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Structural Styles and Hydrocarbon Prospects of Sibi Foreland Basin, Pakistan

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ABSTRACT

On the basis of regional structural interpretation, surface geological expressions and world analogs, two different compression-related, basement-involved structural regimes have been identified in Sibi foreland basin. Briefly, these regimes are: 1) the wrench associated, and 2) the upthrust fault-bounded. The structural traps within these regimes coupled with other favourable pre-requisites for the occurrence of oil and gas, such as source and reservoir rocks indicate good prospects for exploration in the basin, specially considering several producing world areas in comparable tectonic setting.

INTRODUCTION

The study area is located between latitude 28° 30′ to 30° 30′ North and longitude 67° 00′ to 68° 45′ East. It is a wedge shaped tectonic feature situated in the northwestern part of the large Indus sedimentary basin of Pakistan. The feature is bounded by Kirthar fold belt in the west, Kirthar depression in the south and Sulaiman fold belt in the north and northeast (Figure 1). It is covered mostly with Miocene to recent sediments.

The Sibi foreland basin has been inadequately explored, only two wells, Bannh-1 by Pakistan Petroleum Ltd. (1957-58) and Sanni-1 by British Petroleum (1983) were drilled and abandoned as dry holes in the western part of the basin (Figure 1).

The prospectivity of the basin has been evaluated in this paper in the light of global and regional tectonics and world analogs. The nature of deformation, structural patterns, distribution of source and reservoir rocks within sedimentary sequence have been identified by interpreting and integrating geophysical data, composite and wire-line logs, surface geological and tectonic maps, stratigraphic sections, lithofacies distribution, geochemical results and other relevant data concerning the basin and its surrounding areas (these are discussed through Figures 1 to 9)

The tops of Paleocene-Pliocene formations (Figures 3 and 4) are based on information from Jhal well No. 1 in the south, located outside the study area. The tops of Mesozoic formations are speculative, and inferred from surface and subsurface stratigraphic thickness around the area, thickness variation trends and tone of seismic reflectors. The top of basement has been marked on the basis of gravity data.

The following geological studies have helped in developing the concepts and conclusions of this paper:

Wadia (1957), Tainsh et al. (1959), Hunting Survey Corporation (1961), Zuberi and Dubois (1962), Rehman (1963), Bakr and Jackson (1964), Movshovitch and Malik (1965), Wellman (1966), Bishop (1968), Voskresensky et al. (1968), Rehman (1969), Abdel-Gawad (1971), Auden (1974), Farah (1976), Menke and Jacob (1976), Sylvester and Smith (1976), Nicolas et al. (1977), Shah (1977), DeJong (1978), Chaudhry (1979), Abdullah (1979), Armbruster et al. (1980), Desio (1979), Kazmi (1979), Lawrence and Yeats (1979), Powell (1979), Quittmeyer et al. (1979), Sarwar and DeJong (1979), Ahmed and Abbas (1979), Asrarullah et al. (1979), Bordet (1980), Boulin (1980), Gupta and Singh (1980), Lawrence et al. (1980), Jackson (1980), Klemme (1980), Lawrence et al. (1981a), Kazmi and Rana (1982), Kemal et al. (1982), Abid and Siddiqi (1982), Biswas (1982), Ahmed and Ashten (1982), Balli (1983), Ali and Ahmed (1985), Ali (1985), Khan and Raza (1986), Khan et al. (1986), Bank and Warburton (1986), Seemann et al. (1988), Soulsby and Kemal (1988), Ahmed et al. (1988), Malik et al. (1988), Bannert et al. (1989), Raza et al. (1989-91), Hiller and Ahmed (1990), Lowell (1990), Humayon et al. (1990), Iqbal (1990), Shafique and Daniels (1990), Ali et al. (1991), Ahmad and Ali (1991), Ahmed and Ahmad (1991), Jadoon (1991), Hildebrand et al. (1991).

STRATIGRAPHY

The rocks exposed in the basin range in age from Eocene to Recent. The subsurface stratigraphic information from drilling is limited as the two wells drilled in the area were abandoned in Siwalik sequence. However, our geological investigations indicate that subsurface sedimentary patterns of Mesozoic-Cenozoic succession would be the same as that of northern Kirthar and western Sulaiman fold belts, and Kirthar depression which bound the Sibi basin (Figure 1). The generalised stratigraphy is shown in Figure 2. The sedimentation, which took place as a response to

