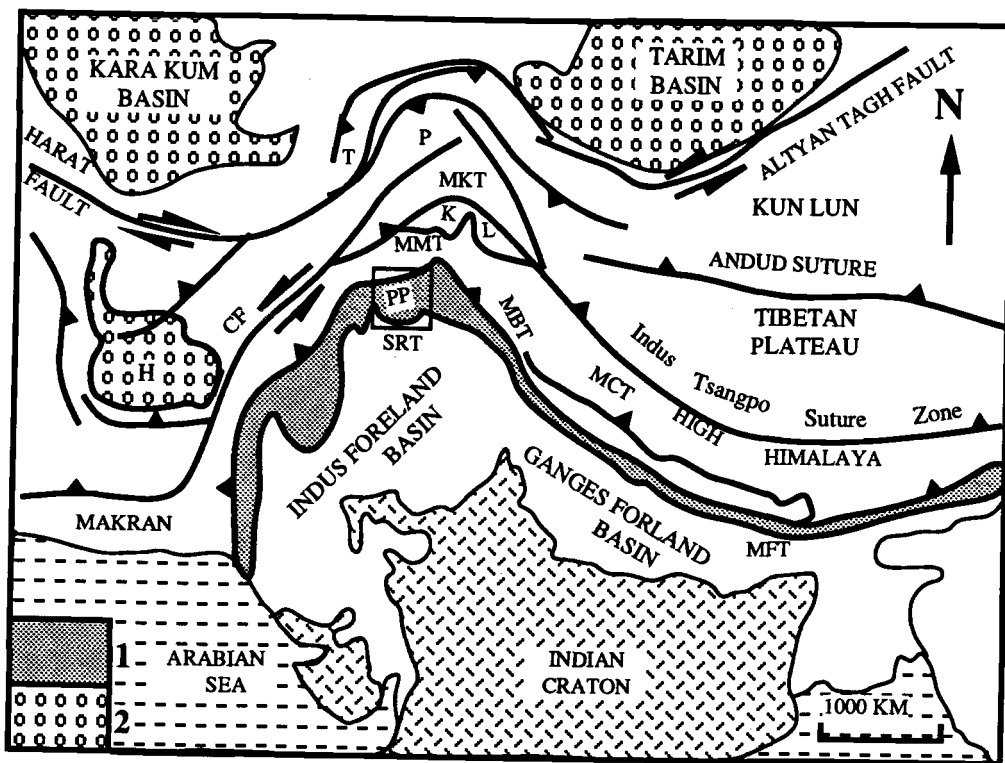


Figure 1

structural loading and lithospheric flexure can be directly tested; (4) the topography of the thrust front at the time of thrusting is still quite well preserved; (5) widespread preservation of young, syn-tectonic molasse sediments means that narrow geochronological constraints about the time and rate of deformation are available; and (6) abundant petroleum exploration wells and seismic reflection profiles provide three dimensional constraints for the study. These facts, therefore, make the Salt Range an ideal locality for the study of thin-skinned deformation in the foreland fold-and-thrust belts of the world.

Most of the previous geological and geophysical studies of the Potwar Plateau have been devoted largely to explore the oil potential and regional structures (Wynne, 1878; Cotter, 1933; Wadia, 1945a, 1945b, 1957; Gee, 1945, 1947, 1980; Martin, 1961; Sokolov & Shah, 1966; Shah, 1977; Farah, 1977; Voskresenskiy, 1978; Fatmi *et al.*, 1984; Duroy, 1986; Leathers, 1987; Lillie *et al.*, 1987; Baker, 1987; Baker *et al.*, 1988; Duroy *et al.*, 1989; Pennock, 1988; Pennock *et al.*, 1989). Butler *et al.*, (1987) focused on the control of salt on the thrust geometry of the Salt Range. However, due to the lack of published seismic and well data their interpretations were speculative in the third dimension. Previous studies (Leathers, 1987; Baker, 1987; Baker *et al.*, 1988) were confined to single section lines entirely across the Salt Range/Potwar plateau on which the Salt Range was a small component. These studies provide only 2-dimensional models of the surface and sub-surface structures. They clearly recognized the role of the basement normal fault in deflecting the platform sequence to the surface. However, they left the structures under the Salt Range obscure and made no attempt to decipher the lateral extent of the different structural features.

The present study is on a much more detailed scale than those of previous workers, and as such adds new insights to some of the unsolved mysteries of the Salt Range. Problems previously unsolved or unrecognized that are addressed herein include: (1) describing the detailed structural features within the Salt Range; (2) identifying the nature of

the structures beneath the Salt Range and delineating their lateral extent; (3) evaluating the total crustal shortening within the Salt Range and its lateral pattern; (4) explaining why the deformational style in the eastern Salt Range is drastically different from that of central and western parts; and (5) determining the nature and the timing of the large basement normal fault that underlies the Salt Range and its implication for the tectonic evolution of the range.

This is the first attempt to specifically address the above mentioned problems and to propose an evolutionary tectonic model for the Salt Range. Recently, excellent geological maps of the Salt Range proper by E. R. Gee (1980) have been published. The geological sections on these maps are based on older structural concepts from the time when the mapping was done (Gee, 1945, 1947). It is possible now to combine the recently achieved regional concepts with this mapping to produce a greatly improved structural interpretation of the leading edge of the Himalayan thrust front in the Salt Range itself. The present study is largely based on four balanced cross-sections constructed across the Salt Range with the help of surface geological mapping, petroleum exploration well information, and seismic reflection data.

REGIONAL TECTONIC SETTING

The Himalaya, the world's youngest and highest mountain chain, has emerged during ongoing collision of the Indo-Pakistan and Eurasian plates. It is generally believed that the collision began in middle to late Eocene (Stöcklin, 1974; Stoneley, 1974; Molnar and Tapponnier, 1975). In the central Himalayas there are four major thrust zones: the Indus-Tsangpo Suture Zone, Main Central Thrust, Main Boundary Thrust (MBT), and Main Frontal Thrust (Fig. 1). These zones mark the progressive southward migration of the thrust front, and are generally considered responsible for the major component of structural underplating and crustal shortening along the advancing edge of the Indian Plate.

In the Northwest Himalayas, the tectonic setting is somewhat different from that of the rest of the Himalayas. In the hinterland, the Indus-Tsangpo Suture Zone bifurcates into two sutures that bound the Kohistan Arc on the north and south. The northern suture, also called the Main Karakoram Thrust (Tahirkheli and Jan, 1979; Tahirkheli *et al.*, 1979), was active from 90-100 Ma (Coward *et al.*, 1987). The southern suture, also called the Main Mantle Thrust (Tahirkheli & Jan, 1979; Tahirkheli *et al.*, 1979), is suggested to have been active in the Eocene and to have involved an estimated 470 km of shortening (Coward *et al.*, 1987). On the basis of zircon fission track data, Zeitler (1982) determined, that the motion along the Main Mantle Thrust was locked by 15 Ma. After this time, the thrust front moved farther southward, and unmetamorphosed Tertiary rocks were thrust over the Neogene molasse along the MBT. Later the Neogene molasse was thrust southward along the Salt Range Thrust. The Salt Range Thrust in the NW Himalayas marks the southernmost position of the thrust front; where the documented deformation is as young as 0.4 Ma (Yeats *et al.*, 1984).

Comparison of Himalayan foreland in Pakistan to Central Himalaya

The deformation style of the thrust front in the foreland of the northwest Himalayas, Pakistan, differs from that of the rest of the Himalayas. The average slope over the thrust front in India and Nepal is quite steep. Topography rises rapidly from the Ganges Plain to about 6000 m north of the MBT (Gansser, 1964). There, the foreland fold-and-thrust belt is < 50 km wide (Fig. 1), with a cross-sectional taper of approximately 8° (Acharyya and Ray, 1982). It is characterized by strong coupling between sedimentary rocks and the basement, which causes large earthquakes underneath the foreland (Quittmeyer et al., 1979, Seeber & Armbruster, 1979).

In Pakistan the regional slope is gentler. The tectonic analog of the Lesser Himalayas has a variable elevation, but a mean of 1500 m can be accepted for the Salt Range hinterland. Much of the fold-and-thrust belt in northern Pakistan is more than 150 km wide with a narrow cross-sectional taper of 1° or less (0.6° for figures given) (David & Engelder, 1985; Jaumé, 1986; Jaumé & Lillie, 1988; Leathers, 1987; Baker, 1987; Baker *et al.*, 1988; Pennock, 1988; Pennock *et al.*, 1989). Due to the presence of an Eocambrian evaporite sequence (Salt Range Formation) there is a weak coupling between the sedimentary rocks and the basement. The area is also characterized by very low seismicity (Crawford 1974; Seeber & Armbruster 1979).

In the rest of the Himalayas, the MBT marks a well defined structural break between pre-orogenic rocks of the Lesser Himalayas (Paleozoic-Mesozoic, metamorphosed to unmetamorphosed, platform sediments and Precambrian metamorphic rocks) and synorogenic rocks of the sub-Himalayas (Tertiary molasse sediments) (Wadia 1931; Gansser, 1964). In contrast, in the NW Himalayas the MBT is not as well defined a tectonic feature (Yeats and Lawrence, 1984). It is generally placed at the southernmost

thrust between Eocene or older platform rocks on the north and Oligocene to Pliocene Murree and Siwalik molasse on the south (Kazmi & Rana, 1982). Here, the total stratigraphic throw and crustal shortening have been distributed along a series of imbricated thrusts bounded by the Nathiagali thrust in the north and the Margala thrust in the south (Baig and Lawrence, 1987).

ACTIVE THRUST SYSTEM OF THE SALT RANGE

The Salt Range is separated from the Himalayan foothills by the Potwar Plateau, nearly 150 km of slightly elevated (about 270 m) land with very little topographic relief (Fig. 2). The roughly ENE-WSW trending Salt Range is bounded by the right-lateral Kalabagh Fault in the west (Gee, 1945; 1947; McDougall, 1985; Leathers, 1987; McDougall and Khan, 1990) and the Hazara-Kashmir syntaxis in the east. The Hazara-Kashmir syntaxis is formed by several fault blocks bounded by forward-and-rearward verging thrusts at the eastern margin of the Potwar Plateau (Johnson *et al.*, 1986).

The Salt Range Thrust, which is the leading edge of a décollement within Eocambrian evaporites, brings Phanerozoic strata over late Quaternary conglomerates and Jhelum River alluvium (Yeats *et al.*, 1984). The allochthonous nature of the Salt Range, with a detachment in the Eocambrian Salt Range Formation, was recognized by many earlier workers (e. g., Wynne, 1878; Cotter, 1933; Wadia, 1945 a, 1945 b, 1957; Gee, 1945, 1947, 1980; Voskresenskiy, 1978). Voskresenskiy (1978) argued that preexisting basement faults played an important role in the tectonic evolution of the Salt Range and Potwar Plateau. Faruqi (1982) interpreted the extensive lateral extension of salt as the remnant of a large, ruptured and discharged salt dome.

The oldest strata exposed in the Salt Range belong to the Eocambrian Salt Range Formation, which is overlain by Cambrian to Eocene platform rocks (Fig. 3). The Salt Range Formation unconformably overlies the Precambrian basement rocks of the Indian Shield. It is mainly composed of marl, gypsum, salt, and dolomite with minor oil shales and extrusive igneous rocks in its upper part. This typical evaporitic sequence has been correlated, on the basis of lithology, with other evaporitic rocks in different areas, e.g., Hazara (Latif, 1973), Multan (Sarwar and DeJong, 1979), Kaghan (Ghazanfar *et al.*, 1990 a), Zagros fold belt of Iran (Ala, 1974; Colman-Sadd, 1978), and Mackenzie,

Figure 2: Generalized tectonic map of the Salt Range and Potwar Plateau showing the major geological subdivisions of the rock units. Northern Potwar Deformed Zone (NPDZ), when compared with the area to the south, is highly dissected by numerous faults. **KMF**, Kheri Murat fault; **RF**, Rawat Fault; **DJ**, Dil Jabba fault; **DT**, Domeli thrust; **KBF**, Kalabagh fault. Other structures have been abbreviated as: **BA**, Buttar anticline; **CBK**, Chak Beli Khan anticline; **TB**, Tanwin Basin; **Q**, Qazian anticline; **A**, Adhi anticline; **M**, Mahesian anticline; **PH**, Pabbi Hills anticline. The lines L-L', BK-BK' and P-P' correspond to the cross sections by Leathers (1987), Baker et al, (1988) and Pennock et al, (1989), respectively.

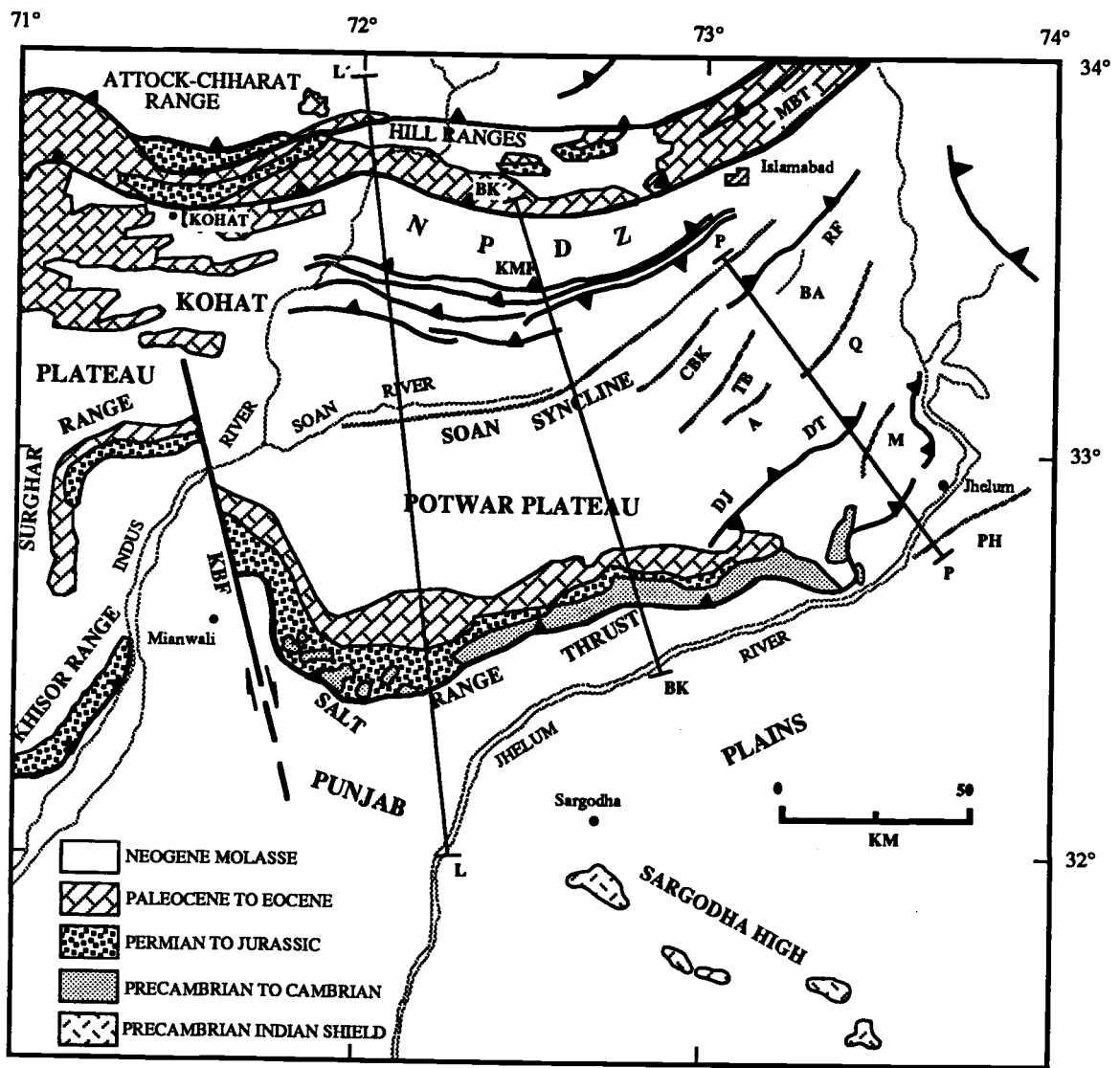


Figure 2

Michigan, Siberia (Zarkov, 1981). These various deposits are essentially contemporary, but it is doubtful that they ever formed a continuous sheet from a single depositional basin (Kozary et al., 1968). At its type section in Khewra Gorge, central Salt Range, it is about 830 m thick with more than 630 m of salt. However, its thickness varies at different localities; *e.g.*, in the Dharialla well it is almost 2000 m thick and the Hayal well encountered almost 1734 m of salt (see Fig. 5 for well locations). These variations in the thickness have probably been tectonically induced. The Salt Range Formation is not only present throughout the Salt Range, but some wells south of the range have also encountered it; *e.g.*, Warnali well has 32 m of it on top of basement, and Lilla well penetrated 219 m before the well was abandoned.

The platform rocks consist of Jhelum (Middle to Lower Cambrian), Nilawahan (Lower Permian), Zaluch (Upper Permian), Musa Khel (Lower to Upper Triassic), Surghar (Lower Jurassic-Lower Cretaceous), Makarwal (Paleocene) and Chharat (Lower Eocene) Groups (Fig. 3). There are two major unconformities, very gently dipping towards the east (Gee, 1980), within the Platform sequence. The dip of the unconformities is so gentle that their effect on the fold pattern is negligible, including the sections presented herein. The first unconformity separates the Jhelum Group from the Nilawahan Group, where the Tobra Formation (Talchir Boulder Bed), lowermost member of the Nilawahan group, unconformably overlies the Baghanwala Formation, the uppermost member of the Jhelum Group. The Tobra Formation documents the Permo-carboniferous glaciation of Gondwana. The second unconformity separates the Nilawahan Group from the Makarwal Group in the central and eastern Salt Range, while in the western part it separates the Musa Khel from the Makarwal Group. Overall the platform succession becomes thicker and more complete from east to west (Shah, 1977; Yeats and Hussain, 1987). In the westernmost part, the Surghar Group disconformably overlies the Musa Khel Group, which in turn is unconformably overlain by the Makarwal Group. On the other hand, in

**Figure 3: Generalized stratigraphic column of Salt Range (modified after Shah, 1977).
Because the seismic interval velocities, used for depth conversion, vary from east to west,
their range is shown.**

AGE			FORMATION	GROUP	TECTONIC SETTING	SEISMIC VELOCITY RANGE (m/s)	
ERA	PERIOD	EPOCH					
CENOZOIC	TERTIARY	PLEISTOCENE	LE I	SIWALIK	MOLASSE	3000 to 3200	
			SOAN				
		PLIOCENE	DHOK PATHAN	RAWALPINDI			
			NAGRI CHINJI				
		MIOCENE	KAMLIAL	MURREE			
			MURREE				
		OLIGOCENE	U?				
			M				
		EOCENE	CHORGALI SAKESAR NAMMAL	CHHARRAT			
			PATALLA LOCKHART HANGU	MAKARWAL			
MESOZOIC	CRETACEOUS	LOWER	LUMSHI WAL	SURGHAR	PLATEFORM	4000 to 4300	
	JURASSIC	UPPER	CHICHALI				
		MIDDLE	SAMANA SUK				
		LOWER	SHINAWARI DATTA				
	TRIASSIC	UPPER	KINGRIALI				MUSA-KHEL
		MIDDLE	TREDIAN				
LOWER		MIANWALI					
PALEOZOIC	PERMIAN	UPPER	CHHIDRU WARGAL	ZALUCH			
		LOWER	AMB SARDHAI WARCHHA DANDOT TOBRA	NILAWAHAN			
	CARBONIFEROUS DEVONIAN SILURIAN ORDOVICIAN						
	CAMBRIAN	MIDDLE	BAGHANWALA	JHELM			
		LOWER	JUTANA KUSSAK KHEWRA				
EOCAMBRIAN		SALT RANGE	INTRA-CRATONIC	4600 to 4800			
PRECAMBRIAN		BASEMENT INDIAN SHIELD		6000			

Figure 3

the eastern part the Makarwal Group unconformably overlies the Jhelum Group. Well data also suggest that the thickness of the platform sequence gradually decreases toward the east and southeast, *e.g.*, in the Mahesian well it is more than 400 m in thickness and the Warnali well has drilled about 370 m of the platform sequence. Unlike wells in the eastern part, the Karang and Dhermund wells in the western Salt Range have drilled more than 1050 and 1250 m of the platform sediments, respectively.

The platform strata are unconformably overlain by nonmarine, time-transgressive, syn-orogenic molasse sediments (Fig. 3). The Rawalpindi Group, mainly Eocene-Miocene and fluvial and deltaic in nature, consists of the Murree and Kamli Formation. The Siwalik Group, mainly Miocene-Pleistocene and fluvial in nature, is composed of the Chinji, Nagri, Dhok Pathan and Soan Formations. These strata lie on progressively older beds to the south; *e.g.*, in the Lilla and Warnali wells they unconformably overlie the Jhelum Group, while in the Kundian well, toward the west, they overlie the Zaluch group. In the Salt Range, however, the molasse sequence unconformably lies on Eocene carbonates (Shah, 1977; Fatmi *et al.*, 1984; Wells, 1984; Khan, 1986; Yeats and Hussain, 1987).

Deposition of the Rawalpindi Group documents the appearance of eroding land in the north, while the Siwalik Group documents the rise of nearby mountainous terrain. The lower Siwalik strata have been derived from the crystalline and metamorphic terrains in the hinterland part of the Himalaya. On the other hand, the upper Siwaliks are composed of recycled lower and middle Siwalik debris, Eocene limestone clasts and granitic clasts derived from the Tobra Formation, due to uplift and erosion as the deformation progressed toward the south (Keller *et al.*, 1977; Abid *et al.*, 1983; Burbank and Beck, 1989). Pilbeam *et al.* (1977) attempted a biostratigraphic correlation of the different units within the molasse sequence. More recently different workers (Johnson *et al.*, 1979; Opdyke *et al.*, 1979; Frost, 1979) have used a chronostratigraphic approach to calibrate ages of

different stratigraphic horizons by using paleomagnetic dating and tephrochronology, particularly in the eastern Salt Range and Potwar Plateau. These studies demonstrate the strongly time-transgressive character of these traditional lithostratigraphic units. Similarly, magnetostratigraphic studies (Johnson *et al.*, 1986; Burbank & Raynolds, 1988; Burbank & Beck, 1989 a, 1989 b) provide excellent constraints on recent structural events and relate these events to the molasse sedimentation.

