CONTROLS ON POROSITY IN THE PAB SANDSTONE, KIRTHAR BASIN, PAKISTAN

by

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Submitted in the partial fulfilment of the requirements for the
Honours degree of Bachelor of Science in
Petroleum Geology and Geophysics
at the

National Centre for Petroleum Geology and Geophysics
University of Adelaide

November 1996

CONFIDENTIALITY

The author has accepted a confidentiality clause with BHP Petroleum Pty Ltd (Melbourne) concerning this study. The sponsors have requested that this thesis be unavailable for public release until the 31st day of December 1998.

STATEMENT OF AUTHENTICITY

To the best of my knowledge, and belief, this thesis contains no material which has been accepted for the award of any degree, or diploma in any University, nor does it contain any material previously published or written by another person, except where due reference is made in the text.

Travis Enman, B.Sc.

ACKNOWLEDGEMENTS

The author is grateful for the financial assistance of the industrial sponsor, BHP Petroleum Pty. Ltd., without whose generosity and commitment to research the successful completion of this project would have been impossible.

Special thanks must go to the Pakistan Exploration team at BHP, in particular Messrs Andrew Christie (team leader), Andrew Logan (geologist), Hywell Thomas (seismic interpreter), Jim Preston (geochemist) and Glen Wormald (petrophysicist) for their supervision and advice.

Additional thanks to the technical assistance of Mr. Mark Lemaire and Miss. Mimi Thet. Also, an enormous thankyou to the CAD drafting personnel at BHP Petroleum for their patience, professionalism and excellent drafting of the enclosures.

To the staff of the National Centre for Petroleum Geology and Geophysics, I would like to thank Professor Cedric Griffiths for providing guidance and supervising this project, as well as Dr. Nick Lemon for his advice and opinion in relation to the diagenesis of the Pab Sandstone.

To the students at the NCPGG, I thank you for being a large part of an enjoyable learning experience.

Finally, I would like to acknowledge the support of my family and friends throughout the year. In particular to my parents and sister, I thank you for your continuous support and encouragement throughout this year and previous years of study. Without their unconditional support none of my success would have been possible.

EXECUTIVE SUMMARY

The Pab Sandstone is a gas producing reservoir in the Middle Indus Basin, Pakistan at the Pirkoh, Dhodak and Loti fields, but as yet is not a recognised hydrocarbon producing reservoir in the adjacent Kirthar Basin. This study attempts to examine the controls on porosity development and destruction in the Pab-Sandstone in the Kirthar Basin.

As part of the Honours program at the National Centre for Petroleum Geology and Geophysics (Adelaide), BHP Petroleum Pty Ltd (Melbourne) supplied a project integrating lithostratigraphy, sequence stratigraphy, petrography, seismic interpretation and wireline log analyses in the Kirthar Basin of Pakistan, with particular reference to the BHP Petroleum permits in the Sindh Province.

The main objective of the study was to map porosity trends in the Pab Sandstone and to predict reservoir quality in the vicinity of a proposed exploration well in Pakistan. The prediction of play fairways was included in this study.

The objectives of the study have been met by initially compiling a regional data base on the Pab Sandstone. Identification of the unit in both wells and outcrop on the basis of litho- and bio-stratigraphy allowed regional correlation of the unit. Porosity evaluations were carried out where data permitted and the possible controls on porosity quality and distribution, such as depth of burial, diagenesis, depositional environment, texture, and temperature were examined.

Empirical relationships and analogies were investigated incorporating outcrop analysis and burial histories. Porosity versus depth relationships were investigated and explained, incorporating depositional and sequence stratigraphic interpretations.

Sand distribution and quality maps including regional isopach, net sand, percentage sandstone and palaeofacies variations were compiled in order to more precisely define play fairways.

The Pab Sandstone is a medium to coarse grained, occasionally fine to very coarse grained, generally massive to thick bedded, cross bedded, occasionally conglomeratic, quartz arenite of Maastrichtian age with intercalations of shale, claystone, mudstone, marl, and limestone beds and is characteristic of a transitional marine environment.

The Pab Sandstone is interpreted to be present in the West Phulji, Dadu and Nawabshah permits. The shelf margin systems tract palaeofacies is interpreted as having good to very good reservoir quality and is interpreted to be present in the Phulji area.

The Pab Sandstone is most commonly carbonate and silica cemented, occasionally dolomite and siderite cemented. Diagenetic clays generally develop microporosity at the expense of macroporosity and diagenetic enhancement has resulted in at least adequate porosity. Despite the loss of original primary porosity, subsequent diagenetic events have led to the development of secondary porosity in the Pab Sandstone.

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Slide NP10: located at Bara Nala measured section; 19 metres

Slide NP 11: located at Bara Nala measured section; 23 metres

Slide NP 18: located at Bara Nala measured section; 79 metres

Slide NP 19: located at Bara Nala measured section; 80.2 metres

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Slide NP 22: located at Bara Nala measured section; 98 metres

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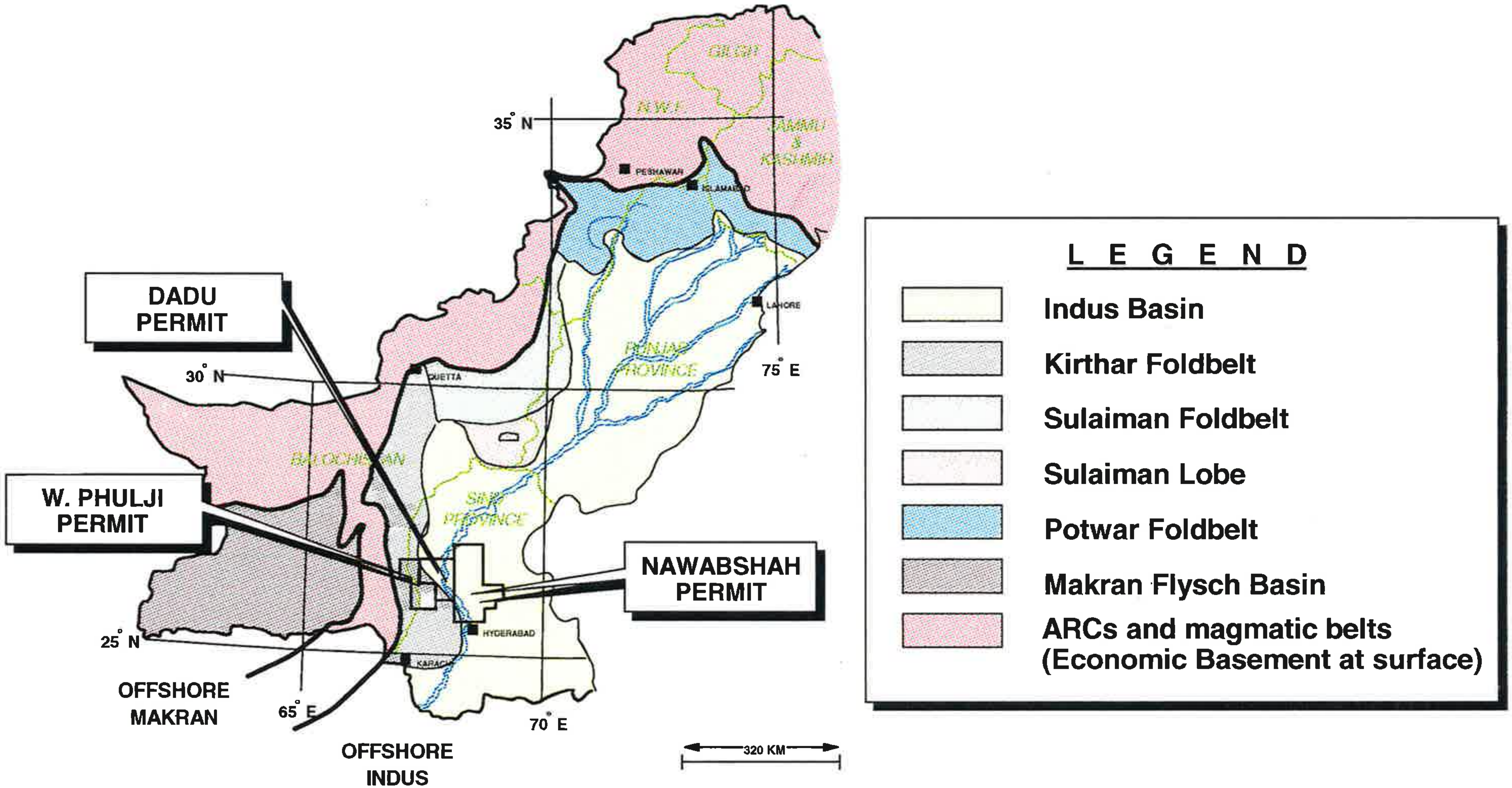
Slide NP 38: located at Bara Nala measured section; 200.2 metres

DADU AND NAWABSHAH PERMITS

PAB STUDY : Location Map



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OCTOBER 1996

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1.2: RESEARCH AIMS AND OBJECTIVES

The principal aim of this study is to determine the controls on porosity development and destruction within the Pab Sandstone in the Kirthar Basin. Ultimately, this is with the view to the prediction of porosity in the Pab Sandstone and specifically the prediction of reservoir quality in a proposed exploration well in the region. The information should also constrain play fairways in the vicinity of the BHPP permits.

1.3: INTRODUCTION

The texturally and mineralogically mature Pab Sandstone is distributed in two main depocentres in Pakistan, representing two main palaeodepocentres, either side of the Jacobabad High (Figure 2). The age of the Pab Sandstone is uncertain, but it is most likely of Maastrichtian age (Nagappa, 1959; White, 1981; Norvick, 1995; Sultan & Gipson Jnr, 1995; Kadri, 1995).

The Pab Sandstone is a valuable and proven producing reservoir rock in the Middle Indus Basin; producing gas/ condensate at Dhodak gas field and gas at both Pirkoh and Loti fields (Figure 2). Commercial hydrocarbons have yet to be found in the Pab Sandstone in the Kirthar Basin despite good porosities and the flow of salt water and gas during a test at Lakhra-4 (Quadri & Shuaib, 1986). This may be attributed to the lack of well intersections to the depth of the Pab Sandstone and the mislocation of Cretaceous traps on the single fold seismic surveys available (Quadri & Shuaib, 1986). Lithological variations between the two basins; occlusion of porosity by quartz overgrowths, carbonaceous clay matrix, calcite and ferruginous cements (Sultan and Gipson Jnr, 1995) and the absence of secondary porosity and microfracture development may, together with low permeabilities, inhibit potential production.

The development of secondary porosity is an important feature of the Pab Sandstone in the Sulaiman Fold-Belt. Secondary porosity is recognised by the partial dissolution of feldspar grains, the development of elongate pores due to the dissolution of grain margins, corrosion of grains, the presence of limestone and feldspar grain moulds, intra-cement and oversized pores (Sultan and Gipson Jnr, 1995). Fracturing and shrinkage of the framework grains, matrix or cement may also encourage secondary porosity development. Secondary porosity may be developed under the influence of migrating fluids (ie. meteoric, thermobaric, connate or compactional waters) or due to changes in mineral phases as mineral stability is attained. Previous studies (Petromin, 1991; Sultan and Gipson Jnr, 1995) have identified the crucial role that secondary porosity and microfracture development have played in enhancing the reservoir quality of the Pab Sandstone and its producibility.

An emphasis of this thesis is to more accurately identify and locate the Pab Sandstone in the Kirthar Basin. Additional objectives include defining and understanding the controls on primary, secondary and micro-porosity development and the preservation and destruction of porosity within this potential reservoir unit. By gaining an appreciation of the controls, reservoir quality and the potential for hydrocarbon production can be predicted. Play fairways can then be constrained in the Nawabshah and Dadu permit areas in the Kirthar Basin, which will aid further exploration.

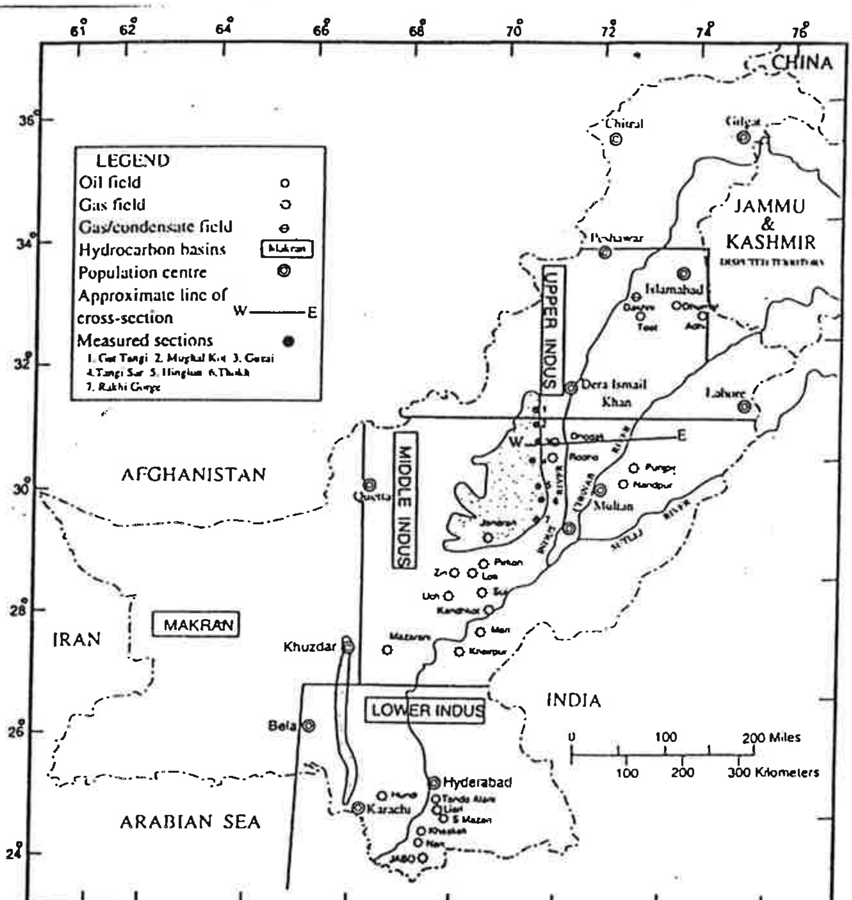

Figure 2. Map showing the locations of hydrocarbon-bearing basins and the major oil and gas-fields in the Indus Basin, Pakistan (from Sultan and Gipson Jnr, 1995).

1.4: PREVIOUS WORK

Previous work undertaken by BHP Petroleum Pty Ltd., in the onshore Indus Basin includes the following.

Kirk (1996) and Brink (1996) undertook a major study involving seismic and sequence stratigraphic interpretations in the Kirthar Basin, which built upon the regional framework outlined by Norvick (1995). In each study stratigraphic horizons and sequences were defined and are outlined in Figure 7. This figure also illustrates the stratigraphic framework adopted for this study (after Norvick, 1995).

Subsequent investigations have included seismic interpretations (Thomas, 1996), source rock assessment (Preston, 1996) ,evaluation of seal capacity in the BHPP permit areas (Logan, 1996) and investigation of possible secondary reservoir targets (Raza, 1996).

1.5: EXPLORATION HISTORY

Hydrocarbon exploration and development commenced in Pakistan in 1866 upon the drilling of seepages 25 miles west of Islamabad. Drilling was generally sporadic and production very low until thirteen wells were drilled between 1885 and 1892 targeting oil seeps at Khattan. Production over the seven years was in the order of 25 000 barrels of oil (Dolan, 1990).

The Burmah Oil Company (known as Pakistan Petroleum Limited (PPL) after 1949) initiated hydrocarbon exploration in the Kirthar Basin with the drilling of *Drigh Road GIB-1* (TD. 511m) in 1939. Following Independence, laws governing prospecting were changed and foreign companies explored extensively under the new regulations. PPL drilled the Lakhra structure in May of 1948 and also discovered gas at Sui in 1951. Oil and gas exploration activity increased markedly in the Kirthar Basin from 1954 and culminated in the discoveries of gas at Zin (1954), Uch (1955), Khaipur (1956), Khandkot (1956) and Mazarani (1959) (Quadri and Shuaib, 1986; Dolan, 1990; Nizami and Nizami, 1987).

The Oil and Gas Development Corporation (OGDC) was formed in 1961 and together with the assistance of Soviet technicians, set out to explore the entire country using seismic, aeromagnetic, gravity and geological field surveys. All seismic surveys between 1955 and 1974 were single fold and were conducted by Standard Vacuum Oil Company (SVOC), OGDC, Tidewater, Hunt Oil, Pakistan Petroleum Ltd. (PPL), and Sun Oil Company (SOC). The increase in activity encouraged the active participation of other foreign companies in hydrocarbon exploration in Pakistan (Quadri and Shuaib, 1986; Dolan, 1990).

The inadequacy of single fold surveys to cope with the interference of basaltic and limestone layers often led to incorrect subsurface interpretations. Fortunately there has been a subsequent increase in the acquisition of multi-fold seismic surveys both onshore and offshore. Companies involved included AMOCO, PPL, British Petroleum (BP), OGDC, Occidental, Pakistani Texas Gulf (onshore since 1974), and Husky Oil, Wintershall, Phillips and OGDC-NORAN (offshore since 1969) (Quadri and Shuaib,1986).

Other field surveys conducted in the Kirthar Basin included aeromagnetic surveys, (SVOC, 1955; OGDC, 1962-1963), gravity surveys (SVOC, 1954-1956; SOC, 1957-1959; PPL, 1949 & 1956-1960; Pak Hunt Petroleum, 1957-1959; Tidewater Oil Company, 1959-1960; OGDC, 1966-1975; and Pakistani Texas Gulf, 1975). In the period 1969-1972 Wintershall conducted combined gravity and magnetic surveys concurrent with their offshore seismic program (Quadri and Shuaib, 1986).

As of 1987 Pakistan was producing from eight oilfields (seven of which are located in the Potwar of Punjab) and oil production peaked when 3.53 million barrels were produced in the first nine months of 1982/83. Gas was produced from six gasfields, three of which are also oil producing, bringing the total number of commercial gas fields discovered to thirteen (Nizami and Nizami, 1987).

2.1: TECTONIC FRAMEWORK

" The majority of fossil fuels are found in sedimentary basins whose formation can be related directly or indirectly to plate motions " (Kearey and Vine, 1990)

The composition of sandstone reservoirs is controlled by the type of sedimentary source or provenance, the influence of the sedimentary processes within the depositional basin and the nature of the transportational link between source and depositional basin (Dickinson and Suczek, 1979).

The break-up of East and West Gondwana which occurred in the Middle Triassic (Dietz and Holden, 1970) to Early Jurassic (Powell et al, 1979) to Late Jurassic (Veevers, 1988; Tectostrat, 1996) was the principal control on the tectonic development of the Indo-Pakistan region.

The Southern Indus Basin (incorporating the Kirthar Basin) is bounded by the Indian shield to the east and the Indian plate margin to the west (Figures 3 and 4). The Central and Southern Indus Basins were originally in open communication, reflecting stable shelf conditions common to a passive continental margin.

Timing of the division of the Indus Basin, which led to the formation of the Sulaiman and Kirthar sub-basins, is not clear and the origins of the division are somewhat contentious. Some authors suggest that it occurred during the Lower/ Middle Cretaceous when the Khaipur-Jacobabad High was activated and uplift initiated (White, 1981; Kadri, 1995). Norvick (1995) describes the Jacobabad High as a large inversion structure which is thought to have developed at the end of the Jurassic. Brink (1996) associated the structure with possible thermal doming. Episodic reactivation is believed to have occurred during the Late Cretaceous and again during the Tertiary (Norvick, 1995; Brink, 1996).

The Kirthar Basin was a component of North-West Gondwana until its dispersal in the Callovian. An Oxfordian-Kimmeridgian sequence is apparently absent from the basin and may be attributed to either the distal location of the basin relative to the plate margin, or it was deposited on a subsequently uplifted and eroded plate margin (Norvick, 1995). From the Tithonian to the Late Cretaceous, sedimentation in the Middle to Lower Indus Basin was driven by the isostatic response of the Indian craton to the east. The quantity of sediment eroded from the Indian craton represented the primary control on sedimentation into the marginal sag basin (Norvick, 1995).

Volcanic activity was widespread and was characteristic of the region in the Late Cretaceous (DeJong and Subhani, 1979) to early Palaeocene time (Norvick, 1995). The volcanism is suggested to have occurred in conjunction with the rifting associatedwith the separation of Madagascar and the Indo-Pakistan plate (Norvick, 1995) which commenced after 80 Ma (Tectostrat, 1996). Alternatively, the major Maastrichtian crustal upwarping event which occurred from Ethiopia and Yemen to the continental margins of the Indian Ocean, producing basaltic flows and shallow intrusions, may have been responsible for the observed volcanism (Bosellini, 1992). The volcanics are mixed with the clastic sediments of the Mughal Kot and the Pab Sandstone and also occur as extensive basalts, above the base Tertiary contact, in the younger Khadro Formation. The separation of Madagascar represented a major rifting event which was responsible for NNW-SSE trending fault blocks and similarly

White (1981) attributes the origin of the volcanics in the Late Cretaceous formations to the erosion of the Porali Volcanics, as defined by DeJong and Subhani (1979). This is the basis for White's (1981) model of a back-arc type basin (Figure 4). The model proposes that the clastic sediments of the Mughal Kot and the Pab Sandstone were deposited in a near shore marine/ continental shelf environment. The model is dependent upon the Porali volcanic arc in the west as the source of the volcanic debris, as opposed to the Deccan Trap to the East and rifting associated with the separation of Madagascar from India. White's model discounts the Deccan Trap source on the basis of:

(a). dating the volcanics relative to other volcanics of known or inferred ages such as in the Laki Range, and in the upper Mughal Kot,

and (b). relative grain sizes of the volcanics and quartz grains.

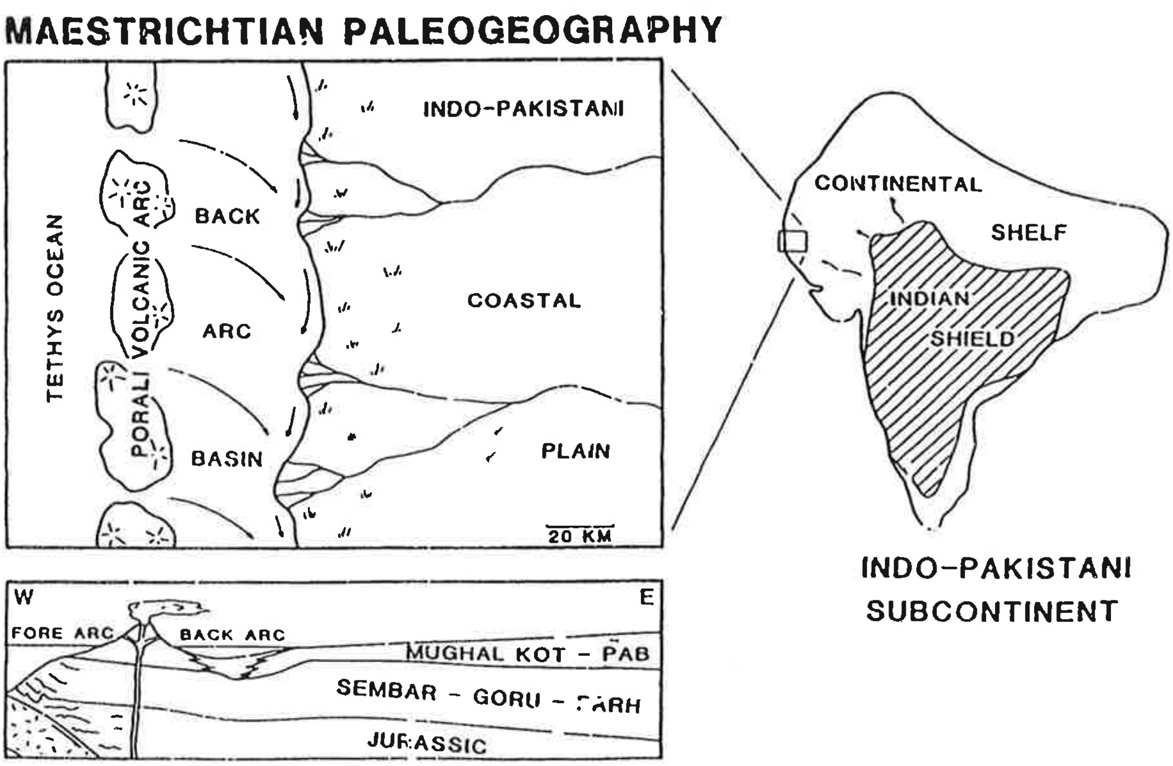

Figure 4. Back-arc depositional model for the Pab Sandstone (after White, 1981).

White (1981) does not contemplate the possible role of diagenesis on influencing grain sizes. Furthermore, the model does not utilise litho, sequence or seismic stratigraphy, to critically analyse the possibility of a western volcanic source. Such methods are used in this study. Furthermore, evidence for subduction 60 kilometres west of the Indo-Pakistan coastal plain (Figure 4) is not apparent in published palaeogeographic reconstructions (Figure 5.1). Additionally, Tectostrat (1996) suggest that an extensional event during the Early Palaeocene (Danian) is responsible for the volcanics in the Khadro Formation. Brink (1996) supports the suggestion that the basalts may be indicative of rifting (Séychelles/ India) but found no evidence in the study area to support it.

The collision of the Indo-Pakistan plate with Eurasia led to the closure of the Tethys Ocean. Three models have been proposed for the continent-continent collision:

(1) underthrusting of India beneath Eurasia,

(2) crustal shortening and thickening, and

(3) eastward lateral extrusion (Metcalfe, 1993).

Dewey et al (1989), however, discounted the models advocating underthrusting and extrusion. This conclusion was drawn on the basis of data collected from Tibet, China and the Himalayas. Patriat and Achache (1984) suggest that crustal shortening associated with the northward drift of the Indo-Pakistan Plate occurred in three phases:

1. 50Ma to 44Ma
2. 44Ma. to 36 Ma.
3. and after 36 Ma.

Ophiolite emplacement along the northern continental margin followed the collision (White, 1981; Norvick, 1995). Dating of the ophiolites places the collision at less than 56-52 Ma (Norvick, 1995) to 45 Ma (Metcalfe, 1993). Based on stratigraphic evidence, Tectostrat (1996) suggest that initial contact between the Indo-Pakistan Plate and the Afghanistan micro-continent occurred prior to 49Ma. Brink (1996) supports a possible earlier collision with a possible micro-continent which possibly developed a foreland bulge and a trough- shaped depocentre.

Rotation of the Indo-Pakistan plate occurred along the Chaman fault zone which connects the Makran Convergence (oceanic subduction) Zone with the Himalayan (India/ Eurasia) Convergence (Figure 6). The Chaman fault zone is an intracontinental transform plate boundary exhibiting north-south left-lateral strike-slip faulting (Farah et al, 1984). Emplacement of the ophiolites continued throughout the Tertiary and accelerated during the Late Miocene or Early Pliocene (White,1981; Norvick, 1995).