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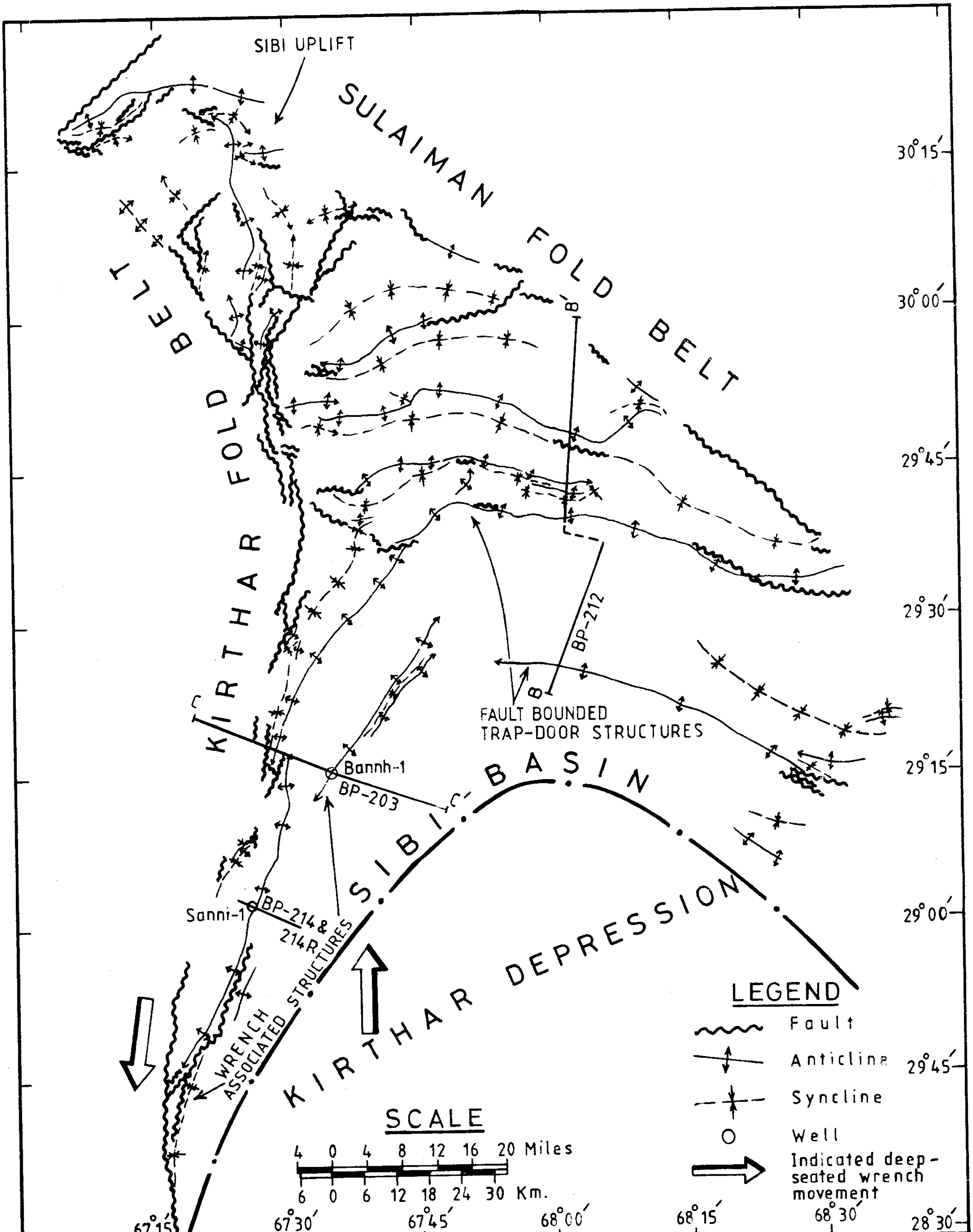

Figure 1— Structural and tectonic map of Sibi basin showing left-lateral en echelon folds in the west and right angle-obtuse angle-acute-angle fold geometry towards north and northwest and fault bounded triangular shaped synclinal features in the northwestern corner. The former are associated with wrench tectonics (Figures 3 and 5) while the latter indicate compression related trap-door structures in the subsurface (Figures 4, 6-9).

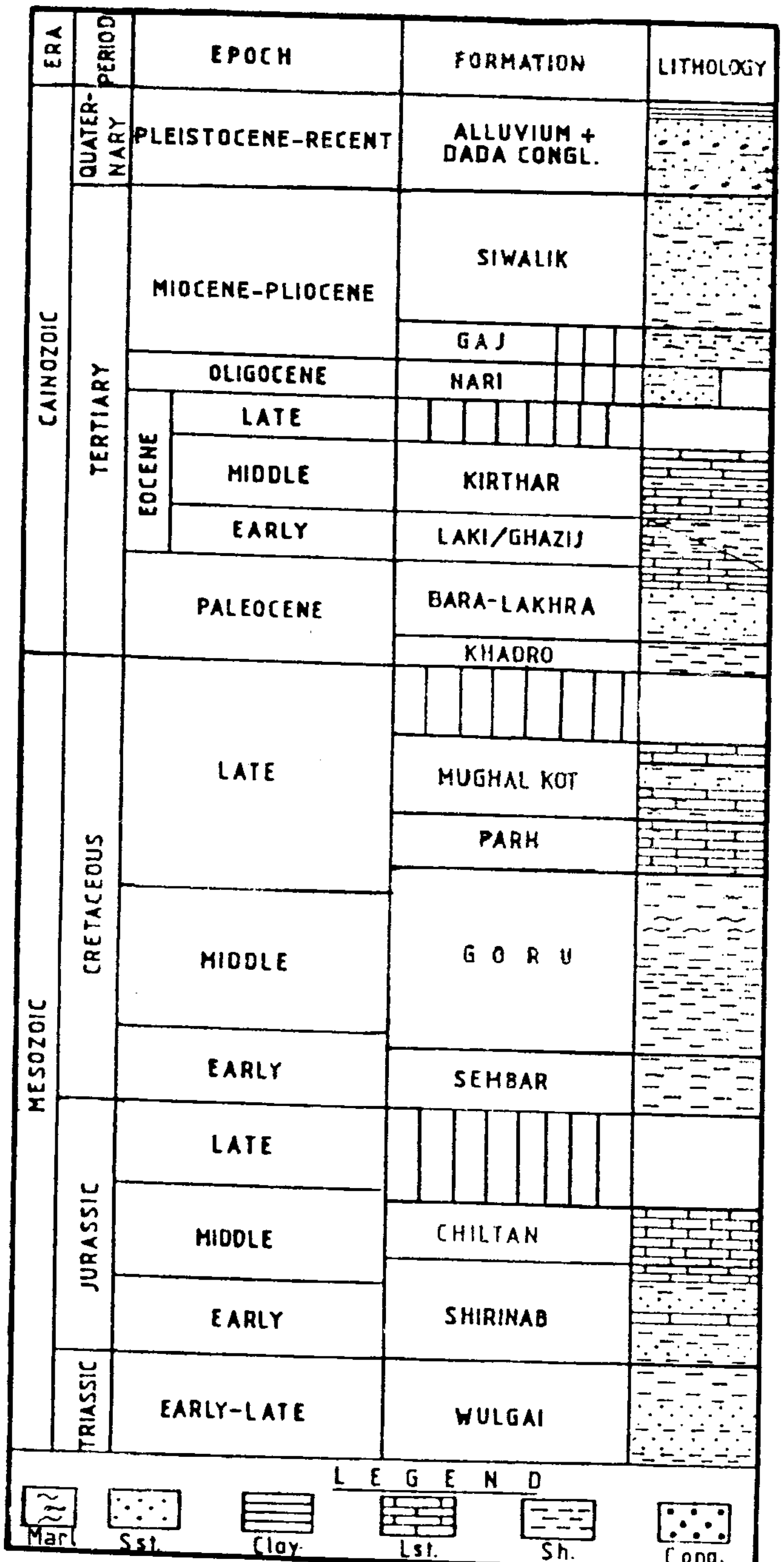

Figure 2— Generalized stratigraphic column of the study area.

regional tectonic events, is marked by a number of unconformities in the study area. The brief description of the stratigraphy is as under.

