Pakistan Journal of Hydrocarbon Research
Vol.3, No.1(January 1991), P.1-17, 12 Figs., 1 Table

A New Concept Related to Structural and Tectonic Behaviour of Balochistan Basin, Pakistan and Its Implication on Hydrocarbon Prospects

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ABSTRACT

The Hydrocarbon prospects of Balochistan basin of Pakistan situated in the west of the country between longitude 61° to 66° 30′ and latitude 23° to 30° are assessed on the basis of a new concept related to the structural and tectonic behaviour of the basin. So far this basin is known as a fore-arc subduction basin. According to our interpretation of the geological, geophysical and other relevant data, the Balochistan is an extracontinental subduction basin which has been subjected to plate convergence to such an extent that the arc has been destroyed by subduction and transform movements, reducing it to a non-arc basin. Thus, oil and gas pools associated with normal faults, positive flower structures, structural anticlines and stratigraphic traps may form the targets for hydrocarbon exploration in the basin.

INTRODUCTION

The Balochistan basin having an area of about 75,000 sq km is Cretaceous-Recent in age and filled mostly with clastic sediments, the sedimentary fill exceeds 15,000m (Figure 1).

The history of exploration in the basin is as follows: (1) 1916-Burmah Oil Company drilled Chandragup well near a major mud volcano without any success; (2) 1955-Hunt Oil Company conducted photogeological and geological field studies, drilled two wells Dhak-1 & 2 between 1956 and 1957 and abandoned them without reaching target due to drilling problems; (3) 1959-62-Tidewater Oil Company carried out geological and geophysical surveys, drilled Kech Band well and abandoned it as a dry hole; (4) 1973- Marathon Oil Pakistan Ltd. conducted geological and geophysical surveys, drilled Garr Koh and Jalpari wells between 1975 and 1977 and abandoned them without reaching target due to structural complexity and high pressure, respectively; (5) 1974-Trend Pakistan Corp. carried out aeromagnetic and vibroseis surveys; (6) 1976-Murphy Oil Company obtained concession and is holding it todate; (7) 1980-85-Hydrocarbon Development Institute of Pakistan (HDIP) in collaboration with Imperial College of Science and Technology (ICST) carried out geological prospecting; and (8) 1981-Allan Spector and Associates Ltd. conducted aeromagnetic survey of northern areas of the basin.

Some of the important previous publications on the geology of the basin are by: (1) Hunting Survey Corporation (1961), (2) Jacob and Quittmeyer (1979), (3) Harms et al (1982), (4) Leggett & Platt (1982), (5) Raza and Alam (1983), (6) Platt & Leggett (1986), and (7) Khan and Raza (1986).

The present study has focussed its attention on structural modelling of the basin by interpreting and utilizing aeromagnetic, gravity, seismic, geological, drilling and geochemical data combined with the information gathered from other subduction basins of the world.

We believe that our structural model (Figure 2) would promote the basin as by placing it in the category of non-arc basins its anticipated hydrocarbon yield per cu km is enhanced (Non-arc basins have the highest yield among all types of basins).

It may be noted that the basin is of frontier category and the exploration has been marginal. Therefore, in absence of complete surface or subsurface stratigraphic sections the thickness and distribution of various stratigraphic units within most of the basin has been indirectly extrapolated and is subject to revision when new seismic profiles are shot and more wells drilled.

STRATIGRAPHY

The Balochistan basin was created as a result of subduction and arc formation during the Late Cretaceous time. Since then the sedimentation is controlled by tectonism related to various phases of basin evolution from fore-arc to non-arc. The known sedimentary rocks in the basin range in age from Cretaceous to Recent (Figures 3, 4). The older rocks (Cretaceous-Eocene) are exposed in the northern part, whereas the younger i.e. Oligocene-Recent outcrop mainly in the southern part of the basin.

In view of the complicated and localized nature of the available stratigraphic nomenclature a new stratigraphic column to explain in total the vertical as well as lateral

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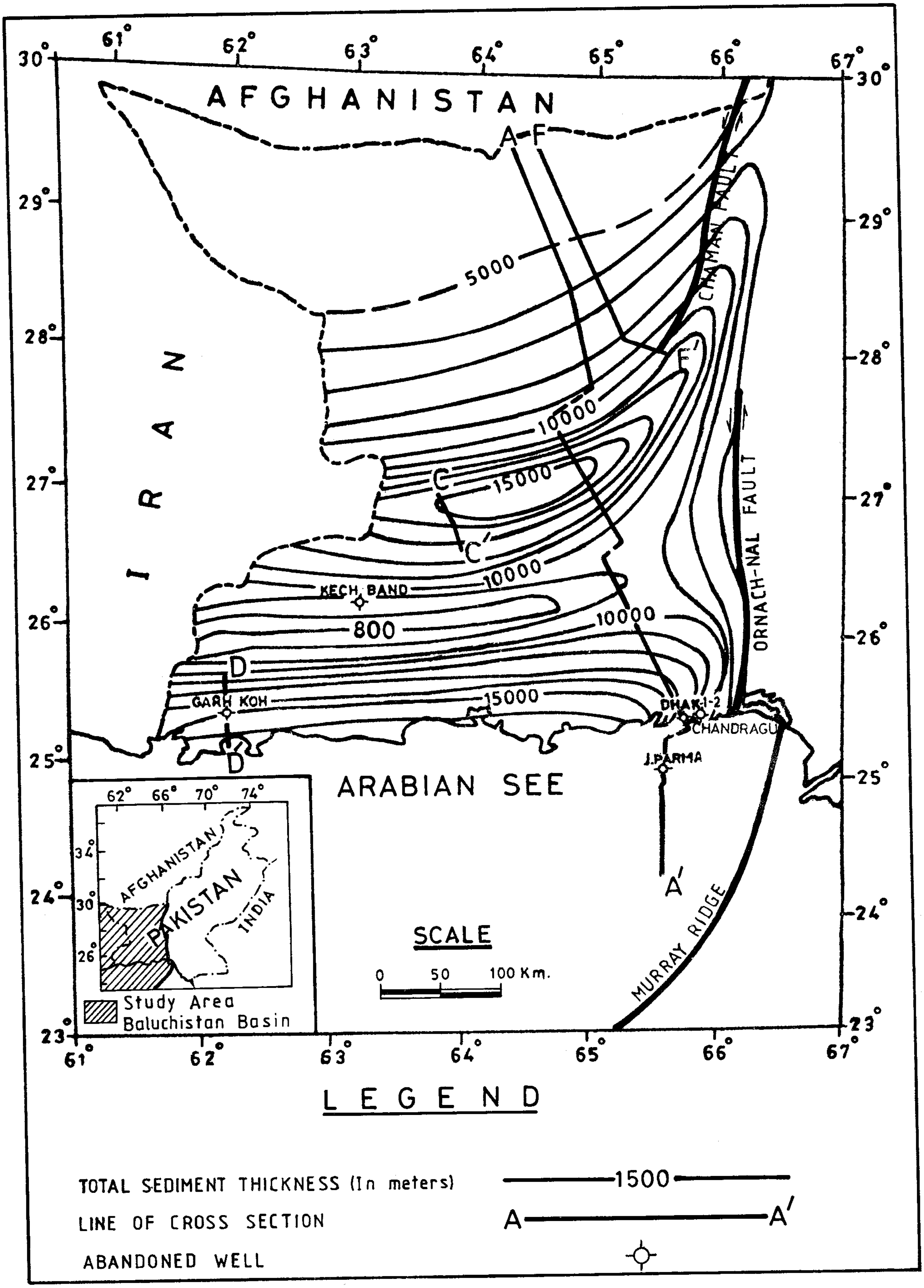

Figure 1— Sedimentary fill of Balochistan basin (modified after Kemal, Raza and Chohan, 1982).