5.1

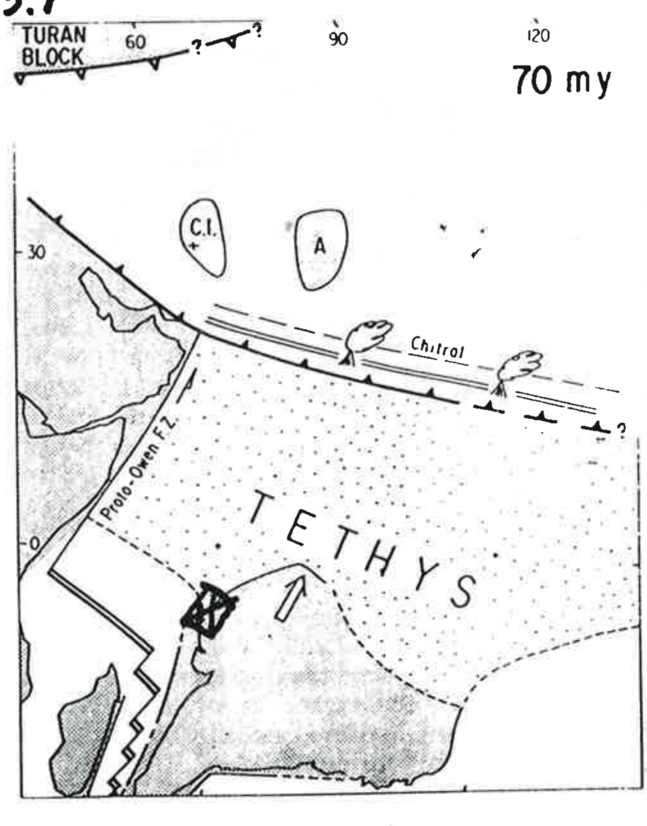

Figure 5. Tectonic sketch of the Indo-Pakistan Plateand surroundings, at 70 Ma (Figure 5.1), 55 Ma (Figure 5.2), 40 Ma (Figure 5.3), 20 Ma (Figure 5.4), and 0 Ma (Figure 5.5). Note the closure of the Tethys, the existence of the convergence along the Owen Fracture Zone and the rotation of India relativeto Africa. A= Afghanistan micro-continent; CI= Central Iran. Pab Sandstone study area is in cross hatched box (after Powell, 1979).

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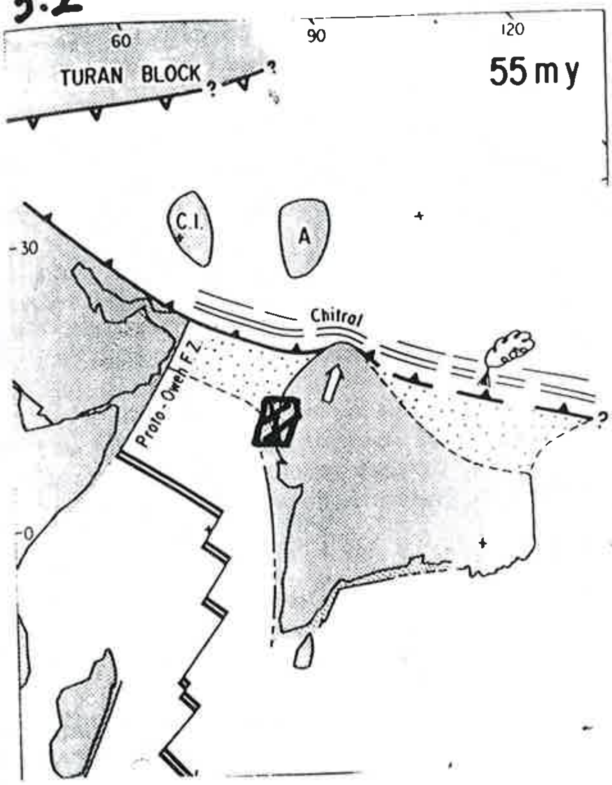
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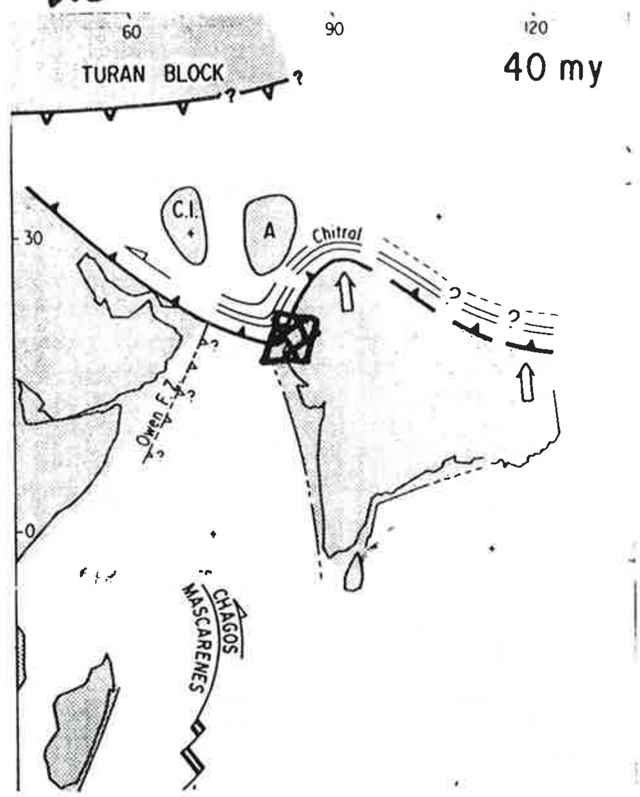
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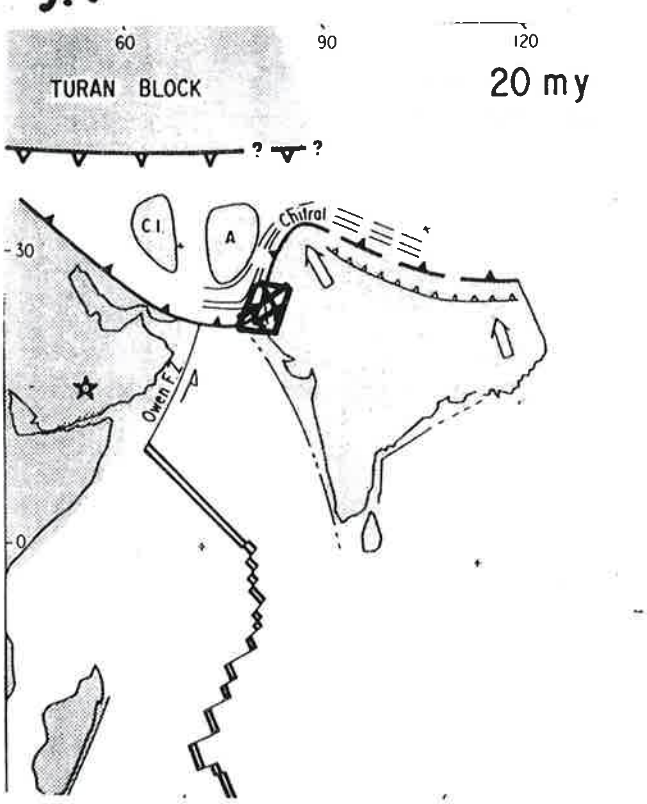
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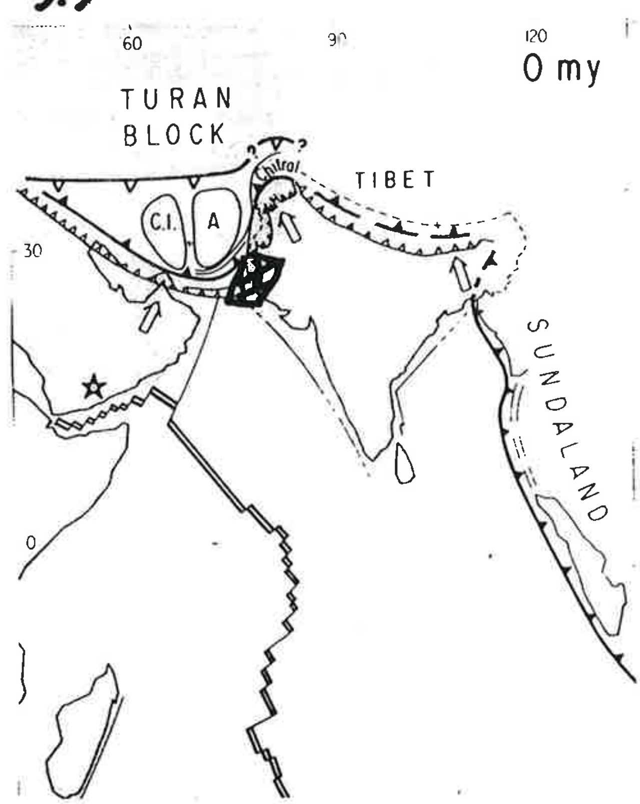
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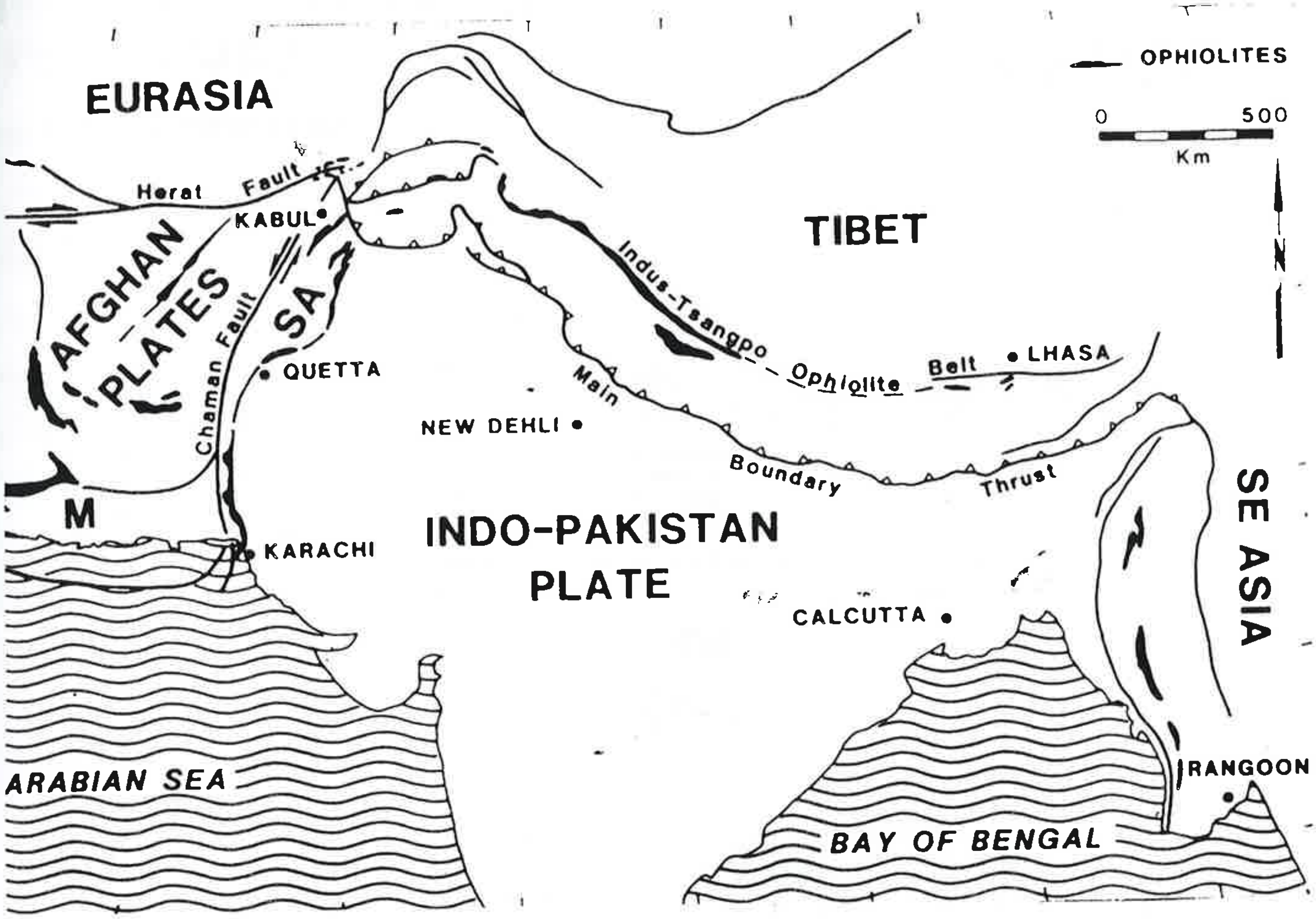
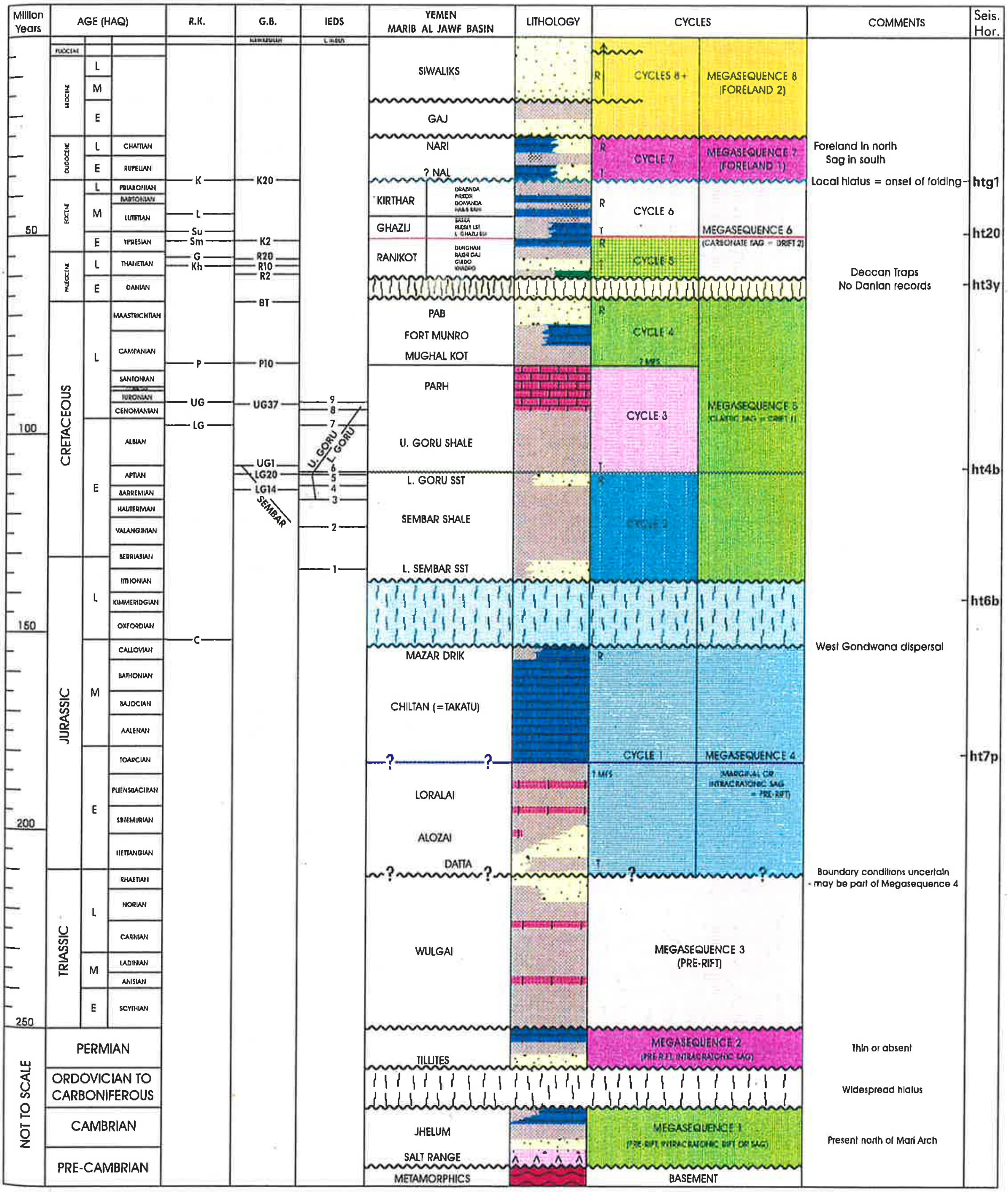


Figure 6. Regional map showing the location of the Chaman Fault Zone and the Himalayan Convergence (from Waheed and Wells, 1990)

Pakistan, Dadu/Nawabshah Permits – Pab Study

Indus Basin Stratigraphy



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2.3: PALAEOENVIRONMENT ANALYSIS

The palaeoenvironmental analysis comprises a review and compilation of climatic patterns associated with the Late Cretaceous, with particular reference to the Maastrichtian. The objective is to gain an appreciation for the oceanographic and climatic controls governing sedimentary processes at the time.

Parrish and Curtis (1982) constructed qualitative palaeoatmospheric circulation models covering seven stages in the Mesozoic and Cenozoic. Figures 8 and 9 illustrate their global atmospheric circulation and upwelling patterns during the Maastrichtian for the northern winter and summer respectively.

A closer examination of the diagrams, with particular reference to the Indo-Pakistan plate suggests that the region was dominated by easterly, or offshore, winds. The prevailing winds were associated with a high pressure system that controlled the climate throughout the Maastrichtian year. The region which was to become the Kirthar Basin is interpreted to be a vast continental shelf bordered to the south by highlands.

Parrish et al (1982) expanded the initial study and applied the previously determined models to predict palaeo-rainfall patterns. The rainfall maps are purely qualitative. Four precipitation regimes are defined; low rainfall, moderately low rainfall, moderately high rainfall and high rainfall. The regimes only represent relative rainfall values and do not incorporate the fine balance that can exist between evaporation and precipitation (eg. a wet climate can prevail with little precipitation, if evaporation is low enough).

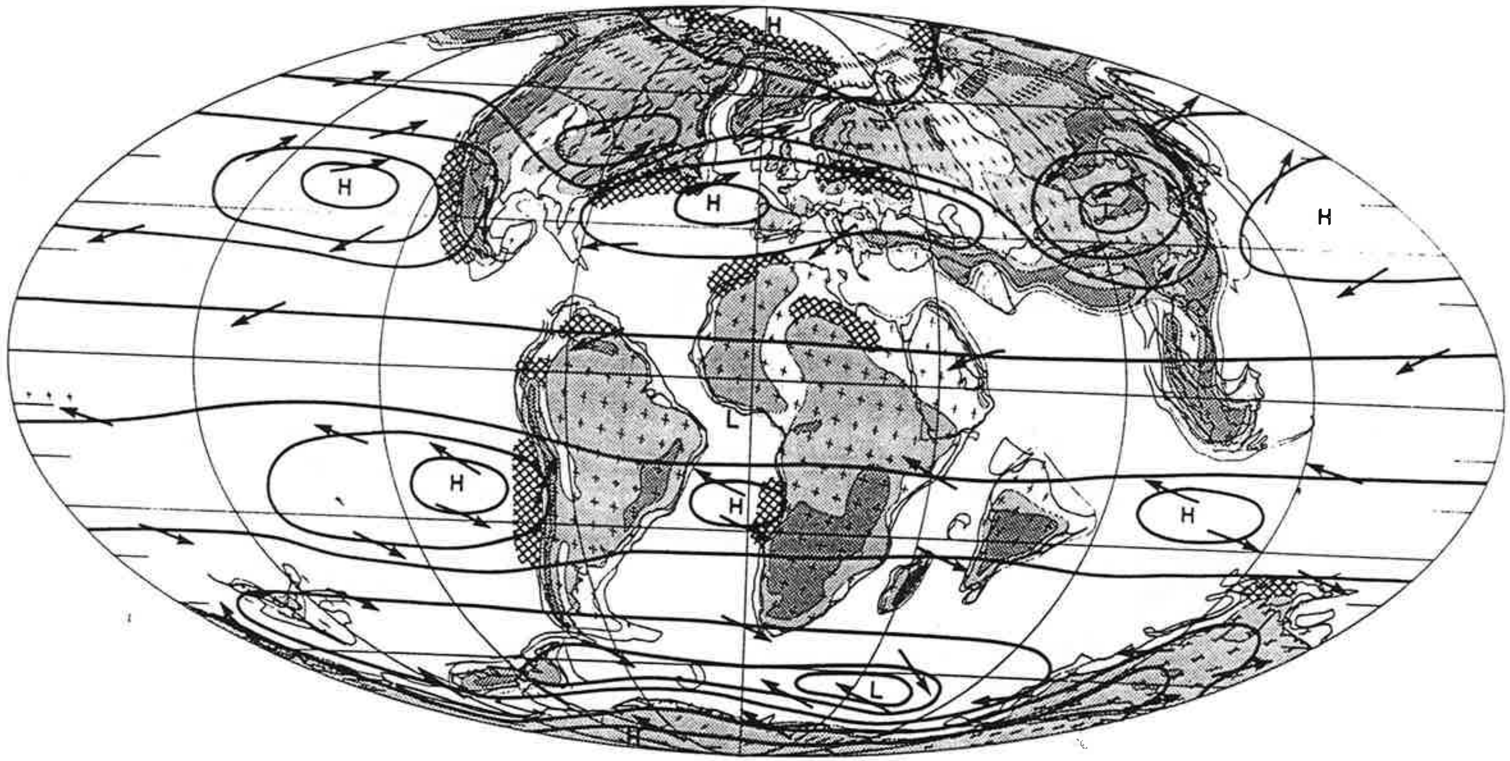

Figure 8. Atmospheric circulation and upwelling in the Maastrichtian northern summer (from Parrish and Curtis, 1982). Shading on this and subsequent maps are indicative of palaeogeography. Light shading = continental shelf; medium shading = lowlands; heavy shading = highlands.

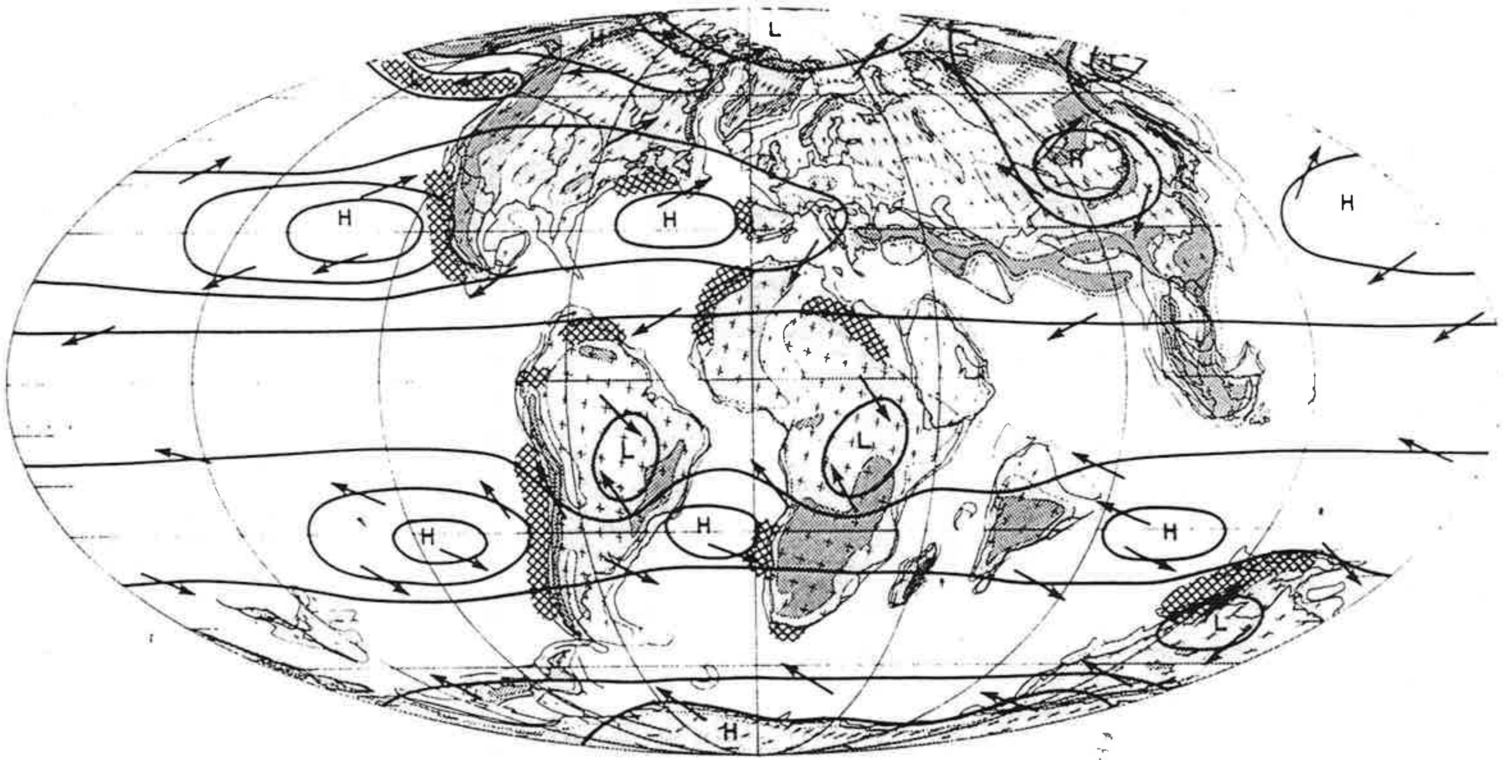

Figure 9. Atmospheric circulation and upwelling in the Maastrichtian northern winter (from Parrish and Curtis, 1982). Note the apparent development of an equatorial, low pressure belt over central South America and Africa.

Parrish et al (1982) infer that, during the Maastrichtian, a wider North Atlantic would have aided the further enhancement of the westerlies and extended a marine climatic influence further into Eurasia. The climatic zones incorporating Africa, South America, and presumably the Indo-Pakistan plate, would have appeared to shift southwards as the continents migrated north.

Figure 10 illustrates the predicted global rainfall pattern during the Maastrichtian. The Indo-Pakistan plate appears influenced by moderate rainfall and would be affected by monsoonal climatic conditions during the northern winter. This would occur as the equatorial low pressure belt migrated south onto the Indo-Pakistan continental shelf. As a consequence seasonal flooding may be apparent in sedimentary structures preserved in sediments deposited at this time.

Frakes et al (1992) suggest that the Late Cretaceous was one of the warmest times in the late Phanerozoic. Global warming may have been a direct result of the increased carbon dioxide (CO_2) content in the atmosphere associated with volcanic activity characteristic of the period.

Opinion concerning the rate of circulation of the Cretaceous atmosphere and hence the oceans is divided. Frakes et al (1992) suggest that the oceans were warm and 'sluggish' and ultimately led to the development of anoxic marine conditions. Barron and Washington (1982) concluded the reverse, based on models that quantitatively examined the relationships between palaeogeography, surface temperature gradients and atmospheric circulation during the Cretaceous period. This conclusion was based upon the suggestion that high evaporation

Figure 10. Predicted distribution of relative rainfall patterns for the Maastrichtian stage (from Parrish et al, 1982). Numbers show relative rainfall values only; no units are implied. <50 = low rainfall; 50-100 = moderately low rainfall; 100-200 = moderately high rainfall; >200 = high rainfall.

rates resulting from the warmer climate simply transferred the heat and maintained the atmospheric temperature gradient. The Cretaceous model further theorised that although the intensity of surface winds reduced at some latitudes, they correspondingly increased at others. The model predicted tropical temperatures to be 1-2 °C above the present. Evidence does exist (Barron and Washington, 1982) to suggest that the Cretaceous climate associated with continental margins could have varied substantially (seasonally?).

