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Tectonic and Structural Development of the Eastern Part of Kirthar Fold Belt and its Hydrocarbon Prospects

Riaz Ahmed[1] and S. Manshoor Ali[1]

ABSTRACT

Some anticlinal structures located on the eastern side of the Kirthar fold belt in Kirthar sub-basin have been evaluated for hydrocarbon prospects in the framework of regional tectonics.

The study indicates the presence of adequate source, reservoir and cap rocks within Mesozoic-Tertiary sedimentary section in the area. The structural traps under review were formed in a tectonic setting associated with left lateral convergent and divergent wrenching and foreland dipping thrust with left-lateral strike-slip component, such traps in other areas of the world have produced hydrocarbons in commercial quantities. Therefore, the area deserves another round of exploration with revised targets and in the background of this new concept of structuring.

INTRODUCTION

The study area is located on the eastern part of the Kirthar fold belt between latitude 25° and 30° north (Figure 1).

Out of the nine anticlines described in this paper, six have been drilled. One gas discovery and a number of oil and gas shows have been found in the drilled structures. Additionally, some surface seepages are also reported.

The factors considered favourable for hydrocarbon accumulation in these drilled and undrilled structures have been discussed in the background of tectonic and structural development highlighted through a cross section, structural maps and analogs. The source rock potential of the area is based on the geochemical data generated by Hydrocarbon Development Institute of Pakistan (HDIP) and Bundesanstalt für Geowissenschaften und Rohstoffe (BGR). The geological and structural maps used in this study are based on information by Hunting Survey Corporation, 1961. Most of the structural and stratigraphic interpretation is based on personal observations of the authors. However, the geological research/studies of the following workers also directly or indirectly helped in creating the present paper: (1) Williams (1959), (2)

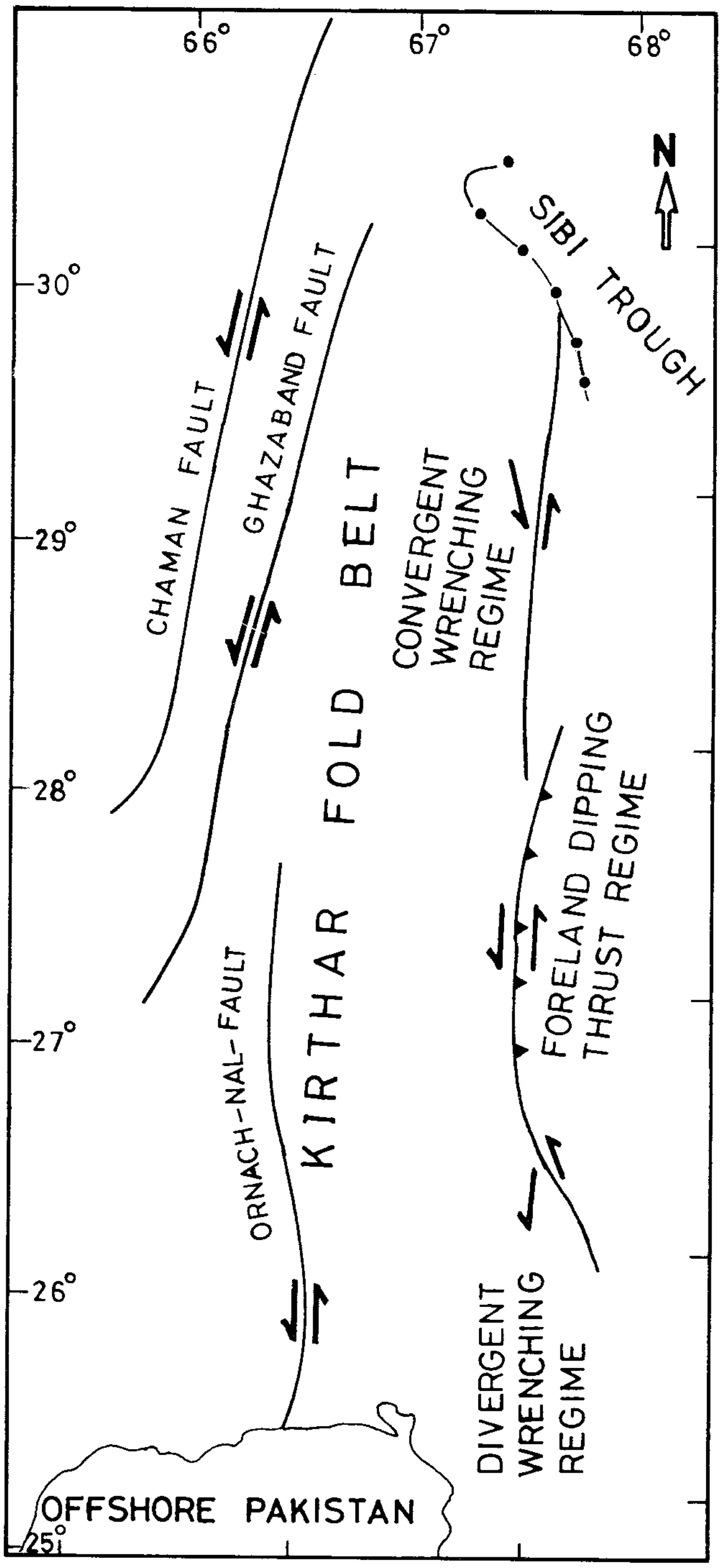

Figure 1— Generalized tectonic map of Kirthar fold belt with main structural regimes in the eastern part.

[1] Hydrocarbon Development Institute of Pakistan, Islamabad.

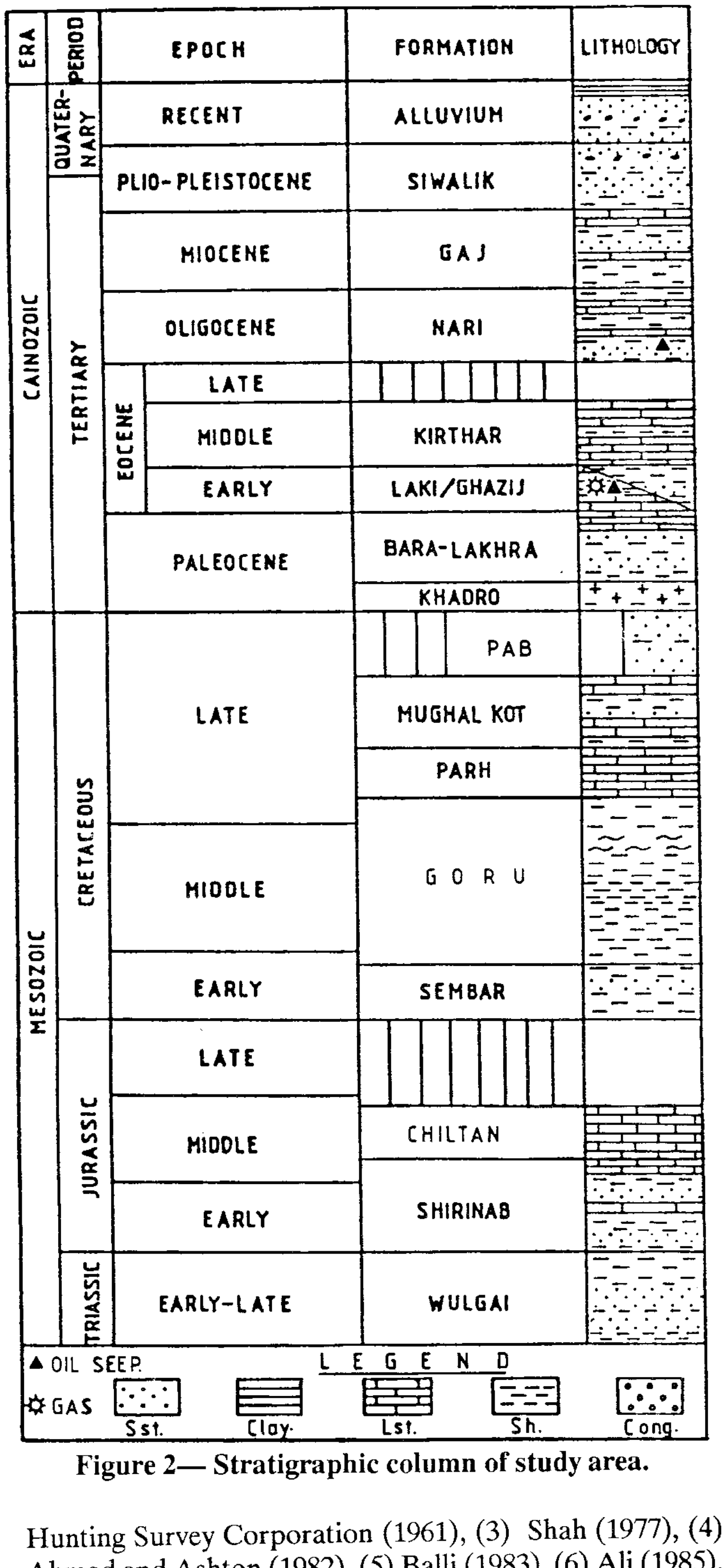

Figure 2— Stratigraphic column of study area.

Hunting Survey Corporation (1961), (3) Shah (1977), (4) Ahmed and Ashton (1982), (5) Balli (1983), (6) Ali (1985), (7) Khan and Raza (1986), (8) Seemann et al (1988), (9) Ahmed et al (1988), (10) Raza et al (1989), (11) Raza et al (1990) and (12) Lowell (1990).

