Pakistan Journal of Hydrocarbon Research
Vol.12, (January 2001). p.1-24, 19 Figs., 7 Table

Computed Tectonic Subsidence and Hydrocarbon Generation in the Offshore Indus Basin of Pakistan

Sher Mohammad Baloch[1] and David G. Quirk[2]

ABSTRACT

This is the most advanced computed technique on Terra Mod software for interpretation of tectonic subsidence and hydrocarbon generation. This technique is used for the first time for a Pakistani geological basin. The actual subsurface data of 6-wells of the Offshore Indus Basin of Pakistan were used for this study. The results were found very useful, as this study negated the earlier concept of existence of immature or partially mature hydrocarbon source rock in this basin. The results of this interpretation may help to attract the oil companies to re-consider Offshore Indus Basin for investment in hydrocarbon exploration.

INTRODUCTION

Offshore Indus Basin of Pakistan is located between the coordinates 64°-25'E to 68°-10'E and 23°-00'N to 25°-00'N in the east of Murray Ridge, covering an area of about 90,000 sq.km (Baloch and Quirk, 1998) (Figure 1). This basin was evolved as a result of Late Cretaceous Rifting of the Indo-Pak Craton from Africa (Powell, 1979). The main tectonic history comprises of rifting, drifting and collision of the Indo-Pak Craton as explained by various earlier workers in the past (Molnar and Tapponier, 1975, Schlich et al.,1975, Powell, 1979, Klootwijk, 1979, Biswas, 1987, Sarwar, 1992). The late Cretaceous phase of the rifting is associated with wide spread extrusion of Deccan Volcanic (Wensink, 1973, Gansser, 1974, Boyd, 1994, Mehmood et al., 1995). The results of present study supports the Late Cretaceous Rifting concept of the Indo-Pak Craton with presence of Deccan Volcanic in most of the Lower Indus Basin wells and the shelf area wells of the Offshore Indus Basin including Patiani Creek-1, Dabbo Creek-1 and Shaikh Nadin-1 (Baloch and Quirk. 1999/un-published).

OFFSHORE INDUS BASIN WELLS

Geology of the Offshore Indus Basin comprised of Mesozoic and Tertiary sedimentary succession as witnessed in the wells (Baloch, 2000/un-published). Data was available for ten wells including nine offshore area and one near shore area, namely Karachi South-1 (Husky Oil Company), Pakcan-1, (OGDC/PCIAC), Indus Marine-A1 (Wintershall) Indus Marine-B1 (Wintershall), Indus Marine-C1 (Wintershall), Shaikh Nadin-1 (Canterbury), Sadaf-1 (Oxy), Dabbo Creek-1 (Sun Oil), Patiani Creek-1 (Sun Oil and Korangi Creek-1 (Sun Oil). Hydrocarbons though un-economical in volume were recorded by DST in the well Pakcan-1 (Table 1). However for evaluation of tectonic subsidence and hydrocarbon generation both in the shelf and basin area, we selected 6-wells with more reliable subsurface data. These wells include Karachi South-1 in the shelf area and all the basin area wells comprising Indus Marine-A1, Indus Marine-B1, Indus Marine-C1, Pakcan-1 and Sadaf-1.

COMPUTED SUBSIDENCE AND HYDROCARBON GENERATION

This modeling programme determines the geological evolution of the basin and makes predicted hydrocarbon generation. The shapes of the curves generated as a result of this analysis provided output of subsidence and hydrocarbon generation histories for 6-wells of the Offshore Indus Basin of Pakistan, one in the shelf area and five in the basin area. These wells were selected due to availability of better quality of subsurface geological data. This interpretation gives detailed analysis of the Offshore Indus Basin, including its source rocks and expelled hydrocarbons that best fits the specific geology of this basin through rigorous calculations, by utilizing automated calibration checks using the "Terra Mod software"

BRIEF INTRODUCTION TO TERRA MOD SOFTWARE

Terra Mod software has been supported by acknowledged basin modeling experts in United Kingdom and United States as the best basin modeling tool available for increasing the chance of hydrocarbon exploration success. The best advantage of this tool is that it does not allow input of unrealistic physical properties of various sediment layers of different formations. The algorithms that calculate the decompaction and compaction processes are precise and iterative and the modeler is constrained by the technical rigorous of the software.

- Terra Mod software precisely simulates deposition, fluid dynamics and heat flow including the process operating during subsidence and uplift & erosion.
- It is organized into project files containing individual wells that can be set up in user preferences.
- It quantifies compaction process through the history of the basin without relying on broad unconstrained assumptions.

[1] Department of Petroleum and Energy Resources, Directorate General of Gas, Ministry of Petroleum and Natural Resources, Islamabad.

[2] Department of Geology and Cartography, Oxford Brookes University, Oxford, UK.

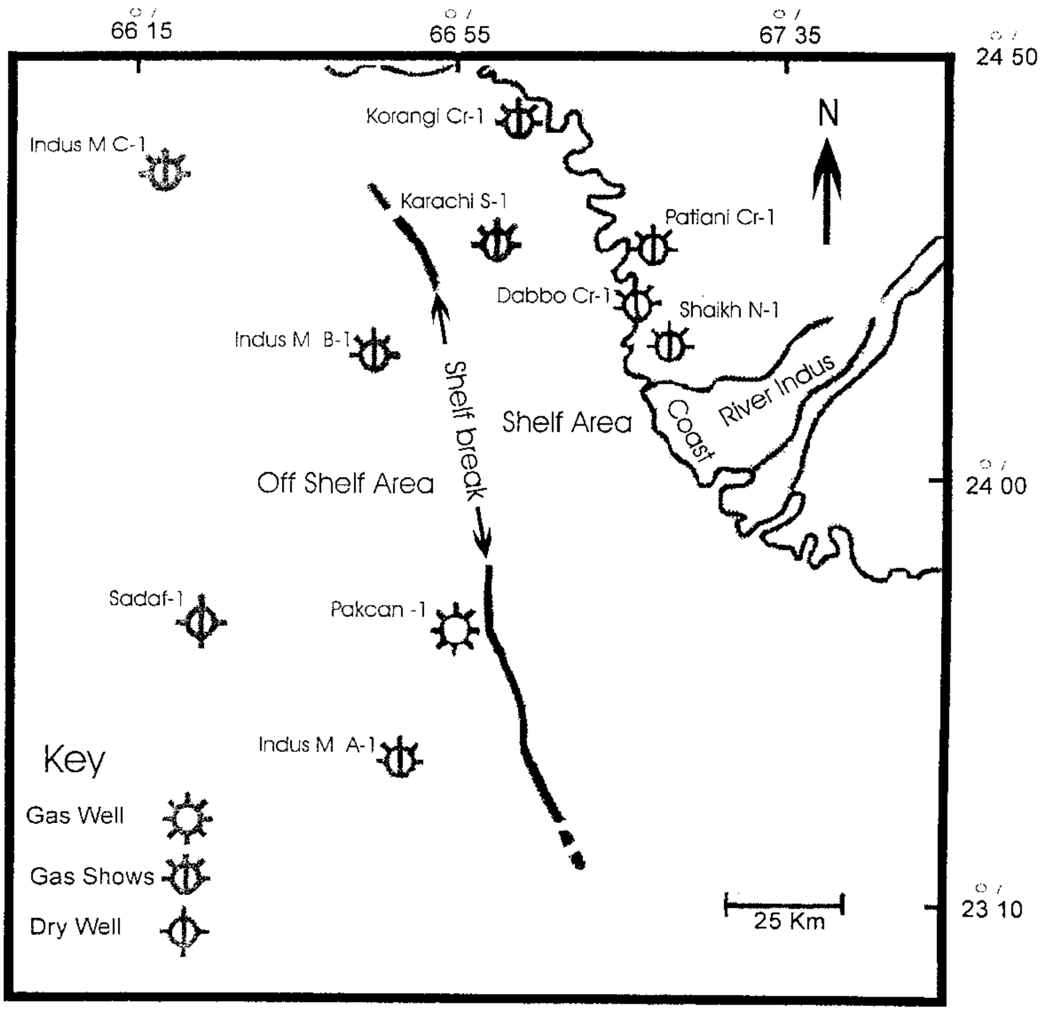

Figure 1- Map showing the location of study area (After Baloch and Quirk 1998, unpublished).

Table 1. Offshore Indus Basin wells.

Well (Company)	Location	Spud Date (Comp.Date)	Depth (m)	Formation (Age)	Remarks
1:Dabbo Creek-1 (Sun Oil)	Shelf area	8/12/63 (8/8/64)	4354m	Sembar (Aptian)	Minor hydrocarbon shows from Paleocene sandstone intervals. Plugged & Abandoned.
2:Patiani Creek.1 (Sun Oil)	Shelf area	19/8/64 (22/10/64)	2476m	Mughalkot (Maastrichtian)	Minor hydrocarbon shows from Paleocene sandstone intervals. Plugged & Abandoned.
3:Korangi Creek.1 (Sun Oil)	Shelf area	25/10/64 (21/2/65)	4140m	Mughalkot (Maastrichtian)	Minor hydrocarbon shows from Paleocene sandstone intervals. Plugged & Abandoned.
4:Karachi South.1 (Husky Oil)	Shelf area	26/2/78 (9/5/78)	3360m	Mughalkot (Maastrichtian)	Minor hydrocarbon shows from Paleocene sandstone intervals. Plugged & Abandoned.
5:Shaikh Nadin.1 (Canterbury)	Shelf area	5/2/92 (28/2/92)	1679m	Deccan Volcanic (Danian)	Minor hydrocarbon shows from Eoc-Oligocene limestone intervals. Plugged & Abandoned.
6:Indus Marine.A1 (Wintershall)	Basin area	12/9/72 (14/12/72)	2532m	Gaj (Langian-Burdigalian)	Minor hydrocarbon shows from Lower Miocene sandstone. Plugged & Abandoned.
7:Indus Marine.B1 (Wintershall)	Basin area	15/12/72 (14/3/73)	3804m	Gaj (Aquitanian)	Minor hydrocarbon shows from Lower Miocene sandstone. Plugged & Abandoned.
8:Indus Marine.C1 (Wintershall)	Basin area	2/2/75 (13/5/75)	6372m	Laki/Ghazij (Lower Eocene)	Minor hydrocarbon shows from Lower Miocene sandstone. Plugged & Abandoned.
9:Pakcan.1 (OGDC/PCIAC)	Basin area	27/9/85 (5/5/86)	3702m	Gaj (Burdigalian)	Declared as a non-commercial hydrocarbon discovery from lower Miocene sandstone. Plugged & Abandoned.
10:Sadaf.1 (Oxy)	Basin area	22/2/89 (8/3/90)	3980m	Gaj (Burdigalian)	No shows. Plugged & Abandoned.

- Rapidly checks against data calibration and modify to ensure the best output solution.
- Calculates geohistory for each kerogene type.
- Calculates source rock hydrocarbon potential and expulsion efficiency and pressure profile.
- Its output reports and plots are of presentation quality.
- It guides in using the programme and parameter selections.
- Terra Mod software computes hydrocarbon generation from type i, ii & iii kerogene for 100% of the same type and for one gram of organic carbon.

INPUT DATA

The parameters from the selected 6-wells drilled in this basin including depth, type of lithology, thickness, porosity, event type (deposition & erosion), time and base age, (in million years), water depth, paleotemperature and heat flow rates have been used for each lithological unit/layers. The porosity variations with depth play an important role in sediment decompaction and compaction in a basin (Clark et al., 1996). The overlying sediments load, water column, and eustatic changes with time and tectonism have crucial impact over the sediments burial history of this basin.

OUTPUT DATA

The output data generated by the software as a result of basin simulation comprises the report including generated hydrocarbon volume for the individual layers encountered in the wells of both shelf and basin areas. In addition the computed total matrix porosity and computed subsidence and type-ii hydrocarbon histories have been generated.

METHODOLOGY AND CONCEPT OF MODELING

The well data of this basin has been utilized to precisely simulate deposition, fluid dynamics and heat flow occurred during the process of subsidence, uplift and erosion while various basin development stages to enable in understanding a model, that best fits the specific geology of this basin. The results determine the potential volume and type of hydrocarbons generated in the basin and the period during which such hydrocarbon generation took place, with the knowledge whether prospects contain oil and gas or not. This process simulates the deposition, compaction, pressure build-up and heat flow process within various geological episodes of the basin to determine the history of source rock maturation and subsequent history of hydrocarbon generation and migration.

Physical and physiochemical processes within the geological mechanisms operating in a geological framework are quantified by accounting for mass and energy transport mechanisms operating in this sedimentary basin. The geological framework of the system is defined by the type and volumetric distribution of the sediments, age of sediments, temporal distribution of sediments, structural features, paleoenvironments, paleogeography, paleoclimate and plate motion (Sengor, 1995).

