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Petroleum Geology and Prospects of Sukkur Rift Zone, Pakistan with Special Reference to Jaisalmer, Cambay and Bombay High Basins of India

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ABSTRACT

Cretaceous rifted features in northern part of the southern segment of the Indus basin of Pakistan are generally grouped with "Sukkur Rift Zone" which comprises of a graben flanked by two horsts. These features partly extend into India and host oil and gas fields including giants on both sides of the Indo-Pakistan border. The present paper describes the petroleum geology and prospects of the Sukkur Rift zone utilizing existing geological, geophysical and drilling data. The results show good possibilities of finding more hydrocarbons in this area.

INTRODUCTION

Sukkur Rift zone is a part of the southern Indus basin. Its Cretaceous rifted features are masked by Tertiary downwarping. The main graben (Cambay graben) is formed on the Indian side which has been extensively explored and many oil and gas discoveries have been made. In Pakistan the graben (Panno Aqil graben) has todate remained almost a frontier and the drilling has been confined to its flanking horsts which have discovery record.

The present paper contains a regional tectonic setting map, a generalized stratigraphic column and 4 cross sections, two of these include the Indian part also. It also includes some prospect maps.

The data source includes Petroconsultants Scouting Service maps, published literature from both sides of the border, HDIP's internal reports and personal observations of the authors.

TECTONIC SETTING

The study area is a part of the Indus basin (Figure 1) which is located on the Indian plate. The history of the Indian plate is well known. It rifted and drifted from the Gondwana in Mesozoic and collided with the Eurasian plate in Early Tertiary, initiating fold belt development and creating frontal depressions and troughs in the vicinity of the collision zone and north and northwesterly tilted platform on the distal side of the plate. It is also well researched that some rifted features were developed in southeastern part of the Indian plate due to anticlockwise rotation in the north and northwesterly compressing plate, Sukkur Rift zone is one of them.

STRATIGRAPHIC DEVELOPMENT

A sedimentary fill with a maximum thickness of 8500 metres exists in the area (Figure 2). The age of the stratigraphic column ranges from Paleozoic to Recent, the sedimentation is marked by a number of unconformities. Sedimentary cycles existing in the column can be correlated to the plate movements. The following sedimentary episodes seem probable:

. During Cambrian period clastics were deposited in a sea resting on a continental plate. The climate was hot and dry as indicated by the colour and grain fabric of the sediments.

. Some sort of ancient plate collision is indicated at the end of Cambrian period which caused raising of the sea floor and a consequent regression, Ordovician to Carboniferous period is represented by an unconformity and no sediments of this age are present.

. Early Permian brought glaciation covering a wide area upto Salt Range with ice sheets. A warming up episode left the area littered with glaciated materials over which a shallow sea deposited Permian-Triassic sediments.

. Late Triassic to Early Jurassic was the time when tension was mounting and break up of Gondwana took place. The study area was the site of paralic sedimentation which gave way to a widely distributed carbonate shelf deposition in Middle-Late Jurassic.

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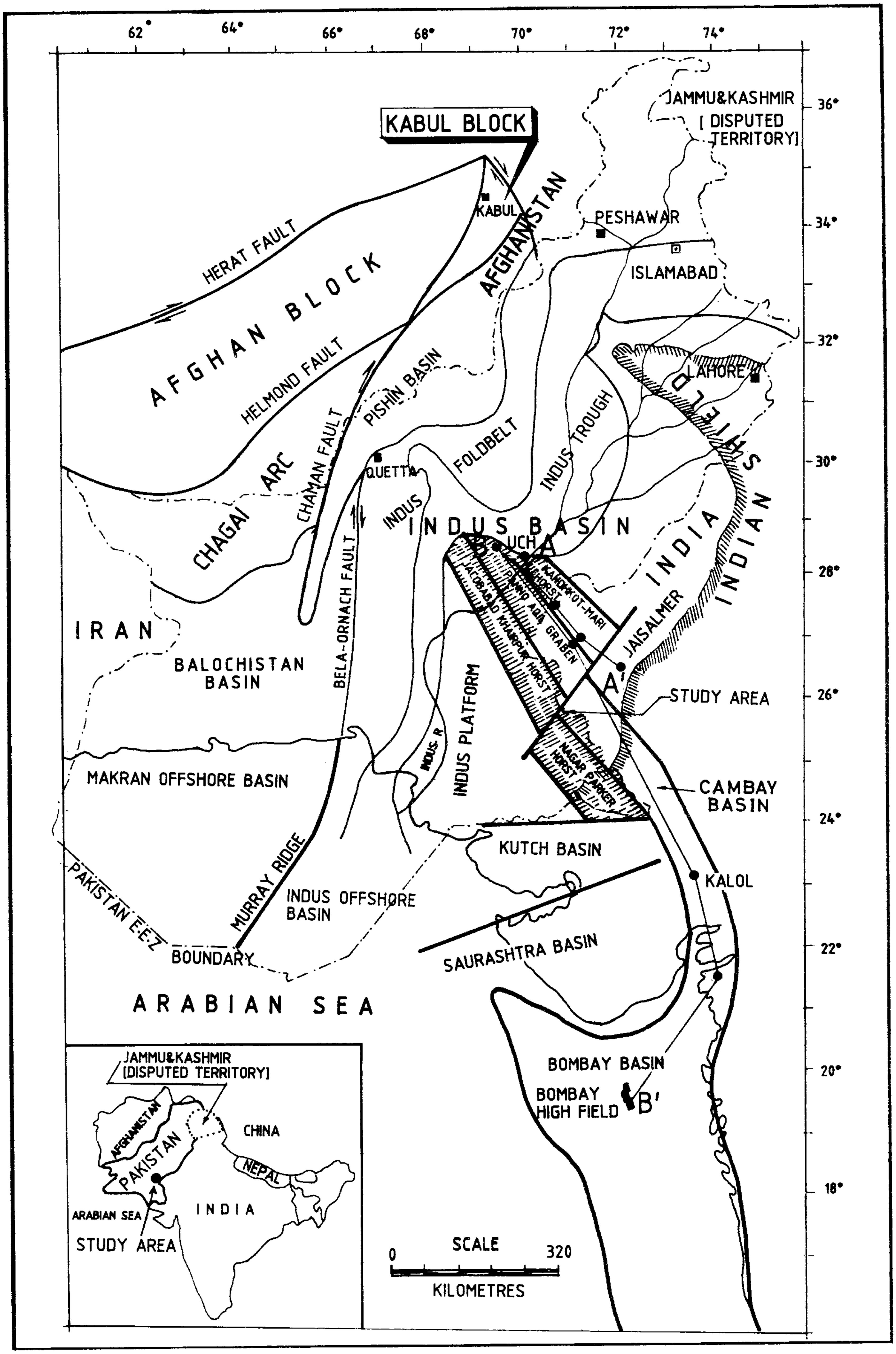

Figure 1— Location of study area with regional tectonic setting.