Alternatively, Herbert and Fischer (1986) suggest that seasonal changes in salinity and temperature occurred in Cretaceous sediments, particularly in the Tethys region. These authors suggest that this was the result of orbital forcing and resulted in the development of a dynamic ocean with apparent cyclical turn-over.

The interpretation of a seasonal climate is further supported by Lehman (1987). Studies investigating Late Maastrichtian caliche-bearing palaeosoils and fluvial regimes in the western interior of North America revealed a markedly seasonal and semi-arid climate. Early Maastrichtian palaeosoils have been associated with tropical to sub-tropical climates in warm, humid environments on well vegetated piedmont surfaces (Sieglo and Reinhardt, 1988)

Ocean temperatures cooled during the Maastrichtian, although temperatures were high compared to the Late Tertiary (Frakes et al, 1992).

A general overview of the climatic 'ingredients' is provided diagrammatically (Figure 11) from Frakes et al (1992).

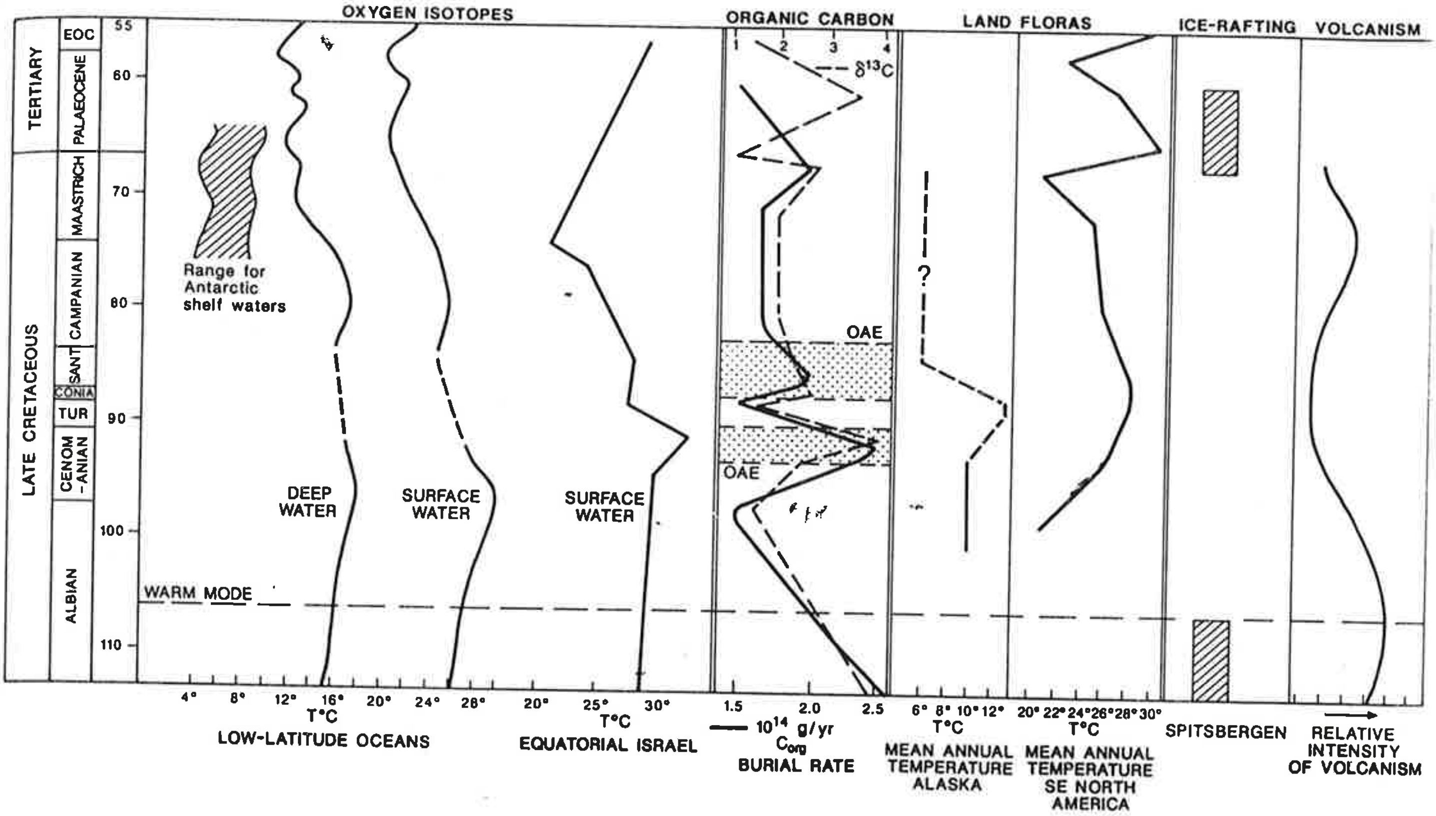

Figure 11. Oxygen isotope curves, organic carbon burial rates, ocean anoxic events and $\delta^{13}C$ data, temperature estimates from land floras , records of ice-rafting and curve of volcanism for the Cretaceous (from Frakes et al, 1992).

3: METHODOLOGY

3.1: DATA BASE

The data base for this thesis included the BHP Petroleum Pty. Ltd. Pakistan GEOLOG data base which includes log suites for 18 wells and 36 outcrop sections, paper copies of composite logs included in well completion reports and 13 2D paper seismic sections. BHP Petroleum inhouse reports (Brink, 1996; Logan, 1996; Kirk, 1996; Preston, 1996; Thomas, 1996; Norvick, 1995), Robertson Research petrographical report and interpretation, and field survey results and interpretations (Tectostrat, 1996) were all used during the study and represent the principal references for this report.

3.2: DATA QUALITY

The hardcopy database suffers from poor reproduction quality, and wireline log suites both on originals and the BHPP digital data are incomplete. The incomplete log suites limited the log analysis of the reservoir, and hence porosity evaluations from logs are limited and of variable quality. A thorough and complete regional biostratigraphic data base was lacking. Measured sections were mostly of 1970 vintage and geological descriptions of sedimentary structures and lithologies were variable but generally insufficient for accurate interpretations.

A deficiency common to all 1970 vintage measured sections is that field descriptions only included brief descriptions concerning lithology. Where sedimentary structures such as cross bedding were observed, descriptions were often vague. Commonly, little or no reference was made to the type (eg. trough or tabular sets), angle of the foreset beds, the approximate direction of the slope of the foreset beds or the amplitudes of individual sets. Hence, neither a quantitative study, nor a statistical approach to the sedimentary structures was possible.

The field survey conducted by Tectostrat (1996) represents the highest quality field work incorporated into this study. For this reason, much of the regional interpretation is based upon this data and because of its central location it is used as a valuable tie between wells in the east and outcrop sections to the west.

3.3: METHODOLOGY

The methodology adopted for the study of the Pab Sandstone can be broadly divided into six categories, each of which will be discussed individually.

3.3.1: Lithostratigraphic Analysis

Twelve principal wells and six measured sections were chosen to facilitate the Pab study on the basis of meeting one or all of the following criteria:

(1). The wireline logs should penetrate the Pab Sandstone,

(2). The log suites should be suitable for log analysis and porosity evaluations (ie. logs should include density, neutron or sonic tools),

(3) Both wells and outcrops should be located so as to enhance the prediction of the presence and quality of the Pab Sandstone in the Dadu and Nawabshah permits,

(4) Outcrop sections should have adequate and detailed lithologies and any sedimentary structures that may be present.

On the basis of these criteria, the wells and sections shown in Table 1 were chosen for the study.

From the well completion reports, composite log suites, cutting descriptions, wireline log traces and available literature, lithostratigraphic picks of the top and base of the Pab Sandstone were made for each well. The author's picks for the top of the Pab Sandstone (ie. the base Tertiary unconformity) agree with picks made in a concurrent study on the Khadro and Ranikot Formations by Mr. Andrew Logan (1996).

Table 1: Principal Wells and Measured Sections used in Pab Sandstone study.

WELLS		
WELL NAME	LOG SUITE	MEASURED SECTIONS
Badhra-01	CAL, SP, LAT, MNOR	Bara Nala
Dabbo Creek-01	LITHO	Bur Nala
Lakhra-1B	SP, RES	Naka Pabni Chauki
Manjhu-01	GR, DT	Drabber Dhora
Mazarani-01	SP, RES	Bungi Nala
Miran-01	SP, GR, ILD, DT	Pahvi Nala
Paitiani Creek-01	LITHO	
Phulji-01	CAL, SP, RES	
Sann-01	GR, NPHI, RHOB	
Sakrand-01	SP, GR, SFL, DT	
Shahdadpur-01	GR, SFLU, DT	

A regional isopach map (Enclosure 6) was constructed following the identification of the Pab Sandstone in the wells and sections. The purpose of the isopach map is to illustrate the variations in thickness of the Pab Sandstone and to aid in the interpretation of its origin and depositional environment. Seismic reflection data was not directly used in the construction of the isopach map.

Three regional correlations A-A' (southwest to northeast), B-B' (north to south) and C-C' (southwest to northeast) were compiled and used as a framework for the sequence stratigraphic model. In addition, a local correlation was constructed specifically for the BHPP permit areas. These correlations are presented in Enclosures 1, 2, 3 and 4 respectively, and their geographical locations are shown in Enclosure 5.

Contoured maps illustrating the regional variations in net sand and the net/ gross ratio were also compiled (Enclosure 7 and 8). Average grainsize, degree of sorting, and grain roundness were plotted onto maps where data were available and suggestions as to gradients of these factors mapped (Enclosures 17, 18 and 19, respectively). As these values are somewhat dependent on the bias of the observer the gradients may not be factual.

3.3.2: Wireline Log Analysis

Where adequate wireline log suites permitted, individual wells were analysed for shale volume (V_{SH}), total porosity (θ_T) and effective porosity (θ_E). Individual sand intervals were identified and their depths defined according to the nomenclature outlined below.

Example: Well Enman-01 is identified as having n intervals. Each interval is allocated the first three letters of the well name (ENM) followed by the interval number. The shallowest interval is assigned the number n, the second interval (n-1), the third (n-3) and so on.

Porosity determinations were based upon the principles outlined in " Schlumberger: Log Interpretation Principles/ Applications " (Schumblereger,1991) and by personal communication from Glenn Wormald (BHPP Petrophysicist). Schlumberger log interpretation charts (1995) were also used. Porosity values can be determined using a sonic log, a density log or a neutron log given the formation lithology, which was determined on the basis of mudloggers reports and cutting descriptions.

3.3.3: Sequence Stratigraphy

The next objective of the study involved a detailed analysis of the sequence stratigraphy of the Pab Sandstone in the Kirthar Basin. The Pab Sandstone study involved a comprehensive review, modification and extension of the previous work conducted by Brink (1996) and IEDS

(1995). The basic stratigraphy of the Lower Indus Basin was adopted from Brink (1996) and Norvick (1995) (Figure 7).

Upon completion of the interpretation, regional palaeofacies maps were drawn to illustrate the regional distribution of each systems tract or palaeofacies.

An attempt was made to investigate any apparent relationship that may exist between porosity and palaeofacies. Excluding fracture porosity, three types of porosity occur in sandstones; intergranular, dissolution and microporosity (Pittman, 1979). The Pab Sandstone at Bara Nala contains all three.

Core porosity, visible porosity and horizontal permeability data were acquired by Robertson Research (1996) for the Bara Nala field samples and ditch cuttings from wells Badhra-01 and Mazarani-01. The core porosity and horizontal permeability data used in this study included only the Bara Nala field samples because they reflected a larger sample base of the Pab Sandstone. Determinations were more precise and palaeofacies relationships were more precisely interpreted at Bara Nala.

A porosity versus depth plot was initially constructed for the Bara Nala section to illustrate any possible trends associated with the sequence stratigraphic interpretation.

The Bara Nala data set was broken down into observed visible porosity values for each porosity type (ie. dissolution, micro, and intergranular). Fracture type porosity was ignored for this initial investigation and samples exhibiting only vuggy and fracture type porosity were omitted from the data set (NP21 and NP23). These effects will be discussed later. The three porosity values were normalised to 100% and re-evaluated. For samples in which a porosity type was measured to occur in only trace quantities, a value of zero was assigned. The data set was further divided into total primary (intergranular) porosity and total secondary (microporosity + dissolution) porosity (Table 3).

3.3.4: Seismic Analysis

The objective of the seismic analysis was to attempt, where possible, to define seismic geometries of the Pab Sandstone and to identify any evidence concerning provenance direction and also to detect the possibility of two sources as suggested by White (1981) and Dolan (1990). The analysis was conducted in the light of the three maps (Enclosures17, 18 and 19) which illustrated the presence of coarse grained sediments in the west of the Kirthar Basin. The analysis was based on three working hypotheses:

1. Two primary clastic sources were supplying the basin at the time of Pab deposition, an eastern and a western source.
2. The western coarse grained sediments represent contemporaneous slump deposits resulting from over-steepening of the delta front of clastic lobes.
3. Laterally continuous channel systems acted as clastic sediment conduits, assisting in the distal deposition of coarse grained sediments below fair weather wave base depth.

The seismic analysis was based on thirteen lines of varying vintage, processing and quality. The recently acquired seismic data (1996) was unavailable at the time of the study and time constraints did not allow for a more detailed investigation. The interpretation was hindered by there being only a single well tie to the interpreted lines (Judge-01 on line TJ89-611). On the basis of the lithostratigraphic study the Parh Limestone and Pab Sandstone are both interpreted to be absent at Judge-01, the only well along that line. Two way times were

Table 2. Seismic Lines used in Pab Sandstone study

Seismic Line	Operator/ Processor
TJ87-1	LASMO/ Western Geophysical
TJ87-2	LASMO/ Western Geophysical
TJ88-300	LASMO/ Western Geophysical
TJ88-306	LASMO/ Western Geophysical
TJ88-307	LASMO/ Western Geophysical
TJ88-408	LASMO/ Western Geophysical
TJ89-611	LASMO/ Western Geophysical
894-NS-01	OGDC
894-NS-02	LASMO/ Western-Geophysical
894-NS-07	BHPP/ Western Geophysical
894-NS-13	OGDC
901-NS-107A	OGDC
901-NS-118	OGDC

adopted from the Judge-01 well completion report (LASMO, 1991). No other check shot or velocity analysis data were available to the author. An average seismic velocity was calculated from the above report based upon the picked formation tops and the two way travel times from the Judge-01 well completion report. The lithostratigraphic picks made by the author differed from those reported by LASMO (1991), but the base Tertiary unconformity pick was within allowable error.

The seismic interpretation was based on a regional concept and was not restricted solely to the Pab Sandstone. The data was examined for structures, reflection geometries, anomalies and other seismic indicators both above and below the Cretaceous - Tertiary boundary in order to aid the interpretation.

3.3.5: Petrographical Analysis

The petrographical analysis involved three steps:

1. A critical review of the study conducted by Robertson Research (1996).
2. A compilation of all available petrographical data, including the above report, and information from well completion reports and composite logs.
3. A critical analysis of all available data to ascertain the dominant controls concerning porosity development, destruction and preservation and their relationship with palaeofacies and depositional environments.
4. The compilation of a new and revised diagenetic history for the Pab Sandstone in the Kirthar Basin.
5. An attempt to use the available data, in combination with other results from this study, as a tool to predict the quality of the Pab Sandstone as a potential hydrocarbon reservoir in the Dadu and Nawabshah permits.

3.3.6: Additional Studies

This step involved an analysis of all outstanding and available data in order to refine the porosity controls on the Pab Sandstone. Such work included the study of the effect of depth of burial, burial history and a regional interpretation of the depositional environment of the Pab Sandstone in the Kirthar Basin.

4: RESULTS

4.1: SEQUENCE STRATIGRAPHY

Vail et al (1977) define a sequence as " a relatively conformable succession of genetically-related strata bounded at the top and base by unconformities and their correlative conformities."

The Pab Sandstone is bounded in the study area by two unconformities. Brink (1996) defined the base of the Pab Sandstone (denoted as the P10 sequence) as a tectonically- enhanced unconformity including its correlative conformity. The Cretaceous-Tertiary contact is recognised in this study as an erosional unconformity (refer seismic analysis).

The Pab Sandstone represents a Type 2 sequence and is bounded at its base by a Type 2 unconformity associated with a marginal sag basin. The sequence is composed of a shelf margin systems tract (SMST), an upper and lower transgressive systems tract (UTST and LTST, respectively) and a highstand systems tract (HST). The characteristics, regional distributions and porosity relationships are discussed individually for each systems tract.

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BHP

Bara Nala Ternary Porosity Plot

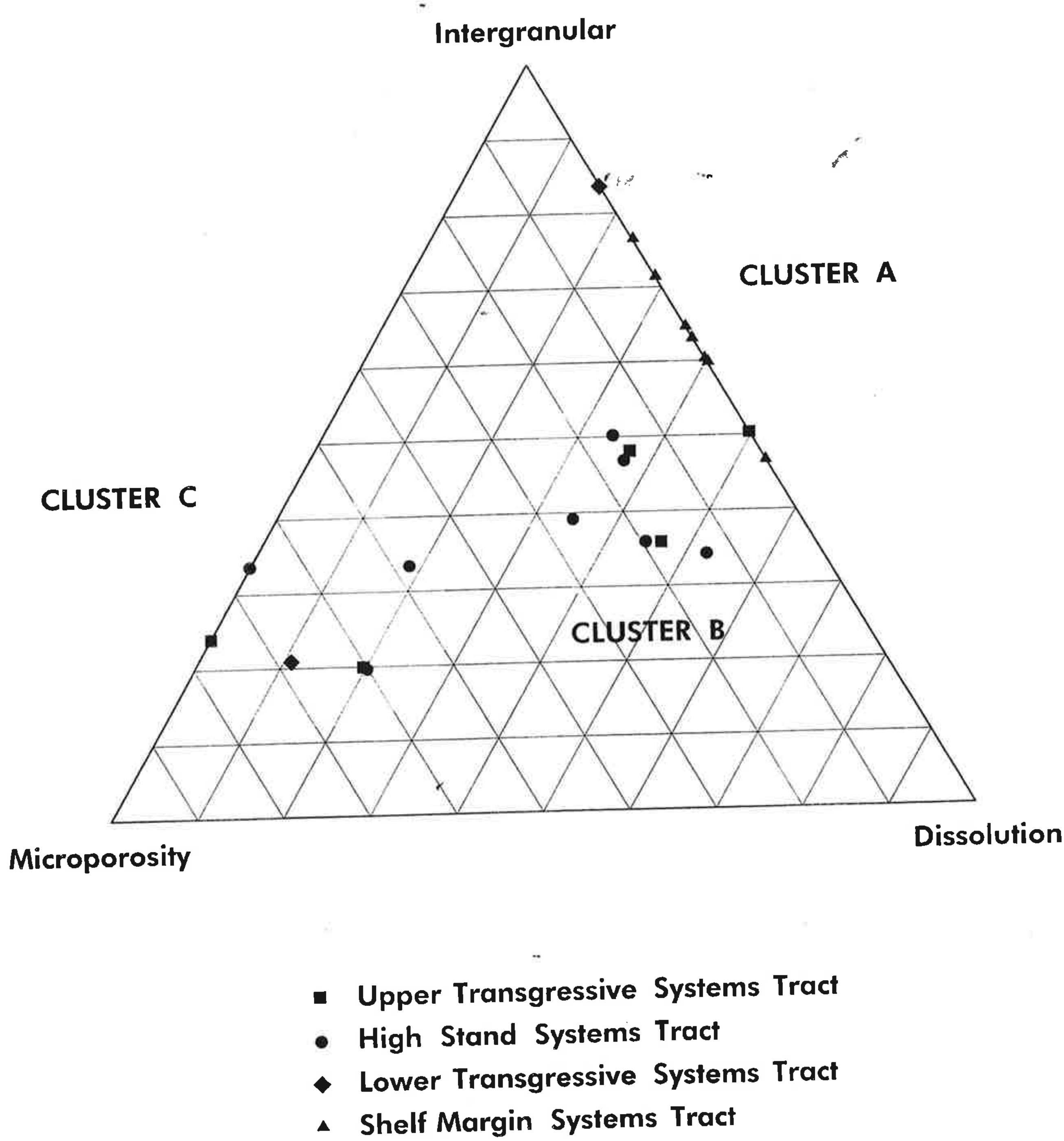


Figure 12. Ternary diagram of visible porosity and system tracts observed at Bara Nala.

Figure 13: Porosity v. Depth Plot, Highlighting Palaeofacies Trends.

TABLE 3: BARA NALA OUTCROP: POROSITY TYPES NORMALISED TO 100%

SAMPLE	SLIDE	HORIZ. PERM (mD)	CORE POROSITY (%)	INTERGRANULAR		TOTAL PRIMARY	DISSOLUTION		MICROPOROSITY		TOTAL SECONDARY	FACIES
				ACTUAL	NORMALISED		ACTUAL	NORMALISED	ACTUAL	NORMALISED		
1	NP 10	2890	21.1	15	71	71	6	29	Tr	0	29	SMST
2	NP 11	mD	19.7	14	64	64	8	36	0	0	36	SMST
3	NP 12	mD	19.8	14	70	70	6	30	Tr	0	30	SMST
4	NP 13	mD	21.2	16	70	70	7	30	0	0	30	SMST
5	NP 14	D	19.7	16	73	73	6	27	Tr	0	27	SMST
6	NP 17	mD	18.4	16	47	47	18	53	Tr	0	53	SMST
7	NP 18	mD	16.5	16	76	76	5	24	Tr	0	24	SMST
8	NP 19	mD	19.2	4	21	21	2	11	13	68	79	LTST
9	NP 20	>10 000	22.4	11	61	61	7	39	0	0	39	LTST
10	NP 22	56.9	6	5	83	83	1	17	0	0	17	LTST
11	NP 24	0.71	12.9	2	20	20	2	20	6	60	80	HST
12	NP 25	mD	(-)	8	53	53	5	33	2	14	47	HST
13	NP 26	930	29.5	9	39	39	8	35	6	26	61	HST
14	NP 27	<0.01	8.8	0	0	0	1	33	2	67	100	HST
15	NP 28	42.6	21.6	7	33	33	4	19	10	48	67	HST
16	NP 29	mD	22.4	9	47	47	7	37	3	16	53	HST
17	NP 30	234	25.5	9	45	45	7	35	4	20	55	HST
18	NP 31	5370	27.3	12	50	50	8	33	4	17	50	HST
19	NP 32	1430	20.8	8	47	47	6	35	3	18	53	UTST
20	NP 33	1.14	7.9	1	25	25	Tr	0	3	75	75	UTST
21	NP 34	2300	26.5	9	47	47	7	37	3	16	53	UTST
22	NP 35	<0.01	2.3	2	50	50	2	50	Tr	0	50	UTST
23	NP 38	1.47	11.5	1	20	20	1	20	3	60	80	UTST

4.1.1: SHELF MARGIN SYSTEMS TRACT

The SMST represents a slightly progradational to aggradational parasequence set as defined by Van Wagoner et al (1988) and is recognised in wireline logs in the study area by an aggradational gamma or SP log motif.

The SMST identified in the Kirthar Basin is characterised by massive to thick bedded, poorly sorted, coarse grained, in places pebbly, sandstone. Pebble strings are common along large metre-scale trough (sometimes planar) cross bedding. Possible channels were identified in outcrop at Drabbar Dhora.

Palaeocurrent measurements (Tectostrat, 1996) at Bara Nala suggest variable current directions. The facies is dominated by northwest-ward to northeast-ward current directions. No southeasterly directed currents were recorded.

The SMST Facies Map (Enclosure 13) illustrates the regional distribution of the SMST. The facies is constrained in the east. In addition the facies is constrained in the west by its interpreted absence at Bungi Nala and Pahvi Nala. The SMST is not interpreted south of Naka Pabni Chauki and is inferred to be absent at Patiani Creek-01 and Dabbo Creek-01 due to the restricted lithostratigraphic data at the two wells. The SMST is poorly constrained in the north due to the poor data quality at Mazarani-01, the absence of Pab Sandstone penetration at Phulji-01 and the ambiguity associated with the Late Cretaceous and Early Tertiary deposits at Gaj East.

The SMST facies at Bara Nala possesses zero to negligible amounts of microporosity as illustrated on a ternary porosity plot (Figure 12). The samples NP10, NP11, NP12, NP13, NP14, NP17, and NP18 are classified as quartz arenites and NP13 and NP17 are sublitharenites. The SMST samples are all grouped into ' Cluster A' on Figure 11. The samples are dominated by primary porosity, notably intergranular type porosities (Table 3). Dissolution type porosities account for the remainder (approximately one third) of the total observed visible porosity. Kaolinite and iron phases are notably rare (up to 1% respectively, in two samples) in the SMST sample base.

The overall porosity versus depth trend associated with the SMST at Bara Nala increases slightly with depth (Figure 13). This reflects the generally aggradational nature of the package and the similar lithologies throughout the SMST.

Quartz overgrowths are common to all samples. Clays are generally indeterminate, although chlorite and kaolinite occur locally. Although total clay content ranges up to 15%, microporosity is only observed in trace amounts.

Core porosity values and visible porosity determinations are comparable (Table 3) Differences in porosity values may be attributed to sample heterogeneity (Robertson Research, 1996).

The reservoir potential of the SMST facies is interpreted to be good to very good based on petrology samples from Bara Nala.

4.1.2 TRANSGRESSIVE SYSTEMS TRACTS

The TST is the middle systems tract of a Type 2 sequence and is interpreted to form during the maximum rate of relative sea level rise. The TST is characterised by higher frequency sequences, a retrogradational parasequence set and is best developed in inner neritic to shallow marine water depths (Van Wagoner, (1988), Mitchum, (1994)).

The transgressive systems tracts identified at Bara Nala (LTST and UTST) are characterised by large, metre-scale, cross bedded sandstones at the base. Apparent traces and burrows are common at bedding surfaces. Large scale tabular cross bedding and trough cross beds are commonly observed in less massive beds. Slip face sorting (medium/ coarse grains) and reactivation surfaces were also observed in outcrop. Sub-tidal and pedogenic sediments are common near the top of the TST. Sandstone intercalations exhibiting high energy cross bedding and deformed cross laminae are common in the upper shales and limestones immediately underlying the regionally correlatable maximum flooding surface (mfs).

Two TSTs (UTST and LTST) were interpreted to be present at Bara Nala and were regionally correlatable and mappable (Enclosures 16 and 14, respectively).