Generation of hydrocarbon is determined from the kinetic equation. The kinetic equations are based on the assumption that oil is generated from degradation of kerogene and gas is generated from cracking oil (Demaison et al., 1984). The generation of gas directly from kerogene is assumed to be negligible for this study.

INTERPRETATION

Shelf Area

The computed subsidence and hydrocarbon generation geohistory plot based on shelf area well Karachi South-1 data indicates convex-up position at Mid-Eocene, Late Eocene-Early Oligocene, Early Miocene and Late Miocene-Early Pliocene are interpreted to be produced as a result of flexure subsidence (Figure 2). The variation in subsidence curve may indicate variation in the tectonic events for Offshore Indus Basin, that is useful in the interpretation of its subsidence history. Two basic geometry of subsidence curves, the concave-up and convex-up were described by Allen and Allen (1990). The higher rate of subsidence from Late Oligocene-Early Miocene and onward witnesses the possible tectonic event of Himalayan Orogeny with deposition of thick siliciclastic deposits in the Offshore Indus Basin of Pakistan. This higher subsidence event with deposition of thick siliciclastic sediments is not only witnessed on seismic facies but also penetrated in the basin area wells (Baloch, 2000/unpublished).

Thickness of Neogene siliciclastic sediments increases in west and south-west direction of the basin area. Thick siliciclastic sediments were sourced by Himalayan Mountains through Indus River from NE (Kolla and Coumes, 1987). The concave-up computed curve indicates thermal cooling in the Eocene, Oligocene, Miocene and younger successions in the Offshore Indus Basin of Pakistan (Figure 2). The concave-up shape are interpreted to represent secular cooling, often related to thermal contraction which occurs after rifting. The convex-up profile is interpreted to result from flexural subsidence due to advancing orogenic loading. (Allen and Allen, 1990).

The hydrocarbon history represents existence of type-ii kerogene generation during Cretaceous and Paleogene in the shelf area well Karachi South-1, (Figure 2 and Table 2). The computed water depth input data and thermal flow for the shelf area well Karachi South-1 with its Paleocene to Quaternary range (Figure 3) is based on information used as input data of Karachi South-1. The computed matrix porosity versus depth plotted for Paleocene and younger strata reveals 18-25% porosity range for the Paleocene Ranikot Formation reservoir in the well Karachi South-1 (Figure 4). Good quality reservoir rocks are present within Paleocene and Eocene age formations. The present study reveals that in the shelf area of the Offshore Indus Basin of Pakistan hydrocarbon generation took place in the Cretaceous Mughalkot and Pab formations, Paleocene Ranikot Formation and Eocene Laki-Ghazij and Kirthar formations (Table 2).

The tectonic subsidence and Paleo water depth act as functions of time date back in the basin evolution history. Organic abundancy and thermal maturation allow geohistory curve to calibrate. The burial and thermal history are useful objects in determination of hydrocarbon potential. The source rocks contain vitrinite in the shelf area Cretaceous Sembar Formation, Lower Goru Formation and Eocene Laki-Ghazij Formation Shales. The type-ii kerogene represents the most favorable hydrocarbons (Figure 2).

The degree of hydrocarbon sorting, proximity of fluvial inputs and the nature of climate and coastal vegetation are some of the important factors for the generation of type-ii kerogene (Brooks and Archer, 1987). The source rock characteristics of clay grade sediments are generally controlled by bottom water oxygenation and proximity to fluvial source. The oceanic upwelling may result in high productivity in the surface water and the accumulation of diatomaceous organic rich sediments in the shelf area of the Offshore Indus Basin of Pakistan.

Basin Area

Computed tectonic subsidence and hydrocarbon generation in the basin area have been interpreted for 5 wells. These wells are Indus Marine-A1, Indus Marine-B1, Indus Marine-C1, Pakcan-1 and Sadaf-1. All these wells are best representatives of the Neogene succession, except the well Indus Marine-C1 that penetrated Eocene at TD, due to its position in the basin. The wells Indus Marine-B1 and Pakcan-1 contain high quality data. Indus Marine-B1 is the deepest well penetrated the Aquitanian (Early Miocene), whereas Pakcan-1 though not drilled as deep as Indus Marine-B1 but it produced hydrocarbon on DST, due to its position of being located close to the slope area on progradational sediments (Baloch, 2000/unpublished).

The data from Indus Marine-B1 and Pakcan-1 wells is found very useful in calibration of rigorous tectonic events of Miocene and younger strata (Figure 5 and 8) with generation of type-ii kerogene (Table 3 and 4). These wells also reveal representative water depth and heat flow (Figure 6 and 9), matrix porosity (Figure 7 and 10) and liquid and gaseous hydrocarbons in the basin area (Figure-5 and 8 and Tables 3 and 4). The well Pakcan-1 was even declared as a non-commercial hydrocarbon discovery in this basin.

Other wells including Indus Marine-A1 and Indus Marine-C1 due to their position in the basin reveal representative tectonic curves for Miocene and younger events (Figure 11 and 14). Indus Marine-A1 indicates hydrocarbon in the Middle Miocene (Figure 11 and Table 5), The computed heat flow and water depth information (Figure 12) with 18-22% porosity range (Figure 13) in Middle-Late Miocene indicate good quality reservoir existence in the well Indus Marine-A1.

The well Indus Marine-C1 does not indicate significant hydrocarbon generation (Figure 14 and Table 6) due to reason that the objective Early-Middle Miocene reservoir were penetrated at a shallow depth in this well due to its position in the basin. Higher heat flow data in the well Indus Marine-C1 (Figure 15) is due to its location close to Murray-Ridge. The reservoir of the Early-Middle Miocene penetrated at a shallower depth in the well Indus Marine-C1 with high porosity of 20-25% (Figure 16).

The latest well Sadaf-1 indicates representative tectonic events for Neogene and younger successions (Figure 17), but does not show significant hydrocarbon generation (Figure 17 and Table 7). Reasons for weak hydrocarbon generation could be that the well was not penetrated in the objective deeper zones and abandoned in the younger horizons than Early Miocene. However information of water depth and heat flow in this well is best representative (Figure 18). The average porosity range within the Early-Middle Miocene is 15-18%. (Figure 19). Reason for decrease in porosity is the load of the overlying thick younger sediments that enhanced the process of compaction and decreased the rate of porosity with depth. The well

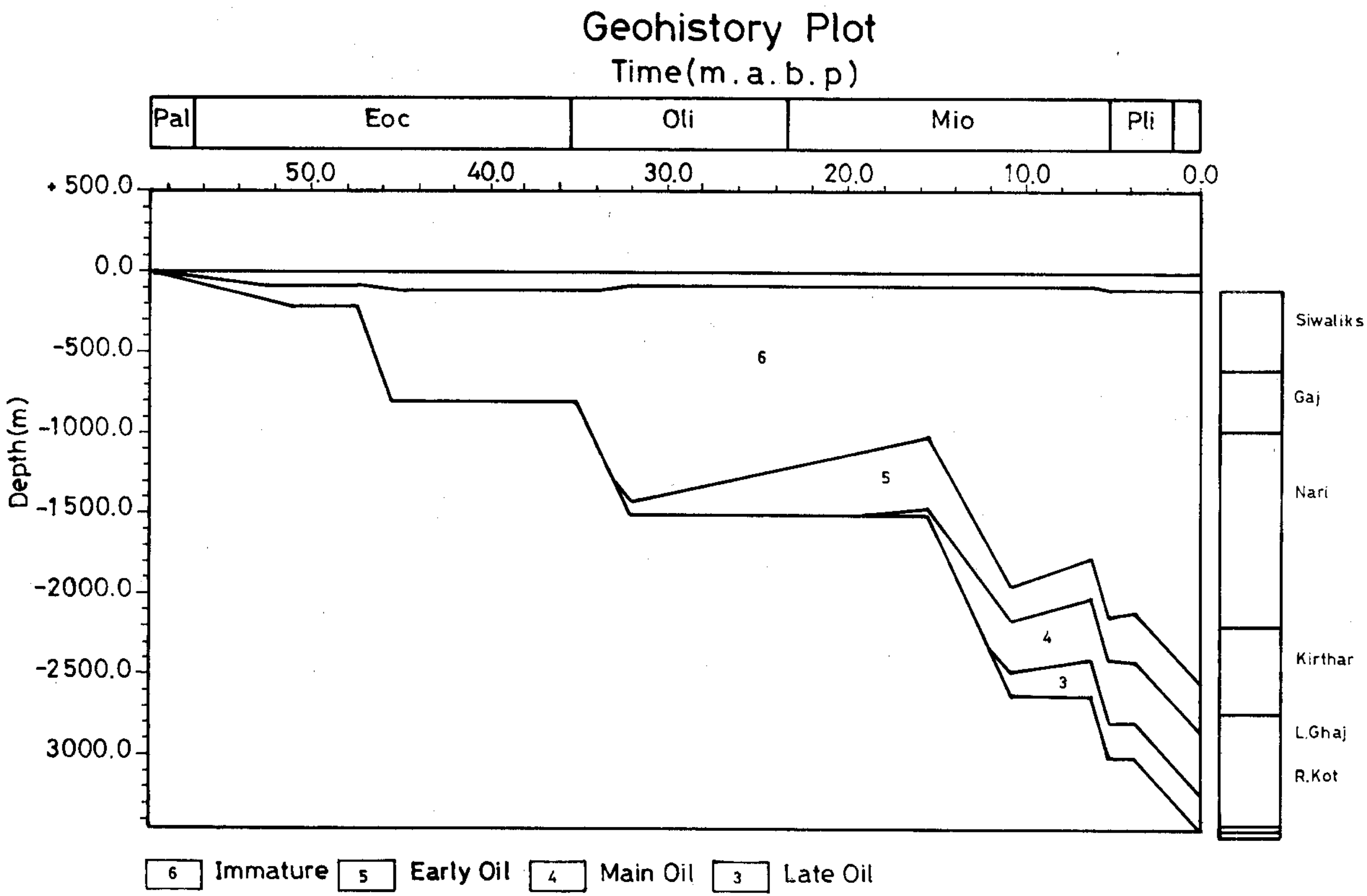

Figure 2- Computed subsidence and hydrocarbon generation (Type II) histories (Karachi South-1 well).

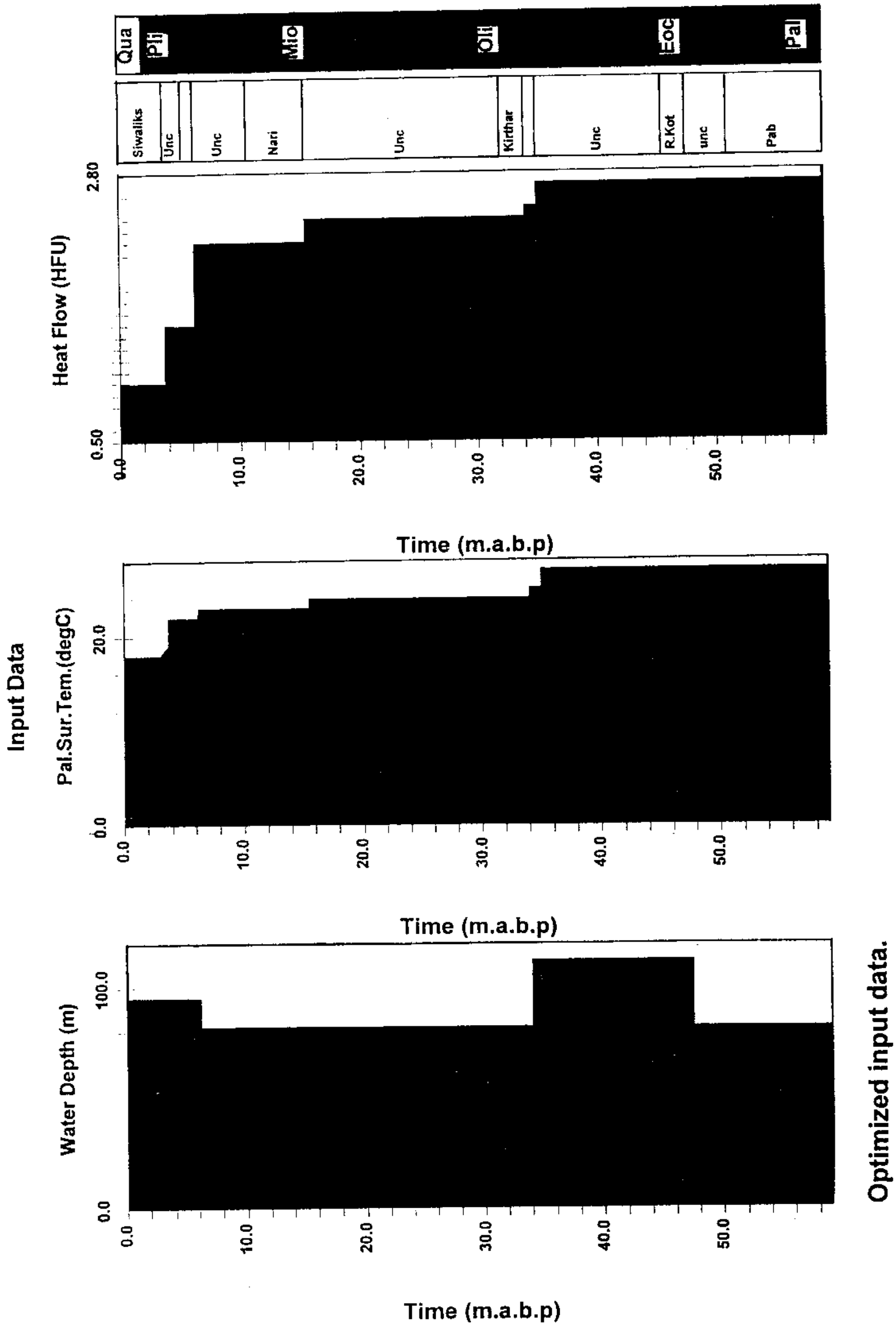

Figure 3- Optimized input data (Karachi South-1 well).