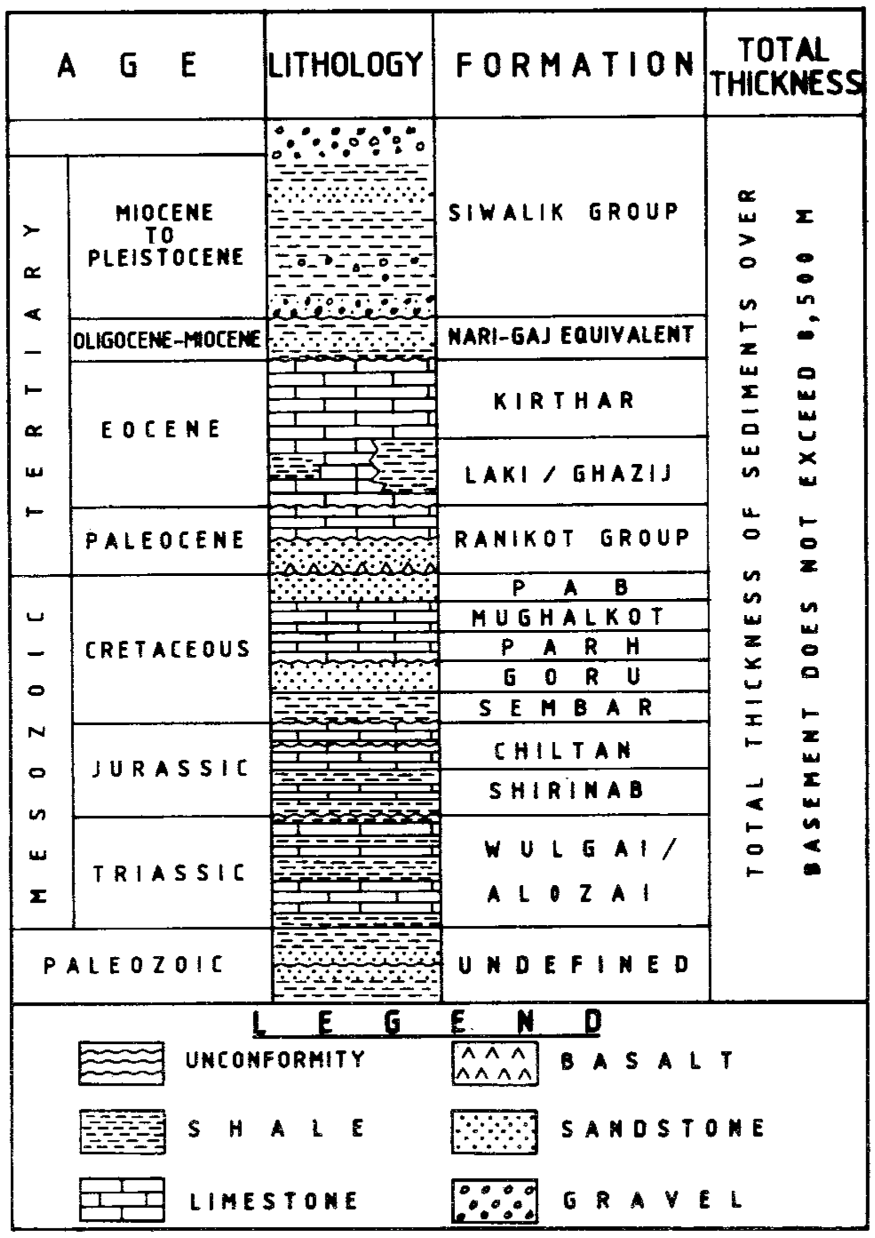

Figure 2— Generalized stratigraphic column.

. Rapid facies changes are noticed in Cretaceous section due to the effect of rifting in the south and northward drift of the newly created Indian plate.

. Widespread limestone dominated deposition took place during Paleocene-Eocene in response to plate collision and downwarping. New regional structures were superimposed due to compression.

. During Oligocene and Miocene periods most of the Indus basin except southern and southeastern parts were uplifted and the marine deposition was restricted to these parts only.

. During Miocene and onward, molasse was deposited in front of the folded and uplifted areas and compressive structuring continued.

A brief description of the stratigraphic units is given below:

Paleozoic

The possibility of the occurrence of marine clastic sediments of Cambrian age exists in the study area as such rocks are present on the Punjab platform and its adjoining areas in India but it is yet to be confirmed through drilling. Ordovician, Silurian and Devonian periods are definitely not represented by sediments. Permian sediments comprising terminal moraines and shallow marine to continental clastics are also expected.

Mesozoic

Shallow marine to continental clastics (Wulgai/Alozai and Shirinab formations) continued in Triassic and Jurassic, basically deposition was the result of a regressive cycle. In Middle to Late Jurassic a wide spread carbonate shelf deposition (Chiltan limestone) took place in the study area and in its surroundings. Cretaceous was a period of intense tectonic activity involving rifting and rapid northerly drift. Anticlockwise rotation produced northwest-southeast oriented block faulting, resulting in uneven distribution of sediments. Shale (Sembar), sand (Goru and Pab), fine-grained limestone (Parh) and mixed clastic-carbonate (Mughalkot) were deposited in fluctuating and varying environments.