STRATIGRAPHY

The sedimentary rocks exposed/drilled in the area under discussion range in age from Mesozoic to Recent and were deposited over drifting edge of the Indian plate. The stratigraphy is shown in Figure 2. The sedimentation which took place in a marginal sag basin is punctured by unconformities and small sedimentary gaps and is characterised by frequent facies changes.

Mesozoic

Wulgai Formation (shale and sandstone) of Triassic age and Shirinab Formation (shale and sandstone with rare limestone) and Chiltan Formation (limestone) of Jurassic age are overlain in an upward direction, by Sembar Formation (shales), Goru Formation (shale and marl), Parh Formation (limestone), Mughal Kot Formation (limestone, shale and minor sand) and Pab Sandstone (sandstone). Local unconformities absenting some Cretaceous formations are also noted.

Tertiary

Khadro Formation (basalt and shale), Bara Formation (sandstone and shale) and Lakhra Formation (limestone and shale) form the Paleocene succession. Eocene is represented by limestone dominated sequence comprising Laki Formation (limestone and shale), Ghazij Formation (shales), Kirthar Formation (limestone and subordinate shale). Oligocene-Miocene sequence comprises Nari Formation (shale, limestone and sandstone) and Gaj Formation (shale, sandstone and limestone). Post-Miocene section is mainly continental and contains fluviatile clastics overlain by alluvium. An unconformity between Miocene and Eocene is noted in the northern part of the area.

TECTONIC SETTING AND STRUCTURING

A number of anticlinal structures were created on the eastern side of the Kirthar fold belt as a consequence of left lateral transform movement from west along Ornach-Nal-Chamman fault to the eastern part of the Kirthar fold belt resulting from plate collision during Oligocene-Miocene time. An active plate boundary is located near the western slope of the fold belt as expressed by the seismic activity and occurrence of ophiolites (mafic and ultramafic rocks). Left lateral convergent wrench features in the north and left lateral divergent wrenching in the south of the study area have been observed . A probable foreland dipping thrust regime with left-lateral strike-slip component has been noted between the two afore mentioned regimes which needs further investigation (Figures 1, 3-10).

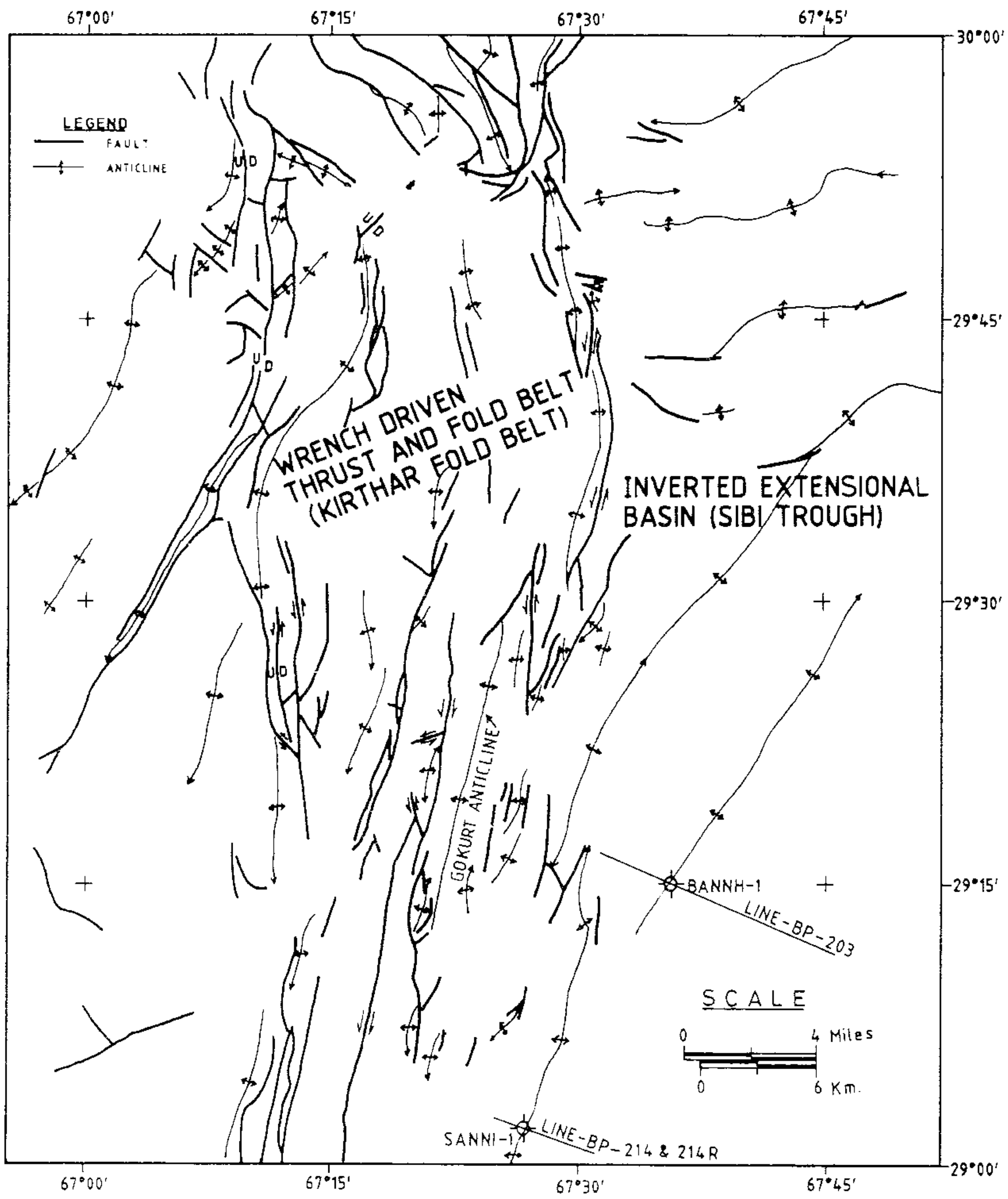

Figure 3— Convergent left lateral wrench movement in the eastern part of Kirthar fold belt.

Table 1. Potential source rocks identified in Badin and Kirthar fold belt (after Seemann et al, 1987).

Area	Formation	Age	TOC %	VR %
Kirthar Range	Kirthar	M.Eocene	0.42-9.75	0.71-1.44
"	Ghazij	E.Eocene	0.32-6.89	0.65-1.70
"	Lakhra	L.Paleocene	0.14-1.19	1.01-1.32
"	Pab	L.Cretaceous	1.57-1.72	1.07-1.09
"	Mughal Kot	L.Cretaceous	0.07-3.48	1.13-2.06
Badin	Sembar	E.Cretaceous	>3	---

Note:- 0.5% TOC and 1.2 % VR are the minimum qualifications for source rocks with hydrocarbon generating potential.

Based on seismic, gravity and surface geological expressions, an east-west geological cross-section has been constructed to study the tectonic evolution and sub-surface structural style of northern part of the area (Figure 11). The area east of the fold belt (Sibi trough) is interpreted as an Intverted Extensional Basin, in which the pre-existing normal faults of Mesozoic rifting were reactivated and inverted to high angle reverse faults due to compression related to left lateral wrench movement in the west and compression from westward prograding Sulaiman thrust and fold belt in the east affecting the Cenozoic and younger section. An analog is given in Figure 12. The wrench-related compression has also developed decollement features within Eocene sediments. PPL's Bannh-1 well was drilled on an anticlinal structure upto 3962.7 meters in Siwaliks. According to our interpretation the thickness of Siwaliks is more than 7000 meters in this area and Eocene targets which are bounded by reverse faults are located deeper than anticipated during drilling of the well (Figures 3, 11 and 13).

The tectonic evolution of the western side of Sibi trough and eastern part of the fold belt is speculative as it is based on inferred seismic and surface geological expressions (Figures 3, 11, 13 and 14).

Towards north, the eastern side of the fold belt is marked by left lateral olique convergent wrenching which developed mumerous en echelon folds and anticlinal welts bounded by faults of up-thrust profile probably caused by sigmoidal-shaped folded faults (Figures 3-5,11,13 and 15). Some examples of convergent wrenching are: Tertiary orogenic belt of Spitsbergen, part of Alborz Mountains in Iran, Portion of Andes in Venezuela and Colombia, and the Caucasus and Dnepr-Doxetz in the USSR (Lowell, 1990). En echelon anticlines, subthrust bed termination, subthrust structures and positive flower structures can serve as excellent traps for hydrocarbon accummulation in this type of setting.

Divergent features caused by left lateral divergent wrenching have been observed in the southern part of the study area (Figures 1, 6-8). Traps associated with en echelon normal fault blocks and negative flower structures are the potential targets for hydrocarbon exploration in such type of tectonic environments (Figures 16 and 17).

The anticlines in the study area are narrow, strongly elongated, often doubly plunging. The surface closure ranges from 300 to 1800 m and the width to length ratios vary from 1:3 to about 1:10.

