ENHANCED RECOVERY FROM A FRACTURED RESERVOIR USING HIGH IMPACT BIOSTRATIGRAPHY: A CASE STUDY FROM THE FIM KASSAR OIL FIELD, PAKISTAN

By

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Boulder, CO

2004

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
July, 2006

ENHANCED RECOVERY FROM A FRACTURED RESERVOIR USING HIGH IMPACT BIOSTRATIGRAPHY: A CASE STUDY FROM THE FIM KASSAR OIL FIELD, PAKISTAN

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PREFACE

High impact biostratigraphy is the integration of high-resolution sequence biostratigraphy and multidisciplinary work to achieve business goals. This study applies high impact biostratigraphy to a fractured reservoir from the Fim Kassar Oil Field in Pakistan. Fim Kassar produces from fractured dolomites of the Eocene Sakesar and Chorgali Formations. Gulf Oil Company first discovered this field but because of low productivity, sold it to the Oil and Gas Development Corporation of Pakistan Limited (OGDCL). OGDCL drilled three wells that were either prolific or came out dry. This erratic production is attributed to poor understanding of fracture occurrence in the sub-surface. Although studies of fracture orientation have been made, the prediction of fracture prone beds remains problematic. Enhanced recovery from this fractured reservoir is contingent upon a better understanding of fracture occurrence in the subsurface. This study integrates several data sets to create a sequence stratigraphic model which is used to predict subsurface occurrence of fracture prone beds. Microfossils identify key-surfaces, delineate systems tracts, and “fingerprint” payzones which are used to design a biosteering program for future horizontal wells in this field.

I sincerely thank my thesis committee—Drs. Darwin Boardman (Chair), Surinder Sahai, James Puckette, and Carlos Cordova—for guidance and support in the completion of this research. I also thank Dr. Saeed Khan Jadoon, Mr. Muhammed Ashraf, and Mr. Shehzad Humayun for providing data and sharing expertise.

ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. Darwin Boardman for giving me the opportunity to conduct research in Pakistan. I am indebted to Dr. Surinder Sahai and Dr. James Puckette for supporting me at every stage of my tenure at Oklahoma State University. Dr. Cordova provided valuable insights into preservation potential of palynofossils in sabkha settings. I also appreciate the expertise on carbonate sequence stratigraphy provided by Dr. Christopher Kendall at the University of South Carolina.

Dr. Saeed Khan Jadoon at the Oil and Gas Developmental Corporation of Pakistan (OGDCL) suggested that I work on Fim Kassar, and without his ideas and guidance this thesis would not have been possible. Mr. Shehzad Humayun of the Oil and Gas Training Institute of Pakistan and Mr. Tariq Jaswal of OGDCL provided all the sub-surface data used in this study. Mr. Muhammed Ashraf of the Petrophysical Research and Training Institute assisted me with Calcareous Nannoplankton analysis for my samples.

I also wish to thank Paul Boni at the University of Colorado for his guidance in the preparation of petrographic slides. Wahab Sadeqi provided pictures and samples from the modern sabkhat of Kuwait, Andy Rihn at Oklahoma State University prepared fossil samples, and Matt Garrison offered pictures of fractures from the Marble Falls Formation.

I would like to dedicate this thesis to my parents who have always encouraged me to learn and pursue higher education, and for giving me the strength to achieve my goals.

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CHAPTER I

INTRODUCTION

A fractured reservoir is defined as a reservoir in which naturally occurring fractures either have, or are predicted to have, a significant effect on reservoir fluid flow either in the form of increased reservoir permeability and/or porosity or increased permeability anisotropy (Nelson, 1985). Producing fractured reservoirs effectively has long been regarded as problematic. Although hydrocarbons are contained within pores, their migration pathways are along fracture planes. The probability of intersecting one of these fractures (which are beyond the resolution of seismic data) with a vertical well is like throwing a dart at a checkerboard and expecting to hit the boundary between one checker box and another (fig 1, fig 2, fig 3). Intersecting a fracture or missing can make the difference between a high fluid volume producing well and a dry hole.