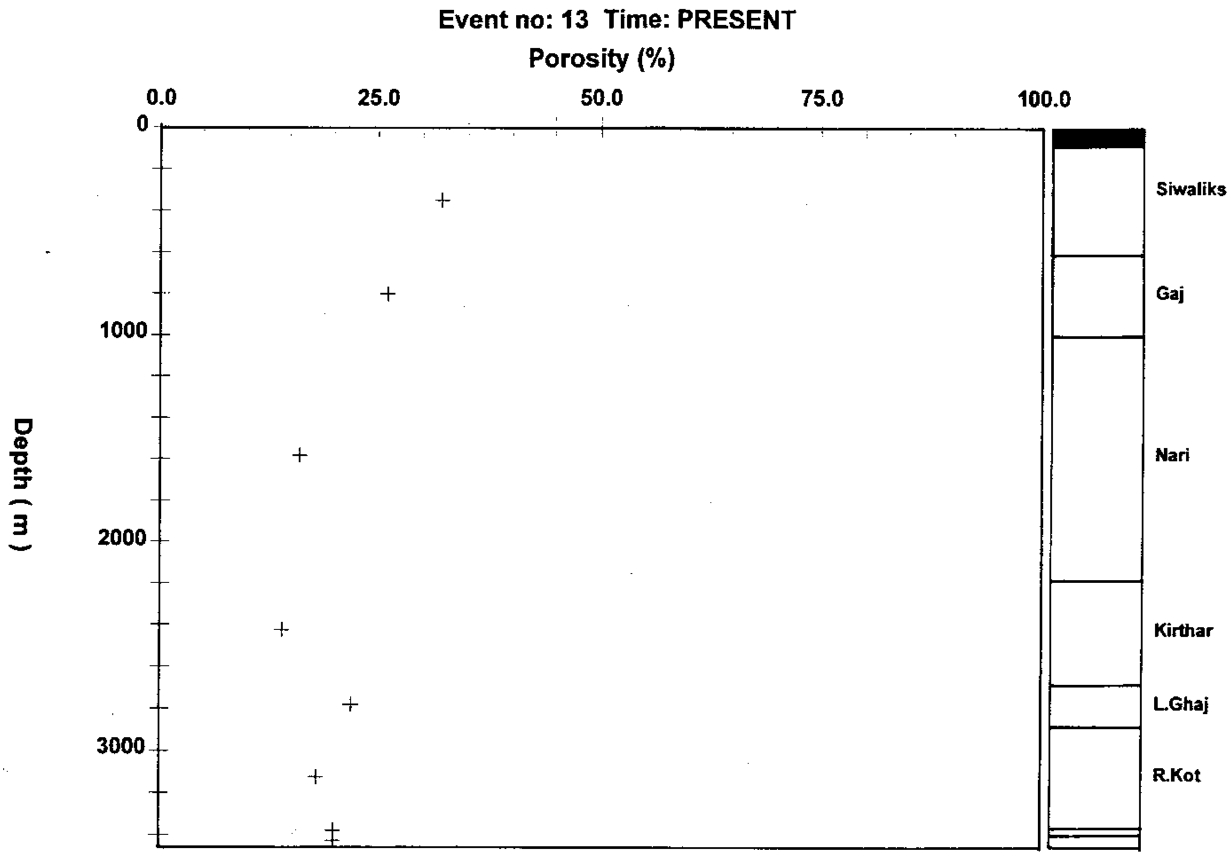

Figure 4- Computed total matrix porosity at PRESENT (Karachi South-1 well).

Table 2. Output data report: Hydrocarbon volumes generated (Karachi South-1 well).

Layer No.	Layer Name	Thickness (metres)	Lithology	Total Oil Generated per Km 2/ S.R. Thickness (mm tonnes)	Total Gas Generated per Km 2/ S.R. Thickness (mm cubic metres)
1	M.Kot	44.00	shly slty Sst w/ cal	0.401	5.616
2	Pab	27.00	crs. Sd. & Sltst	0.192	2.130
4	R.Kot	503.00	crs. Sd. & Sltst	3.180	30.644
6	L.Ghaj	186.00	carb. calc. Sh.	0.589	0.122
7	Kirthar	545.00	Lst w/ dol.	0.557	0.000
9	Nari	1215.00	Lst w/ dol.	0.418	0.000
11	Gaj	375.00	crs. Sd. & Sltst	0.010	0.000
13	Siwaliks	502.00	crs. Sd. & Sltst	0.000	0.000

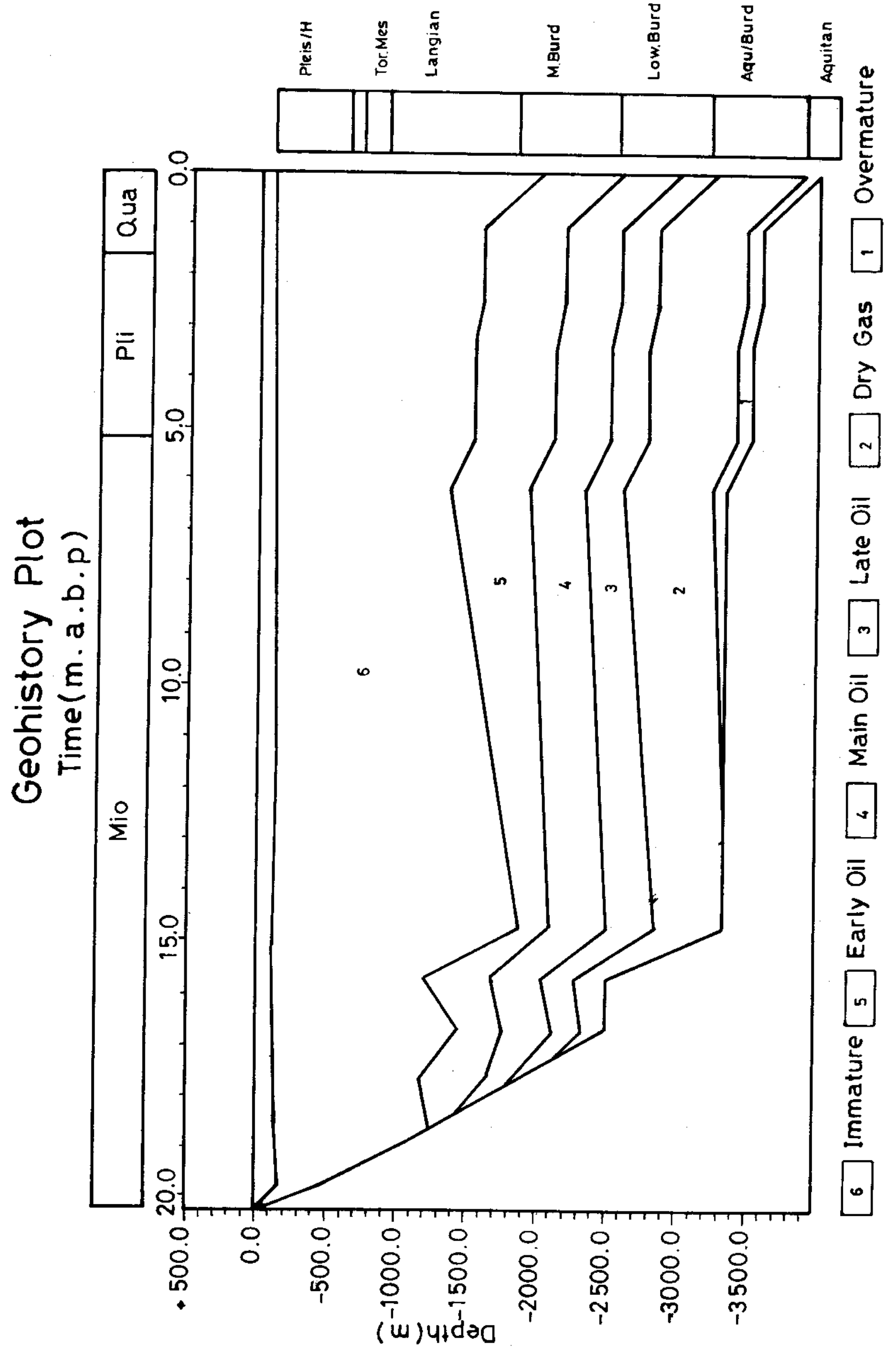

Figure 5- Computed subsidence and hydrocarbon generation (Type II) histories (Indus Marine-B1 well).

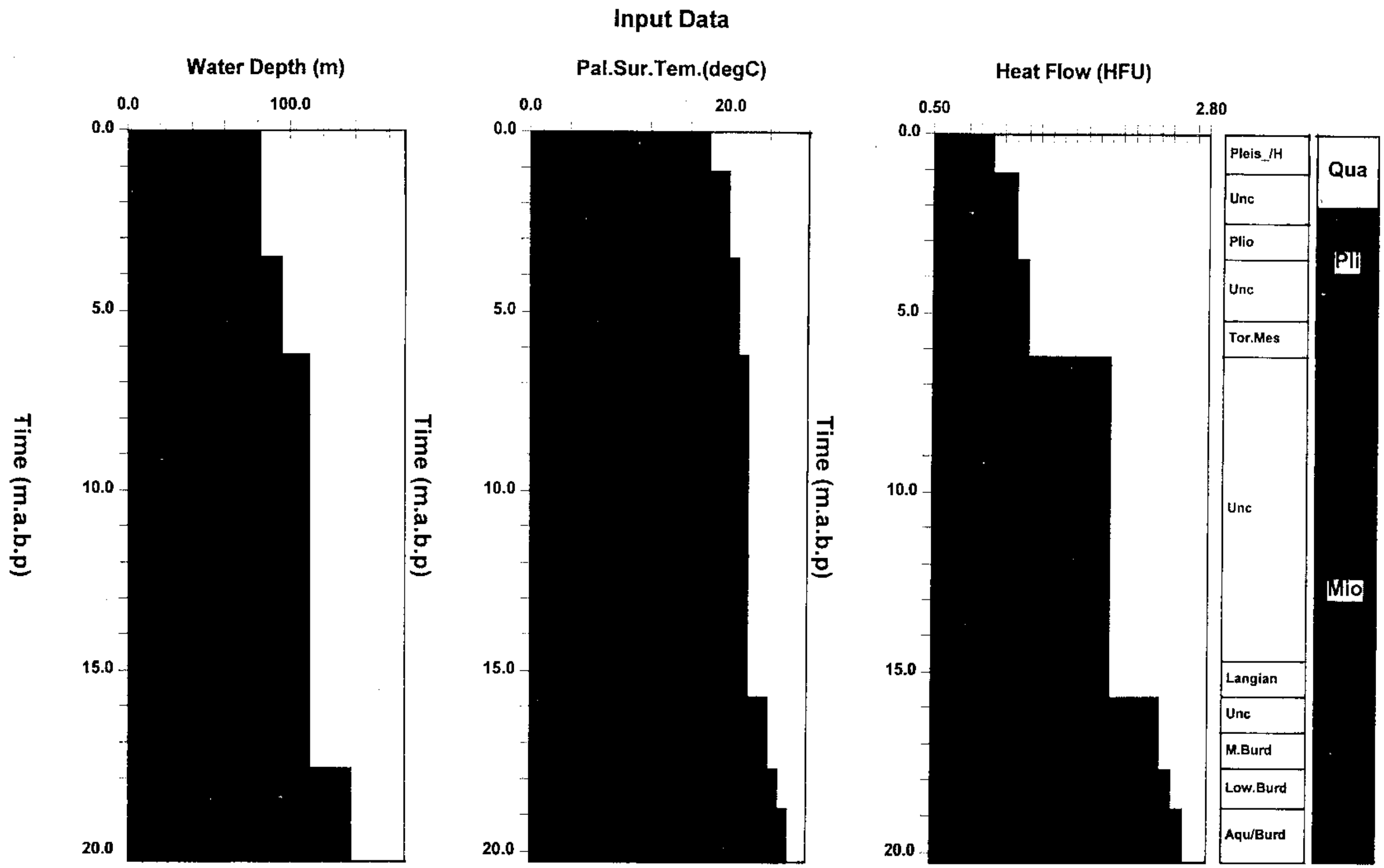

Figure 6- Optimized input data (Indus Marine-B1 well).