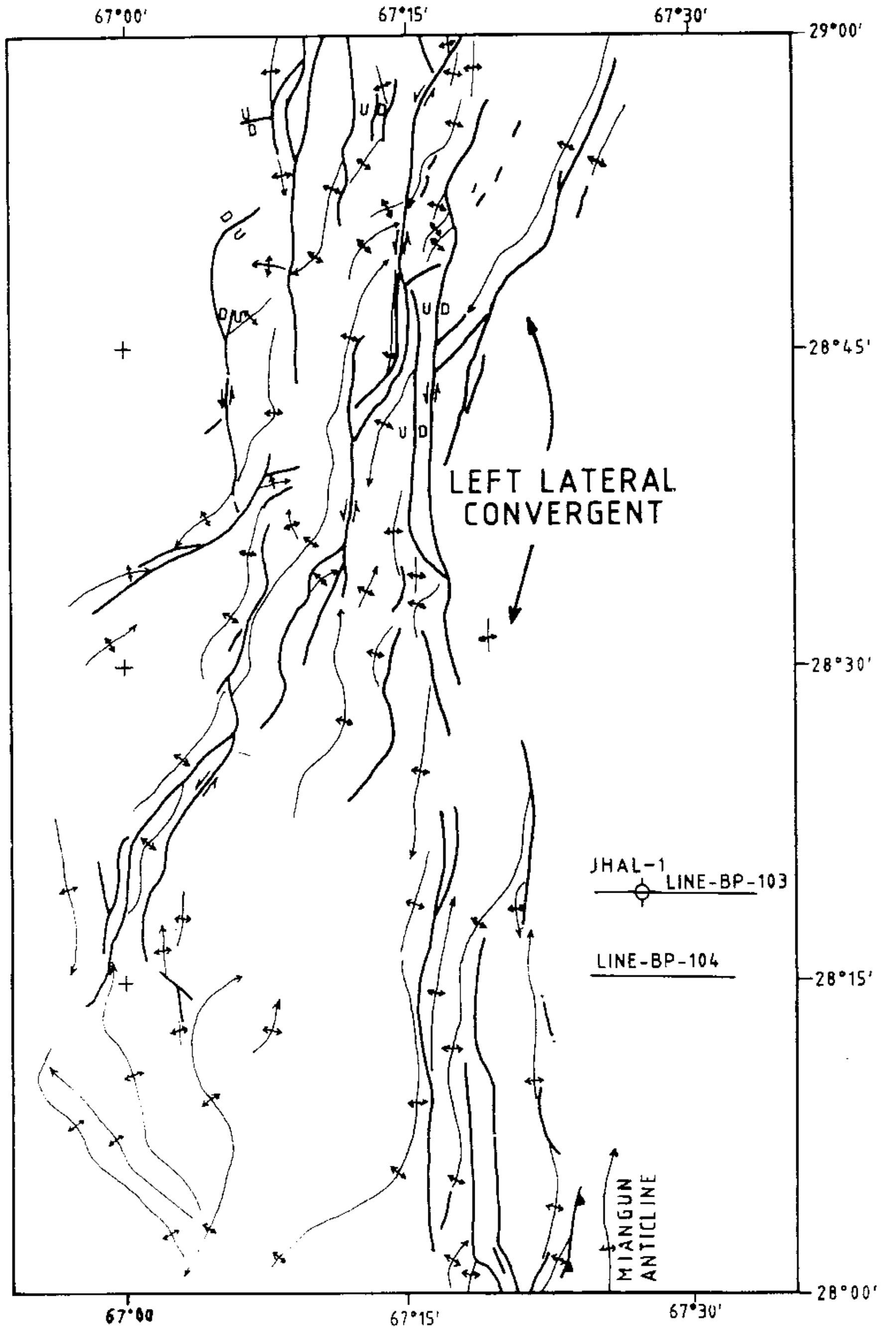

Figure 4— Convergent left lateral wrench movement in the eastern part of Kirthar fold belt (continuation of features from Figure 3).

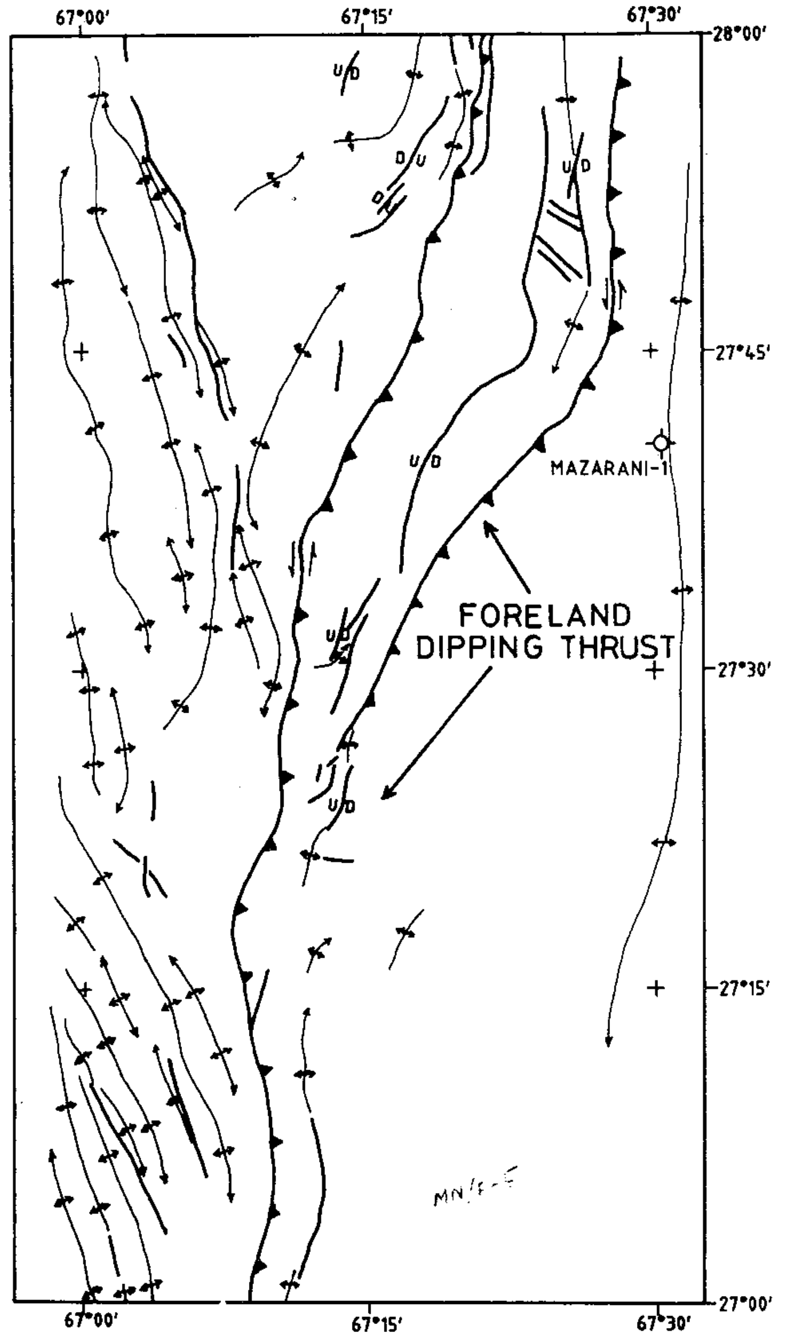

Figure 5— Convergent left lateral wrench movement in the north and left lateral foreland dipping thrust in the eastern part of Kirthar fold belt.

HYDROCARBON PROSPECTS

Source Rocks

A number of potential source rocks have been identified from the foreland in the east (Badin wells) and Kirthar fold belt (Seemann et al, 1987), and given in Table 1.

The study of geothermal gradients by Khan and Raza (1986) indicates that the geothermal gradient in the study area ranges from about 2-3°C/100m. Thus the source rocks within Paleocene-Cretaceous section fall within oil window.

Reservoir Rocks

Reefal, oolitic and pellatic carbonates in Jurassic, frequent sandy porous beds in Cretaceous and fractured, vuggy and channeled shelf carbonates in Paleocene-Eocene are the potential accumulators.

Cap Rocks

Shale beds occur above almost every potential reservoir rock mentioned earlier and form convenient cap rocks.

Traps

The traps described here are the surface anticlinal expressions of the structural regimes mentioned earlier, one of which has been illustrated through a cross section (Figure 11). It is suggested to obtain extensive seismic data for delineating many more fault-produced traps expressed only in the sub-surface.

Left Lateral Convergent Wrenching Regime

Gokurt Anticline.— It is a strongly elongated northeast-southwest oriented large anticlinal trend (Figure 3). It is recommended for testing pre-Tertiary targets in its