The LTST is constrained in the west by its absence at Bungi Nala, Pahvi Nala and Naka Pabni Chauki. As with the SMST Facies Map both the LTST and UTST are interpreted to be present in the south (Patiani Creek-01 and Dabbo Creek-01) and north (Mazarani-01 and Phulji-01). Data quality does, however, hinder a more accurate interpretation. Notably, the UTST and LTST are both constrained in the northeast by the absence of the Pab Sandstone at Sagyun-01.

Common to the TSTs is the presence of marl, marly limestones and calcareous sandstones in the west. The upper section of the UTST is characterised by shales and hard, micro-fossiliferous limestones as opposed to sub-tidal and pedogenic limestones in the LTST.

No palaeocurrent data were available for the LTST. Data recorded at Bara Nala suggest a strong southwest-ward to northwest-ward palaeocurrent direction in the UTST.

No direct correlation was observed between visible porosity type and the TSTs (figure 12). The TST samples (Table 3) demonstrate the greatest variation in position on the ternary diagram. This may be attributed to the greater variation in lithologies within the UTST and LTST sample base, which includes quartz wackes, quartz arenites, calcareous sandstones, sublitharenites and lithic wackes, as compared to the other facies.

The LTST observed at Bara Nala has the greatest porosity variation with depth (Figure13). This observation is most likely to be attributed to the presence of limestones (pedogenic?) at the top. The overall porosity versus depth trend of the UTST is less pronounced, but never the less a wide variation in porosity measurements is apparent (Figure 13) because of the numerous lithologies present in the UTST.

The reservoir potential of the TSTs is variable from very poor to moderate to good depending on the various lithologies, each of which would respond differently to the prevailing diagenetic processes. On the weight of the evidence, however the general reservoir potential of the TST facies can be defined as poor.

4.1.3: HIGHSTAND SYSTEMS TRACT

The HST is the upper systems tract in the Type 2 sequence. The HST is the most widespread on the shelf (Enclosure 15) and is characterised by an overall progradational parasequence set. The HST is interpreted to have formed during the latter part of a relative rise of sea level and continued during a relative fall in sea level (Mitchum et al ,1994).

The HST identified at Bara Nala is characterised by an irregular contact with the underlying TST. The base is characterised by a sub-tidal to pedogenic, pebbly sandstone layer. The HST is generally a massive, thick bedded sandstone with mega and low angle cross bedding. Large, metre-scale trough cross bed sets, which are occasionally slightly erosive, are present. Burrowed bed surfaces, scours and erosive contacts (channels?) are common throughout.

Eight HST samples (Table 3) were plotted on the porosity ternary diagram (Figure 12). Five of the eight samples plot just right of the centre of the diagram ('Cluster B'). Each of the three remaining samples is poorly sorted and modal grain size is in the range very fine upper to fine lower.

Sample NP27 is a haematitic sandstone with 43% diagenetic iron. The iron phase appears to replace a depositional carbonate mud matrix in which microporosity is inferred to occur (Robertson Research, 1996). Primary porosity has been totally occluded and replaced completely by secondary porosity.

Sample NP28 is clay rich (17%) and microporosity would develop at the expense of macroporosity. Similarly, iron phases, clays and terriginous muds account for up to 33% of sample NP24.

As with the SMST, LTST and UTST Facies Maps, the regional distribution of the HST is poorly constrained in the north and south. The HST is interpreted to be the most regionally correlatable, mappable and widespread facies identified.

Porosity decreases with depth in the HST observed at Bara Nala. This is attributable to the depositional environment responsible associated with the HST. The sandstones observed in the HST clean upwards associated with a possible late relative fall in sea level. The relatively low porosity samples at the base are associated with reworked sub-tidal to pedogenic sediments (limestones).

The reservoir potential of the HST identified in the Pab Sandstone, based upon the samples obtained from Bara Nala, is classified as poor to moderate to good. Generally, the HST demonstrates moderate reservoir potential.

4.2.1: BADHRA-01

Latitude: 26° 06' N Longitude: 67° 39' E

Pab Sandstone:	Top Pab................	1024 metres rkb
	Base Pab...............	Not reached
	Pab Thickness.........	>300 metres
	Net Sand...............	>255 metres
	Net/ Gross.............	>85%

A thick, sand rich, Pab sandstone succession is present at Badhra-01 (Enclosure 1). No porosity tools were available at the time of this study. The well is characterised by a thick SMST (the base of which is not reached) and TST's. The UTST is identified by the presence and increase in limestones toward the base Tertiary unconformity.

The impressive, apparently high net sand thickness (>255 metres) is of importance to the Phulji area as the regional net/ gross map (Enclosure 8) indicates that Phulji-01 should have about the same sandstone percentage in the Pab as does Badhra-01.

4.2.2: DABBO CREEK-01

Latitude: 24° 02' N	Elevations: KB - 19.00 metres
Longitude: 67° 42' E	

Pab Sandstone:	Top Pab	1804 metres rkb
	Base Pab	1840 metres rkb
	Pab Thickness	36 metres
	Net Sand	30 metres (predicted)
	Net/ Gross	85% (predicted)

No electric log suites were available for Dabbo Creek-01 at the time of this study (Enclosure 2). The interpretation is based upon the lithostratigraphy recognised by BEICIP (1986).

Sequence stratigraphic determinations were not possible due to the restricted data set.

Net sand is predicted to be approximately 30 metres in thickness, assuming a net/ gross of 85% (Enclosures 7 and 8).

The notable feature concerning the Pab Sandstone in this locality is the relative thinness of the formation (Enclosure 6). This observation may be attributable to a distal location from the primary sediment source, structuring and faulting may have removed the unit, or the sediments may have been deposited in a shallow, inner neritic/ shelf environment.

4.2.3: LAKHRA-1B

Latitude: 25° 42' N Longitude: 68° 12' E

Pab Sandstone:	Top Pab	893 metres rkb
	Base Pab	997.5 metres rkb
	Pab Thickness	104.5 metres
	Net Sand	45 metres
	Net/ Gross	44%

The only electric logs available for interpretation at Lakhra-1B were an SP log and two resistivity logs (Enclosure 2). No well completion reports were available at the time of the study.

The Pab Sandstone is constrained at the top by the large resistivity 'kick' between 876 metres and 893 metres. The author has attributed this response to the basalts at the base of the Khadro Formation. The base of the Pab Sandstone is easily recognised by the static SP and resistivity responses associated with the underlying Parh Limestone. Sand intervals within the Pab Sandstone were identified on the basis of the SP response.

The SMST, LTST, HST and UTST which are all interpreted to be present at Lakhra-1B (Enclosure 2). The SMST is well developed and is sand rich. The regionally correlatable mfs associated with the upper boundary of the LTST is easily recognised by an SP peak at 958 metres.

A net/ gross value of 44% is interpreted (Enclosure 8). This value is relatively low compared to adjacent wells (Manjhu-01 (66%), Sann-01 (83%)) and this is reflected in the Pab Percentage Sandstone Map (Enclosure 8). The low net/ gross is associated with a relatively thick section of Pab Sandstone (104.4 metres) as compared with nearby wells (Manjhu-01 (47 metres) and Sann-01 (47 metres)). This observation may indicate that shallow shelf conditions existed to the north and east at the time of deposition.

No porosity tools were available for log analysis.

4.2.4: MANJHU-01

Latitude: 25° 35' 11" N Longitude: 68° 25' 28" E	Elevations: KB - 89.9 metres AMSL

Pab Sandstone: Top Pab......................1138 metres rkb
Base Pab....................1185 metres rkb
Pab Thickness...........47 metres
Net Sand....................31 metres
Net/ Gross.................66%

The sonic (DT) log was the only porosity tool available for calculations (Table 3). Manjhu-01 is sand rich (Enclosure 2).

Table 4: Manjhu-01: Porosity Evaluation

			DT	
Interval	**Depth**	θ_T	V_{SH}	θ_E
MAN3	1144-1150 mrkb	22%	10%	20%
MAN2	1158-1170 mrkb	31%	15%	26%
MAN1	1174-1180 mrkb	29%	15%	24.5%

Three distinct sand intervals were interpreted to be present in Manjhu-01 and are described as follows:

Interval MAN1 (1174-1180 mrkb):sharp based sand overlying a six metre thick shale. The sand has a distinct shaling (ie. fining) upward nature as inferred from the GR response. The distinct 'Christmas tree' shaped response is indicative of a fining upward, channel bed-load deposit; a fluvial point bar or a transgressive shelf sand (Walker and James, 1992). The baseline GR response is the highest (approx. 18 API units) for the three intervals identified.

Interval MAN2 (1158 - 1170 metres rkb): Thick, sharp based sand which on the basis of the GR trace has a low sand content. Thin, high GR responses are common in this interval possibly suggesting thin shale, siltstone and/ or claystone intercalations are present. The GR response is generally irregular and exhibits a mixture of clean and shaly lithologies. Sharp based sands are indicative of channels and the entire interval may be attributed to a fluvial flood-plain type deposit.

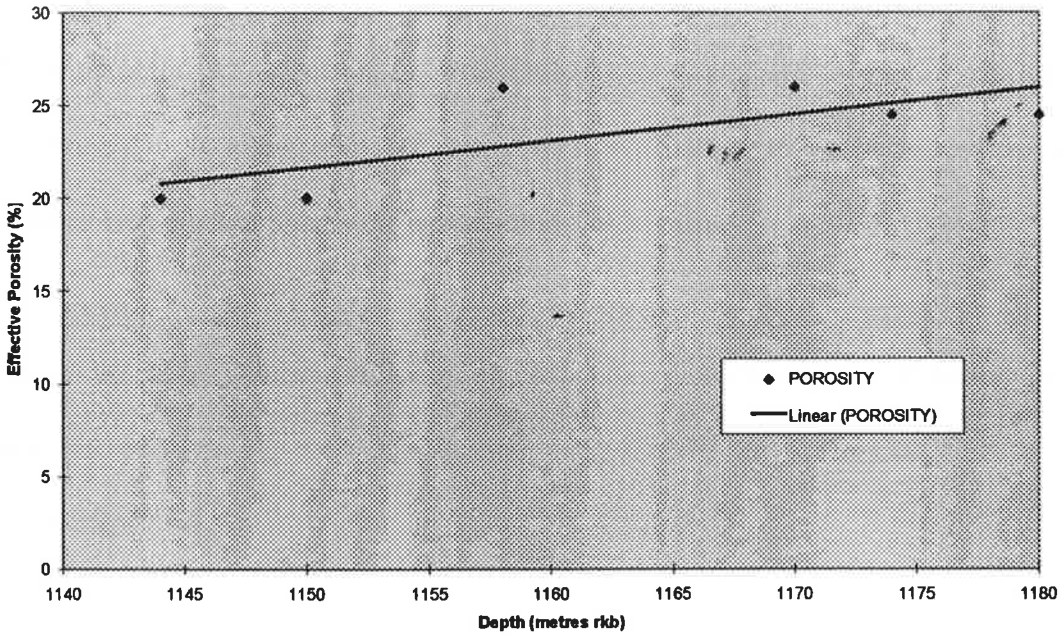
Interval MAN3 (1144 -1150 mrkb): The GR trace is notably symmetrical and records the lowest GR baseline response(approx. 12 API units) of the three intervals. The interval is clean, the motif is rounded at its base and symmetrical about a coarsening and then fining upward trend. The GR response is common to transgressive shelf sands (Walker and James, 1992).

The baseline shift towards 0 API units suggests that the sand intervals are cleaning upward. This may suggest implications concerning the rate of sediment supply. The sonic (DT) trend for each sand interval is similar. The DT log characteristically has low values at the base of the sand (40, 80 and 60 μs/ ft respectively) which increase up each interval to a maximum value (140+, 122 and 130 μs/ ft, respectively). The DT response may be attributed to porosity trends, diagenetic effects or the depositional environment at the time of sedimentation.

Three systems tracts were identified within the well; the lower transgressive systems tract(TST), the highstand systems tract (HST) and the upper transgressive systems tract. A regional maximum flooding surface separates the lower TST and the HST. A regional sequence boundary separates the HST and the upper TST.

The porosity generally decreases upwards in the Pab Sandstone identified in Manjhu-01(Figure 14).

Figure 14. Manjhu-01 log analysis: Effective porosity versus depth.



4.2.5: MAZARANI-01

Latitude: 27° 40' N Longitude: 67° 30' E

Pab Sandstone:	Top Pab	2917 metres rkb
	Base Pab	2966 metres rkb
	Pab Thickness	48 metres
	Net Sand	14(?) metres
	Net/ Gross	29(?)%

The interpretation of Mazarani-01 is restricted by the availability of only SP and RES tools (Enclosure 2). No log or sequence stratigraphic evaluations were possible, but the author is confident that the Pab Sandstone is present at this location.

The low net/ gross determination is questionable based on the data, but if the Pab Sandstone has a shale equivalent such as some authors suggest is the case at Gaj East, then the prediction may be valid.

4.2.6: MIRAN-01

Latitude: 26° 09' N	Elevations: KB - 38.4 metres AMSL
Longitude: 68° 33' E	

Pab Sandstone:	Top Pab....................1985 metres rkb
	Base Pab....................2060 metres rkb
	Pab Thickness...............75 metres
	Net Sand....................32.5 metres
	Net/ Gross.................43%

Porosity determinations were based upon the sonic (DT) log only (Table 5). Miran-01 is sand poor but the percentage of sandstone increases up section, which may be indicative of an overall progradational package (Enclosure 1). Seven intervals were isolated for the purpose of porosity investigations.

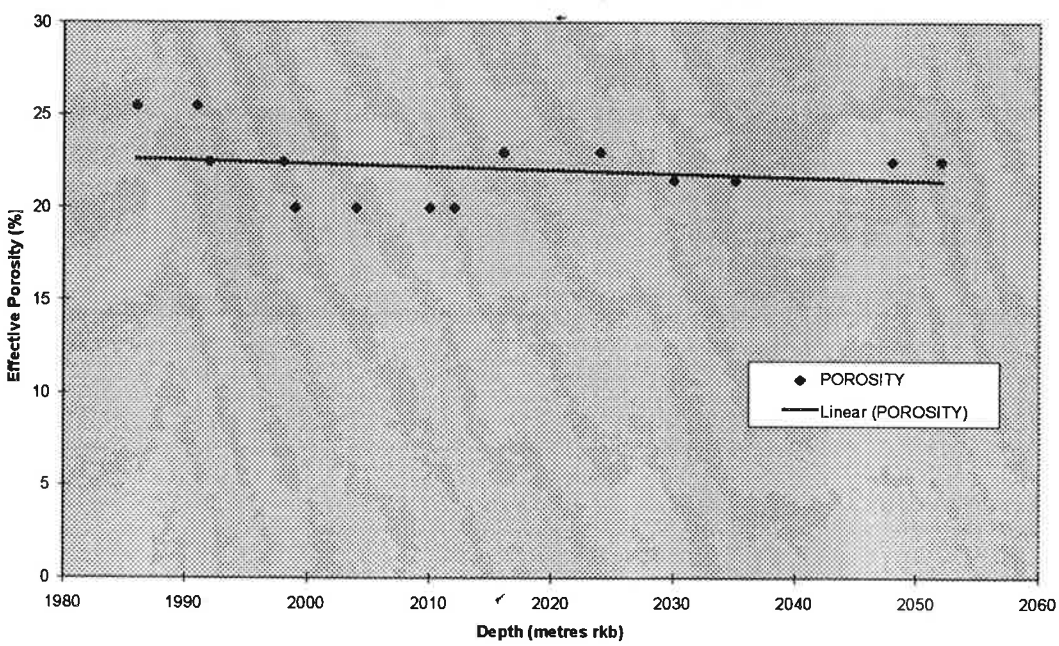
Table 5: Miran-01: Porosity evaluation.

		DT		
Interval	**Depth**	θ_T	V_{SH}	θ_E
MIR7	1986-1991 mrkb	27.5%	18%	25.5%
MIR6	1992-1998 mrkb	25.0%	10%	22.5%
MIR5	1999-2004 mrkb	22.0%	10%	20.0%
MIR4	2010-2012 mrkb	26.5%	25%	20.0%
MIR3	2016-2024 mrkb	25.5%	10%	23.0%
MIR2	2030-2035 mrkb	25.5%	15%	21.5%
MIR1	2048-2052 mrkb	25.0%	10%	22.5%

The sands identified are variable and appear strongly influenced by varying quantities of shale and/ or claystone which ultimately reduces the macro porosity. The upper TST and the HST were recognised to be present and the regional mfs was easily identified. The TST is depleted in sand. The GR response suggests a variable shale content due to the variability of the shale baseline. Identifying the type of shale present here is the key to understanding this observed variability. The MIR7 sand interval shales upward (transgressive shelf sand?), while the MIR6 sand, which is thicker, coarsens upwards and is truncated by a sharp top. MIR6 may be indicative of a clastic strand plain or shallow marine sheet sandstone. The sands identified in the HST are variable in thickness. The five sands commonly exhibit a "W" shaped GR baseline response (especially MIR5, MIR2, less pronounced in MIR1 and MIR4). The irregular nature of the GR responses may be associated with a fluvial flood-plain dominated by meandering channels.

The porosity versus depth profile of Miran-01 (Figure 15) increases upwards.

Figure 15. Miran-01 log analysis: Effective porosity versus depth.



4.2.7: PAITIANI CREEK-01

Latitude: 24° 45' N	Elevation: KB- 19.00 metres
Longitude: 67° 29' E	

Pab Sandstone:	Top Pab.................2342 metres
	Base Pab................2393 metres
	Pab Thickness.........51 metres
	Net Sand................N/A
	Net/ Gross..............N/A

No electric logs were available for Paitiani Creek-01 at the time of this study (Enclosure 2). The interpretation is based upon the lithostratigraphic picks recognised by BEICIP (1986). No determinations of net sand or net/ gross were possible due to the limited data. In addition the author was not able to complete a sequence stratigraphic interpretation with confidence.

The author is confident that the Pab Sandstone is present at Paitiani Creek-01. As noted at Dabbo Creek-01 the Pab sandstone is relatively thin in this region compared to the north and north west of the study area (Enclosure 6).

4.2.8: PHULJI-01

Latitude: 26° 50' N Longitude: 67° 39' E

Pab Sandstone:	Top Pab................3780 metres (predicted from seismic data)
	Base Pab...............3905 metres (predicted from seismic data)
	Pab Thickness.........125 metres (predicted from seismic data)
	Net Sand................N/A
	Net/ Gross..............N/A

The Phulji-01 interpretation was restricted because the well did not penetrate the Pab Sandstone (Enclosures 2 and 3). Drilling ceased upon the intersection of basalts at 3706 metres which has been interpreted as the top of the Khadro Formation (A. Logan, pers. comm., 1996).

A concurrent seismic study by Thomas (1996) has confirmed the lithostratigraphic results of this study by recognising the presence of the Pab Sandstone in the Phulji area. The top of the Pab Sandstone is interpreted at 3780 metres. The most likely thickness is 125 metres and is based upon an average seismic velocity of 2847 ms^{-1} (H. Thomas, pers. comm., 1996). The maximum likely thickness of the Pab Sandstone is 164 metres assuming an average seismic velocity equal to 3500 ms^{-1}. A minimum thickness of 75 metres is predicted (H. Thomas, pers. comm., 1996).

Due to the absence of well data and poor seismic resolution the author was unable to complete a comprehensive log and sequence stratigraphic analysis of Phulji-01.

4.2.9: SAKRAND-01

Latitude: 26° 08' 4" N	Elevations: GL - 31.77 metres AMSL
Longitude: 68° 19' 55" E	KB - 37.97 metres AMSL

Pab Sandstone:	Top Pab	1767 metres rkb
	Base Pab	1854 metres rkb
	Pab Thickness	87 metres
	Net Sand	47.5 metres
	Net/ Gross	55%

The Pab Sandstone is interpreted to exist between 1767 and 1854 metres rkb on the basis of log analysis (Enclosure 1). This conflicts with OGDC's (1993 (b)) interpretation in which the Pab Sandstone was interpreted to be absent on the evidence provided by cuttings. OGDC (1993(b)) however divided the overlying Khadro Formation into an upper and lower entity. The Lower Khadro description is indeed similar to Pab descriptions elsewhere (Shahdadpur-01, Sann-01) and is outlined below:

" the lower part comprises of sandstone with subordinate clay/ claystone and occasional beds of basalt. The sandstone is white, brownish white, transparent, dirty white, medium hard to hard, at places loose, friable, fine to medium grained, occasionally coarse grained, sub-angular to sub-rounded, fairly sorted, fairly cemented, calcareous, visual porosity 5-10%. The claystone is rusty brown, reddish brown, medium hard, at places soft, hydrophilic and pasty. "

Nine sand intervals were evaluated for porosity based only on the sonic (DT) log (Table 6). Other porosity tools were unavailable at the time of this study.

The effective porosity of the Pab Sandstone intervals identified at Sakrand-01 decreases with depth (Figure 16). Apart from effects associated with depth of burial and compaction the trend may be attributed to the thick sand intervals and a high percentage of sandstone near the top of the unit, associated with the HST.

Table 6: Sakrand-01 - Porosity evaluation

		DT		
Interval	**Depth**	θ_T	V_{SH}	θ_E
SAK9	1768-1776 mrkb	25.5%	15%	21.5%
SAK8	1782-1792 mrkb	29.5%	20%	23.5%
SAK7	1794-1796 mrkb	23.0%	10%	20.5%
SAK6	1808-1812 mrkb	28.0%	10%	25%
SAK5	1820-1824 mrkb	26.5%	10%	24%
SAK4	1830-1832 mrkb	22.0%	10%	20%
SAK3	1836-1840 mrkb	21.5%	10%	19.5%
SAK2	1841-1844 mrkb	24.5%	15%	22%
SAK1	1848-1852 mrkb	22.0%	20%	17.5%

The sand intervals evaluated vary in thickness and character. Most notably, the Pab section does exhibit a major transgressive and regressive episode. The transgressive gamma ray (GR) signature begins at the base of the Pab in Sakrand-01 and culminates in a regionally correlatable maximum flooding surface (mfs) located at 1802 metres rkb. The mfs is characterised by a peak GR response.

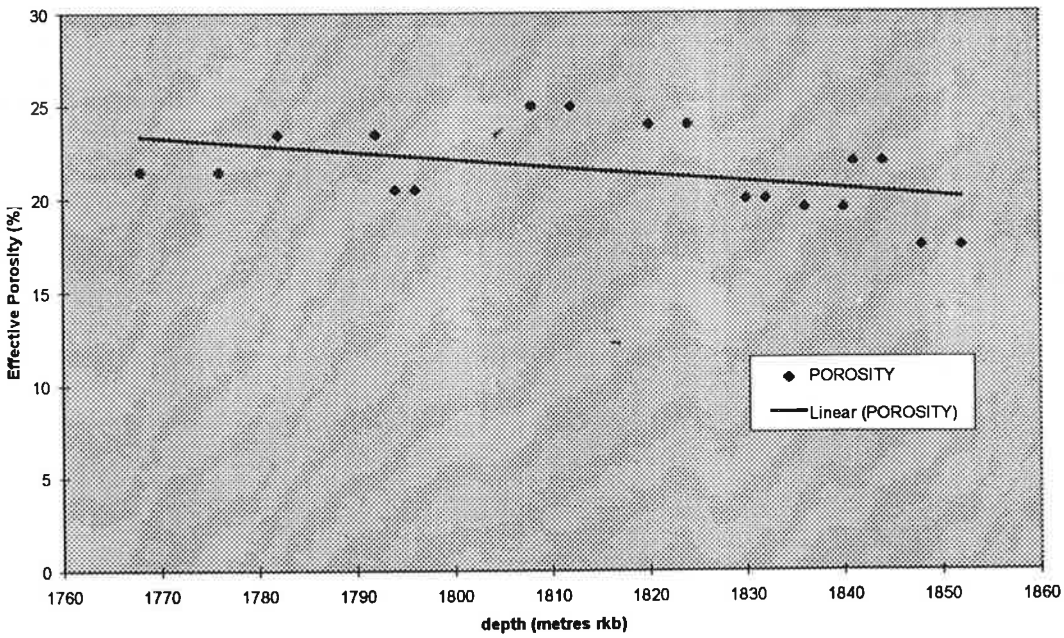
The sand intervals are best described in association with the systems tracts prevalent in Sakrand-01. Three systems tracts were identified in Sakrand-01:

1. The SMST in Sakrand-01 is a sand rich lithofacies and is characterised by thick, sharp based sands at the base (1852 metres rkb) with an increasing shale and/ or claystone content towards the top (1822 metres rkb). The upper sands of the SMST are thin and appear cleaner on the basis of the associated GR response. The author interprets the sands to be channels associated with an alluvial/ coastal plain environment.
2. The lower, regionally correlatable TST immediately succeeds the SMST and its upper limit is defined by the regional mfs. The Sakrand-01 TST is a retrogradational package. The

interval is generally sand poor. However, two main sand bodies (SAK5 and SAK6), which differ in their GR response, are present. SAK5, located at the base of the TST, has a distinct sharp base and a shaling (ie. fining) upward trend, followed by a sharp top. The higher SAK6 interval has both a sharp base and top but demonstrates an opposite trend to the lower interval, that is it coarsens (ie. cleans) upward. The log motifs are characteristic of clastic strand plains and transgressive shelf sands (Walker and James, 1992).

3. The uppermost systems tract is a highstand. Intervals SAK7, SAK8 and SAK9 are within the HST. The sands thicken upward and also become massive with decreasing depth. The HST is notably sand rich. The HST appears more influenced by shale intercalations, which are irregular in their occurrence and GR response. The author interprets the sand intervals associated with the HST to be characteristic of a fluvial flood-plain/ meandering channel system. The irregularity observed with the shale intercalations are indicative of crevasse splay type and over-bank deposits due to periodic flooding.

Figure 16. Sakrand-01 log analysis: Effective porosity versus depth.



4.2.10: SANN-01

Latitude: 25° 47' 50" N	Elevations: GL - 132.9 metres AMSL
Longitude: 68° 05' 21" E	KB - 36.81 metres AMSL

Pab Sandstone: Top Pab ....1036 metres rkb
Base Pab......................1083 metres rkb
Pab Thickness.............47 metres
Net Sand......................39 metres
Net/ Gross...................83%

The Pab Sandstone is identified to occur between 1036 metres rkb and 1083 metres rkb (Enclosure 2). Four intervals within this section were analysed for total porosity (θ_T), volume of shale (V_{SH}) and effective porosity (θ_E). Sann-01 was the only well within this study to have both neutron porosity (NPHI) and density (RHOB) logs. Both tools were used to ascertain porosity values for each of the four intervals (Table 7).

Table 7: Sann-01 - Porosity evaluation

		NPHI			RHOB		
Interval	**Depth**	θ_T	V_{SH}	θ_E	θ_T	V_{SH}	θ_E
SAN4	1035-1047 mrkb	30%	10%	27%	22.5%	10%	20%
SAN3	1048-1060 mrkb	18%	10%	16%	18%	10%	16%
SAN2	1062-1068 mrkb	30%	10%	27%	21%	10%	19%
SAN1					0%	10%	0%

The porosity determinations were calculated in consultation with the Sann-01 Geological Composite Log (OGDC, 1986). The caliper log suggests that hole conditions are variable and consequently porosity values calculated on the basis of the NPHI response may be inaccurate. The utilisation of the RHOB log for log analysis is justified by the DRHO response on the composite log.

