Hydrocarbon Potential of Tight Sand Reservoir (Pab Sandstone) in Central Indus Basin-Pakistan*

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Abstract

Pab Sandstone of Late Cretaceous age has not been adequately evaluated in the Central Indus Basin of Pakistan. More than 90% of hydrocarbon accumulations in this basin are contained in the Eocene carbonates. Pab Sandstone forms the second major reservoir in the basin, and prior to discovery at Sui, four significant discoveries had been made in Pab Sandstone in the Central Indus Basin. Discoveries of Bhit (Lasmo) and Zamzama (BHP) in the Southern Indus Basin and at Sui in the Central Indus Basin have provided new impetus for the exploration companies and their interest in Pab Sandstone as an exploration target in the region. Pab Sandstone in the Central Indus Basin is generally of shallow marine to fluvio-deltaic environments and is composed of multiple coarsening upward cycles separated by short lived transgressive events. Porosity is mostly of secondary origin created by dissolution of feldspar grains and locally of cement/matrix. As seen in the outcrops and wells, the upper part of Pab Sandstone is tight. Therefore, previously, these sands were categorised as tight with limited potential. In Sui-1 well, these sands were overlooked by interpreting them to be tight and/or water bearing but subsequent testing has resulted in a reasonable size gas discovery. The reasons for masking the prospectivity of these sands could be deceptive results of wireline logs due to hole rugosity and stress break-outs which are observed to be a common and conspicuous phenomena in almost all the wells drilled through the Pab. Local argillaceous nature of sand and the presence of certain other iron rich minerals (glauconite, chlorite, pyrite, and siderite) also make the evaluation of hydrocarbons complex and deceptive. However, it is possible that these tight sands may contain considerable potential in the region after proper stimulation. It is also inferred from the regional data that sand fairway of Pab runs along the Sulaiman Foldbelt. In view of recent discoveries from the Pab Sandstone there is a need to drill more exploration wells for further evaluation of these sands and to re-evaluate the Pab Sandstone in the existing wells. Stratigraphic pinch outs of Pab Sandstone at the margins of the basins are also likely to be prospective and should also be explored for stratigraphic and combination traps.

Introduction

Pab Sandstone in the Central Indus Basin (Figure 1) has been attracting the oil and gas explorers since the last century due to condensate seepages in it at Moghalkot in the Central Sulaiman Foldbelt. But it was only in 1974 when the first discovery of gas/condensate was made

from the Pab by OGDCL at Rodho on a thrusted anticline on the eastern edge of the Sulaiman Foldbelt. This discovery, although small was the first significant liquid petroleum discovery outside the Potwar Basin.

Further discoveries from the Pab Sandstone have been made at Dhodak (1976), Pirkoh (1977), and Loti (1985). Recent discoveries in the Southern Indus Basin by Lasmo and BHP in their Bhit, Zamzama, and Bhadra wells have provided new impetus to the potential of the Pab Sandstone and have opened new exploration areas, previously considered to bear little potential.

The most recent discovery to join this list is by Pakistan Petroleum Limited (PPL) in the Sui Deep Well at Sui Field (Figure 2) about half a century after discovery of the field.

Sui Gas Field was discovered as a result of drilling the first exploratory well, Sui-1 on a surface anticline in 1952 by PPL. Sui Field is still the largest gas field of Pakistan and continues to produce gas from two Lower Eocene reservoirs i.e. Sui Main Limestone and Sui Upper Limestone. Prior to the drilling of Sui Deep Well, 86 wells had been drilled on Sui structure and none of these wells except the discovery well Sui-1 (TD 3062.80 m in Parh Limestone of Cretaceous age) was drilled down to the formations below Sui Main Limestone.

After recent gas discoveries from Cretaceous formations in the Central Indus Basin, PPL undertook a review of available data in order to evaluate the potential of deeper horizons at Sui structure. The wireline logs, ditch samples, and core data of Sui Well-1 were analysed which indicated that few sandstone intervals in the Pab had good reservoir quality but were not tested. Whereas, the zone tested properly was very tight. Therefore, on the basis of the tested zone, Pab Sandstone at Sui structure was assumed tight and water bearing.

The long interludes in the discoveries from Pab Sandstone reflect the need to improve our understanding about its reservoir potential. This paper is an attempt towards this objective. It is a review of existing information about Pab Sandstone incorporating data from Sui Deep Well. This is also an attempt to share our observations of various factors which may help in the proper evaluation of this so deceptive Pab Sandstone. It is hoped that other companies will also come forward and share their experience in further improving our understanding about the characteristics of Pab Sandstone.

Generalized Stratigraphy of the Central Indus Basin

The oldest rocks penetrated in the area are from Pre-Cambrian to Cambrian age. These were drilled in Karampur, Sarai Sidhu, Bahawalpur East, and Marot wells in the northeastern part of the Central Indus Basin with a thickness of about 800-1100 m and are represented by the Salt Range Formation, Khewra Sandstone, Kussak Formation, Jutana Dolomite, and Bhaganwala Formation.

Sediments of Ordovician, Silurian, Devonian, and Carboniferous are missing in the Central Indus Basin; whereas the Permian rocks in the area comprise mainly sandstone inter-bedded with shale and dolomite as encountered in the above referred wells having a thickness of 350-450 m. An angular unconformity separates the Permian from Triassic. Depositional conditions of Permian probably continued through Triassic in the basin which is supported by the presence of almost similar lithological sequence of Permian encountered in Tola and Sarai

Sidhu wells with a thickness of about 130 m. Triassic was not encountered in Karampur, Marot, and Bahawalpur East wells (Shoaib et. al., 1993).

Gondwana break-up during Middle Jurassic established carbonate platform sedimentation in the area. Consequently, thick development of carbonates took place in the central portion of the basin, which is represented by Chiltan and Jandran formations with maximum thickness of about 2100 m in Jhatpat well-1. Jurassic section in the eastern portion of the basin consists of sandstone, shale, limestone, and dolomite having a maximum thickness of about 300 m based on well data. Jurassic limestone with shale interbeds outcrops at several localities along the Sulaiman Foldbelt and has been penetrated in many wells drilled in the area. The generalized stratigraphic succession of the area from Jurassic to recent is shown in Figure 3.

The Cretaceous section in the Central Indus Basin comprises alternating clastic and carbonate intervals and includes the Sembar-Goru Formations (shales interbedded with limestone and sandstone) with more than 1500 m thickness along the Giandari-Mari axis. Parh Formation (compact, hard, argillaceous limestone) attains a maximum thickness of 720 m and Moghalkot Formation (limestone interbedded with shales) is more than 450 m at Giandari. Pab Sandstone (with interbeds of shale and minor siltstone) has maximum thickness of more than 700 m at Giandari. It is about 500 m thick at Sui.

The Cretaceous section is separated from Paleocene by a locally preserved unconformity marked by red lateritic nodules (observed in the Kandhkot-20 core). The overlying Paleocene strata is represented by Ranikot of Lower Paleocene (dominantly sandy in the eastern part and shaly in the western part) deposited under variable conditions and the Dunghan Limestone (dominantly limestone in the eastern and western portions and shaly in the central part) of Upper Paleocene age.

The Laki Formation of Lower Eocene age, which includes the Sui Upper Limestone, Ghazij Shale and the Sui Main Limestone underlies the Kirthar Formation. The lower part of the Sui Main Limestone is considered to be of the Paleocene age.

The Kirthar Formation includes Drazinda Shale, Pirkoh Limestone, Habib Rahi Limestone, and Domanda Shale Members. Siwaliks are the youngest and most widely exposed rocks in the area. These overlie the shales and sandstones of the Gaj-Nari Formations (Miocene to Oligocene) with an unconformable contact. The sediments of the Siwalik Group, ranging in age from Miocene to Pleistocene are composed of sandstones, clays, and conglomerates. These rocks were folded and faulted during the Himalayan orogeny to form part of the Sulaiman arcuate belt.

Lithology of the Pab Formation

It would be appropriate to mention it here that following lithological description of Pab Sandstone is mainly based on well samples and wireline logs of the Sui Deep Well due to nonavailability of a petrographic study which is currently in progress. However, where necessary, lithological and petrographic information available through published literature has been used.