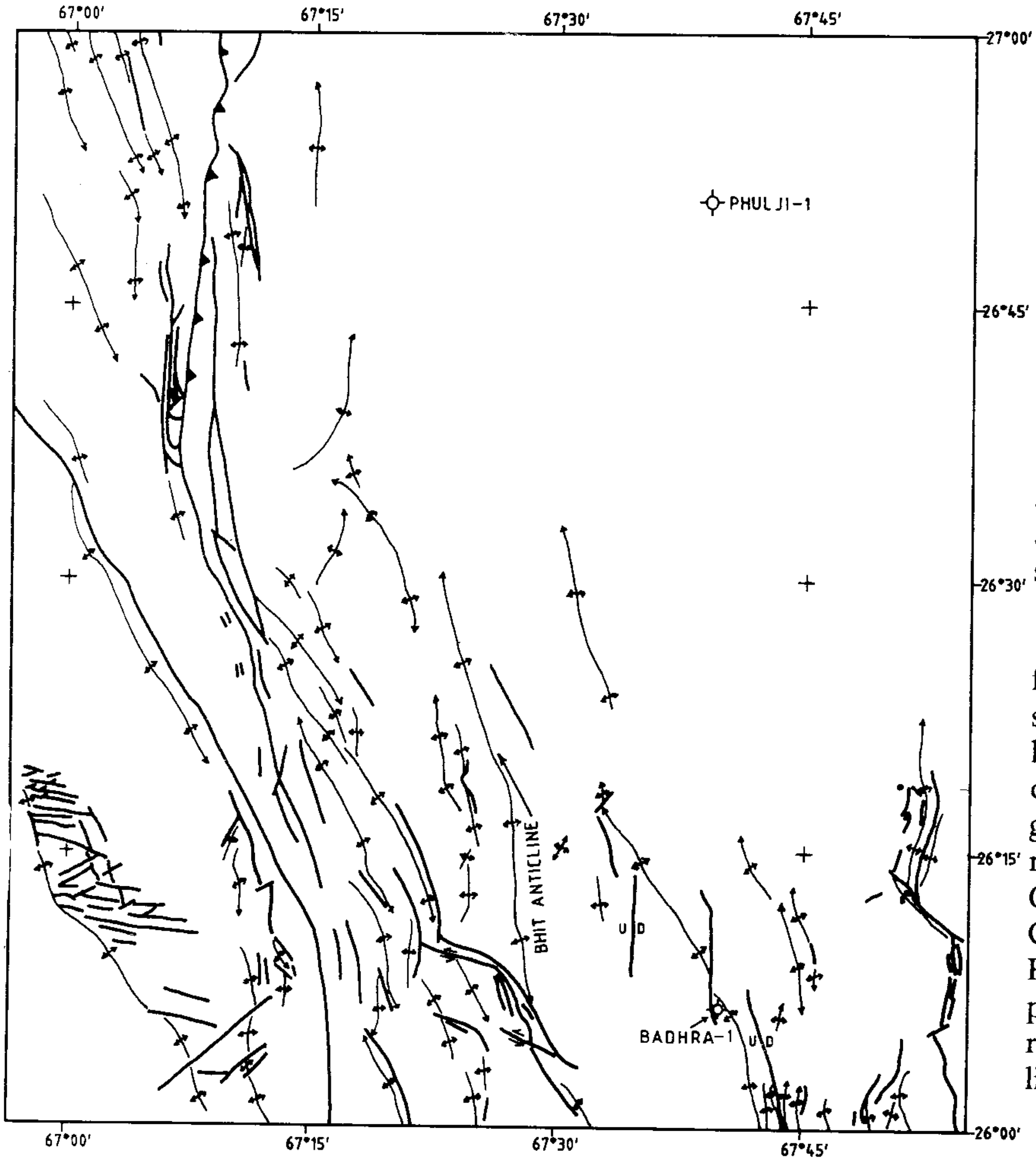

Figure 6— Left lateral foreland dipping thrust in the north and left lateral divergent trend appearing towards south of the eastern part of Kirthar fold belt.

southern part. Evidence of oil is present in the northern part of this trend in the form of an oil seep and oil and sulfur water show in a shallow old well. A fault runs parallel to its eastern flank, it curves in and cuts the northern plunge of the trend. Another fault coming from its western flank also cuts the northern part of this trend and meets the fault coming from the eastern flank.

Sanni Anticline.— The structure was drilled on a wrong location, an Eocene decollement feature was mistaken as an anticline. The well drilled Miocene, a little Eocene and entered again into Miocene sediments (Figures 3 and 14). Drillable Eocene prospects probably lie in the southwest of the Sanni area.

Left Lateral Divergent Wrenching Regime

Sunbak Anticlinal Trend.— It is an asymmetrical struture exposing Laki Limestone (E.Eocene) in the core. Pak-Hunt Sunbak no.1 was drilled in 1957 and abandoned in Paleocene at 1933 m depth. An oil and gas show was encountered in lower part of Laki Limestone but was considered non-commercial. Slight fluorescence was also noted in an interval in Ranikot. The well was abandoned in Paleocene due to its resemblance to Hunt's Sari Singh well, but later OGDC Sari Singh well proved to be a discovery. It is also interesting to note that the oil window in the well lies in 2200-4000 m depth range which indicates that the shows are sourced down in the succession. Therefore, it is recommended to consider re-drilling of the structure upto Cretaceous in the light of divergent wrench pattern. The traps associated with divergent wrenching are also expected toward west and east of the structure (Figures 7,16-17).

Lakhra Anticline.— It is a large, well formed, gently folded anticline without any significant faulting (Figure 7). The structure has been tested by five wells including two deep wells. There was a direct evidence of gas in Hunt no.1 (Lower Ranikot). Gas cut mud and salt water were noted in Hunt no.4. Gas shows were also indicated in the Cretaceous shaly section in PPL no.1 and Hunt no.1. The anticline in our opinion is a part of the left lateral divergent wrenching regime and merits further exploration in the light of this concept.

Left-Lateral Convergent-Foreland Dipping Thrust Regime

Miangun Anticline.— It is comparatively a better formed anticline oriented roughly in a north-south direction. Jhal well was drilled off- structure on the northern plunge of this anticlinal trend (Figures 4, 5 and 9). A main fault runs parallel and west of the anticline. A major syncline separates this structure from the productive Mazarani anticline on the southeast. Furthermore a gas show on the northwestern part of the Mazarani field enhances its potential. Eocene and younger rocks are exposed over this anticline, therefore Paleocene and older targets can be explored.

Thrust related to compression in the foreland area might have influenced the geometry of the fold in the subsurface (Figure 10).

Foreland Dipping Thrust Regime(?)

Mazarani Anticline.— It is a large strongly elongated, narrow anticline exposing Pliocene and younger sediments on the surface. The structure has been drilled upto

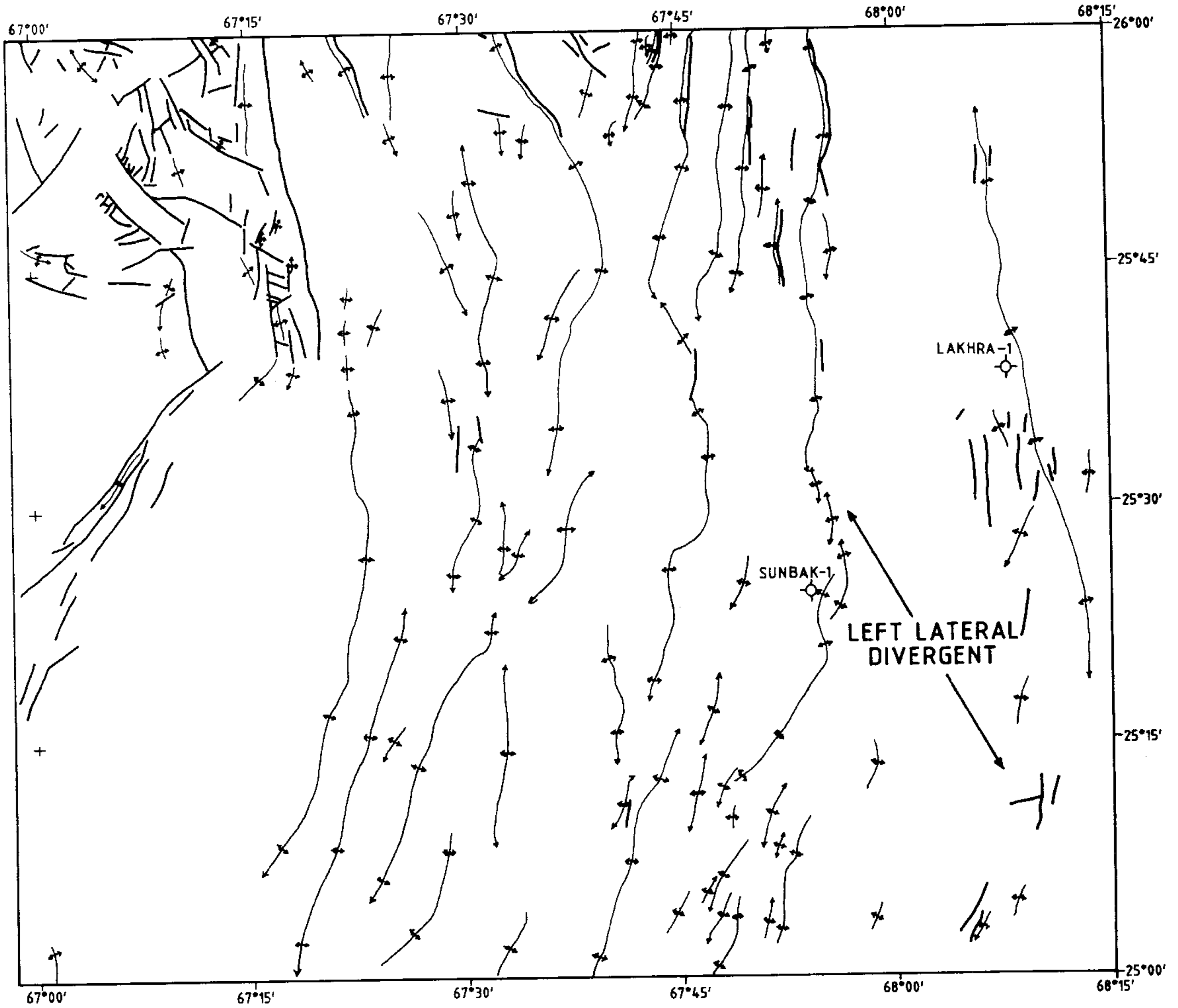

Figure 7— Left lateral divergent feature in the eastern of part of Kirthar fold belt.

Cretaceous and a gas discovery has been made from the Early Tertiary. It is recommended that some wells should also be planned on the eastern flank where possibility of discovering oil also exists (Figure 5) in view of the easterly directed hydrodynamics.

Phulji Anticline.— It is a simple north-south oriented anticline buried under alluvium, west of Indus River. It has been drilled upto Paleocene but the Paleocene-Eocene limestones have not been tested. Therefore the structure is recommended for deeper drilling based on new seismic data (Figure 6).

Foreland Dipping Thrust Regime-Left-Lateral Divergent Regime

Bhit Anticline.— It is a well formed anticline oriented in a northwest- southeast direction (Figure 6). Middle Eocene and younger rocks are exposed over the structure, therefore, E.Eocene-Paleocene and older targets can easily be tested in this nearly symmetrical anticline.