Recent studies of the active thrust system have been particularly fruitful in the Salt Range/Potwar Plateau regions. Yeats *et al.*, (1984) provided evidence that the Salt Range Thrust is probably still active; *i.e.*, Holocene fan gravels are overthrust by Tertiary molasse. Seismic reflection data released by the Oil and Gas Development Corporation (OGDC) of Pakistan allowed Lillie *et al.* (1987) to document the presence of a major basement normal fault, with about 1 km of vertical offset, under the north-dipping beds along the northern flank of the Salt Range proper. This normal fault acted as a buttress and caused the development of a thrust ramp along which the overthrust wedge was deflected to the surface. Three regional balanced cross-sections across the Potwar Plateau and Salt Range (Fig. 2), which take advantage of abundant seismic and well hole data as well as surface geology, interpret the gross structure of the area (Baker *et al.*, 1988; Leathers, 1987; and Pennock *et al.*, 1989). Determinations of overall shortening across the Salt Range/Potwar Plateau range from 20 to 34 km.. Gravity models provide additional constraints for the bending of the basement under the Himalayan foreland in Pakistan (Farah *et al.*, 1977; Duroy, 1986; Duroy *et al.* 1989). Related studies have applied the Coulomb wedge mechanical model to the thrust system and emphasized the role of salt in the thrust tectonics (Davis & Engelder, 1985; Jaumé, 1986; Jaumé & Lillie, 1988). These studies are all regional in nature and emphasize the interaction between evaporites and thrusting.

METHODOLOGICAL APPROACH

The present study is based on data from 15 petroleum exploration wells and approximately 450 km of commercial seismic reflection profiles, with the help of surface geological control from the maps published by Gee (1980). The reflection data were 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, Pakistan Petroleum Limited and Pakistan Oil fields Limited. Although none of the 15 wells has ever encountered a repeated platform sequence, convincing evidence for subsurface thrusting and repetition of beds beneath a roof sequence in the Salt Range is seen on seismic reflection profiles that cover the major portion of the section lines.

The quality of the seismic data in the region is generally very good, particularly north of the basement fault and associated ramp. However, the data quality deteriorates in the area of critical interest to this study, where the leading part of the thrust wedge, herein called the roof sequence (Fig. 4), starts to ramp to the surface. This deterioration in quality is mainly due to three factors: (1) more rugged topography; (2) deformation within the roof sequence, which gradually increases towards its leading edge; and (3) repetition of the platform sequence, which sandwiches the low velocity molasse sequence between the high velocity salt and platform sequence. These factors make it difficult to resolve the structural details of the area concealed under the roof sequence.

The seismic data have been converted to depth by using interval velocities derived from stacking velocities, with the help of the well control (Fig. 3). Once tied to the well data, either on the line or extrapolated along strike, the seismic expressions of different stratigraphic units were characterized. Generally, the seismic profiles can be further subdivided into four different stratigraphic units, based on seismic signatures. The molasse is characterized by semicontinuous, parallel reflectors of moderate amplitude. The

platform sequence is typically marked by a series of strong, parallel, continuous reflections of moderate to high amplitude, and is easy to recognize. A seismically transparent zone, below the platform sequence, corresponds to the Salt Range Formation. At a few places, this zone shows some semicontinuous reflections that represent either deformation within the evaporites or bedded intervals. Below the seismically transparent zone is a set of very gently dipping strong reflections. This set marks the top of the crystalline basement. Note that, because of the gradual northward thickening of the low-velocity molasse, the basement and other reflectors appear to be dipping more steeply than they actually are. Similarly, the throw on the basement normal fault is also exaggerated. These abnormalities on the seismic lines are due to velocity pull-up effects. However, throughout the region, the relatively consistent nature of the seismic signature of the different rock sequences increases one's confidence in the interpretation, even where velocity and/or well control is lacking.

The surface structure has been constructed by using the kink method of fold construction (Suppe, 1983). Kink folds are angular folds formed to accommodate interlayer slip with no appreciable thickening or thinning of the folded layers (Wojtal, 1988). The same kink fold geometry has also been recognized and used in other orogenic belts of the world underlain by ductile salt (*e.g.*, Dewey, 1965; Faill, 1969, 1973, Laubscher, 1977; Thompson, 1981). Similarly all the assumptions for the construction of kink fold geometry were used while constructing the surface geology. All the thrusts, both foreland and hinterland verging, and the normal faults have been constructed with a planar geometry. Perhaps many of these faults are listric in detail, but in the absence of better subsurface data one cannot draw them with more exact geometries. Not all Salt Range folds are true kinks, as incompetent layers, particularly the salt, produces various fold styles, especially in the vicinity of the frontal ramp. However, the kink approach produces

readily balanced sections. For the Salt Range, non-kink structures are mostly small, and they do not detract from the overall value of the simplified sections.

All the sections have been balanced by using line length method (Dahlstrom, 1969; Dixon, 1982) for the mechanically competent platform rocks of Cambrian to Eocene age. Their competent nature provides necessary structural control, which is essential not only for drawing the overlying structures that have been eroded away, but also for conserving the bed lengths during deformation. In contrast, the salt has been area balanced, because of its ductile nature. The area of salt in the deformed section has been calculated to get an idea that how much salt has flowed into the system from the north, assuming no salt has flowed in or out of the plane of the section. The molasse sediments, on the other hand, were not balanced because their fluvial nature and poor consolidation results in a lack of reproducible stratigraphic thickness and passive draping over the platform structures. Moreover, the uppermost part of the molasse sequence is contemporaneous with the deformation. This means that on the upthrown side of the normal fault the Siwalik rocks were eroded away and correspondingly may have been deposited on the down thrown side of the basement normal fault. Similarly, all the faults within the roof sequence have been constructed and restored only for the platform sequence, particularly where younger faults cut the older faults in the molasse sequence.

STRUCTURE AND CRUSTAL SHORTENING

The deformational style of the Salt Range is typically marked by broad synclines and long, narrow anticlines similar to those in other shallow décollement fold-and-thrust belts, underlain by salt; *e.g.*, Jura (Laubscher, 1972), Franklin Mountains of Canada (Hills *et al.*, 1981; Cook and Aithen, 1973; and Aithen *et al.*, 1982, as cited by Davis and Engelder, 1985). The roof sequence is very gently folded into box folds and is moderately faulted by both forward and back thrusts. Folding becomes more complex towards the leading edge of the thrust system and faulting is more abundant in the west. The overall structure at the leading edge of the Salt Range thrust front is increasingly complex. On the frontal culmination wall (Fig. 4), gravity tectonics (Gardezi and Ashraf, 1974; Butler *et al.*, 1987) are manifested by platform sequence slide blocks of different sizes that increase the exposure of the Salt Range Formation. Substantial parts of these blocks may have been eroded away due to weathering, although the platform sequence is more resistant to weathering than the molasse. However, I assumed while constructing the geological section that these blocks are part of a continuous structure, as insufficient data are available to resolve the influence of gravity tectonics.

The absence of well data and good quality seismic signatures under the roof sequence make it very difficult to document the exact thickness of the salt and other stratigraphic units. Two important questions arise. How much salt is sufficient for the horizontal translation of the roof sequence over the décollement? What is the geometry of the décollement zone?

The minimum thickness of salt required to effectively translate a thrust sheet is poorly known. The thickness of salt varies greatly in different salt based fold-and-thrust belts. The Appalachian Plateau, which lies north and west of the Valley and Ridge province, is underlain by approximately 100-200 m of salt (Kreidler, 1963; Cate, 1963;

Figure 4: Explanation of the terminology used for the different stratigraphic units and structural features in this study. Note that thick salt pad forms the wedge shaped geometry due to the buttressing effects of the northern ramp localized by the basement normal fault. Also note the deformational style of the roof sequence into sharp, salt cored anticlines and broad, flat based synclines.

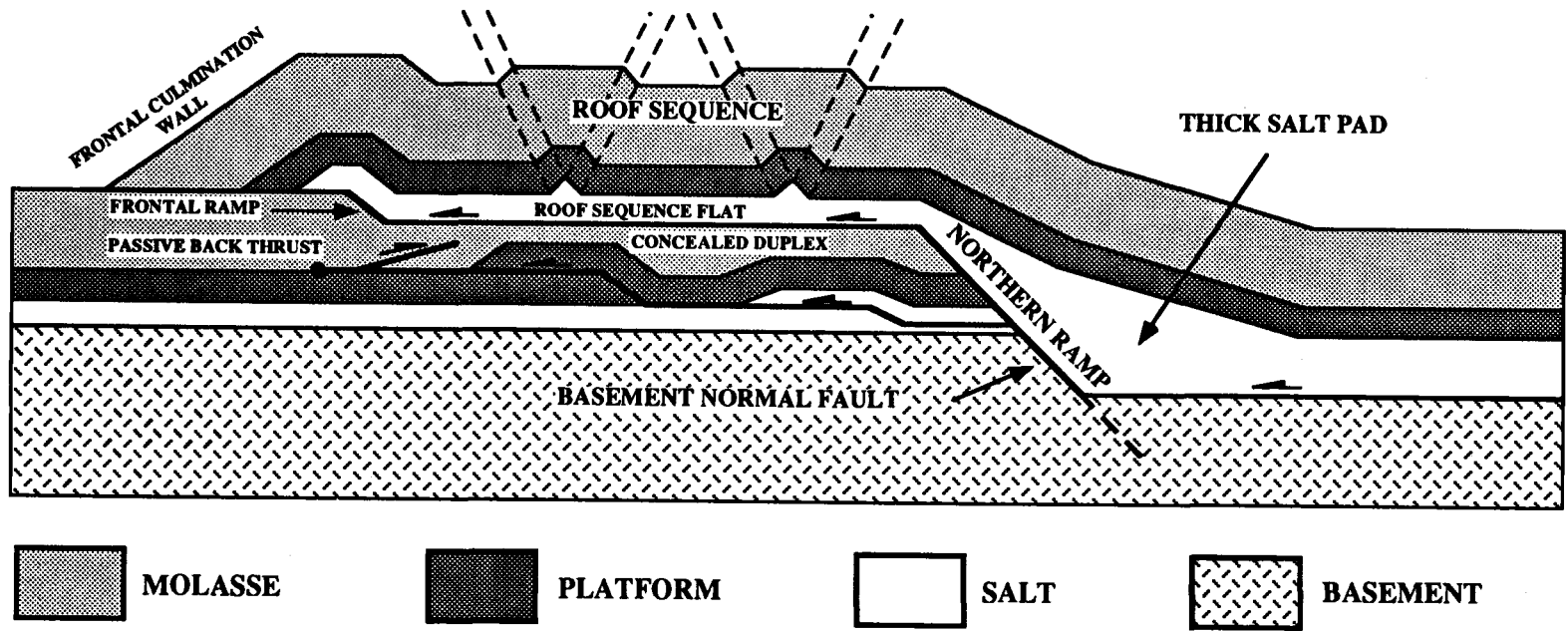


Figure 4

Chen, 1977; as cited in Davis and Engelder, 1985). However, under anticlines the salt is well over 500 m in thickness (Wiltchleo and Chapple, 1977; Mesoella, 1978). The evaporitic sequence is approximately 100 m thick under the Jura Mountains (Anderson, 1978), while in the Franklin Mountains, in front of the Mackenzie salient of northwest Canada, the thickness varies from 200-670 m (Hills *et al.*, 1981). The Zagros mountains of Iran are underlain by Hormuz salt typically about 300 m thick (Colman-Sadd, 1978).

In the Salt Range, the interpretation of the thickness of the salt must also meet the general constraints established by well data, seismic data, and previous workers. The thickness of the salt generally decreases towards both the south and the east (Davis and Engelder, 1985; Leathers, 1987; Baker, 1987; Baker *et al.*, 1988; Pennock, 1988; Pennock *et al.*, 1989). Under the Potwar Plateau in the north, previous workers (Baker *et al.*, 1988; Pennock *et al.*, 1989) have shown an average of 700 m thick salt on their restored sections, mainly based on seismic data and the Dhermund well (see Fig. 5 for location). To account for the known lateral variations as well as possible under the roof sequence, I have used thicknesses of 700 m in the western Salt Range, 600 m in the central Salt Range, and 500 m in the eastern Salt Range. This is in contrast to the triangular salt mass, almost 2.5 km thick, just south of the basement normal fault (Baker *et al.*, 1988). The seismic data also show that north of the basement normal fault the salt is very thick, up to 2.6 km. Elsewhere, well data also show that at places the salt is abnormally thick; *e.g.*, the Dharialla well penetrated about 2 km of salt while another well Hayal has drilled approximately 1.7 km of salt. I have been able to relate such abnormal thickness of salt to variations in the thrust geometry as discussed below.

The second question is the geometry of the décollement zone under the roof sequence. There are two possibilities. First, the décollement may make a long flat by staying at a certain stratigraphic horizon as it steps up the section. The second possibility is that the décollement may cut up section to form a listric shape with very thick salt (Baker *et*

al., 1988). In other fold-and-thrust belts different workers have found that the décollement marks a distinct flat instead of a listric shape; e.g., in the Appalachians (Rich, 1934; Harris and Milici, 1977) and Juras (Laubscher, 1972). However, in the absence of good seismic data at a larger scale it is difficult to define the exact geometry of the décollement. In view of this above discussion, I infer that the geometry of the décollement is not listric, rather it is a distinct flat and ramp as suggested by seismic line KK-13. I place the hanging wall flat of the roof sequence in the shaley lithology of the Chinji Formation, a suitable décollement horizon. This long roof sequence flat again ramps up along the frontal ramp (Fig. 4) to expose salt and the older platform sequence to the surface along the Salt Range Thrust Front.

Structural Cross-Sections

Due to more seismic coverage and a better understanding of the role of the basement normal fault in localizing the northern ramp, the sections in the central Salt Range will be discussed first. Subsequently; an attempt has been made to extend the structural features recognized in the central Salt Range to the west and east.

The Central Salt Range

Two sections, B-B' and C-C', have been constructed along the two seismic lines KK-13 and KK-19, respectively (for location see Fig. 5). The surface geology along the section line B-B' manifests the gradual exposure of older platform strata toward the south. Siwalik and Murree molasse, with dips of 15°-30° N, mark the surface expression of the ramp over the basement normal fault. The basement normal fault has acted as a buttress against which the salt has thickened. It also constitutes the lower part of the northern ramp and brings the older platform sequence to the surface. The north-dipping reflectors, offset

Figure 5: Geological map of the Salt Range (simplified after Gee, 1980). It also shows the locations of four balanced cross sections, seismic lines, and petroleum exploration wells used in this study.

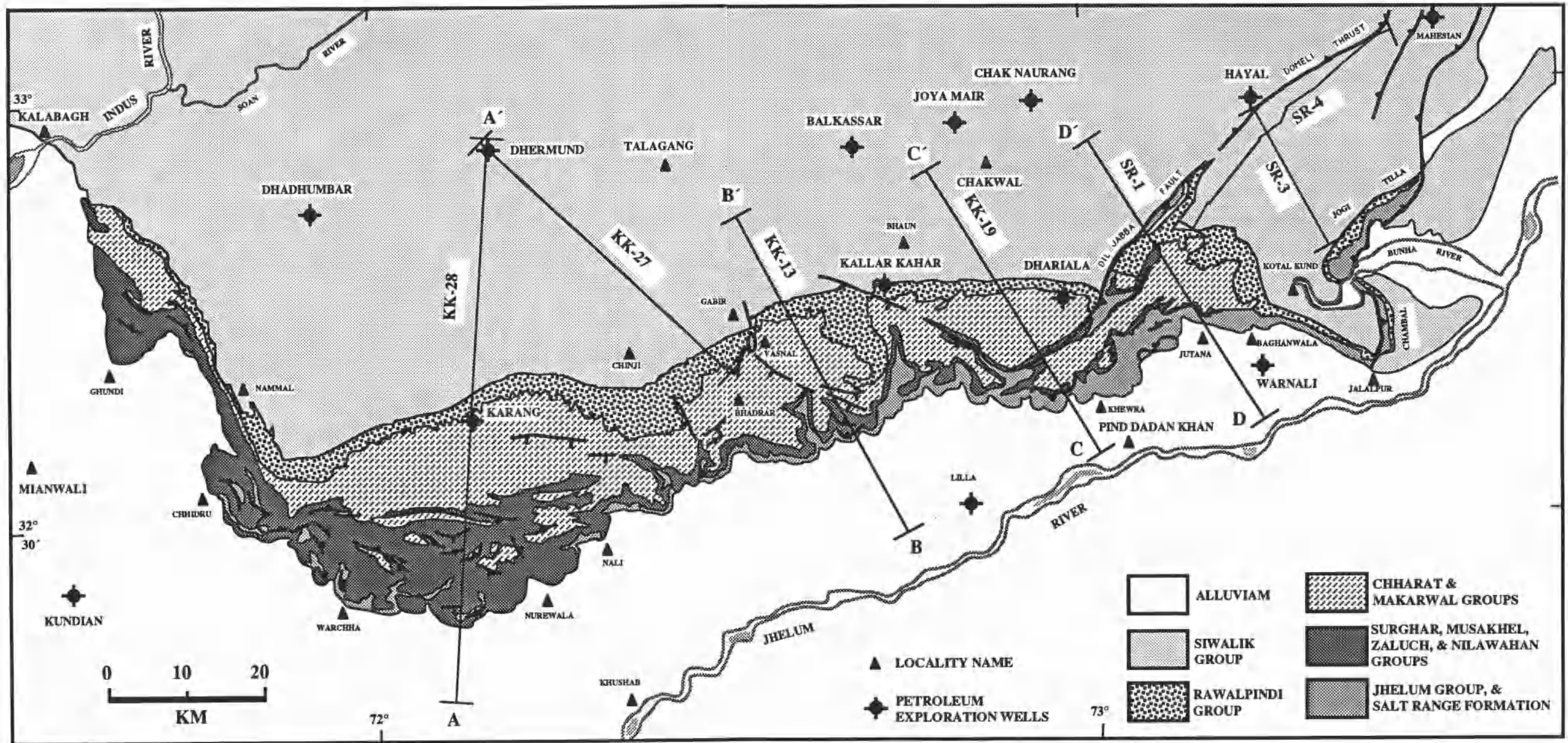


FIGURE 5

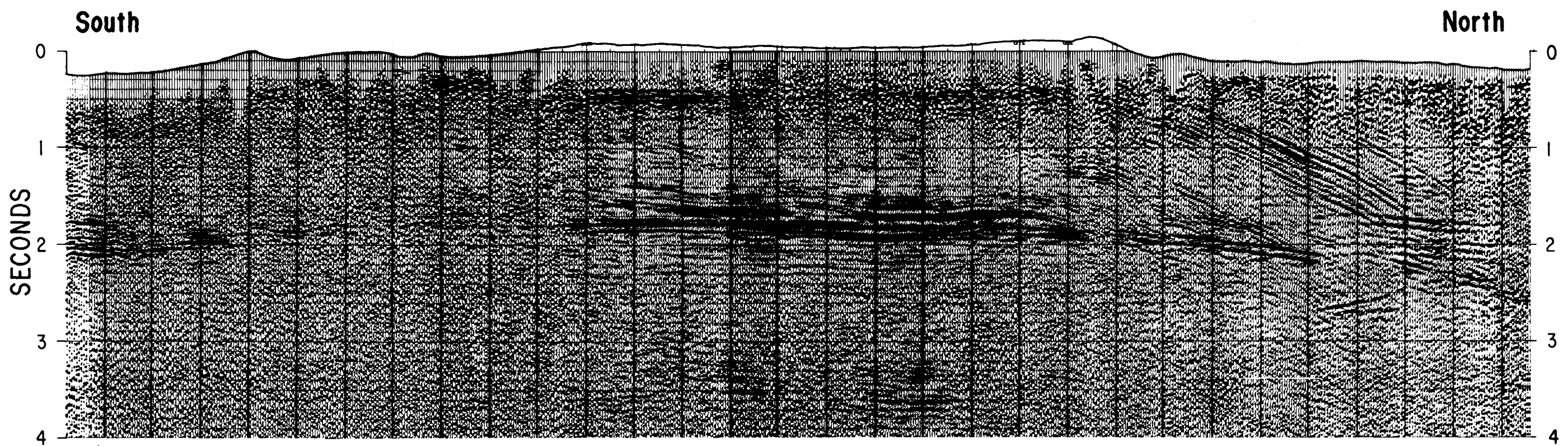
due to the basement normal fault, and the thickening of the salt north of the fault, can be clearly seen on the seismic line (Fig. 6). As the roof sequence rides over the northern ramp due to the basement normal fault, the strata become almost horizontal. This is also clearly portrayed on the geological map (Gee, 1980; and Fig. 5) by a very wide (almost 12 km) outcrop width of the Chharat Group, which is only about 170 m thick. This overall flat pattern of the roof sequence is best explained by a nearly horizontal underlying detachment.

Deformation within the roof sequence is minor. On the seismic line (Fig. 6), flat reflectors to a depth of 0.5 seconds mark the presence of the platform sequence within the roof sequence. This sequence is cut by numerous normal faults with very minor stratigraphic throw (Fig. 7). It has been very gently folded into broad synclines. Sharp, small anticlines that connect two successive broad synclines are cored by salt. The roof sequence is very gently folded into a series of small salt-cored anticlines near the leading edge. These anticlines are generally bounded by minor normal faults. Near the leading edge, there is a back thrust that brings Salt Range Formation over either the Jhelum Group or the Nilawhan group. This back thrust may have developed late in the geological history to build topography in order to maintain the forward motion of the roof sequence.