Mesozoic

The oldest rocks known so far through drilling and outcrops in the surrounding areas of the basin belong to Wulgai Formation (shale and sandstone) of Triassic age. It is succeeded in ascending order by Shirinab Formation (shale and sandstone with rare amount of limestone) and Chiltan Formation (limestone) of Early-Middle Jurassic age. The Chiltan Formation is unconformably overlain by Sembar Formation (shale) of Early Cretaceous age followed by Goru Formation (shale and marl), Parh Limestone and Mughal Kot Formation (limestone, shale and rare amount of sandstone) of Early-Late Cretaceous age. Pab Formation of Late Cretaceous age is probably absent in the area.

Tertiary

Tertiary sequence which unconformably overlies the Cretaceous rocks comprises Khadro Formation (basalt ? and shale), Bara Formation (sandstone and shale) and Lakhra Formation (limestone and shale) of Paleocene age conformably overlain by a dominantly carbonate sequence of Early-Middle Eocene age which is represented by Laki Formation (limestone and shale), Ghazij Formation (shale) and Kirthar Formation (limestone and subordinate shale). The Kirthar Formation is unconformably overlain by Nari-Gaj Formation (clastics) of Oligocene-Early Miocene age followed by continental molasse sequence of sandstone and shale/clay (Siwalik Group) of Miocene-Pliocene age which is overlain by fluviatile deposit of Pleistocene-Recent age.

TECTONIC CONSIDERATIONS, STRUCTURAL STYLES AND HYDROCARBON PROSPECTS

Sibi re-entrant (Movshovitch and Malik, 1965), Sibi Molasse trough (Banks and Warburton, 1986) and Sibi depression (Raza et al., 1986) is a triangular shaped foreland basin bounded in the west by left-lateral strike-slip fault zone of Kirthar fold belt (Ali et al., 1991, Ahmed and Ali., 1991), and in north by a compression-related thrust (Ali et al., 1991). Towards south it is succeeded by Kirthar depression (Figure 1). Total thickness of Mesozoic-Recent sediments is considered to be exceeding 15,000 metres in the deepest part of the basin (Figure 4), out of this more than 7,000 metres of Miocene-Pliocene sediments have been accumulated in the depression (Figure 3) as a result of erosion from Kirthar and Sulaiman fold belts (Movshovitch and Malik, 1965; Banks and Warburton, 1986; Ali et al., 1991). The basin is covered predominantly with Siwaliks and alluvium deposits with some outcrops of Eocene age in the east, north and northwest. Its northern part is more elevated than the southern part (Hunting Survey Corporation, 1961; Raza et al., 1989). The surface anticlines