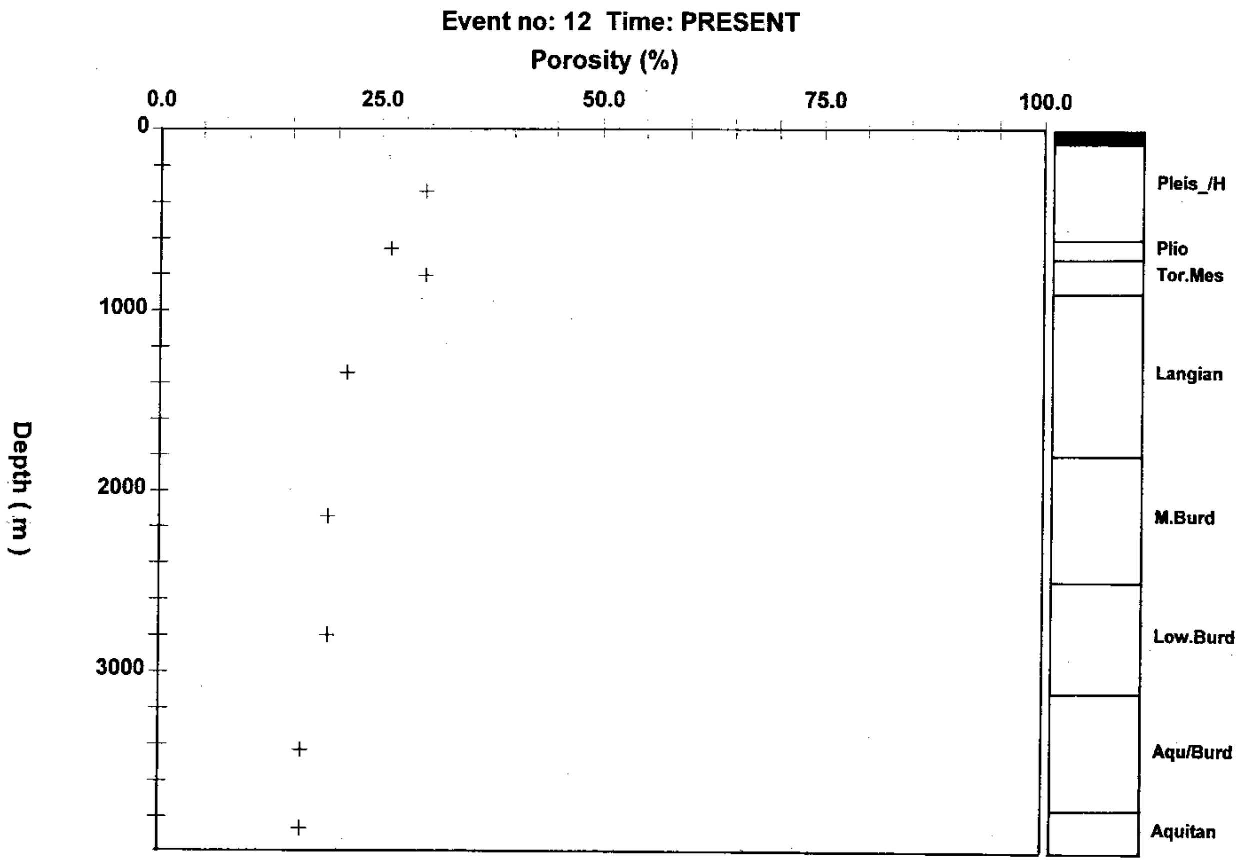

Figure 7- Computed total matrix porosity at PRESENT (Indus Marine-B1 well).

Table 3. Output data report: Hydrocarbon volumes generated (Indus Marine-B1 well).

Layer No.	Layer Name	Thickness (metres)	Lithology	Total Oil Generated per Km 2/ S.R. Thickness (mm tonnes)	Total Gas Generated per Km 2/ S.R. Thickness (mm cubic metres)
1	Aquitan	232.00	crs. Sd. & Sltst	1.550	43.397
2	Aqu/Burd	674.00	crs. Sd. & Sltst	4.322	117.419
3	Low Burd	664.00	slty Sst # 2	4.009	28.270
4	M. Burd	729.00	crs. Sd. & Sltst	1.414	0.216
6	Langian	926.00	crs. Sd. & Sltst	0.311	0.000
8	Tor. Mes	171.00	slty shly Sst.	0.005	0.000
10	Plio	107.00	crs. Sd. & Sltst	0.000	0.000
12	Pleis_/H	533.00	crs. Sd. & Sltst	0.000	0.000

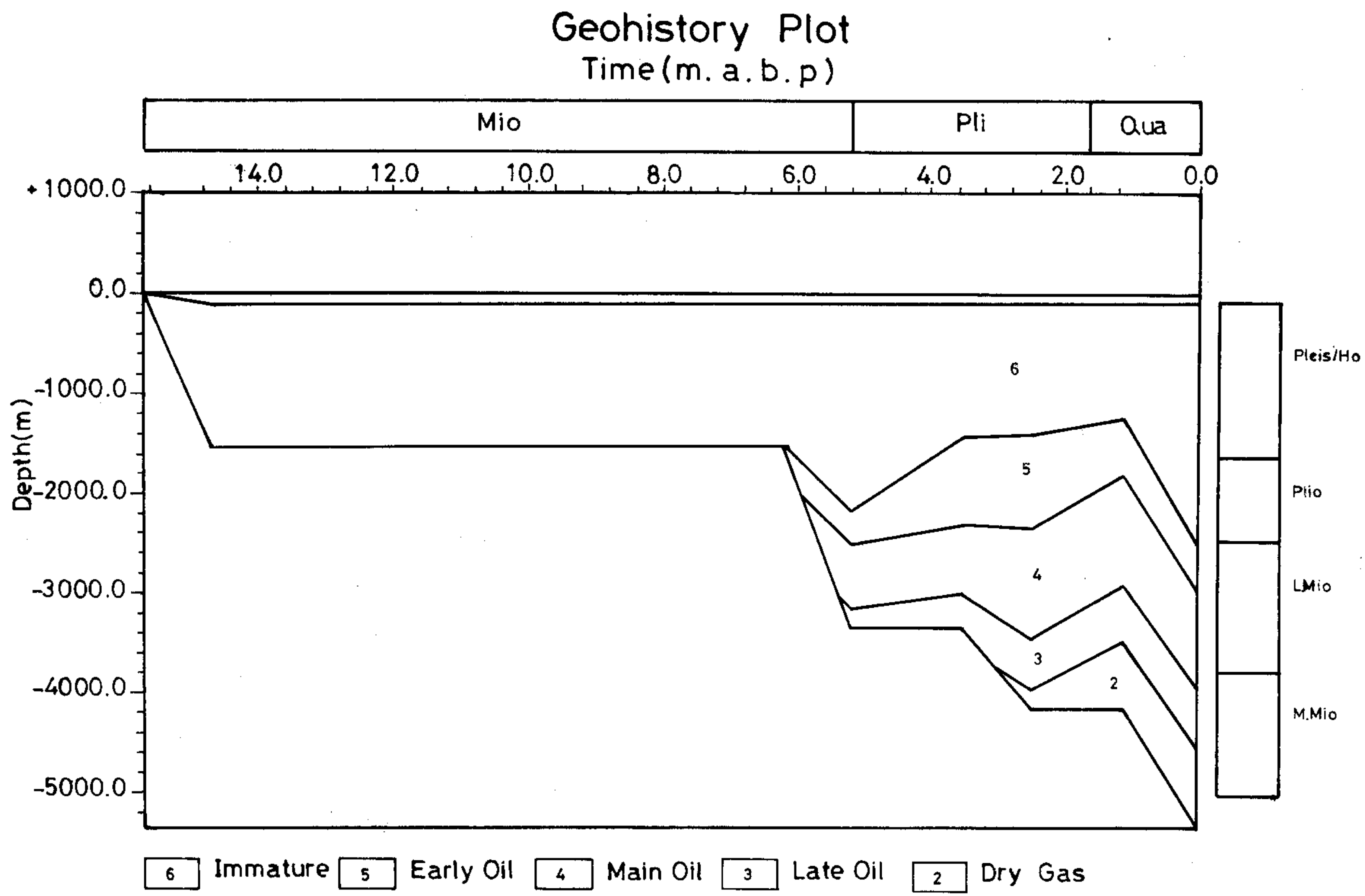

Figure 8- Computed subsidence and hydrocarbon generation (Type II) histories (Pakcan-1 well).

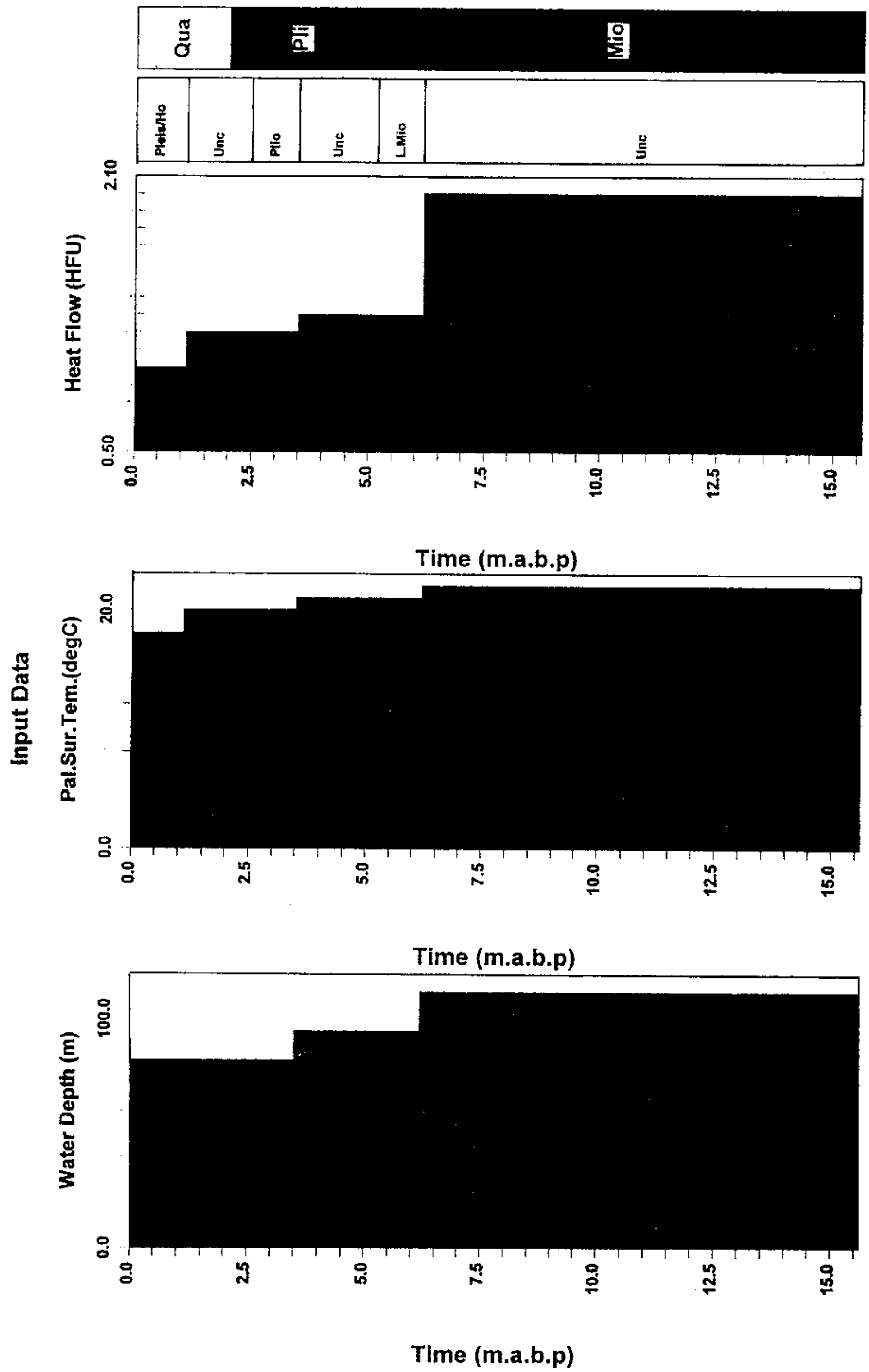

Figure 9- Optimized input data (Pakcan-1 well).