Badhra Anticline.— It is one of the principal structure of the area. the anticline is well formed, gentle and broad. The anticline trends in northwest-southeast direction (Figure 6). All the objectives are well protected by development of more than 150 m thick shale facies in upper part of the Laki Formation. Only one well was drilled (1333.46m, Paleocene) but Paleocene-Eocene objectives were not tested. The structure merits re-evaluation. A well upto Jurassic can be an interesting proposition, especailly in view of the deeper location of the oil window due to low geothermal gradient.

CONCLUSION

Three main structural regimes namely, left lateral convergent wrenching, left lateral divergent wrenching and foreland dipping thrust have been recognized within the study area.

Using world analogs the above-mentioned structural regimes are considered prospective not only in terms of the known surface anticlines but also for additional sub-surface fault- produced structural traps which can be located through detailed seismics.

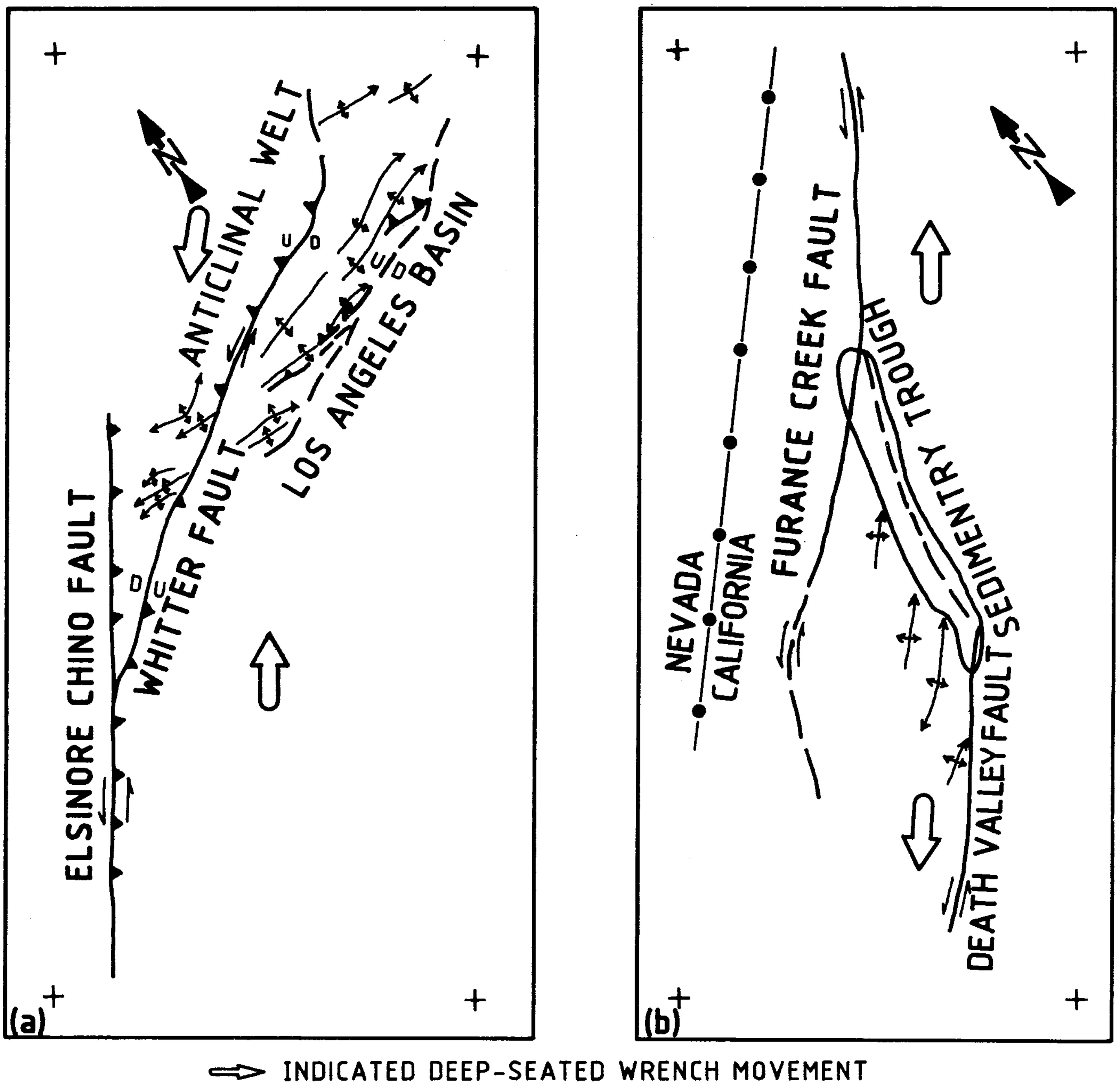

Figure 8— Inverted impression of Los Angeles and California showing left lateral (a) convergent and (b) divergent wrench examples (Harding, 1974b, *in* Lowell, 1990), similar features can be seen in Figures 1, 3-7.

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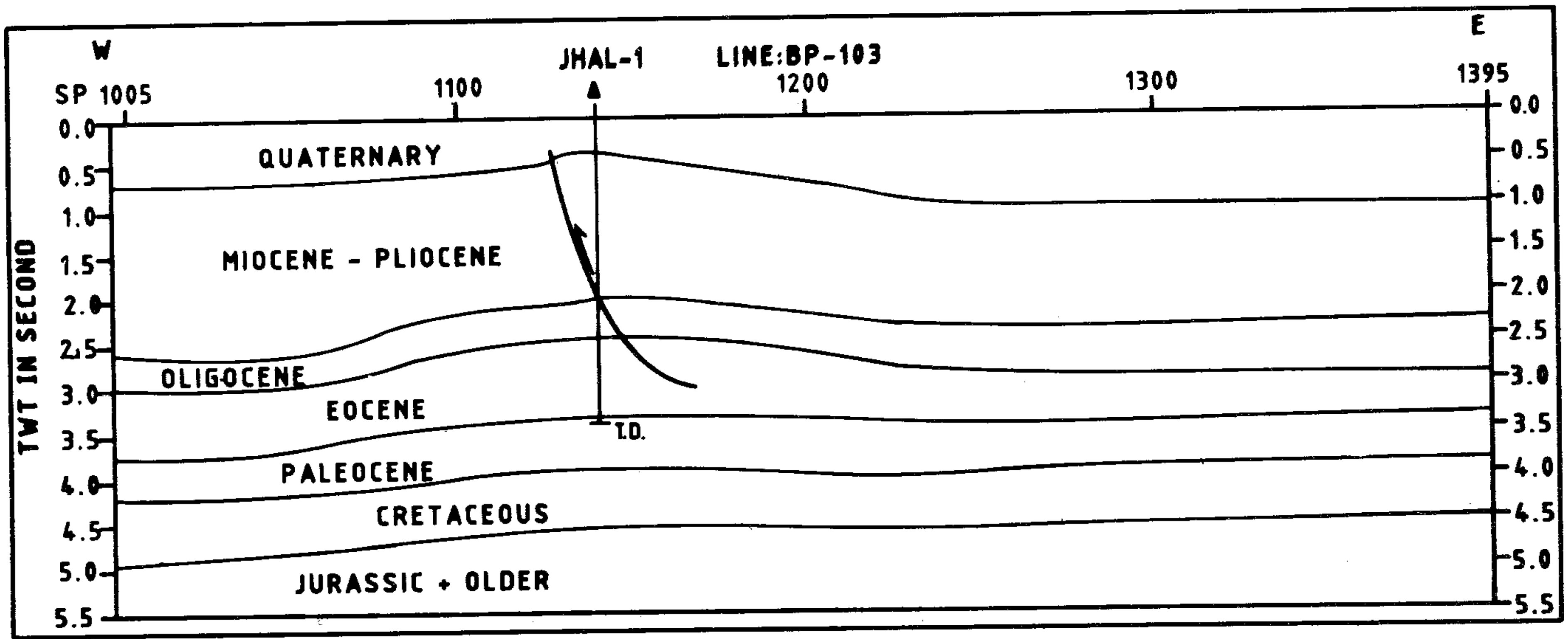

Figure 9— Impression of seismic line across Jhal well no.1 showing foreland dipping thrust developed due to compression related to left lateral wrenching. According to our interpretation the well was drilled on the plunge of a north-south oriented Miangun anticline. Minor displacement is noted in Eocene-Miocene-Pliocene sediments in contrast to earlier interpretation indicating repeated Oligocene section in the well (after Ali et al, 1991). For location see Figure 4.