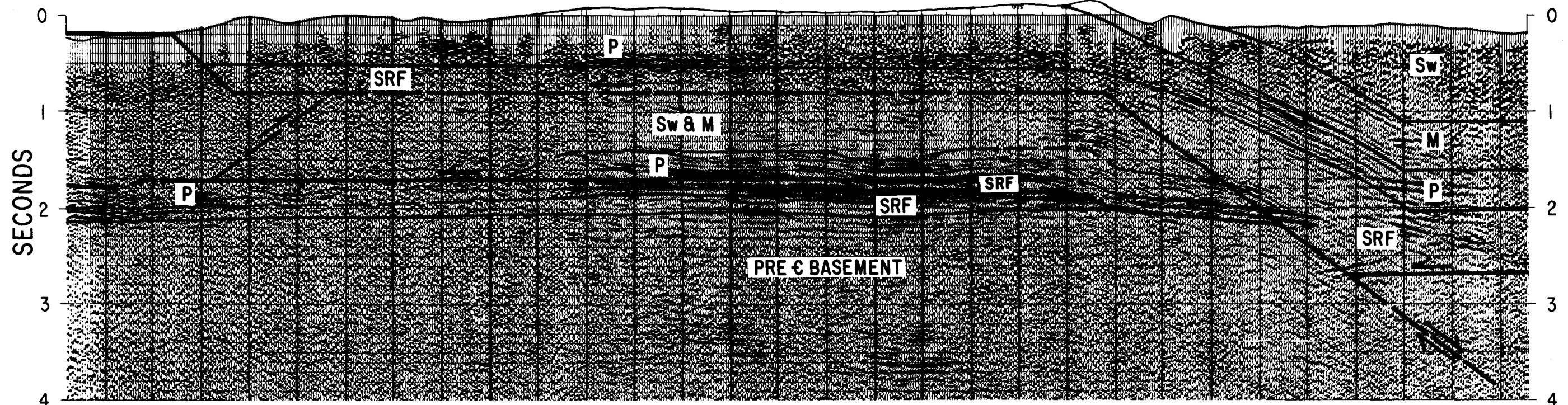
A very important new finding of this study is the recognition of a duplex structure under the roof sequence. On the seismic line (Fig. 6), south of the basement normal fault, between 1.5 - 2.0 seconds, the reflectors manifest fault bend fold geometry below the roof sequence. This has caused the repetition of the salt and platform sequence. I infer that the décollement first stays within the Salt Range Formation, and then steps up in the section on a small ramp to just above the platform sequence. Shaley horizons near the base of Murree molasse appear to have acted as a favorable site for a flat. The displacement along the flat in the Murrees at the top of the platform sequence does not continue indefinitely. In the south, Lilla and Warnali well data show that the Siwalik molasse unconformably

Figure 6: (A) Seismic line 815-KK-13 across the central Salt Range, used for balanced cross section B-B' (see Fig. 4 for location). It is unmigrated, 24 fold, dynamite source, recorded in 1981 by Oil and Gas Corporation (O.G.D.C.) of Pakistan and processed by Petty-Ray Geophysical. Abbreviations used on the seismic line are **SRF**, Salt Range Formation; **P**, Platform Sequence; **M**, Murree Formation, **Sw**, Siwalik Molasse. These are same on rest of the seismic lines used in this study.

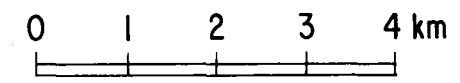
(B) Generalized interpretation of "A".



A



B



KK-13

Figure 6

Figure 7: (A) Balanced cross section showing present day structure along B-B' in the central Salt Range.

(B) Balanced and restored structural cross section shows that about 27 km shortening has occurred along B-B'.

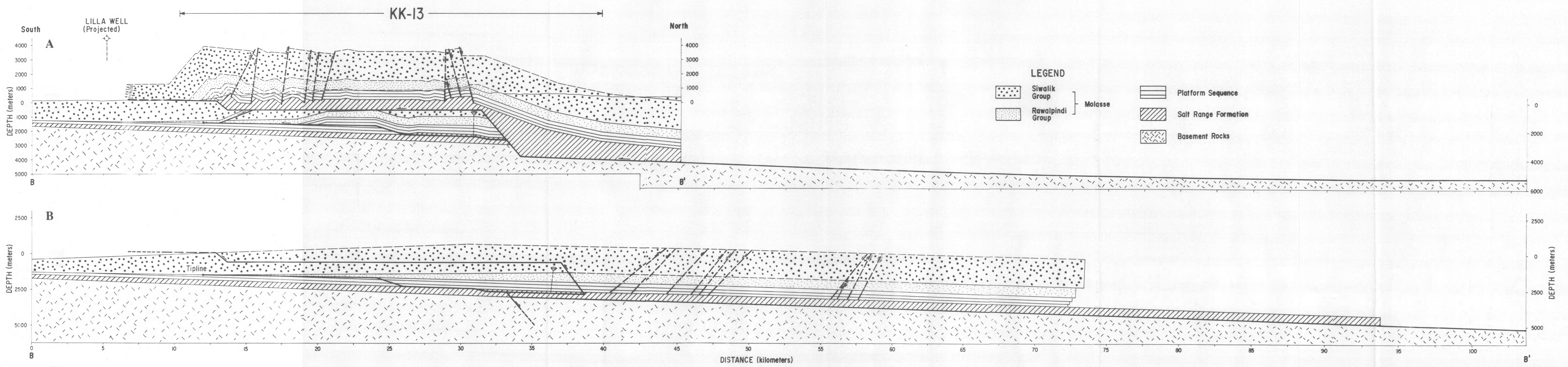


Figure 7

overlies the top of the platform sequence, and the contact is not faulted. All the Murrees and part of platform sequence are missing. This implies that the displacement has to die out between the duplex structure in the north and the well in the south. On the other hand, no fault has been recognized either within the alluvial fans immediately adjacent to the Salt Range thrust or in the Punjab plains further to the south. Therefore, I have inferred that a triangle zone with a passive back thrust lies under the roof sequence. A similar structure has been identified (Jaswal, 1990) in the northern limb of Soan syncline. It is probable that such a back thrust would degrade the quality of the seismic data in its vicinity. Therefore, the back thrust has been placed where the quality of the data is poorest.

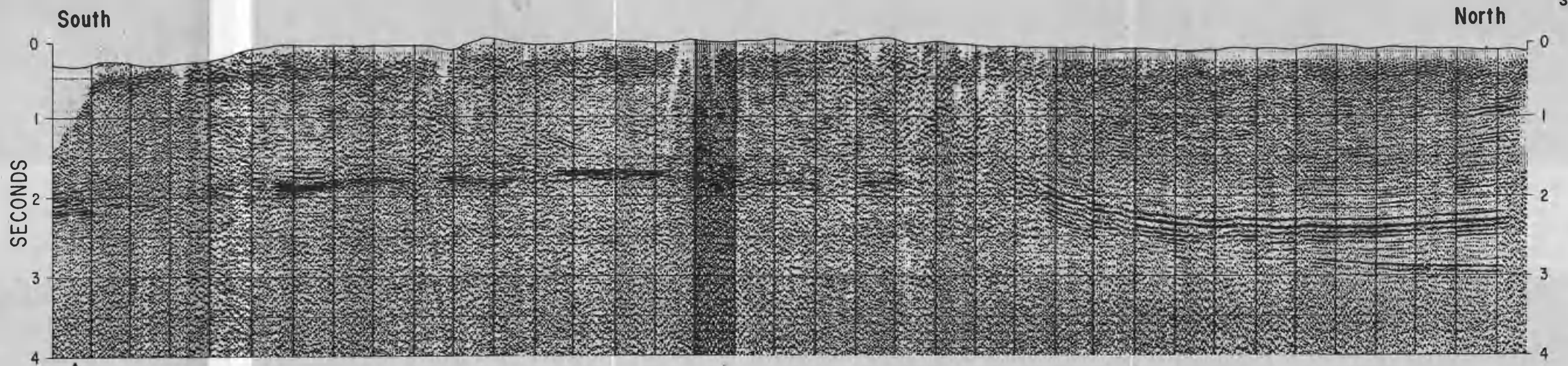
Palinspastic restoration results in a total shortening of 27 km in the central Salt Range (Fig. 7). About 5.5 km of shortening, 20 % of the total, has been accommodated within the duplex structures under the roof sequence. Almost 1.7 km of shortening, 6% of the total shortening, has been accommodated within the roof sequence. Approximately 20 km, 74 % of the total shortening, have been accommodated across the northern ramp.

On the restored section (Fig. 7), the positions of the normal faults within the roof sequence have no mechanical significance. Either these faults were developed as thrusts when the roof sequence was tilted while overriding the ramp and were later reactivated as normal faults, or they developed after the roof sequence had already overridden the ramp.

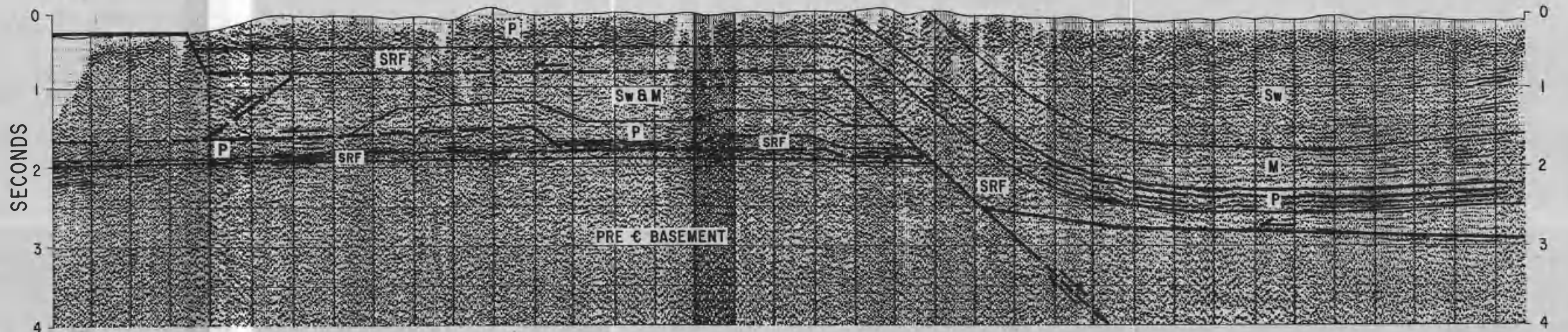
Section line C-C' is located approximately 35 km east of B-B' in the central Salt Range. The outcropping sequence becomes gradually older towards the south (Fig. 5). In the north, the molasse sequence dips about 30°-50° N, and marks the position of the subsurface ramp due to the basement normal fault. The typical north-dipping reflectors, north of the basement normal fault, on the seismic line KK-19 (Fig. 8) suggest that the platform sequence gradually become nearly horizontal at about 2.3 seconds. North of the basement normal fault, the platform sequence is buried under about 2.8 km of molasse

Figure 8: (A) Seismic line 815-KK-19 across the central Salt Range used for balanced cross section C-C' (see Fig. 4 for location). It is unmigrated, 24 fold, dynamite source recorded in 1981 by O.G.D.C. of Pakistan and processed by Petty-Ray geophysical.

(B) Generalized interpretation of "A".

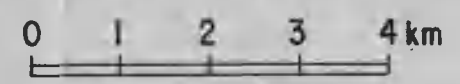


A



B

Figure 8



KK-19

sequence (Fig. 9), which has been eroded away from the top of the roof sequence to the south. The seismic section also shows that the salt is approximately 800 m (0.33 seconds.) thick on the downthrown side of the normal fault. The molasse sequence outcrop band is followed by almost flat laying Chharat Group to the south. The Chharat Group, with almost 10 km of outcrop thickness, has been gently folded into a broad syncline flanked by a small anticline and the Karangal fault to the south. The Karangal fault brings the platform sequence and Salt Range Formation over the Murree molasse. South of this fault is a salt core anticline. The Nilawahan Group is exposed in its core while the Makarwal and Chharat Groups are exposed on its flanks. This anticline is followed by an almost 4 km wide, flat bottomed syncline where the Chharat Group is exposed. In its south it is flanked by another steep, overturned, salt-cored anticline. Towards the southernmost position of the leading edge, this anticlinal structure is linked with another salt cored anticline through a steep overturned syncline. A steep back thrust separates the overturned syncline from the salt cored anticline, in the south. I infer that these structures were very gentle to start with, similar to those south of the Karangal fault. The flanks of the syncline became progressively steeper and steeper to accommodate more shortening. At some stage, it was no longer possible for the structures to accommodate additional shortening, and the back thrust developed. This implies that the overturning of the syncline postdates the back thrust and the Karangal fault. This rotation of the fold axis has also caused a substantial rotation of the back thrust, which is now dipping at a very steep angle. If this is correct, then it further suggests that the Karangal Fault is an out of sequence fault that developed after the deformation at the leading edge. After the development of the back thrust, when the roof sequence got stuck at the frontal ramp, the Karangal fault developed to maintain the critical taper necessary to keep the roof sequence in forward motion.

Figure 9: (A) Balanced cross section showing present day structure along C-C' in the central Salt Range.

(B) Balanced and restored structural cross section shows that about 24 km shortening has occurred along C-C'.

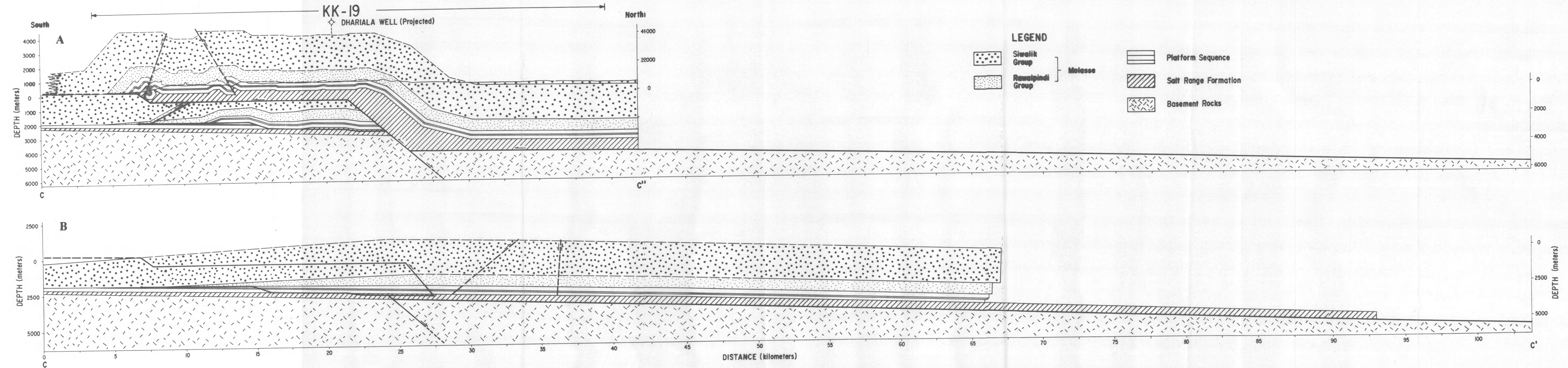


Figure 9

The poor resolution of the seismic data makes it difficult to delineate the duplex structures concealed under the roof sequence. However, one critical reflector, north of basement normal fault, at about 1.3 seconds, mimics the fault bend fold geometry. This reflector was modelled on the computer with the help of Mac Fault Software (Wilkerson and Usdansky, 1989) for balanced cross-section construction, using the same geometry of ramps as seen on the previous seismic line KK-13. The décollement in this case also first stays within the salt and then steps up and stays within the Murrees, near its contact with the platform sequence.

Palinspastic restoration of the section C-C' (Fig. 9) indicates that total shortening of 24 km. The duplex structures have accommodated 3.3 km, about 14 % of the total, shortening; while 17.8 km of shortening, 74 % of the total, has been accommodated across the northern ramp. About 3 km, 12% of the total shortening has been accommodated within the roof sequence due to folding and faulting.

In summary, the overall internal deformation and shortening within the roof sequence in the central Salt Range generally increases towards the east. Overall shortening decreases towards east. The largest component of shortening has been accommodated across the northern ramp. There is a 3 km decrease of total shortening within the central Salt Range towards the east. There is 1.7 km of total shortening within the roof sequence in the western and 3.0 km in the eastern part of the central Salt Range, respectively. It seems that about 1 km of the difference in shortening within the roof sequence has been compensated across the ramp towards the west. That is why the position of the frontal ramp is farther south in the western part of the central Salt Range.

The Western Salt Range

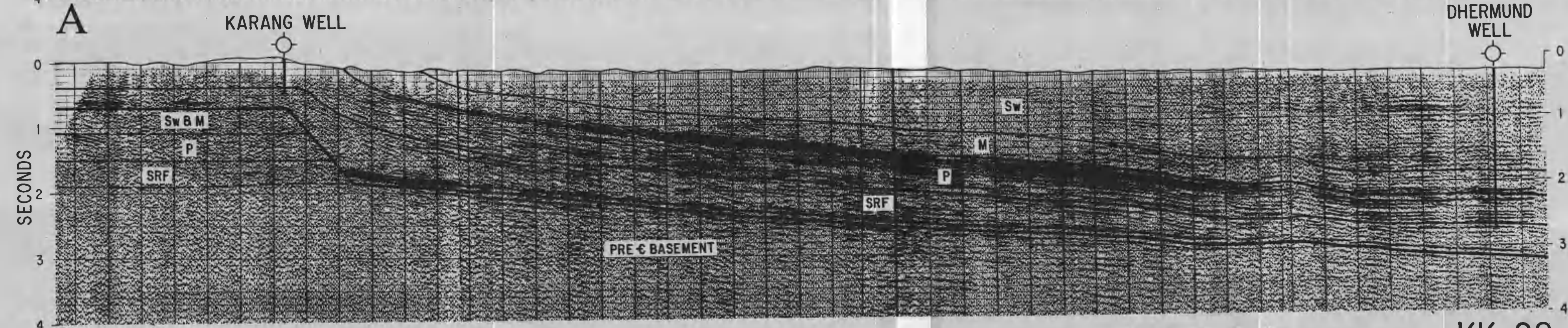
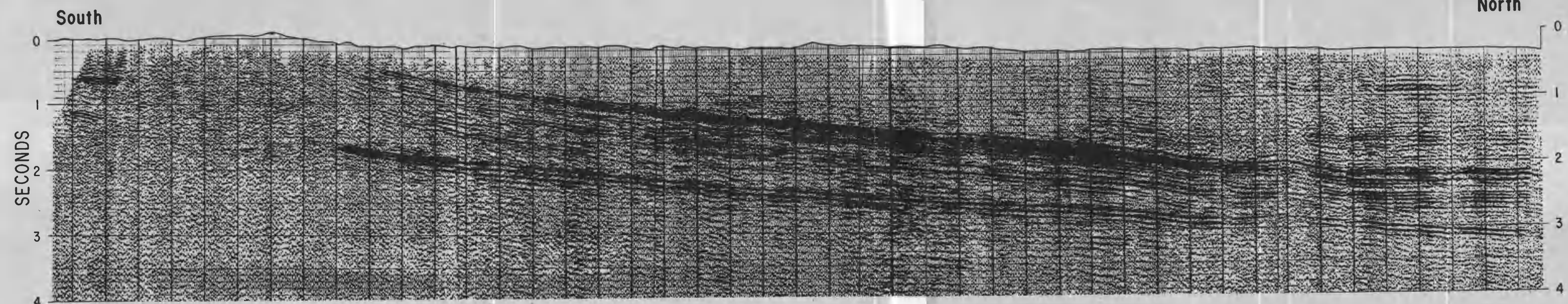
The Salt Range thrust has a broad lobe shape in the west (Fig. 2) where it has been truncated by the right lateral Kalabagh fault (Gee, 1980; Leathers, 1987; McDougall and Khan, 1990). The frontal ramp is farthest south here. A balanced cross-section A-A' (Fig. 11) has been drawn along seismic line KK-28 (Fig. 10) in the western Salt Range. It is located approximately 50 km west of section line B-B' in the central Salt Range. The undeformed section becomes gently to intensively deformed as the thrust front approaches its present position in the south. Unlike the central Salt Range, the roof sequence is frequently folded and faulted, particularly in its southern part where it is marked by numerous forward and backward verging thrust and normal faults.

In the western Salt Range the basement dips approximately 3° towards the north. On seismic line KK-28 the apparent steeper dip occurs because of velocity pull-up as less low-velocity molasse is exposed on the surface toward the south. Two exploration wells, Karang in the south and Dhurmund in the north, have been drilled on this line. Both wells have penetrated the Salt Range Formation. The Dhurmund well drilled 3150 m of molasse before it reached the platform sequence. The molasse sequence dips almost horizontally in the southern part. About 1 km north of the Karang well, the platform sequence makes its first appearance. In this vicinity the molasse and the upper part of the platform sequence dip about 20° to the north. The exposed platform sequence, eroded overlying molasse, and 20° dip of the strata support the probability of a ramp in the subsurface. Geomorphic evidence for this ramp is the north-directed, moderate density drainage compared with very low density drainage in the south.

On the seismic line (Fig. 10), typical high amplitude platform reflectors are almost horizontal in the north. Near the Karang well these dip towards the north, and then, due to topographic and structural factors, data quality deteriorates farther south. However, below

Figure 10: (A) Seismic line 815-KK-28 across the western Salt Range, used for balanced cross section A-A' (see Fig. 4 for location). It is unmigrated, 24 fold, dynamite source, recorded by O.G.D.C. of Pakistan and processed by Petty-Ray Geophysical.

(B) Generalized interpretation of "A".



A

B

Figure 10

KK-28

Figure 11: (A) Balanced cross section showing present day structure along A-A' in the western Salt Range.

(B) Balanced and restored structural cross section shows that about 32 km shortening has occurred along A-A'.