The Pab section appears dolomitic with higher density responses in tight sections than is possible in clean sandstones (ie. SSθ =0% @RHOB=2.65). The effect of this is to reduce θ_T and θ_E given in Table 4 due to the probable presence of dolomitic cement. In order to compensate, three to four porosity units should be added to the RHOB determined porosity values (Wormald, G., pers. comm., 1996).

Net sand was interpreted to be 39 metres (Enclosure 7). A net/ gross ratio of 83% was calculated for the Pab Sandstone in Sann-01 (Enclosure 8). The Pab Sandstone is dominantly sandstone with intercalations of shale and/ or clay. The cutting descriptions (OGDC, 1986) are as follows:

Sandstone: *white to dirty white, light brown violet, pink, medium hard, massive, medium grained, at places fine grained, sub-angular to sub-rounded, poorly sorted, at places fairly cemented, sugary textured, slightly calcareous (dolomitic? (from above)), pyritic.*

Shale/ clay: *reddish brown, soft, pasty, hydrophilic, laminated, sandy, calcareous, pyritic.*

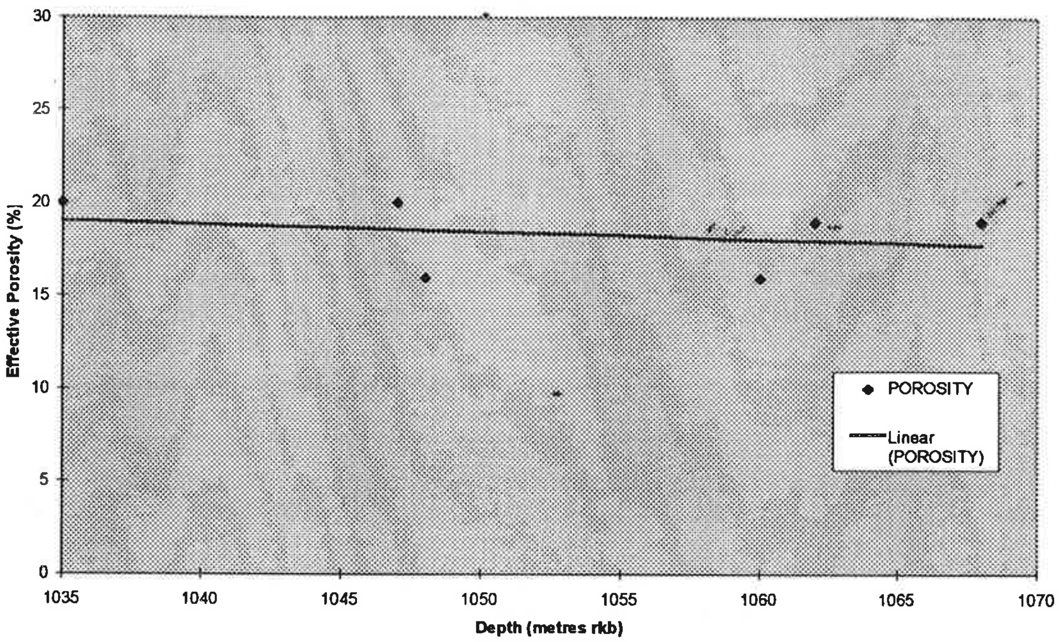
The SMST, LTST, HST and UTST are all identified to be present in Sann-01 (Enclosure 2).

The SMST is characterised by a shale intercalation at the base, maybe suggesting an initial distal location from the sediment source. The regionally correlatable mfs which defines the top of the LTST is easily identified.

The HST and UTST are characterised by blocky sands and are indicative of a braided fluvial deposit.

The overall porosity trend (Figure 17) for Sann-01 does not vary greatly. The unit is tight at its base (perhaps dolomitised) and porosity decreases slightly with depth, perhaps due to a combination of burial effects and an overall cleaning upward profile.

Figure 17. Sann-01 log analysis: Effective porosity versus depth.



4.2.11: SHAHDADPUR-01

Latitude: 26° 09' 37" N	Elevations: GL - 26.54 metres AMSL
Longitude: 68° 31' 57" E	KB - 34.75 metres AMSL

Pab Sandstone: Top Pab........................1656 metres rkb
Base Pab........................1700 metres rkb
Pab Thickness.............44 metres
Net Sand........................15 metres
Net/ Gross....................34%

Porosity evaluations were conducted using the sonic log only (Table 8). Shahdadpur-01 is sand poor but the sands increase and (generally) thicken upward (Enclosure 1).

Table 8: Shahdadpur-01 - Porosity evaluation

Interval	DT Depth	θ_T	V_{SH}	θ_E
SHA3	1656-1660 mrkb	33%	10%	29.5%
SHA2	1668-1674 mrkb	34%	10%	30.5%
SHA1	1689-1694 mrkb	34%	25%	25.5%

The sands exhibit a characteristic and common gamma ray (GR) response (Enclosure 1). The sands commonly have a sharp base (especially the thin sand at 1692 metres rkb). The sharp base is succeeded by a shaling (ie. fining) upward trend. The increase in shale content decreases with each successive and younger sand.

Two systems tracts were identified in Shahdadpur-01; the lower transgressive systems tract (TST) and the highstand systems tract (HST). The two systems tracts are separated by a maximum flooding surface of regional extent.

The upper part of the section consists of sandstone with intercalations of shale, siltstone and claystone as observed by OGDC (1985):

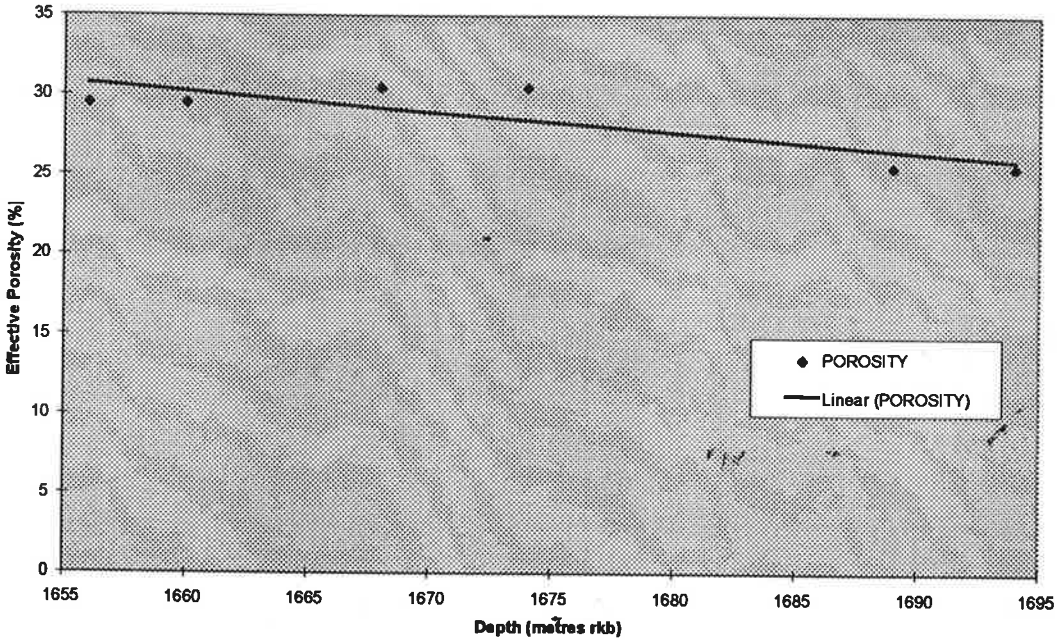
Sandstone: *white to translucent, medium to coarse grained, sub-angular to sub-rounded, cemented with silica cement, oftenly conglomeratic.*
Shale: *multicoloured, soft to medium hard, in part laminated, fossils(?), calcareous to non-calcareous, silty to sandy.*
Siltstone: *white to pink, soft to medium hard, slightly calcareous, the lower part consists of sandstone with streaks of claystone and shale. Sandstone, shale, siltstone as above.*
Claystone: *red, brown, soft, ferruginous, calcareous, sticky.*

The LTST recognised at Shadadpur-01 is sand poor and only one significant sand interval is recognised. The sand may be associated with a transgressive shelf sandstone.

The HST is recognised by its thick, clean, symmetrical GR responses. These are indicative of individual channel sands which lack the meandering nature of sand intervals recognised further west. The author suggests the channels are possibly high order channels, suggesting a close location to the original sediment source.

The overall porosity trend (Figure 18) clearly decreases with depth. This is a result of compaction, and cleaner sand intervals associated with the HST at the top of the unit.

Figure 18. Shahdadpur-01 log analysis: Effective porosity versus depth.



4.2.12: ADDITIONAL WELLS

The Pab Sandstone was interpreted to be absent in the following wells and this interpretation enabled the author to constrain the Pab Sandstone in the east of the Kirthar Basin (Enclosure 6).

Table 9: Additional wells in Pab Sandstone study.

WELL	LATITUDE	LONGITUDE	INTERPRETATION
Bobi-01	25° 51' N	68° 55' E	PAB ERODED
Judge-01	26° 54' N	68° 47' E	PAB ERODED
Kadanwari-01	27° 08' N	69° 13' E	PAB ERODED
Mithrao-01	26° 07' N	68° 53' E	PAB ERODED
Sagyun-01	27° 15' N	68° 19' E	PAB ERODED
Sultan-01	27° 41' N	68° 13' E	PAB ERODED
Sohro-01	25° 26' N	68° 50' E	PAB ERODED

4.3.1: DIAGENETIC HISTORY

The diagenetic history proposed for the Pab Sandstone in the Kirthar Basin is based upon a critical analysis of the report from Robertson Research (1996) on the Bara Nala field samples and ditch cuttings from wells Mazarani-01 and Badhra-01, combined with the current wireline log and lithostratigraphic results.

The petrographical observations made by me are based entirely on the photomicrographs supplied by Robertson Research and I have accepted in good faith that they are a true and accurate representation of the samples analysed. I accept no responsibility if this is not the case.

I propose two diagenetic models. The distinction is made on the basis of the observation by Robertson Research (1996) that the well samples show a greater marine influence than the field samples. The differing environments had different influences on the diagenetic history of the Pab Sandstone, especially in relation to carbonate cementation, grain dissolution and diagenetic minerals. This is reflected in the two models. Although the terms 'terrestrial' and 'marine' are assigned to the two models, the description is purely relative and the assigning of 'terrestrial' does not necessarily preclude any marine influence during the depositional history, and vice versa.

Model A: Terrestrial (Bara Nala)

1. Clay rims
2. Feldspar dissolution
3. Silica cementation/ Quartz overgrowth development
4. Kaolinite (alteration phase)

5. Kaolinite (cement phase)

-----------------COMPACTION--------------------

6. Calcite cementation

7. Dolomite replacement

8. Siderite replacement

9. Carbonate dissolution

--------------COMPACTION---------------------

10. Pyrite

11. Haematite (pore filling phase)

Model B: Marine

1. Grain coating clays (chlorite)

2. Siderite replacement

3. Pyrite

4. Quartz overgrowth development

5. Chlorite (authigenic - 2nd phase)

6. Kaolinite (cement phase)

7. calcite (ferroan) cementation (bioclast seeds)

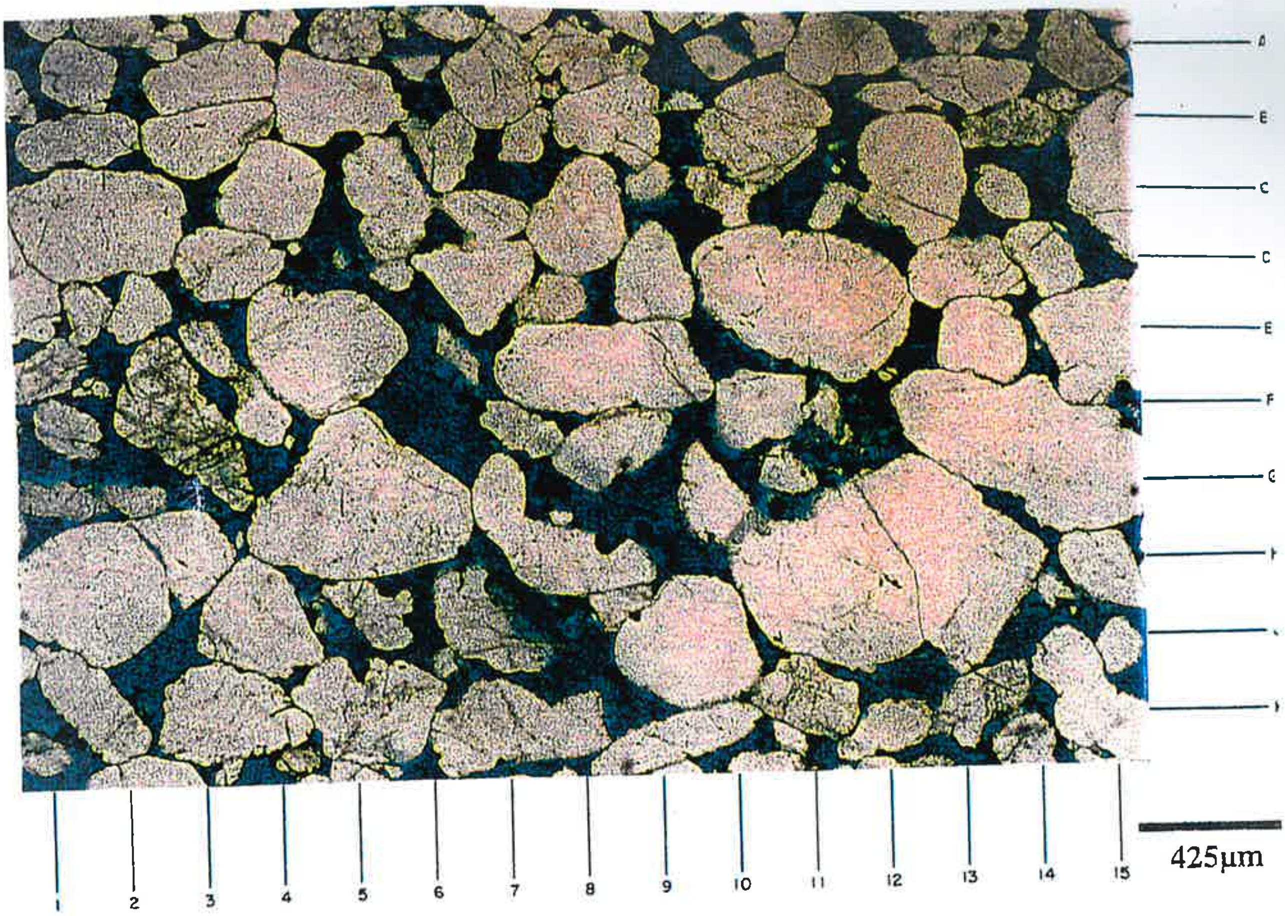
8. Ferroan dolomite (replacement)

Evidence to support the proposed diagenetic models can be seen in the 25 photomicrographs of the Bara Nala thin sections prepared by Robertson Research (1996) in addition to the well samples. Although many of the slides provide a somewhat ambiguous insight into the diagenetic history with not all events being apparent in any one slide, all observations are consistent with the models proposed. The diagenetic models proposed are applicable to the sandstones (ie. quartz arenites, sublitharenites, etc) and not to the Pab Formation limestones and shales.

Important differences and similarities between the models are as follows:

1. Siderite is an early and replacive phase in the marine model and predates kaolinite. Conversely, siderite is late and postdates kaolinite in the terrestrial model.
2. Haematite is apparently absent in the marine model.
3. Pyrite is a minor constituent in the marine model (Tr-1%). It is more prevalent in the terrestrial model.
4. Chlorite appears to predate and postdate feldspar dissolution in the marine model. Only one phase is observed in the terrestrial model.
5. Dolomite almost totally occludes porosity in the marine model.
6. The author has recognised the occurrence of two main phases of compaction in the terrestrial model. The author suggests that compaction was also a factor in the diagenetic history of the marine model, but its exact timing of occurrence can not be ascertained from the data provided. Evidence for compaction prior to carbonate cementation is provided in slide NP 38 by the presence of concavo-convex contacts (C12, J13) between quartz grains.

The individual diagenetic components will be discussed separately.



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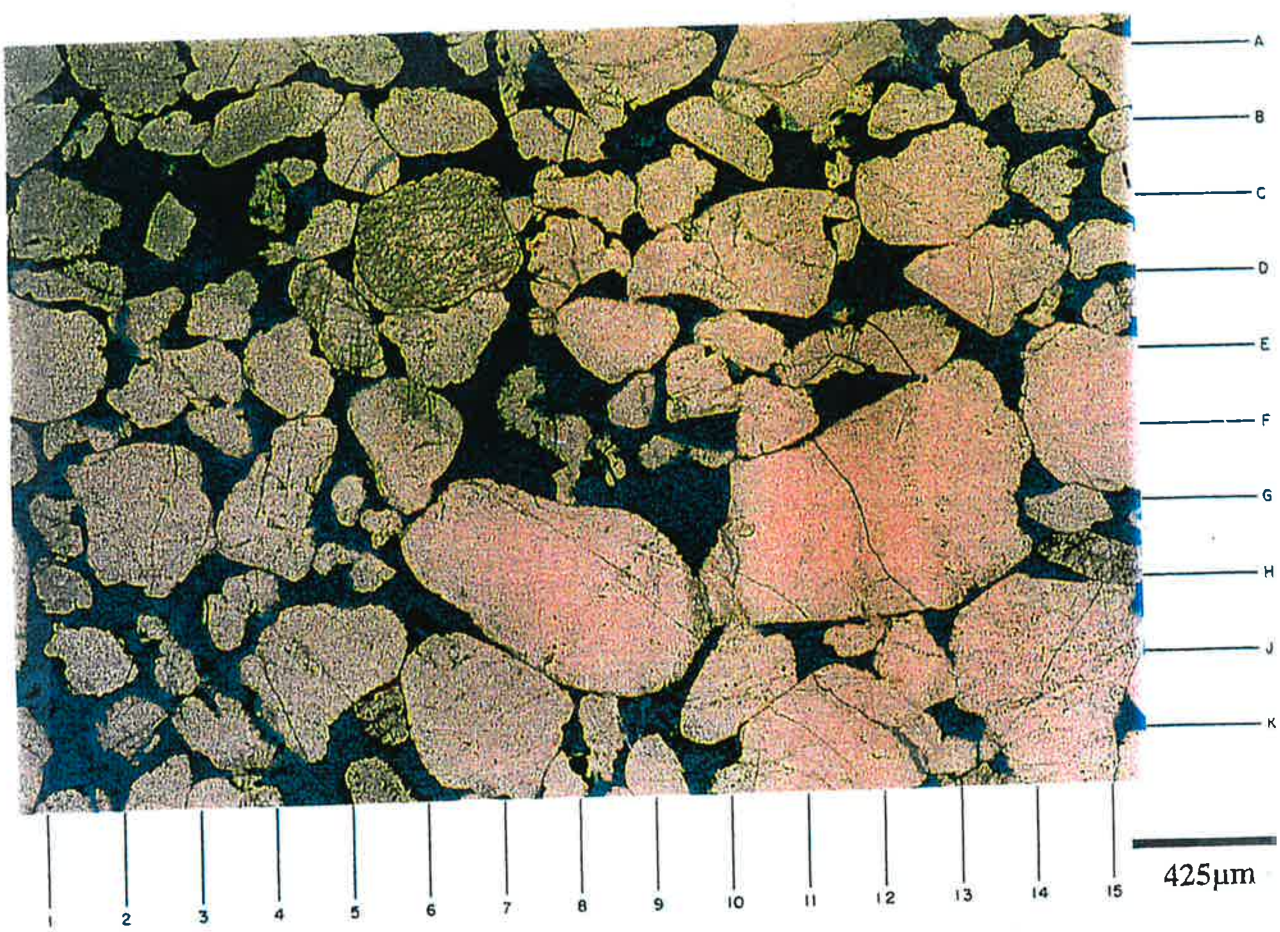