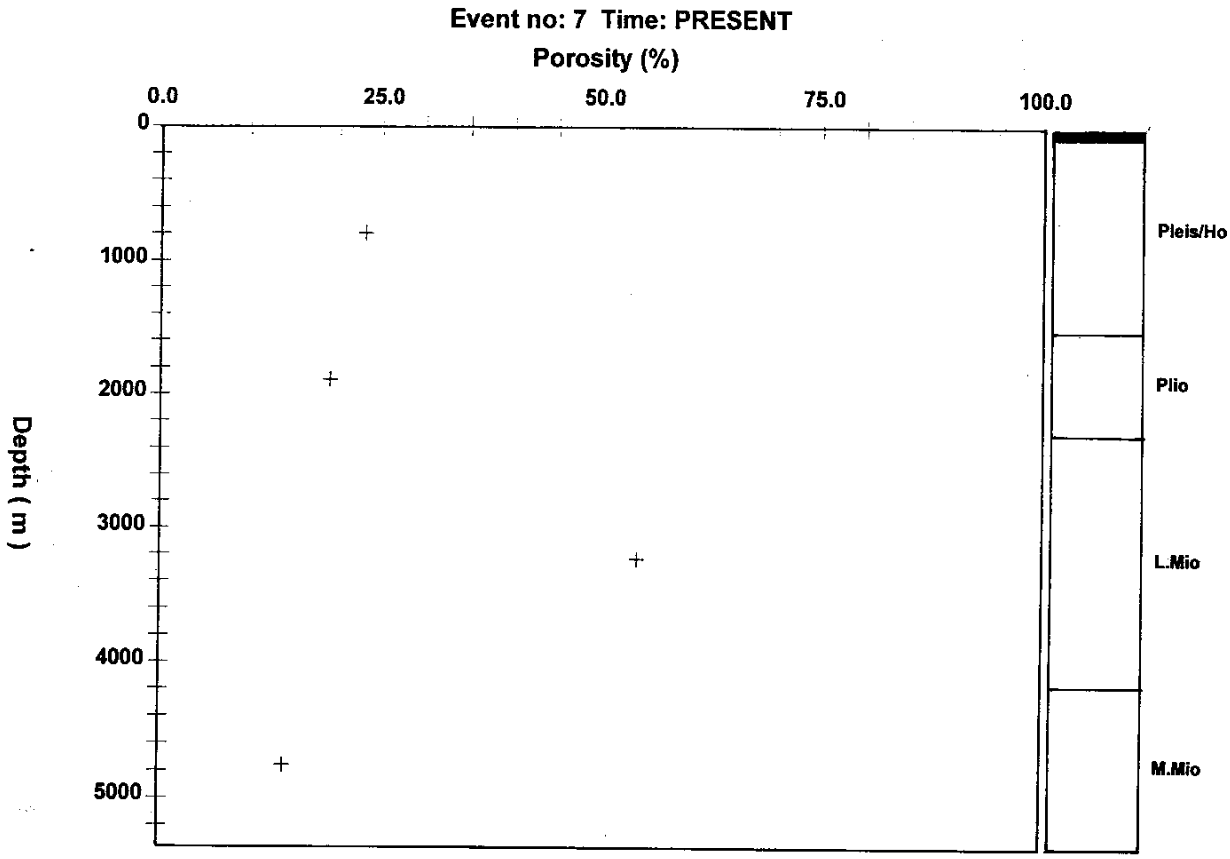

Figure 10- Computed total matrix porosity at PRESENT (Pakcan-1 well).

Table 4. Output data report: Hydrocarbon volumes generated (Pakcan-1 well).

Layer No.	Layer Name	Thickness (metres)	Lithology	Total Oil Generated per Km 2/ S.R. Thickness (mm tonnes)	Total Gas Generated per Km 2/ S.R. Thickness (mm cubic metres)
1	M. Mio	1250.00	crs. Sd. & Sltst	8.152	199.490
3	L. Mio	1307.00	slty shly Sst.	10.171	19.478
5	Plio	840.00	crs. Sd. & Sltst	0.037	0.000
7	Pleis/Ho	1553.00	crs. Sd. & Sltst	0.000	0.000

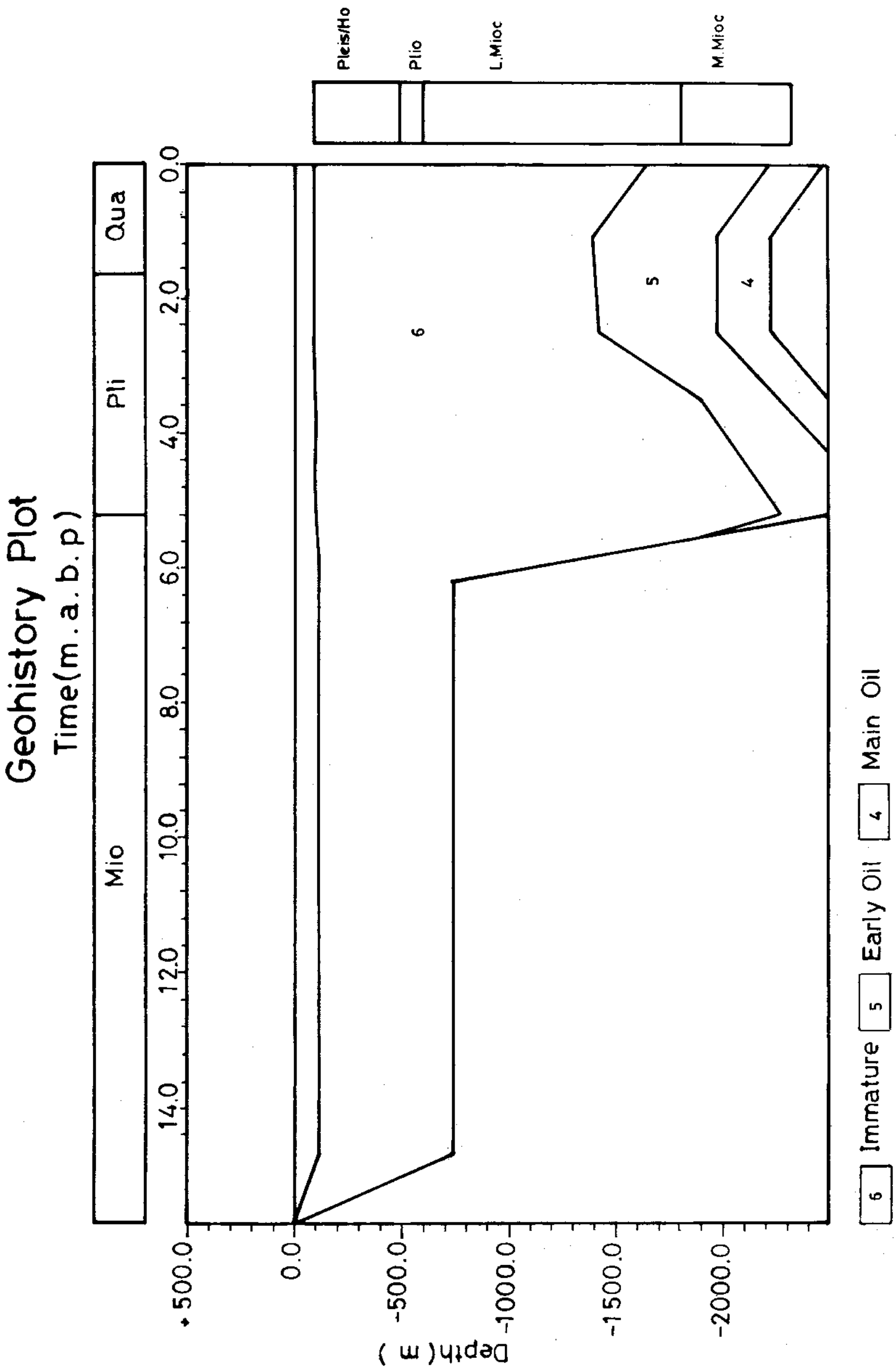

Figure 11- Computed subsidence and hydrocarbon generation (Type II) histories (Indus Marine-A1 well).

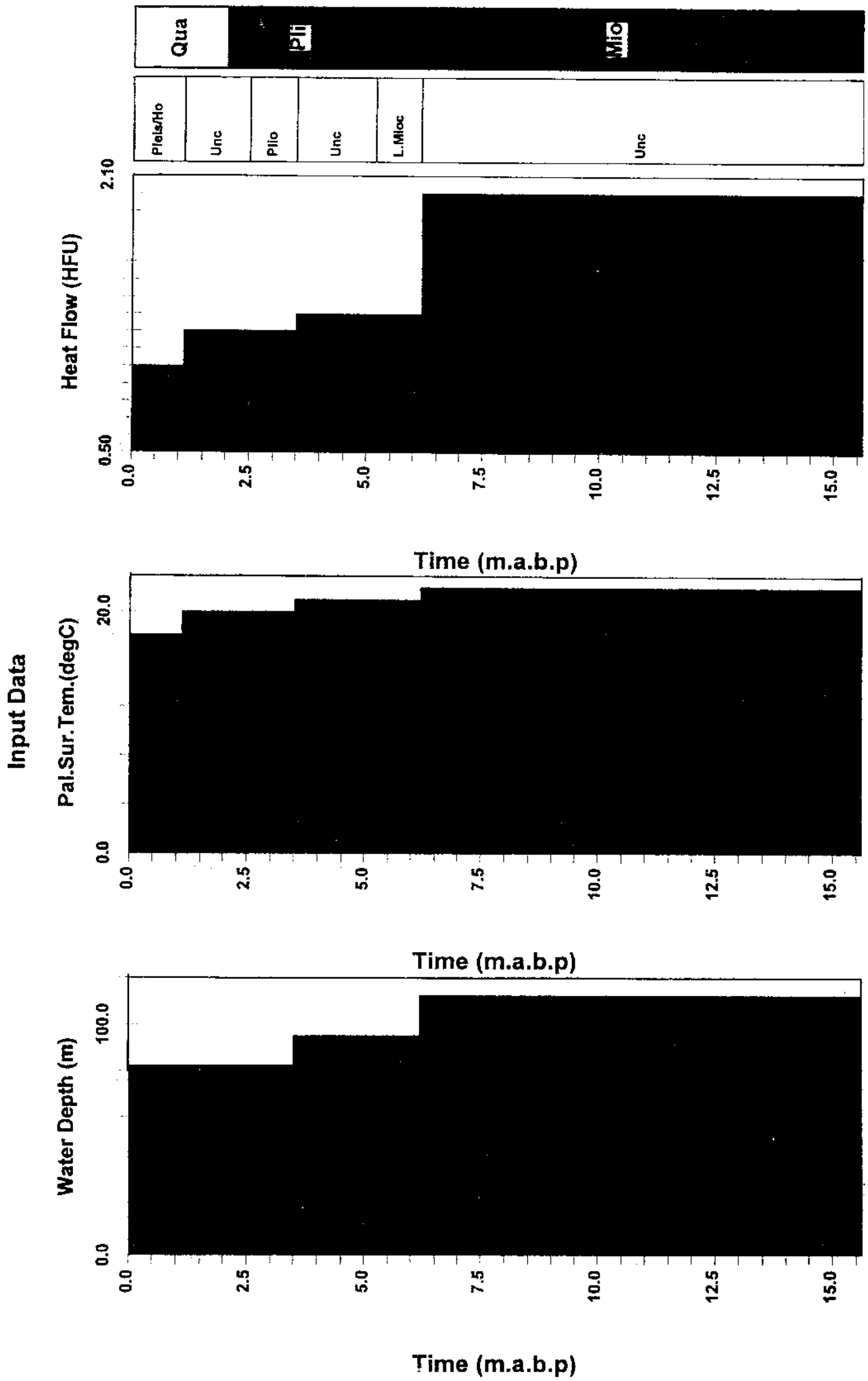

Figure 12- Optimized input data (Indus Marine-A1 well).