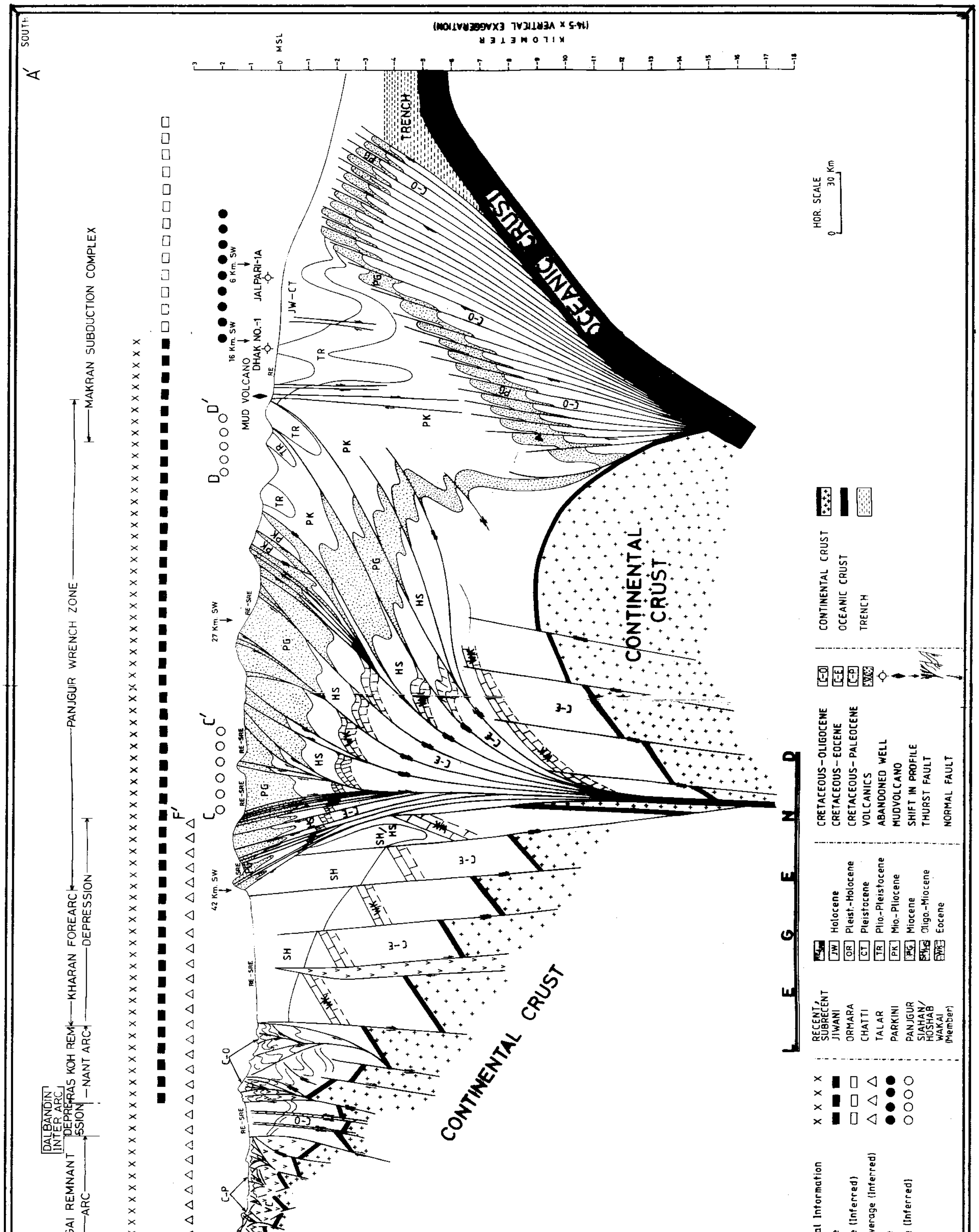

Figure 2— Structural and tectonic model of Balochistan basin.

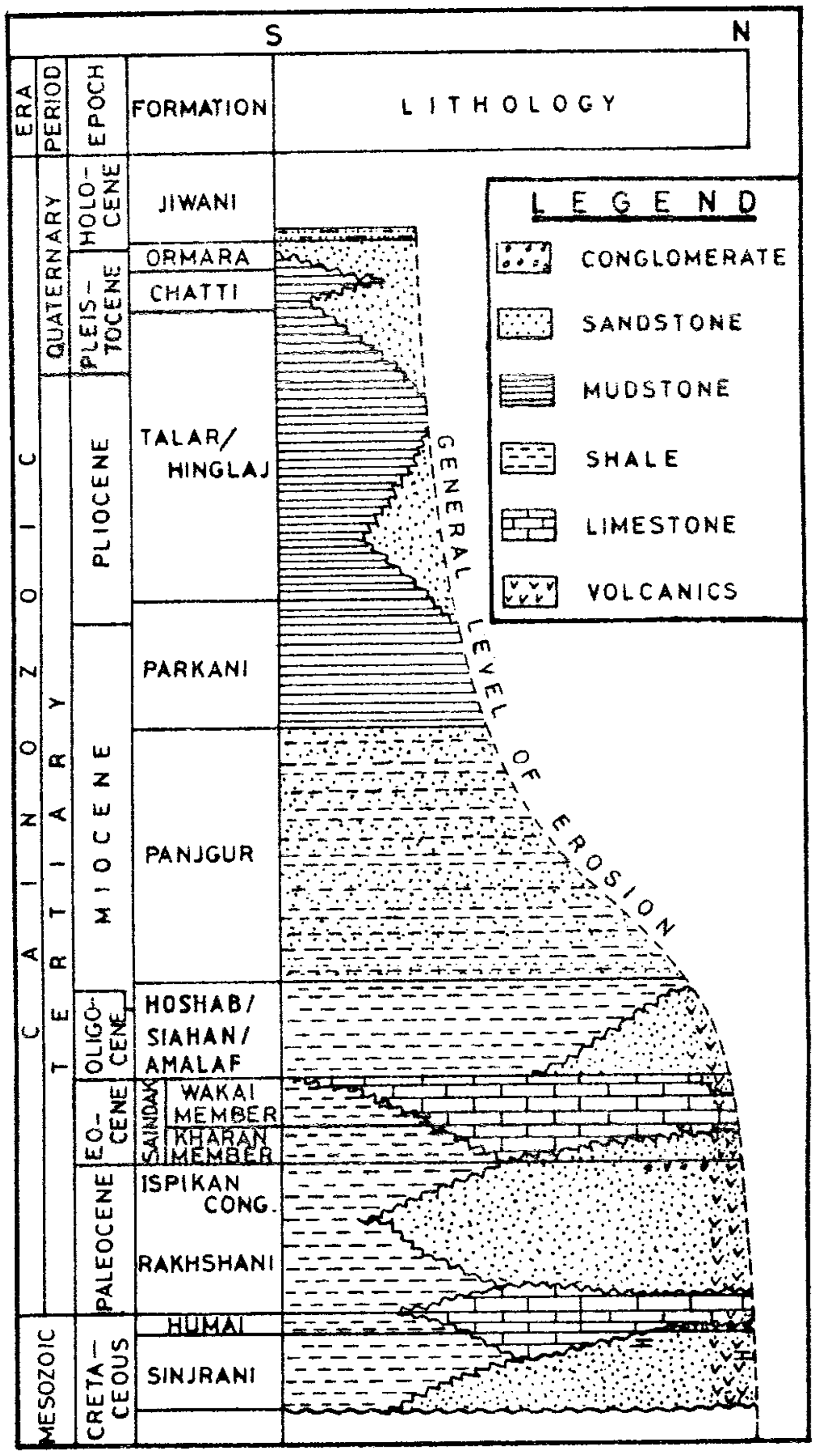

Figure 3— Stratigraphic column of Balochistan basin.

distribution and inter-relationship of the sedimentary rocks in the basin has been prepared (Figure 3).

Age of various stratigraphic units illustrated in this column have been derived from the publication "Stratigraphy of Pakistan" by Shah (1977) and foraminiferal micropaleontological work of Tidewater Oil Company (1959-61). The latter recognized the following planktonic zones which are now considered as international datum lines and have also been renamed.

Zones with new names	New ages
1. *Orbulina universa*	N_9 - R
2. *Orbulina bilobata* (New name: *O. universa*)	(Late Oligocene-Recent)
3. *Globorotalia mayeri* (New name: *Globoratalia* (T) *mayeri*)	N_2-N_{14} (Middle Oligocene-Middle Miocene)
4. *Globigerina dissimilis* (New name: *Catapsydrax dissimilis*)	P_{13} - N_6 (M.Eocene-Early Miocene)
5. *Globorotlia centralis* (New name: *Turborotalia centralis*)	P_{15} (Late Eocene)
6. *Globorotalia aragonensis* (New name: *Morozovella aragonensis*)	P_7 - P_{11} (Early-Middle Eocene)
7. *Globorotalia velascoensis* (New name: *Morozovella velascoensis*)	P_5 (Early Paleocene)
8. *Globotruncana ssp.*	Cretaceous

The entire sequence of sedimentary rocks shown in the column (Figure 3) is briefly described below:

Cretaceous

The Cretaceous rocks are exposed in the northern region. Two units are recognized: (1) Sinjrani formation, comprising volcanic rocks and thin beds of shale, sandstone and limestone; and (2) Humai formation composed of fossiliferous limestone, shale, siltstone and some volcanics.