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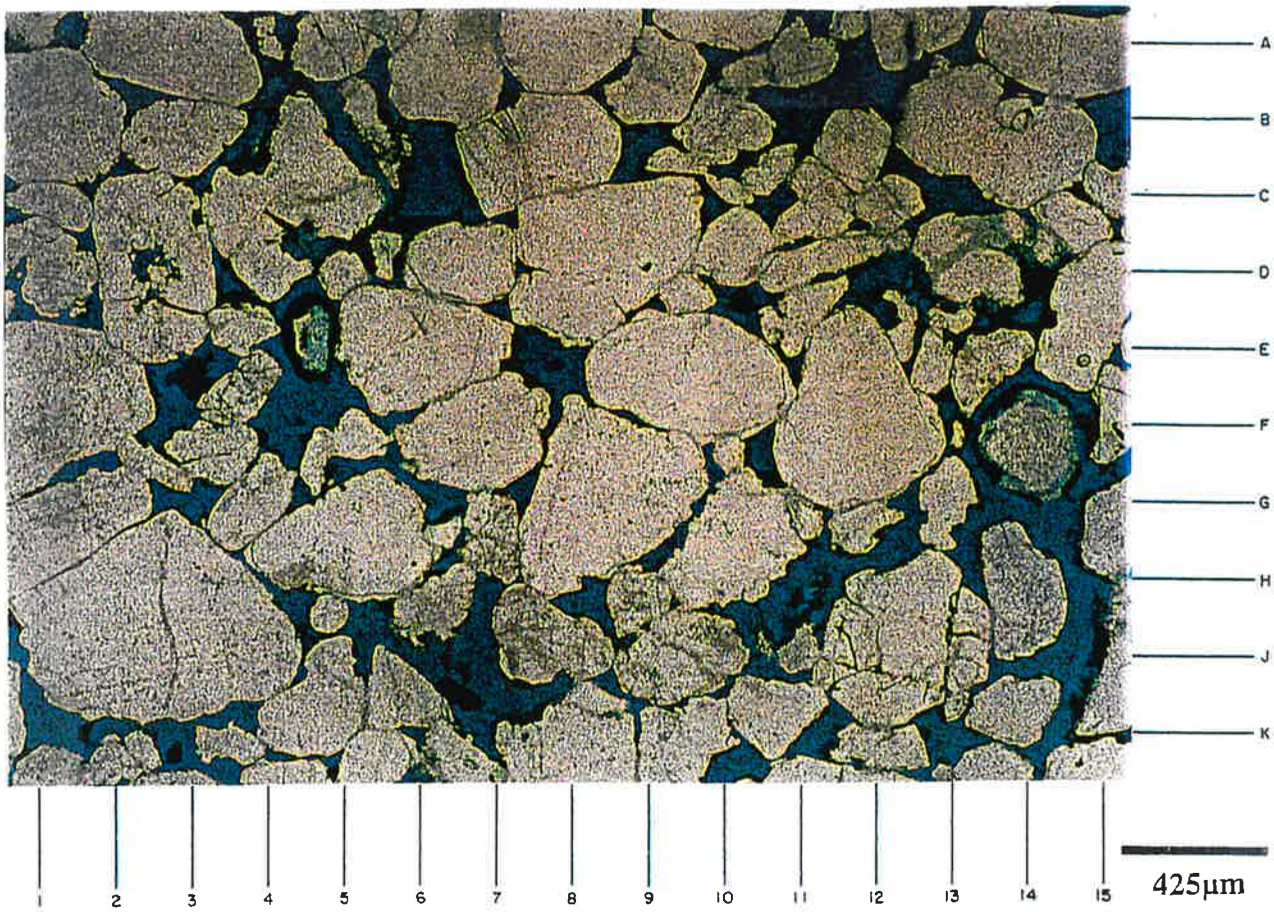
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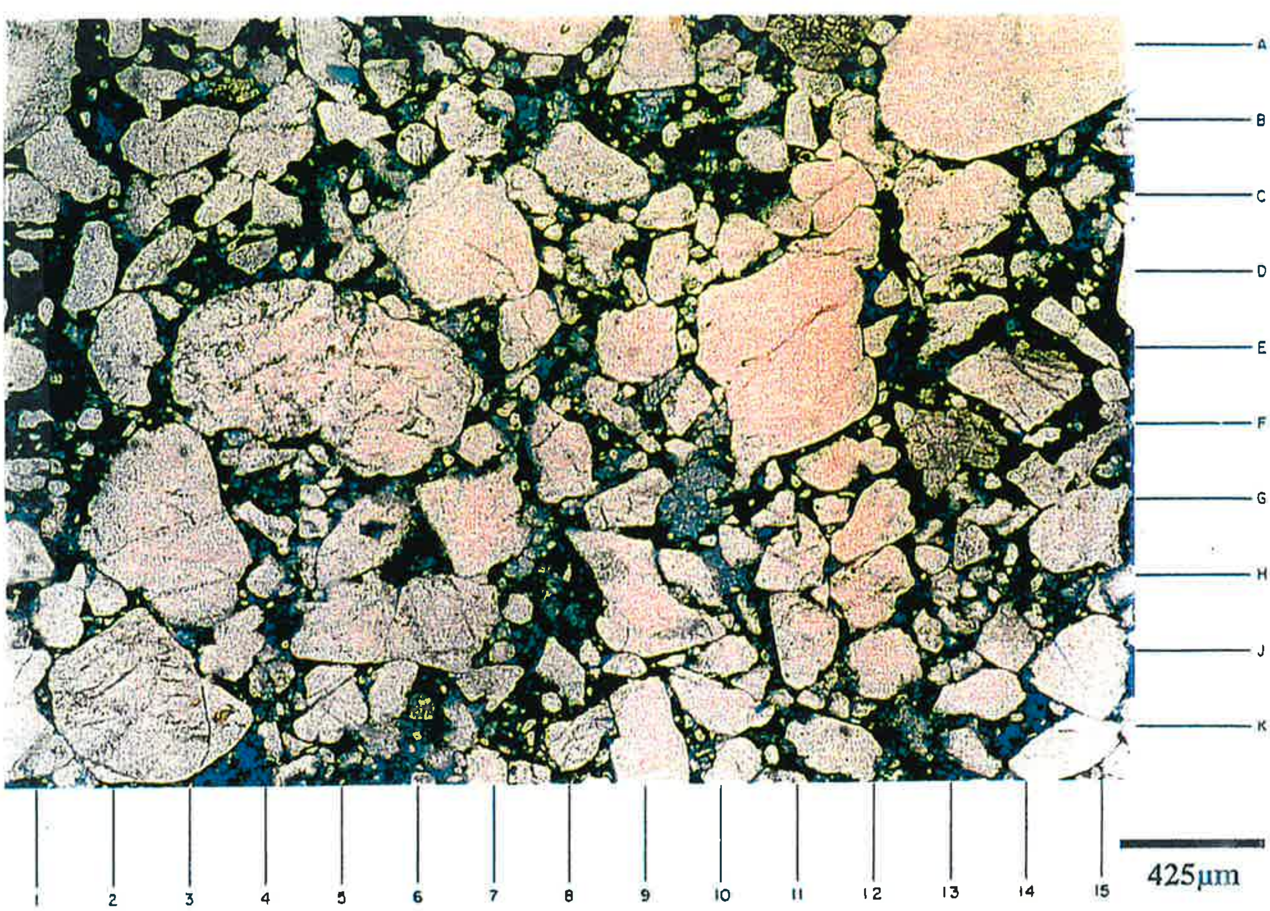
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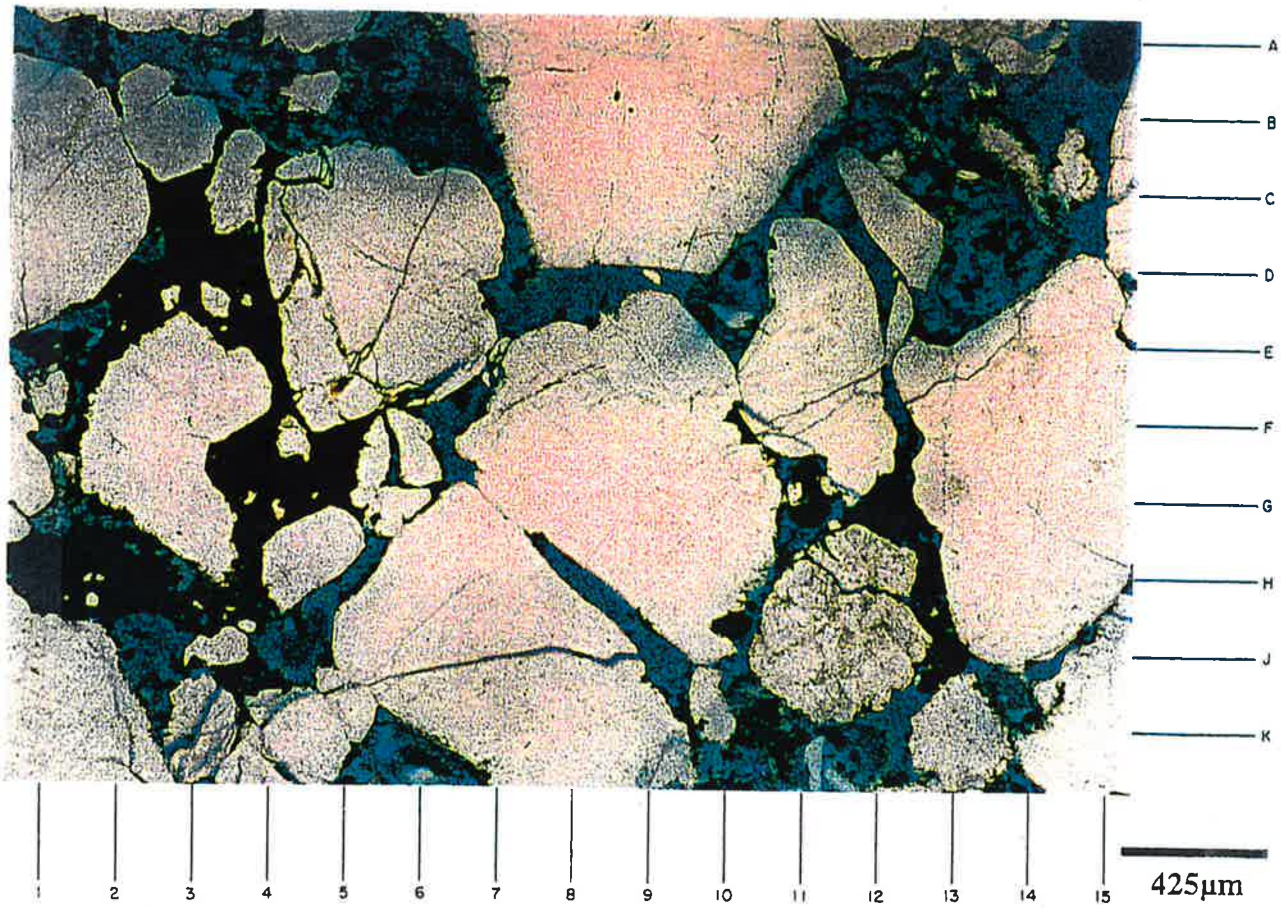
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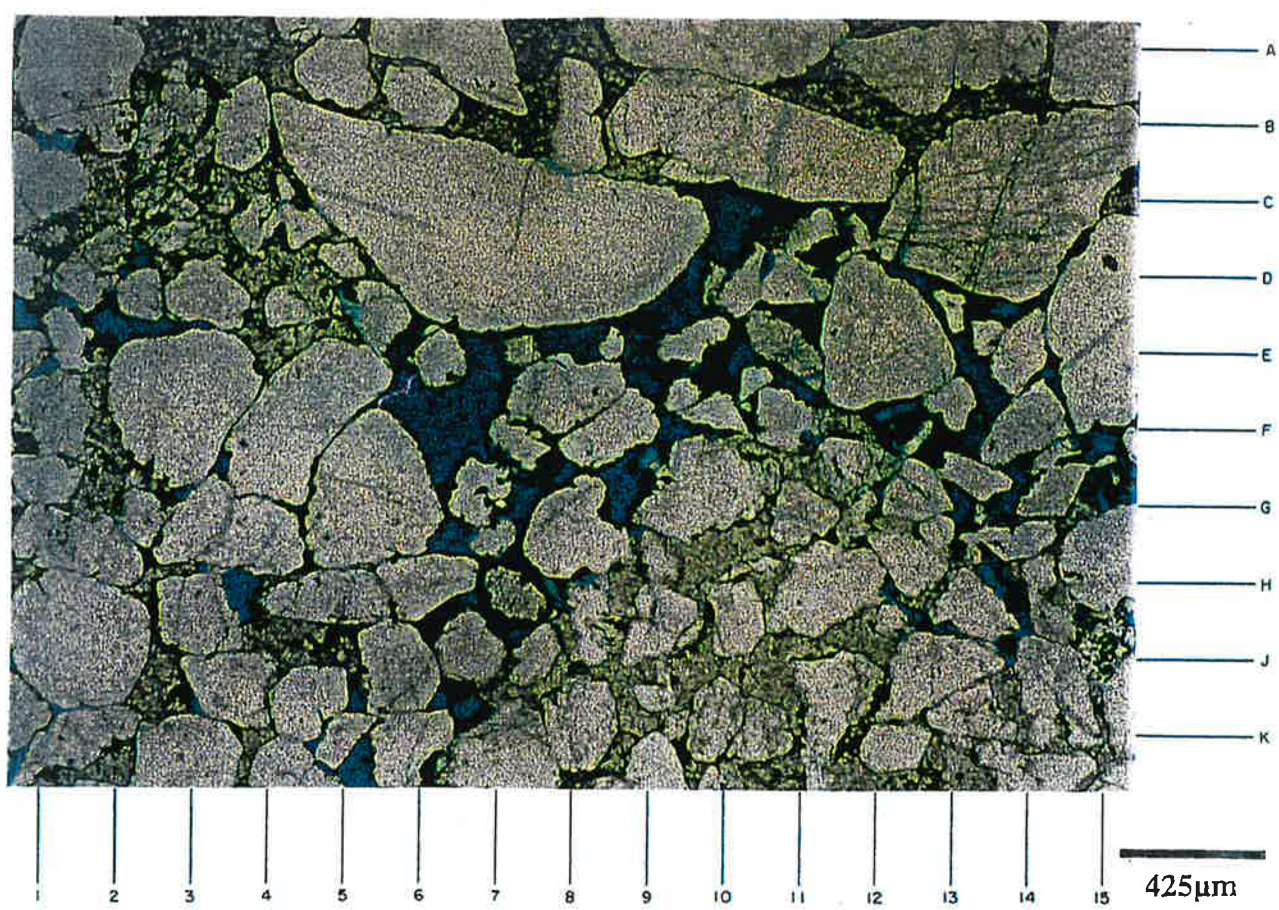
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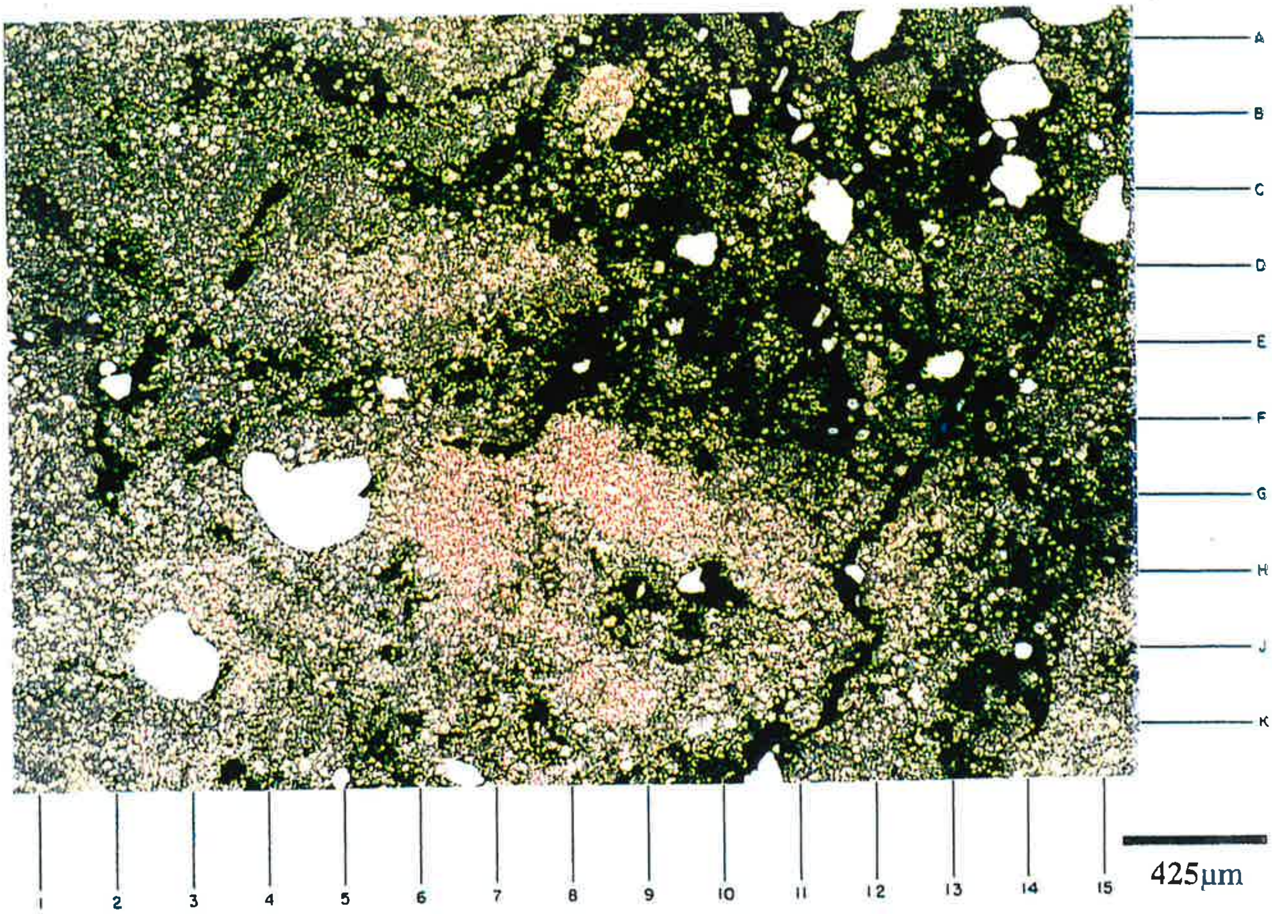
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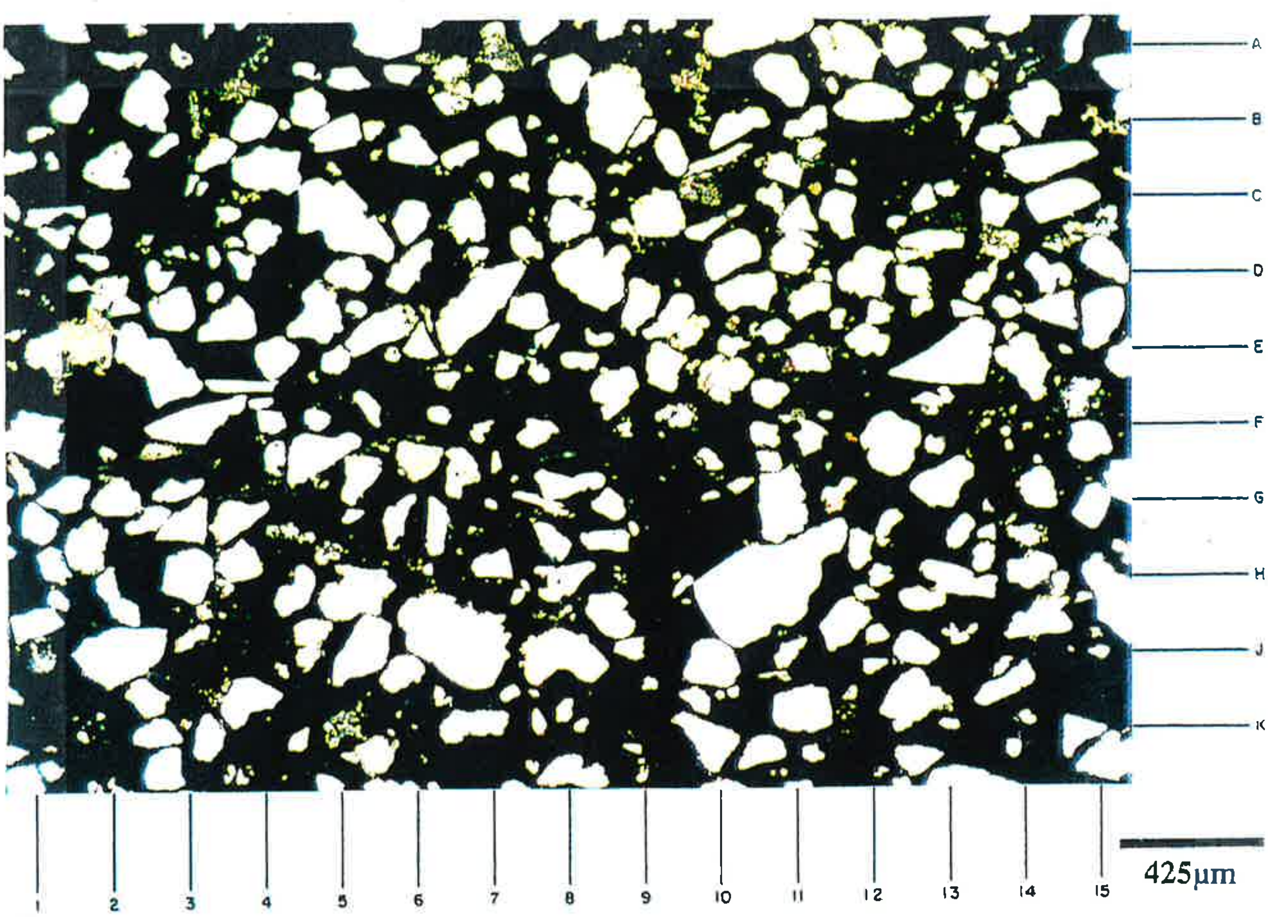
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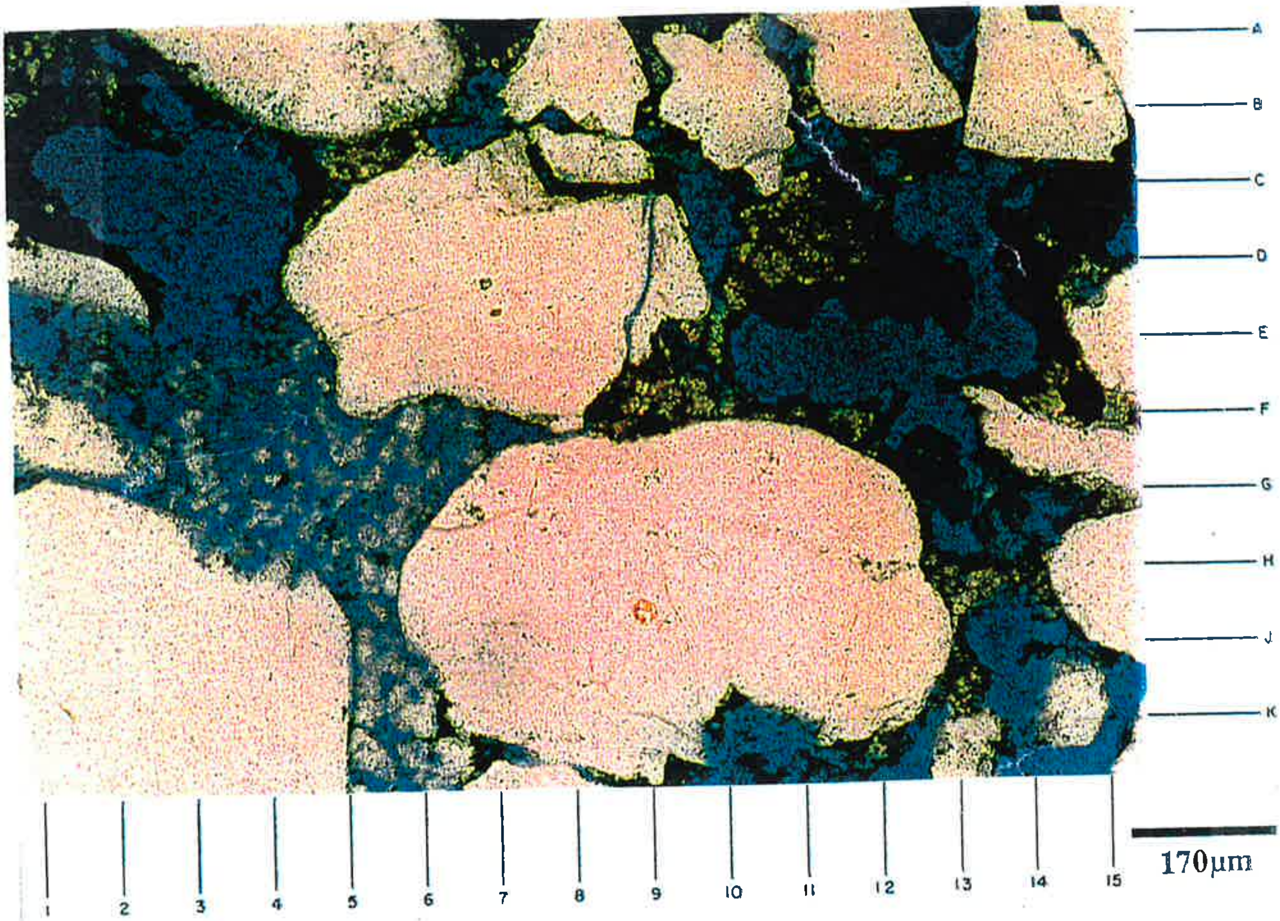
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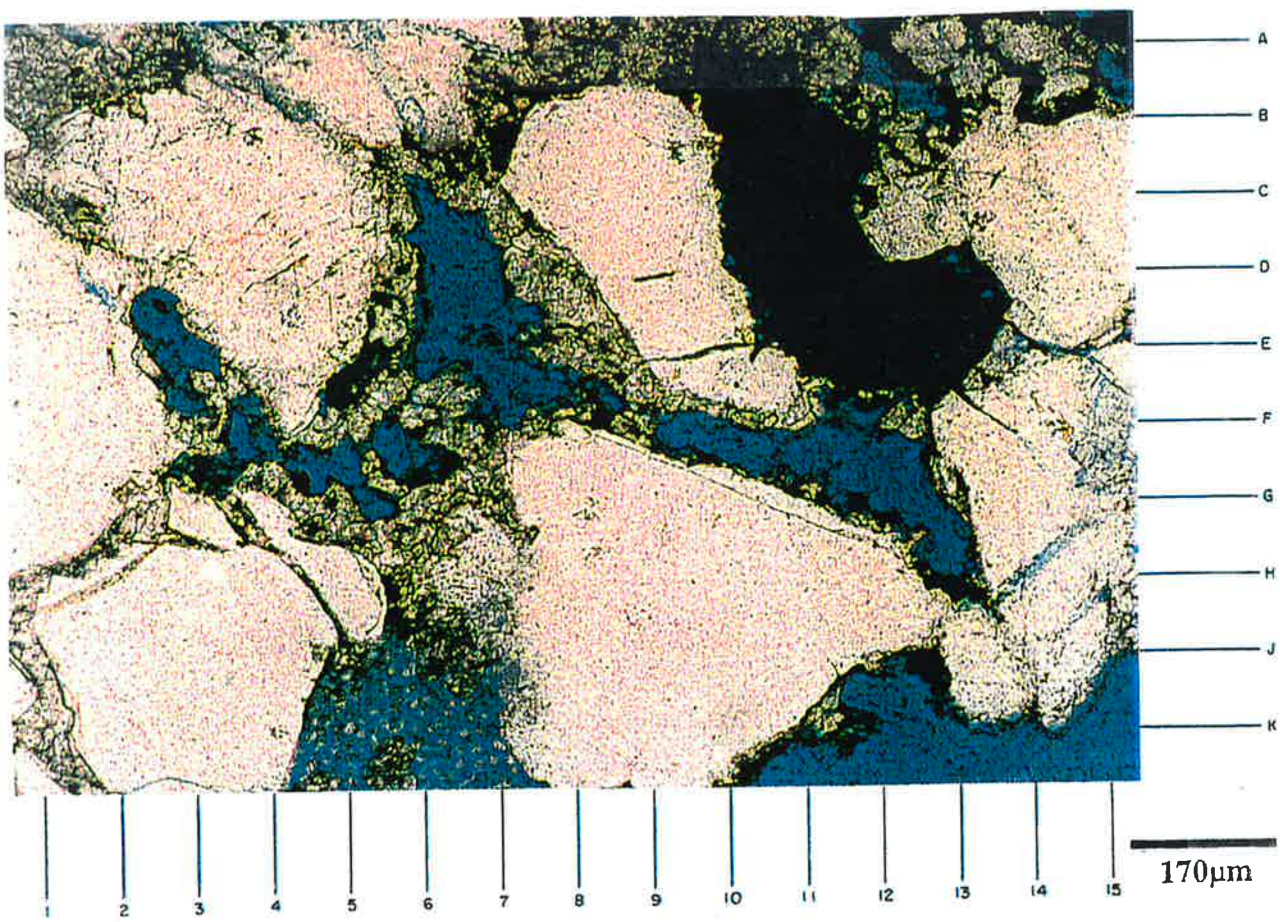
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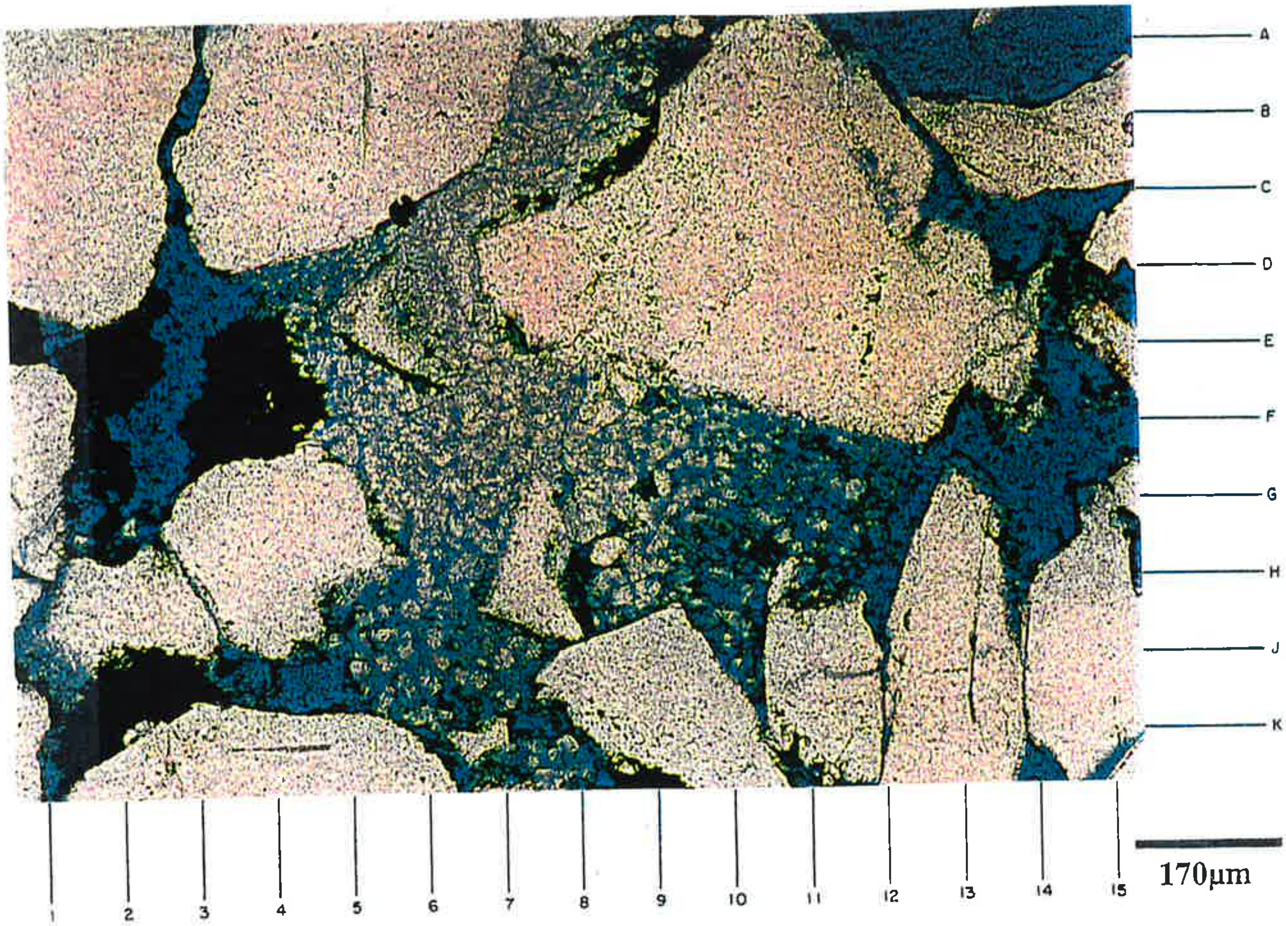
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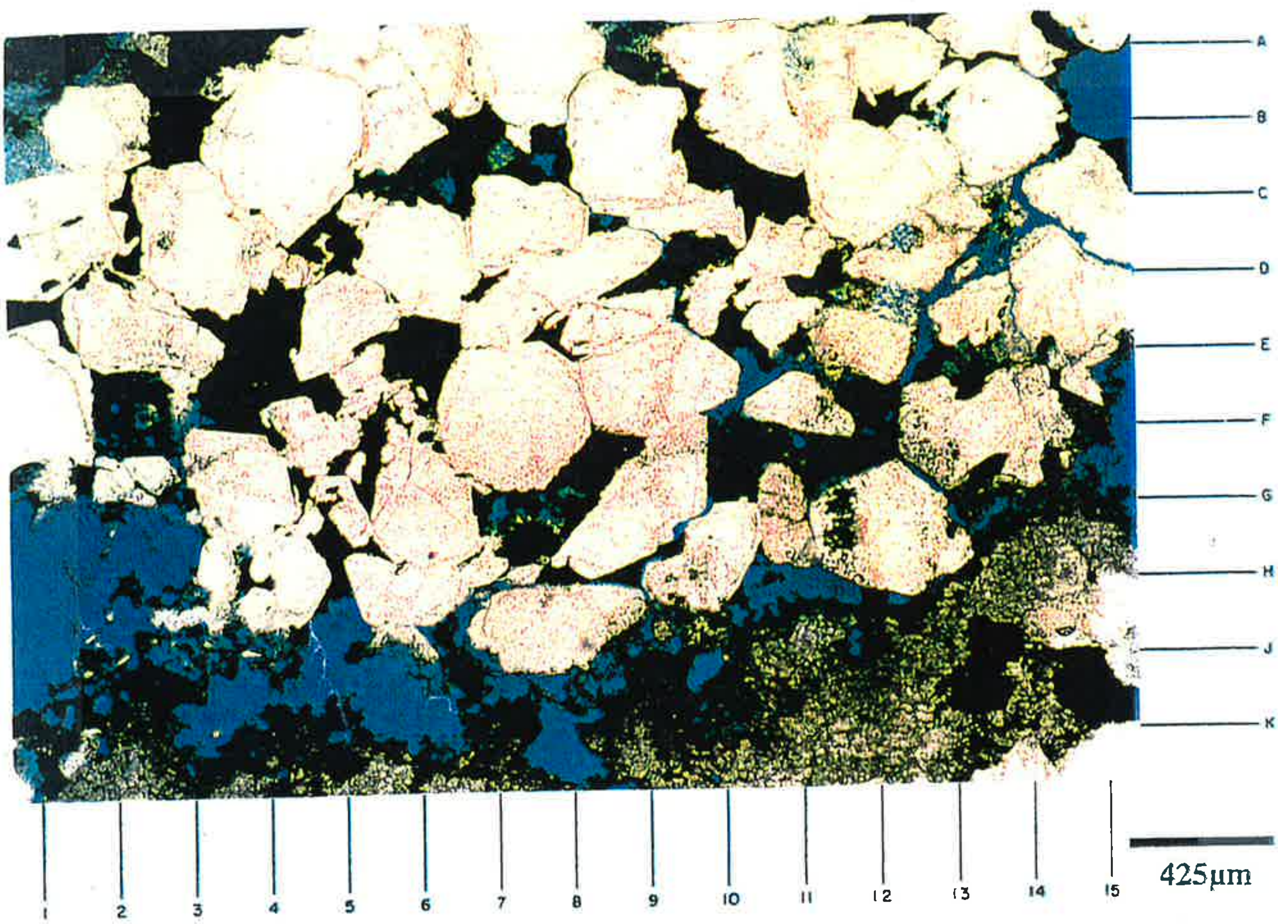
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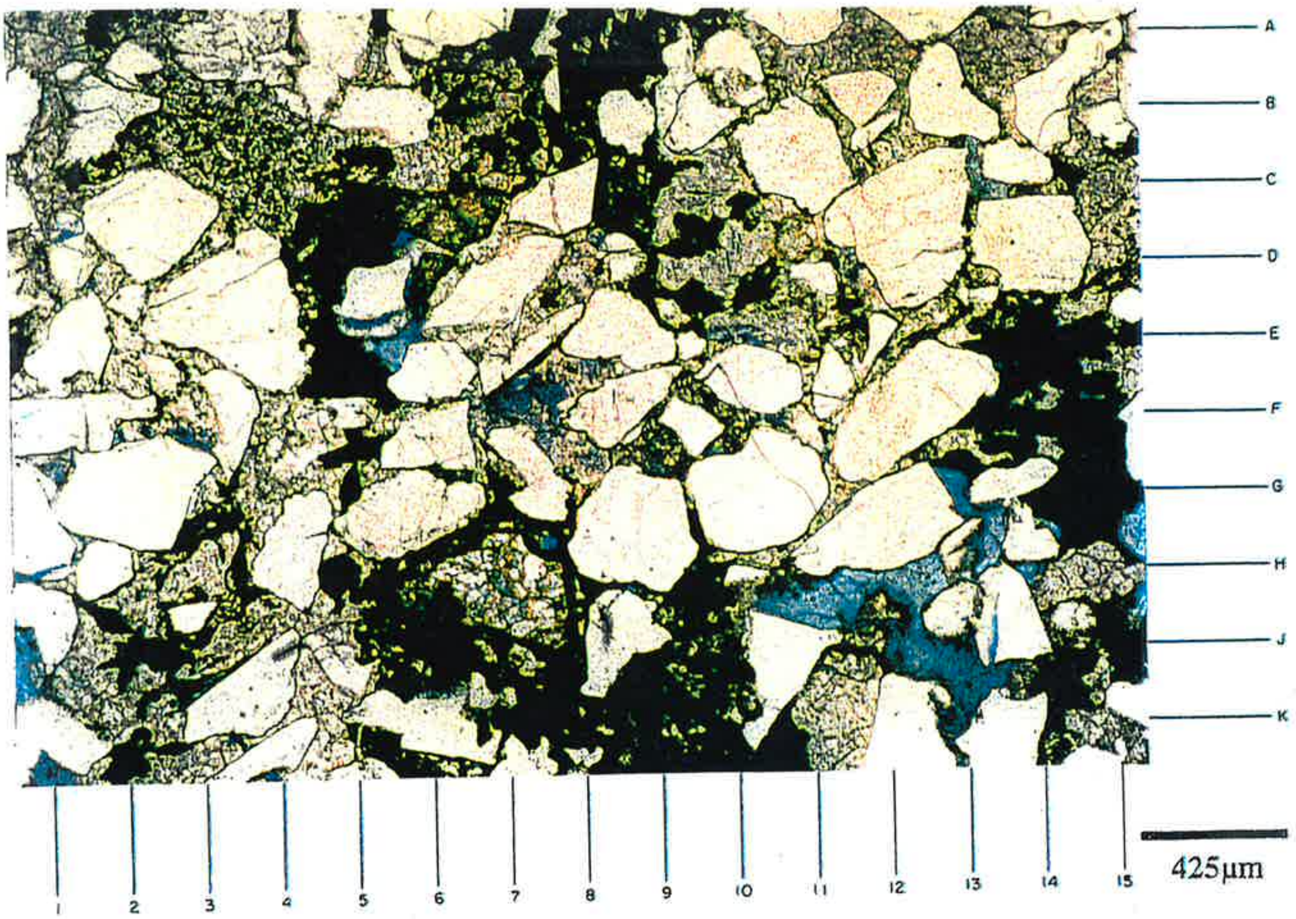
NP 35