Generally, the true thickness of Pab Sandstone is difficult to determine because of transitional basal contact with the Moghalkot Formation. Moreover, about 100 m of sandstone below the shales of the Ranikot is extremely lean in fossils and therefore, it is difficult to assign any particular age to this section. This section is regionally correlatable and forms reservoirs in most of the gas/condensate fields with Pab Sandstone as reservoir. For practical purposes the top of Pab Sandstone is taken here at the base of the shales of Ranikot, whereas, the base of the formation is taken at the bottom of the prominent sandstone bed overlying limestone of the Moghalkot Formation. This sandstone is highly calcareous and may mark a transition from Moghalkot to Pab.

Pab Sandstone is widely developed in the Sulaiman and Kirthar provinces and the Axial Belt. It is readily recognizable in surface outcrops (in the Central Indus Basin) as a pronounced ridge of steep cliffs. It is almost monotonous in character comprising a series of predominantly mature sandstone units. Most common framework constituents are monocrystalline quartz, polycrystalline quartz, potassium feldspar, plagioclase, and lithic grains. Based on Folk's classification it can be termed as mainly quartz arenite, and less commonly as sub-arkose (Sultan and Gipson, 1995) at certain stratigraphic horizons where feldspar is present in appreciable amount. The sandstones of Pab are generally fine to medium grained with significant proportion of coarse grains, sub-angular to subrounded, moderately to well sorted, and mostly well cemented with traces of pyrite and glauconite. Rare intraclasts present in the sandstone are usually the fragments of limestone, claystone, and siltstone. Sandstones of Pab are cross bedded in various intervals with intercalations of mostly shale/claystone, occasionally siltstone, carbonaceous shale, and pebbly sandstone. In the basal part of the formation abundant thin laminations of carbonaceous material are present.

Pab Sandstone as observed in Sui Deep Well essentially appears to correlate with the exposed sections with subtle variations. It is noticed that the colour of Pab sediments, both sandstone and interbedded shales along with the type of cement appear to change almost simultaneously. The sandstone in the upper 80 m exhibits light grey to white colour with pervasive siliceous cement which in the well cuttings appears as lumps of dust/amorphous silica. In the next 300 m sandstone is reddish white to brownish and pinkish white. The cement in this interval changes gradually from predominantly siliceous to admixture of silica and clay. In the basal section sandstone again assumes light grey to white hue but the dominant cement type in this portion is calcareous.

Likewise, the colour of shales in the upper portion of the Pab is light to dark grey. These are micro-micaceous, to slightly calcareous, with traces of pyrite and glauconite. For the next about 300m the shales exhibit red to brownish red, chocolate brown and occasionally greenish grey colour although, these are still micro-micaceous, slightly to non calcareous, and with traces of glauconite and pyrite. In the basal part the shales interbeds again to become light to dark grey, more frequent, relatively thicker, and highly calcareous with depth.

The above noted increase in the calcareous content and change in colour of sediments is also related with the abundance of limestone fragments and appearance of limestone streaks. The fragments of limestone consistently present in the formation give way to sparse bands of limestone in the basal part where the shales become highly calcareous and cement of the sandstone also changes from dominantly siliceous/argillaceous to calcareous. Some of the limestone samples in this interval grade into calcareous sandstone.

In the basal 65 m extremely thin black laminations of carbonaceous material are observed to be dispersed in the well cuttings which give off faint yellow florescence and very weak solvent reaction.

The heavy minerals, generally present in the order of decreasing abundance in the Pab Sandstone, are tourmaline, zircon, and rutile with rare opaque minerals. These are more abundant in the northern part of the Central Indus Basin and form about 3% of the sample, but elsewhere rarely exceed 1 % (Sultan and Gipson, 1995).

Tectono-Sedimentological History and Provenance

Pab Sandstone exists in two areas separated by the Khairpur-Jacobabad High and as such it may be divided as the Pab Sandstone of the Central Indus Basin and that of Southern Indus Basin (Figure 4). Pab Sandstone of the Central Indus Basin is confined between the Sargodha and KhairpurJacobabad Paleo-Highs whereas, that of Southern Indus Basin lies in the south of KhairpurJacobabad high. In the Central Indus Basin its thickness gradually increases towards the south and it wedges out in the extreme northern part of the Sulaiman Range. An isopach map indicates its pronounced north-south orientation almost wrapping Sulaiman mega-anticlinorium (Figure 5 and Figure 6).

Pab Sandstone in both, Central Indus Basin and Southern Indus Basin, appear to have been deposited in different depositional settings in spite of similarities in lithological constituents except that volcanic debris are almost absent in the Central Indus Basin. The volcanic debris in the Southern Indus Basin is mostly related to subaerial Deccan Volcanics in the east and partly to an offshore development of the Porali Volcanic Arc and its subsequent erosion in the west.

The Pab Sandstone in the Central Indus Basin appears to have been deposited near the western edge of the continental shelf with comparatively gentle slope almost similar to that on which older Cretaceous strata was deposited which kept pace with the subsidence (Figure 7). This is manifested by almost complete profile of numerous nearshore and fluvio-deltaic·cycles and their consistency in the north-south direction. It is now established that the source of Pab sediments lied in the east and northeast of the basin and the metamorphic and igneous rocks that make up the hills of Jodhpur and Chinniot (Sargodha High) are the exposed remnants of the source terrain for the Pab Sandstone of the Central Indus Basin. The gradual decrease in the percentage of heavy minerals (zircon, tourmaline, rutile with traces of magnetite) from north to south also suggests the influence of the northeastern provenance.

Following simple but obvious inferences about the depositional conditions of Pab in the Central Indus Basin can be made on the basis of evidence obtained from the outcrops and the Sui Deep Well:

- As observed in various outcrops, the presence of trough shaped cross bedding, large bed form structures, bioturbation, and some fossils in selective horizons are indicative of near shore environments.
- Consistent westerly transport direction of paleo-currents coupled with the presence of thickening upward cycles are indicative of westward progradation over the Moghalkot marine shelf.
- The presence of glauconite in most part of the formation suggests continuous marine influence in the southwestern part of the basin.

- The reddish and brownish hue of sediments in the central part of the formation is indicative of aerial/subaerial exposure of the area which might have been experiencing fluvial influences.
- Grey to dark grey colour of sediments with presence of carbonaceous material in the basal part of formation is indicative of deposition in restricted marine conditions i.e. lagoonal environments.

In the Central Indus Basin, four nearshore facies have been identified within Pab which include fluvial, lagoonal, estuarine, and shoreface. The upper shoreface is the most widespread, while fluvial, lagoonal, estuarine, and lower shore face are only locally preserved (Sultan and Gipson, 1995).

Generally, the cyclic shoreline deposition is supported by rapid subsidence relative to structural uplift, the rate of relative sea level change and high rate of sediment input conditions which help to develop regressive prograding asymmetric cycles. Transgression may terminate these regressive profiles when the rate of sediment supply cannot keep pace with the relative rise in sea level. Sometimes, it may leave no stratigraphic record or may even erode preexisting stratigraphy (Ryer, 1977).

During the deposition of Pab Sandstone the above conditions appear to have been mostly present in the area. The Cretaceous-Paleocene sequence suggests a rather uniform rate of subsidence with episodic transgressions and controlled sediment supply progradation. In response to these, the main part of Pab was deposited as repetitive beds of sandstone and shale of variable thickness. This is more clearly evidenced in the Eastern Sulaiman Range where shallow-marine carbonate rocks of the Cretaceous Moghalkot Formation grade abruptly into twenty six (26) shoreface and ten (10) fluviatile to fluviotidal cycles of the Cretaceous Pab Sandstone (Pryor et al., 1979).

The evidences also suggest that prograding barrier bar island system (Figure 8) with multiple sources and with no interaction of fluvial processes, might have been operative in many parts of the Central Indus Basin during deposition of Pab which produced repetitive sequences of upper and lower shoreface sediments. An idealized barrier island system is typified by clean, well sorted, fine grained sands, with common cross stratification and bioturbation. All these features are present in several parts of Pab.

The depositional setting of Pab in the Southern Indus Basin appears to be more complex with a variety of environments. Prior to the deposition of Pab in the Southern Indus Basin, the area was already severely faulted passive (rift) margin probably as a result of Jurassic-Cretaceous rifting. Consequently, the area had assumed an irregular topography of horsts and grabens which appear to be a major controlling factor in the deposition of Pab Sandstone in the area. Accordingly, the formation displays rapid lateral variations in different outcrops over short distances. Studies of the textural attributes of Pab Sandstone indicate that a substantial part of Pab sediments in the Southern Indus Basin came from a close by provenance i.e. Khairpur-Jacobabad High and Thar/Badin Platform.