Paleocene

The Paleocene rocks comprising sandstone and limestone with volcanic agglomerates (Rakshani formation) are exposed in the northern part of the basin. Some conglomerates composed of pebbles of igneous and sedimentary rocks (Ispikan congl.) are exposed near the Iranian border in the west of the central part of the basin.

Eocene

The Eocene rocks comprising alternations of fossiliferous limestone, shale, sandstone and volcanics (Saindak formation) are exposed in the eastern part of the northern region (Dalbandin area). Some foraminiferal limestone (Kharan member) is exposed in the eastern part of the northern region (Ras Koh area). Sporadic exposures

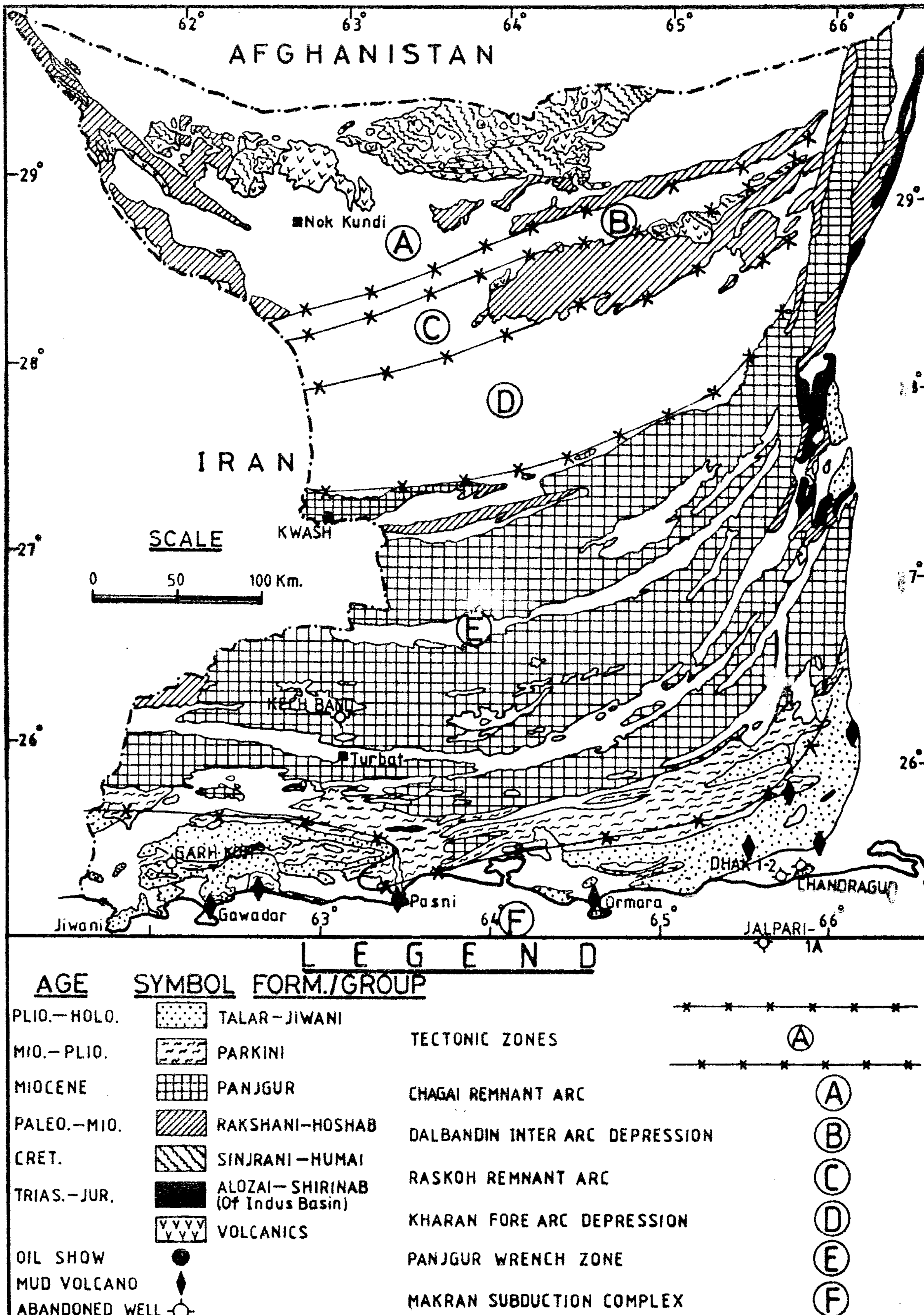

Figure 4— Geological map of Balochistan basin (modified after Bakr and Jackson, 1964) with tectonic zones.

of reefoid limestone (Wakai member) are found in the west of the central part of the basin (Kech Band area).

Oligocene

In the northern areas of the basin sandstone and shale with volcanics (Amalaf formation) are exposed. Deep water shales with subordinate sandstone (Siahan/Hoshab formation) are exposed in the central part of the basin. The formation extends into Miocene in the south.

Miocene

A thick sequence of turbidites (Panjgur formation) is emerging in the central and southern parts of the basin. The unit becomes younger southwards. In the southern part of the basin slope-shelf predominantly mudstone deposit (Parkini formation) is exposed. The formation extends into Pliocene.

Pliocene

Talar formation is exposed in the southern part of the basin. It is composed of sandstone and mudstone/shale. The formation extends into Pleistocene.

Pleistocene-Holocene

A mudstone, shale and sandstone unit (Chatti formation) overlies the Talar formation in the south. Ormara formation comprising mudstone and siltstone/sandstone alternating sequences overlies Chatti formation. It is succeeded by Jiwani formation of Holocene age consisting of shale, sandstone and sandy limestone.

All the Plio-Holocene formations are shore line shelf-slope cyclic facies.

TECTONIC MODEL AND HYDROCARBON PROSPECTS

The Balochistan basin is considered an arc-trench system of a shallow dipping subduction zone with no well developed Benioff zone (Farhoudi and Karig, 1977; Jacob and Quittmeyer, 1979). Workers like Leggett and Platt (1982) and Raza and Alam (1983) have described Balochistan as a fore-arc subduction basin evolved from Cretaceous to Recent time as a consequence of subduction of oceanic crust of the Arabian plate beneath the Eurasian plate.

Our study indicates that in Late Tertiary the arc was destroyed and basin later on modified to a non-arc subduction category. We also believe that in addition to the convergence related to northward subduction of the oceanic slab beneath a large continental block (Afghan block extending from Ornach-Chaman fault in the east to Harirud fault in the west) contrary to a smaller block thought by earlier workers, of the Eurasian plate, transform movement in the east and west and digitation of the continental slab (Figure 5) and not the oceanic slab as postulated by Dykstra and Birinie (1979) have also contributed to the shaping of the present day tectonic features of the basin and their structural manifestation is the combined effect of all these forces. The non-arc status of the basin is also confirmed by the absence of any recent volcanic activity within the basin, and the arc elements in Chagai and Ras Koh deformed regions belong to remnant arcs (Segment-1, Figure 5). The younger volcanic activity of Koh-i-Sultan is related to the transverse break between the two segments of the continental slab. The volcanic arc on Segment-1 became remnant earlier than on Segment-2 because of relatively faster southward overriding of the Segment-1 than Segment-2.

The evolution of the Balochistan basin can be summarized in the following sequence: (1) Volcanic activity occurred sporadically in the Chagai and Ras Koh regions from Cretaceous to Oligocene time due to subduction and buckling up of the Afghan block under convergence pressure. (2) In Oligocene/Early Miocene time transform movement in the east and west accelerated and plate collision took place affecting the severe plate convergence taking place in Balochistan basin where Chagai and Ras Koh arc regions were uplifted and deformation produced supply centers for clastics which rapidly filled the depressions, south of the remnant arc regions. (3) Further intensification in plate convergence associated with subduction and deformation related to transform movements in the east and west since Middle Miocene produced wrench faulting south of the Kharan area where younger clastics were squeezed-up and pushed to the north and south. Thus, new supply centers for clastics were produced and the sedimentary prism prograded further to the south. At the same time the hind part of the formerly leading edge of the down-going oceanic slab attained the new leading edge position shown in Figure 2, with trench moving southward and active subduction shifting along the coast as manifested by the line of mud volcanoes. The position and configuration of the concealed continental basement as shown in our structural and tectonic model (Figure 2) nearly coincides with the structural highs and lows marked on Hunting Survey Corporation maps concerning Panjgur wrench zone.