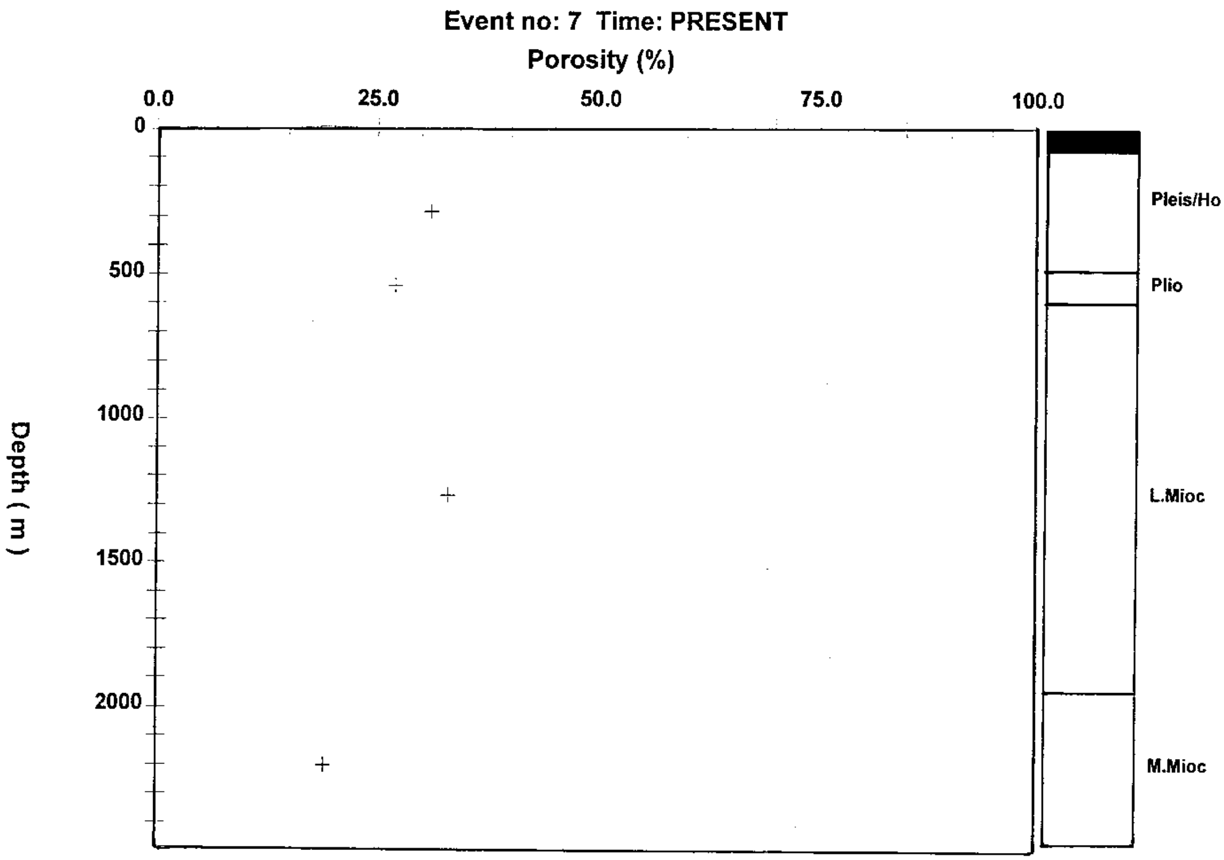

Figure 13- Computed total matrix porosity at PRESENT (Indus Marine-A1 well).

Table 5. Output data report: Hydrocarbon volumes generated (Indus Marine-A1 well).

Layer No.	Layer Name	Thickness (metres)	Lithology	Total Oil Generated per Km 2/ S.R. Thickness (mm tonnes)	Total Gas Generated per Km 2/ S.R. Thickness (mm cubic metres)
1	M. Mioc	520.00	crs. Sd. & Sltst	2255	0961
3	L. Mioc	1210.00	slty shly Sst.	1407	0000
5	Plio	107.00	crs. Sd. & Sltst	0000	0000
7	Pleis/Ho	407.00	crs. Sd. & Sltst	0000	0000

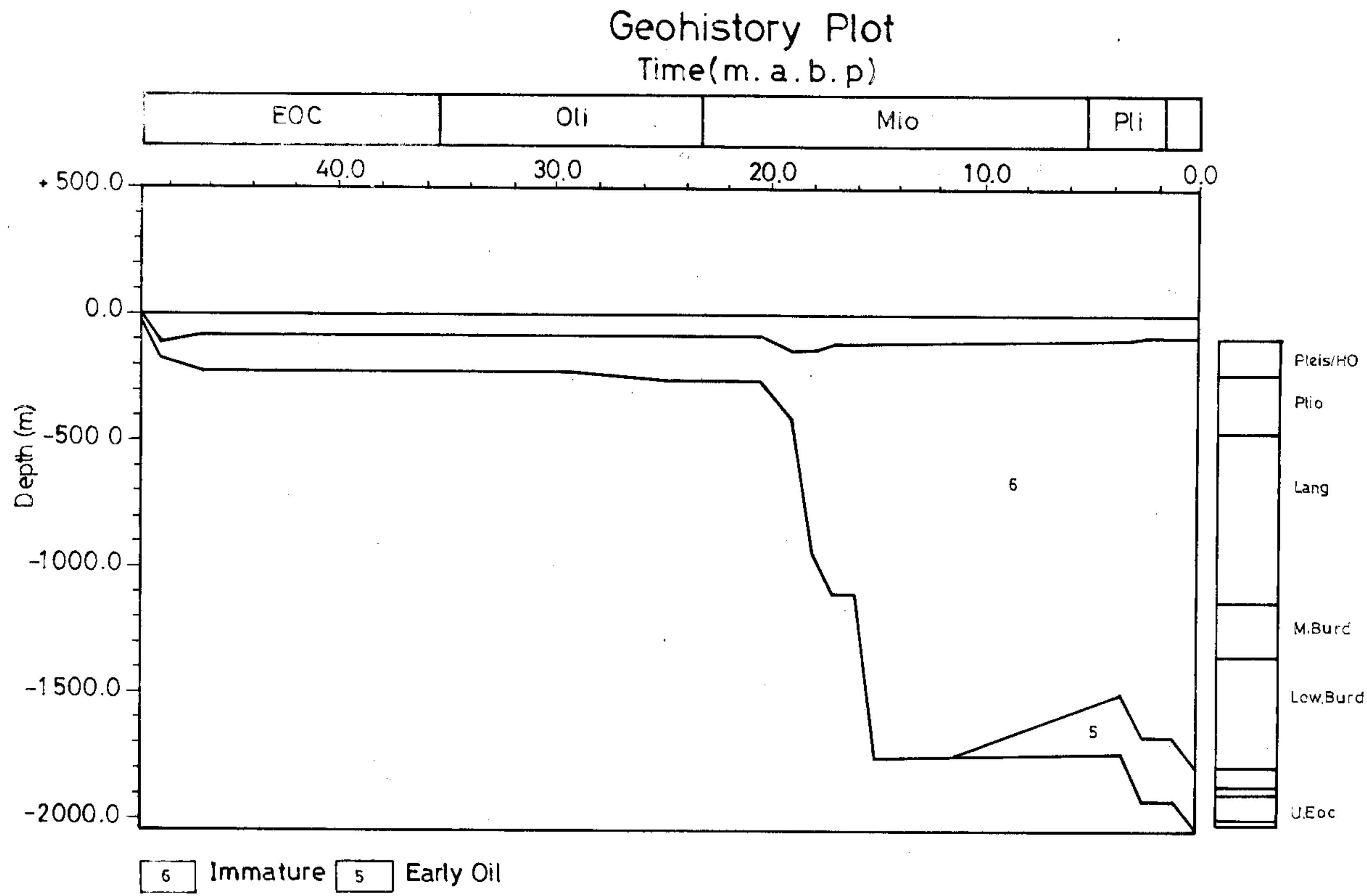

Figure 14- Computed subsidence and hydrocarbon generation (Type II) histories (Indus Marine-C1 well).

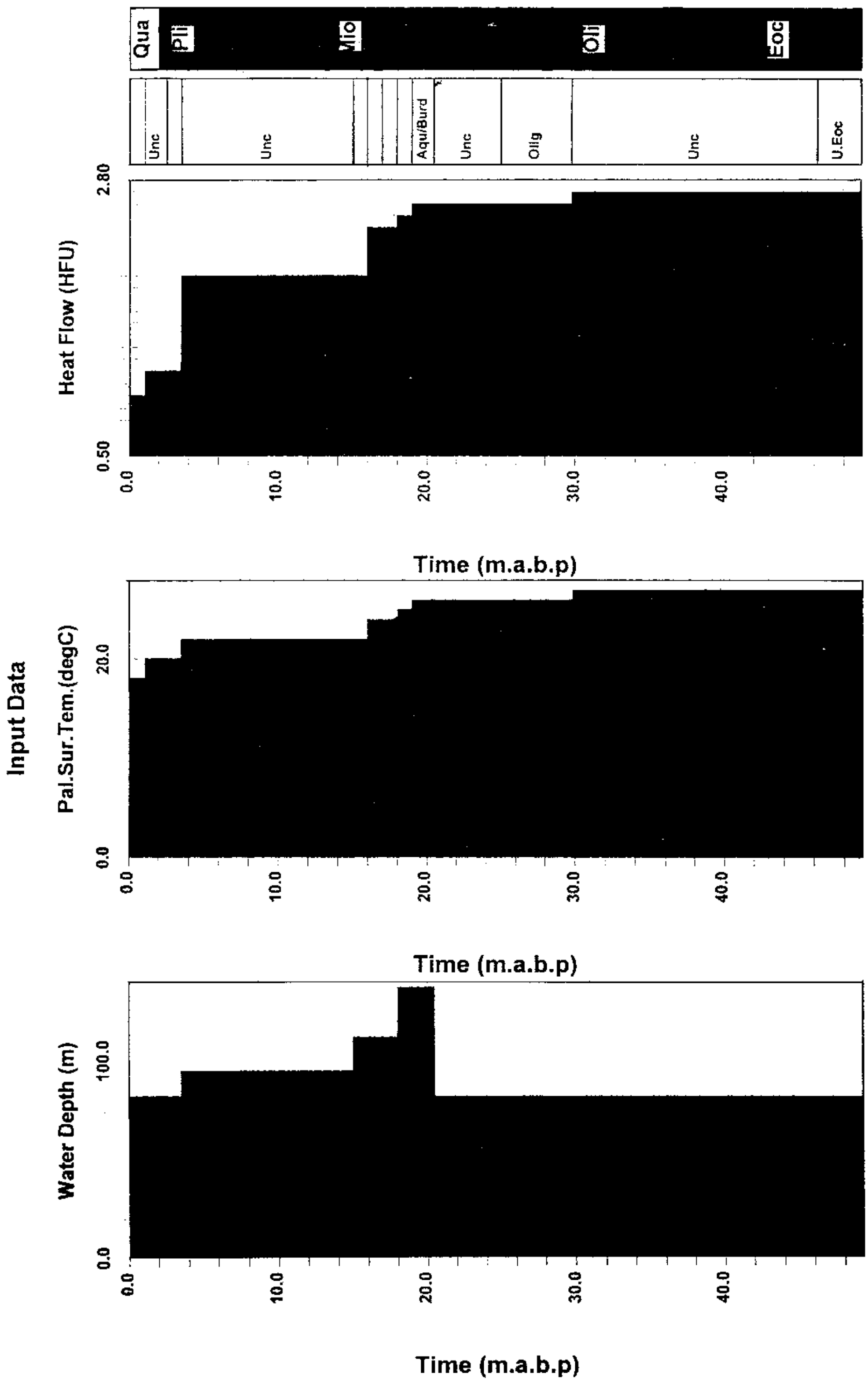

Figure 15- Optimized input data (Indus Marine-C1 well).