It is now widely and justifiably believed that the Khairpur-Jacobabad High is not really that old a feature. It started growing at the end of the Maastrichtian thus off loading the sediments to the western basinal areas. However, it effectively came into existence as a result of wrenching at the time of the Himalayan Orogeny. Therefore, it is inferred that the Pab Basin, with its northeastern limit at the Sargodha High, was originally continuous and extended north-south with two depositional centers. The data suggests that the Pab Sandstone first

deposited over Thar, Badin, and Sanghar Platform and over the present day Khairpur-Jacobabad High which was not a prominent feature yet. Subsequently, it was eroded from platform and Khairpur-Jacobabad High as it continued growing, and re-deposited in the present day Laki Range, Pab Range, and Kirthar Foldbelt in a variety of environments ranging from fluviatile, shoreface, shallow marine to slope and basin floor turbidites.

Development and Evaluation of Porosity

Generally, the original porosity of a clean sandstone may range from about 26% to 47% in perfect spheres depending upon whether they are packed cubically or rhombohedrally, with a mean of about 37%. In general, porosity decreases with an increase in depth of burial, temperature, and age. Extremely low porosity may be generally due to excessive argilleceous content (dirty sand) present as pore filling material, irregularity of grain sizes, high proportion of matrix material, and tight cementation with silica, calcite, dolomite, or some other mineral. Compaction and cementation reduces porosity whereas local solution channels increase it.

Original porosity of clean sands of Pab might have been equal to a mean porosity of sandstones ranging between 35% to 40%. However, this original porosity should have been completely destroyed or altered by later diagenetic processes. The destruction and alteration of porosity in Pab appears to have been made in different phases as a result of various circulation patterns that developed in response to tectonism, faulting, folding, erosion, deposition, recharge from meteoric water, and osmosis (Levorson, 1967). Selective cementation of different horizons in various phases of diagenesis might have been responsible for the change of the direction of water movement. Consequently, in the Pab Sandstone the contained water moved at different times in different directions at different rates. This might have resulted in making and unmaking of porosity in the Pab Sandstone and this process might have persisted as long as acidic waters continued percolating in selective horizons (Figure 9) and moving the solvents through the pores.

The analysis of water sample collected during a DST at the Sui Deep Well showed the presence of both chloride and a sulphate-carbonate-bicarbonate content in significant amounts which characterizes mixed waters suggesting its multiple origins: presumably meteoric water mixed with the connate water of the rock. This leads us to believe that various circulation systems might have been operative during the deposition and diagenesis of the Pab Sandstone. Mixed waters may occur near the present ground surface or may be found below unconfomities.

Unconformities, representing aerial/subaerial surfaces may undergo weathering and erosion, generally mark the zones of dissolution porosity that may serve as reservoir. Top of Cretaceous (Pab Sandstone) is an unconformity marked by laterite band at some locations. This might have contributed in the development or enhancement of porosity in the upper section of the Pab Sandstone which makes it the main portion of reservoir in most of the fields with discoveries from Pab including the recent one at Sui.

In the cementation process, resulting from dissolution in place, two processes work in opposite directions. Normally the increased porosity develops in those parts of the rocks where dissolution goes on more rapidly than re-deposition and vice versa. Some of the dissolved matter, however, is precipitated, thus forming a cement that reduces the porosity (Levorson, 1967). In the case of the Pab Sandstone it is observed

that only relatively cleaner sands, with lower Gamma Ray values, have preserved porosity which indicates that these sands had such an amount of original porosity that process of dissolution exceeded that of re-deposition.

Siliceous cement is the most pervasive type in the Pab Sandstone which might have been deposited along with sand grains or precipitated during diagenesis (orthoquartzite). As it generally occurs in clastic reservoir rocks, the first cement which precipitated in the Pab Sandstone was siliceous and deposited as quartz overgrowths. Silica might have been sourced from silica bearing surface or meteoric water, silica carried by streams and precipitated along with the sand being deposited, silica dissolved out of clay minerals and carried in water squeezed out of shales during loading or compaction, or produced as a result of mutual rubbing of the sand grains during severe tectonism, deposition, or diagenesis.

About 120 m of Pab Sandstone underlying the reservoir part is generally tight with development of porosity in its central portion. Sandstone of this section is characterized by its argillaceous nature with relatively higher Gamma Ray values. Drilled hole against these sands is generally very large, resultant to stress break out and locally gas burst outs. It is interesting to note that the behaviour of hole in such sandstone sections is consistent in almost all the wells drilled in the basin. It may be inferred that the tightness of Pab sands is also related with the concentration of clay content which might be present as pore filling substance along with siliceous cement and is responsible for destroying the porosity in its various parts.

Calcareous cement in the basal section (transition between Pab and Moghalkot) of Pab is as pervasive as siliceous in the upper part of the formation and is considered to be responsible for the loss of porosity in this zone. The source of carbonate cement is readily explained by the abundance of limestone fragments and limestone beds in this section which were dissolved and precipitated to provide abundant calcareous cement. Calcite cementation might have occurred after silica cementation in the basal section of Pab, whereas, in the upper horizons, where samples are slightly calcareous, calcite cement might have been provided to sandstones in the later stages of cementation.

Clay minerals, although, not always readily soluble are physically unstable and respond quickly to changes in pressure, temperature, and the character of circulating water. Both, authigenic and diagenetic clay material are present in the Pab Sandstone. Dominant clay type believed to be present as pore filling material in Pab Sandstone is chlorite. Smectite is present in negligible amount throughout the formation and appears to have been altered to illite. The overburden of Paleocene and Tertiary sediments should have provided suitable pressure and temperature to cause alteration of smectite to illite and feldspar to other clays i.e. kaolinite and chlorite. In about more than 200 m of the middle part the Pab Sandstone appears to contain appreciable amount of clays/argillaceous content along with siliceous cement. This argillaceous content should have been provided by authigenic clays produced as a result of alteration of feldspar or/and deposited with sand.

Feldspar occurs in the Pab Sandstone in varying proportions at selective stratigraphic horizons and its dissolution/alteration is widely considered to be responsible for generating secondary porosity in such intervals. The feldspar was probably eroded rapidly from northeastern igneous/metamorphic source and from weathered/unweathered shales/clays and transported only a short distance and deposited without extensive alteration under such variable conditions as might prevail in delta and flood plains. As noted by Sultan and Gipson (1995) the alteration of feldspar is more extensive in the south of the Central Indus Basin and its dissolution is almost negligible in the north but in both

cases it creates secondary porosity. The reasons why alteration and dissolution occurred only in the south is not clear. These processes resulted probably from differential diagenetic alteration. The compaction resultant to deposition of several thousand meters of sediments and intensive tectonism during Paleocene and Tertiary periods should have created adequately high temperatures and pressures for dissolution of feldspars.

Compaction of the sediments occurs chiefly due to increase in the weight of overburden and in affect (like cementation) reduces porosity. Generally, the reduction of pore spaces by compaction in a sealed reservoir system causes an increase in reservoir fluid pressure. The Central Indus Basin received several thousand meters of sediments and experienced extensive and intensive phases of tectonism during Paleocene and Tertiary periods which should have created significantly high temperatures and pressures in the basin. Consequently, the original pressure of the Pab reservoir should have been much more than the actual Bottom Hole Pressures (BHP) that have been recorded in various fields including Sui, which are hardly equal to normal hydrostatic pressure. This may be due to the existence of continuous fluid phase, at least in porous/permeable parts of Pab Sandstone even after the diagenesis and tectonism of Pab Sandstone, which might have resulted in dissipation of pressures, generated due to compaction and uplift, until these stabilized to present conditions. The presence of about subnormal pressure in the Pab reservoir also supports the idea that of various circulation systems remained operative in the Pab Sandstone during different periods of its history.

Evidence from Sui Deep Well

Based on the interpretation of well data of the Sui Deep Well, Pab Sandstone may be sub-divided into the following six alternating porous and tight zones, from top to bottom, which appear to relate with the shaliness of the sandstone, the type of cement, and relative abundance of shale interbeds (Figure 10). It is worth mentioning here that Sp log serves as a good tool for differentiating porous/permeable zones from tight zones in the Pab Sandstone.