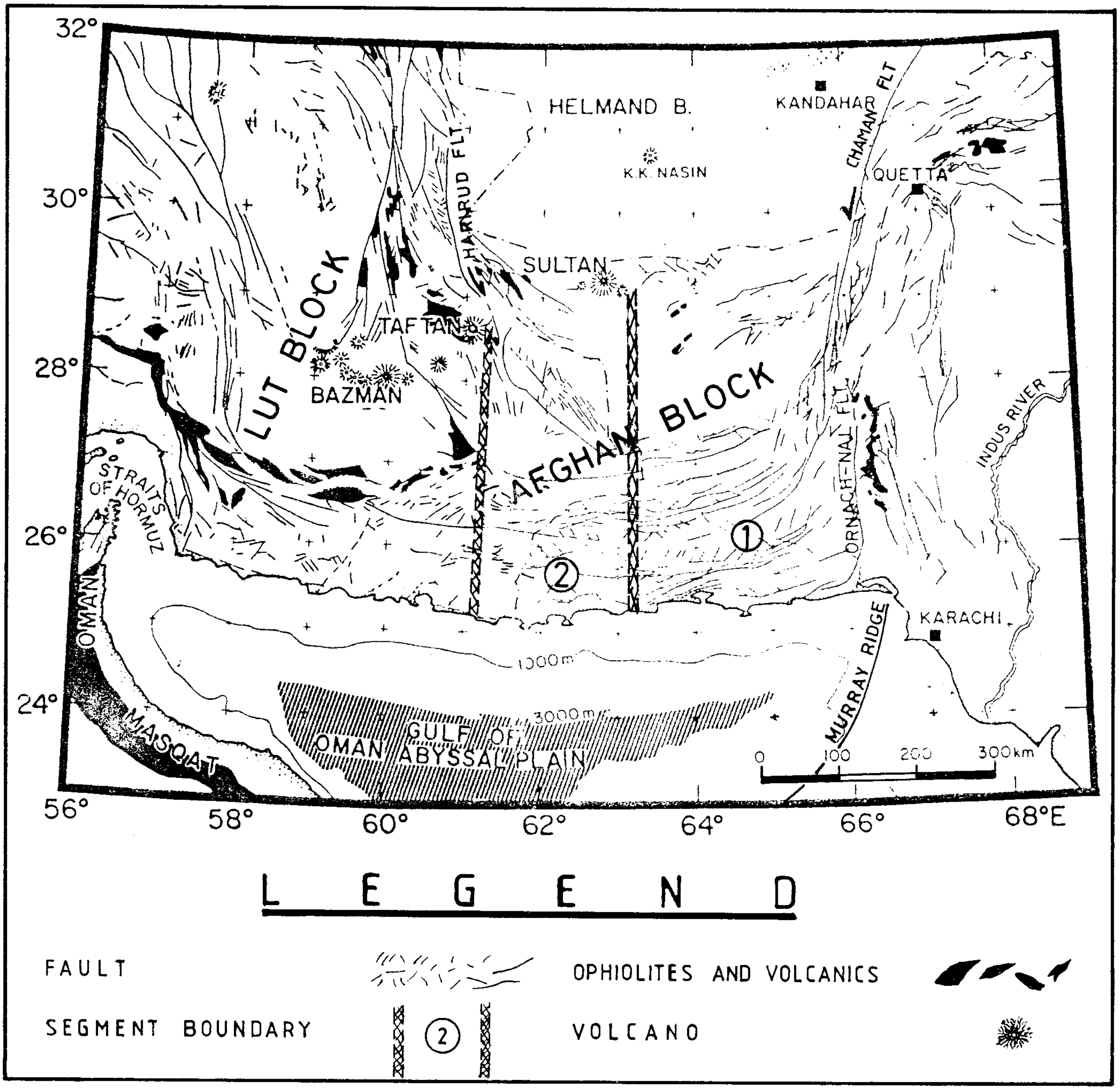

Figure 5— Tectonic sketch map of Balochistan basin and its surrounding areas (modified after Jacob and Quittmeyer, 1979) with segments of the Afghan block (modified after Dykstra and Birinie, 1979).

The subsurface structural adjustments related to the modification of the fore-arc subduction basin to a non-arc basin with a pronounced wrench fault zone development is explained in our model by projecting surface faults and sub-surface faults on aeromagnetic and seismic data to the basement depth obtained from the gravity data to substantiate the fore-going discussion on history of the basin (Figures 1, 5-9).

The hydrocarbon prospects of the basin were earlier thought to be linked with simple anticlines and stratigraphic traps, presumably developed in younger rocks in the south due to rapid sand-shale variations in lithology. Doubts have also been expressed regarding source rocks, heat flow, maturity and migration of hydrocarbons.

In present model (Figure 2) a new and highly prospective area with a large number of possible oil/gas pools resulting from flower pattern of wrench fault zone development has been indicated. The model also shows the occurrence of traps associated with normal fault blocks beneath Kharan depression where Paleogene targets are expected at

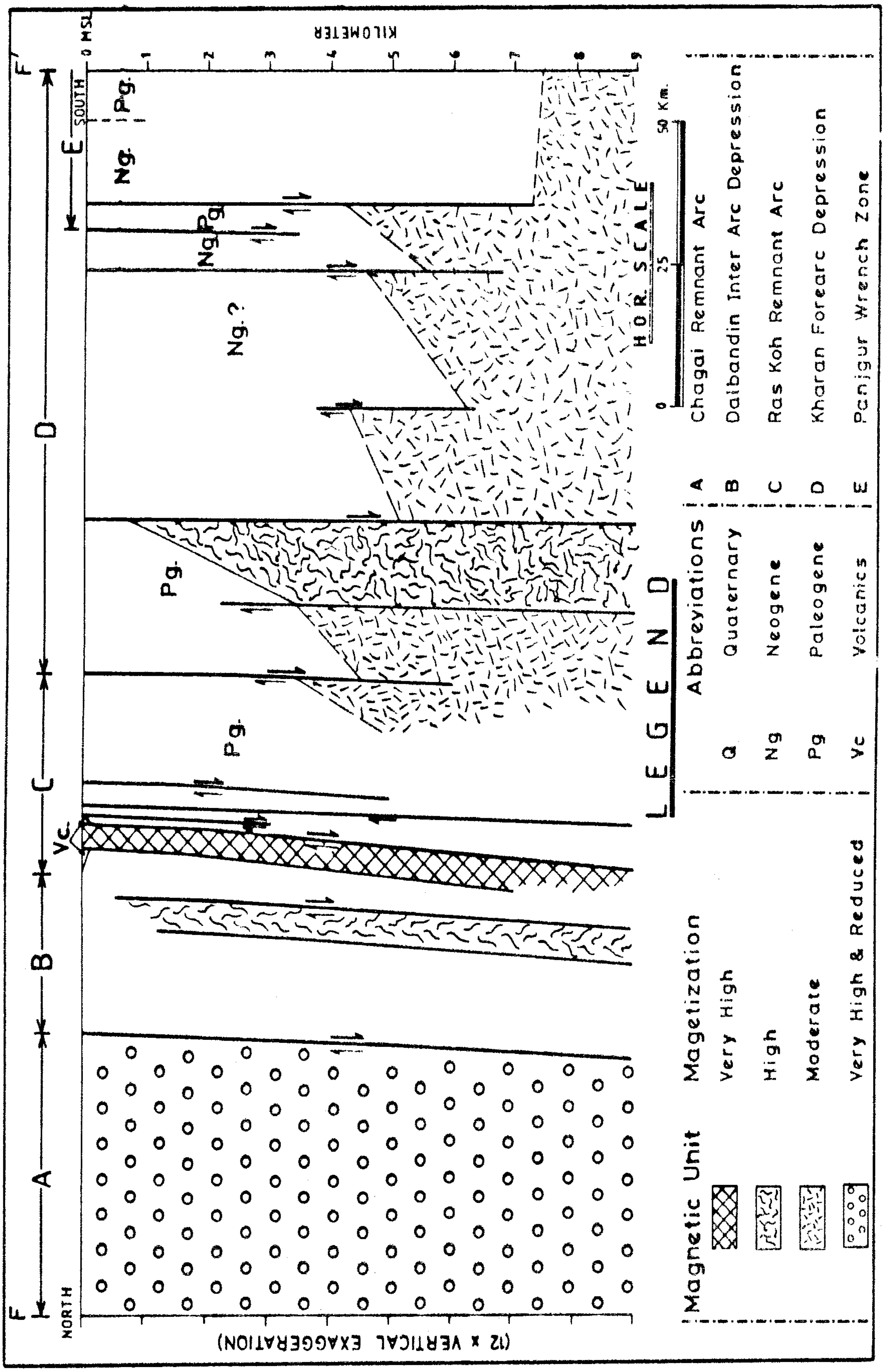

Figure 6— Geological cross section showing normal faults down to basement, interpreted from aeromagnetic data of northern region of the Balochistan basin (slightly modified after Allen Spector and Associates Ltd., 1981). For location see Figures 1 & 2.