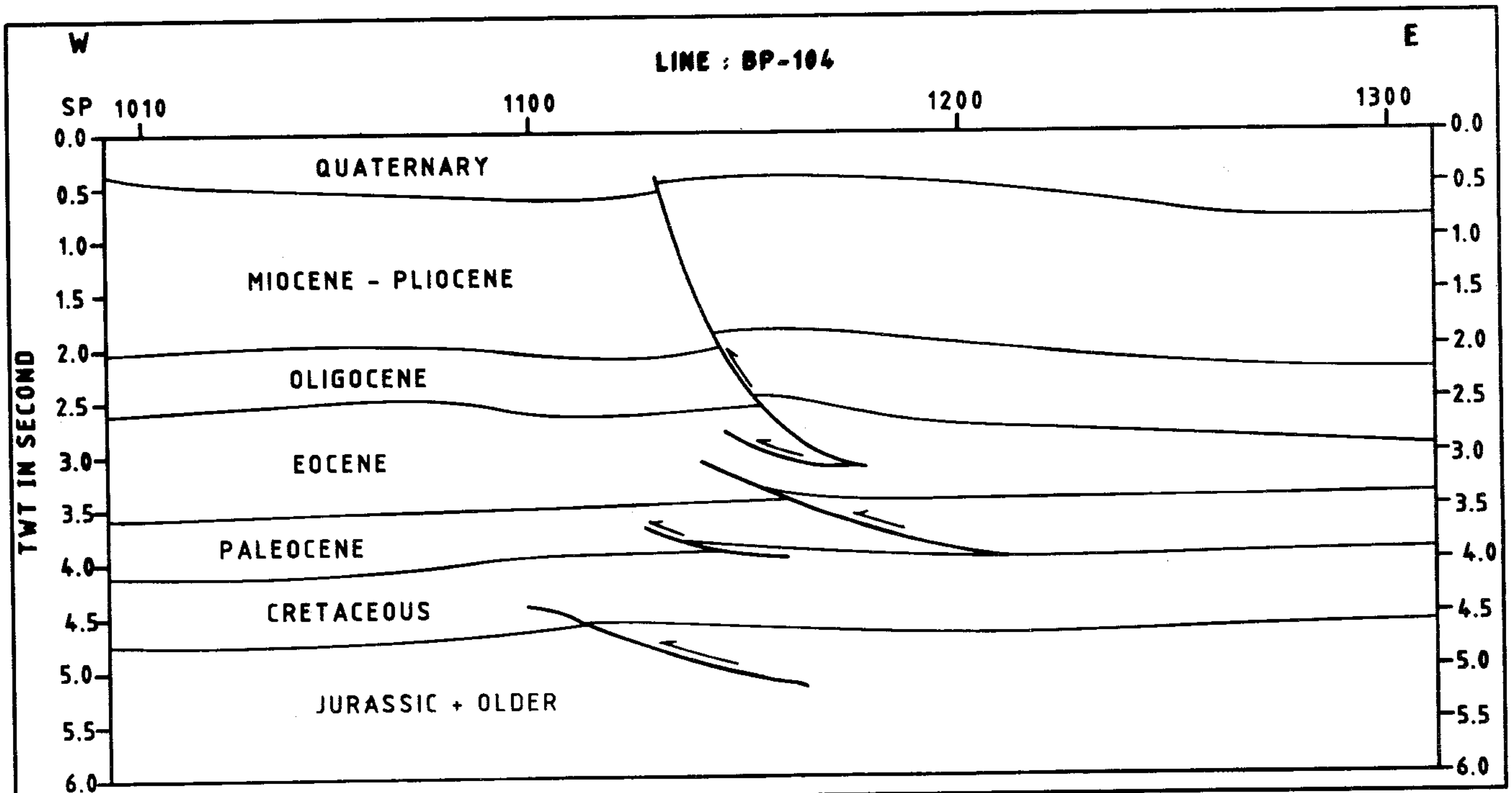

Figure 10— Impression of seismic line south of Jhal well no.1 showing foreland dipping thrusts developed due to compression related to left lateral wrench movement (after Ali et al, 1991). For location see Figure 4.

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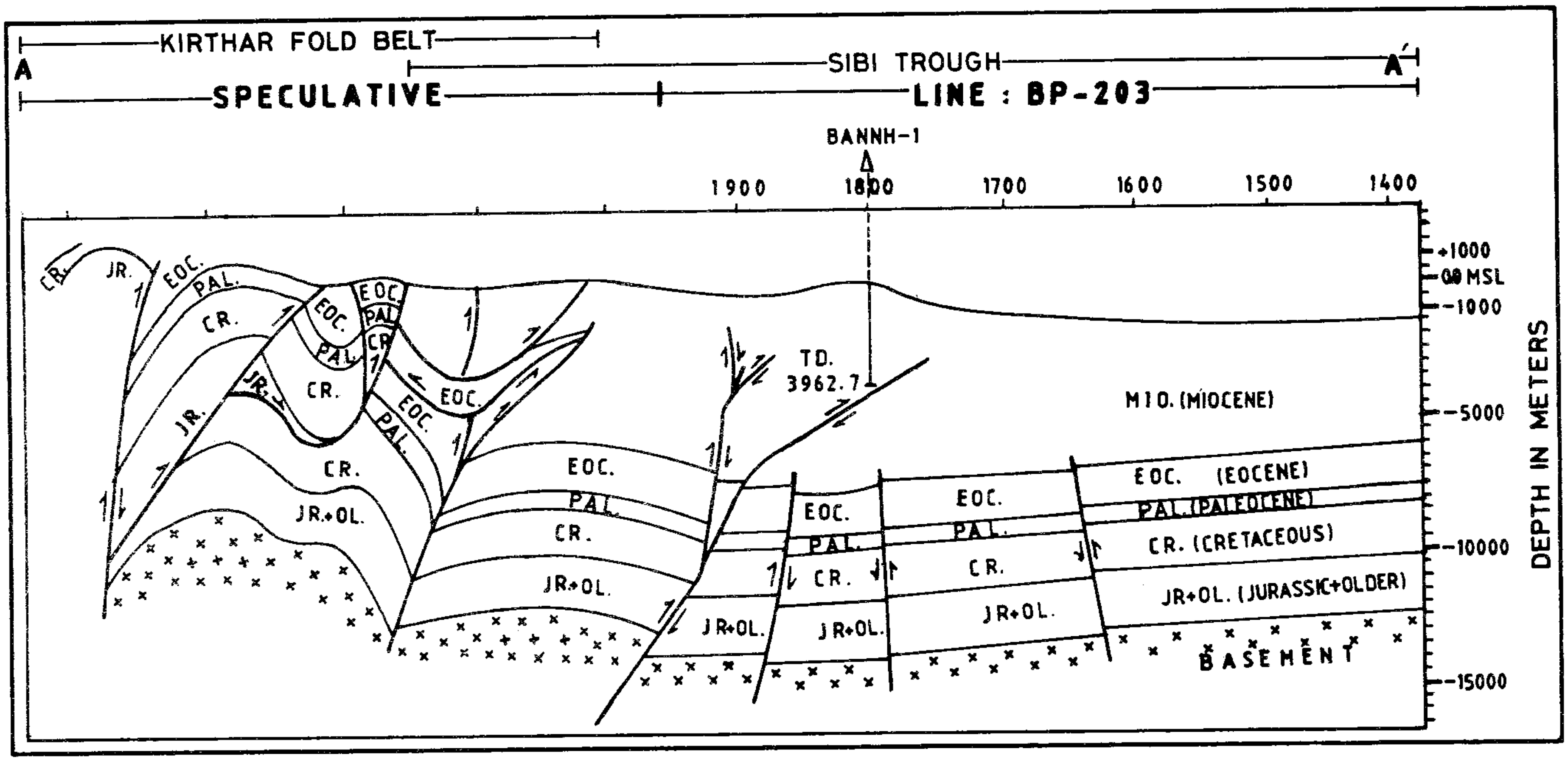

Figure 11— Structural cross-section across Sibi trough and Kirthar fold belt (modified after Ali et al, 1991). For location see Figures 3 and 13.

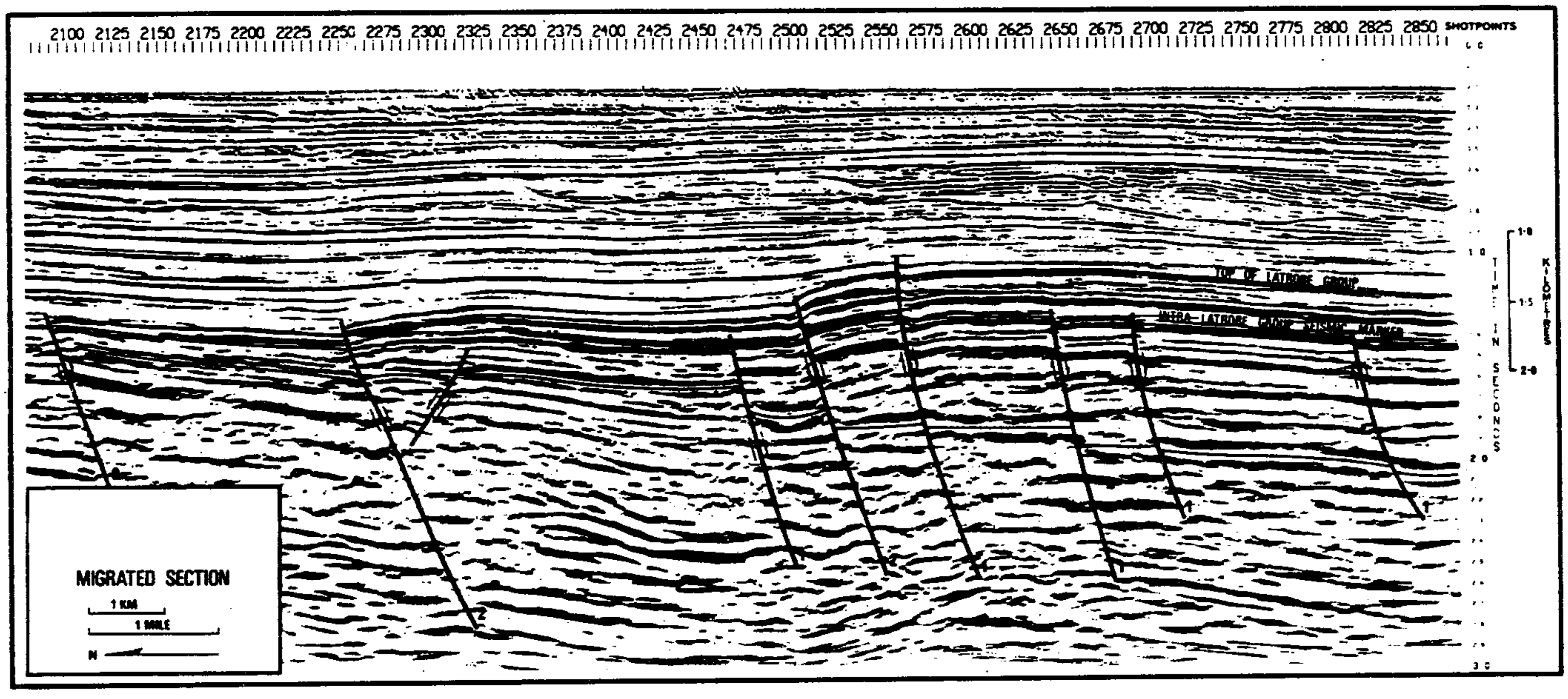

Figure 12— Inverted extensional basin, Offshore Gippsland, South-eastern Australia (Davis, 1983, *in* Lowell, 1990) Compression related to right-lateral wrench movement has inverted the basin by reactivating the pre-existing normal faults, similar features have been developed in Sibi trough, which are associated with compression related to left lateral wrench, see Figure 9.