Fim Kassar Oil Field was selected for this study because it is a textbook example of this "hit or miss" phenomenon. In 1980 Gulf Oil Company discovered and drilled Fim Kassar. Their initial well produced 20 barrels/day, and the field was declared non-commercial and sold to the Oil and Gas Development Corporation of Pakistan Limited (OGDCL). OGDCL drilled a well that encountered the same formations and penetrated a fracture that produced 4700 barrels of oil per day.

Figure 1. Fractured Marble Falls Formation from the Pennsylvanian of northern Texas, USA. (photo courtesy of Matt Garrison)

Figure 2. Fractured carbonates of the Kilve Anticline of the United Kingdom. Note the presence of fractures in certain layers and their absence in others. (photo taken from http://n.ethz.ch/student/sgeiger/COSMIC/SKM_fractured_reservoirs2.htm)

The primary objective of this study is to introduce a new technique that can be used to enhance recovery from fractured reservoirs. However, for this technique to be effective the following conditions must be met:

1. Fractures must be a function of mechanical stratigraphy (some layers must have a higher density of fractures than others-- fracture density being dependant on rheology).

2. Seismic/well-log/core/outcrop data must allow sequence analysis.

3. Reservoir must contain microfossils that can be identified in drill cuttings by well-site geologists while drilling.

The author believes that the techniques used in this thesis can be applied not only to Fim Kassar but fractured reservoirs worldwide.

1) Fim Kassar production history

Fim Kassar Oil Field is located 75 kilometers southwest of Islamabad, in northern Pakistan (fig. 4). The field produces from Eocene dolostones of the Sakesar and Chorgali formations. These are deformed in an anticline known as the Fim Kassar Structure. The field was discovered in 1980 by Gulf Oil Company, which drilled well the Fim 1-X well (fig. 7). Because of low productivity (20 barrels of oil per day) the field was declared non-commercial and sold to a local Pakistani company: Oil and Gas Development Corporation Limited (OGDCL). OGDCL drilled the Fim-1A well and abandoned