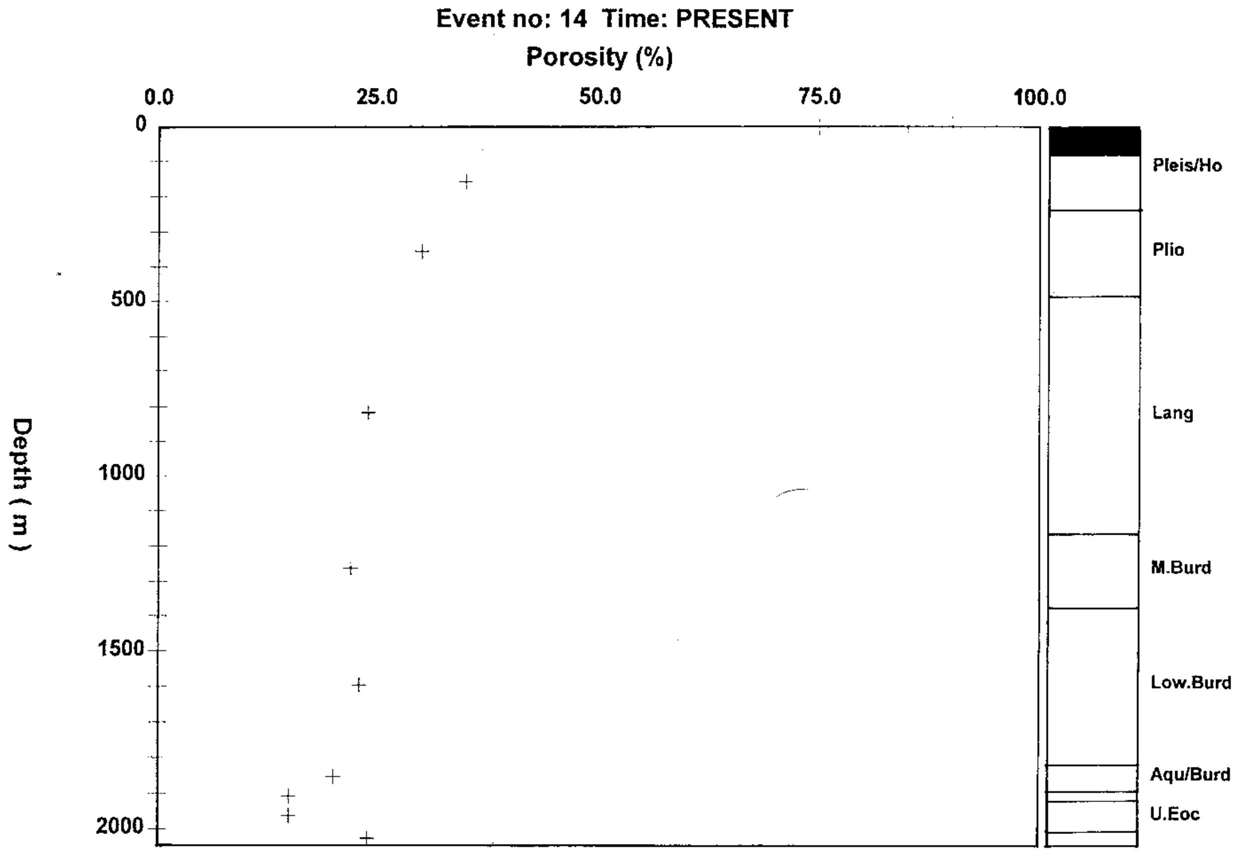

Figure 16- Computed total matrix porosity at PRESENT (Indus Marine-C1 well).

Table 6. Output data report: Hydrocarbon volumes generated (Indus Marine-C1 well).

Layer No.	Layer Name	Thickness (metres)	Lithology	Total Oil Generated per Km 2/ S.R. Thickness (mm tonnes)	Total Gas Generated per Km 2/ S.R. Thickness (mm cubic metres)
1	L. Eoc	34.00	carb. calc. Sh.	0.063	0.000
2	U. Eoc	94.00	Lst w/ dol.	0.134	0.000
4	Olig	28.00	Lst w/ dol.	0.036	0.000
6	Aqu/Burd	79.00	crs. Sd. & Sltst	0.083	0.000
7	Low. Burd	437.00	slty Sst # 2	0.382	0.000
8	M. Burd	220.00	crs. Sd. & Sltst	0.066	0.000
10	Lang	672.00	crs. Sd. & Sltst	0 .146	0.000
12	Plio	232.00	crs. Sd. & Sltst	0.006	0.000
14	Pleis/Ho	146.00	crs. Sd. & Sltst	0.000	0.000

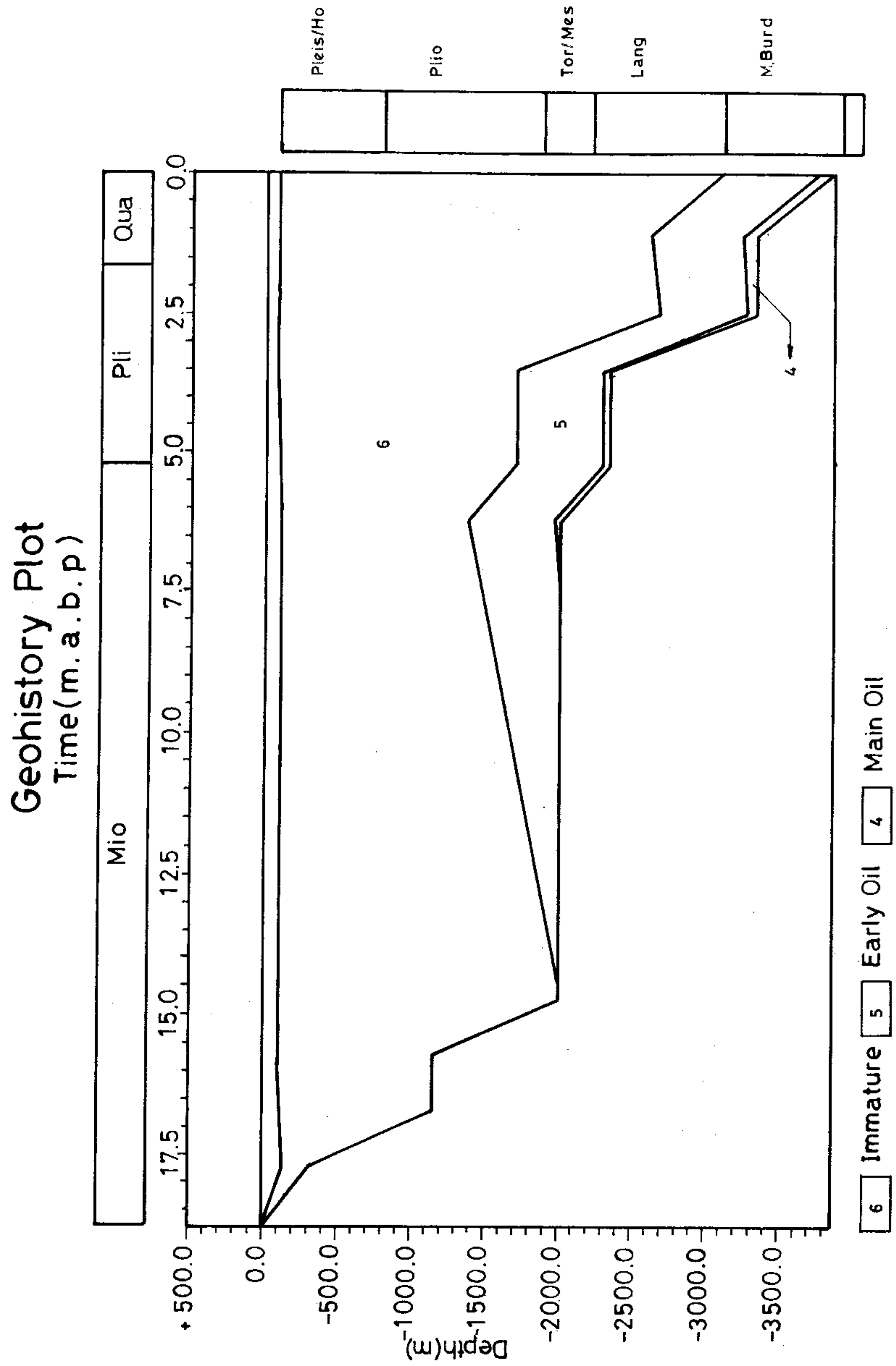

Figure 17- Computed subsidence and hydrocarbon generation (Type II) histories (Sadaf-1 well).

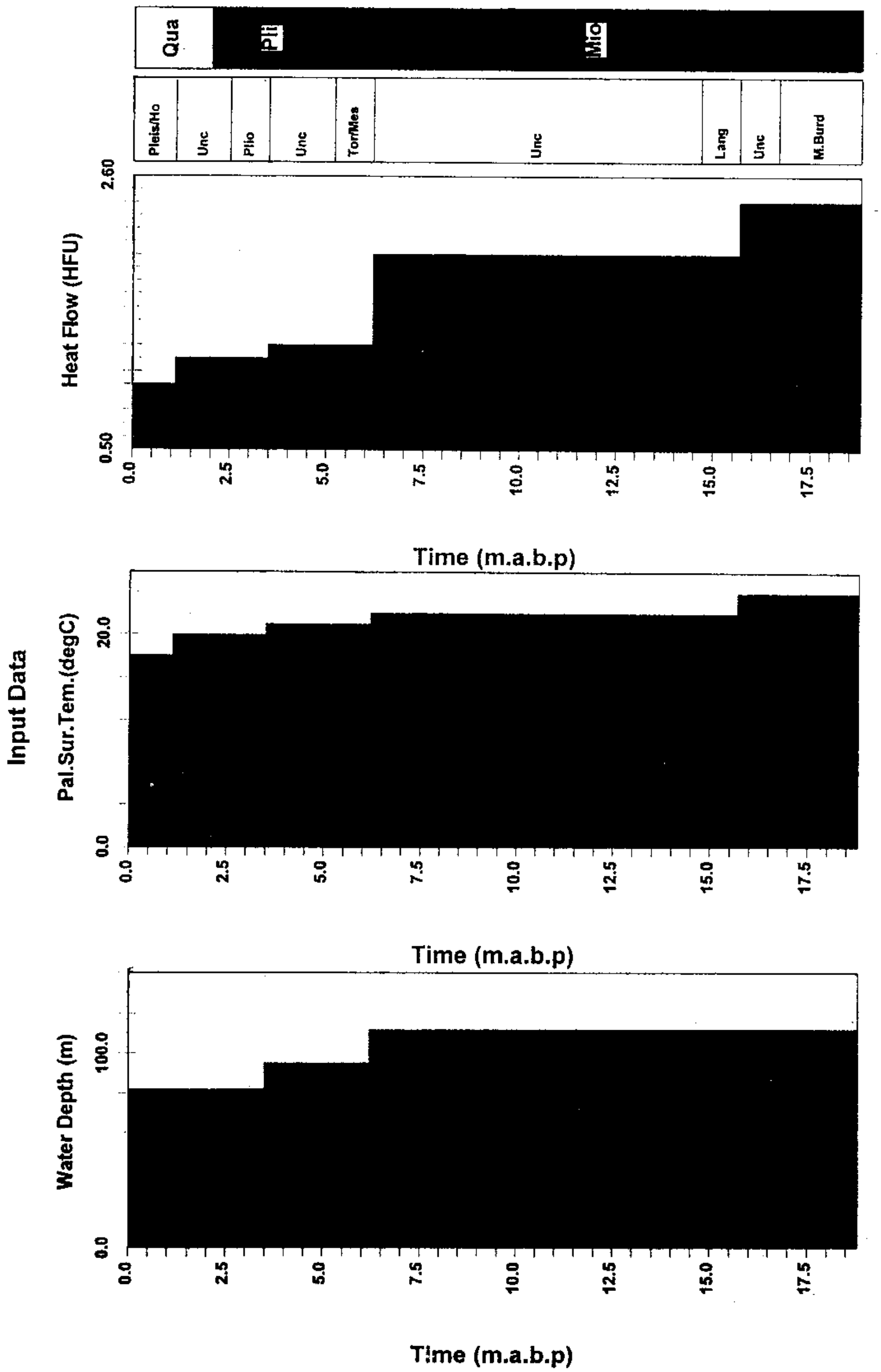

Figure 18- Optimized input data (Sadaf-1 well).