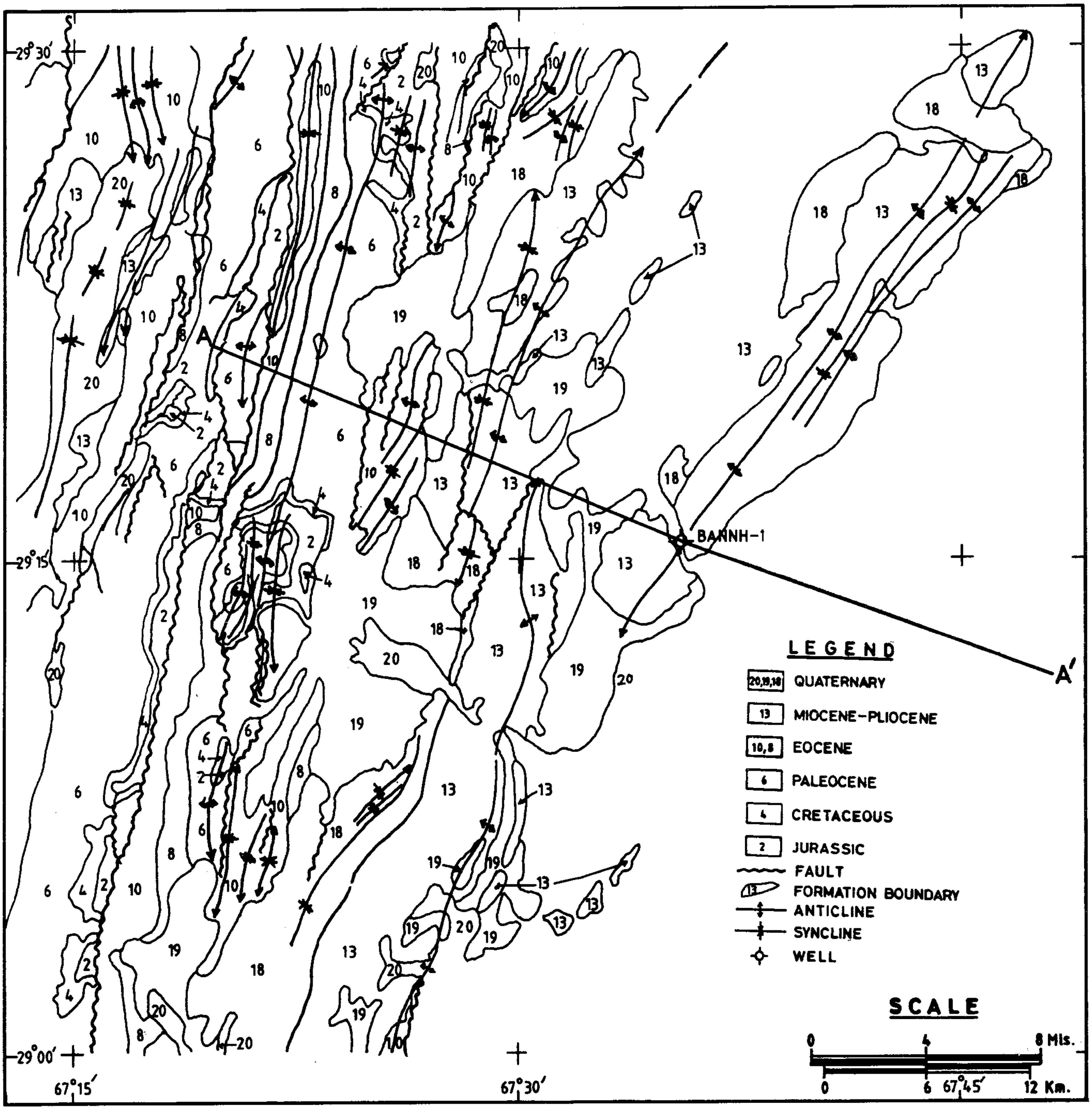

Figure 13— Geological and structural map of the northern part of study area (modified after Hunting Survey, 1961).

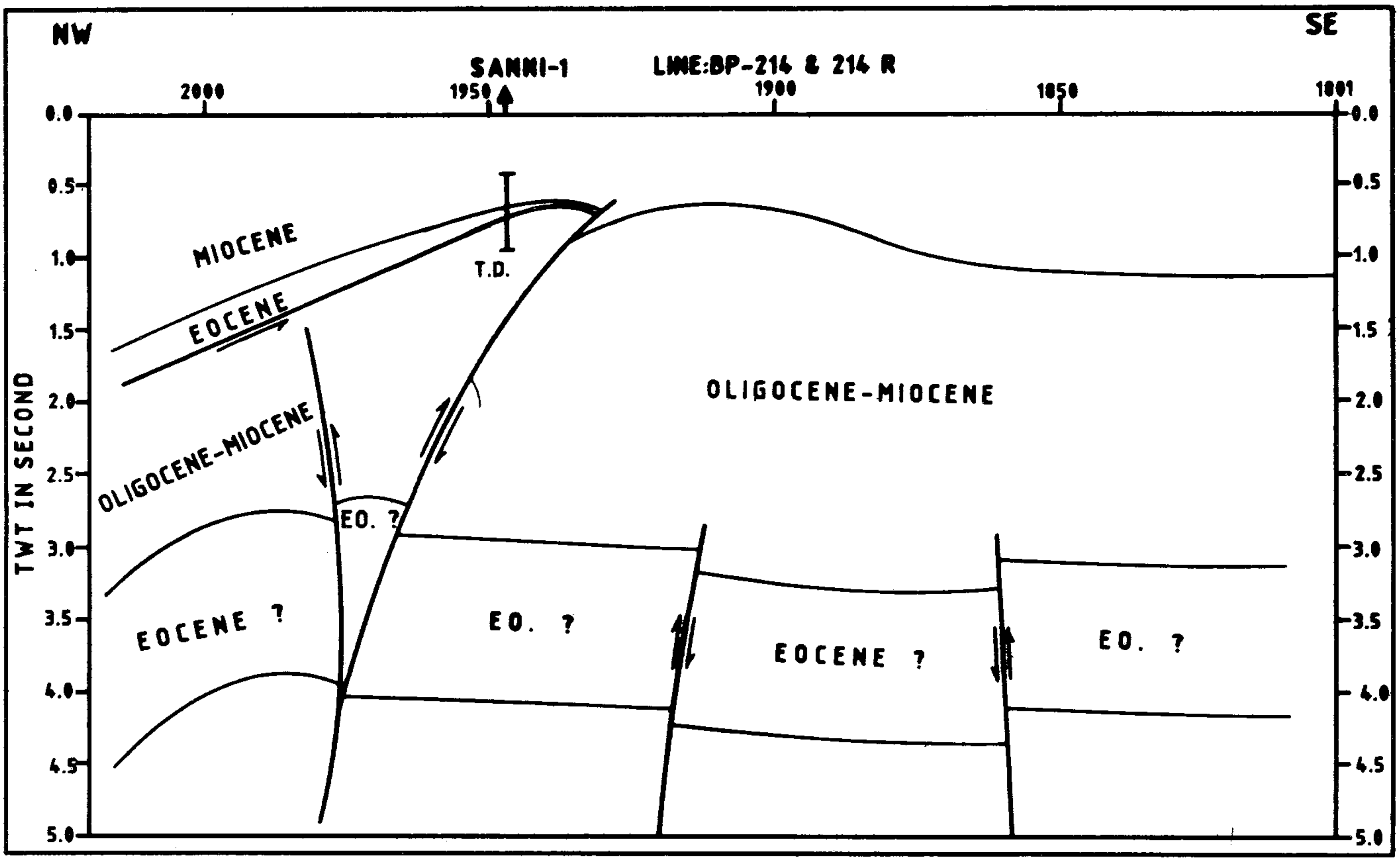

Figure 14— Impression of seismic line (Brute stack) across Sanni well no.1. The well encountered thrusted Eocene sediments implaced by decollement. The decolment feature is inferred in Figure 11. Inverted extensional basin can also be seen (after Ali et al, 1991). For location see Figure 3.