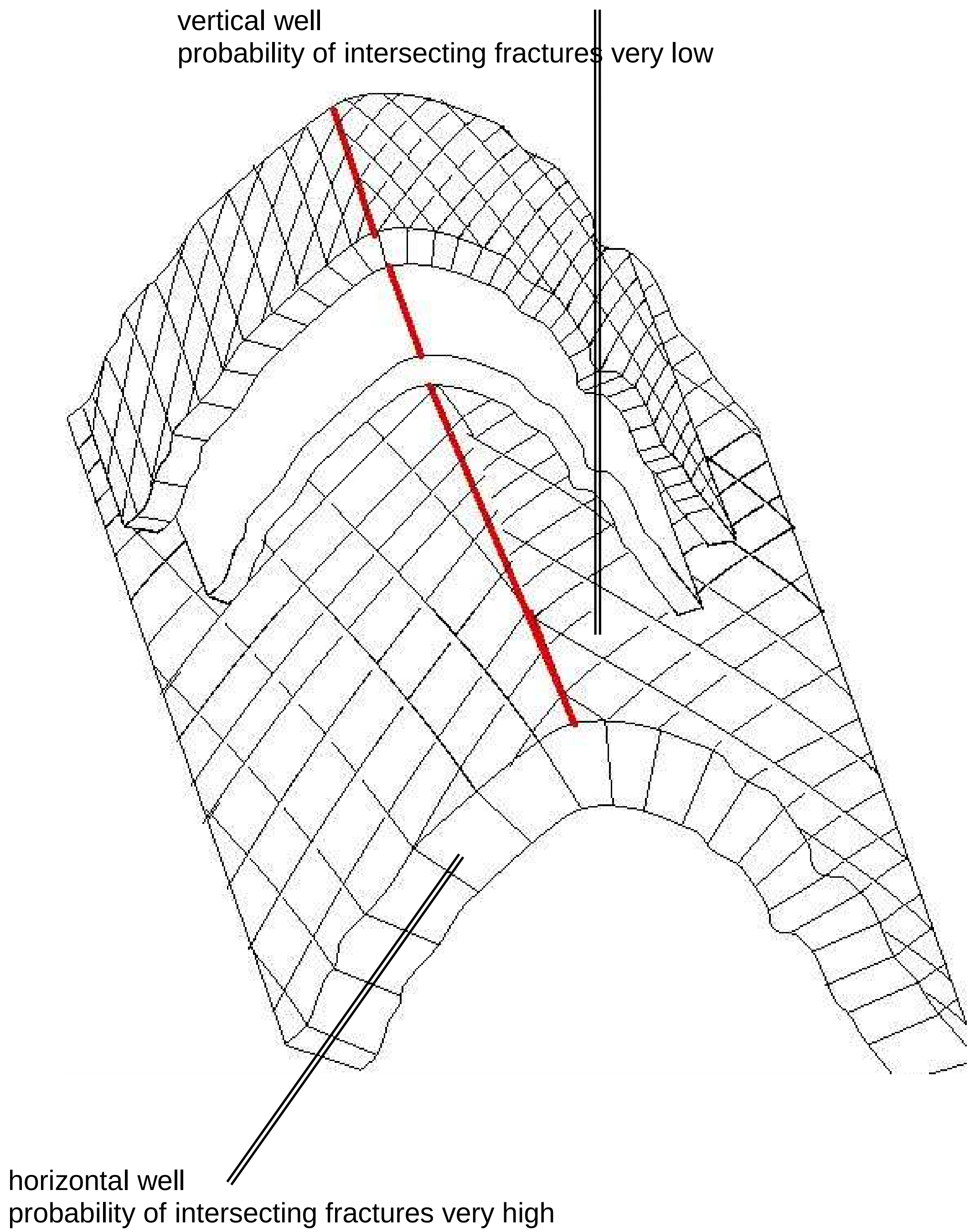

Figure 3. Model of the Khair-E-Murat anticline showing fractures and the efficiency of directional drilling in a fractured reservoir which shows mechanical stratigraphy at reservoir scale.