1 Porous Zone (60 m)

This is the top most zone of the Pab Sandstone in the Sui Deep Well and may be subdivided into two zones separated by a shale band of about 5 m. The upper zone is essentially sandstone with frequent shale interbeds. Cleaner sandstone exhibits the highest resistivity with log porosity range from l5-20%. The drilled hole in such sections shows thick mud cake. The hole is generally washed out only against shales/shaly intervals. Density-Neutron log also shows gas affect in this part.

The shale band, separating the upper and lower part of the reservoir, appears to be arenaceous (relatively low GR value) with fining upward trend and enlarged hole. Abrupt decrease in resistivity at shale-sandstone contact, coupled with relatively low resistivity in the lower reservoir part, gives the false impression of GWC.

The lower portion comprises predominantly clean sandstone, slightly argillaceous in the middle part, with abundant mica. Although this zone is also a confirmed gas bearing zone, water saturation in this zone is mostly high which may be attributed to higher percentage of

bound water and local presence of iron rich clay mineral constituents. Hole is generally good. Porosity is in the range of 12-18% and resistivity in this section is lower than that in the upper part of reservoir.

Dominant cement type in this zone is siliceous which in the well cuttings appears as lumps of amorphous silica with appreciable content of argillaceous material.

2. Tight Zone (30 m)

This zone comprises generally argillaceous sandstone with occasional thin clean sandstone beds and several reasonably thick shale/clay beds. Few contiguous sandstone and shale beds show gradational contact with fining upward trend. Porosity is generally 5-8% (up to 18% in clean sandstones) with as low as zero in some beds. Water saturation in tight clean sandstone is generally higher (100% in argillaceous sandstones) than the above zone with indication of movable hydrocarbons. Hole is mostly excessively enlarged probably due to stress break outs and burst outs by the entrained gas, which is a common phenomena in tight sandstones. Resistivity values in this zone are very low and obviously influenced by the enlarged hole and as such are not reliable. Similarly, the response of the Density-Neutron log is influenced by the enlarged hole. Sp log is almost featureless over this interval indicating lack of ionic permeability. Dominant cement type in this zone is also siliceous with appreciable content of argillaceous material. This zone is categorized as "tight gas zone" in view of the test results of the underlying section which flowed minor amount of gas with no additional water production.

3. Porous Zone (35 m)

This zone comprises sandstone, locally micaceous and argillaceous with few shale beds. Cement type in this zone is still siliceous with increased content of clays. Sandstone, although, generally tight (as manifested by stress break outs) with little shift in the amplitude of the Sp curve is relatively porous than the above zone. This zone is categorized as porous gas zone on the basis of test results. It can be sub-divided into two parts. The upper part consists of inter-bedded clean and argillaceous sandstone. Porosity ranges from 20-25% and the hole is generally rugged. High water saturation and lower resistivity in this zone is considered due to abundance of bound water associated with relatively greater clay (chlorite) content of the sandstone.

The lower part contains almost clean sandstone with good mud cake build up and porosity ranging from 15-20%. In spite of the apparently high water saturation this zone flowed some gas.

4. Tight Zone (60 m)

This zone contains mainly very tight sandstone which is generally argillaceous and is almost a replica of the above-mentioned tight zone. Tightness, causing stress break outs and gas burst outs in this zone, is manifested by enlarged hole even in cleaner sandstone beds. Sp log also indicates it to be very tight with few slightly porous/gas bearing thin sandstone beds. Water saturation varies with shaliness/clay content of the sandstone. This zone is considered to be gas bearing based on the similarity of log response over this zone with that of the gas bearing

zone. Resistivity in this section is generally very low and Density-Neutron log mostly does not exhibit gas affect. However, few clean sandstone beds with gauge hole exhibit good porosity in the range of 15-20%. In such sections Density-Neutron log also displays Density-Neutron cross over and the values of water saturation and resistivity are comparable with that of the main gas zone. Cement type in this zone appears to be a mixture of silica and clay with more increased argillaceous and calcareous content.

5. Porous Zone (250 m)

This is the thickest zone and may be subdivided on the basis of relative abundance of shale beds. This section, unlike the upper zone, is characterized by consistently good porosity of sandstones which is also supported by stable/gauge hole against these sands. SP shows reasonable ionic activity throughout this zone. A prominent positive deflection of Sp and change in the relative change of resistivity values immediately below the upper tight zone appear to indicate this zone as water bearing/transition zone in the Sui Deep Well which was confirmed by the results of test conducted in the upper part of this zone.

6 Tight Zone (65 m)

This zone contains dominantly sandstone, locally argillaceous and silty with few thin shale beds. The sandstone is very tight with predominantly calcareous cement and grades to arenaceous limestone. The tightness of the sand is manifested by anomalous enlarged hole due to stress break outs, with almost negligible ionic activity on Sp log and higher resistivity and density values over this interval. This zone is characterized by the presence of very thin laminations of carbonaceous material and appearance of occasional limestone beds. Carbonaceous material gives faint yellow florescence and may be indicative of lagoonal influence in the area. This zone may be marking the transition from the limestone of Moghakot to sandstone of Pab.

Problems in Interpretation of Logs over Pab Sandstone

The following account is a description of a qualitative evaluation of the hydrocarbon potential of the Pab Sandstone on the basis of experience from the Sui Deep Well with reference to few problems which may make the interpretation of various wireline logs and establishment of Gas Water Contact (GWC) deceptive.

The interpretation of wireline logs, especially resistivity log, in the Pab Sandstone may lead to erroneous conclusions if carried out without due consideration of the relative difference of resistivities of the fluids (mud, mud cake, and mud filtrate), mineralogy of the formation, affects of the shaliness of sands, and hole rugosity (Figure 10).

Minor to abundant amount of authigenic and diagenetic clays are present in sandstones of Pab. These are relatively more in tighter sandstone sections than reservoir parts. Dominant clay type present as pore filling material is probably authigenic chlorite. It affects the porosity by making the sandstones argillaceous, lining the pre-existing porosity, and choking the pore throats. Presence of chlorite lowers the resistivity thus masking the affects of hydrocarbons on resistivity log.

As discussed earlier, formation resistivities of porous/permeable sandstone beds in the upper part of gas zone are relatively higher. Whereas, the resistivity values in the lower part of the gas zone is comparatively so low (and in the absence of gas affect on the Density-Neutron log probably due to some mineralogical reason) that it might be taken as water bearing. However, this zone is actually porous and gas bearing with no affective seal between the upper and lower parts of the gas zones. A plausible explanation for this could be slight shaliness of the sandstone with greater bound water which endows lower resistivity to the gas zone.

The resistivities in the underlying alternating tight and porous zones (zone 2, 3, and 4 in the previous section) are apparently lower than those in the above gas zone. The interpretation of this phenomena requires careful consideration of the relative difference in the resistivity of mud, filtrate, and formation water and their contrasting affect (in hydrocarbon bearing and water zones) to hole enlargement and formation shaliness. This phenomenon can be better understood by imagining the passage of current through various metallic plates of different resistivities placed in series.

Deep resistivity in these alternating tight and porous gas zones is observed to be changing proportionately with the change in hole size and shaliness. It may be inferred that in these hydrocarbon bearing sections (proved by Drill Stem Test results) resistivity is attenuated by the intervening media such that the resultant resistivities are relatively lowered in the gas zone. This is further supported by the evidence that in these zones where the hole is good against porous sandstones, the resistivities are less affected (by mud, mud cake, and mud filtrate) and are almost comparable with that of the gas zone. Such zones also exhibit gas affect on the Density-Neutron log. This leads to the inference that the tighter sandstone beds in this section are also gas bearing in spite of low resistivity and absence of other hydrocarbon indications on wireline logs. Deep resistivity of such sandstone beds could be actually comparable with the gas zone if the affects of hole enlargement and shaliness are eliminated. It is believed that these tight gas bearing sections may yield significant production with proper stimulation.

Low resistivity values in the gas zones, especially at sandstone-shale contacts may sometimes look like sharp Gas Water Contact (GWC). The MDT data with pressure points taken wide apart may also not be conclusive in establishing GWC in tight gas zones. At the Sui Deep Well an interpretation of MDT pressure plot indicated gas gradient only in the upper part and water gradient in the lower part (Figure 9). This was further tipped-off by coincidental decrease of resistivity at that point. However, based on another MDT plot and interpretation of logs it transpired that the GWC might be lying about 120 m deeper than what was initially suggested by the interpretation of MDT data. Initially gas and water gradients were established on the basis of about 10 pressure points ignoring few which did not fit to the other data and the GWC, thus marked coincided with drop in resistivity. This paradox may have been produced due to heterogeneity of the formation in respect of porosity, lithology, and spread of only few MDT pressure points over a long interval.