Tertiary

Tertiary sedimentation was affected by plate collision. Downwarping, buckling and uplifting resulted in shallow water shale (Ghazij) and limestone (Laki) and mixed shale-limestone (Kirthar) sedimentation. Temporary and wide-spread shelf carbonates dominated the stratigraphy of the area. Some high places also show erosion of parts of the Tertiary sequence.

Most probably a permanent regression of the sea stopped marine deposition in the area. Oligocene-Miocene (Nari-Gaj equivalents) are continental sand-shale/clay deposits. In Panno Aqil graben, however, there is a possibility of Oligo-Miocene marine sedimentation but no confirmatory evidence is available as yet due to lack of drilling.

REGIONAL CORRELATIONS

Four cross sections have been constructed to define regional structures and sedimentation. These are described below:

Cross Section AA′ (Kandhkot, Mari, Manari Tibba and Jaisalmer)

This cross-section has been drawn along the Mari-Kandhkot horst and extended southward upto Jaisalmer in

India (Figure 3). It is an uplifted relatively flat area. Paleozoic sediments are truncated in the east. These sediments are commonly shown absent in the study area by geologists, but careful examination of seismic data leads to the inference that thin Paleozoic marine clastics overlie the basement. A regional unconformity (not shown in the section) intervenes Paleozoic sequence. Clearly the Mesozoic and younger rocks thicken toward and in the study area. Some faulting is indicated in Mesozoic, Paleozoic and the basement in India, in the study area, also basement and Paleozoic are probably involved in faulting.

Cross Section BB′ (Uch, Panno Aqil Graben, Cambay and Bombay High Basins)

It has been drawn along the Panno-Aqil graben and extended through Cambay graben upto Bombay high of India (Figure 4). The section shows faulting in Cretaceous-Paleocene section in Indian side, where Deccan volcanics form a second basement. The Bombay high area is separated from the Cambay graben by an uplift northeast of Surat. The Cambay graben is dislocated by another uplift and a regional northeast-southwest trending fault near the Indo-Pak border. Panno Aqil graben takes its westward tilt and depth from this fault. The basement deepens westward with accumulation of a thick Paleozoic (?), Mesozoic and Tertiary sedimentary section.

Cross Section CC′ (Panno Aqil Graben)

Seismic lines in between the Jacobabad and Kandhkot wells i.e. through and across the Panno Aqil graben were studied to demarcate the line between horsts and graben. The data available is not adequate for a confident interpretation as most of these profiles were shot during 1975-76 and are 12 fold, dynamite source, unmigrated and poorly processed.

This cross section (Figure 5) is based on the above mentioned seismic data. It may be noted that at the base of Tertiary, faulting of nearly 30 milliseconds two-way time is indicated at locations A and C, these two points are considered the boundaries between horsts and graben blocks. Location X represents the deepest part of the graben on this cross section.

Block faulting clearly seen at the base of Cretaceous is similar to the Jacobabad horst, which confirms the involvement of extensional tectonics in these areas.

A small depression bounded by faults B and C is also noted within the Panno Aqil graben.

Cross Section DD′ (Jhatpat and Jacobabad)

It has been prepared to show the structural and stratigraphic configuration in the area through Jhatpat and Jacobabad wells (Figure 6a) in a northeast-southwest direction. Cretaceous and Tertiary sediments are comparatively thin in crestal part of Jacobabad high. Syn-sedimentary faults are also seen in Tertiary and Cretaceous rocks in the northeastern flank of the Jacobabad high which confirms the presence of extensional tectonics in the area. A similar development of such fault patterns can also be seen on seismic to the southwest of Jhatpat-1 well (not shown in the section). Similar structural styles from Malaysia and Argentina are shown in Figures 6b and 6c.

Cretaceous truncation is clear on northeast and southwest of Jhatpat-1 well.

PETROLEUM PROSPECTS

There are significant discoveries on both sides of the border related to rifted features which provide evidence for the occurrence of hydrocarbons. Source rocks for hydrocarbons which qualify in terms of TOC and HI exist in the west (within Ghazij and Kirthar formations of Early and Middle Eocene ages respectively in Kirthar Range) and in the south (mainly shales of Sembar formation of Early Cretaceous age in Badin area) of the study area (Seemann et al, 1988). Incidentally the migration of hydrocarbons to the study area could also have taken place from these directions. The prospects of the each feature are further highlighted.

Kandhkot-Mari Horst

The feature has proved very rich in hydrocarbons. Gas has been discovered at shallow depth from Early Eocene limestone reservoir in Kandhkot and from Middle Eocene carbonate reservoir in Mari and Qadirpur. Seismic data indicates that the Early Eocene limestone reservoir (mainly Sui Main limestone) shows a facies change from Qadirpur-1 to Mari X-1 and in the area between these two wells it is replaced by shale. Further towards Sandh structure (Figure 7), the limestone is again developed. The limestone facies also seem to be replaced by shale from Mari X-1 toward southwest and east (Ahmad, 1991). On the Indian side also gas discoveries are reported at Manari Tibba and Dandewala, etc. All these structures are located in a regional anticlinal trend. India has drilled Dandewala and found gas just on the international border, whereas in Pakistan a broad no-man zone has been left untapped. Sandh structure (Figure 7) which forms a gentle saddle with Mari dome has its main updip closure in Pakistani side and it should be drilled for an easy Mari field like situation. All the structures on this feature are broad, dome-like anticlines created during Tertiary plate collision due to compression caused by northwesterly convergence. The