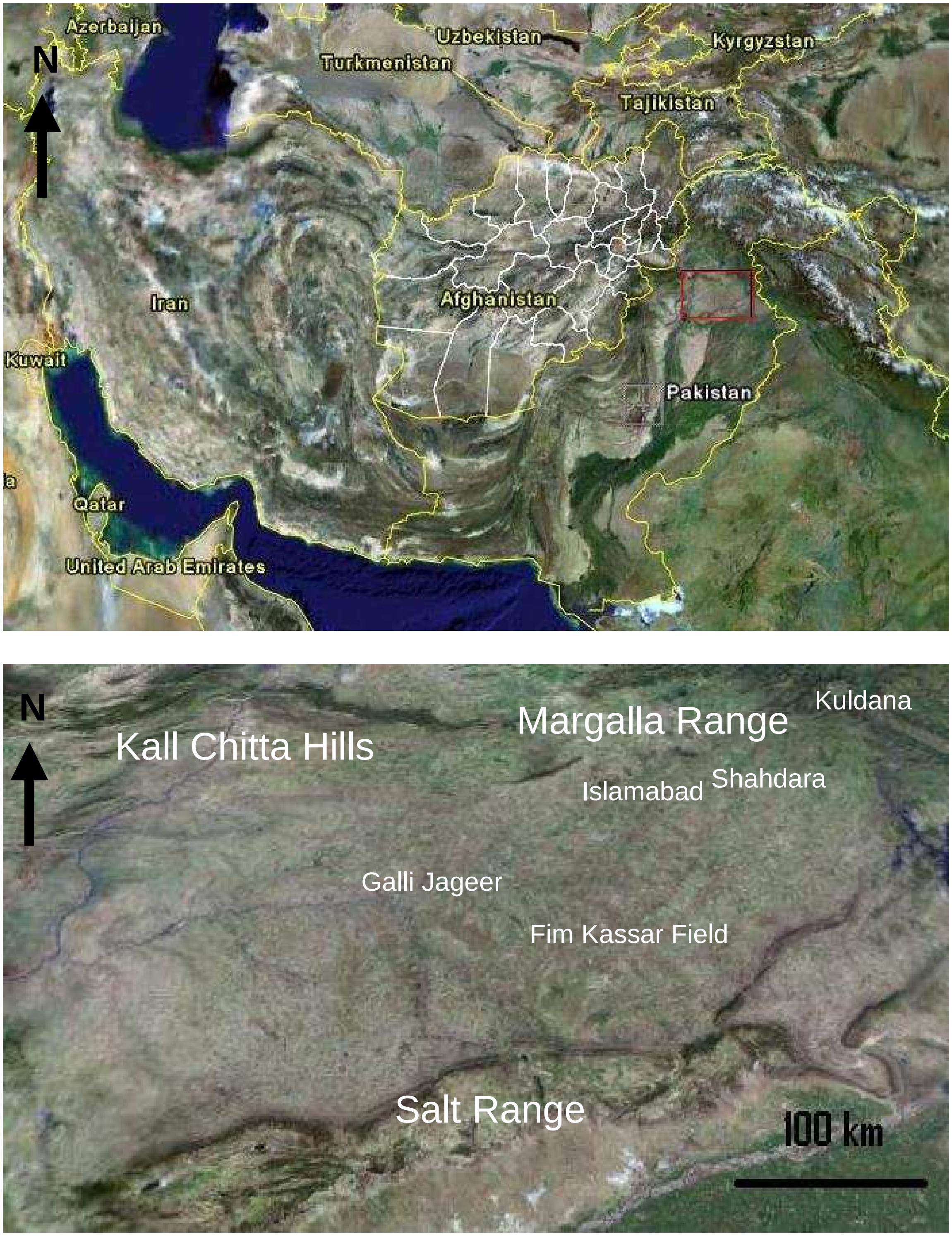

Figure 4. Study area in Pakistan (red rectangle) enlarged below

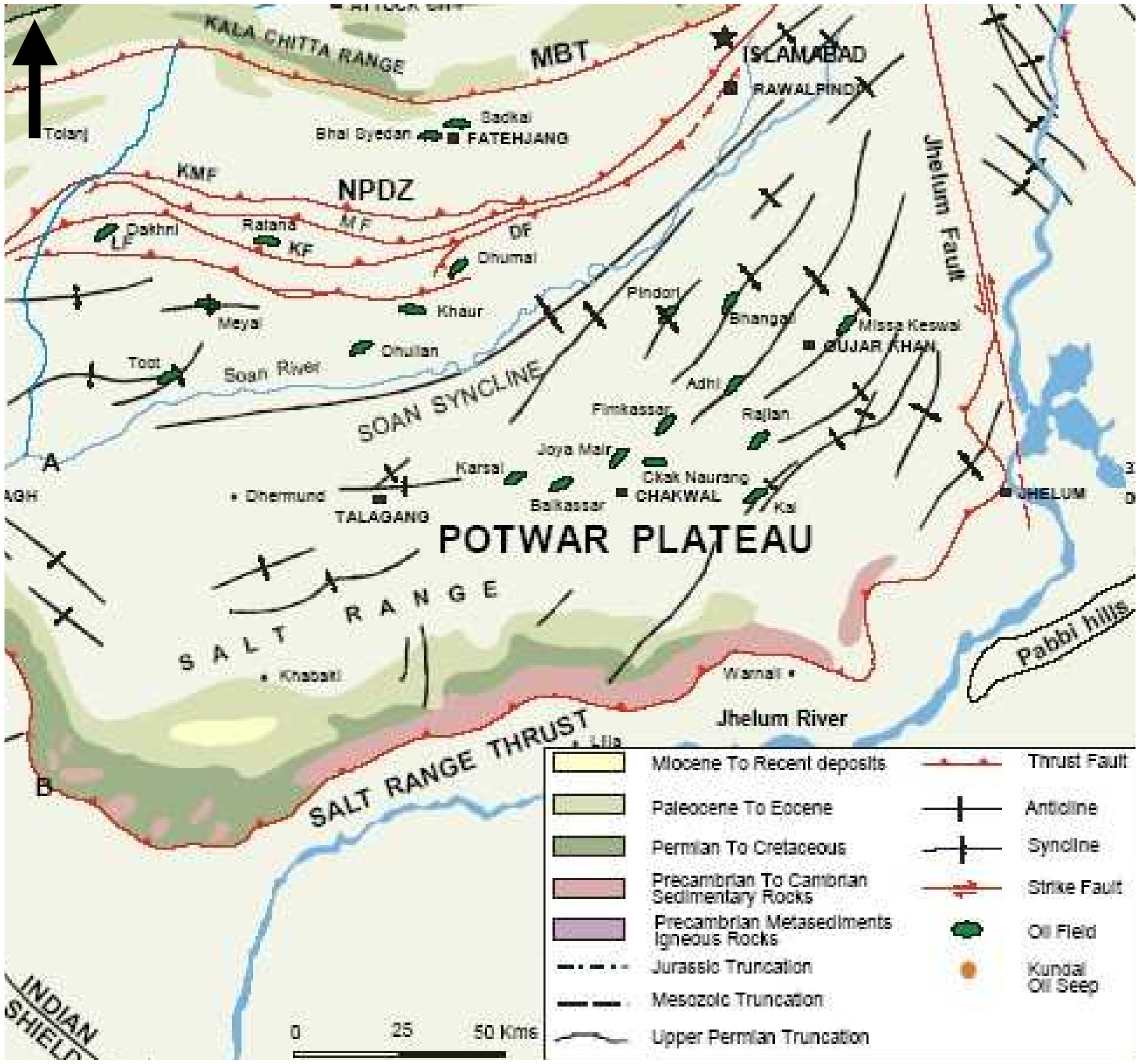

Figure 5. Geological map of the Kohat-Potohar Basin showing location of oil fields (reproduced from Wandrey et al., 2003)

the well due to technical difficulties. The Fim-1-X borehole was re-entered and sidetracked; this well was renamed Fim-1-ST. The Fim-1-ST well is the highest oil volume producing well to date and produced 4000 barrels/day. A third well, the Fim-2 was drilled in 1990. This initially produced 1960 barrels of oil per day. Due to a decrease in formation pressure and consequent decrease in production, an injector well (Fim-3) was drilled. By 2002, Fim Kassar Field produced 2 million barrels of oil. In 2004, Fim-4 well was drilled but produced very little oil and was plugged and abandoned.

Fim Kassar is an unconventional play as it produces from very tight limestones that contain very little primary porosity and are low permeability. Epigenetic dolomitization has created porosity values of 25% (Malik et al., 1988), whereas tectonic deformation of the Fim Kassar structure created fractures that provide migration pathways for hydrocarbons. The source of oil at Fim Kassar is from the underlying Mianwalli (Triassic), Datta (Jurassic), and Patala (Paleocene) Formations (Khan et al., 1986). Thick shales of the overlying Kuldana Formation provide a seal for hydrocarbon entrapment.

The production history of Fim Kassar Field indicates that oil production is erratic because success in this play depends on the prediction of fractures. The causes of fracturing have been studied in detail (Jadoon et al., 2002; Benchilla et al., 2002) but fracture orientation and occurrence are poorly understood. This study shows that the Fim Kassar structure does not conform to the standard model for fracture distribution in anticlines as suggested by Nelson (1985) and Nurmai (1991). Although OGDCL reservoir