Stratigraphic/Combination Traps

So far, the exploration activities for hydrocarbons in Pakistan have been directed towards finding the structural traps. Exploration efforts specially targeted for stratigraphic or lithological traps have not been made, primarily due to relatively limited exploration activities in Pakistan.

Many of the structural traps in the Central Indus Basin may be too young for the entrapment of liquid hydrocarbons. The formations like the Pab Sandstone may provide favourable lithologies and depositional trends for investigating stratigraphic and combination traps in it, especially in the vicinities of Paleo Highs and on the eastern flank of the Sulaiman depression where it merges with the Punjab platform.

The regional trend of Pab reservoir sands indicates that these should be extending up to the southern depositional limit in the Central Indus Basin at Khairpur-Jacobabad High which started growing at the end of Maastrichtian thus off loading the older sediments. It effectively came into existence as a result of wrenching at the time of the Himalayan Orogeny. Seismic data of the Block-22, located almost parallel on the eastern limb of the Khairpur-Jacobabad High, furnishes some indications of truncations of reflectors below the base Tertiary in the southwestern direction which may be attributed to the Pab Sandstone. Structural mapping of top of the Cretaceous in this area also indicates some small to medium sized four way dip closures. Pab Sandstone encountered in Kandhkot-20 and Uch wells displayed good reservoir characteristics and there is likelihood that a similar reservoir trend would be extending up to the Khairpur-Jacobabad High. Thus, the Pab Sandstone offers an attractive target for investigating stratigraphic and combination traps in this area in view of the truncation of the Pab Sandstone against the Paleo-High in proven petroleum habitat, sealed with shales of Ranikot, and the presence of viable structures at the location of possible truncations with anticipated good reservoir characteristics.

Conclusions

Pab Sandstone in the Central Indus Basin comprises predominantly sandstone which is locally argilleceous. Abundance of shale interbeds is limited to particular stratigraphic horizons. Pab sediments were generally deposited in shallow marine to fluvio-deltaic environments and contain multiple cycles separated by short lived transgressive events.

Porosity is mostly secondary and is preserved in selective stratigraphic horizons. Porosity appears to have been influenced mainly by cementation and clay/shale content of the sands. On the basis of porosity it can be sub-divided into alternating porous/permeable and tight zones. The thickest porous section is about 200 m below the top of the Pab Sandstone. Tighter sections are not completely devoid of hydrocarbons rather the indications of hydrocarbons on the logs may be masked due to enlarged hole conditions, clay content of sandstones, and local presence of iron rich minerals. These apparently tight sands may present significant potential subsequent to proper stimulation.

Pab Sandstone also offers attractive exploration target for stratigraphic and combination traps at appropriate locations.

Acknowledgments

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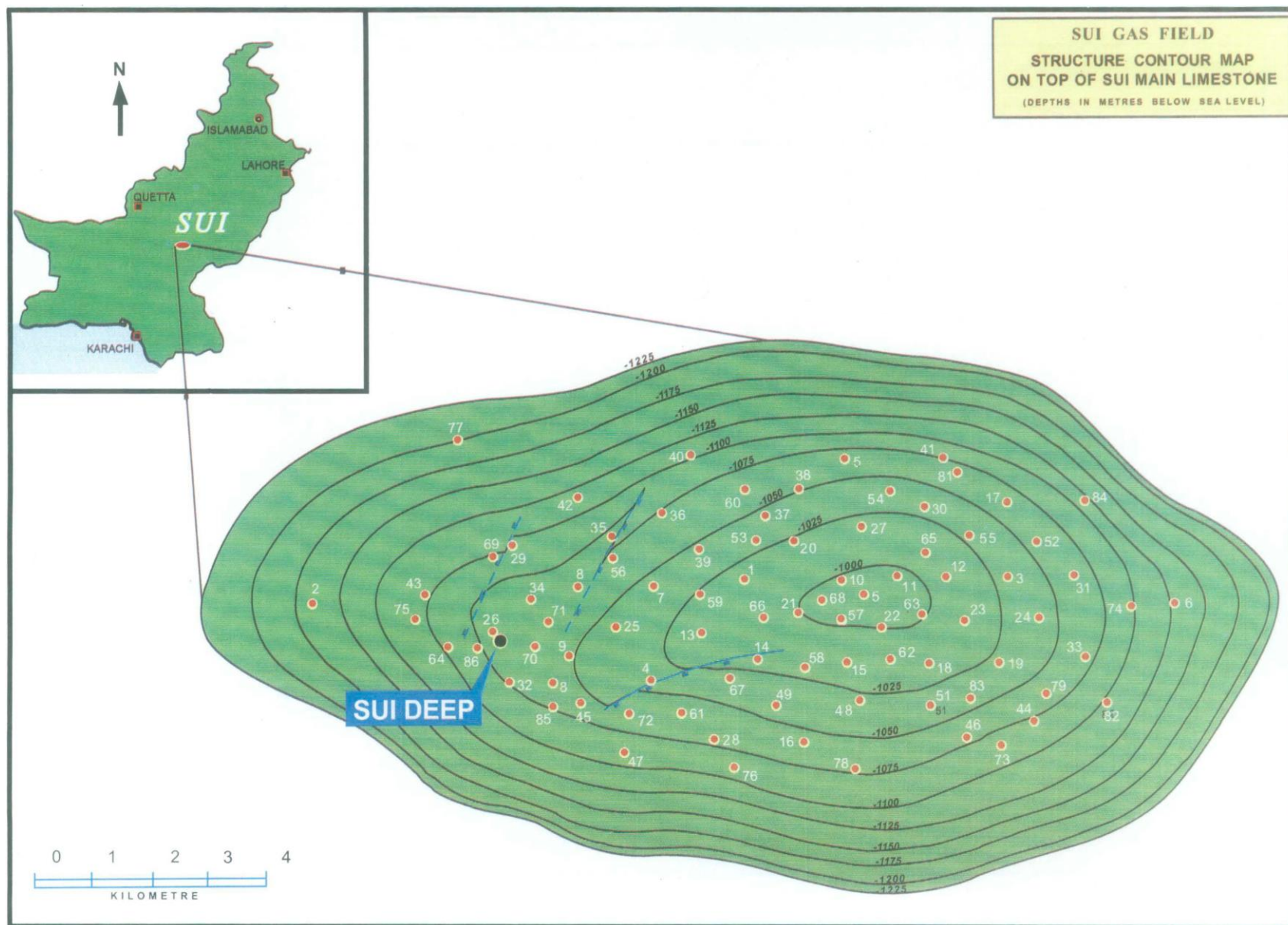
Figure 1. Location Map of Study Area.

Figure 2. Sui Gas Field – Structure Contour Map on Top of Sui Main Limestone.