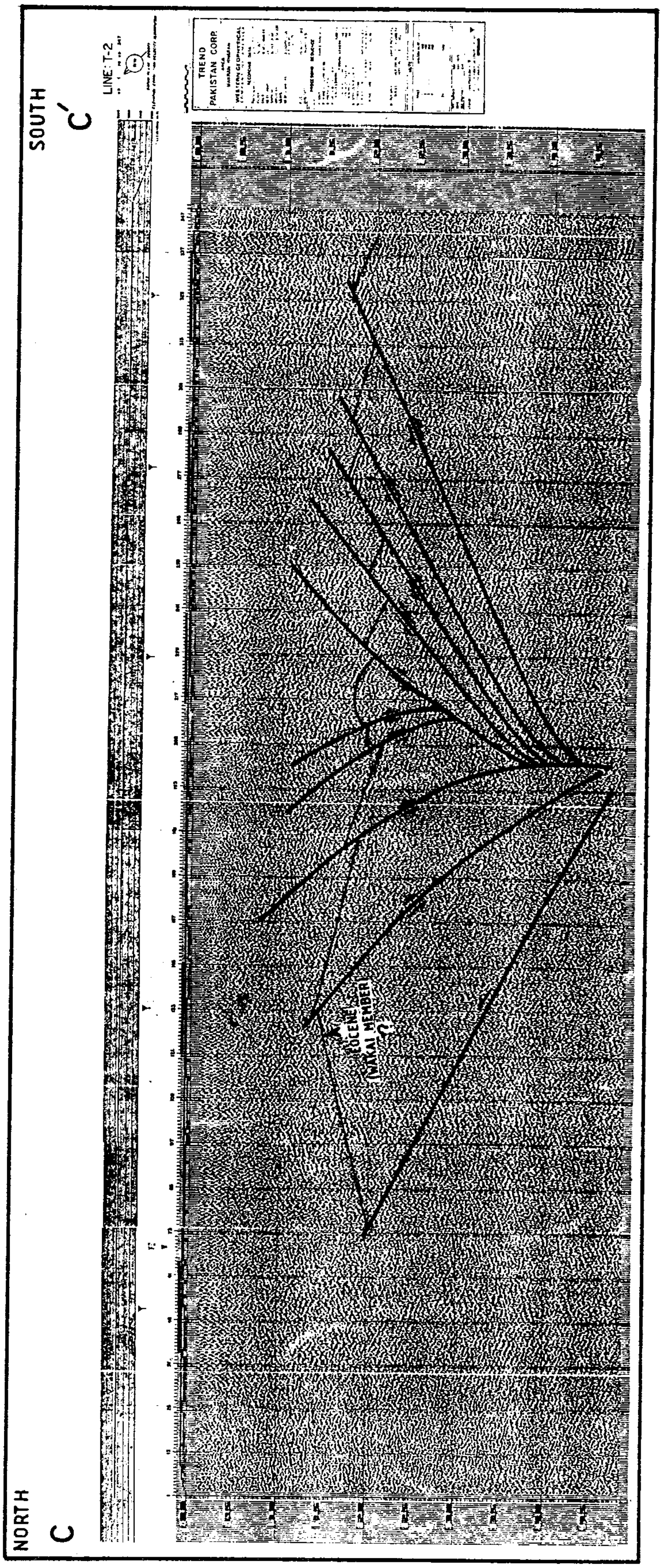

Figure 7— Seismic section indicating probable flower structure in Panjgur wrench zone. For location see Figures 1 & 2.

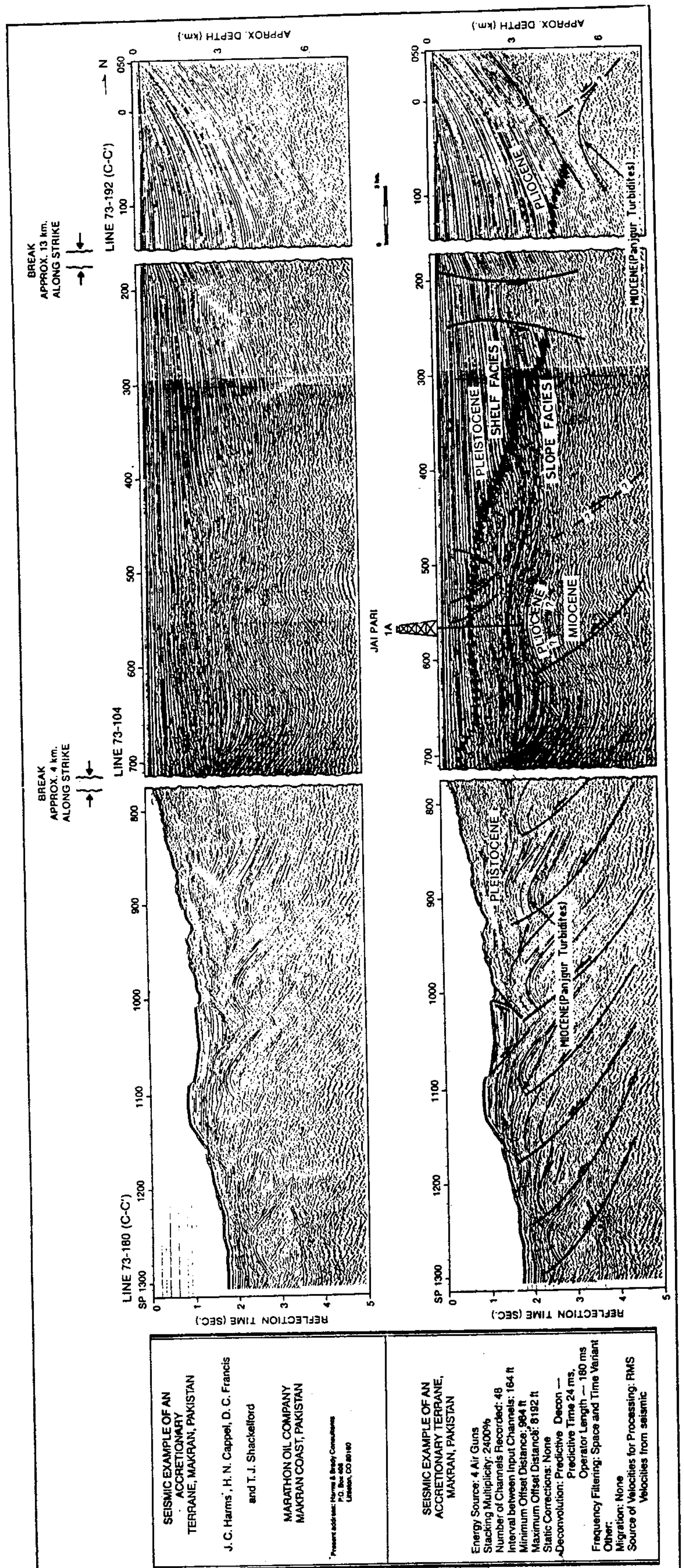

Figure 8— Seismic section representing southern part of line AA' in Offshore Makran showing structural pattern at Panjgur level and facies distribution of various stratigraphic units (modified after Harms et al, 1983). For location see Figures 1 & 2.