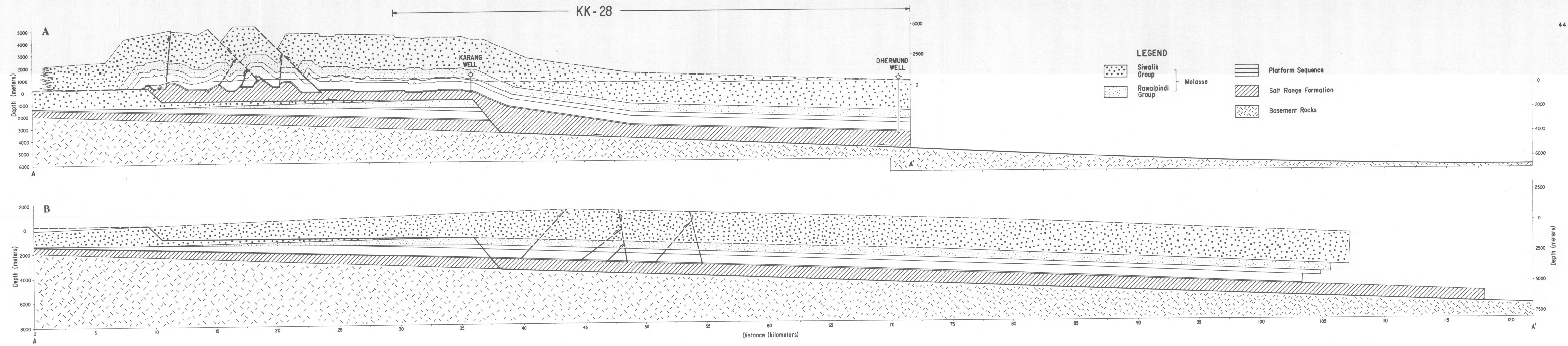


Figure 11

the platform reflectors one can still see the thickening of the salt in this region. The second important observation is the clear divergence of some reflectors, north of the Karang well, within the salt at about 1.5 seconds. These factors suggest that a subsurface ramp structure is present to generate the structural changes. Although the quality of the data is quite poor, there is no convincing evidence of basement offset on the seismic line, and I infer that the northern ramp is entirely within the sedimentary sequence.

On seismic line KK-28 no basement normal fault is present in contrast to seismic lines KK-13 and KK-19. This implies that the basement normal fault dies out between section lines KK-28 and KK-13. On another seismic line, KK-27 (Fig. 15), located between lines KK-28 and KK-13, the basement normal fault can still be seen, but with less offset than it has to the east. Therefore the basement normal fault dies out between KK-27 and KK-28 in the west as its throw gradually decreases. Note that the position of the northern ramp in the western Salt Range is approximately 15 km south of the one caused by the basement normal fault in the central Salt Range.

As the platform sequence rides over the northern ramp, it immediately becomes horizontal with a few very gentle folds (Fig. 11). The deformation gradually increases towards the south and the southern portion of the overridden roof sequence is substantially deformed. This part is deformed into salt cored anticlines. At two places the leading limbs of these anticlines have been disrupted by north-dipping thrust faults. There are also two backthrusts on the section line. At one place the trailing limb of an anticline has been displaced by a backthrust. The surface geology and reconstruction of the section suggest that the two forward thrusts possibly postdate some of the normal faults and back thrusts and are out of sequence in nature. These thrusts probably were developed as the leading edge of the roof sequence got stuck at the frontal ramp. This might have happened due to increased friction when the main décollement ramped up the section along the frontal ramp and started following a flat at the top of the Siwaliks.

On the retrodeformed section, all the faults dip quite steeply compared to the deformed section (Fig. 11). This suggests that these faults were developed after the roof sequence had overridden the ramp. However, it is quite possible that substantial rotation of some faults might have occurred after these originally developed. Palinspastic restoration indicates that 32 km of total minimum crustal shortening has occurred along A-A'. Approximately 28 km of shortening, 89 % of the total, has been accommodated across the northern ramp. The remaining 3.6 km of shortening, 11% of the total, has been occurred within the roof sequence.

In short, overall deformation within the roof sequence and the total shortening increase towards the west. The basement normal fault and the duplex structures underneath the roof sequence, seen in the central Salt Range, disappear. The northern ramp that caused the surface exposure of the platform sequence is entirely within the sedimentary sequence. It is located about 15 km south of the position of the basement normal fault that acts as a part of the northern ramp in the central Salt Range. This suggests that a lateral ramp must connect these two structures. The major component of shortening has been accommodated across the northern ramp.

The Eastern Salt Range

Balanced cross-section D-D', constructed in the eastern Salt Range, is located approximately 25 km east of C-C' in the central Salt Range (see Fig. 5 for location). The surface geology in the eastern part of Salt Range is marked by the two NE-SW oriented back thrusts (Gee, 1980) within the roof sequence. The northern back thrust is quite persistent, extends further in the northeast direction, and is called the Dil Jaba fault (Fig. 5). The southern back thrust has been named the Chail fault. It is a local fault and dies out in both NE and SW directions, across the section line. These back thrusts make it difficult

to locate surface evidence of a possible position for the subsurface northern ramp in the eastern Salt Range. Seismic line SR-1 (Fig. 12), however, shows the position of the ramp within the sedimentary sequence. High amplitude, nearly horizontal platform reflectors north of the ramp can be seen at about 2.0 seconds at the top of the seismically transparent zone that is characteristic of salt. The salt extends from 2.34 to 2.6 seconds where it overlies the top of the basement, which dips gently to the north at about 1° - 1.5° . Farther south the quality of the data becomes poor because of topographic and structural complexities. The seismic data further suggest the absence of any basement normal fault. Thus, the basement normal fault gradually dies out towards the east between lines KK-19 and SR-1.

Another important observation is that in the eastern Salt Range, unlike to the west, the northern ramp is located approximately in line with the basement normal fault observed in the central Salt Range. This suggests that the timing of the ramping of the roof sequence in the eastern Salt Range should be consistent with the initial ramping of the roof sequence over the basement normal fault in the central Salt Range.

The roof sequence, compared with its central part, is relatively more deformed both in its northern and southern parts as it rides over the northern ramp (Fig. 13). The deformation in its northern part is due to the frontal ramp and in its southern part is related to the back thrusts. The central portion is relatively little deformed with small salt-cored anticlines and broad, flat-bottomed synclines. Near the leading edge, a series of relatively small, salt-cored anticlines is present. At places these structures are disrupted by two steeply-dipping normal faults. At the trailing edge of the roof sequence, the strata are substantially more deformed between the two back thrusts. Dil Jabba fault, in general, brings Salt Range Formation and, at places, Chinji and Murree Formations over the Nagri Formation. I consider the Dil Jabba fault to have initiated as a passive back limb thrust. The strata in the hanging wall started moving passively, to accommodate more shortening,

Figure 12: (A) Seismic line 782-SR-1 across the eastern Salt Range used for balanced cross section D-D' (see Fig. 4 for location). It is unmigrated, 12 fold, dynamite source, recorded and processed by O.G.D.C. of Pakistan in 1978.

(B) generalized interpretation of "A".

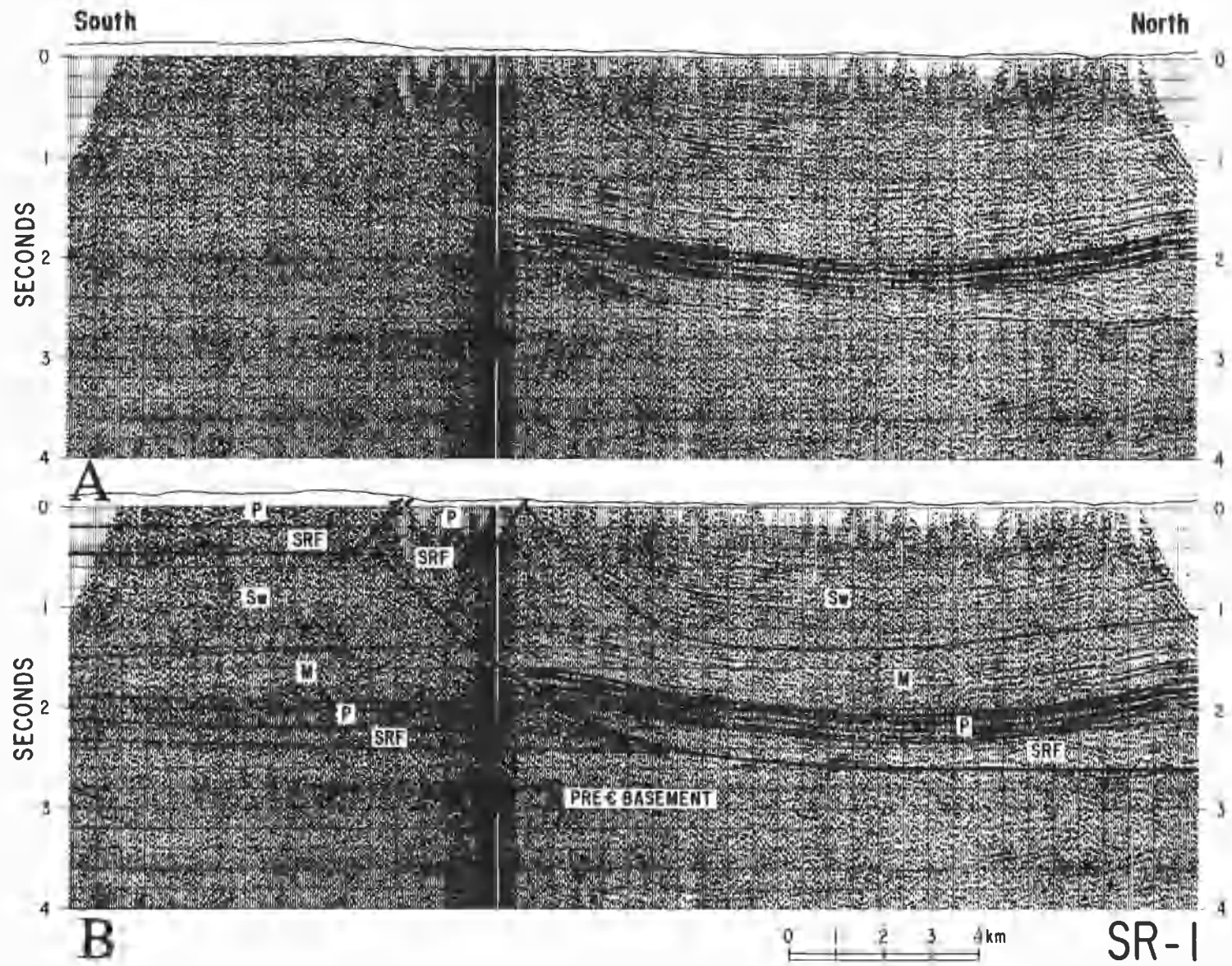


Figure 12

Figure 13: (A) Balanced cross section showing present day structure along D-D' in the eastern Salt Range.

(B) Balanced and restored structural cross section shows that about 17 km shortening has occurred along D-D'.

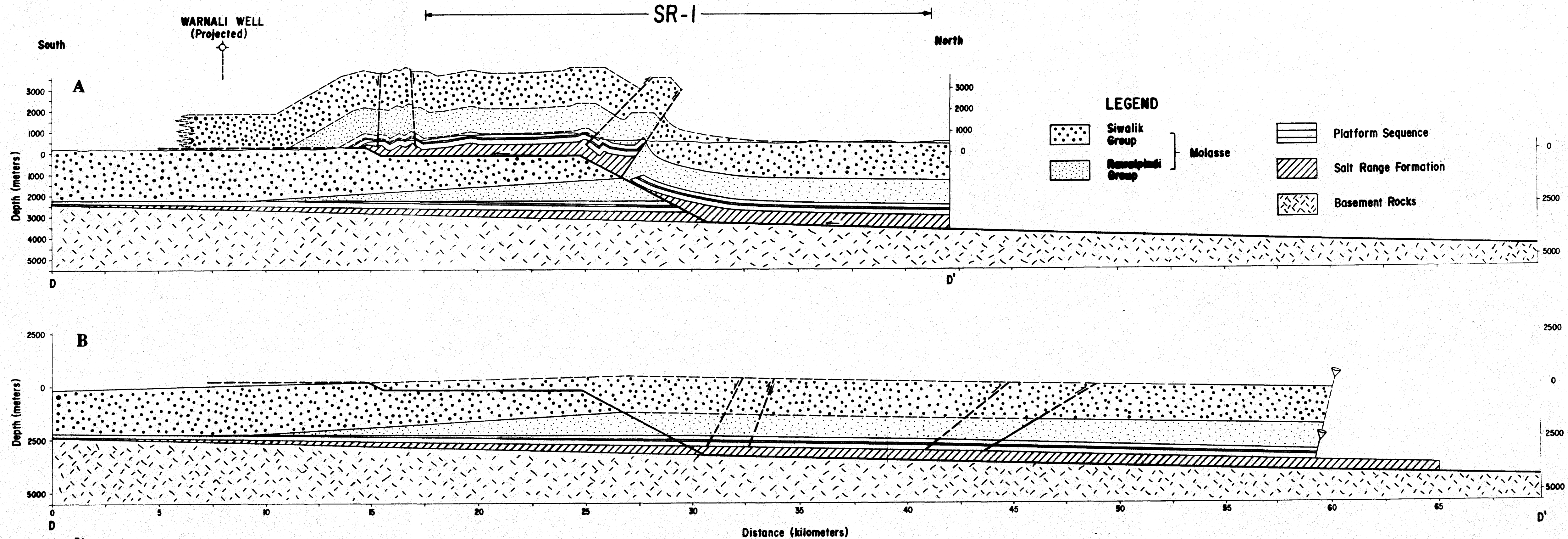


Figure 13

as the strata in the footwall kept moving southward. Fig. 14 shows the successive development of the Dil Jabba thrust, which has acted as a passive roof thrust as the roof sequence moved to the south. Probably, the deformation in the hanging wall of the Dil Jabba fault is contemporaneous with the development of this passive roof thrust. The strata were gradually folded in response to this passive movement. This was followed by the out of sequence development of the Chail thrust to facilitate the forward motion of the roof sequence, by building topography.

Palinspastic restoration shows that a minimum of about 17 km of shortening has occurred along this section line (Fig. 13). Approximately 15 km of shortening, 89 % of the total, has been accommodated across the northern ramp, while approximately 1.8 km of shortening, 11 % of the total, has been accommodated within the roof sequence. Section balancing also indicates that approximately 0.8 km of shortening, 4 % of the total shortening within the roof sequence, has been accommodated along the Dil Jabba and Chail thrusts.

To summarize, overall crustal shortening in the Salt Range decreases towards the east. However, the total shortening within the roof sequence is comparable to what has been seen along section line B-B', but is substantially less than that observed on A-A' and C-C'. This implies that there is an irregular shortening within the roof sequence. The northern ramp that deflected the sedimentary sequence to the surface and caused the repetition of the platform sequence is within the sedimentary sequence. The position of the northern ramp in this part of the eastern Salt Range is consistent with the position of the basement normal fault in the central Salt Range, but the basement is not offset. The major component of shortening, as in the rest of the Salt Range, has been accommodated across the ramp.

Figure 14: Schematic diagram showing the successive development of Dil Jabba fault. Note that the roof sequence kept on moving forward and only a part of the deformation has been accommodated along the back thrust. Also note the gradual development of a salt wedge in the footwall of the back thrust that altered the geometry of the footwall.

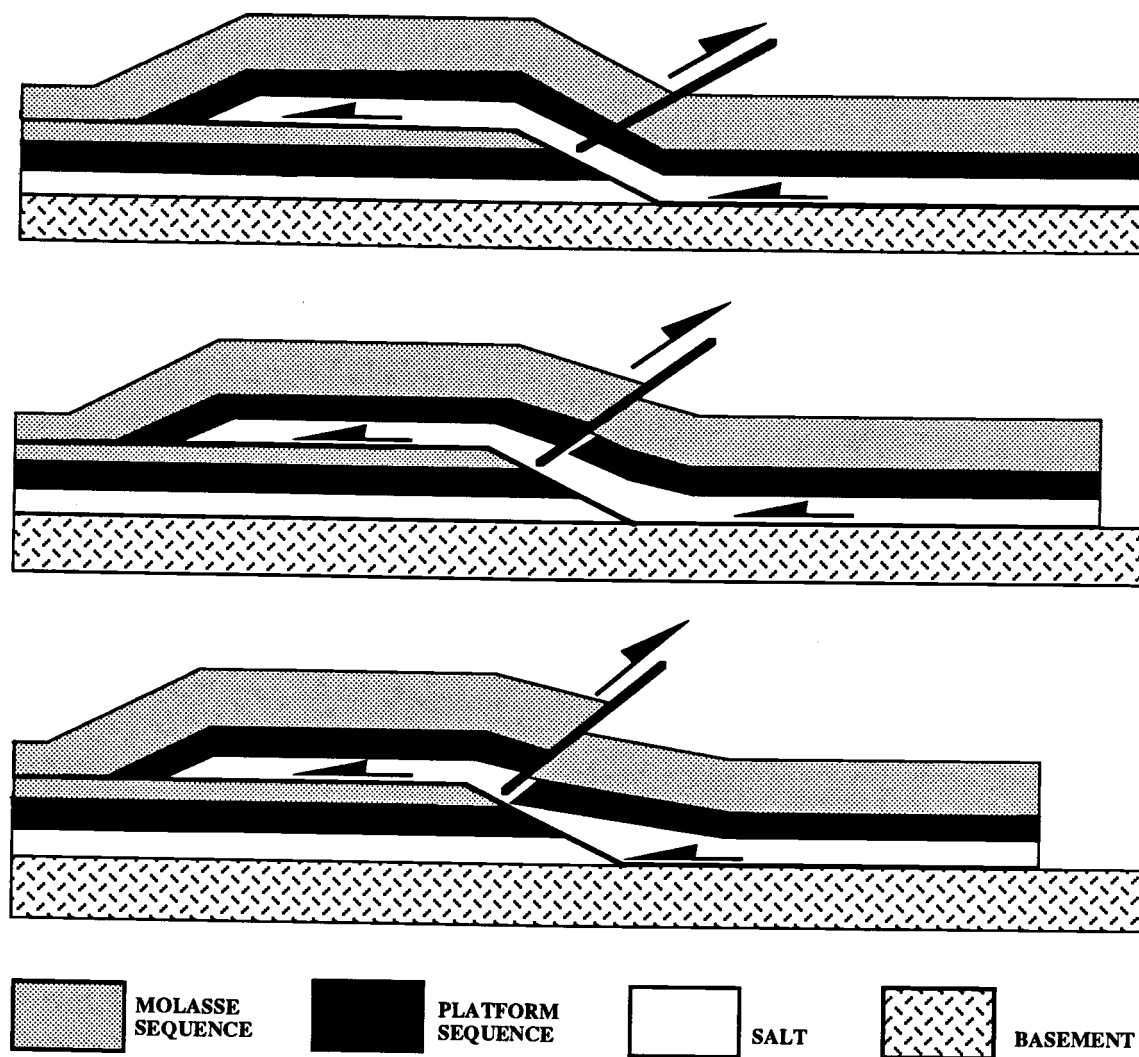


Figure 14

DISCUSSION

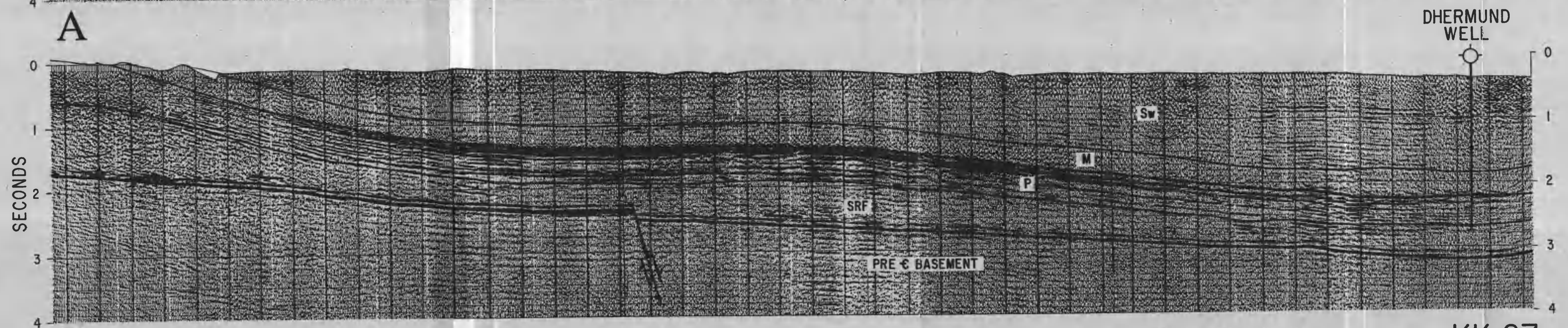
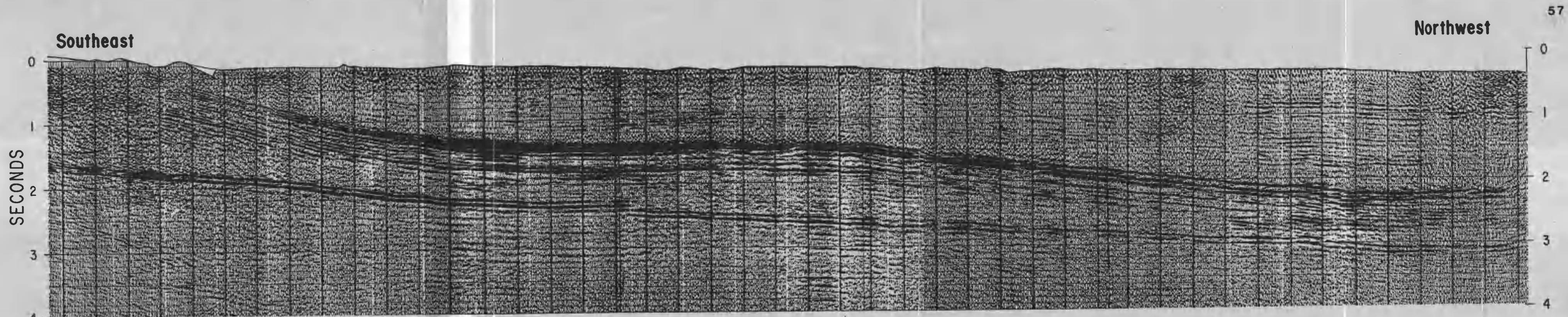
Concealed Duplex

The newly recognized duplex structure in the central Salt Range extends more than 40 km along strike. Seismic lines show the décollement of this structure gradually stepping up section. First, a gentle 10° ramp within the Salt Range Formation repeats part of the salt section and then a 30° ramp further steps up and repeats the platform sequence. Section balancing shows that approximately 5.5 km and 3.3 km of shortening have accumulated along these structures in the western and eastern parts of the central Salt Range, respectively. These structures formed before the basement normal fault.