Figure 3. Generalized Stratigraphy and Petroleum Geology, Central Indus Basin.
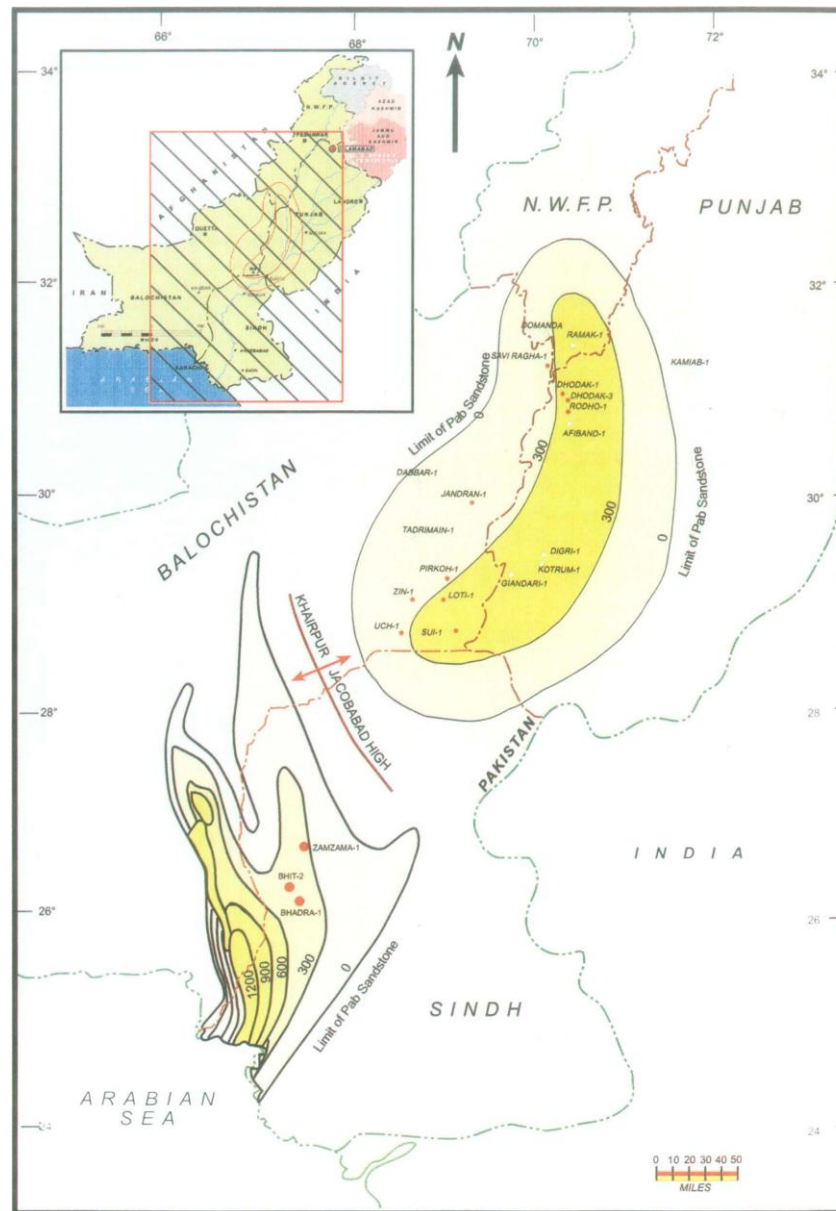
Figure 4. Isopach Map of Pab Sandstone.
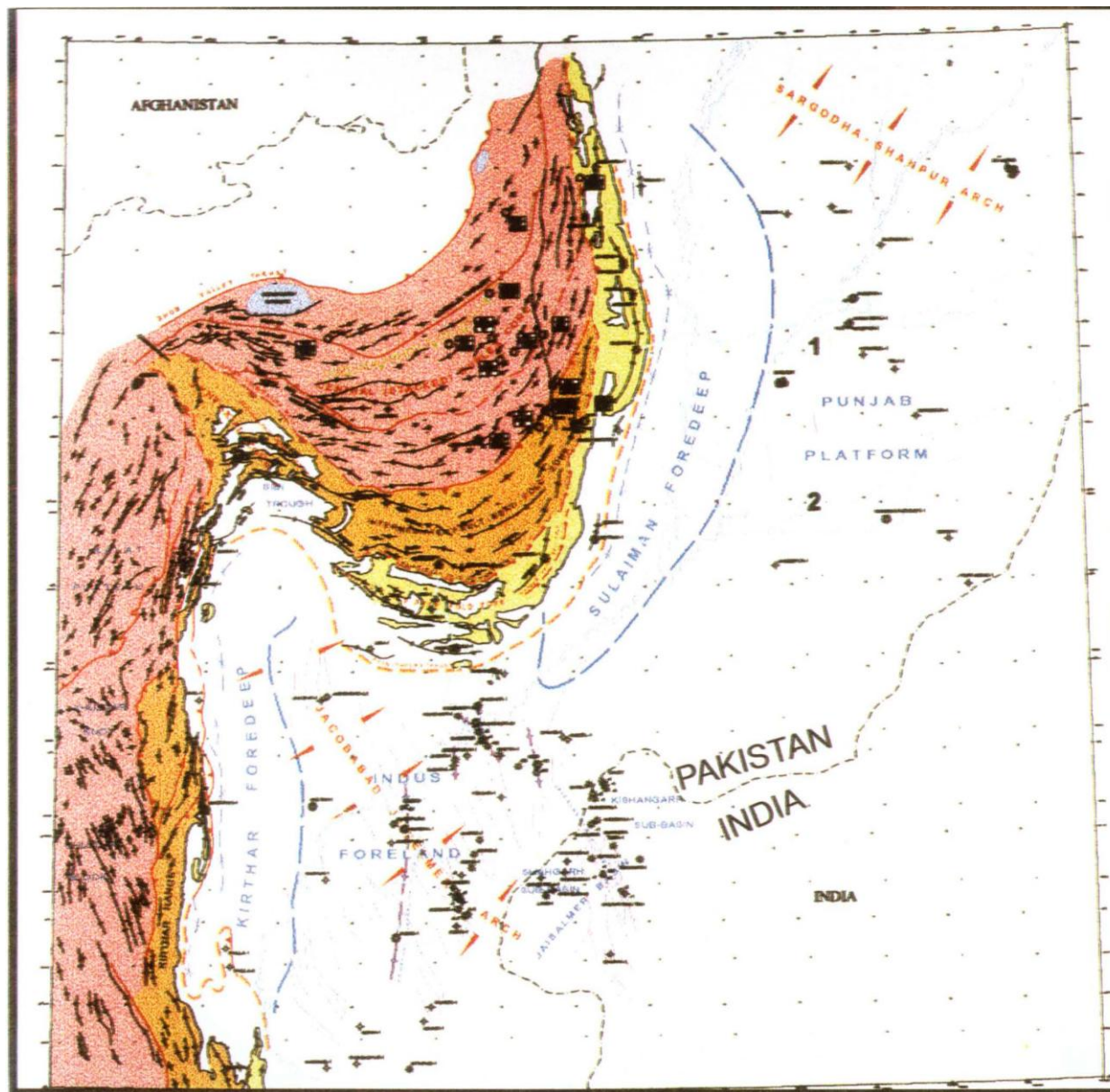
Figure 5. Structural Elements of Central Indus Basin.
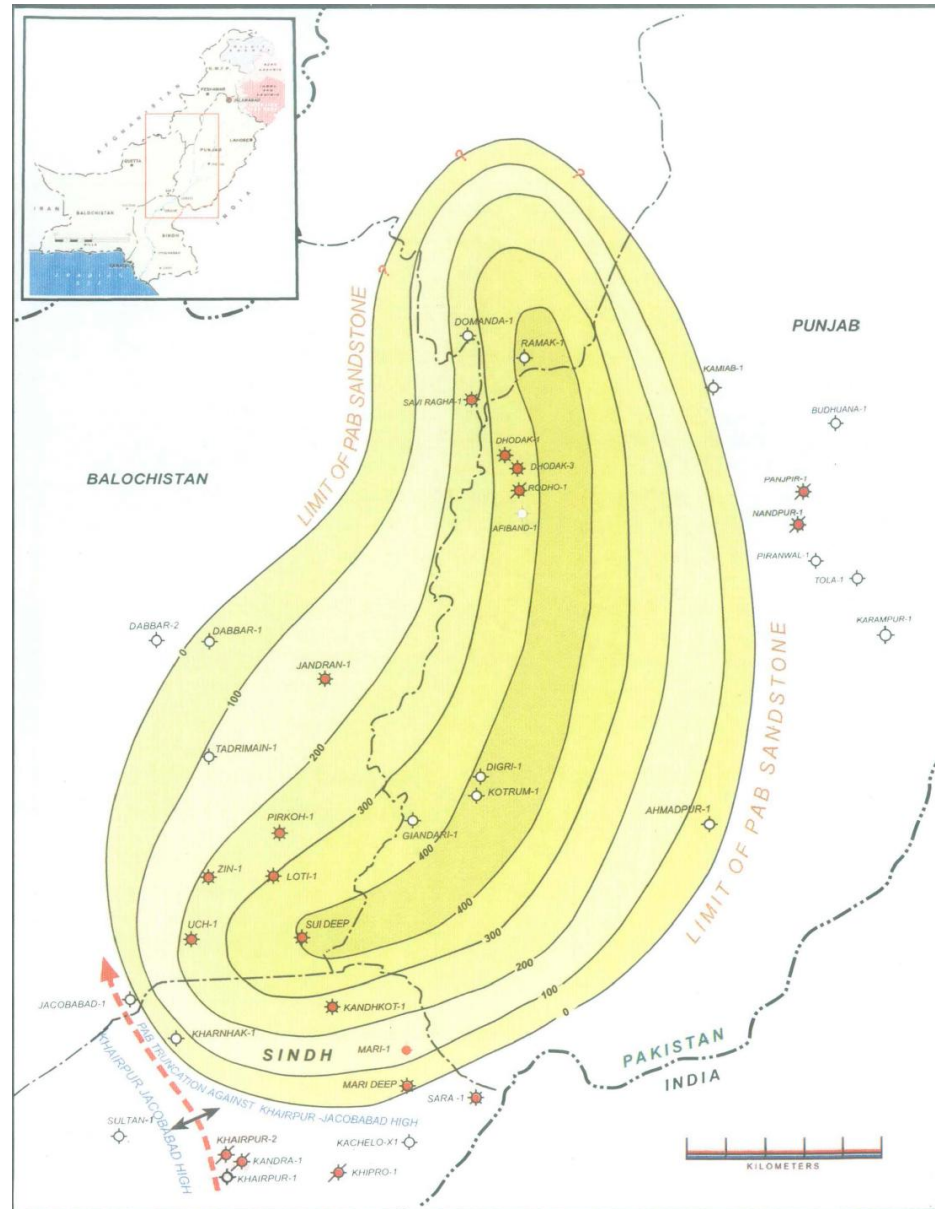
Figure 6. Isopach Map of Pab Sandstone in Central Indus Basin.
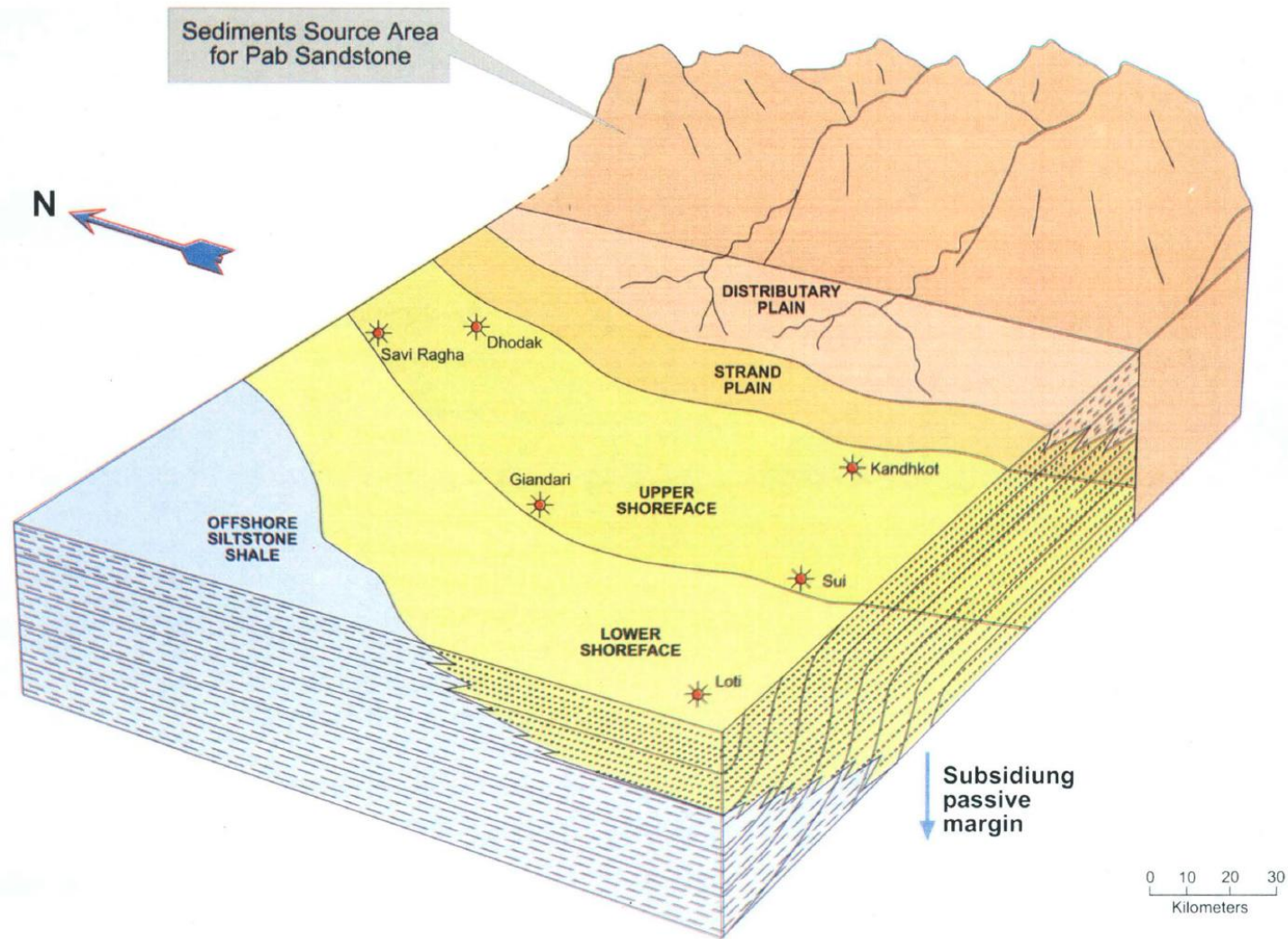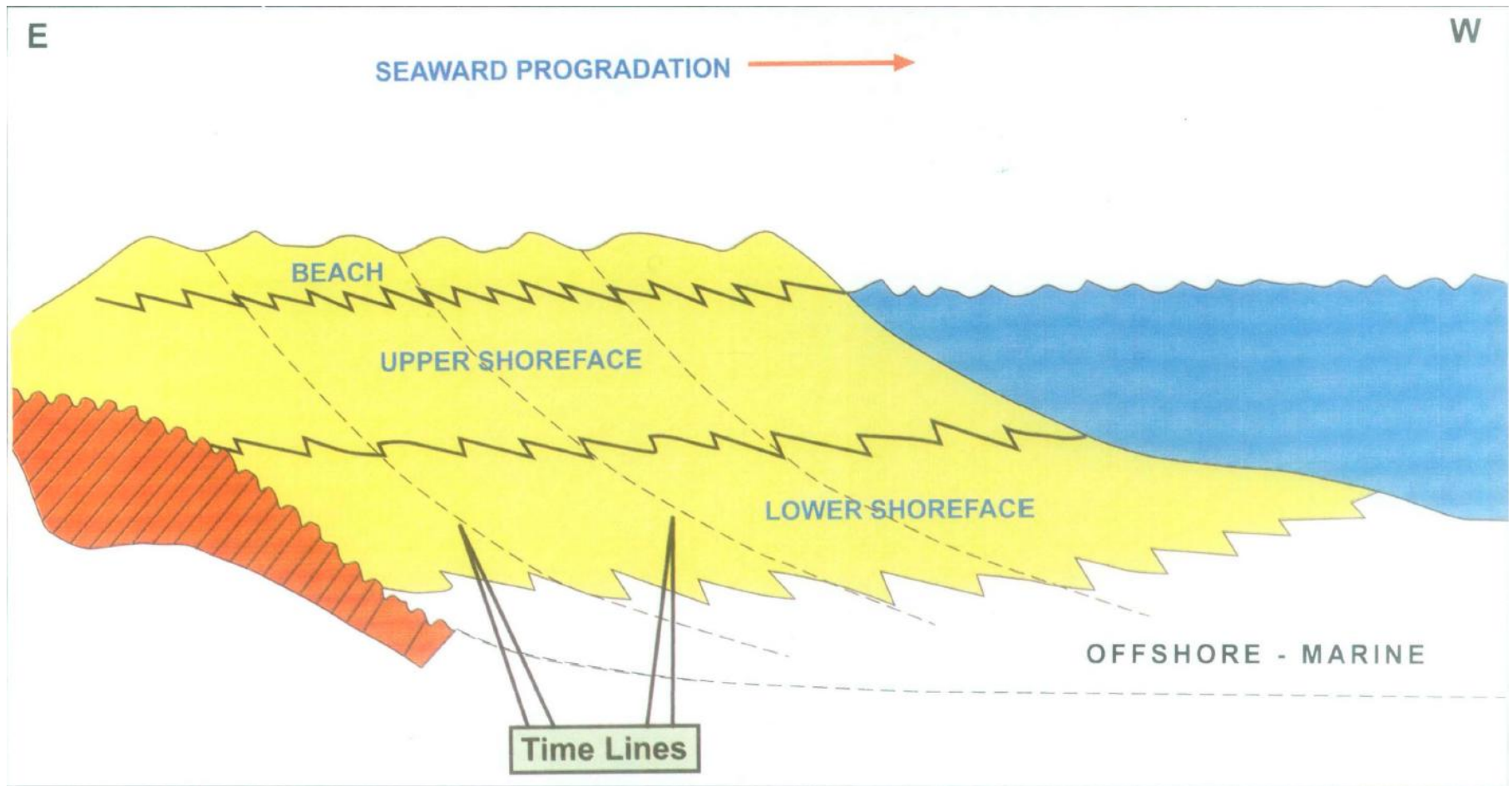
Figure 7. Paleographic Model of Pab Sandstone.