engineers are currently developing reservoir simulation models to better understand fracture orientation, the prediction of these fractures in the subsurface remains a challenge. The fractures are beyond the resolution of reflection seismology and although they may be visible on borehole image logs, their occurrence between wells remains enigmatic.

This study provides a) a better understanding of the depositional system for reservoir carbonates, b) creates a high-resolution sequence stratigraphic model, c) predicts occurrence of fracture prone beds in the subsurface, and d) designs a biosteering program for horizontal wells.

2) High-Impact Biostratigraphy and its application to Fim Kassar Oil Field

High-impact biostratigraphy (HIB) is defined as the integration of high-resolution sequence biostratigraphy and multidisciplinary work to achieve business goals (Payne at al., 1999). It is a concept developed by British Petroleum (BP) geologists working out of Aberdeen, United Kingdom to solve geological problems encountered during development and appraisal of oil fields located in the North Sea Basin. Unlike traditional biostratigraphy which focuses on the identification of defining taxa and their correlation with standardized biozones to acquire ages for strata, HIB focuses on the recognition of bioevents on a field scale. Whereas traditional biostratigraphy is used in the exploration phase, HIB is usually employed in the development and appraisal phase. Specific problems such as poor understanding of reservoir geometry, connectivity and compartmentalization, reserves estimation and optimal recovery can be solved using HIB (Jones & Simmons, 1999). Traditional biostratigraphy is done by micropaleontologists or palynologists with a high degree of specialization within one group, HIB requires the geoscientist to be well versed in a wide range of microfossil groups along with a good working knowledge of geophysical data and reservoir engineering.