The duplex structure is only present in the central Salt Range, which implies that the décollement at its base must step down section and join the main décollement both in the west and the east. The westward termination of these duplex structures can be further constrained with the help of seismic line KK-27 (Fig. 15). Further west along the duplex edge, on both this line and line KK-28, the platform sequence is flat and has not yet ramped upward. This implies that the décollement at the base of the duplex structure steps down along a lateral ramp to joins the main décollement, and that the lateral ramp is located somewhere between seismic lines KK-13 and KK-27. On the basis of these observations I conclude that the lateral ramp (W-W' on Fig. 16) lies east of the southern tip of seismic line KK-27.

The eastward truncation of the duplex structures can be constrained with the help of well data. The Dhariala well, approximately 8 km east of section line C-C' (see Fig. 5 for location), shows a large thickness (approx. 2 km) of salt under the platform sequence. It is noteworthy that the platform sequence in the Dhariala well dips very gently from 0° to 4° , unlike the steeply dipping underlying salt, which dips 25° - 70° (Faruqi, 1982). Davis and Engelder (1985) interpreted these abnormal thickness to be due to the flow of salt from

Figure 15: Uninterpreted (A) and generalized interpretation (B) of seismic line 815-KK-27 (see Fig. 5 for location). It is unmigrated, 24 fold, dynamite source, recorded in 1981 by O.G.D.C. of Pakistan and processed by Petty-Ray Geophysical.



KK-27

B
Figure 15

Figure 16: Simplified map of Salt Range showing the position of different ramps that control the overall thrust geometry of the leading edge. W-W' and V-V' corresponds to the western and eastern lateral ramps associated with the duplex structures. X'-Y is the northern ramp, Y-Y' is eastern oblique ramp, Z-Z' is eastern lateral ramp, X-X' is western lateral ramp associated with the roof sequence. F-F' shows the position and lateral extent of the basement normal fault.

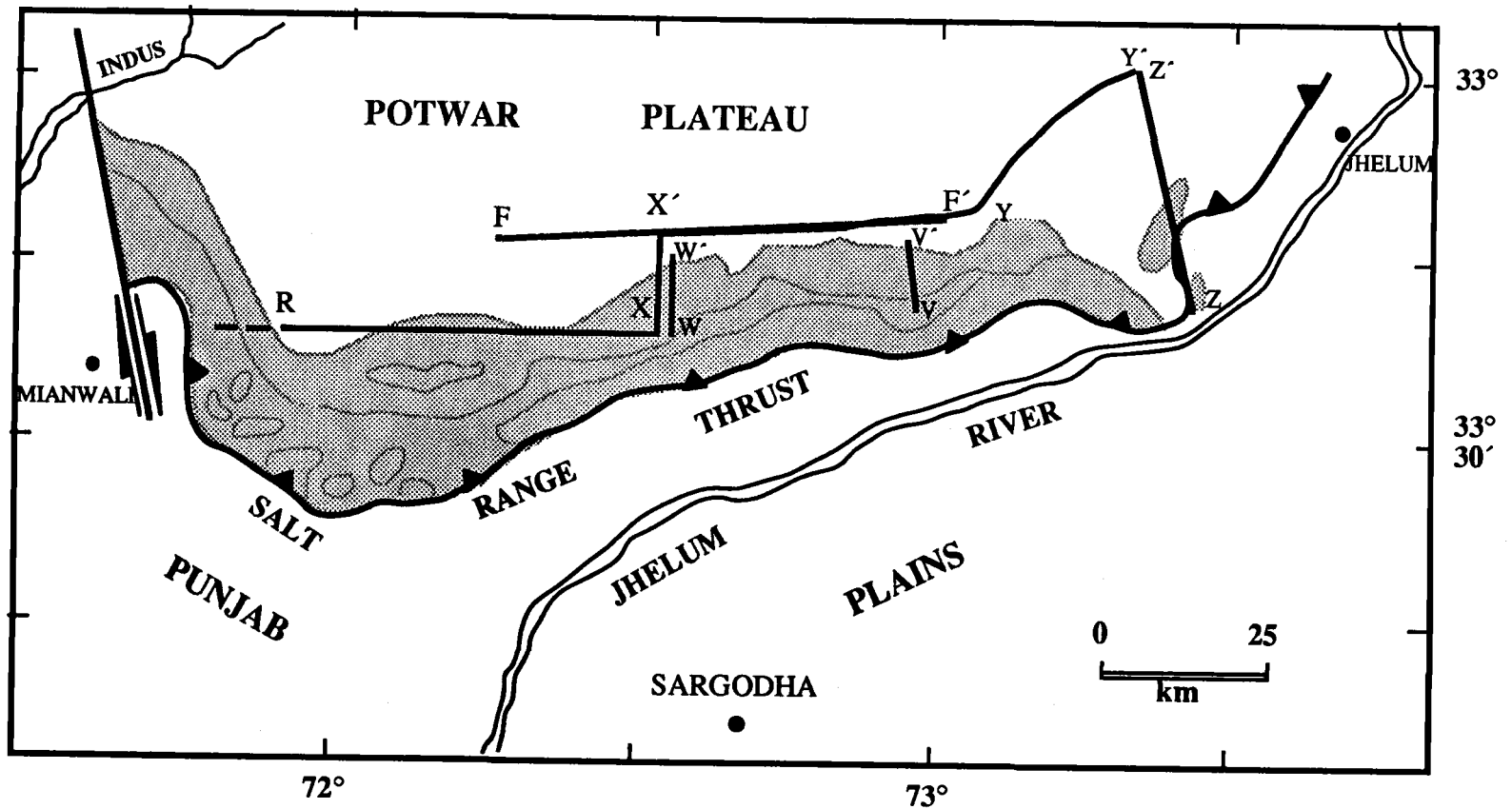


Figure 16

beneath synclines into anticlines, but such structures are not found in either the surface geology or on the seismic data in the central and western Salt Range. On the other hand, if the duplex structure extended to the east, then the Dhariala well should penetrate it, which is not the case. Moreover, on the surface approximately 5 km east of the well, the platform strata also dip toward the east (Gee, 1980), and this is inferred to mark the position of a lateral ramp (V-V' on Fig. 16). I infer that these dips in the roof sequence record the culmination wall of the eastern lateral ramp of the concealed duplex over which the roof sequence is draped. The platform sequence of the roof sequence has lower dips than the culmination wall above the lateral ramp, and the intervening space is filled by the salt wedge to produce the large salt thickness observed in the Dhariala well. However, in subsequent geological time the surface expression of this lateral ramp has been modified by the development of the Dil Jabba back thrust.

Nature of the Basement Normal Fault

Seismic lines KK-13, KK-19 and KK-27 demonstrate the presence of the basement normal fault, which deflects the platform sequence to the surface and produces the north-dipping hanging wall ramp between the Salt Range and the Potwar Plateau (Figs. 5, 6, 8 and 15). This structure was previously interpreted as an anticline cored by thick salt (Khan et al., 1986). On the first two lines the vertical offset is approximately 1 to 1.5 km, while on the later it is substantially smaller, *i.e.*, only a few hundred meters. However, even there the salt thickened on the down thrown side of the fault can be recognized on seismic line KK-27. Furthermore, seismic lines SR-1 (Fig. 12) in the east and KK-28 (Fig. 9) in the west show no basement offset, which implies that the normal fault gradually dies out. This north dipping fault not only offsets the evaporites but also the overlying sedimentary sequence and has localized the major northern ramp in the central Salt Range. Buttressing

during thrusting is responsible for the abnormally thickened salt on the down thrown side of the normal fault.

Northeast of the main basement normal fault, seismic line SR-3 (Fig. 17) suggests the presence of another basement normal fault, but one that dips to the south. This fault also offsets the overlying sedimentary sequence. The vertical offset on this fault is only a few hundred meters, relatively small compared to the one seen in the central Salt Range.

There are two schools of thought regarding the nature of the basement normal fault. Prior to plate tectonic ideas, most investigators of the foreland fringe of the subcontinent inferred that various basement faults were produced during late Precambrian or Mesozoic rifting of the Indian Plate (Gupta, 1964; Valdiya, 1976; Ahmad and Ahmad, 1980; Yeats and Lawrence, 1984)). This provides one model for the Salt Range feature. More recently, others (Duroy, 1986; Lillie et al., 1987; Baker *et al.*, 1988; Duroy *et al.*, 1989) related it to the flexural bending of the Indian Plate during Himalayan deformation. The fault would have formed as thrusts were developing to the north but prior to the development of the Salt Range ramping.

Seismic data from a variety of tectonic settings, i.e., passive margins and across different orogenic belts, suggest two varieties of normal faults (Lillie, 1984; Lillie and Yousaf, 1986). Some of these faults are rift related, while the other are related to plate flexure bending in a convergent setting. The rift related faults are associated with dipping reflections indicative of the syn-rift strata, while the overlying horizontal reflectors mark the presence of post-rift shelf strata. In the event of subsequent thrust faulting, the décollement will normally be located in the relatively continuous post-rift strata and will not intersect the normal fault. Thus the normal faulting predates all the shelf sedimentation and any later thrusting. Furthermore, the rift related normal faults have relatively large offsets, up to 7 km. Rift related normal faults have been recognized both in modern passive margins,

Figure 17: Uninterpreted (A) and generalized interpretation (B) of seismic line 782-SR-3 (see Fig. 5 for location). It is unmigrated, 12 fold, dynamite source, recorded and processed by O.G.D.C. of Pakistan in 1979.

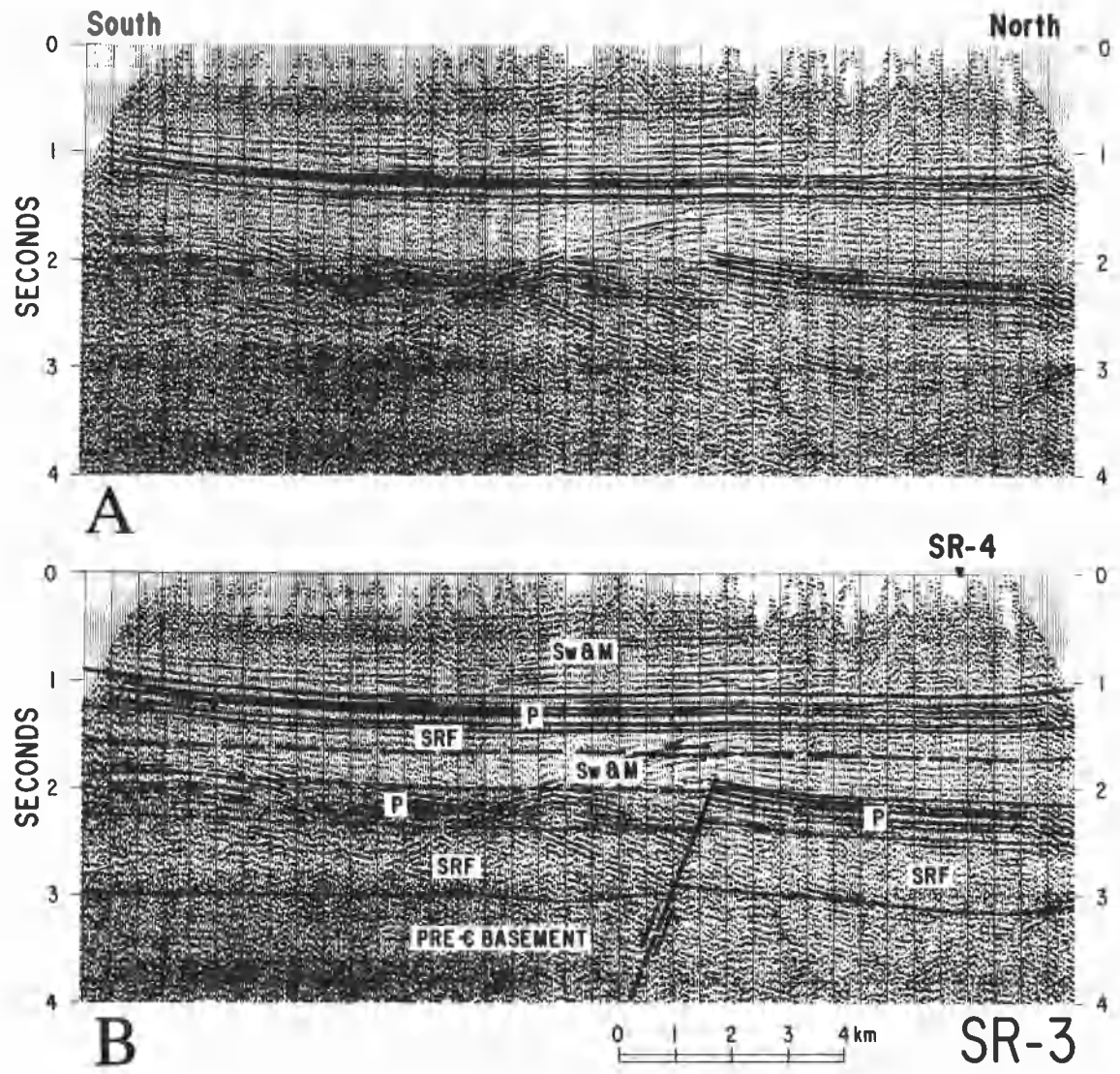


Figure 17

e.g., Atlantic margin (Grow *et al.*, 1983) south-western African continental margin (Jaunich *et al.*, 1983) and in ancient orogenic belts, e.g., Appalachian Inner Piedmont and Blue Ridge (Harris *et al.*, 1981; Nelson *et al.*, 1985; Favret and Williams, 1989).

Flexural normal faults most commonly form due to thrust loading and have no associated dipping reflections. They develop after most sedimentation and, therefore commonly offset pre-orogenic as well as syn-orogenic strata. If any older detachment levels are present, they will also be offset. Furthermore, compared with the rift related faults these faults have relatively small offsets, less than 2.0 km (Lillie, 1984; Lillie and Yousaf, 1986). Thrust fault detachments, if low enough in the stratigraphic section, may encounter the basement offset along these normal faults.

Wiltschko and Eastman (1983) suggested that pre-existing, high-angle faults act as zones of stress concentration and thus control the locations of the younger thrust ramps. Seismic data from the southern Appalachians (Harris *et al.*, 1981; Cook *et al.*, 1983) show such fault control of the upward deflection of the Brevard fault. Similar types of faults control the locations of the thrust ramps in the Appalachians of southern Quebec (Laroche, 1983) and in the foreland of the Ouachita Mountains of Arkansas (Buchanan and Johnson, 1968). Most of the basement offsets in each of these areas have been interpreted as flexure related normal faults (e.g., Lillie and Yousaf, 1986).

In the Salt Range, there are no syn-rift strata associated with the basement normal fault. The seismic data available on these faults show no reflections dipping into the fault such as those which characterize rift-related faults. As seen in the central Salt Range, the fault not only offsets the décollement and the overlying platform strata, but it also controls the location of the ramp. Similar faults are also seen on seismic line SR-3 and have been reported farther north under the Potwar Plateau (Baker *et al.*, 1988; Pennock *et al.*, 1989). However, the vertical offset on these other faults is relatively small, *i.e.*, few hundred

meters at the most, compared to 1 to 1.5 km for the fault beneath the central Salt Range. All of these faults probably developed at different stages of the evolutionary history of the leading edge. Some may have quite recent movement, *e.g.*, Molnar *et al.*, (1973) related fault plane solutions for the 1967 Ganga Basin earthquake near Dehli to the normal faulting associated with the flexural bending of the Indian Plate. A general interpretation of these basement offsets, beneath the Himalayan foreland thrust belt, is that they are related to the flexural bending of the full continental crust of Indian plate due to the loading by the thrust sheets in the north.

Lateral Ramp Structures Associated with the Roof Sequence

Lateral ramp at west end

The roof sequence is disrupted on the west by a north-south trending lateral ramp. The interpreted position of the northern ramp in the west (R-X on Fig. 16) is approximately 15 km south of the northern ramp caused by the basement normal fault in the central Salt Range (X'-Y in Fig. 16). This important observation provides three very important clues. First, the shortening accommodated by the duplex structures in the central Salt Range developed along the lower décollement before the ramping of the roof sequence occurred. Second, the riding of the roof sequence over the ramp in the west is either contemporaneous to that observed in the central Salt Range or, alternatively, the initial ramping of the roof sequence in the west might be contemporary with the duplex structures in the central Salt Range. Third, there should be a lateral ramp that joins these two segments of the northern ramps.

Seismic line KK-27 (Fig. 15, for location see Fig. 4) does not show the northern ramp but it does show the basement normal fault with relatively small offset. Moreover on line KK-27 the reflectors south of basement normal fault are quite smooth. This suggests

that the lateral ramp should be east of the line KK-27. Furthermore, at the southern end of this seismic line, there is an unusual, wedge-shaped geometry within the salt. Previous experience in the Salt Range has shown that such abnormal wedge-shapes are commonly due to the salt climbing ramps. This lateral ramp, therefore, is inferred to be located immediately east of the southern tip of seismic line KK-27, over the western culmination wall of the concealed duplex (Fig. 18). It further suggests that the development of the western ramp (X-X' in Fig. 16) was probably facilitated by the pre-existing western lateral culmination wall above the older lateral ramp (W-W' in Fig. 16) that truncates the duplex structures. The orientation of this feature can be constrained by surface geology. Due to the ductile nature of underlying salt, its westward stratigraphic thickening and later blanketing by the roof sequence, we do not see the typical monoclinical surface expression of this lateral ramp. However, in the vicinity of Bhadrar and Vasnal (for location see Fig. 5), abnormal outcrops of salt are shown by Gee (1980), and the roof sequence is also frequently faulted. These faults are either NE or NW oriented, in contrast to the rest of the Salt Range where the minor faults are mainly E-W oriented. I infer that these structural features reflect the presence of the lateral ramp.

Oblique ramp at east end

The central Salt Range northern ramp changes character in the east. The E-W trending ramp within the sedimentary strata east of the basement normal fault (F'-Y on Fig. 16) is short. Farther east, seismic line SR-3 does not show the northern ramp, although it does show a duplication of the platform sequence. On SR-3, there are two distinct high amplitude reflectors at about 1.15 and 2.2 seconds, respectively. These reflectors are fairly horizontal, although the data quality of the southern part of the lower reflectors is poor. However, the consistent horizontal trend of the upper reflectors suggests that the lower

Figure 18: Generalized E-W cross section across the Salt Range showing the roof sequence, concealed duplex structure and associated culmination walls, lateral ramps associated with the concealed duplex structure and the roof sequence, and different levels of detachment due to the variations in the footwall geometry in different parts of the Salt Range.

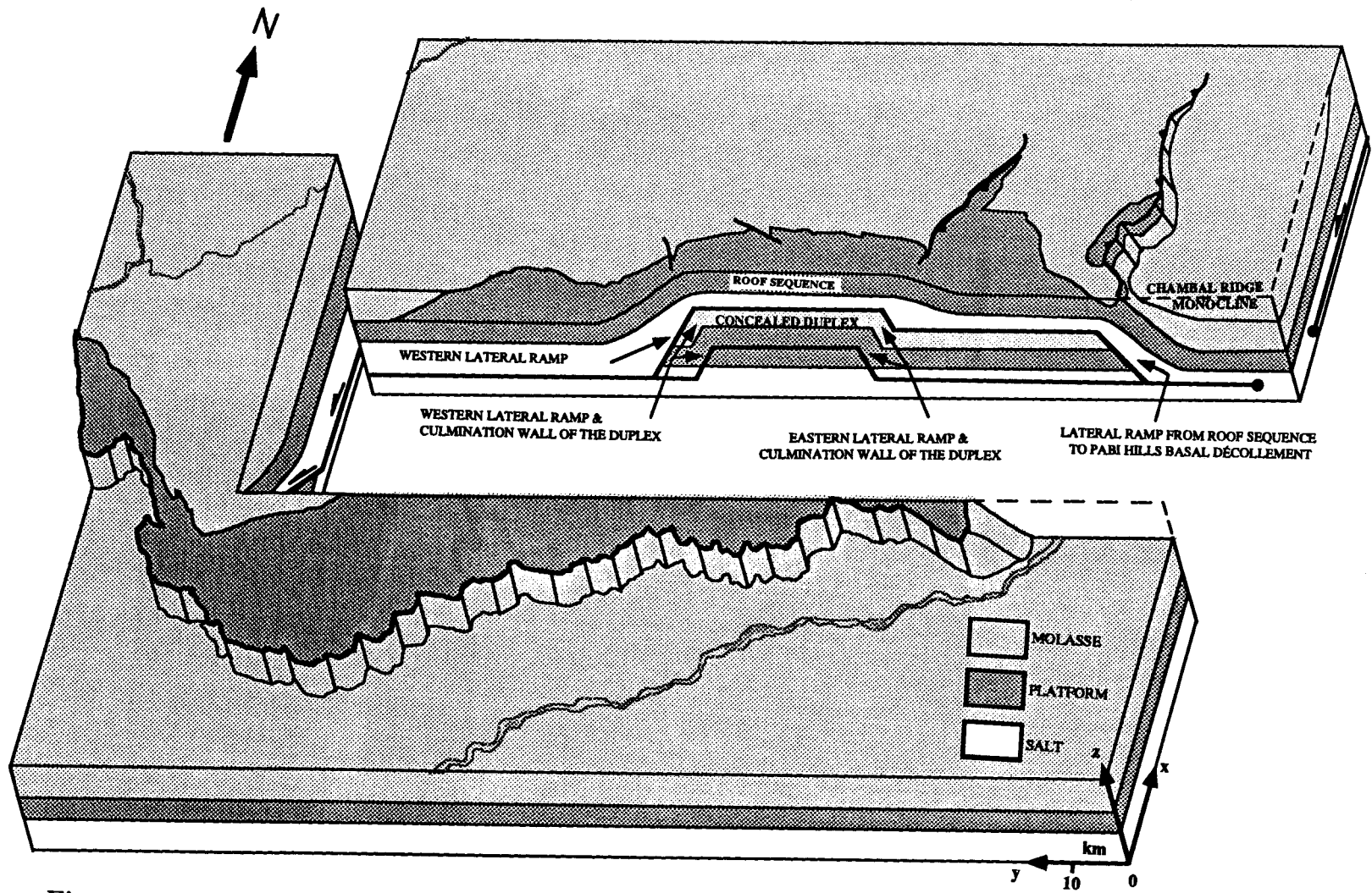


Figure 18

Z-axis exaggerated

reflectors also continue to the south. The upper platform sequence is overlain by approximately 2 km (1.15 seconds) of the molasse sequence and underlain by salt. The platform sequence here is only 750 m (0.35 seconds) thick, because the Nilawahan Group is missing and the Makarwal Group unconformably overlies the Jhelum Group. It is difficult to determine, because of the poor seismic data quality, the exact thickness of salt. However, I have estimated that approximately 550 m (0.23 seconds) of salt lies under the upper platform sequence. The salt then overlies the molasse sequence again, which in turn overlies the lower platform sequence. The lower platform sequence then overlies about 1.5 km (0.65 seconds) of salt at the top of the basement. Thus the roof sequence extends farther northeast here.