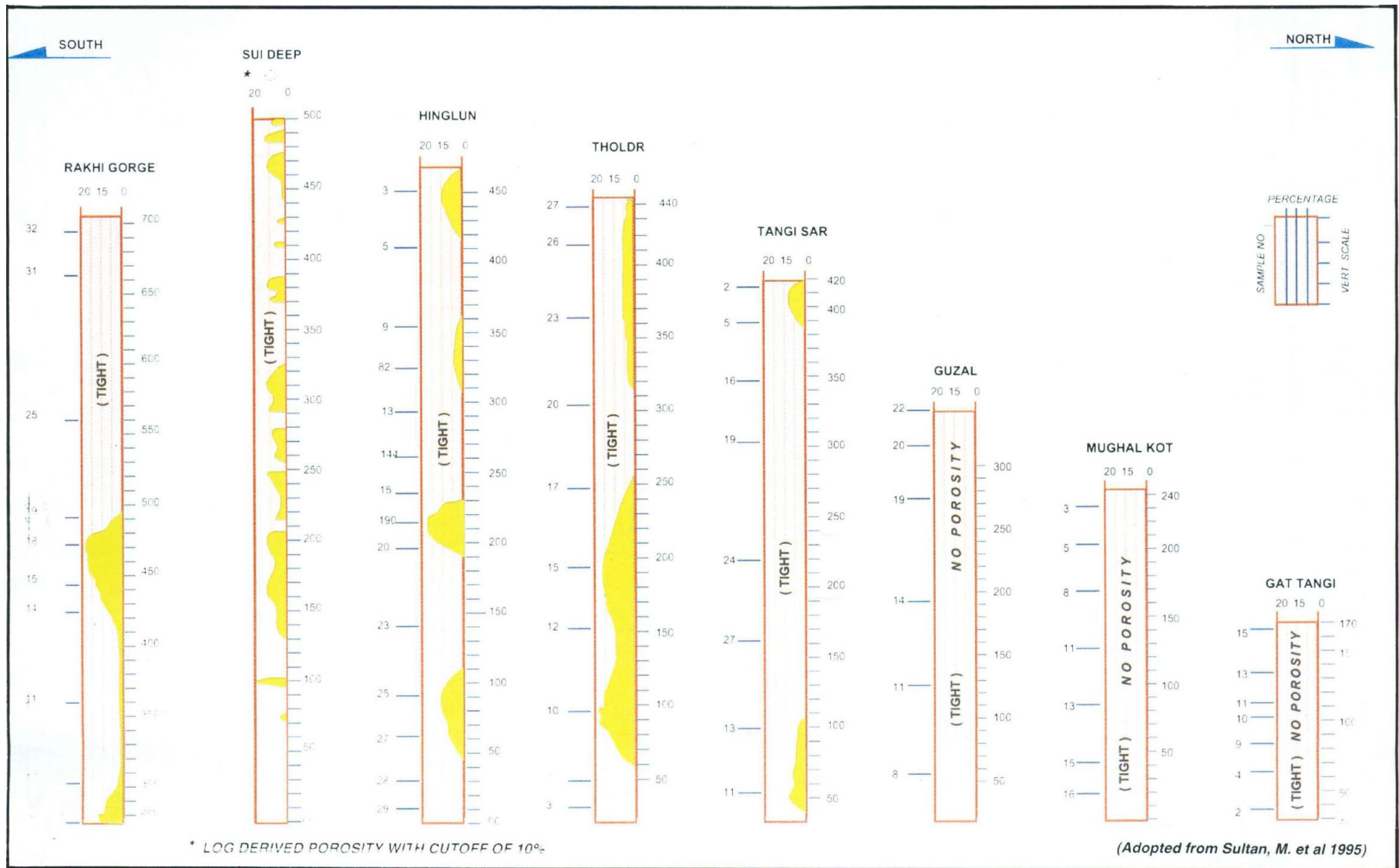Figure 8. Generalised Cross-Section, Pab Sandstone Barrier Bar System.