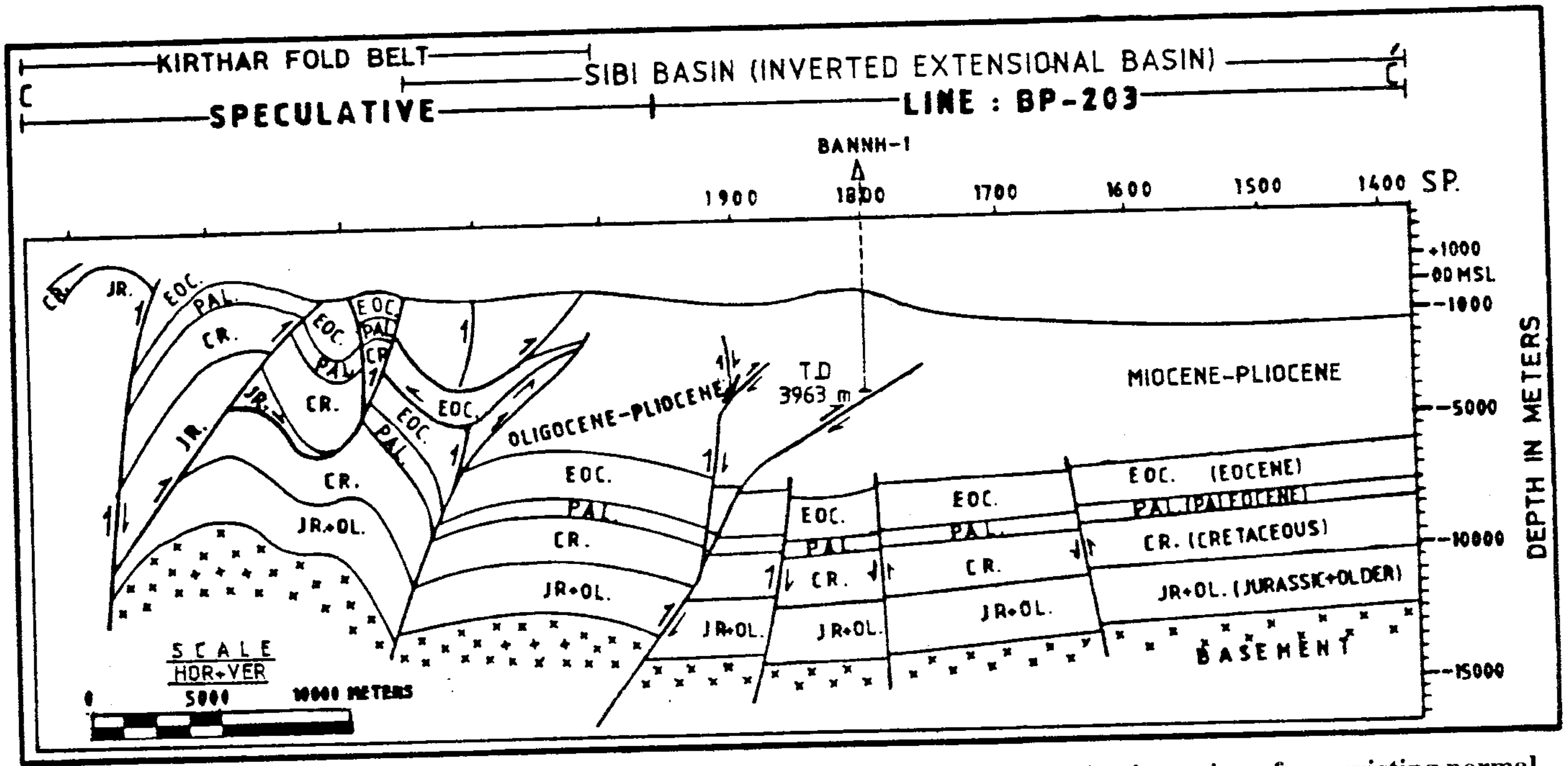

Figure 3— Structural cross-section CC′ across Bannh well No.1 in Sibi basin showing inversion of pre-existing normal faults of Mesozoic rift to high angle reverse fault due to compression, affecting the Cenozoic sediments also (modified after Ali et al., 1991). For location see Figure 1.

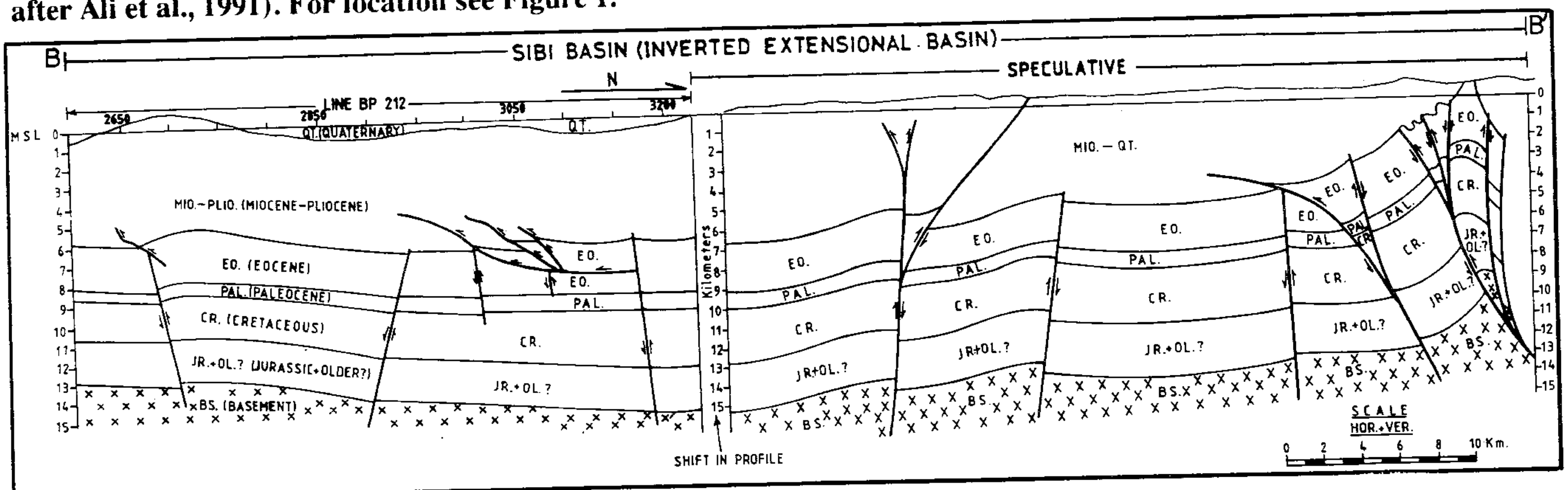

Figure 4— Structural cross-section BB′ in Sibi basin, showing compression related inversion and decollement. The upthrust faults are believed to be associated with fault bounded trap-door structures. (after Ali et al., 1991). For analog see Figure 8, for location see Figure 1.

are mainly formed in Siwalik sequence and are narrow and asymmetric.

Variable fold and fault trends on the surface are the distinct geological features of this foreland basin (Figure 1) which have provided basis for identifying different structural regimes and interpreting and predicting the subsurface structural patterns in the area.

Banks and Warburton (1986) have proposed a passive roof duplex system of deformation in western Sulaiman and northern Kirthar fold belts through cross-sections. These lines have been extended into Sibi basin in which a decollement level is marked in Eocene strata with undisturbed underlying rest of Cenozoic and Mesozoic sediments. According to Ali et al. (1991) and Ahmed and Ali (1991) the Sibi basin is an inverted extensional basin in which the pre-existing normal faults of Mesozoic rift were reactivated during Oligocene-Early Miocene time and inverted to high angle reverse faults due to the combined effect of compression from (1) Sulaiman thrust and fold belt in the north and east and (2) left-lateral transform movement in the west in Kirthar fold belt. The inversion has also affected the Cenozoic section (Figures 3-5).