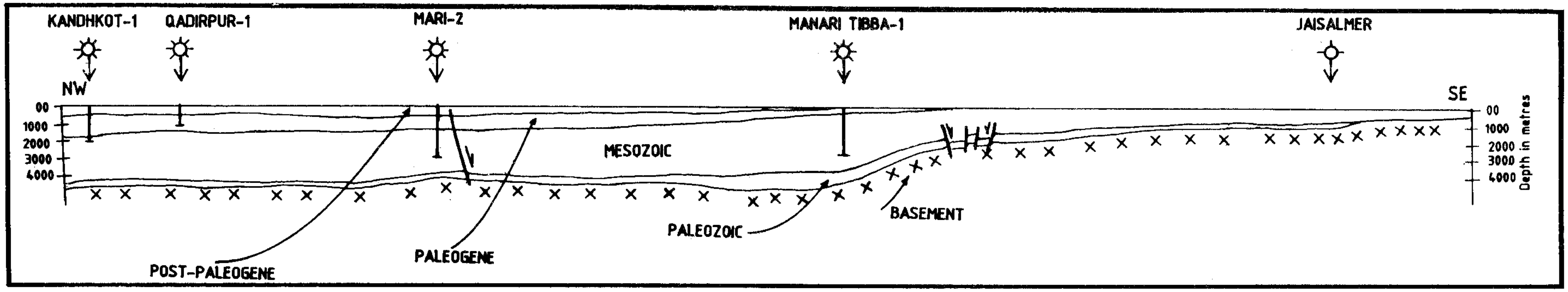

Figure 3 — Cross section AA′, through Kandhkot, Mari, Manari Tibba and Jaisalmer areas (Indian part after Raju, 1979). For location, see Figure 1.

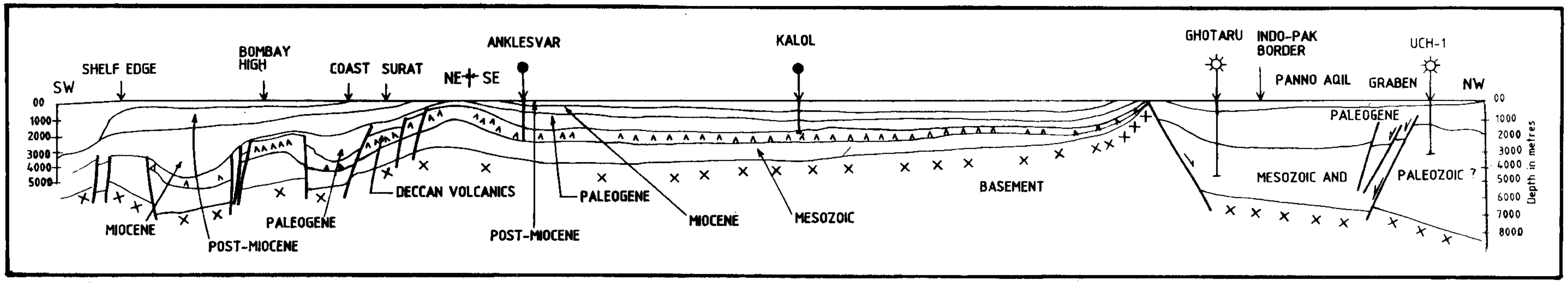

Figure 4— Cross section BB′, through Uch structure, Panno Aqil graben, Cambay basin and Bombay high; structural details in Cambay basin not shown for sim plification purpose (Indian part modified after Raju, 1979). For location, see Figure 1.

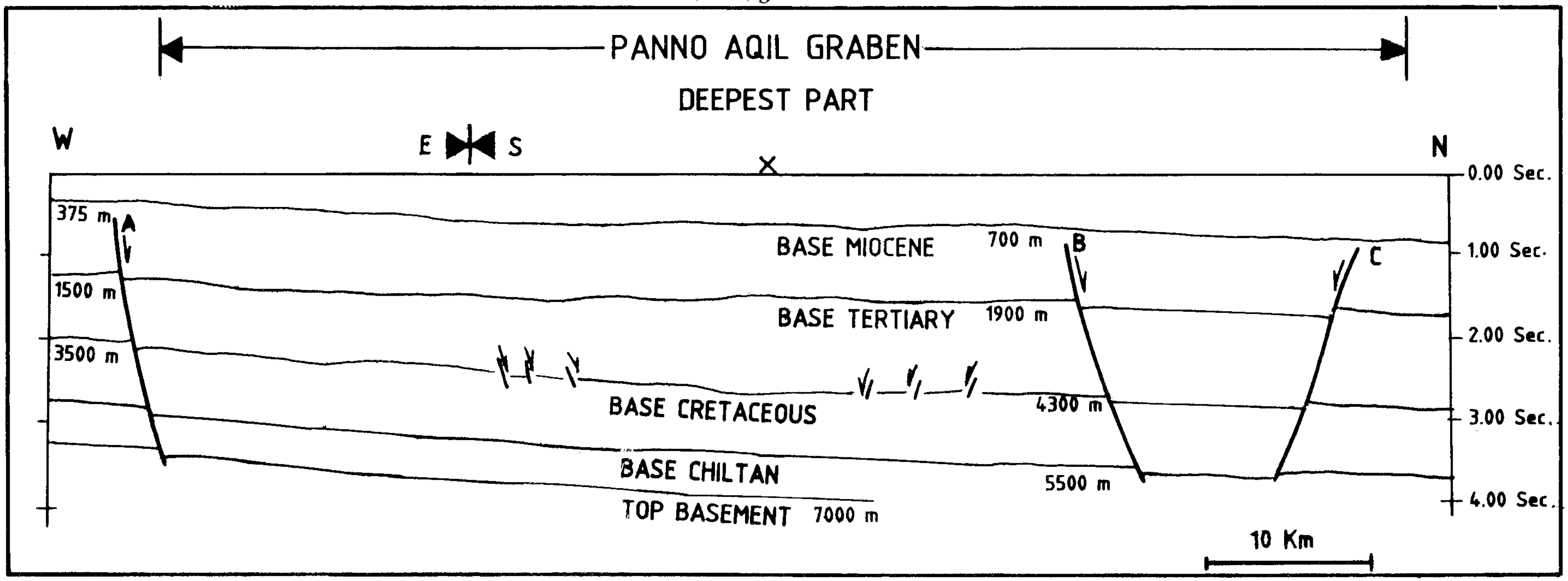

Figure 5— Cross section CC , through and across Panno Aqil graben. For location, see Figure 7.