NP 38

4.3.2: IRON PHASES

Robertson Research (1996) identified two predominant iron phases in the Pab Sandstone, namely haematite (Fe_2O_3) and siderite (Fe_2CO_3). The fundamental difference between the two phases is the oxidation state of the iron. Haematite contains Fe^{3+} and is associated with strongly oxidising conditions such as sub-aerial exposure. Siderite, containing Fe^{2+}, can only form under reducing conditions. I suggest on the basis of the photomicrographs available to me, that in many samples haematite, although commonly present, was incorrectly identified. On the weight of the evidence outlined below the current author proposes that pyrite (FeS_2) was more prevalent than previously thought and may have been present as a precursor iron phase. The following photomicrographs add weight to this proposition.

Slide NP 23: The existence of mudstones suggest the existence of pyrite (cf. haematite) due to the presence of root traces (K11 to G13) suggesting that the sample was rich in organic matter. Sultan and Gipson Jr (1995) suggest that the replacement of woody and carbonaceous clay material by pyrite is an early diagenetic phase.

Slide NP 22: Illustrates pyrite post-dating carbonate cementation. It is suggested that meteoric H_2O dissolves the carbonate cement and leads to the direct precipitation of haematite (pore filling phase?), possibly suggesting that the iron oxide is a weathering artefact. Doubt does exist as to the existence of a pyrite precursor in this slide, suggesting that perhaps pyrite replacement is patchy and occurs locally.

Slide NP 35: Iron sulphide (pyrite) phase is present and identifiable by the corrosive nature of the assemblage which is indicative of pyrite. To illustrate this, compare the grain boundaries of quartz grains where pyrite is present (D6, D10) and where it is absent (D14, J8). The presence of pyrite has etched the grain boundaries which is indicative of an early phase. The iron phase appears to etch through quartz overgrowths and replaces kaolin (Dr. N. Lemon, pers. comm., 1996).

Slide NP 27: Robertson Research (1996) observed 43% haematite in this slide. Such a high value seems unrealistic (Dr. N. Lemon, pers. comm., 1996) and is probably a combination of haematite (both diagenetic and as a weathering artefact) and diagenetic pyrite. The evidence for the presence of pyrite is convincing and includes the etching of grains (top of grain at J7) and the fact that the grains are all isolated and floating. This may suggest also that pyrite may be as aggressive as carbonate in its attack on silicate phases. The pyrite phase postdates carbonate dissolution.

Slide NP 34: Iron phase (presumably pyrite) postdates kaolinite phase (E4), suggesting late pyrite.

Further evidence to support the presence of pyritic mineral assemblages include the observation of pyritic assemblages in well cuttings from Sann-01.

Although I suggest the presence of pyrite, and evidence does exist in the photomicrographs to support its existence in both the terrestrial and marine models, the evidence for the paragenesis of pyrite is unclear, especially in the terrestrial model.

It is important in analysing the diagenetic history of a rock unit to be able to distinguish between surface and sub-surface diagenetic processes; this is particularly the case with iron phases. Oxidised Fe^{3+} may be liberated from ferrous silicates such as biotite, amphiboles, pyroxenes and olivines during surface diagenesis. Time is needed to continuously precipitate Fe^{3+} as limonite and ultimately transform the oxide to haematite (Leeder, 1982). Limonite has been commonly observed in outcrop (Weingart et al, 1970) in the study area at Bungi Nala and Pahvi Nala, but may represent a weathering artefact only, as opposed to a diagenetic feature.

4.3.3: DIAGENETIC CLAYS

The most commonly observed diagenetic clay in the field samples analysed by Robertson Research (1996) is kaolinite. I have recognised two types of authigenic kaolin to be present in the samples; an alteration phase and a cement phase.

Precipitation of the cement phase kaolinite is particularly encouraged under the influence of acid water flushing of sandstones or from meteoric water interaction as a consequence of uplift (Leeder, 1982). The alteration of alkali feldspars leads to the formation of illite and upon release of silica (Si^{4+}) and potassium ions (K^{+}), kaolinite precipitation may occur.

Both alteration (E6) and cement phase kaolin (G6) are present in slide NP 34. Alteration kaolin results from the direct transformation of alkali feldspars. The presence of the alteration phase acts as a nucleus for precipitation of the later cement phase.

The cement-phase kaolin (G6) is present in slide NP 31 and is typical loosely packed (cf. alteration phase). The presence of an unhindered and continuous flow of meteoric and/ or connate waters through the pore throat has permitted the continuous growth and precipitation of kaolinite crystals through connecting pores.

Kaolinite precipitation clearly post-dates quartz overgrowths (refer slide NP 31 (F6)).

Chlorite occurs in rare quantities and in localised patches. The current author has interpreted two chlorite phases to exist in the marine model. The early phase is commonly grain coating and is common to both models.

A large proportion of the diagenetic clays are indeterminate and commonly grain coating. Robertson Research (1996) suggest that these clays are illitic in composition. The indeterminate grains commonly coat framework grains. As with kaolinite, the indeterminate clay types postdate the development of quartz overgrowths.

4.3.4: OTHER DIAGENETIC CEMENTS

In addition to pore fill kaolin some terriginous and carbonate muds are present in the Pab Sandstone in varying amounts. Carbonate and silica are the principal cements in the Pab Sandstone. Cementation is the principal process leading to porosity reduction in the Pab Sandstone.

Silica cements may result directly from the dissolution of k-feldspars, from the conversion of smectite to illite in muds associated with the sandstone host during compaction (Land and Dutton, 1982; Leeder, 1982), dissolution of quartz grains at points of contact by pressure solution during compaction, dissolution of quartz grains by circulating pore fluids (particularly those associated with carbonate precipitation) or simply result from mineral reactions (Leder and Park, 1986). I suggest that feldspar dissolution was the primary mechanism prevailing in the Pab Sandstone. The virtual absence of feldspar grains throughout the entire section supports this claim. The varying proportions of intercalated shales and claystones could aid silica cementation during deep burial of the Pab Sandstone. Prevention or inhibition of quartz overgrowths may occur if early authigenic clay rims exist. Clay rims appear as dark rims which predate the quartz overgrowth as is the case in slides NP 11 (D5), NP 18 (E8, F10), NP 20 (E10) but are generally considered a minor constituent and are most likely matrix.

Mechanisms for quartz precipitation from solutions saturated with respect to silica in sandstones include (1) lowering pore pressure, (2) cooling hot, silica-saturated solutions, (3) lowering of pH, (4) evaporation, (5) mixing with saline waters, and (6) semimembrane osmosis through shale intercalations (Leder and Park, 1986).

Porosity occlusion due to early quartz cementation is small, but, quartz overgrowths, particularly where they are extensively developed, aid in minimising porosity reduction by compaction by strengthening the overall framework of quartz grains.

Carbonate cements occur in three forms in the Pab Sandstone. Ferroan calcite is the primary cement. Siderite cement is common as nodules (depositional?), tightly packed laths and as a replacement phase. Ferroan dolomite is common, more so in the marine samples, but is variably distributed and is commonly poikilotopic, possibly suggestive of a late phase.

Notably, calcite is more prevalent in the terrestrial model (Bara Nala samples) than in the well samples. The reverse is apparent for siderite.

In addition to the aforementioned carbonate mud (micrite) present, sparry calcite is also observed in thin section. Spar is coarse and is commonly a pore-filling cement suggesting precipitation long after deposition of the original allochems and carbonate mud (Adams et al, 1994).

Siderite (Fe_2CO_3) cemented sandstones are common in the cuttings descriptions of Badhra-01. Within these samples, siderite is observed (Robertson Research, 1996) as tightly packed laths. This suggests continuous crystal growth. Marine siderite often forms large laths, commonly exhibiting a radiating habit (Dr. N. Lemon, pers. comm., 1996) but such microscopic features are unable to be differentiated in the data provided.

Siderite precipitation is encouraged in an iron-rich environment with a high dissolved carbonate content and reducing conditions. Stagnant waters and diagenetic environments where bacterial activity is present are conducive to high carbonate values. Bacterial activity is clearly evident throughout the Pab Sandstone as suggested by an association with the numerous burrows and traces observed in outcrop. Siderite production is further enhanced in sulphur and calcium depleted environments with low Eh values (-0.25 to -0.35 volts) and near neutral pH (Curtis and Spears, 1968). Leeder (1982) suggests that siderite can only precipitate if the Ca:Fe ratio is less than 20.

Siderite precipitation is common in non-marine diagenetic environments exhibiting low SO_4^{2-} where abundant Fe^{2+} is present such as in tropical weathering zones. Abiotic reactions between ferric compounds and organic matter may result in very low sulphide activities (Curtis and Spears, 1968). Siderite is particularly common to deltaic swamp facies (Leeder, 1982). Siderite may also occur as a late stage burial cement, particularly in coarse grained sediments, where Fe values build up in pore waters that have restricted circulation by the dewatering of shales and matrix clays (Dr. N. Lemon, pers. comm., 1996; Curtis and Spears, 1968).

Curtis and Spears (1968) consider it difficult to envisage the absence of sulphide formation within a marine environment that is by its nature very rich in SO_4^{2-}, organic matter and bacterial activity. Sulphate production in essentially marine conditions suggests that fresh, meteoric water has flushed the seawater or that, the sulphate-reducing bacteria usually present are not operating; this is considered uncommon (Dr. N. Lemon, pers. comm., 1996). Evidence does exist within the Pab Sandstone that fresh water flushing has occurred. The dissolution of carbonate cement late in the diagenetic history, may be attributable to such a process. The dissolution of any mineral assemblage can only ever proceed if the solute is depleted in the constituent elements of such a mineral. Fresh water is commonly low in dissolved carbonate and calcium ions. Hence, the resulting increased dissolved carbonate concentration in the water will aid the formation of siderite and possibly pyrite if one considers the possible influence of HS^- and HCO_3^- ions.

Siderite is observed by Robertson Research (1996) to occur in varying forms:

1. As tightly packed laths
2. As a replacement of intergranular detrital mud and indeterminate grains (probably mud-filled foram chambers or pellets), suggestive of localised reduction of organic matter in shells and chambers.
3. As nodular siderite.

Siderite appears to predate grain dissolution in some samples, suggesting that siderite is a depositional and/ or replacement phase only. Siderite also appears to predate quartz overgrowths in some marine samples.

An important diagenetic process, common in the terrestrial model especially, is the dissolution of carbonate cements. Slide NP 19 shows the effect of this process. The removal of carbonate cement has succeeded in isolating framework grains, which initially opens secondary porosity, but may lead to another phase of compaction. An important comparison can be made showing the composition during carbonate dissolution and before compaction (NP 22) and after compaction (NP 19). Slide NP 19 further supports the proposition that carbonate dissolution occurred at depth and not solely at the surface.

Slide NP 32 illustrates the corrosive nature of the carbonate cement on quartz overgrowths (F8 to G12) and the presence of dissolution edges on the carbonate cement. Quartz druse overgrowths are apparent in this slide also (H2).

4.3.5: BIOSTRATIGRAPHY

A biostratigraphic analysis of the Pab Sandstone was conducted on field samples from the Bara Nala outcrop and ditch cuttings from wells Badhra-01 and Mazarani-01 by Robertson Research (1996). The analyses included palynological and micropalaeontological determinations.

The Pab Sandstone is generally devoid of assemblages and in previous studies (Nagappa, 1959) age determination is most commonly constrained by formations below (Ft. Munro Formation and Parh Limestone) and immediately above (the Ranikot Group).

Robertson Research (1996) assigned a Campanian to Maastrichtian age to the Ft. Munro Formation. The age is based on the observation of *Globotruncana* species and *Omphalocylus macroporus*. A possible Tertiary age was assigned based on the questionable identification of a single *Nummulites* or *Amphistegina*.

Vredenburg (1909) first identified *Orbitoides minor* (Maastrichtian) to be present in the Pab Sandstone. Williams (1959) concurred on the basis of the identification of Maastrichtian aged mixed benthonic and pelagic assemblages. Similarly the Hunting Survey Corporation (HSC) (1960) concluded the Pab Sandstone was most probably of Early Maastrichtian age (Senonian). HSC observed *Globotruncana, Lentinculina, Marginulina* and *Orbitoides* in samples collected from marl interbeds.

Robertson Research (1996) were unable to directly determine the age of the Pab Sandstone in three samples (NP21, NP23, NP30) due to the absence of foraminifera. Possible echinoid, gastropod and other bioclastic material was prevalent (NP21) but was of little use due to the small size and fragmentary nature of the specimens.

Robertson Research (1996) suggest that " there is no strong evidence of penetration of Cretaceous sediments " in well Mazarani-01. The well samples are rich in dinocysts and it is the most marine, or at least most marine influenced, site of deposition. The age assigned is based upon palynological investigations on the interval 8530' to 9840'. Species observed included the rare occurrence of *E. trianguliformis* and additionally *Apectodinium homomorphum, Fibrocysta* taxa, *Mathanomadiasulcites maximus, Cordospaeridium* taxa restricts the age to Upper Palaeocene (after Frederiksen, 1994).

On the basis of the lithostratigraphic framework outlined in this study which interprets the Pab Sandstone to be present in Mazarani-01 (9570' to 9730' rkb) an apparent contradiction exists. The biostratigraphic absence of the Pab Sandstone may be attributed to one or more of the following circumstances:

1. Possible reworking of the sediment leading to the mixing of Tertiary aged assemblages and Cretaceous sediments.
2. Inaccurate depth matching of ditch cuttings with wireline log suites. This may be particularly prevalent considering the poor data quality of Mazarani-01.
3. Biased sampling. The Pab Sandstone represents only 12% of the interval under consideration.
4. Single, vagrant, long ranging and poorly diagnosed calcareous benthonics may be present and suggest younger ages.

5. The Pab Sandstone is actually absent, possibly structurally removed, such as is the suggestion at Gaj River East (Mr. A. Logan, pers. comm., 1996). The author rejects this theory on the weight of evidence at the time of writing.
6. Poor slide preparation leading to fragmentation of samples due to picking may have inhibited accurate determinations.
7. The Pab Sandstone is diachronous. That is to say that it is a lithofacies and not a time formation.

Seven samples were analysed in a 457 metre interval (792m - 1249m) in Badhra-01. The samples were dominated by miospores and the varying occurrence of *Echitriporites trianguliformis* (Robertson Research, 1996). Similarly to Mazarani-01, the sampling transcends the base Tertiary unconformity and hence age determination is not solely confined to the Pab Sandstone as defined in this study.

The overlying Ranikot Formation is rich in foraminiferal assemblages and, based upon micropalaeontology and palynology of field samples and ditch cuttings from Badhra-01 and Mazarani-01,the age of the formation was determined to be Upper Palaeocene to Middle Eocene.

The determination of the age of the Pab Sandstone is based upon restricting the age between the Ft. Munro Formation below and the Ranikot Formation above. Therefore, on the weight of the biostratigraphic evidence, the author concludes that the Pab Sandstone is most likely Maastrichtian in age.

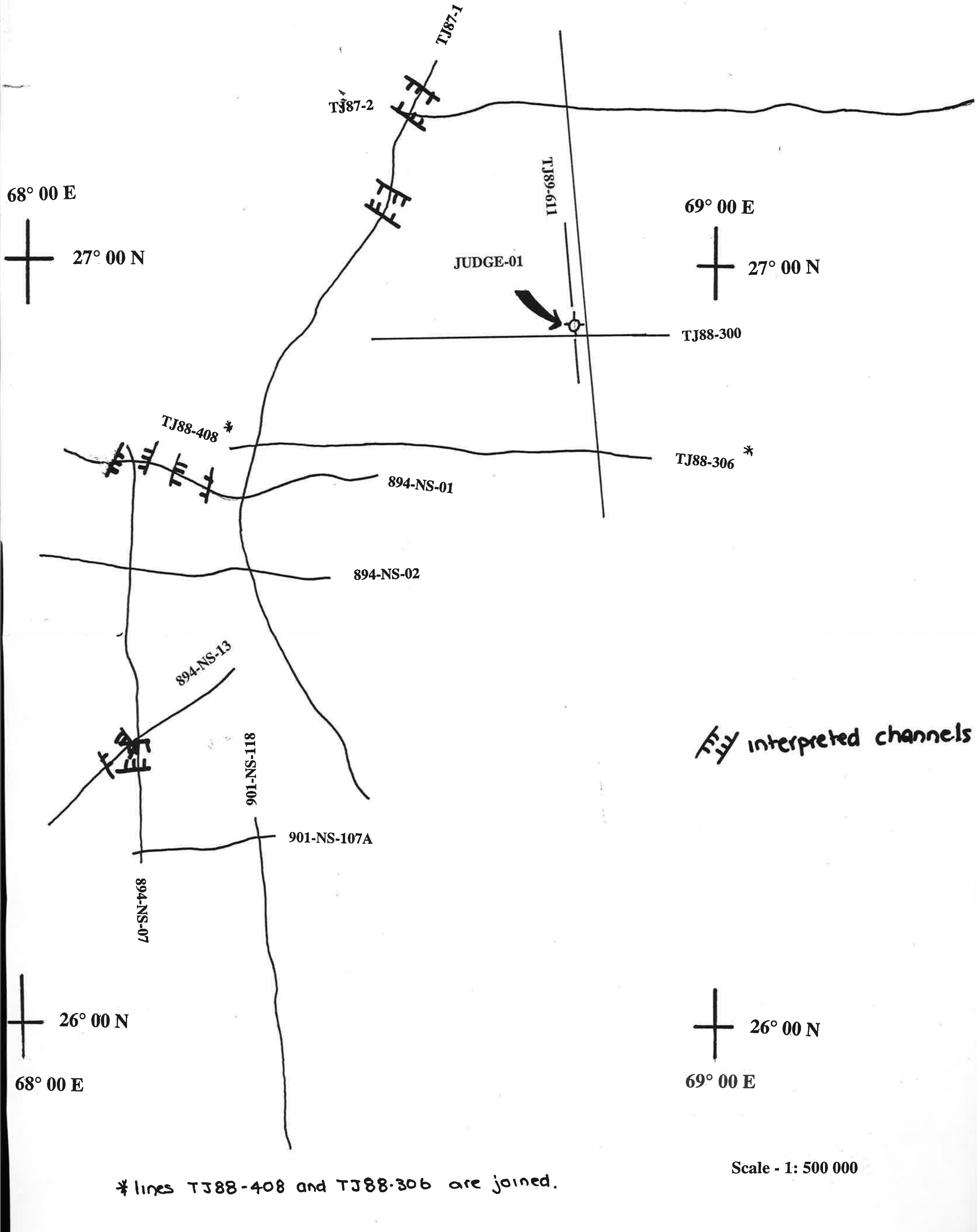
4.4: SEISMIC ANALYSIS

The seismic analysis revealed numerous structures that may be indicative of source direction and give an insight into the depositional environment pertaining to the Pab Sandstone. The author has described the most notable structures with individual interpretations of each line outlined below. Figure 21 illustrates the location of the seismic lines used in this study relative to the study area and the location of identified structures.

Line 894-NS-01 (VP. 101-1241); unmigrated (Enclosure 20)

1. The base Tertiary unconformity is seismically visible as a truncation surface (VP. 1120-1180 @ TWT=1.70 sec) suggesting sub-aerial exposure preceding Tertiary deposition.
2. Two concave structures are apparent below the Cretaceous - Tertiary boundary (VP. 700-830 and VP. 900-1030 @ TWT=1.55-1.70 sec and 1.55-1.80 sec respectively). The reflectors exhibit off-lap on the western surface of the structures, suggesting a possible western sedimentary influence. It is of importance to note however that the apparent structures may be attributed to multiple reflections. Land surface multiples are discounted due to the absence of a two-fold increase in dip associated with the apparent structure, which one would expect with multiple reflections due to the land surface. The possibility does exist for interbed multiples which could be generated by the high impedance reflectors located between 1.0 and 1.2 seconds along the line. The author is also concerned with the data quality. Immediately above each concave structure the seismic section is characterised by low fold coverage and mute effects. Apparent vertical faults at VP. 825 and 845 (@TWT=0.75 sec) may indicate static errors, and pose questions concerning the quality of the data processing on this line (Mr. Andy Mitchell, pers. comm., 1996). Furthermore, reflectors at depth appear to be absent below the regions exhibiting low fold. Any interpretation should err on the side of caution.

Figure 21: Pab Study Seismic Lines - Geographical Location



Line TJ87-1; migrated

Two broad, concave structures appear to exist or at or near the interpreted base of the Pab Sandstone.