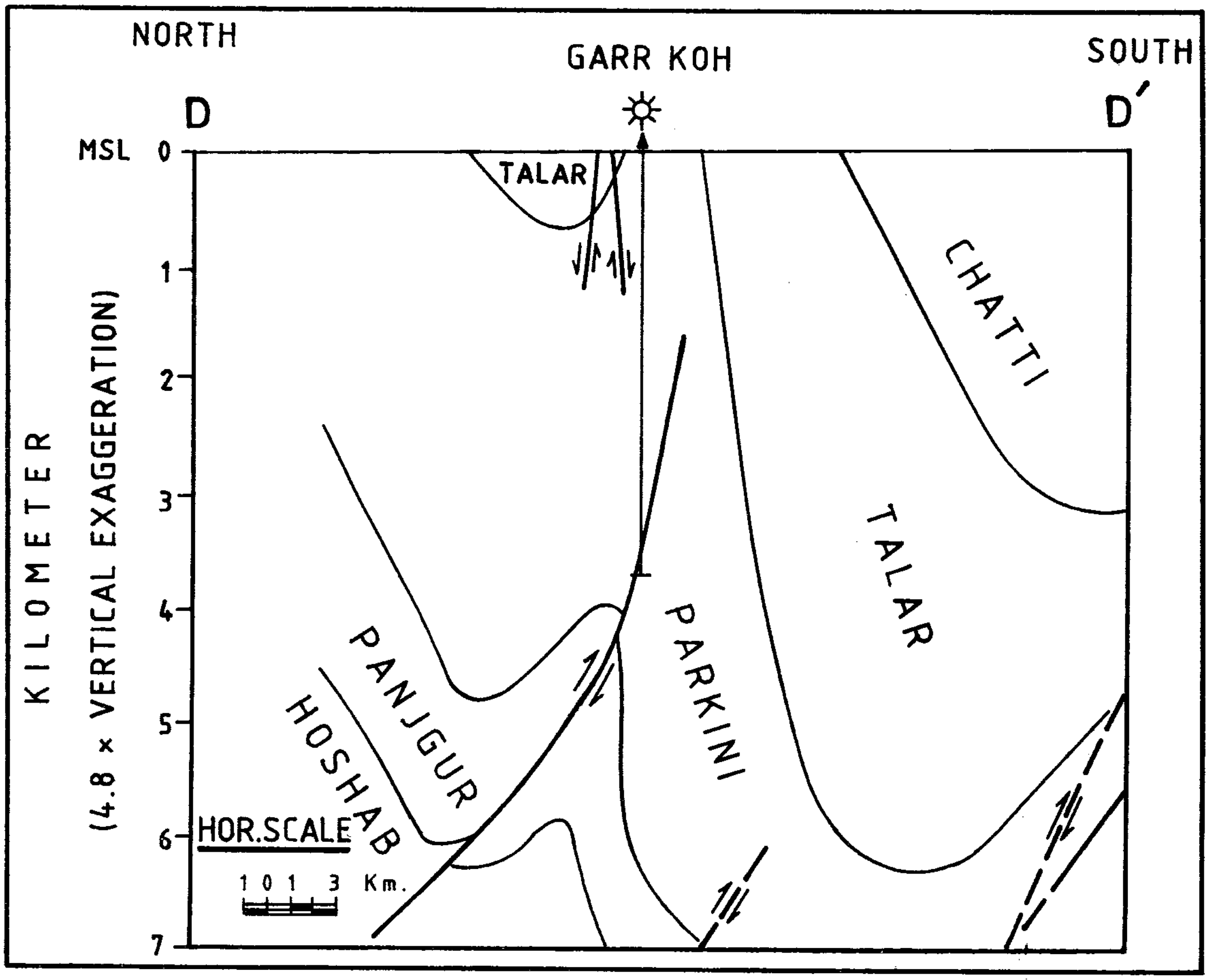

Figure 9— Structural cross section showing flank of flower structure at Panjgur level in the coastal Makran (modified after Harms et al, 1982). For location see Figures 1 & 2.

drillable depth. The 1983 Balochistan earthquake event (m_b 6.5, $M_o = 1.2 \times 10^{19}$ Nm) occurring in an area of low recent seismicity between 61° and 64° E at a depth of 65 ± 5 km (Figure 10) has been interpreted as a large normal faulting event (Laane and Chen, 1989) which also confirms the deformation style shown in our model. Similarly the aeromagnetic survey over northern parts of the basin (Allen Spector and Associates Ltd., 1981) including Dalbandin and Kharan depressions also shows subsurface occurrence of normal faults in these areas (Figure 6).

The basin is now practically modified to a non-arc basin stage with only remnant arcs. Therefore, its hydrocarbon potential should also be compared to non-arc basins which have the reputation and history of the highest oil recovery per sediment volume (Riva, 1983), good maturation, high geothermal gradients and multiple-pay type, predominantly sandstone reservoirs of shelf and turbidite facies. Examples with similar tectonic setting can be seen in some American (Los Angeles, Ventura, San Jaquin, Sacramento, Salinas), European (Vienna) and Russian (Baku) basins. All these basins contain giant fields.

The hydrocarbon prospects of the basin are discussed according to the following scheme of sub-division (Figures 2, 4).

i) Chagai remnant arc,
ii) Dalbandin inter-arc depression,
iii) Ras Koh remnant arc,
iv) Kharan fore-arc depression,
v) Panjgur wrench zone,
vi) Makran subduction complex.

Chagai Remnant Arc

The zone contains Cretaceous to Early Tertiary sedimentary and volcanic rocks. The region does not hold any hydrocarbon prospects due to overcooking of possible source rocks.

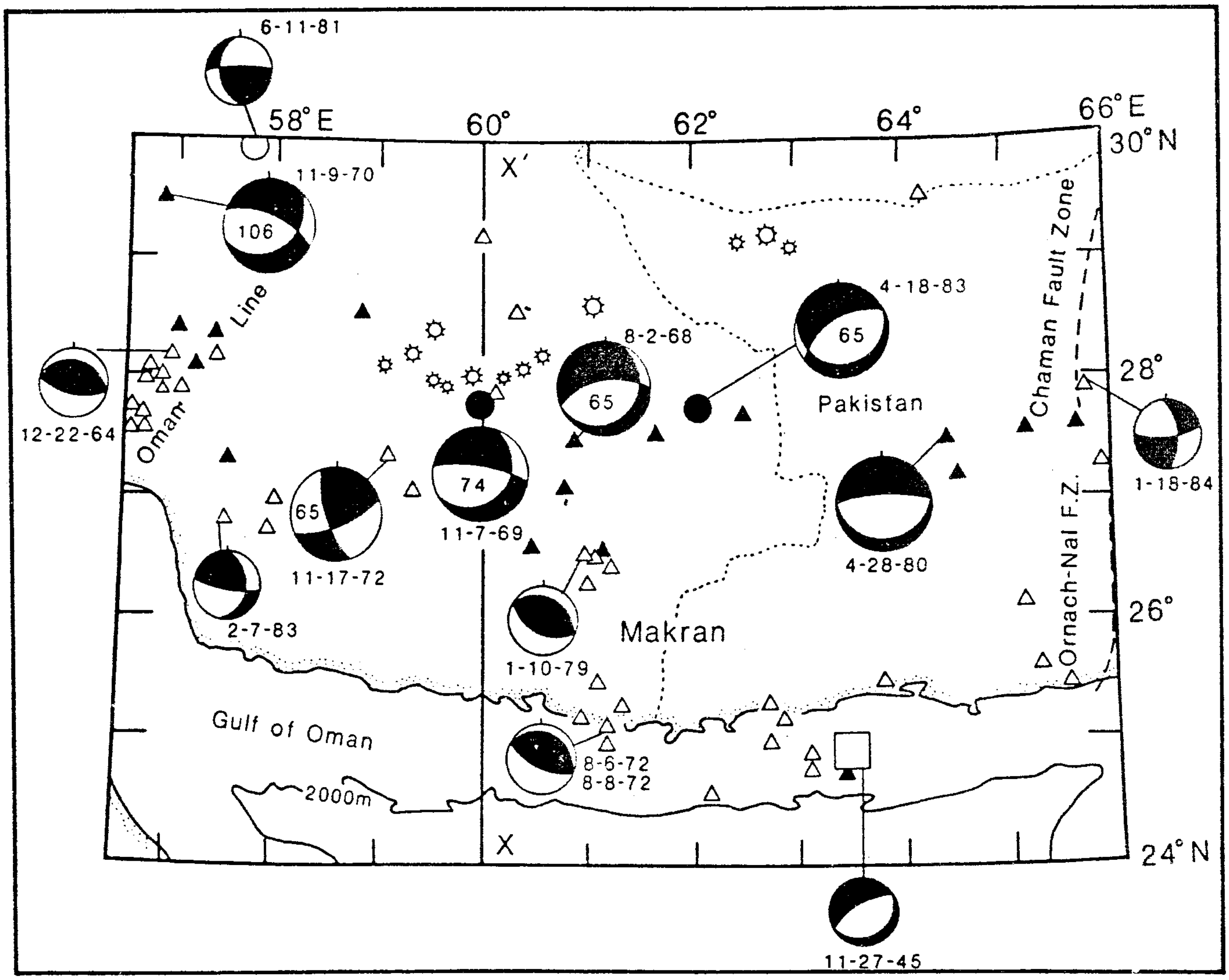

Figure 10— Seismicity map of the Makran region of southern Iran and Pakistan (after Laane and Chen, 1989).