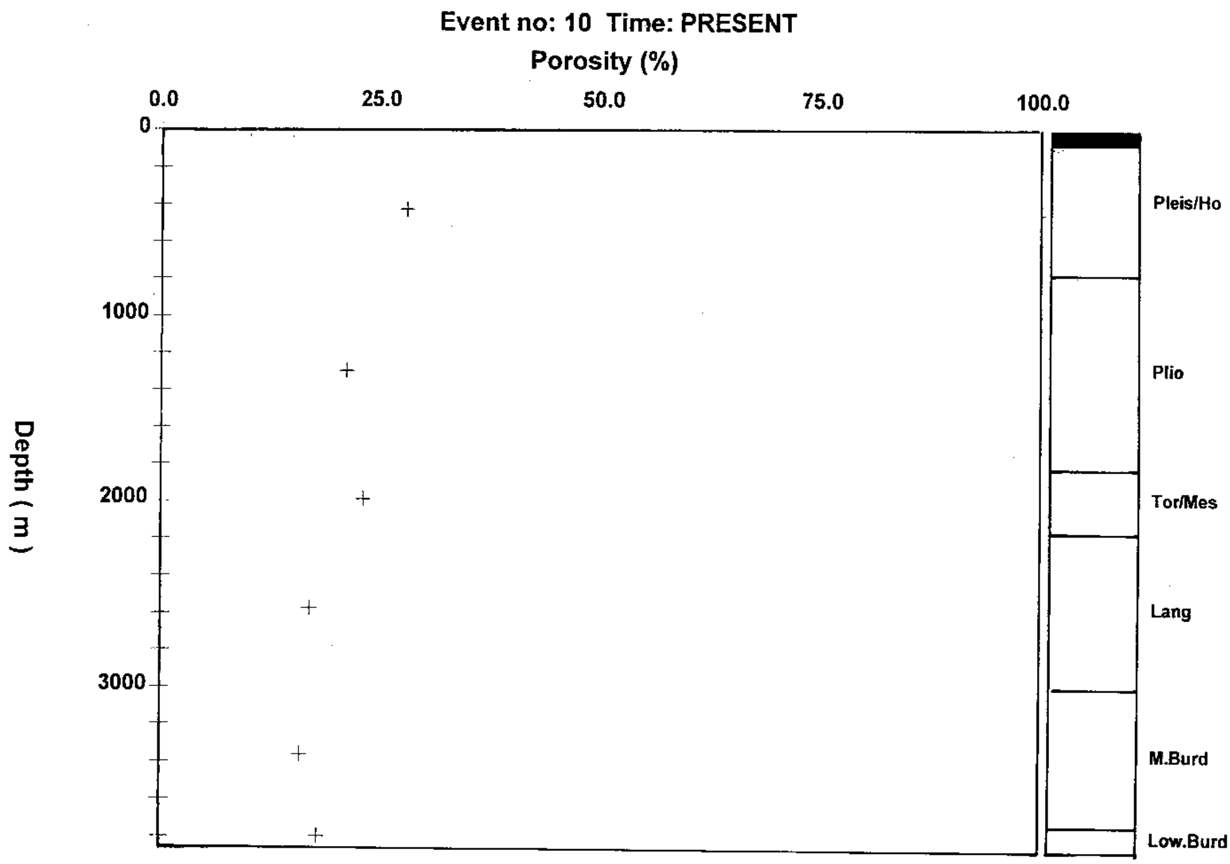

Figure 19- Computed total matrix porosity at PRESENT (Sadaf-1 well).

Table 7. Output data report: Hydrocarbon volumes generated (Sadaf-1 well).

Layer No.	Layer Name	Thickness (metres)	Lithology	Total Oil Generated per Km 2/ S.R. Thickness (mm tonnes)	Total Gas Generated per Km 2/ S.R. Thickness (mm cubic metres)
1	Low. Burd	140.00	slty. Sst. #1	0.484	0.156
2	M. Burd	795.00	crs. Sd. & Sltst	1.876	0.236
4	Lang	911.00	crs. Sd. & Sltst	0.448	0.000
6	Tor/Mes	334.00	slty shly Sst.	0.033	0.000
8	Plio	1084.00	crs. Sd. & Sltst	0.050	0.000
10	Pleis/Ho	716.00	crs. Sd. & Sltst	0.000	0.000

Sadaf-1 is located in a SSW basin area where younger sediments than Early-Middle Miocene are thickest and the objective horizons are deeper.

The possible basin area vitrinite containing source rocks in the Neogene Formations exist within the intra-formational shales of Early-Middle Miocene. The Late Cretaceous and Eocene shales discussed earlier may provide source material through high angle normal faults in the proximal basin area. However in the distal basin area where the younger sediments are very thick the source potential of Late Cretaceous may get over mature or even burnt due to high temperature conditions. The important index minerals found in abundance in the Offshore Indus Basin within the siliciclastic sediments of Neogene Formations are illite and smectite. The crystallinity of illite and reflection of smectite are thermal maturation indices, which allow geohistory curve to calibrate. The type and amount of hydrocarbon generation is mainly a function of heating rate (Brooks and Archer, 1987). For typical type-ii kerogene peak oil generation occurs between 0.7 and 0.8 Ro under normal heating rate (one to three degree Celcius/Ma) with low heating rate(less than one-degree celcius/Ma). Peak hydrocarbon generation occurs at vitrinite reflectance value lower than 0.7%. High heating rates may also result in high hydrocarbon generation rates (provided that adequate amount of organic matter exists in the potential source rock) that may result in the high expulsion efficiencies for oil. Such organic organisms have been found in abundance in the shelf and basin area wells of the Offshore Indus Basin (Shaw. 1965, Martin, 1973, Robertson Research, 1978, and Nuricon Petroservices, 1990). Consequently low heating rates may result in lower expulsion efficiencies.

SUMMARY

Tectonic Events

The major computed subsidence episodes generated for the basin using Terra Mod software include the followings:

- The first episode from about 60-55Ma shows evidence of minor subsidence in the basin. This was a time of extension and transtension along the north-western marginal basins of Indo-Pak Craton including Offshore Indus Basin of Pakistan.
- The second episode from 55-45Ma is associated with the Paleocene thermal cooling event of the basin. The concave-up shape is interpreted to represent secular cooling, often related to thermal contraction which occurs after rifting, which suggests tectonic subsidence due to an advancing orogenic load. The effect was recorded along the slope and in the basinal area.
- The third episode from 45-35Ma represents slow rate of subsidence that may indicate the flexuring of this foreland basin. This indicates that the sediments load was not significant during the episode representing Eocene. A possible explanation is that Indo-Pak Craton was advancing northward preventing the major loading and then subsequently entered a passive margin phase, with development of carbonate during Eocene.
- The fourth episode from about 35-25Ma was recorded as a result of advancing load caused by the Himalayan Orogeny.
- The fifth important episode between 25-7Ma with the convex-up shape is representing rapid subsidence event followed by high sediment supply rate during Miocene tectonism.
- The rest of events younger than Middle Miocene include the convex-up curve between 7-2.2Ma representing the regional subsidence of Late Miocene-Pliocene, followed by orogenic event of the Karakoram Range. The younger curve between 2.2-0Ma represents the latest Plio-Pleistocene phase of tectonims with the deformations evidenced in the siliciclastic sediments of younger strata.

Hydrocarbon Generation

This computed interpretation reveals generation of type-ii hydrocarbon in both the shelf and basin areas. The shelf area represents generation of type-ii Kerogene in Cretaceous and Early Paleogene carbonate and siliciclastic. The basin area has also indicated type-ii kerogene generation in the Early Miocene (Aquitanian) to Early-Middle Miocene (Aquitanian to Burdigalian).

- The source rocks contain vitrinite in the shelf area Cretaceous Sembar Formation, Lower Goru Formation and Eocene Laki-Ghazij Formation Shales.
- Good quality reservoir rocks are present within Cretaceous, Paleocene and Eocene age formations. The present study reveals that in the shelf area of the Offshore Indus Basin of Pakistan hydrocarbon generation took place in the Cretaceous Mughalkot and Pab formations and Paleocene Ranikot Formation.
- Vitrinite containing source rocks in the basin area in the Neogene Formations exist within the intra-formational shales of Early-Middle Miocene.
- The Late Cretaceous and Eocene shales which are important source rocks in the shelf area may also provide source material through high angle normal faults in the proximal basin area. However, in the distal basin area, where the younger sediments are very thick the source potential of Late Cretaceous may get over mature or even burnt due to the overlying sediments load and high temperature conditions.
- The wells Indus Marine-B1 and Pakcan-1 contain high quality data. Indus Marine-B1 is the deepest well penetrated the Aquitanian (Early Miocene) whereas Pakcan-1 though not drilled as deep as Indus Marine-B1, but it produced hydrocarbon on DST, due to its position on the progradational sediments of Early-Middle Miocene in the slope area.
- The well Indus Marine-B1 data not only found in calibration of rigorous tectonic events of Miocene and younger strata but also reveals high quality water depth, heat flow, matrix porosity and liquid and gaseous hydrocarbon generation in the basin area.
- Wells Indus Marine-A1 and Indus Marine-C1 due to their position in the basin though reveals representative

tectonic curves for Miocene and younger events, but does not indicate significant hydrocarbon generation.

The latest well Sadaf-1 shows weak hydrocarbon generation due to reason that the well was not penetrated in the objective deeper zones and was abandoned in the younger horizons than Early-Middle Miocene. It is located in a SSW area, where younger sediments than Early-Middle Miocene are thickest and the objective horizons are deeper.

REFERENCES

Allen, P.A and J.R. Allen, 1990, Basin analysis principals and applications: Blackwell Science, Inc. Cambridge, Massachusetts, U.S.A., 451p.

Baloch, S.M. and David G. Quirk, 1998, Sequence stratigraphic and structural interpretation of the Offshore Indus Basin of Pakistan, American Association of Petroleum Geologists, Annual Conference Salt Lake City (May 1998 Abstract), Utah, U.S.A., p.1-4.

___ and David G. Quirk, 1999, Sequence Stratigraphy of the Paleogene Carbonate of the Offshore Indus Basin of Pakistan. Under submission to American Association of Petroleum Geologists, U.S.A., (un-published).

___, 2000, Seismic interpretation and sequence stratigraphy of the Offshore Indus Basin of Pakistan. (Ph.D thesis, un-published).

Biswas, S.K., 1987, Regional tectonic framework, structure and evolution of the western marginal basins of India: Elsevier Science Publishers B.V: Amsterdam, Netherlands, p.307-327.

Boyd, T.D., 1994, Limits of deccan trap volcanic and its probable source vents: Union Texas, Pakistan Inc. (unpublished).

Brooks, J.C. Conford and R. Archer, 1987, The role of hydrocarbon source rocks in petroleum exploration; *In:* J. Brooks and A.J. Fleet (eds); Marine Petroleum Source Rocks. Geological Society Special Pub, no.26, p.17-46.

Clark, M.S., I.M. Beckley, T.J. Crebs and M.T. Singleton, 1996, Tectono-eustatic control on reservoir compartmentalization and quality: An example from the upper Miocene of the San Joaquin basin, California. Marine and Petroleum Geology, v.13. no.5, p.475-491.

Demaison, G.J., A.J.J. Holck, R.W. Jones and G.T. Moor, 1984, Predictive source bed and stratigraphy: A guide to regional petroleum occurrence, North Sea Basin and Eastern North American Continental Margins, Proc.: 11th World Petroleum Congress London, p.17-29.

Gansser, A., 1974, The ophiolite mélange, a world-wide problem in Tethyan example: Ecol. Sed.,v.67, p.479-507.

Klootwijk, C.T., 1979, A review of palaeomagnetic data from the Indo-Pakistani Fragment of Gondwanaland, *In:* Abu ul Farah and De. Jong (eds); Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, Pakistan. p.41-80.

Kolla, V. and F. Coumes, 1987, Morphology, internal structure, seismic stratigraphy and sedimentation of Indus Fan: American Association of Petroleum Geologists: Tulsa Oklahoma, U.S.A. Bulletin, v.71, p.650-677.

Martin, E., 1973, Nannoplanktonic determination: Report on Shell Oil Company Offshore Indus wells, University of Frankfurt, U.S.A. (Unpublished).

Mehmood, K., B. Francoice, G. Edwin, M. Patrick, and N. Adolphe, 1995, Emplacement of Muslimbagh Ophiolites Pakistan: Tectonophysics: v.250, p.169-271.

Molnar, P. and P. Tapponier, 1975, Cenozoic tectonics of Asia: Science: v.189, p.419-426.

Nuricon Petroservices, 1990, Report on micropaleontological studies on Occidental of Pakistan Inc. (Oxy) well Sadaf-1 (unpublished).

Powell, G.Mc.A., 1979, A speculative tectonic history of Pakistan and surroundings: Some constraints from Indian Ocean, *In:* Abu ul Farah and DeJong (eds); Geodynamics of Pakistan, Geological Survey of Pakistan, Quetta, Pakistan. p.3-24.

Robertson Research, 1978, Geochemical analysis on Lower Cretaceous and Paleocene shale in well Karachi South-1: Robertson Research Singapore (unpublished).

Sarwar, G., 1992, Tectonic setting of the Bella Ophiolites, Southern Pakistan. Tectonophysics: v.207, p.359-381.

Schlich, R., E.S.W. Simpson, and T.L. Vallier, 1975, Regional aspect of deep sea drilling in Western Indian Ocean: Initial report deep sea drilling project, v.25, p.743-759.

Sengor, A.M.C., 1995, Sedimentation and tectonics of fossil rifts, *In:* Cathy J. Busby and Raymond V. Ingersoll (eds.); Tectonics of Sedimentary Basins, Blackwell Science, Inc. Massachusett, U.S.A., p.53-117.

Shaw, W.G., 1965, Paleontological report on Offshore Indus Basin wells of Sun Oil Company: (unpublished).

Wensink, H. 1973, Newer paleomagnetic results of the deccan traps, India: Tectonophysics, v.17, p.41-59.