Figure 9. Comparison of Sui Deep Log Porosity with Outcrop of Pab Sandstone in the Eastern Sulaiman Fold-Belt.
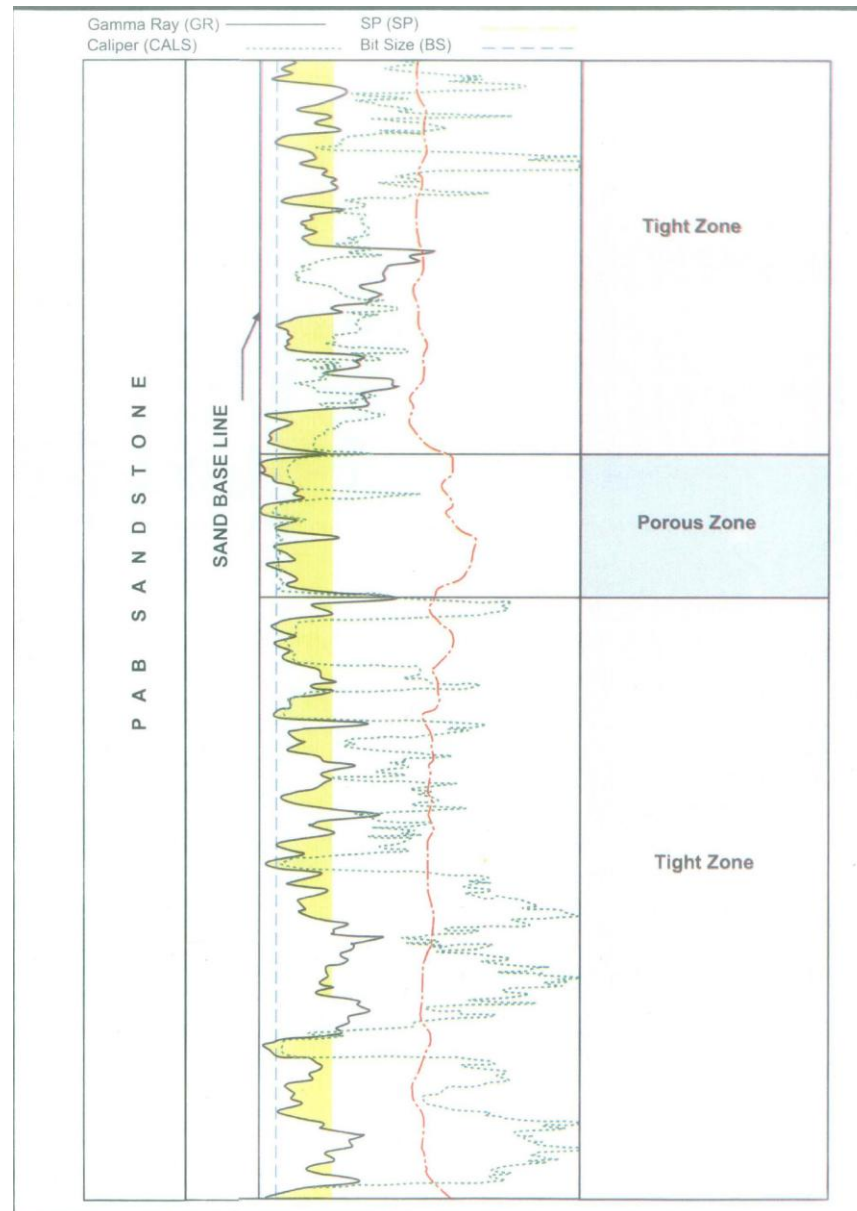
Figure 10. Relationship of Hole Washout/Shaliness and Tightness of Pab Sandstone.