Dalbandin Inter-arc Depression

Deformation of older rocks in Chagai and Ras Koh arcs resulted in the formation of an inter-arc depression which is filled mainly with Cretaceous-Paleogene sediments. The hydrocarbon prospects are reduced because of closeness to arcs. However, some possibilities may exist within normal fault blocks.

The temperature regime extrapolated from the vitrinite reflectance data from Ras Koh area is characterized by high geothermal gradient (6-7°C/100m). The oil window is approximately between 786-1500m falling within Amalaf formation of Oligocene age (Table 1, Figures 11, 12). The following Source-Reservoir-Seal trilogies may be present.

Source	Reservoir	Seal
Saindak(Lst/Sh)	Amalaf (Sst)	Amalaf (Sh)
	Saindak (Lst/Sst)	Amalaf (Sh)
Older Source	Saindak (Lst/Sst)	Amalaf (Sh)

Ras Koh Remnant Arc

It is made up of deformed Cretaceous-Paleogene sediments of the frontal arc. Paleogene source rocks have been overcooked in the zone due to the presence of igneous bodies.

Table 1. Preliminary geochemical results of 29 random samples from Balochistan basin. For location, see Figure 12. (Source: HDIP-BGR for Ras Koh, and HDIP-ICST for rest of the basin).

Age	Formation	Sample Location	Litho-logy	TOC	VR	Tectonic Zone	Remarks
Plio-Pleisto	Talar	1	Sh	0.57	-	Panj-gur Wren-ch Zone.	OM: Amarphous mixed humic-liptinic
		2	"	0.33	-		
Mio-Plio	Parkini	3	Mud	0.59	-	Panjgur Wrench Zone	OM: Mixed, humic-liptinic
		4	"	0.51	-		
		5	"	0.46	-		
		6	"	0.98	-		
Miocene	Panjgur	7	Sh	0.66	-		OM: Mixed, humic-liptinic
		8	"	0.69	-		
		9	"	5.62	-		
Oligocene-Miocene	Hoshab	10	Sh	0.47	-		OM: Amorphous, liptinic
		11	"	0.25	-		
		12	"	0.47	-		
	Amalaf	13	Mud St	0.16	1.26	Raskoh Remnant Arc	Composition of organic matter mostly
		14	"	0.38	-		
		15	"	0.27	-		
Oligocene-Miocene	Amalaf	16	Sh	0.49	-	Raskoh Remnant Arc	bituminous-liptinite. OM: destroyed and overcooked, due to igneous activities.
		17	"	0.33	-		
		18	"	0.35	-		
		19	"	0.02	2.21		
		20	"	0.36	-		
		21	"	0.26	-		
		22	"	0.25	-		
Eocene	Kharan	23	Marl St	0.17	-		
		24	"	0.20	1.96		
		25	Lst	-	1.88		
		26	"	0.25	-		
		27	"	0.13	3.53		
		28	"	0.21	-		
Paleocene	Rakshani	29	Sh	0.25	-		

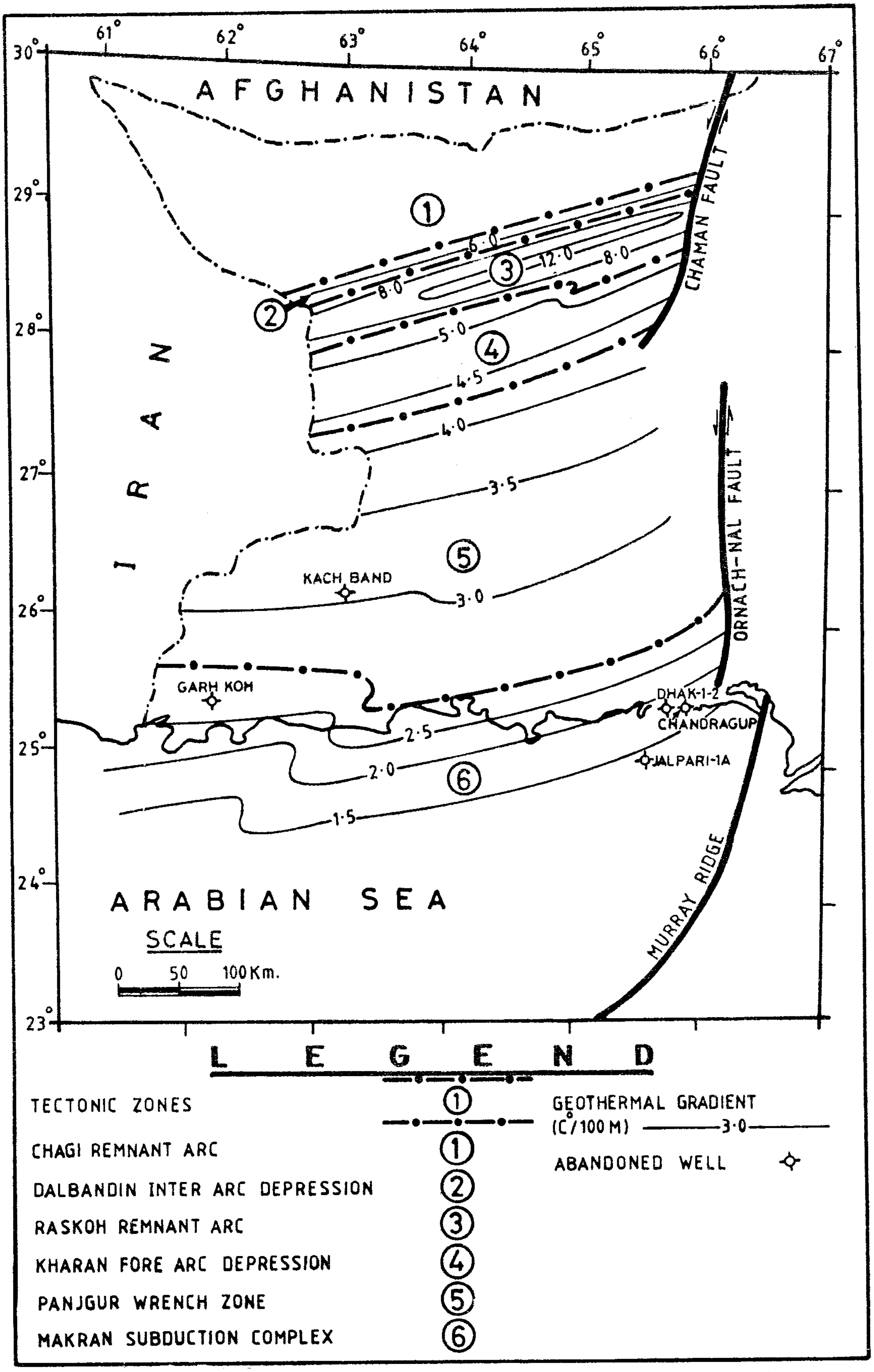

Figure 11— Geothermal gradient distribution in Balochistan basin as interpreted and extrapolated from bottom hole temperature and vitrinite reflectance data.