Further studies by Ali et al. (1991) indicate that the compression related inversion has produced distinct structural expressions on surface and in the subsurface. On surface these expressions are marked as variable fault and fold patterns ranging from left-lateral en echelon folds in the west to right angle-acute angle-obtuse angle fold

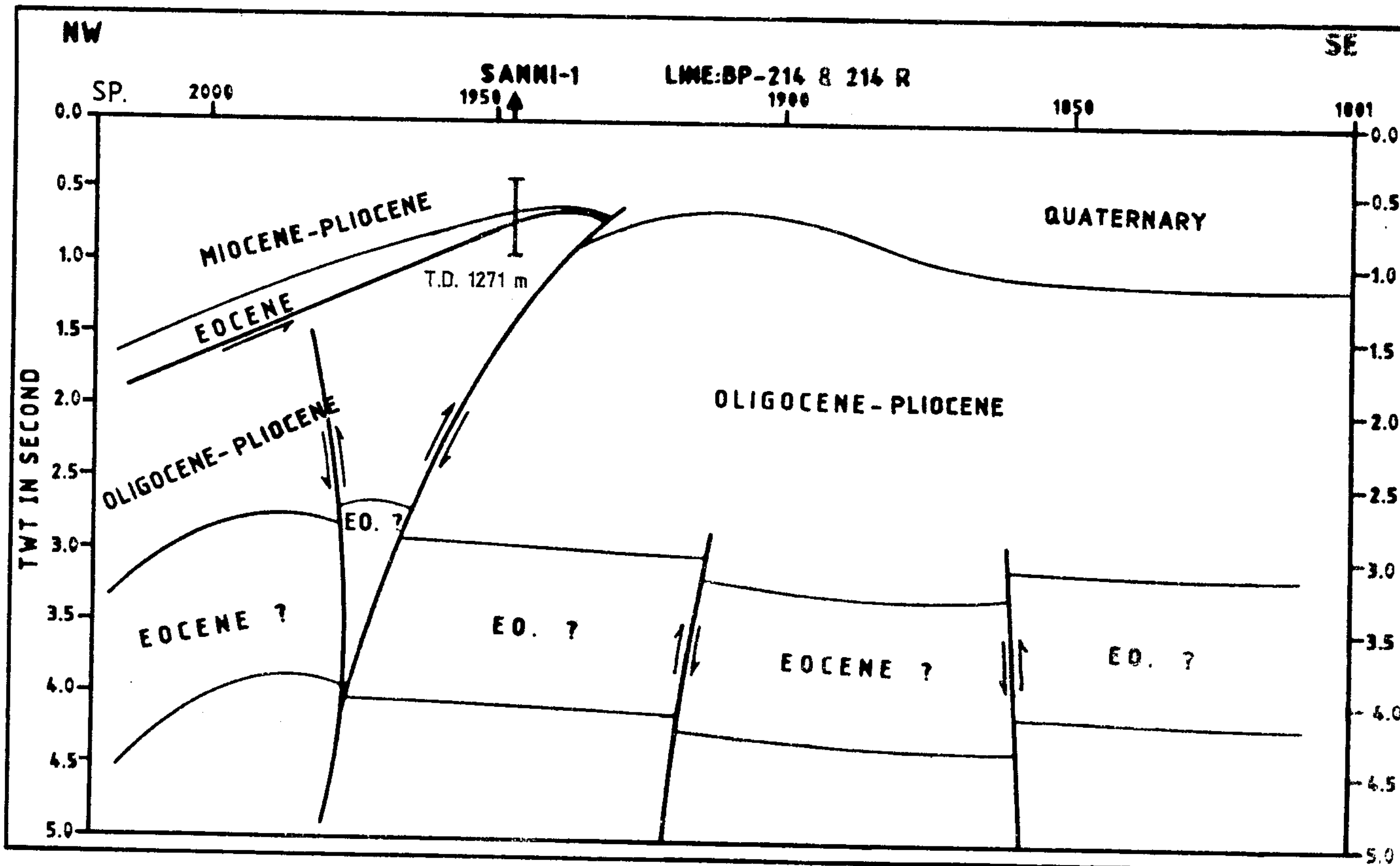

Figure 5— Impression of seismic section BP-214 & 214-R (Brute Stack) across Sanni well No. 1 in Sibi basin. The well was abandoned in Miocene-Pliocene sediments (Siwaliks) after drilling through Eocene strata implaced by decollement. The line also shows inversion of Mesozoic rift features. The inversion of normal faults to high angle reverse faults and decollement features are the result of left-lateral convergent wrench movement in the west (Kirthar fold belt) and compression generated by Sulaiman fold belt in the north and east (after Ali et al., 1991). For location see Figure 1.