1. Structure A occurs on the north west of the line and can be located between STN 1210 and 1295 @ TWT=1.2 to 1.7 secs.
2. Structure B occurs at the intersection with line NS-02 between STN 900 and 980 @ TWT=1.6-1.8 secs.

Both structures show evidence of clastic infilling of each depression. The depressions are wide (three and four kilometres, respectively) and are relatively shallow (between TWT=0.05 and 0.075 sec.).

The misinterpretation of multiples is discounted due to the absence of any similar depression-like structures below. One would expect a multiple reflection to be apparent on the high impedance reflectors at TWT=2.6 secs, this is not the case.

Numerous depositional or environmental conditions could account for these broad structures.

1. The depressions may represent broad feeder channels associated with the deposition of clastic lobes as identified on the regional Pab isopach map (Enclosure 6). This is based on the assumption that the channels, if present, are laterally continuous.
2. Meteoric waters may have caused the development of large depressions in the Parh Limestone prior to, or contemporaneous with Pab Sandstone deposition. This is

based on the alternate assumption that the depressions are individual, isolated features lacking lateral continuity.

3. The depressions may be collapsed sinkholes or dolines developed in the Parh Limestone and infilled during the regional marine incursion associated with the deposition of the Pab Sandstone. This is based on the assumption that sub-aerial exposure of the Parh Limestone occurred, leading to the development of karst.

<u>Line 894-NS-07; SP: 101-1421 (migrated) (Enclosure 21)</u>

Two features are apparent on line 894-NS-07 and both may represent incised valley fills. The two structures may be the same as those identified by Brink (1996).

A valley occurs between SP 460-360 @TWT 1.5-1.7 sec. The author has interpreted mounds and infilling type structures to be present. The evidence may be suggestive of laterally continuous channels. The valley is underlain by a set of high impedance, parallel reflectors which is interpreted to be associated with the Parh Limestone. The Cretaceous-Tertiary boundary is well defined and identified by the lower Khadro basalts along the extent of the line. The inference is that the Pab Sandstone represents a clastic fill in the incised valleys. A second structure is identified at SP 1320-1100 @ TWT 1.7-1.85 sec.

Both structures are broad, approximately 5 km and 11 km wide, respectively. The wider of the two may be the result of channel migration, or alternatively the line was shot oblique to the palaeo-channel.

Line TJ88-300; STN: 130-958.

The most striking feature contained on this line is the interpreted appearance of the Pab Sandstone in the west @ TWT 1.65 secs. The location of this point on the base map confirms the location of the Pab zero edge as predicted in the Pab Isopach Map (Enclosure 6). The clastic deposit appears to mound and prograde in a westerly direction, onto strong, high impedance reflectors which are most likely to be associated with the Parh Limestone.

Line 901-NS-107A; STN: 101-531 (migrated)

An interpreted incised valley. Infilled and cutting into the underlying Parh Limestone, exists between VP 485-435 @ TWT 1.45-1.5 secs. Notably the depth of the channel has decreased compared to the previously identified structures. This observation may suggest a more distal location relative to the sediment source. A distal location characteristically exhibits less gradient, decreasing the rate of sediment transport and the erosive power of the river in question.

5.1: PRIMARY POROSITY DEVELOPMENT

Grain size, degree of sediment sorting, grain roundness and the initial lithological composition are the primary controls governing primary porosity development in a sandstone. Each of these controls have been investigated with respect to the regional distribution of the Pab Sandstone. Although the regional data base is constrained by the absence of data immediately adjacent to the West Phulji permit, regional trends are apparent.

Grain sorting in the Pab Sandstone improves from poor to fair to well sorted in a line from Manjhu-01 to Sakrand-01 to Mazarani-01 (Enclosure18). On the basis of moderate sorting at Badhra-01, I predict that a similar degree of sorting is prevalent in the sandstone intervals of the Pab Sandstone in the West Phulji area.

Relative grainsize of the Pab Sandstone (Enclosure 17) decreases from the west (Bungi Nala and Pahvi Nala) and east (Shahdadpur-01, Sakrand-01 and Bara Nala) to the centre (Badhra-01) and north (Mazarani-01) of the study area. Combined with an uninterrupted succession of fine grained, argillaceous deposits at Gaj River (referred to by Butt (1992) as the Korara Shales), I predict that laterally extensive, fine to medium grained sandstones associated with the Pab Sandstone can be anticipated in the West Phulji area.

Enclosure 19 illustrates the regional distribution of grain roundness of the Pab Sandstone. Data are insufficient in the north and west, but the available data suggest that grain roundness distinctly improves towards the Bara Nala outcrop from the west and east. On the basis of the regional distribution I predict sub-angular to sub-rounded grained sandstones, in the Pab Sandstone in the Phulji area.

5.2: PRIMARY POROSITY PRESERVATION

Primary porosity in the Pab Sandstone is preserved by two sequential processes. The early precipitation of grain coating clays, which is present in both diagenetic models, inhibited, but did not prevent the development of quartz overgrowths. Although quartz overgrowths are observed in nearly all samples (Robertson Research, 1996) and photomicrographs, they do not totally occlude primary porosity but aid in its preservation. The quartz overgrowths protected the framework grains from destruction by increasing the net strength of these grains.

Previous studies (Walderhaug, 1996; Bjorlykke and Egeberg, 1993) have noted the porosity and permeability reduction in deeply buried (greater than 3 km), quartz-rich sandstones due to silica cementation. The quartz overgrowth development has been recognised in this study and others (Robertson Research, 1996) to be an early diagenetic phase which predates kaolinite precipitation. Quartz is inferred to have precipitated in the Pab Sandstone, at a shallow depth of burial, before the maximum depth of burial (MDB) was attained.

5.3: PRIMARY POROSITY DESTRUCTION

The dissolution of framework quartz and feldspar grains is the principal mechanism that destroyed primary porosity within the Pab Sandstone in the Kirthar Basin. The reservoir potential of the Pab Sandstone has been significantly reduced due to the reduction of primary porosity. The initial, high content of soluble minerals no doubt aided in the development of dissolution type porosities as evident in the photomicrographs studied, but primary porosity was occluded by re-precipitation of these minerals as cements and diagenetic clay minerals.

6.1: SECONDARY POROSITY DEVELOPMENT

Secondary porosity within the Pab Sandstone is very well developed, and commonly microporosity associated with diagenetic clays is developed at the expense of macro or primary porosity. The dissolution of quartz and feldspars has created initial macro-secondary porosity, but more importantly leads to the development of microporosity within clay precipitates. The carbonate cements which succeeded grain dissolution are in turn dissolved at depth.

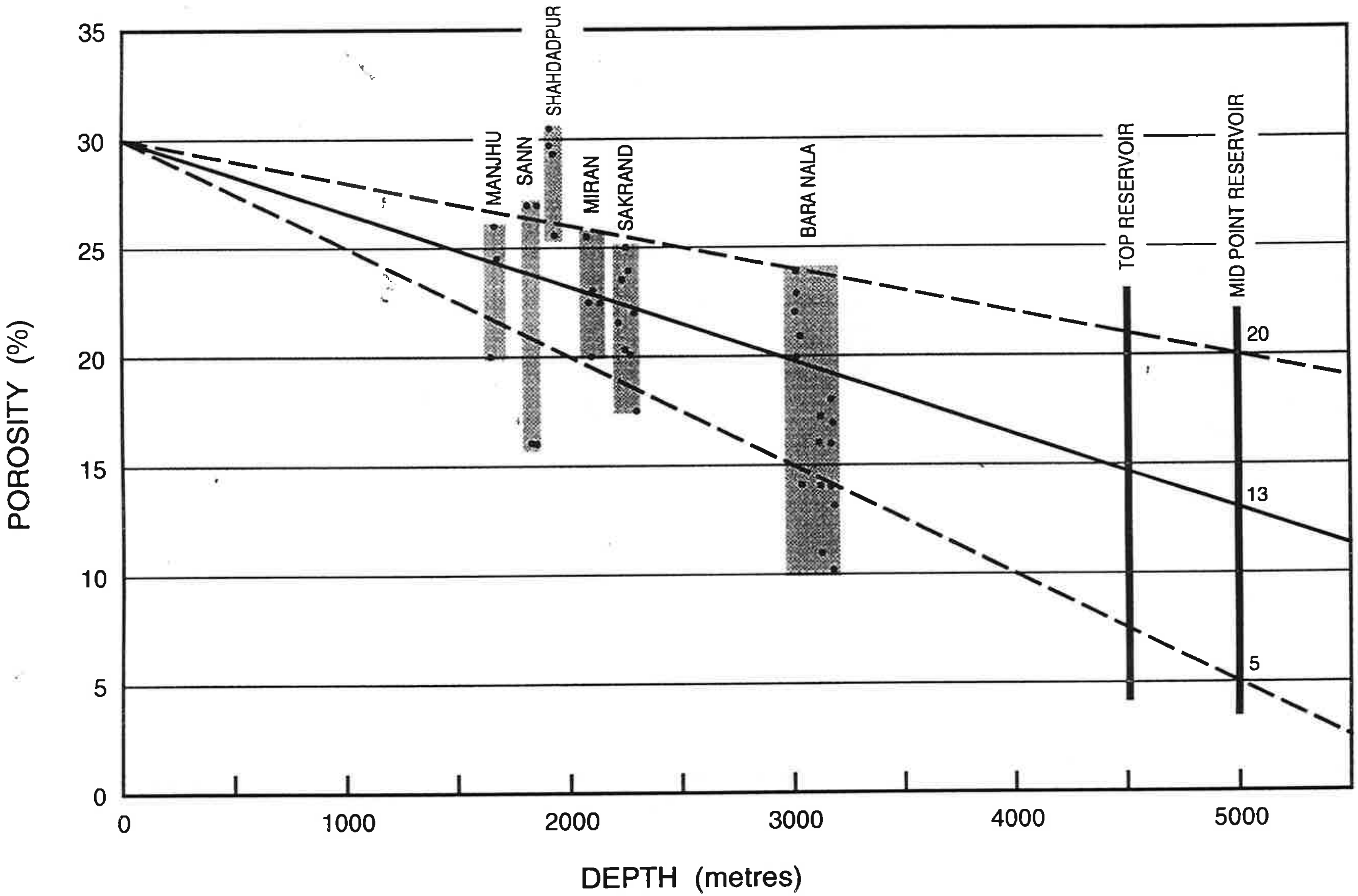
Schmidt and McDonald (1979) suggest that the dissolution of calcite, dolomite and siderite account for the major portion of all secondary porosity. All three minerals are recognised in the Pab Sandstone. The dissolution of diagenetic carbonates, especially cements, is the primary mechanism for the development of secondary porosity in the Pab Sandstone.

Scherer (1987) suggests that leaching can be especially important in sandstones at great depths. Leaching may be aided by elevated temperatures. A composite regional geothermal gradient map (Enclosure 11) was compiled based upon data provided by Christie (pers. comm., 1996), Preston (1996), IEDS (1995) and Khan and Raza (1986). The map illustrates that the Phulji area has a relatively low present-day geothermal gradient (approximately 25°C/ km). Importantly, Scherer (1987) suggests that temperature plays a somewhat inferior role in influencing porosity, but its role probably increases above a geothermal gradient of 40°C/ km (cf. Phulji-01 @ 25°C/ km). This study confirms the negligible role that geothermal temperatures exert on porosity in the Pab Sandstone and is illustrated in Figure 20. The plot uses a porosity cut-off of 8%.

Pab Sandstone: Porosity v Maximum Burial Depth Plot

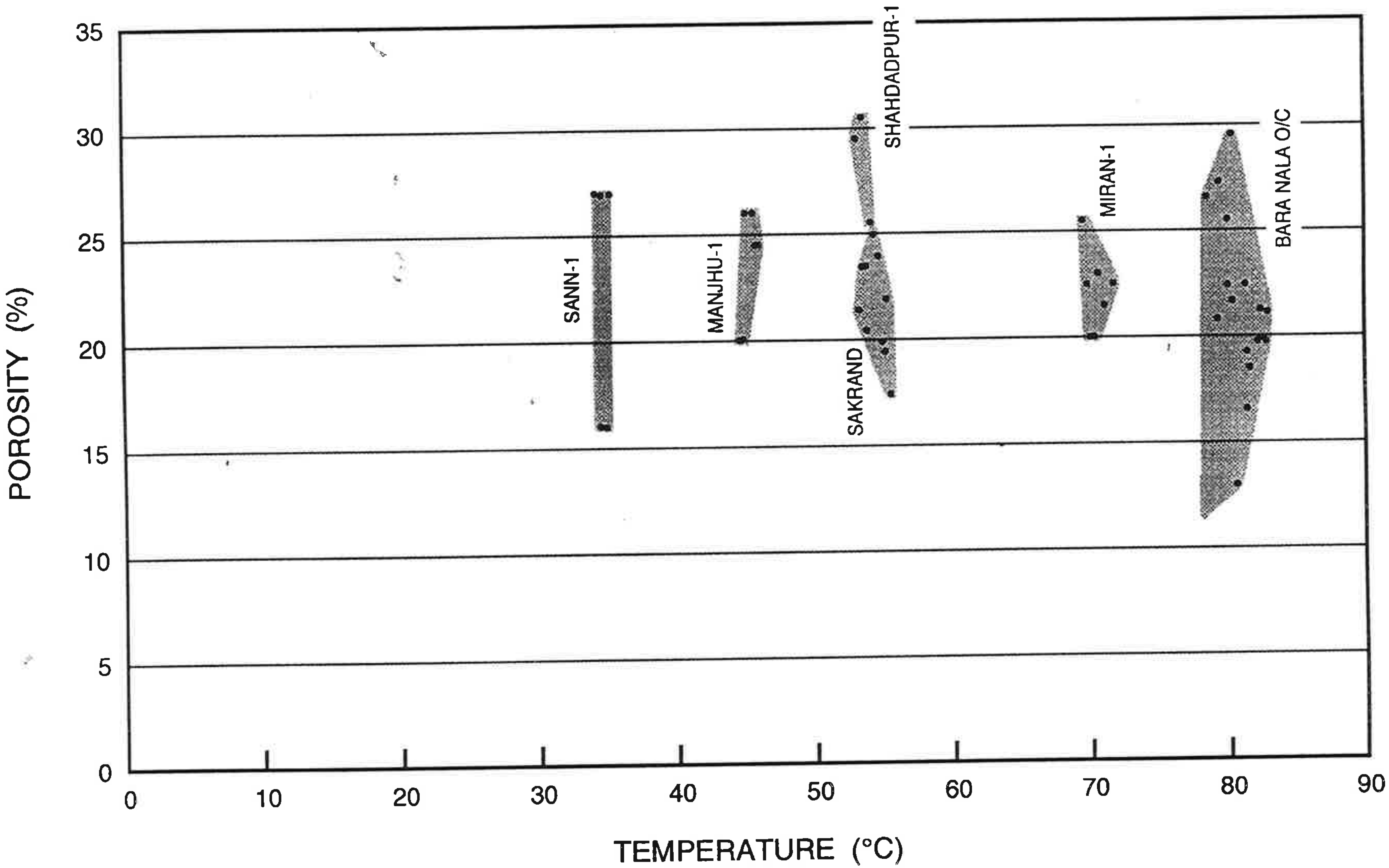
Dadu Permit - Phulji Evaluation

BHP



Combined Wells Porosity v Temperature Plot

Dadu and Nawabshah Permits - Pab Study



A regional map (Enclosure 10) illustrating the base Tertiary depth at the time of MDB (after Preston, 1996) was compiled. The map is based upon the stratigraphic picks used by Preston (1996), and although they differ to those used in this study I chose not to correct the models because the relative thinness of the Pab Sandstone would not have significantly altered the models (J. Preston, pers. comm., 1996). The map illustrates that, in the Phulji area, the MDB of the top of the Pab Sandstone is estimated to be 4500 metres but is likely to be as deep as 5500m (Mr. A. Christie, pers. comm., 1996). I chose a MDB of 5000 metres to represent the most likely scenario.

Relative uplift can be determined from Enclosure 9 which illustrates the present depth to the base Tertiary, based upon the stratigraphic picks identified in this study. The base Tertiary contact in the Phulji area is shown to occur at 3500 metres below mean sea level. Although the area of interest has been subjected to relative uplift, decompaction will not create intergranular porosity (Dr. N. Lemon, pers. comm., 1996). The relationship between fracture porosity development and decompaction was unable to be determined in this study, due to the nature of the data base.

Fracture porosity was observed by Robertson Research (1996) in some Bara Nala samples and was mostly associated with limestones. Fracture porosity is important in the Pab Sandstone reservoirs in the Pirkoh Gasfield. No evidence was available to the author to accurately assess the presence of microfracture development in the Pab Sandstone in the Phulji permit areas. Fracture porosity may be expected to occur in tightly folded and fractured structures observed in concurrent seismic studies, but this inference is purely speculative. Fracture porosity, if present, may have important implications concerning the deliverability of the reservoir unit particularly in uplifted areas.

Mechanisms that may encourage secondary porosity development in the Pab Sandstone include flushing by meteoric waters leading to the development of carbonic acid and lowering of the pH of interstitial fluids. The carbonic acid may result from the degradation of organic matter in associated intercalated shales, claystones and mudstones. The presence of hydrogen sulphide (pyrite precipitation?) may also cause dissolution of carbonates (Schmidt and McDonald, 1979).

No evidence was observed by Robertson Research (1996) or the current author to suggest that shrinkage of the rock unit has occurred or increased the porosity of the Pab Sandstone.

Although burrows, traces, rootlets, forams and chambers were observed in thin section and outcrop no evidence is present which may suggest that organisms directly or indirectly created secondary porosity of any importance. The dissolution of foram chambers may have aided the development of mouldic type porosities but this is considered negligible.

6.2: SECONDARY POROSITY PRESERVATION & DESTRUCTION

Preservation of secondary porosity in the Pab Sandstone is inhibited by the presence of late stage pyrite, pore-filling haematite (terrestrial model) and late stage occlusion by calcite cementation and dolomite replacement (marine model). As noted in the diagenesis discussion (Chapter 4.3.2) the paragenesis of the iron phases is uncertain and this clouds any prediction on the degree to which secondary porosity is preserved. Similarly, the extent of calcite cementation and dolomite replacement is based upon questionable sampling in only two regions. The regional extent of late stage carbonate cementation and replacement can not be determined beyond speculation, on the basis of the data available.

Schmidt and McDonald (1979) observed that chemical compaction associated with grain dissolution generally reduces primary porosity in sandstone lithologies more than secondary porosity. Whether carbonate dissolution occurs at depth or is a weathering artefact (Robertson Research, 1996), secondary porosity will be preserved relative to primary porosity.

Secondary porosity development does not necessarily result in a net increase in porosity. Phases precipitating from dissolution, leading to re-distributional secondary porosity, may compensate the rock volume loss due to dissolution which is termed enhanced secondary porosity (Giles and de Boer, 1989; Bloch, 1991). Both type of porosities have been recognised in this study and others (Robertson Research, 1996), in the Pab Sandstone.

The destruction of secondary porosity by compaction is a function of mechanical strength. Bloch (1991) suggests that deeply buried sandstones experience less secondary porosity reduction if a high content of non-ductile grains are present. The Pab Sandstone is widely recognised (Petromin, 1991; Sultan and Gipson Jnr, 1995; Robertson Research, 1996) as a stable, quartzose sandstone and hence compaction of secondary pores would be of negligible concern.

7: DEPOSITIONAL ENVIRONMENT

The depositional model proposed for the Pab Sandstone in the Kirthar Basin is based upon the compilation of all the environmental indicators assessed in this study. I have attempted to describe the depositional interpretations in respect to the palaeofacies interpretation, as was accomplished with other results in this study.

The base of the SMST is characterised by moderately sorted sandstones. Cross beds are evident and are possibly current derived (Tectostrat, 1996). The lower section is interpreted to be deposited in a coastal/ inner deltaic environment. Rare clay and iron phases suggest a moderate energy, non-restricted environment. A site of sub-aerial exposure and non-deposition (except for possible incised valley fills) is interpreted to exist east of the Pab Sandstone zero edge (Enclosure 6) as identified in the seismic analysis.

The central SMST is interpreted as a coastal/ clastic strand plain. Tectostrat (1996) suggest that metre scale trough cross-beds are of a possible aeolian origin (sheet sands?). This interpretation may only be of local extent (Bara Nala) as structures observed further west are not as conclusive. Possible shallow water, lagoonal limestones were observed (Tectostrat, 1996). Evidence exists to support sub-aerial exposure, accompanied by poorly sorted channel fills.

The remainder of the SMST suggests a braid plain setting. Palaeocurrent directions associated with the SMST are variable (Enclosure 13) and reflect the variable environments of deposition observed in the facies. Channels of varying sizes may be indicative of stream flow deposits associated with moderate year round rainfall. The upper SMST is thick and massive. The aggradational nature of the facies suggests that basin subsidence kept pace with sediment input. The SMST is indicative of moderately high flow regimes of generally short duration as suggested by the generally poorly sorted sandstones.

The LTST marks the return of marine conditions associated with a coastal/ inner deltaic, sub-aqueous environment. Palaeocurrent directions are generally unidirectional. Lagoonal and sub-tidal to pedogenic limestones are of regional extent and signify the time of maximum marine flooding. High energy, cross bedded, thin and intercalated sandstones record possible single event debris flow deposits, possibly associated with seasonal climatic conditions (monsoonal?).

The HST is characterised by sub-tidal to pedogenic, pebbly sandstones at the base, suggesting possible reworking of underlying pedogenic and Parh limestones. A lower deltaic plain with fluvial flood-plains and meandering (occasionally erosive) channels is envisaged and although the data set is limited, palaeo-currents are directed westward. The HST wireline log motifs (Enclosures 1, 2 and 3) are characteristic of scour and channel deposits associated with crevasse splay and over-bank deposits. Ripple marks and traces of glauconite near the top of the HST are indicative of a marine influence, possibly associated with progradation into the basin. Over-steepening of the delta front led to contemporaneous slumping and subsequent deposition of coarse grained deposits at depth in the west. Cross beds in individual sandstones decrease in size upwards, possibly suggesting decreasing flow regimes.

The UTST is similar to the LTST, but the presence of shales and possible micro-fossiliferous limestones suggest a deeper environment (shallow marine) compared to the LTST.

Generally the Pab Sandstone represents a transitional marine environment, varying from coastal plain deposits and braid plain at the base, to inner deltaic to shallow marine deposits at the top. This regional interpretation is supported by the degree of grain sorting improving to the west (Enclosure 18) associated with a coastal plain followed by higher energy marine environments. Similarly, grain roundness (Enclosure 19) improves to Bara Nala and then decreases to the west suggesting western deposits are laid down below fair weather base in an inner neritic zone. A similar trend is observed for grainsize distributions (Enclosure 17).

8: CONCLUSIONS

The Pab Sandstone is a medium to coarse grained, occasionally fine to very coarse grained, generally massive to thick bedded, cross bedded, occasionally conglomeratic, quartz-arenite of Maastrichtian age with intercalations of shale, claystone, mudstone, marl and limestone beds and is characteristic of a transitional marine, clastic environment.

The Pab Sandstone is most commonly carbonate and silica cemented, occasionally dolomite and siderite cemented, and generally microporosity, associated with haematite, kaolinite and illitic precipitates, develops at the expense of macroporosity.

Enclosure 12 identifies the Pab Sandstone Play Fairways. The West Phulji and Dadu permit areas are constrained within the main play. The Pab Sandstone is identified to be present in the BHPP permits. The SMST palaeofacies is interpreted as having good to very good reservoir quality and is interpreted to be present in the permits (Enclosure 13).

The Pab Sandstone is likely to posses a potential reservoir lithology of moderate to good quality in the West Phulji area. In excess of 50 metres of net sand is interpreted to be present in the Phulji area. Furthermore, the net/ gross is interpreted to be greater than 25%. Enclosure 12 illustrates the seal capacity of the Khadro Formation as identified by Logan (1996).

The major diagenetic factors contributing to the destruction of the reservoir potential of the Pab Sandstone are late stage pyrite, pore filling haematite and late stage occlusion by calcite cementation and dolomite replacement.

Diagenetic clays generally develop microporosity at the expense of macroporosity and diagenetic enhancement has resulted in at least adequate porosity

The reservoir anticipated in the Phulji area has undergone deep burial. The early development of quartz overgrowths, combined with a relatively low geothermal gradient has permitted the preservation of at least adequate porosity throughout the maximum burial experienced by the reservoir (Figure 20).

Decompaction may have aided the development of fracture porosity, however, insufficient data were available to assess the role and importance of fracturing on the reservoir quality. Minor fracturing was evident in the limestone beds and if regionally persistent may improve the quality of otherwise tight lithologies within the Pab Sandstone.

Despite the loss of original primary porosity, subsequent diagenetic events have led to the development of secondary porosity in the Pab Sandstone.

9: RECOMMENDATIONS

1. A more comprehensive petrographical data base should be built up with particular reference to sub-surface samples. Petrographical analyses should include reflected light microscopy, SEM and XRD analysis where possible, with the principal objectives being to clarify:

   a).the diagenesis and paragenesis of iron phases in the Pab Sandstone

   b). the composition of indeterminate diagenetic clays in the Pab Sandstone,

   c). the degree to which microporosity develops at he expense of macroporosity.

   d). the nature of carbonate dissolution (ie. surface dissolution versus dissolution at depth).

2. The study area is poorly constrained in the north. I acknowledge that presently the area is politically unstable and potentially life threatening. I also acknowledge that BHP Petroleum have made previous attempts to gain access to the Gaj River area but have been advised against entry. If circumstances changed, the section at Gaj River should be visited and the Pab Sandstone (or time equivalent) should be thoroughly investigated and sampled.
3. Any future field work in the study area should extend the BHP Petroleum data base with particular reference to lithology descriptions, grain characteristics, and sedimentary structures, including palaeocurrent determinations and measurements. Previous high quality field work undertaken by Tectostrat (1996) should act as a framework for future surveys. A more quantitative approach should be taken so that statistical modelling can be undertaken.

4. A complete and thorough comparative study should be undertaken concerning the reservoir quality of the Pab Sandstone at producing gas-fields such as Pirkoh, Loti and Dhodak with that encountered in the Kirthar Basin.
5. Future drilling of the Pab Sandstone in the Kirthar Basin should incorporate thorough testing and sampling of the Pab Sandstone including core and biostratigraphic analyses. Wireline log runs should incorporate all available porosity tools where possible. In addition all sampling should be correctly and accurately depth matched with wireline logs.
6. Upon the compilation of a regionally representative petrographical data base, consideration should be given to undertake a quantitative electron microscopy study of the Pab Sandstone similar to those conducted by Hurst and Nadeau (1995) and Walderhaug (1996). Any mathematical modelling should consider the effect of variation in parameters such as grain size, detrital quartz content, clay content, and temperature history etcetera and would be a valuable predictive tool.

7. GENEX maturation modeling should be extended to incorporate previously un-modelled wells in the Kirthar Basin using the updated lithostratigraphic data contained within this study and others (eg. Logan A, 1996). Particular reference should be made to those wells where the potential reservoir and seal are present together.

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