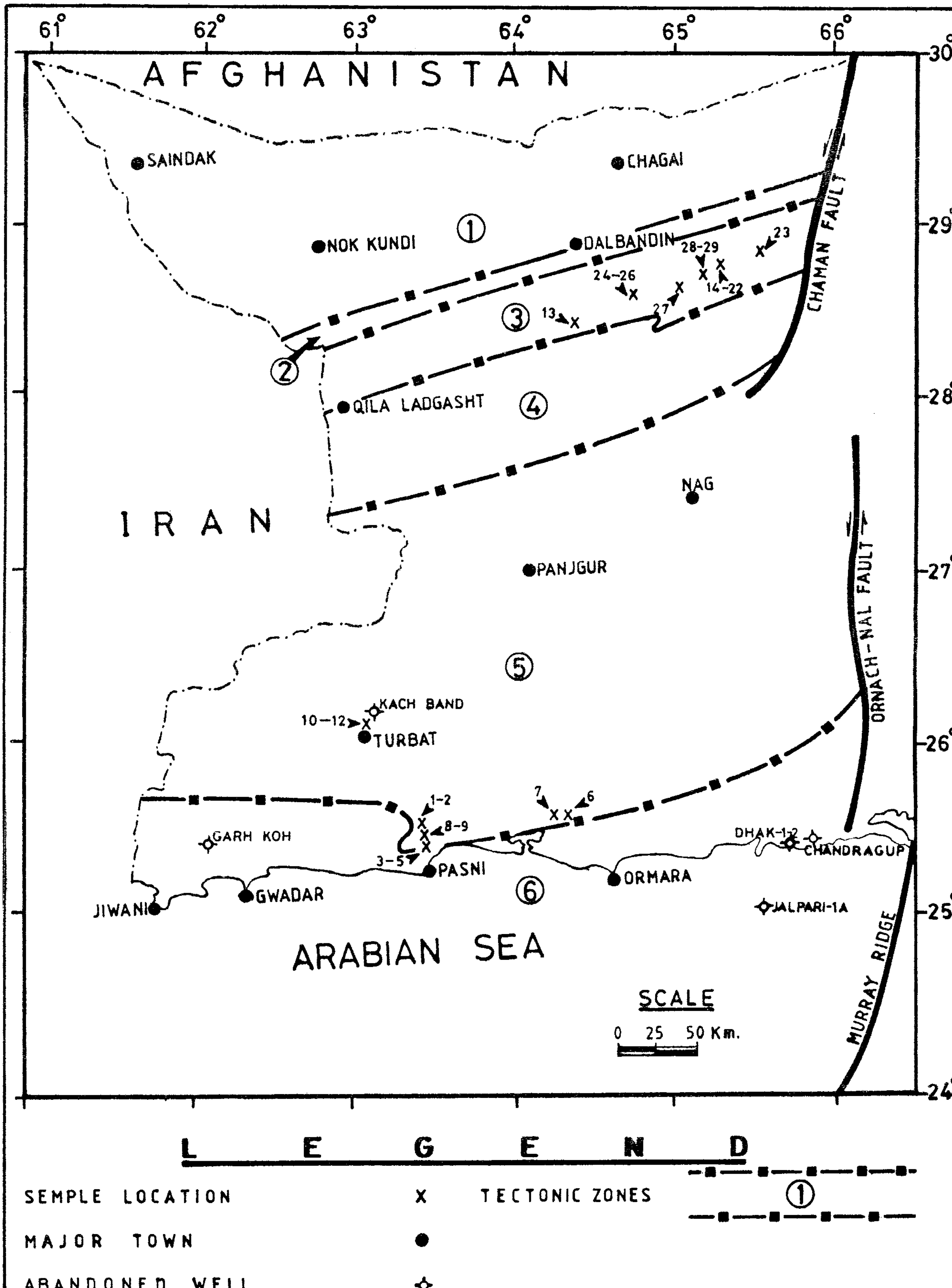

Figure 12— Geochemical samples location map. For tectonic zones see Figure 1:.

Kharan Fore-arc Depression

The depression is covered by Quaternary sands. The aeromagnetic and gravity data indicate sediment fill from 5000 to 7000m (Figures 1, 6). Paleogene sediments are the main targets which may contain good source and reservoir rocks. Carbonate reservoir could be the primary target for exploration (Figure 2). Oligocene-Miocene sands (Amalaf/Panjgur) might form secondary targets. Traps associated with normal fault blocks and some anticlinal flexures could be productive. Source rock data (Table 1) from Ras Koh arc indicate that away from the arc, Paleogene shales could act as source rocks. According to our model, maturation and migration are efficient.

The temperature regime should still be high in the zone. The geothermal gradient is estimated as 6°C/100m in the north and 4.4 °C/100m in south. The oil window in the north lies between 917 and 1750m, and in the south it ranges from 1250 to 2386m. Siahan/Hoshab-Wakai succession is within the zone of oil generation. The following Source-Reservoir-Seal trilogies may be present.

Source	Reservoir	Seal
Siahan/Hoshab (Sh)	Siahan(Sst)	Siahan(Sh)
Wakai mb/ Kharan mb (Lst/Sh)	Siahan(Sst) Wakai (Lst)	Siahan(Sh) Siahan/Wakai (Sh)
Older Source	Kharan(Lst/Sst)	Wakai/Kharan (Sh)

Panjgur Wrench Zone

This zone has been previously neglected due to surface complexities. The zone contains Eocene/Miocene sediments at drillable depths. Panjgur turbidites form the bulk of exposed sediments. According to our model this zone should contain a large number of potential traps related to wrench faulting caused by the pressure of the subduction from the south and deforming northern regions, in combination with transform movements both in the east and west of the basin squeezing up the sediments along the fault blocks in the form of a flower (Figures 5,7,9). Maturation and migration should be excellent and traps to be found at drillable depths. Shales of Hoshab and Panjgur formations have been rated as modest source rocks (Alam, 1986; Table 1). Older shales may also act as source rock. Wakai limestone member (Eocene) and Panjgur sandstone may form potential targets (Figure 2). An oil seepage is also reported from this zone at Kwash near Pak-Iran border (Figure 4). Two wells Kech Band and Garr Koh were drilled which were abandoned as dry holes, they were located off-structure.

The geothermal gradient in the zone varies from 4.3°C/100m in the north to 2.7°C/100m in the south. The oil window in the north is estimated between 1280-2442m and in the south between 2047-3839m. Parkini-Wakai section falls within the zone of oil generation. The temperature regime in the zone averages 3.5°C/100m. It matches well with the producing zones of Los Angeles non-arc basin where Miocene-Pliocene sediments are productive and the geothermal gradient averages to 3.1°C/100m. The following Source-Reservoir-Seal trilogies may be present.

Source	Reservoir	Seal
Panjgur (Sh)	Panjgur (Sst)	Panjgur (Sh)/ Parkini (Mud)
Siahan/Hoshab (Sh)	Panjgur/Siahan (Sst)	Panjgur/Siahan/ Hoshab (Sh)
Wakai (Lst/Sh)	Siahan(Sst)/ Wakai (Lst)	Siahan/Hoshab/ Wakai (Sh)
Kharan (Lst/Sh)	Wakai/Kharan (Lst)	Wakai/Kharan (Sh)

Makran Subduction Complex

This represents an active subduction zone which is filled with younger Tertiary rocks. A large number of mud volcanoes emit gaseous discharge along the coastline expressing the on-going subduction. Jalpari well drilled by Marathon was abandoned before reaching the Panjgur turbidite target, thus leaving the whole region virgin. Although HDIP-ICST workers have been indicating prospects in younger formations, especially Talar formation, yet according to our model the real target could be the Panjgur turbidites (Figures 2, 8). Structural and stratigraphic traps can be explored for hydrocarbons.

The temperature regime is relatively on the lower side. The geothermal gradient ranges from 1.4°C/100m to 2.6°C/100m. The values are in accordance with the other subduction zones of the world. The oil window in the north is between 2115 and 4038m and in the south between 3928 to 7500m. Talar-Hoshab section falls within the zone of oil generation. The following Source-Reservoir-Seal trilogies may be present.

Source	Reservoir	Seal
Parkini (Mud)	Talar (Sst)	Chatti (Mud)/ Talar (Sh)

Panjgur (Sh)	Panjgur (Sst)	Parkini (Mud)/ Panjgur (Sh)
Hoshab (Sh)	Panjgur (Sst)	Panjgur (Sh)

CONCLUSIONS

Projection of the surface geological data in the subsurface in combination with seismic, aeromagnetic and gravity information fits well in our model of non-arc subduction basin containing a wrench zone modification of the originally fore-arc basin. Non-arc subduction basins have the reputation of containing giant fields and their yield per sediment volume is the highest among all the categories of sedimentary basins.

Kharan depression with pools associated with normal fault blocks and Panjgur wrench zone with pools brought up due to the flower pattern of faulting are the two most prospective areas of the basin where exploration is recommended first.

According to our model maturation, migration and trapping factors are highly favourable. Therefore, we expect that systematic exploration may result in the discovery of substantial amount of hydrocarbons.

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