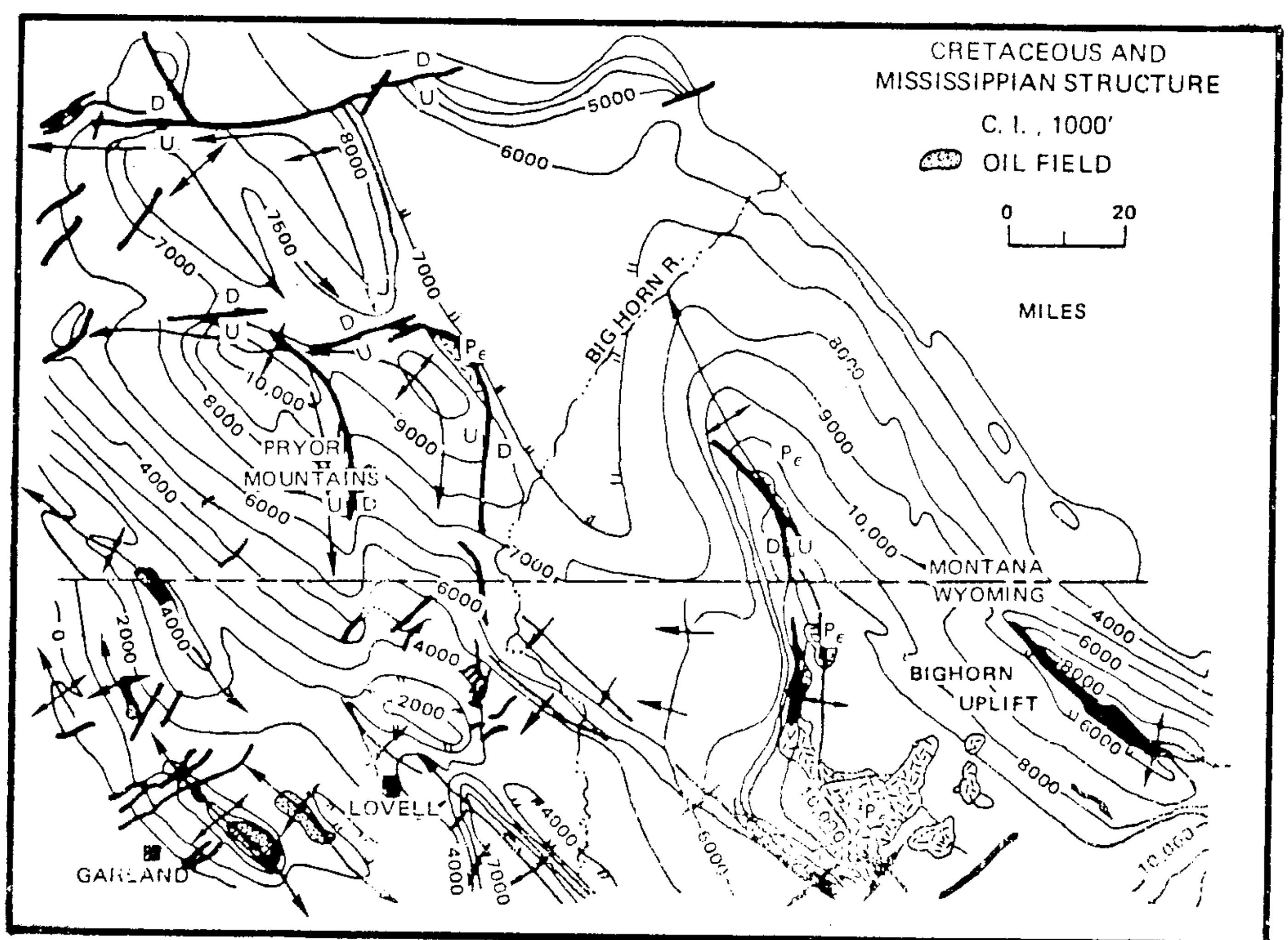

Figure 6— Structure at northeast corner of Big Horn basin, Wyoming, demonstrates three dominant trend orientations of general Wyoming foreland province. Fold axes parallel dominant block-bounding faults where latter are exposed at surface or are demonstrated by seismic (not shown). Similar faults may be inferred in structures lacking this control on basis of constant fold-fault relations observed elsewhere (after Pierce et al., 1947, Dobbin and Erdman, 1955., Darton, 1906, in Lowell, 1990). Similar type of structural patterns can be seen towards north and northwest in Sibi basin, Pakistan (Figure 1).

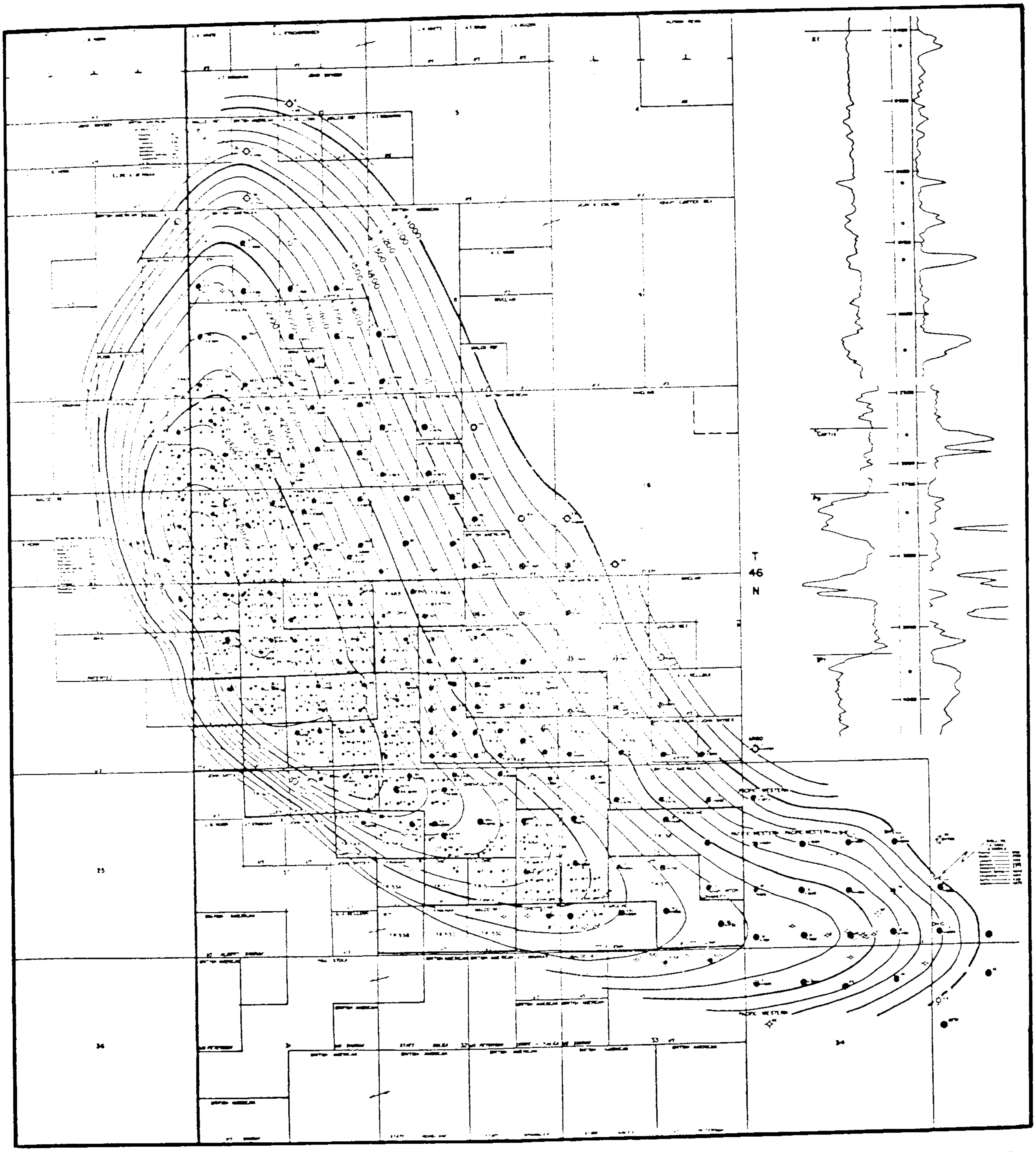

Figure 7— (Wyoming Geological Association, 1957)-Grass Creek field, Big Horn Basin, Note WNW and NNW trends (dog-leg) shown by close spacing of contours on steep (SW) side of structure which is fault controlled at depth. Note that production is established farther down the gentle (NE) flank than the steep flank because of hydrodynamic flow from the SW. Most Rocky Mountain foreland basement structures have reservoir porosity and permeability increased by fractures (after Lowell, 1990). Such type of structures are expected in the subsurface in north and northwest in Sibi Basin.