Structurally, this means that either the Central Salt Range ramp ends against a north-south lateral ramp which transfers the motion to another ramp farther north, or it is linked with the northern ramp through a curved oblique-displacement ramp. This further implies that the position of the ramp is further towards north, and there should be a lateral or oblique ramp that joins this ramp with the northern ramp seen on SR-1. The position of this ramp can be constrained with the help of oil exploration well data. Hayal well, about 4 km north of SR-3 had drilled 1.7 km of salt when the well was abandoned. This abnormally thick salt can be interpreted in two ways. (1) It may be because of a big salt cored anticline into which the salt has flowed from the adjacent synclinal structures. Surface geology, however, does not support this interpretation. (2) This unusual thickness of salt may be due to the buttressing effect of a ramp. This interpretation most logically explains the abnormal thickness of salt and the repeated platform sequence.

Now, what is the shape of the ramp? Either it is a lateral or oblique ramp. This can be constrained with the help of the surface geology. Gee (1980) has shown two NE-SW trending faults, in continuation of each other, in the eastern Salt Range. Towards the SW is the Dill Jabba Fault, while in the NE is the Domeli Thrust (Fig. 5). Note that the Dill

Jabba fault is a back thrust, while the Domeli Thrust is a forward verging thrust. Further field mapping is required to solve this problem properly, however, if the interpretation of the evolution of Dill Jabba fault is correct, i.e., it started as a back limb thrust then the subsurface ramp should be in the vicinity of its surface NE-SW orientation. This implies that instead of a lateral there is an oblique ramp (Y-Y' in Fig. 16) that joins the two ramps, i.e., the northern ramp on the seismic line SR-1 and the one interpreted in the north of the seismic line SR-3.

Lateral Ramp Connecting Salt Range Roof Sequence to Pabi

Hills Deep Décollement

The structural style of the thrust wedge in the eastern part of the eastern Salt Range is quite different because of the absence of the major ramp to the north that caused the repetition of the platform sequence in the rest of the Salt Range. Pennock *et al.*, (1989) constructed a balanced cross-section (P-P' on Fig. 2) based on seismic reflection data in the eastern Salt Range (Fig. 19) approximately 25 km east of SR-3. They found that, contrary to Butler *et al.*'s (1987) interpretation that thrusting was confined to the molasse sequence, the décollement in the eastern Salt Range/Potwar Plateau is in the salt. The shortening in this case has been accommodated along the main décollement at the greater depth. Structures like the Domeli thrust, Mahesian anticline, Rohtas anticline in the eastern part of the eastern Salt Range show similar shortening to that seen along D-D'. The amount of total shortening, i.e., 24 km (Pennock *et al.*, 1989), in the easternmost part of the eastern Salt Range is comparable to the amount of shortening in the western (32 km), central (27 - 24 km), and eastern (17 km) Salt Range. It is, however, interesting to contrast the deformation style of this part of the eastern Salt Range with the rest of the Salt Range. Pennock *et al.*'s (1989) seismic line suggests that: 1) there is no widespread repetition of

Figure 19: Composite seismic line across eastern Salt Range/Potwar Plateau from Pennock et al., 1989 (for location see P-P' on Fig. 2).

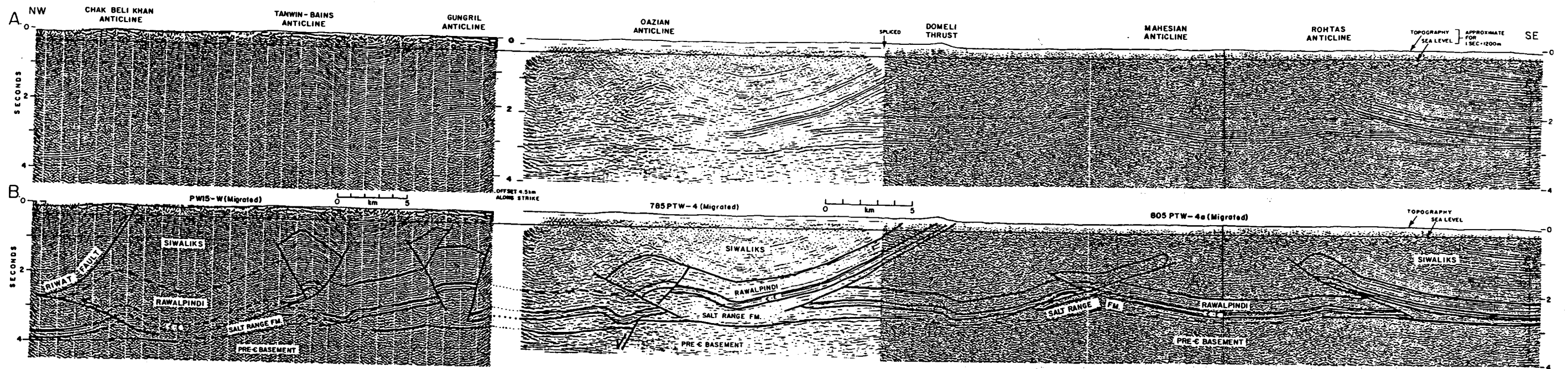


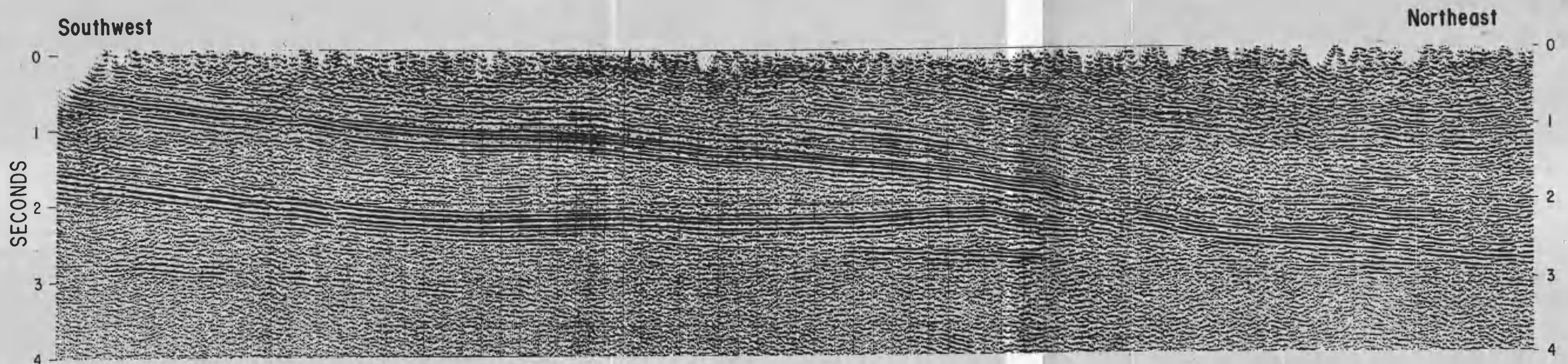
Figure 19

the platform sequence as seen in the other seismic sections of the Salt Range; 2) the structural style of the thrust wedge is typically marked by the blind thrusts, and pop-up structures, unlike the rest of the Salt Range where the roof sequence is very gently deformed; 3) depth of the main décollement is at about 3 km below the mean sea level, while in the remaining Salt Range there are two décollement levels. The basal décollement is, however, at a comparable depth to that in the easternmost part of the eastern Salt Range. This implies that there is a lateral ramp that joins the upper décollement under the roof sequence in the central Salt Range with the Pabi Hills basal décollement, and causes the eastward truncation of the lower platform sequence in the footwall of the roof sequence.

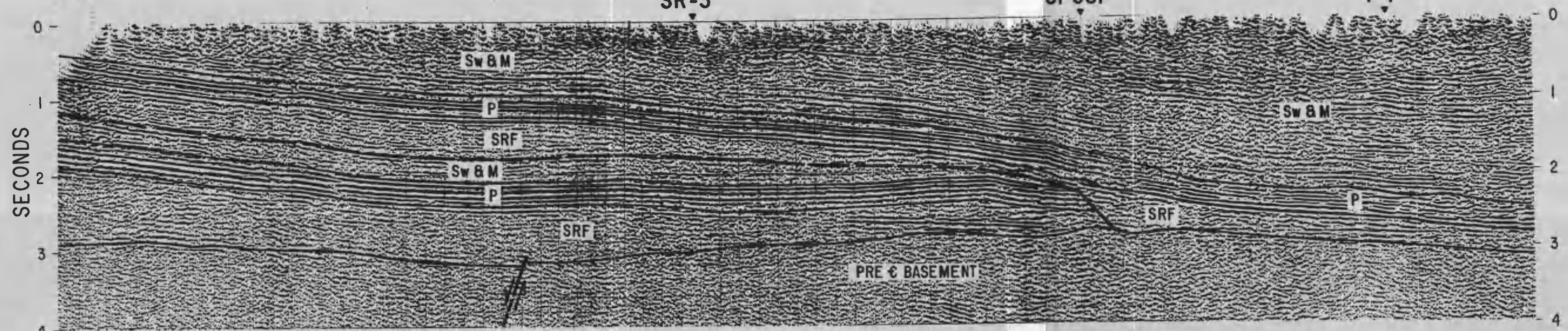
The location of this lateral ramp can be documented with the help of seismic line SR-4 (Fig. 20). At the southwestern end of SR-4 two apparent high amplitude reflections show the repeated platform sequence, and suggest the presence of two detachment levels. On the other hand, towards its easternmost end there is no repetition of the platform sequence. At about shot point 381, the lower platform sequence has been truncated along a lateral ramp. Furthermore, the upper décollement along the lateral ramp gradually steps down in the section and joins the main décollement. The other important observation on this seismic line is the wedge shaped geometry due to the thickening of salt east of the lateral ramp. The seismic data further suggests that the molasse sequence is only about 700 m (0.4 seconds) thick at the western end and approximately 4.5 km (2.5 seconds) thick towards the northeastern end of the seismic line SR-4. As the décollement steps down towards the east, the thickness of the molasse sediments also gradually increases. On the western part much of the molasse sequence has been eroded away.

The NNW-SSE orientation of this lateral ramp (Z-Z' in Fig. 16) can be constrained with the help of surface geology. In the south, there is a prominent S-shaped structure that causes the eastward truncation of the Salt Range Thrust (Fig. 5). The northern half of this structure is Jogi Tila. The NE trending Jogi Tila is an anticlinal structure plunging toward

Figure 20: Uninterpreted (A) and generalized interpretation (B) of seismic line 782-SR-4 (see Fig. 4 for location). It is unmigrated, 12 fold, dynamite source, recorded and processed by O.G.D.C. of Pakistan in 1979. Note at SP 381 the upper décollement under the roof sequence steps down along a lateral ramp and joins the main décollement that causes the eastward truncation of the platform sequence in the footwall.

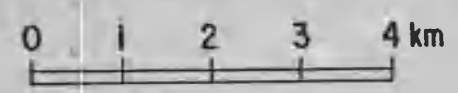


A



B

Figure 20



SR-4

the east. Its southern limb has been disrupted by a NE-SW trending fault dipping to the north. The southern half is known as Chambal ridge. This is a N-S trending monoclinical structure, which dips towards the east (Fig. 18). The monoclinical surface expression of the Chambal ridge is similar to that of the northern ramp due to a basement normal fault in the central Salt Range. The almost horizontal dips of the upper molasse sequence in the east become gradually steeper and steeper towards the west where the older sequence becomes gradually exposed at the surface. The dips of the strata in this vicinity vary from 40° - 60° to the east. The strata further west become almost horizontal again. I infer that the monoclinical structure of Chambal ridge mimics the position of a subsurface lateral ramp. Furthermore, N-S trending Chambal ridge marks the southernmost continuation of the lateral ramp seen on seismic line SR-4 in the north. This lateral ramp not only truncates the eastward extension of the lower décollement but also the platform sequence in the footwall (Fig. 18). Moreover, this lateral ramp also truncates eastward extension of the ramp interpreted in the north of SR-3.

Leading Edge Structures and Frontal Ramp

In the vicinity of the leading edge of the Salt Range Thrust, there are isolated blocks of platform sequence surrounded by the Salt Range Formation. Gee (1980) has interpreted these as thrust blocks, since the northern contact of most of them is faulted against the Salt Range Formation. However, it seems more probable that most of these thrust blocks of Gee are gravity slide blocks over the salt in the hanging wall ramp of the leading edge of the roof sequence. These gravity slide blocks at the leading edge may have created further resistance to the forward motion of the thrust front. Their frequently high angle, faulted northern contacts as shown by Gee (1980) support this interpretation. Gee interpreted these as the thrust contacts. It is more probable that these are gravity slide blocks that are

being pushed forward by rising salt. Incorporation of such blocks within the décollement will increase resistance to motion.

The frontal ramp brings the Phanerozoic strata over the late Quaternary fanglomerates and Jhelum river alluvium (Yeats *et al.*, 1984). Due to the scale limitation, it is not possible to resolve the exact geometry of the frontal ramp on the seismic data. One problem here is the shape of the frontal ramp. Either it is a distinct ramp with planar geometry or it is a poorly defined ramp with listric geometry. What are the effects of southward progradation of the décollement on this ramp ?. In the Warchha salt mine (for location see Warchha on Fig. 5), Faruqi (1982) described debris of Warchha nallah (creek) that are in direct contact with gently dipping salt. The salt makes its first appearance at 305 m in the adit. This part of the adit has been driven in the loose Warchha nallah debris, which becomes gradually more compact and brecciated near their first contact with salt. Furthermore, 137 m up the contact, he noticed abundant layered and irregularly shaped bodies embedded in salt; most commonly these are variably deformed Permian limestone blocks. Other blocks are so deformed that their origin is unclear. For the sake of simplicity, I have shown the frontal ramp with a distinct planar geometry on my sections within the upper molasse sequence. Keeping in view the above discussion, I infer that the frontal ramp actually started with listric geometry within the upper molasse. After that it has gradually developed with the southward progradation of the thrust front. The listric shaped geometry has developed with the gradually ramping of the thrust front over the debris shed from the topographic front of the leading edge.

TECTONIC EVOLUTION

The tectonic evolution, timing and age of the basement normal fault, and the timing of initial ramping has been a matter of debate for quite some time. Out of sequence thrusting in the Salt Range/Potwar Plateau has been advocated by different earlier workers (*e.g.*, Burbank and Raynold, 1984, 1987; Burbank and Beck, 1989 a; Jaswal, 1990). North of the Salt Range, the Rawat fault that truncates the southern limb of the Soan syncline has been estimated to have been active 3.0-3.5 Ma ago (Johnson *et al.*, 1986). Burbank and Raynolds (1988) suggested out of sequence thrusting events in Salt Range/Potwar Plateau on structures as much as 30 km apart. Similarly, Burbank and Beck (1989 a) documented large scale (≥ 100 km) out of sequence thrusting in the foreland fold-and-thrust belt. Likewise, Jaswal (1990) recognized, on the bases of section balancing, out of sequence development of the Kheri Murat fault in the Potwar Plateau. This study is a first attempt to document a model that explains the deformational sequence and mechanics of the leading edge of the thrust system, within the Salt Range. It suggests four stages of out of sequence tectonic evolution of the Salt Range with the help of seismic, well, and surface geologic constraints, taking all the available fission track (Zeitler, 1982) and magnetostratigraphic (Johnson *et al.*, 1979; Opdyke *et al.*, 1979; Burbank, 1983; Burbank and Raynolds, 1984; Burbank and Tahirkheli, 1985; Johnson *et al.*, 1986; Burbank and Beck, 1989a, 1989b) data into consideration.

Chronology of Events

Motion on the duplex structures

The concealed duplex structure records the first tectonic event in the Salt Range. This interpretation is based on two very critical observations. First, if this structure formed

late as a part of a purely prograde deformation, then it should control the surface structures of the overlying roof sequence, and it does not do so. Second, if this structure was younger than the overlying roof sequence, then along the ramp and lateral ramps there should be thinning of the salt instead of the abnormal thickening reported herein. Therefore, these duplex structures in the Salt Range are the earliest structures of the leading edge of the thrust front.

In the Potwar Plateau Burbank and Beck (1989 b), on the basis of rate of subsidence and sediment accumulation, have recently identified a thrust loading event that initiated at 11.5 Ma and terminated at about 8.0 Ma. They relate this event to middle to late Miocene flexural loading in the foreland fold-and-thrust belt. However, they admit that there are contrasts in the absolute amount of subsidence from north to south. Moreover, this is the time span when the MBT zone was still very active (Burbank, 1983). The present study relates the contrasts in the subsidence rates and changes in the paleocurrent directions with the newly recognized duplex structures. Burbank and Beck (1989 a, 1989 b) on the basis of paleocurrent data and sediment accumulation rates have suggested that at 10.5 Ma the drainage was mainly to the south and southwest at Gabir Kas, north of the basement normal fault in the central Salt Range (Fig. 21 A). However, at about 9.0 Ma the direction of paleocurrents at the Gabir and Bhaun sections (Fig. 21 B) shifted to the southeast. Furthermore, the east directed drainage at Kotal Kund and Jalalpur, in the eastern Salt Range, remained persistent during this time. This can be understood if the newly emergent E-W trending duplex structures actually obstructed the south and southwest directed drainage and forced the drainage to the east at about 9.0 Ma. I interpret that 9.0 Ma is the time when the duplex structure started to develop. In addition, data from Bhaun and Gabir Kas (see Fig. 5 for location) also show a decrease in the rate of sediment accumulation at about 8 Ma (Burbank and Beck, 1989 b). This supports the above interpretation that the change in the sediment rate was because of the newly built

Figure 21: Paleocurrent data collected from large-scale (> 1 m width) trough cross-strata at 10.5 Ma. (A) and 9.0 Ma. (B), after Burbank and Beck (1989 a; 1989 b).

AT 10.5 Ma.

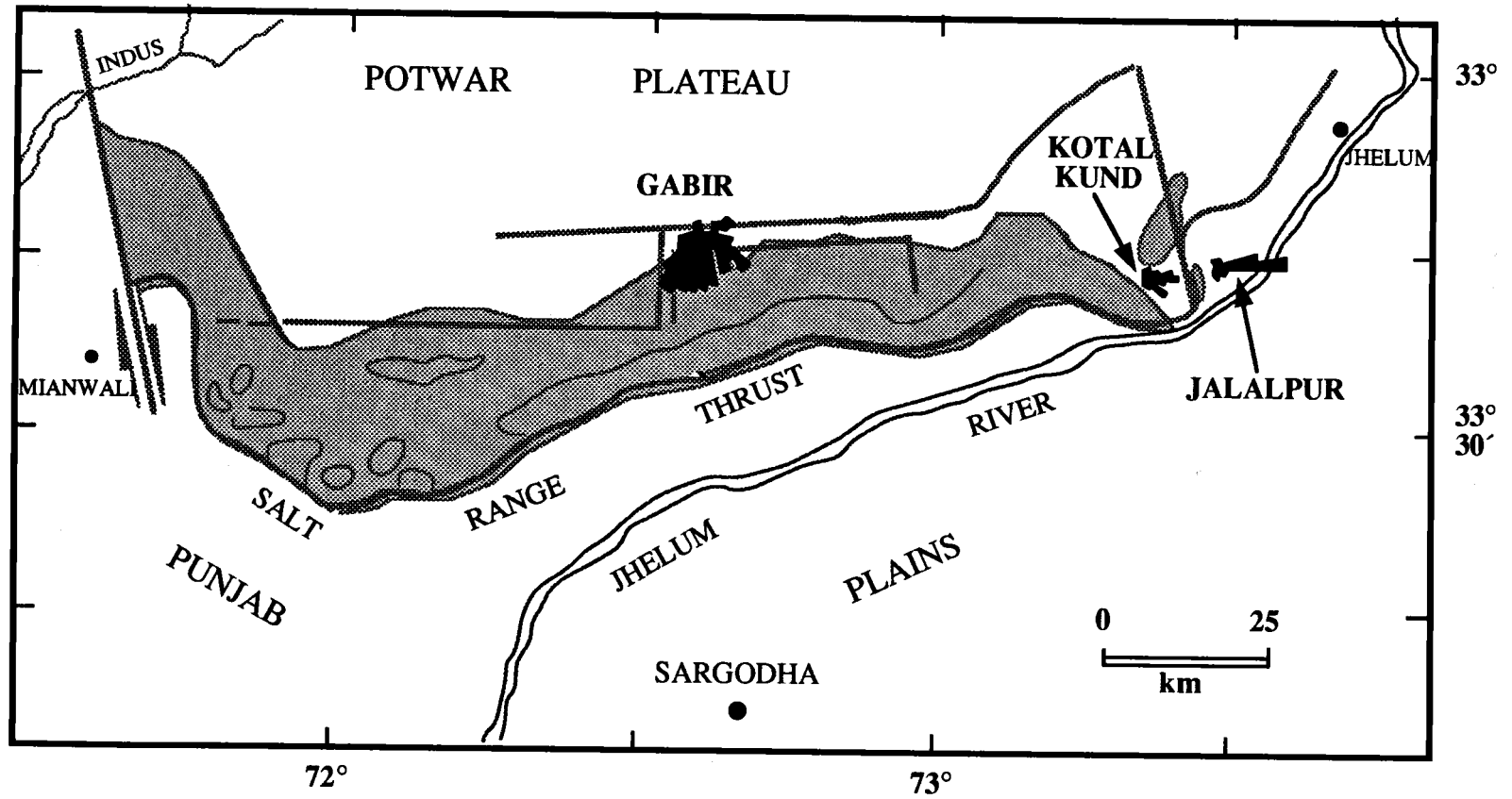


Figure 21 (A)

AT 9.0 Ma.