HIB has been successfully employed to solve geological problems in fields in the North Sea (Mouray Firth Area, Magnus Field, Valhall-Hod, and Grane Field), the Gulf of Mexico (Mars and Bonnie Fields), Venezuela (Lake Maracaibo), Denmark (Dan Field) and Nigeria (Oso Field). Perhaps one of the most important goals a geoscientist can attain while using HIB is going beyond the resolution of reflection seismology. The key to successful HIB is the identification of distinct bioevents. These can be Local First Historical Appearances (FHA_o) or Local Last Historical Appearances (FHA_l) in the sense of Walsh (1998). They can also be local assemblage or acme zones, and taphonomic characters that can help the geoscientist distinguish one layer from those below or above it. This characterization of a lithostratigraphic bed by paleontology is known as "fingerprinting". This technique uses "anything goes" field scale biostratigraphy in the sense of Payne et al (1999) and is extremely useful when trying to solve engineering problems that demand higher resolution stratigraphy than provided by reflection seismology.

An example of such high resolution is the creation of bioevents in the Gulf of Mexico. In 1965 benthic foraminifera were used to recognize 5 bioevents (Armentrout, 1991). The incorporation of planktonic foraminifera into this dataset allowed further refinement and the number of local bioevents was increased to 19. By 1998 the addition of Calcareous Nannoplankton to this dataset increased the number of recognizable bioevents to 50.This improved biochronology from a resolution of 1 ma in 1978 to 0.3

ma in 1998 (Armentrout, 1998). HIB allowed geoscientists to target sub-salt prospects that lacked high seismic resolution in the Bonnie Field.

Another instance where HIB was used to go beyond the resolution of seismic was in Lake Maracaibo, Venezuela. The Early Eocene in this basin was represented by a single pollen zone. Rull (2000) recognized eight palynocycles in these strata and correlated these with third order global eustatic cycles to get a resolution of 1-2 ma.

More applicable to Fim Kassar is the applications of HIB to the Dan Field of Denmark. Like Fim Kassar, this field produces from a homogeneous carbonate reservoir. The payzone (effective reservoir) lies in Early Paleocene limestones that look lithologicaly similar to underlying Cretaceous limestones that are barren. Geosteering in such reservoirs can be problematic because well-site geologists encounter bit-cuttings that are lithologically identical. By fingerprinting the payzone using planktonic foraminifera, a successful biosteering program was developed (fig 8).