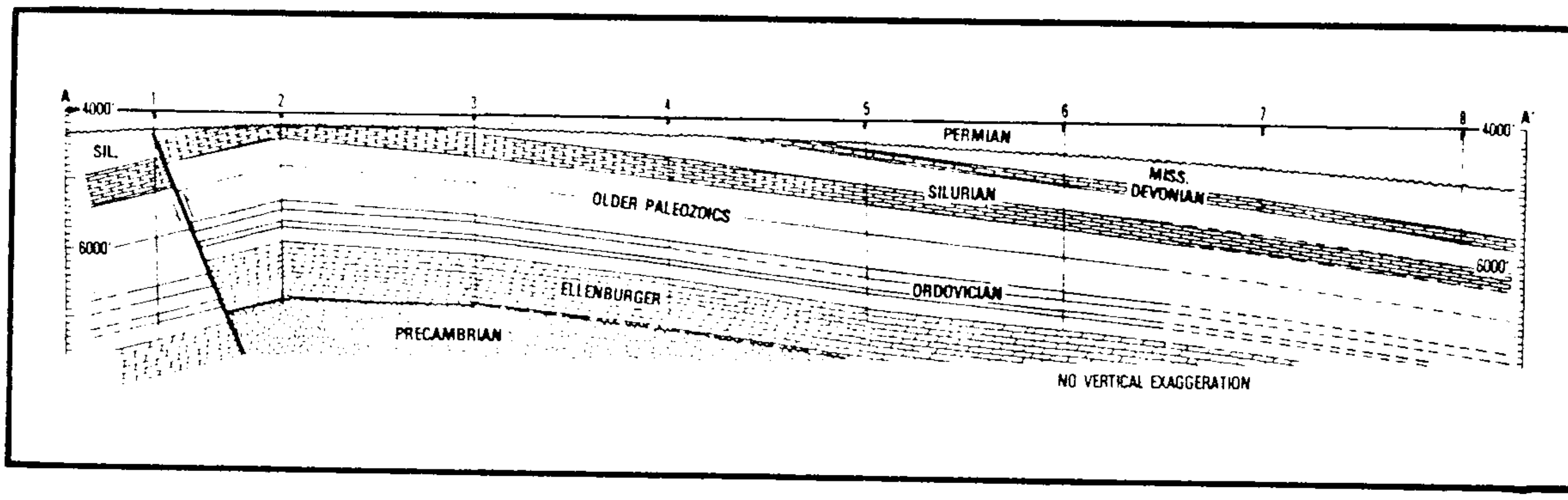

Figure 8— Cross-section AA′ across Keystone field, Permian basin,Texas (Figure 9). Steep dip of fault at top of basement in sedimentary cover which is associated with trap-door structure, indicated by well control. Seismic and subsurface control demonstrates similar steep faults at these levels elsewhere in the basin (Elam, 1969 in Lowell, 1990). Similar type of compression related structural pattern can be seen on cross-section BB′ in Sibi basin (Figure 4).

geometry toward north and northwest with small scale transform faults and fault bounded triangular shaped synclinal features in the northwestern corner which we may call "Sibi Uplift" (Figure 1).

Toward north, in the subsurface, compression related basement- involved reverse fault patterns (upthrust) and minor scale decollement features in Eocene strata are interpreted from seismic line BP-212 and are shown in structural cross-section BB′ (Figure 4). The northern part of the structural cross-section BB′ is speculative and based on southward structural pattern on seismic line BP-212, gravity information, surface geological expressions and thickness of Miocene-Quaternary sediments which decreases to the north. According to our opinion the upthrust fault patterns from seismic section BP-212 and the speculative part on cross-section BB′ are probably associated with fault bounded trap-door structures (for analog see Figure 8) and the upthrust Eocene outcrop marks the northern extent of Sibi basin. This outcrop is a narrow northwest-southeast elongated feature represented as "Spintangi limestone" of Eocene age on geological map No. 25 and 26 (Hunting Survey Corporation, 1961). Since no seismic information is available toward northwest, according to our opinion based on seismic information on line BP-212 and analogs, the variable faults and fold patterns on surface probably represent fault bounded trap-door structures in the sub-surface which may range from right angle-acute angle-obtuse angle in aerial extent. Big Horn basin of Wyoming and Permian basin of Texas are the prime examples of such type of structural patterns (Figures 1, 4, 6 to 9). In the west, compression related, wrench associated, basement involved inverted structural patterns and decollement features are shown in the subsurface on cross-section CC′ and impression of seismic line BP-214 & 214R (Figures 3 and 5).

The geochemical studies conducted by Hydrocarbon Development Institute of Pakistan (HDIP) and Bundesanstalt fur Geowissenschaften und Rohstoffe (BGR), Hannover, Germany, in Kirthar and Sulaiman fold belts show good source rock potential of the Mesozoic-Eocene section for generation of hydrocarbons (Raza et al., 1989, and 1990). Probable reservoir carbonate facies of Jurassic-Eocene age and Paleocene sandstones are expected in the area. Sand facies of Goru Formation which is a producing horizon in the south in Badin area and Sukkur rift zone (Ali, 1985; Raza et al., 1990; Ahmed and Ahmad, 1991) is not developed in the basin. Pab sandstone is also believed to be missing due to non-deposition as a result of Mesozoic rift events.