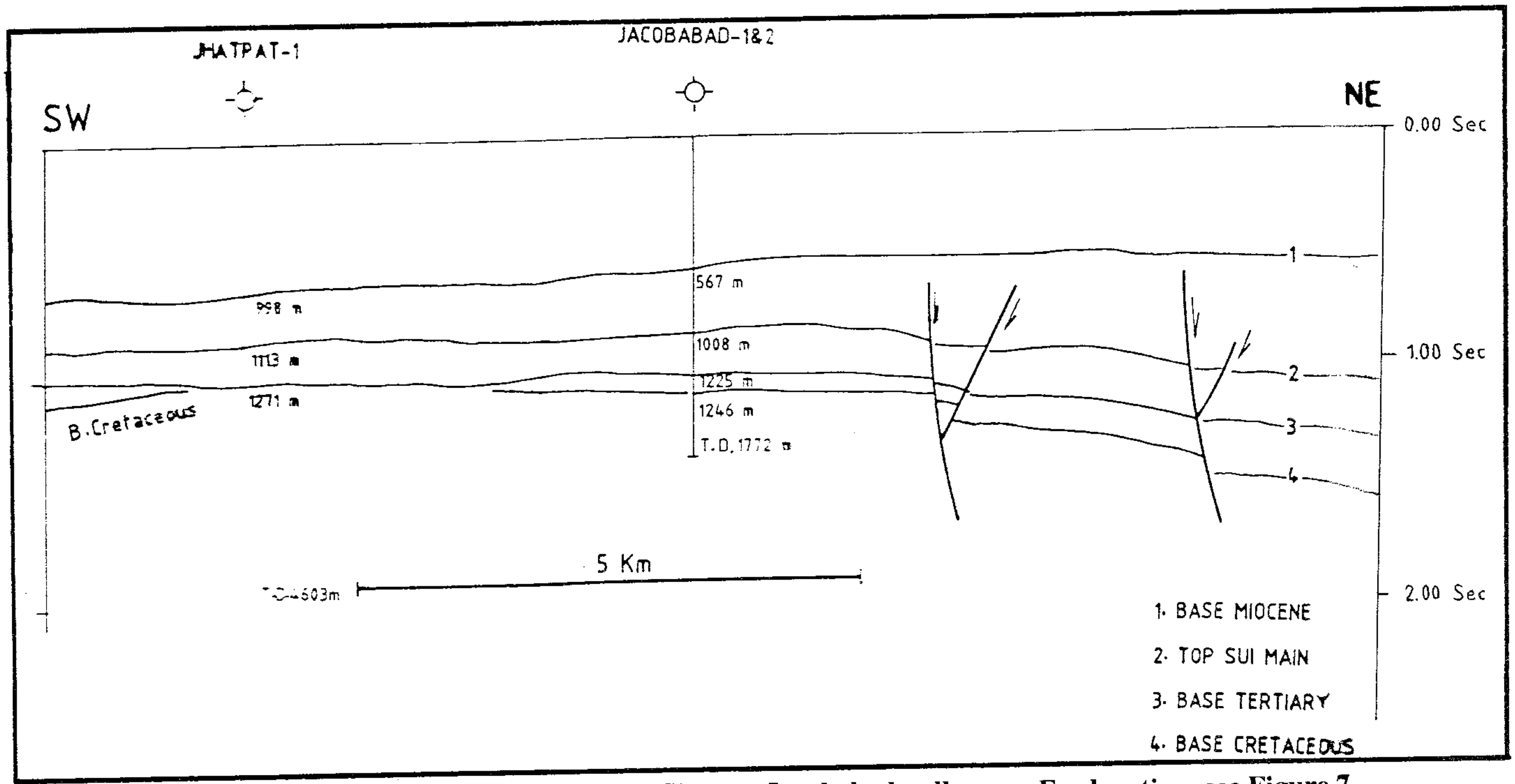

Figure 6a— Cross section DD', through Jhatpat-Jacobabad well areas. For location, see Figure 7.