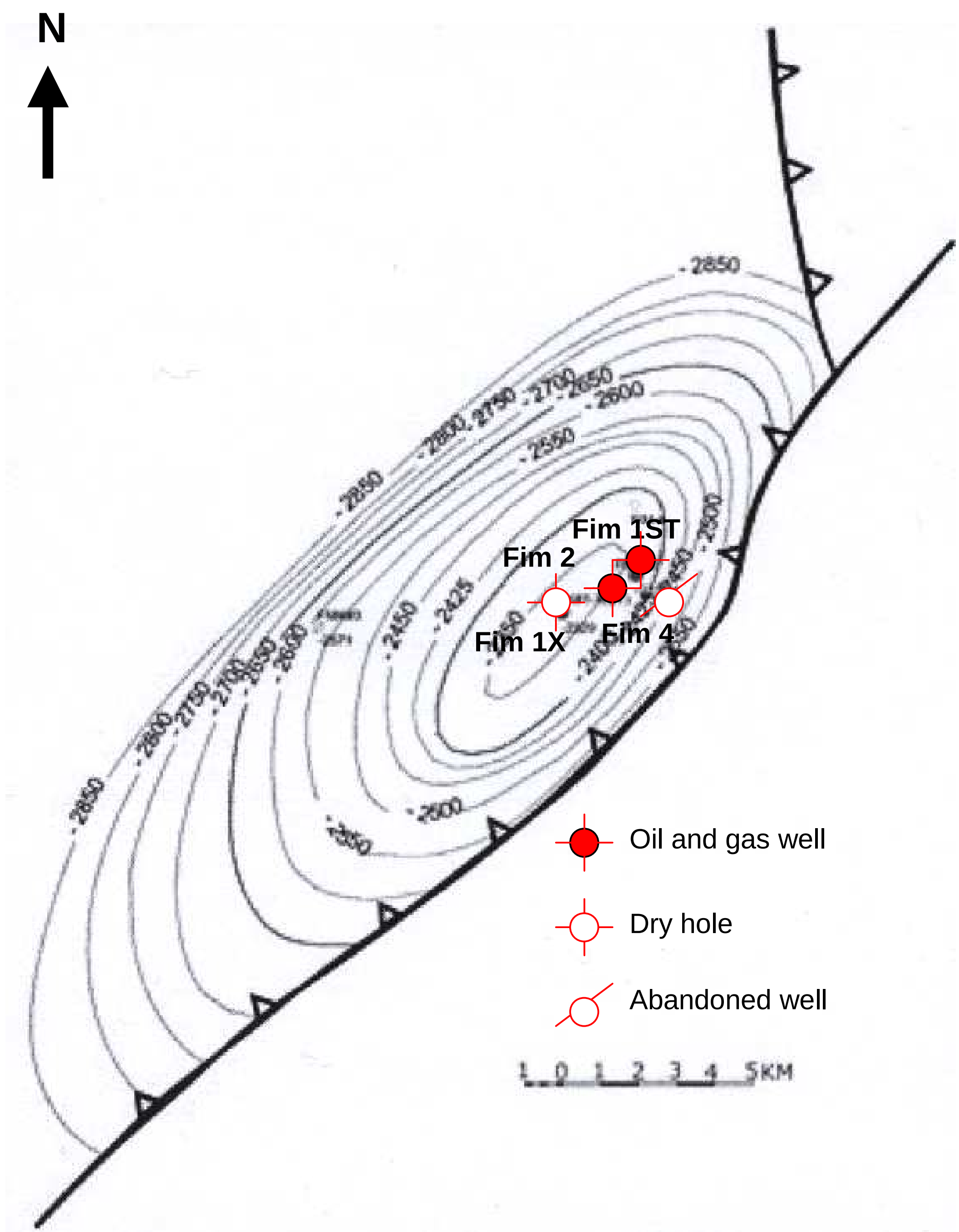

Figure 6. Structure contour map of Fim Kassar Oil Field (reproduced from OGDCL data)

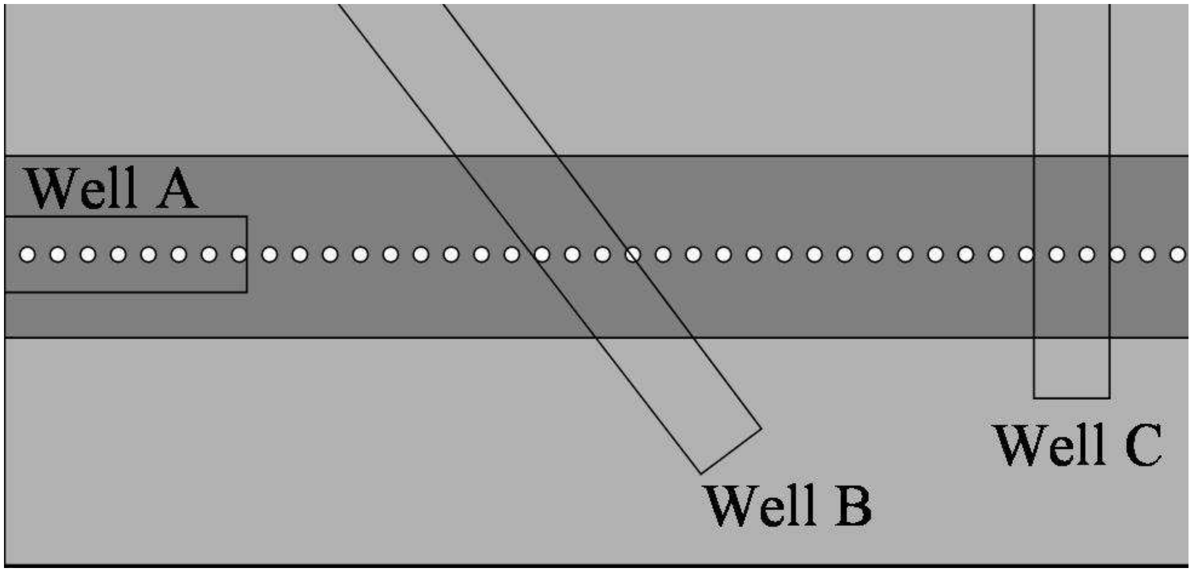

Figure 7. Diagram to illustrate the different number of microfossils recovered from a thin bed depending on the angular relationship of the bed to the well path. Darker layer is the horizon of interest. Well A path parallels the bed microfossils are common. When Well B path cuts the beds at 45^{o} spores are occasional. When Well C cuts the beds at a right angle spores are rare. (Modified from Shipp, 1999).