The basin witnessed little exploration activity, only two wells Bannh-1 and Sanni-1 were drilled and abandoned at 3,963 and 1,271 metres depth respectively in Siwaliks (continental molasse) in wrench associated structural zone in the west. Generally, the Siwalik sequence is considered non-productive in terms of hydrocarbons. In wrench associated zone the prospective target may lie in the west at drillable depth in Paleocene-Eocene carbonate and Paleocene sandstone reservoirs which may be associated with subthrust and upthrust structures, subthrust bed termination and positive flower structures (Figures 1, 3 and 5).

Toward north and northwest, the prospects are expected to be associated with fault bounded trap-door structures, in Jurassic- Eocene carbonates and Paleocene sandstone reservoirs at shallow depths.

Keystone field of the Permian basin of foreland of the Marathon thrust-fold belt in west Texas (Figure 9) and Grass Creek field in the Big Horn basin (Figure 7) are the producing examples of compressive block style with trap-door configurations. Los Angeles basin is a producing example of traps associated with wrenching (Lowell, 1990).

CONCLUSIONS

In the study area two different compression-related structural regimes with variable structural patterns have

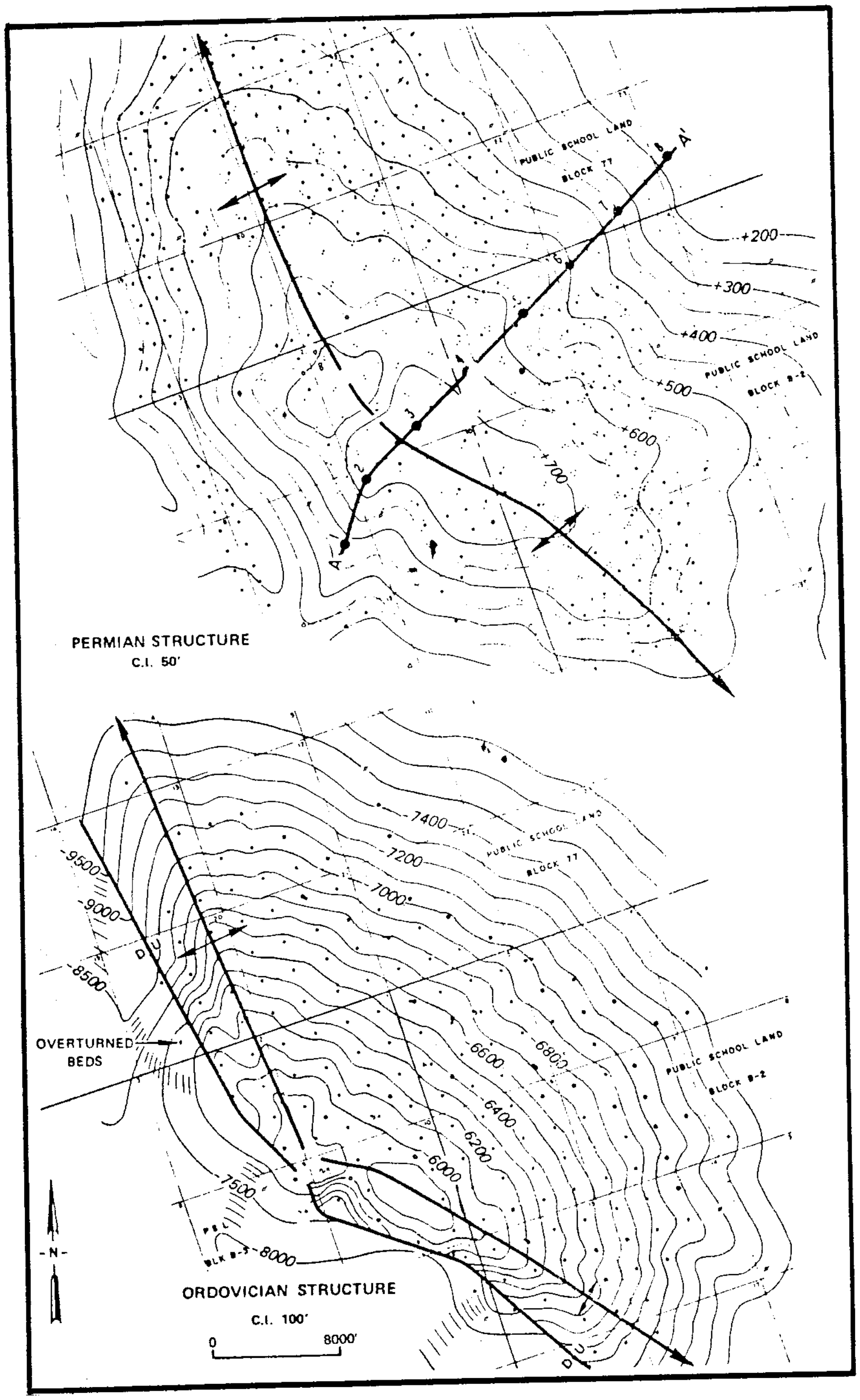

Figure 9— Structure at Keystone field, west edge of central basin platform, Permian basin, Texas (Osborne, 1957), shallow flexure (Permian, upper diagram) reflects drape over buried Ordovician trap-door block (lower) and has characteristic culmination opposite obtuse-angle junction of bounding faults. Other angles of fault junctions in area range from obtuse to acute. Trap-door flexures associated with latter appear as triangular faulted domes (after Lowell, 1990). The structural pattern shown in the upper diagram and fault bounded triangular shaped synclinal features can be seen in the north and northwestern side of the Sibi basin (Figure 1). Fault bounded trap-door structures shown in the lower part are expected in the subsurface towards north and north west in the study area at Mesozoic-Eocene level (Figure 4).

been identified. These are: (1) Wrench associated flower structures, subthrust bed termination, upthrust and subthrust structures in the western part and (2) Fault bounded trap-door structures of right angle- acute angle-obtuse-angle aerial extent in the north and northwest at drillable target depths within Mesozoic to Cenozoic sediments. These types of structural traps have often produced oil and gas in several sedimentary basins of the world.

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