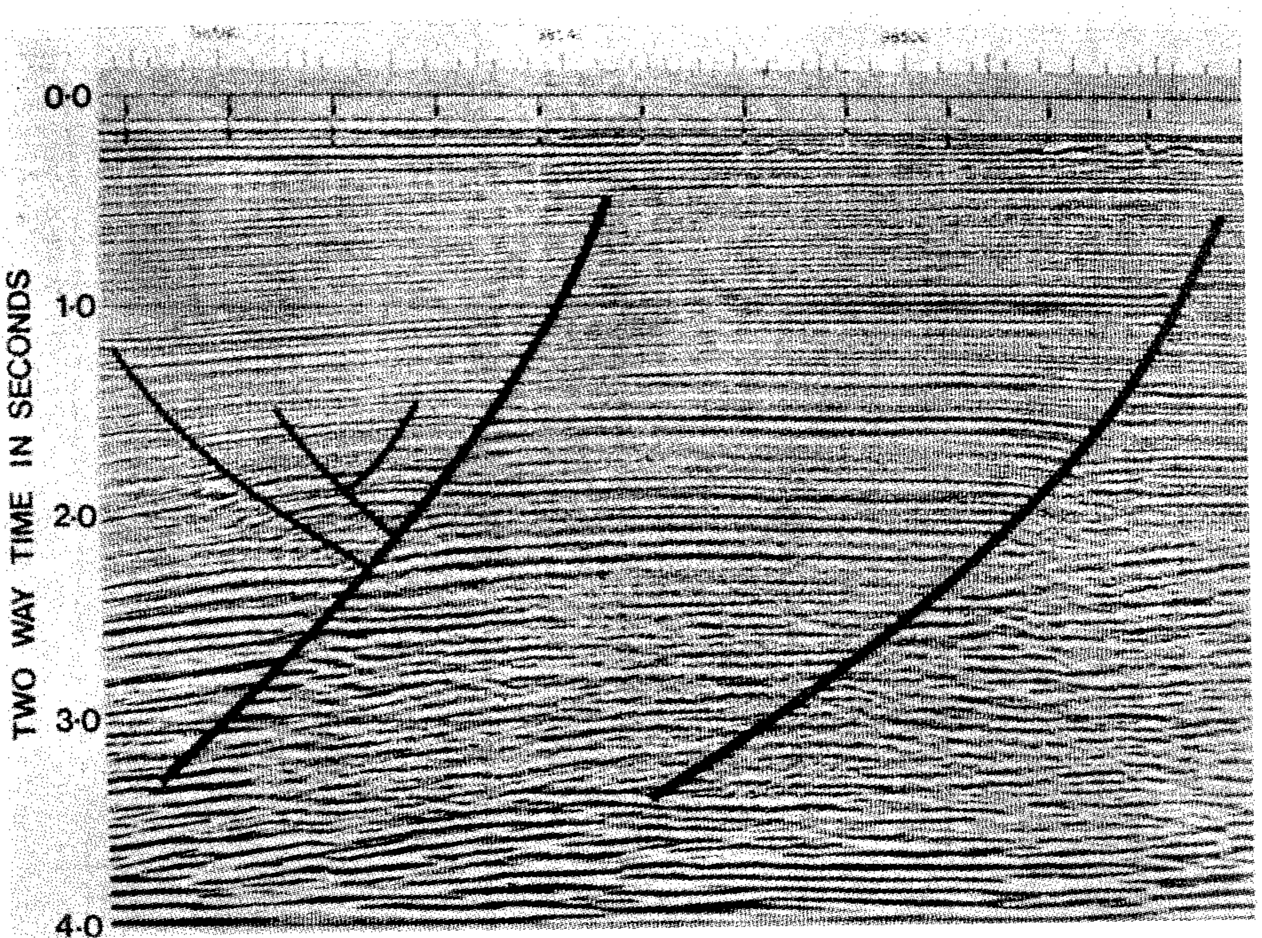

Figure 6b— An example of oil productive trap development related to growth faults from Malaysia (after Jenyon and Fitch, 1985).

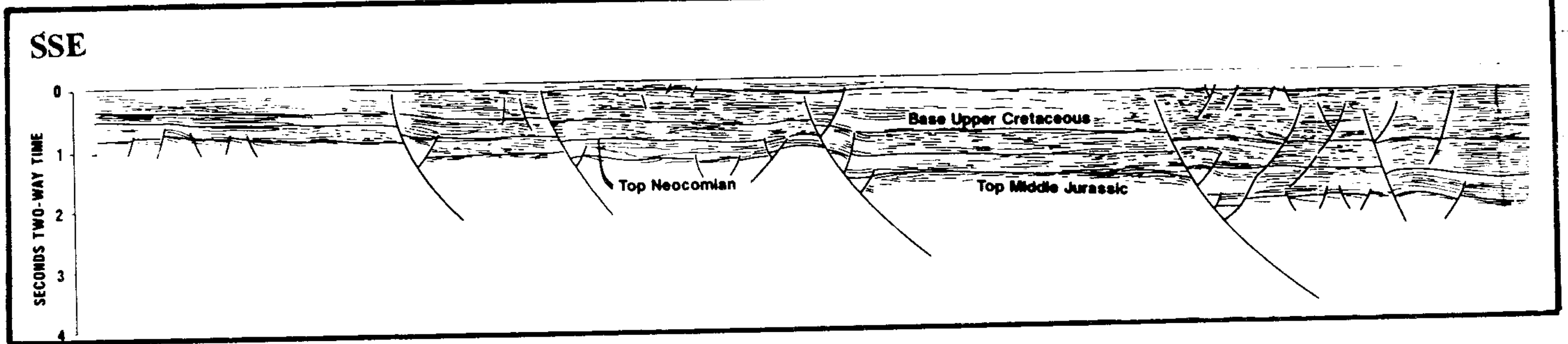

Figure 6c— An example of synthetic-antithetic normal faults which form hydrocarbon traps in the San Jorge basin, Argentina (after Uliana et al, 1989).