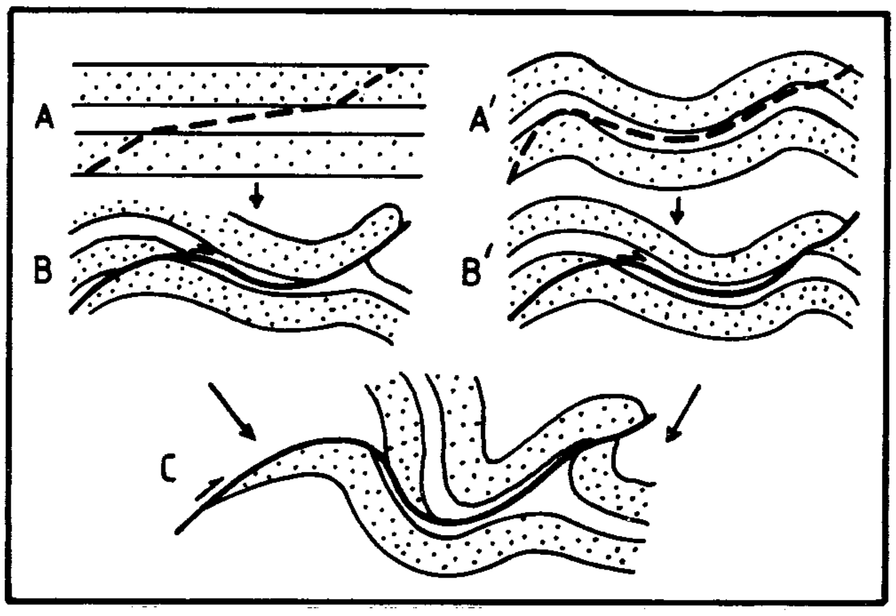

Figure 15— Evolution of sigmoidal shaped folded fault surface, caused by convergent wrenching in the Broggerhalvoya area of Spitsbergern (Challinor, 1967, *in* Lowell 1990). Similar evolution is interpreted in the northern part of the study area, see Figure 11.

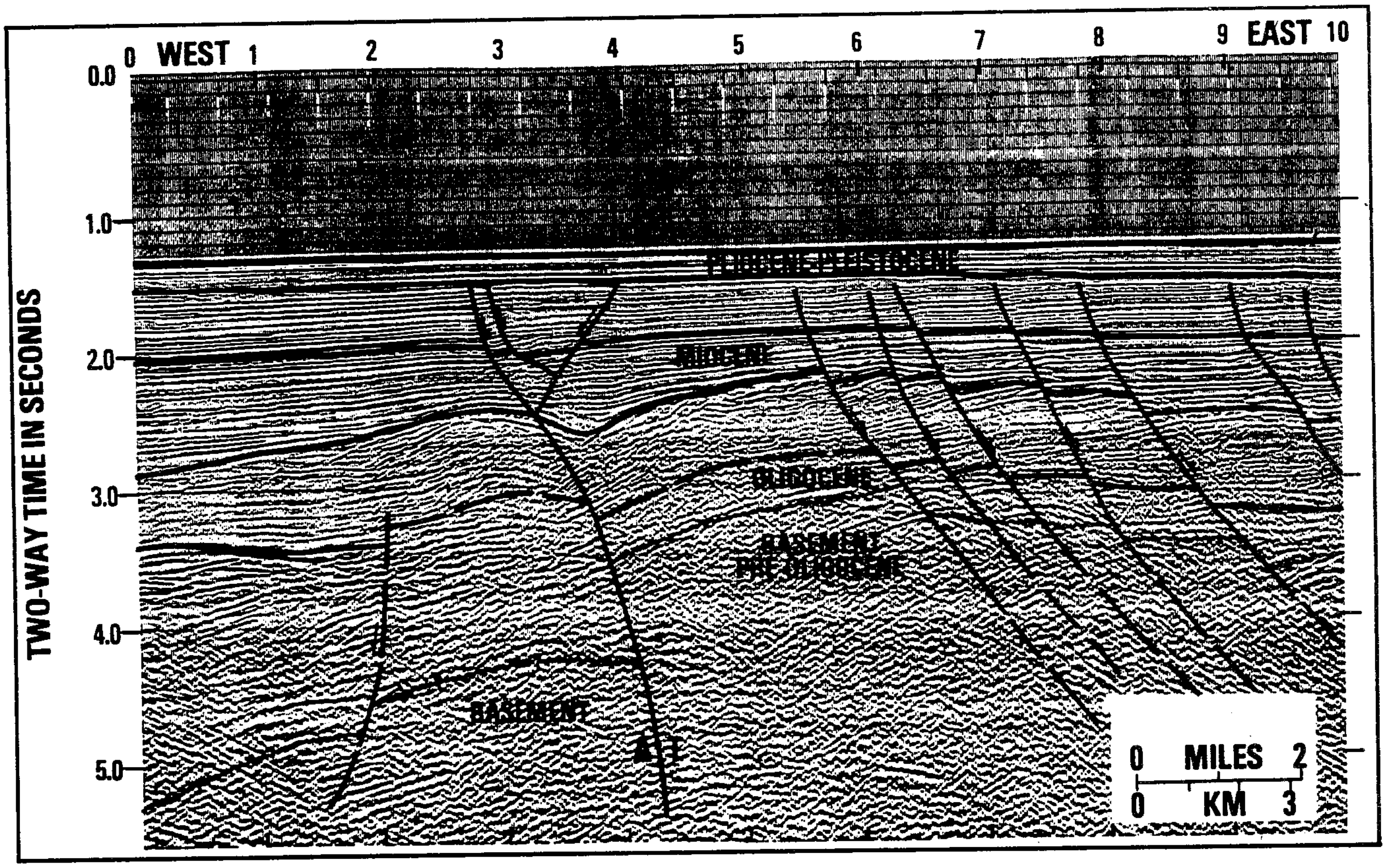

Figure 16— Seismic line from Andaman sea showing divergent wrench fault with en echelon normal faults developed in the east and negative flower pattern in the west (Harding, 1983, *in* Lowell, 1990). Similar patterns are expected in the sub-surface of southern part of the study area, see Figure 7.

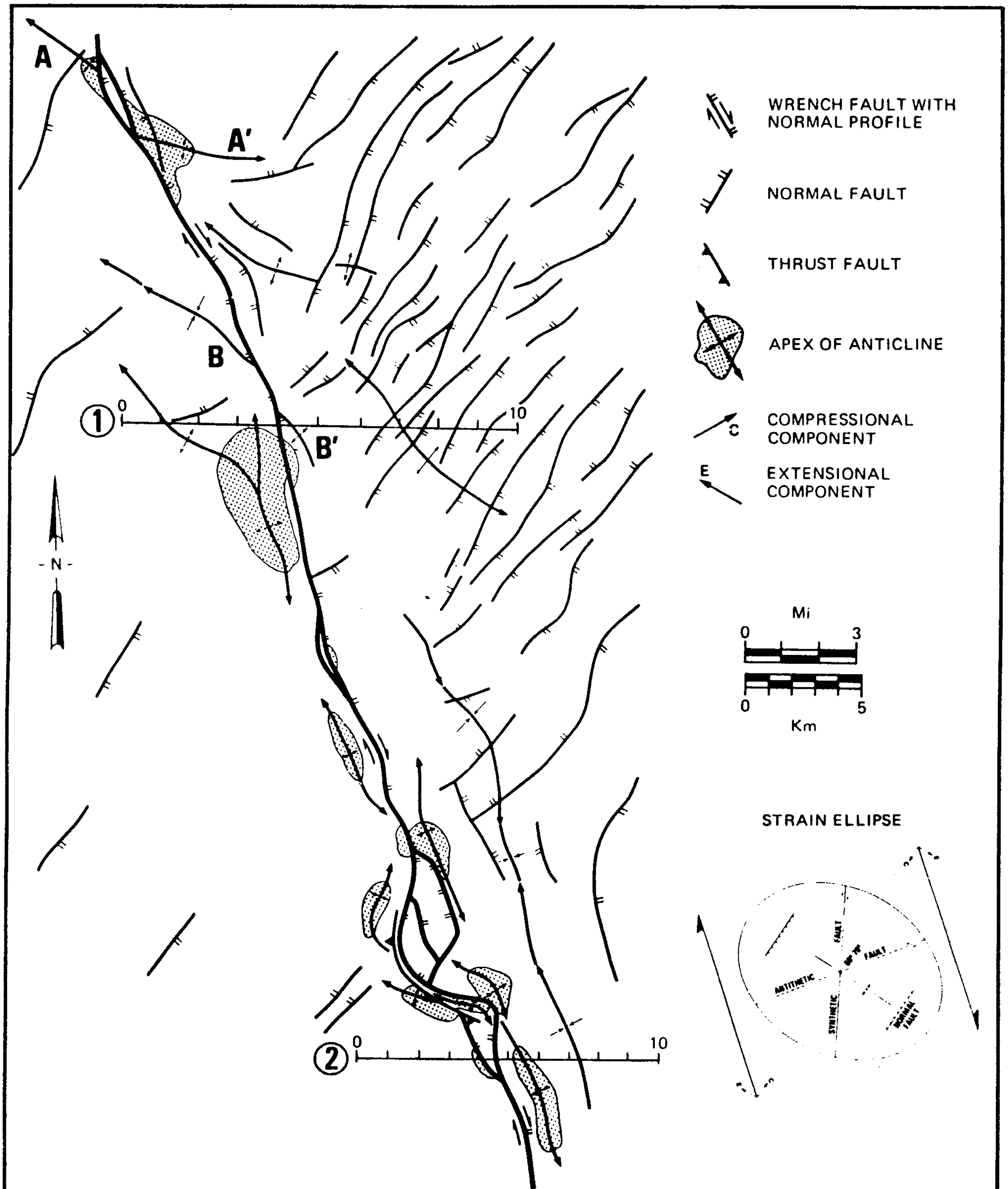

Figure 17— An analog of divergent wrench features (Harding, 1983, *in* Lowell, 1990). Similar anticlinal features can be seen in the study area, see Figure 7.