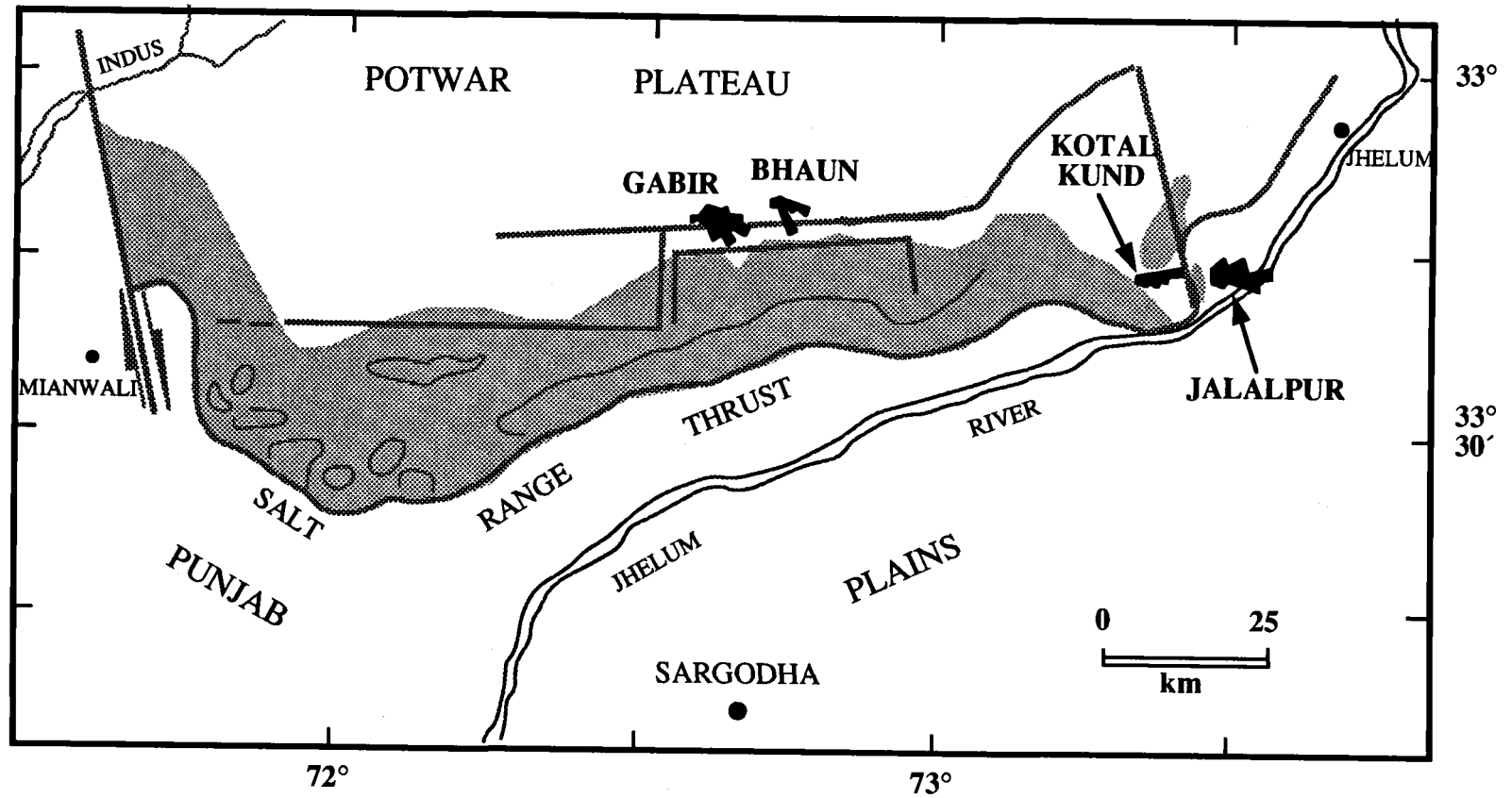


Figure 21 (B)

topography (Fig. 22) due to the duplex structures that caused a lateral shifting of the depocenter.

The minimum age of these duplex structures can be constrained with the help of the shortening rate. Burbank and Beck (1989 a) have estimated the age of ramping to be as old as 5.2 Ma. Cross section balancing indicates that 21.7 and 20.8 km of shortening has occurred since then with a rate of about 4.2 and 4.0 mm/year along B-B' and C-C', respectively. Assuming that the timing of ramping in the western Salt Range is the same as that of in the central Salt Range, then 31.6 km of shortening at a rate of about 6.0 mm/year has occurred since 5.2 Ma along A-A'. However, it is most likely that part of the total shortening may be contemporaneous with the duplex deformation to the east. In the eastern Salt Range palinspastic restoration of section D-D' also suggests that 17.1 km of shortening at a rate of 3.3 mm/year has occurred since 5.2 Ma.

This suggests that at 9.0 Ma, when these structures started to build, the MBT zone (Attock Thrust) was quite active and the major component of shortening at that time was accommodated along it. Burbank and Beck (1989 b) have recently identified a very important thrusting event from 11.5 to 8.0 Ma to the south of the MBT. This further implies that the rate of shortening at that time should be less than or equal to that estimated for the period since 5.2 Ma. Using a rate of shortening of 3-4 mm/year suggests that it took about 1.5-2.0 Ma to accommodate the 5.5 km of minimum shortening estimated for the duplex structures. This indicates approximately 7 Ma as the minimum age limit for the duplex structures (Table 1).

Development of normal fault and salt pad

The concealed duplex structure provides an important new constraint on the time of first movement of the basement normal fault. There are two important considerations

Figure 22: Schematic three dimensional diagram showing the successive development of the Salt Range and the relationship between footwall and hanging wall structures at different evolutionary stages. (A) Footwall configuration of the concealed duplex structures. (B) Hangingwall structures after the first movement of the thrust wedge when the concealed duplex structures were formed in the absence of basement normal fault. The anticlinal structures shown on either sides of the duplex structures are possible structures that may be present under the roof sequence and have accommodated equivalent amount of shortening as the décollement steps down along the lateral ramp. (C) Development of the basement normal fault and the footwall geometry of the roof sequence, i.e., the northern ramp, eastern oblique ramp, eastern and western lateral ramps.

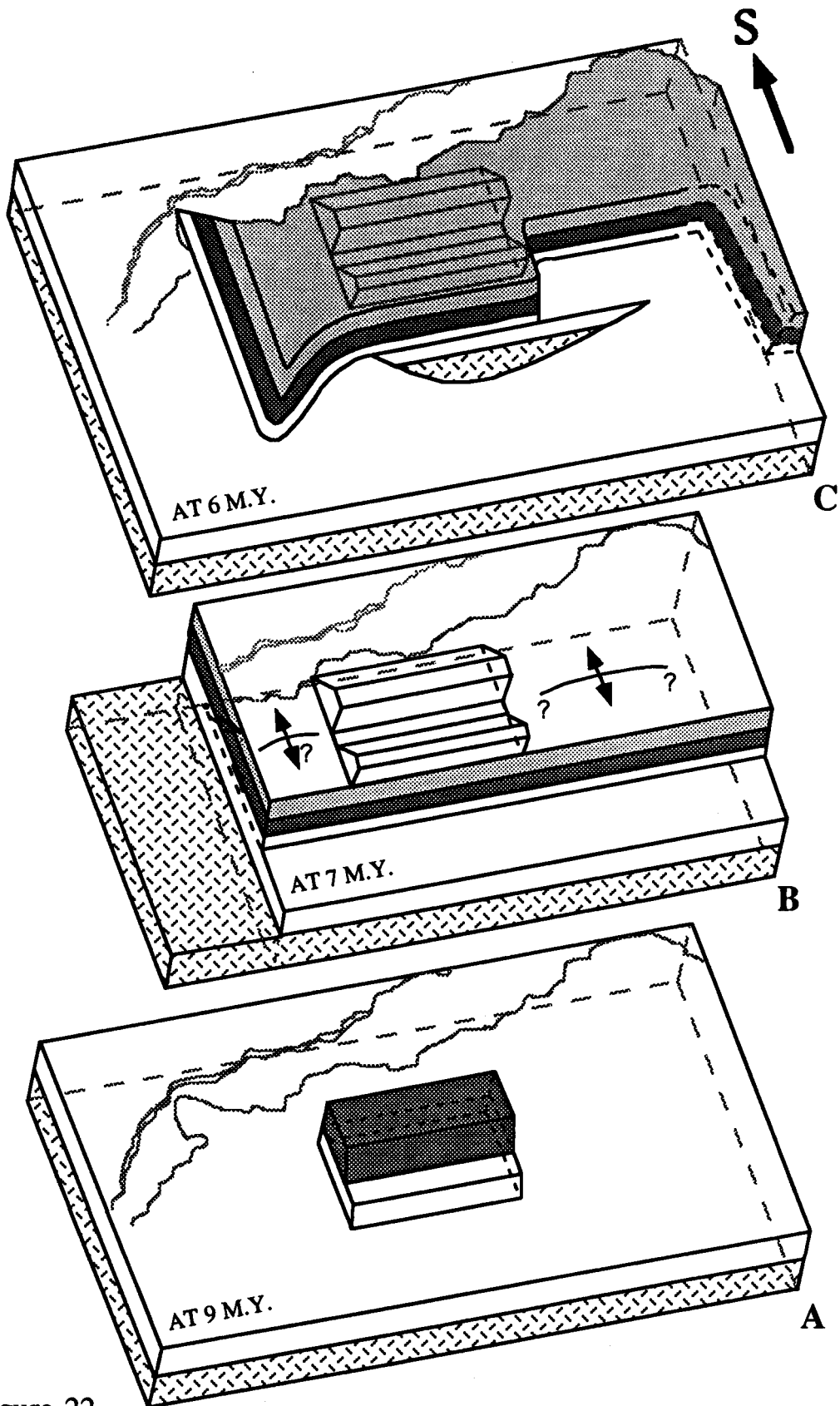


Figure 22

Table 1: Summary table showing the chronology of the major structural events in the Salt Range/Potwar Plateau and farther north. It also suggests extensive out-of-sequence thrusting within the thrust wedge during past 9 Ma. (for sources see text).

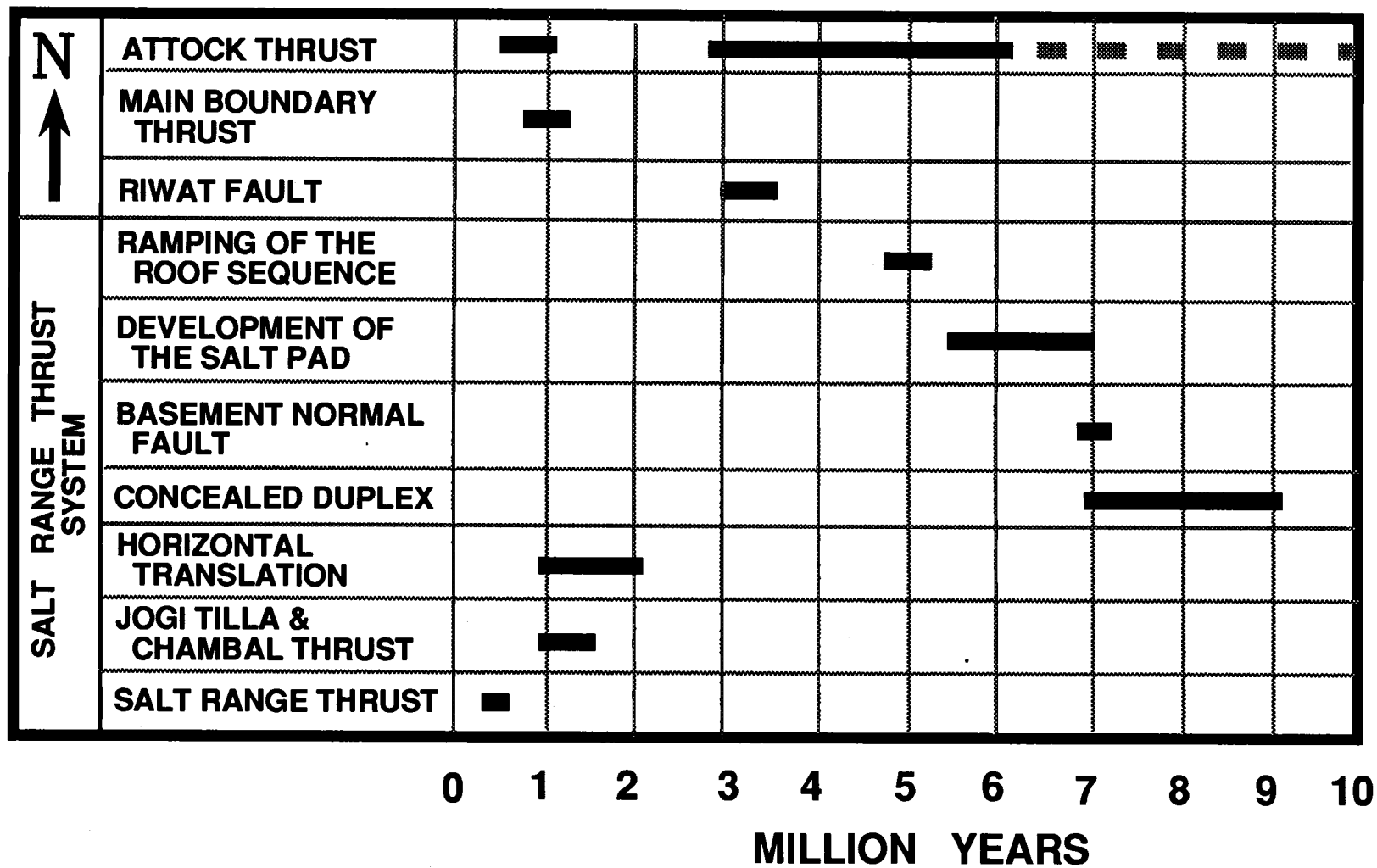


Table 1

regarding this interpretation. First, this duplex type of deformation style, involving only a thin layer of salt, is not seen elsewhere in the Salt Range. This implies that this type of structure could not develop if at the time of their development the normal fault was already there, that have now caused the thickening of the salt under the roof sequence. Second, if the normal fault was already there, then it would not have been possible to accommodate shortening from the north along the lower décollement, under the concealed duplex structure. The well data, as stated earlier, also suggest southward thinning of the salt. This gradual thinning of salt is only consistent with the early creation of duplex structures. Furthermore, seismic line KK-13 suggests that these duplex structures have been truncated by the normal fault, and the normal fault therefore postdates these duplex structure.

If the ramping of the roof sequence is as old as 5.2 Ma (Burbank and Beck, 1989 a) and the concealed duplex structures are as old as 9.0-7.0 Ma, then the timing of the normal fault ranges from 5.2-7.0 Ma. In order to ramp the roof sequence over the basement normal fault around 5.2 Ma, there must be a sufficient salt wedge to translate the roof sequence over it. Forward flow of salt to form a thick pad against the normal fault buttress has been shown to occur by Moussouris (1990). Furthermore, enough time is required to erode the overlying molasse and substantial parts of platform cover to expose the source for the Tobra clasts found in the north of the basement normal fault (Burbank and Beck, 1989 a). This leads to the conclusion that this normal fault developed at about 7 Ma, after the development of the duplex structure (Table 1). The development of the basement normal fault had a very profound impact on the deformational sequence of the leading edge and caused out of sequence thrusting in the north. The basement normal fault not only displaced the basement but also disrupted the salt layer, which is the main horizon for the progradation of the décollement. This further suggests that, due to the development of the basement normal fault, the displacement along the duplex structure also stopped abruptly. After the development of the basement normal fault, the thrust front got totally

stuck in the south, and crustal shortening was taken up by out of sequence motion on the MBT zone in the north (Table 1), which is considered to be quite active during this time (Burbank, 1983). Meanwhile, under the constant compressional stress field, a thick pad of salt started to build up. When this pad developed sufficient size the roof sequence ramped up along an incipient thrust that developed within this salt wedge.

Ramping of the roof sequence

The ramping of the roof sequence is another matter of controversy in the Salt Range. Yeats *et al.*, (1984) suggested that the time of initiation of ramping is difficult to constrain. Johnson *et al.* (1984), on the basis of their magnetostratigraphic work, paleocurrent measurements, observations on the rotation of the strata, and the presence of Tobra and Eocene Limestone clasts in the Upper Siwalik sequence the eastern Salt Range considered that the ramping of the thrust wedge over the basement ramp took place between 2.1-1.6 Ma. Baker *et al.* (1989) favored their interpretation and postulated that the development of the basement normal fault caused the derivation of Tobra clasts, change in the paleocurrent directions, and rotation in the beds. However, Burbank and Beck (1989) questioned their interpretation and objected that the rotation of the beds, in the north of Salt Range thrust, cannot be produced just by a simple normal fault and favored the idea of a thrust. Quite recently in the central Salt Range, at the Bhaun section, Burbank and Beck (1989 a) found Tobra and Eocene limestone clasts in an older (5.0 Ma) sequence of Siwalik Molasse. On the bases of their work they revised the age of initiation of ramping to 4.8-5.2 Ma and advocated the idea of "an incipient thrust" to justify the rotation, and changes in paleocurrent direction observed in the younger strata.

This study suggests that the motion of the roof sequence over the northern ramp (Fig. 22) has two profound effects on the forward motion of the leading edge. First, the older sequences were exposed and became the source of Tobra and Eocene clasts now

found in the upper molasse sequence, north of the Salt Range thrust and caused the change of paleocurrent direction from south to north. Second, the new thrust-built topography, caused substantial resistance to the continued advance of the thrust. However, this resistance was not sufficient to totally stop the forward motion of the leading edge. Thus, the leading edge kept on moving forward, but at the same time the resistance to forward motion also gradually increased due to the gradual increase in the size of the roof sequence over the ramp. This caused further out of sequence thrusting in the Potwar Plateau, e.g., Rawat Fault (Johnson *et al.*, 1986; Burbank and Reynolds, 1988) and along the recently recognized Kheri Murat Fault (Jaswal, 1990). Even some younger movements, as young as 1.9 - 2.1 m.y., have also been recorded along MBT farther north (Table 1). This interpretation is consistent with the experimental numerical and scale modeling of fold-and-thrust belts over salt by Moussouris (1990).

Horizontal translation of the roof sequence

Horizontal translation of the thrust wedge over the roof sequence flat is the last major structural event in the Salt Range. Previously Johnson *et al.*, (1986) defined two major structural events in the Potwar Plateau and adjacent regions. The first event, marked by strong folding, uplift and rotation in the areas adjacent to present Salt Range, occurred between 4.5-3.5 Ma. The second event, marked by massive deformation throughout the Potwar region, occurred between 2.1-1.6 Ma. The second event was interpreted as due to the overriding of the basement normal fault by the thrust wedge over that caused the uplift of the Salt Range and was followed by southward horizontal displacement. This general interpretation was later modified by Burbank and Beck (1989 a), who advocated that approximately 12 km of minimum shortening was accommodated during 1.0-2.0 Ma (Table 1). All the thrusts and normal faults now present within the roof sequence are either

contemporaneous with or postdate the horizontal translation of the roof sequence. The forward motion of the thrust front has caused frequent small scale out of sequence thrusting in the vicinity of the leading edge. Most of the younger, out of sequence faults developed, as the leading edge stuck against the frontal ramp, to facilitate the forward motion of the thrust front by building the topography.

Gee (1980) has shown that the roof sequence is frequently marked by normal faults dipping almost vertically, which is unusual in a zone of compression. The geometry of these faults can be explained in two possible ways: 1) these faults manifest the periods of relaxation in between the major compressional episodes; or 2) they are in fact thrust faults with listric geometry, which have been rotated and overturned near the surface to appear to be high angle normal faults. These types of faults have been referred as the "pseudonormal faults" by Ghazanfar *et al.* (1990 b) further north in the foreland fold-and-thrust belt.

Lateral Variations In Deformational Style

The Salt Range changes deformation style along its irregular ENE-WSW trend. The Salt Range thrust is strongly emergent in its central and western parts, whereas in the east it is entirely a buried thrust (terminology of Morley, 1986) and folding predominates (Lillie *et al.*, 1987). Davis & Engelder (1985) suggested that the difference in the structural style between east and west is the result of eastward thinning of the evaporites. By this reasoning, Butler *et al.*, (1987) advocated that in the western and the central Salt Range the décollement lies in evaporites while in the east it is higher in the stratigraphic section in molasse. Studies (Jaumé, 1986; Lillie *et al.*, 1987; Jaumé and Lillie, 1988) in the central and western Salt Range based on seismic profiles, gravity, and well logs have determined a 2°-3° basement dip and virtually no topographic slope, producing a very low critical taper angle. This is appropriate to a low friction salt layer along the décollement. An observed

low 1° basement dip in the eastern Salt Range requires deformation within the wedge to build topographic slope (Pennock *et al.*, 1989), even in the presence of a salt décollement, if the same taper angle is to be present.

Coward (1983) suggested that the variation in deformational style of a thrust wedge is a function of change in the resistance to shear. But he does not explain what are the factors that influence the resistance to the shear. The change in resistance can be due to a variety of factors, e.g., presence of a ductile layer; thickness of the ductile layer; thickness of the overlying thrust sheet; and the amount of shortening involved. It is not very well understood, what minimum thickness of salt is required to translate a thrust sheet without substantial internal deformation. Most of the previous workers in Salt Range, however, have related this remarkably different style of deformation either with the eastward thinning of salt (Davis and Engelder, 1985) or with the stepping of the detachment level in molasse sequence from salt (Butler *et al.*, 1987). The present study has revealed that the amount of relative shortening involved within a thrust wedge is directly related to the variations in deformational style, even in the presence of salt.

Apparently, the total shortening is comparable throughout the Salt Range (Table 2). In the rest of the Salt Range about 74-90% of the total shortening has been accommodated across the ramp and only 6-12% of the total shortening has occurred within the thrust wedge. That is why in the rest of the Salt Range the roof sequence is very gently deformed and the amount of shortening within the roof sequence is mainly related to broad folds and a few forward and/or back thrusts. On the other hand, in the easternmost part of the Salt Range all of the shortening has been accommodated within the thrust wedge above the basal décollement and has been distributed over a region in a prograde fashion. Therefore, one finds frequent blind thrusts, both foreland and hinterland verging, pop-up zones and a few emergent thrusts. This internal deformation of the thrust wedge into fault propagated

Table 2: Summary table showing distribution of shortening along different structures and convergence rate in the western (A-A'), central (B-B' and C-C'), and eastern (D-D') Salt Range, respectively.