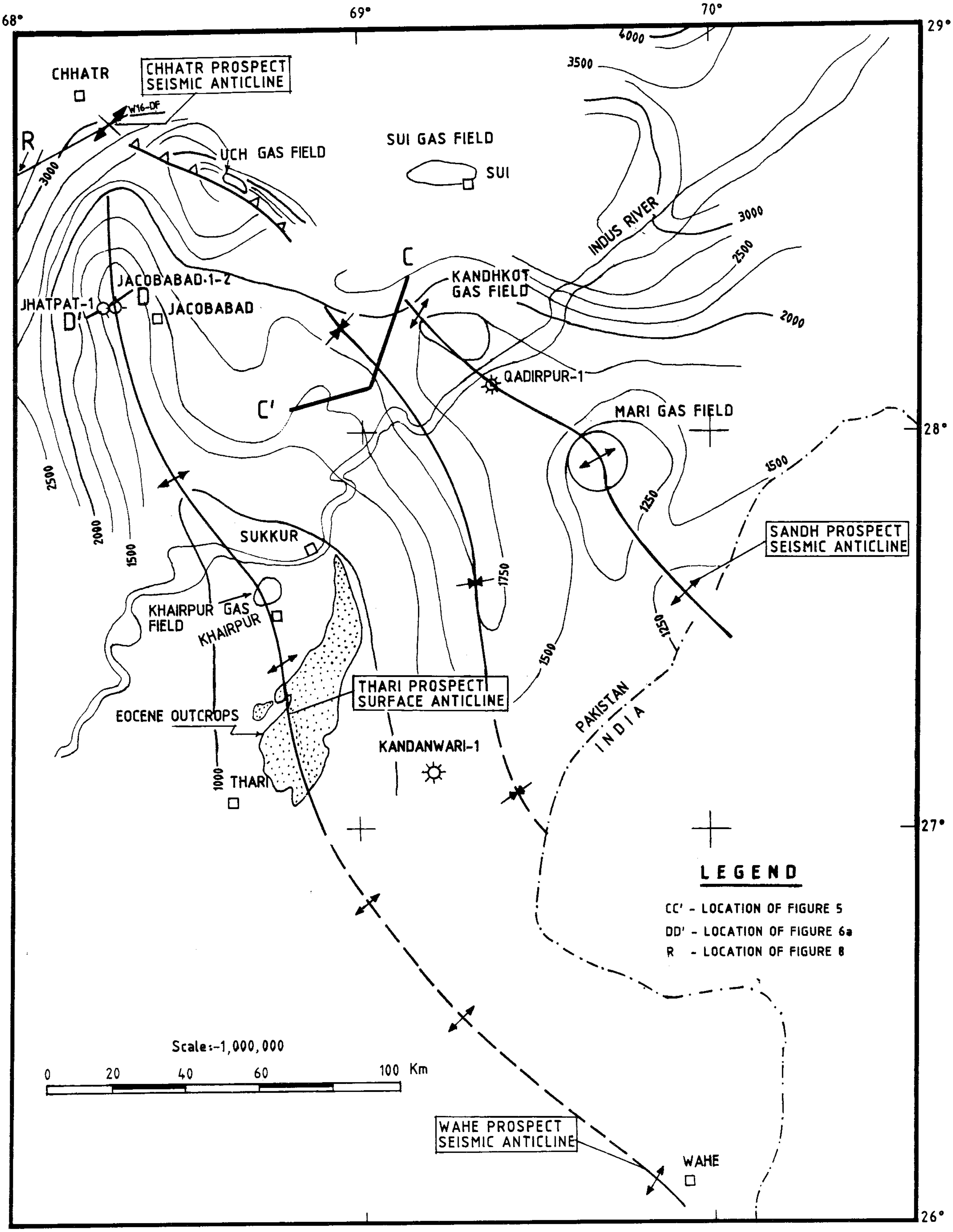

Figure 7— Prospect map with depth (BMSL) contours at base-Tertiary. Contour interval 250 m.

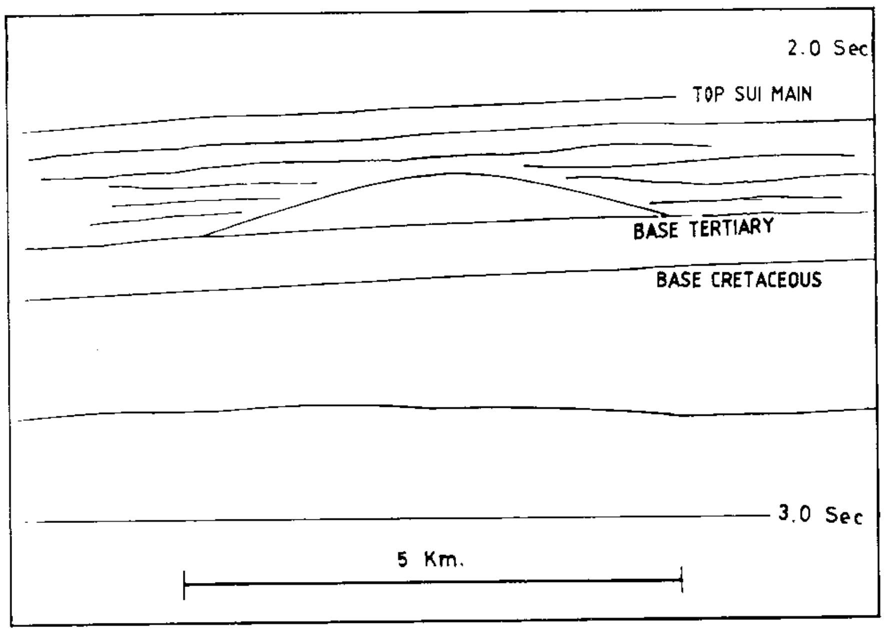

Figure 8— Reefal build-up within Tertiary on western flank of Jacobabad culmination. For location, see Figure 7.

shallowness of targets is due to the uplifted position of this feature attained during Cretaceous rifting. The main reservoir is a carbonate unit (Habib Rahi limestone) of Kirthar formation which is very porous (porosity about 20%), fine grained and foraminiferal. Facies-wise this limestone differs from typical Habib Rahi limestone exposed in northwest and southwest of the study area where it is a dense limestone containing nodular and bedded chert with poor primary porosity and reservoir characters (personal communication by Shaji Alam, Chief Geologist, HDIP). It contains gas with 73% methane, 19% nitrogen and 8% carbon dioxide. The estimated reserves of gas at Mari alone are 6 tcf. Since the reservoir is located at shallow depth (less than 1000m) and the geothermal gradients are about 3°C/100m, (Khan and Raza, 1986) the oil window indicates an older and deeper source, probably the Sembar formation of Early Cretaceous age, or there might be hydrocarbon pathways developed across major rift lines, thus feeding the Habib Rahi reservoir from some deeply buried Tertiary source in the adjoining Panno Aqil graben. Therefore, there is a strong probability that the entire Habib Rahi limestone is filled with gas and it should be productive (Qadirpur is an example), and any high or updip closure located on this feature could be a promising target.

Jacobabad Horst

The feature is located south-southwest of Panno Aqil graben and continues south-eastward into India with some dislocation caused by a northeast-southwest trending regional fault (Figure 1) which crosses the rifting trend. Three gas discoveries have been made so far (Khairpur, Jacobabad and Kandanwari). The Khairpur and Jacobabad discoveries are from Early Eocene carbonate (Sui Main limestone) which is a highly foraminiferal,

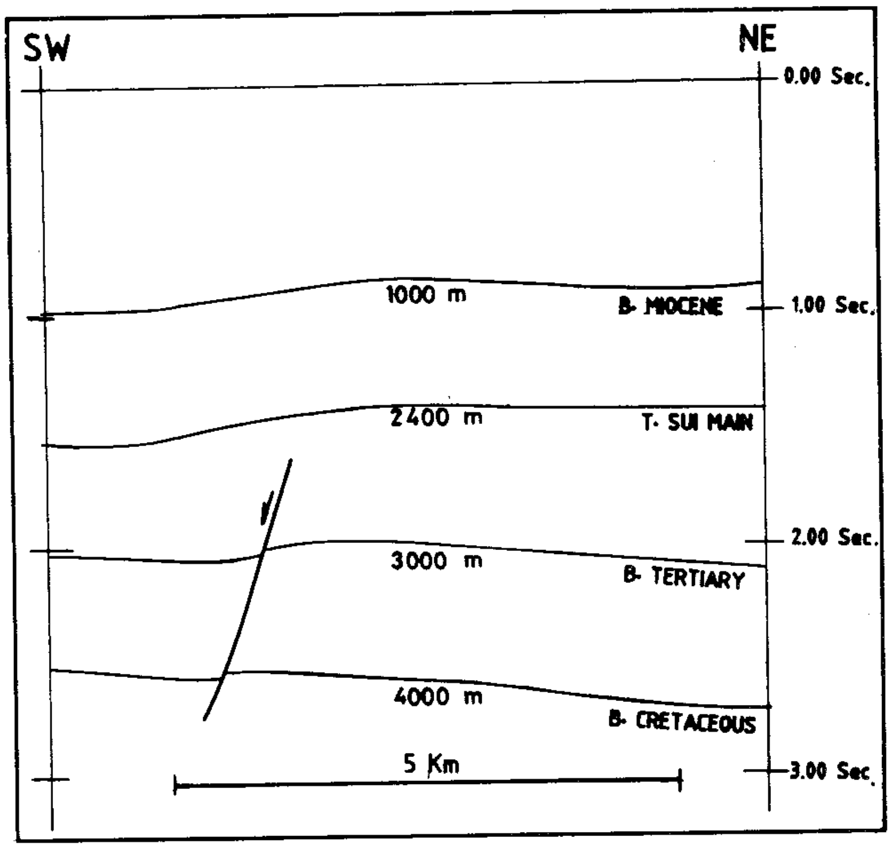

Figure 9— Structural development over Chhatr prospects.

porous limestone (porosity about 12%). The Kandanwari discovery is from Goru sandstone (Cretaceous) which is a continuation of Badin's Goru reservoir and is sourced by Sembar (Early Cretaceous) source rock.

The deepest stratigraphic horizon drilled so far is Permian-Triassic Alozai/Wulgai formation in Jhatpat-1 well. Entire Cretaceous is missing at Jhatpat, while upper part of the Cretaceous section is absent at Khairpur and Kandanwari indicating uplifting of the feature. At Nagarparker, the basement is exposed (Figure 1).

Seismic studies indicate that presently prospects of finding oil and gas are at Jacobabad-Jhatpat, Thari and Wahe structures (Figure 7). At Jacobabad a sub-economic gas discovery in Sui Main limestone was made in 1958 by PPL. The reason for this sub-economic discovery is discussed in the following paragraph. It is expected that a commercial gas discovery can be made by drilling southern culmination where Habib Rahi and Pirkoh limestone reservoirs are present and effective seal is provided by the increased content of shale towards south.

Some new leads are also indicated on the existing seismic data which can further be confirmed by running fresh seismic profiles. These are: (1) Northeast of Jacobabad wells there is a roll-over developed as a syn-sedimentary feature against a fault (Figure 6a). This roll-over can be tested for Sui Main limestone reservoir; (2) further to the northeast another closure is formed by two growth faults associated with antithetic faults. Tertiary and Cretaceous targets are in a trap position and merit testing. Here the target depths to base-Tertiary and base-Cretaceous are around 1400m and 1700m below mean sea level (BMSL) respectively (Figure 6a). Such trap situations have produced petroleum in other areas e.g. Malaysia and

Argentina (Figures 6b and 6c). Cretaceous is absent on main Jhatpat structure, however on southwest and northeast of Jhatpat Cretaceous truncation is well marked where prospects exist. Apparently, Jhatpat and Jacobabad wells were drilled in a flank position and that could have been the reason for their failure. Another interesting observation, that is, the lateral velocity changes over Jacobabad high could be related to shift in crestal position in the subsurface, merits re-evaluation of the Jacobabad and Jhatpat wells (Hildebrand et al, 1991).

A reefal build-up (Figure 8) is indicated on seismic in the northwest of Jacobabad wells. Location of this feature is shown in Figure 7. The target is within Lower Tertiary at a depth of 3500m BMSL. Some block faulting in Mesozoic is also visible on seismic in this area. Minor carbonate build-ups are also present on other parts of the same line (W16-DF).

Panno Aqil Graben

The rifted basin (graben) of India's oil and gas producing Bombay high and Cambay where exploration has been aimed at sediments above Deccan traps, extends into Pakistan and forms an extensional basin, known as Panno Aqil graben. Figure 4 shows that at a little distance east of India-Pakistan border, Panno Aqil and Cambay grabens are partially separated by an uplift probably caused by a transverse fault. The basement sharply deepens in Panno Aqil graben towards northwest (in the direction of Uch structure).

Since detailed seismic has not so far been carried out in this area and also there is no drilling in the main graben, only two structures are promoted for the time being that is Chhatr (Figure 9) which is a high located northwest of Uch field where a gas discovery can be made from the Sui Main limestone (Early Eocene), at a depth of 2400m BMSL. Detailed seismic survey is required to pick leads, if any in this area. Secondly a roll-over on the upthrown side of fault B (Figure 5) is indicated on seismic data. This location could also be further explored to develop it into a prospect at the Tertiary level, where the depth to the base-Tertiary is less than 2000m BMSL.

The graben most probably was a hydrocarbon kitchen from where the gas could have migrated towards relatively higher surroundings and accumulated in available Tertiary traps. The main source could be the Cretaceous shales (Sembar formation). The estimated geothermal gradients of 2.5-3^{o}C/100m would have been enough to cook kerogen embedded in Sembar formation.

CONCLUSIONS

The study area, although located in a dominantly compressional tectonic regime, has also been influenced by extensional tectonics and shares some characteristics with its adjoining areas in India.

Eocene source rocks have been identified in the west and Cretaceous in the south of the study area by HDIP. Hydrocarbon pathways can also be drawn from these directions to the study area.

Gas has been discovered in Eocene carbonates and more gas is expected in a few leads mentioned in the present paper, these range from simple domal anticlines to roll-overs produced by growth faults and some reefal carbonate build-ups. However, further seismic survey is required to properly delineate these possible trap situations.

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