DISPLACEMENT ALONG	SECTION LINE				
	A-A'	B-B'	C-C'	D-D'	Pennock et al., 1989
CONCEALED DUPLEX		5.5 km	3.3 km		
NORTHERN RAMP	28.0 km	20.0 km	17.8 km	15.3 km	17.8 km along and south of Domeli Thrust
INTERNAL	3.6 km	1.7 km	3.0 km	1.8 km	
TOTAL	31.6 km	27.2 km	24.1 km	17.1 km	
Dispalcement rate (mm/yr)	6.0	4.2	4.0	3.3	4.0

Table 2

fold geometry provides the required surface topographic slope necessary to maintain a critical taper and keep the thrust wedge in motion.

The deformation style east of the lateral ramp (Z-Z' in Fig 16) is marked by fault propagation folds, blind thrusts and pop-up zones (Pennock et al., 1989), while to the west it is marked by fault bend fold geometry. The section line D-D' suggests that 17.1 km of total shortening has occurred along this line. Out of 17.1 km approximately 15.3 km, almost 90% of the total, has been accommodated across the ramp while only 1.8 km of shortening has occurred within the thrust wedge. On the other hand, Pennock *et al.* (1989) have shown that approximately 17.8 km of shortening has occurred within the thrust wedge along and south of Domali thrust. This implies that the amount of crustal shortening accommodated across the northern ramp has been distributed over the main detachment along and south of Domali Thrust in the easternmost Salt Range. It also suggests that this deformation is contemporaneous to the youngest episodes of the horizontal translation and internal deformation of the roof sequence in rest of the Salt Range.

Development of the S-shaped Structures

The S-shaped zone is, in fact, a transitional zone from a fault bend fold geometry to fault propagation fold geometry. This zone developed due to the marked difference in the shortening within the thrust wedge. As the thrust sheet ramped down along the lateral ramp (Z-Z' on Fig. 16), all the shortening has been accommodated within the thrust wedge itself, which caused the E-W trending folding. The whole thrust sheet, at the same time was propagating towards south along the main décollement, in the east of the lateral ramp. On the other hand, almost 90% of the shortening to the west of the lateral ramp has been accommodated across the northern ramp. The development of these structures to the east of the lateral ramp seems contemporaneous with the last phases of horizontal translation of

the thrust wedge in the rest of the Salt Range. Paleomagnetic data (Burbank and Beck, 1989 a) also suggest that the Chambal ridge is likely to have deformed contemporaneously with the Jogi Tila structure at about 1.5 Ma, while the last phases of horizontal translation in rest of the Salt Range have also been estimated to have occurred between 2.0-1.0 Ma (Table1).

Rotation

Previous workers (Opdyke *et al.*, 1981; Johnson *et al.*, 1986; Burbank and Beck, 1989 a) on the basis of paleomagnetic data have discussed the sense and amount of structural rotation in the Salt Range/Potwar Plateau. Most of their studies are confined to the eastern part of the eastern Salt Range/Potwar Plateau. However, at the Bhaun section in the central Salt Range, 30° counter clockwise rotation at about 5 Ma is reported. On the other hand the degree of counter clockwise rotation ranges from less than 10° to more than 45° at some sections. This suggests that there is an irregular distribution of structural rotation, however, counter clockwise rotation is common to all these sections along the leading edge of the thrust front. The present study shows that 5.5 km of shortening along section line B-B' and 3.3 km of shortening along C-C' is associated with the duplex structures. There is a difference of 2.2 km in shortening between these two sections. If the estimate of shortening is correct, then it suggests that 4° counter clockwise rotation has occurred across the duplex structure (Fig. 23). Similarly, approximately 28 km of shortening along section line A-A' and 15 km of shortening along D-D' has been accommodated across the northern ramp in the western and eastern Salt Range respectively. There is a difference of 13 km in shortening between these two sections, which implies that approximately 9° counterclockwise structural rotation has occurred across the northern ramp. This implies that overall atleast 13° of counter-clockwise rotation has occurred across the northern ramp and along the concealed duplex.

Figure 23: Kinematic analysis of difference in shortening from east to west in the Salt Range. It suggests that overall about 13° counter clockwise rotation has occurred across the Salt Range along the concealed duplex structure and across the northern ramp.

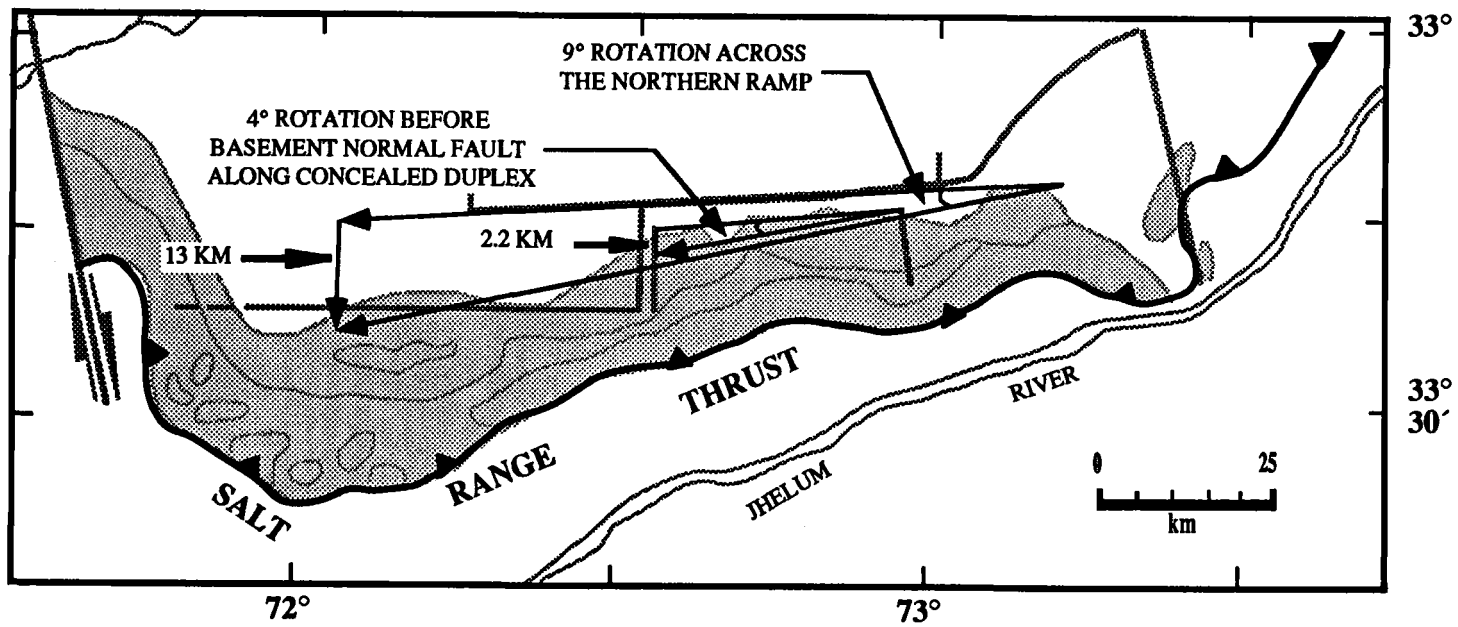


Figure 23

Hydrocarbon Potential and Prospects

Gee (1983) described the southward displacement of the roof sequence, a major obstacle in evaluating the oil prospects of the region. The present study not only helps to define clearly the thrust geometry but also generates very significant new prospects for oil/gas exploration in the vicinity of the leading edge in the Salt Range.

The presence of quite a few source rocks in the Salt and Surghar Ranges and Kohot area has been reported by Raza (1973, as mentioned by Khan *et al.*, 1986). He identified the Mianwali (Triassic), Datta (Jurassic), and Patala (Paleocene) Formations of the Platform sequence as potential source rocks. Abid (1980) identified the shaley horizons of Khewra Formation as a potential source rock. The lithology of the platform sequence ranges in composition from clastics to carbonates. The clastics range from coarse sandstones to impervious shales, while the carbonates varies from very dense to highly fractured limestones. These are also capable of acting as an excellent reservoir and cap rocks. The platform sequence is also frequently marked by two regional and numerous local unconformities, which are also very significant for the oil entrapment and can play a key role in locating stratigraphic traps. Raza (1981) suggested that the geothermal gradient in the Potwar Plateau ranges from 1.5°-2.6° C/100 m, with an of average is 2° C/100 m (Fig. 24). His studies further suggest that the geothermal gradient in the southern Potwar Plateau/Salt Range is slightly higher than in the northern part. The depth of the oil window in the Potwar plateau ranges approximately from 2500-5500 m (Raza, 1981; Khan *et al.*, 1986). Furthermore, numerous oil seeps in the vicinity of the leading edge in the Salt Range have been reported (Faruqi, 1982; Khan *et al.*, 1986). Above all in the Potwar Plateau, north of the study area, the platform rocks have been drilled and contain oil at several stratigraphic horizons. The present study suggests that the newly identified duplex

Figure 24: Geothermal gradient from the exploration petroleum well data showing the oil window in the Salt Range/Potwar Plateau and Kohat area (simplified after Khan et al, 1986). The shaded area defines the position of concealed duplex structures and the platform sequence in the footwall of the roof sequence. Note that this is only the minimum estimate without taking into consideration the eroded topography, which can be roughly estimated to be 1.5-2.0 km in thickness.

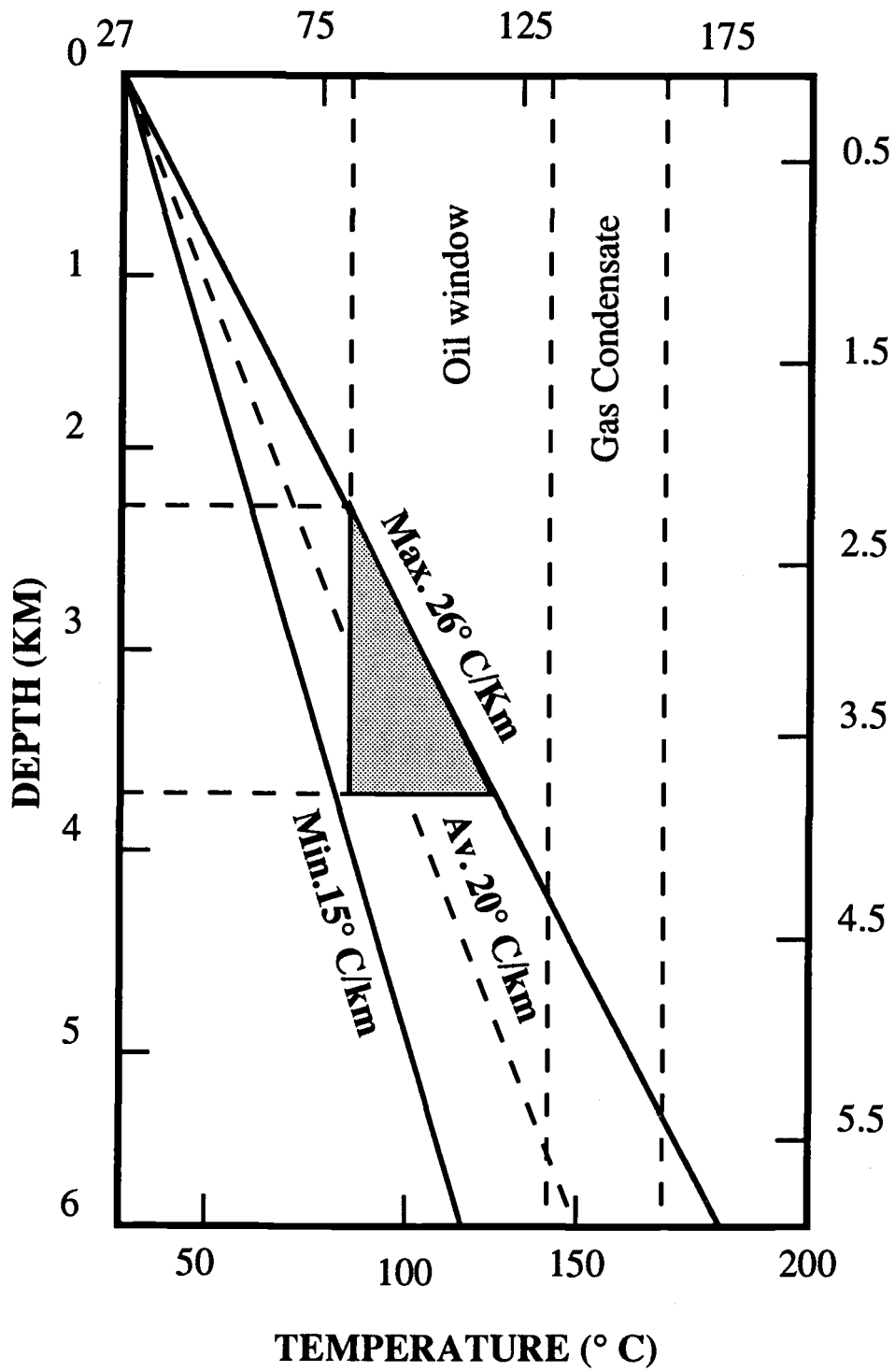


Figure 24

structures and the platform sequence in the footwall of the roof sequence (Fig. 25) fall within the oil window and thus are very significant potential targets for the future oil/gas exploration.

Figure 25: Areas with duplicated (1), due to northern ramp, and triplicated (2), due to the concealed duplex structure, Cambrian-Eocene platform sequence are very vital for the future oil/gas exploration.

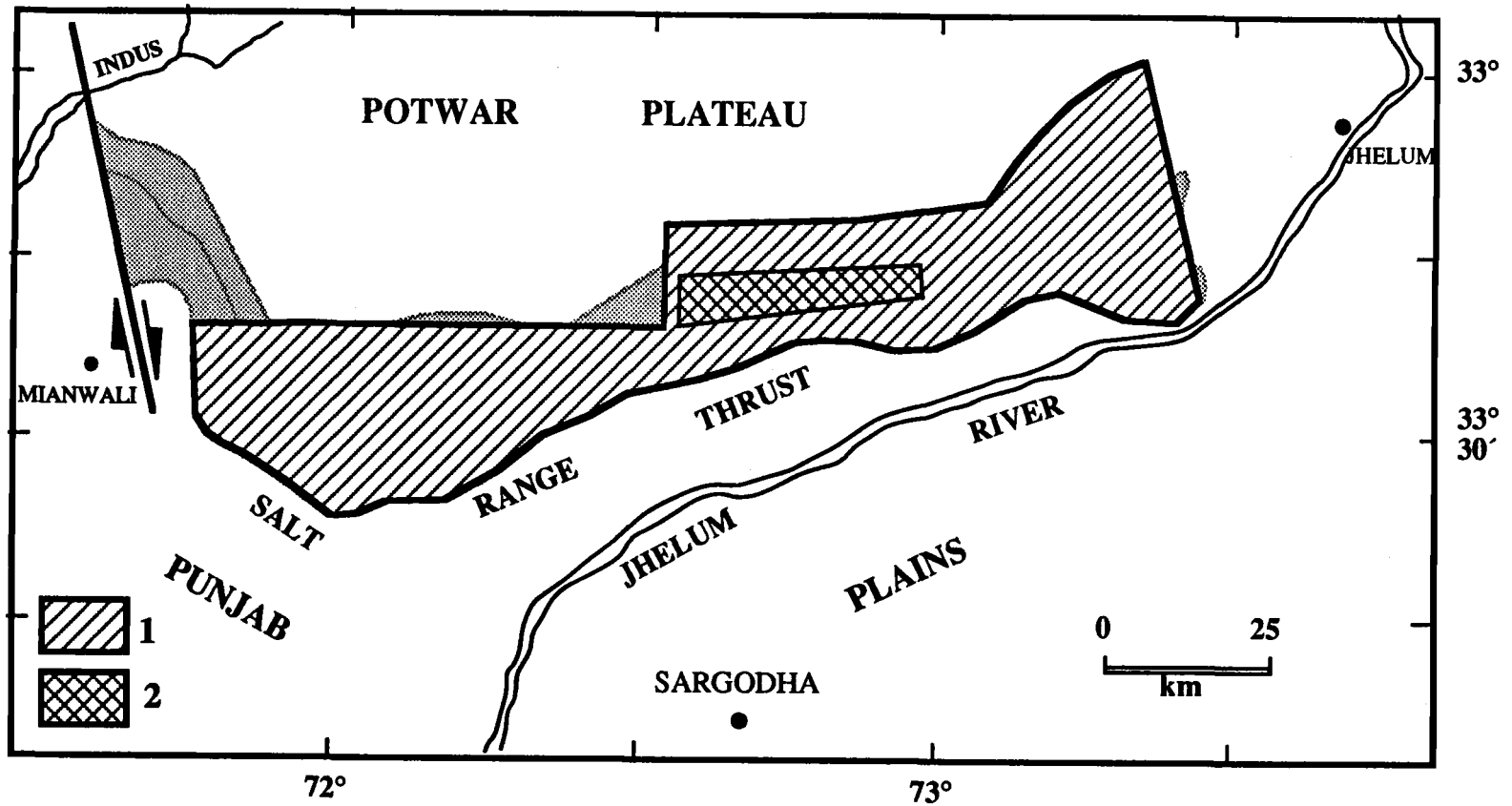


Figure 25

CONCLUSIONS

The present study provides new insights to the structure and tectonic evolution of the leading edge of part of Himalayan thrust front in Pakistan, which can be summarized as follows:

- (1) The overall structure of the Salt Range, except the easternmost part of the eastern Salt Range, involves basically a fault bend fold geometry modified due to the presence of the underlying ductile salt.
- (2) The roof sequence has been folded into sharp, salt cored anticlines and broad, flat synclines, which in its southernmost part frequently have been disrupted by forward and back verging thrusts and almost vertical dipping apparent normal faults.
- (3) A concealed duplex structure is newly recognized. It was evolved along a décollement with two ramps and extends more than 40 km along strike. The first ramp is within the Salt Range Formation. The second ramp crosses the platform sequence and follows shaley horizons of the overlying Murree Formation near the contact. Two lateral ramps truncate this structure in the east and west.
- (4) The basement normal fault in the central Salt Range not only localizes the northern ramp in the footwall of the roof sequence, but also constitutes its lower part. The upper part of the ramp is within the overlying sedimentary sequence. It has caused the repetition of the salt, platform, and molasse sequence in the Salt Range.
- (5) The northern ramp changes its position and characteristics in the eastern and western Salt Range.
 - (A) In the western Salt Range the ramp is located 15 km farther south and is entirely within the sedimentary sequence. These two segments are linked by a lateral ramp that developed over the western culmination wall of the lateral ramp associated with the underlying duplex structure.

- (B) In the eastern Salt Range, the northern ramp first continues within the sedimentary sequence beyond the end of the basement normal fault and farther east it changes into an oblique ramp.
- (6) The overall structure of the eastern part of eastern Salt Range across the Chambal ridge involves basically a fault propagation fold.
- (7) The oblique ramp is truncated to the east by another N-S trending lateral ramp. The monoclinical structure of the Chambal Ridge marks the southernmost extension of this lateral ramp. Along this lateral ramp the roof sequence steps down and joins the basal décollement. The change in deformational style across the Chambal ridge from a fault-bend fold to a fault propagation fold geometry is, in fact, due to this down stepping.
- (8) Dill Jabba Fault in the eastern Salt Range has been interpreted as a passive back thrust. The strata in the hanging wall started moving passively to accommodate more shortening as the strata in the footwall kept on moving southward.
- (9) The overall shortening in the Salt Range systematically decreases towards east with 32 km in the western, 27-24 km in the central, and 17 km in the eastern Salt Range respectively. On the other hand there is unsystematic shortening distribution within the roof sequence.
- (10) In the central and western Salt Range the major component of shortening, i.e., 74-90 % of the total has been accommodated by sliding across the northern ramp and only 6-12 % of shortening has been accommodated by folding and faulting within the roof sequence. However, in the eastern Salt Range farther to the east, comparable shortening, i.e., 17.8 km, (Pennock et al., 1989) has been accommodated by folding and thrusting within the thrust wedge and is distributed over a broad region. Thus, the thrust wedge is internally more deformed there, to provide the surface topographic slope necessary to maintain a critical taper..

- (11) S-shaped structures, Jogi Tilla and Chambal ridge, mark the eastern termination of the Salt Range Thrust and are the surface expression of the transition zone from fault bend fold to fault propagation fold geometry.
- (12) The newly recognized concealed duplex structure marks the first tectonic event in the Himalayan foreland fold-and-thrust belt and probably developed between 9.0-7.0 Ma. Furthermore these also suggests that out-of-sequence thrusting has occurred on a large scale, i.e., approximately 150 km during the past 9.0 Ma.
- (13) The concealed duplex was disrupted by the development of a basement normal fault at about 7.0 Ma, which is related to the flexural bending of the Indo-Pakistan plate in response to thrust loading in the north. This fault not only disrupted the basement but also the overlying sedimentary sequence. Due to the dislocation of the salt layer, the easiest horizon for the thrust wedge progradation, the thrust motion was stopped in the south. All the shortening then was taken up out of sequence motion on the MBT zone in the north, which was quite active during this time.
- (14) This event was followed by the development of a thick salt pad between 7-6 m.y., on the down thrown side of the basement normal fault, and then motion of the roof sequence over the northern ramp between 5-6 m.y.
- (15) The newly built roof sequence topography resisted the southward progradation of the roof sequence. Substantial horizontal movement along the roof sequence flat was contemporaneous with the out-of-sequence thrusting in the Potwar Plateau and further in the north. This was followed by a major episode, between 2.0 - 1.0 Ma (Burbank and Beck, 1989 a), of horizontal translation of the roof sequence over the roof sequence flat that also caused substantial deformation within the roof sequence.
- (16) This study also suggests that 13° counter clockwise rotation has occurred along the northern ramp and the concealed duplex structure.
- (17) The recognition of the duplex structure, determination of the footwall and hanging geometries of the leading edge at different evolutionary stages, delineation of the areas with

duplicated and triplicated platform sequence generate very bright prospects for the future oil/gas exploration in the Salt Range.

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