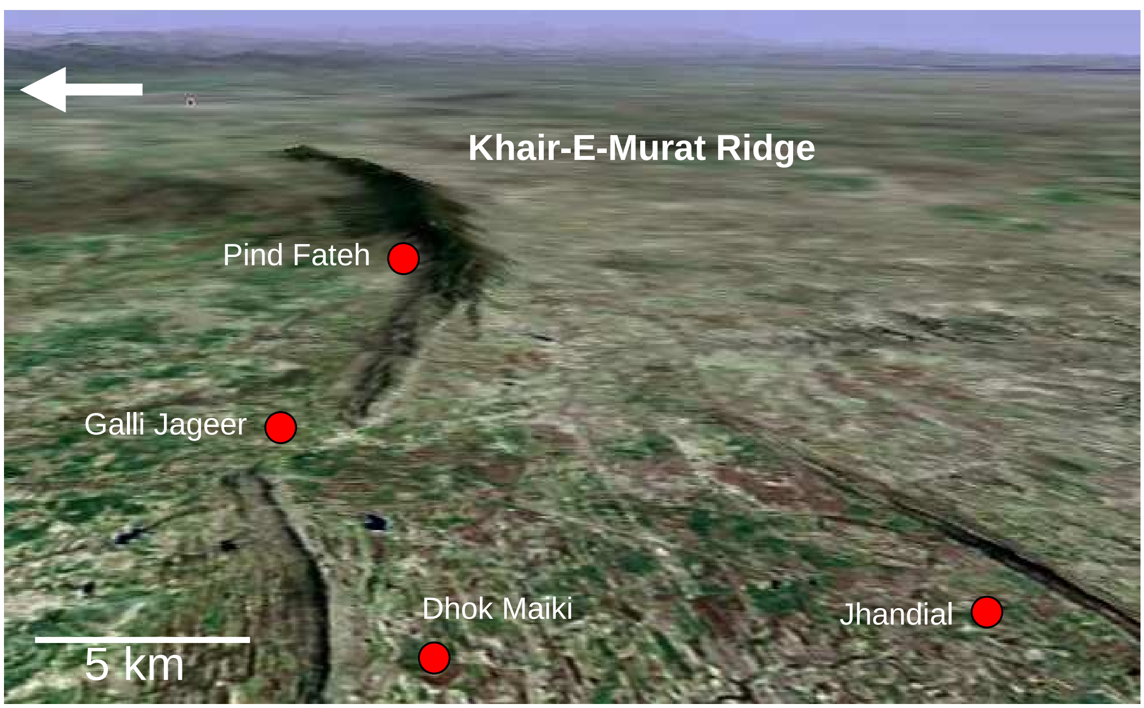

Figure 8. Map showing Khair-E-Murat Ridge

Figure 9. Khair-E-Murat outcrop at the top of Chorgali Pass

3) Tectonic History

About 60 million years ago the entire Indian-Subcontinent (an exotic terrane that contained parts of present day Pakistan, India and Nepal) was an island off the coast of Africa, very close to the locality of present day Madagascar (Powell, 1979). The island rested on the Indo-Australian plate. This plate moved at an unusually fast rate, about 15 centimeters per year in a northeast direction (Powell, 1979) . A vast sea known as the Tethys Sea that enveloped most of the globe at the time separated this island from the Asian mainland to the north (fig. 15). A large portion of the plate underlying this island was covered with oceanic crust. The subduction of this plate under the Eurasian plate gave rise to a volcanic island arc between the island and the Asian mainland. This island arc is known as the Kohistan Volcanic Arc, and its remains extend from Dobair in the Kohistan district to Chalt in the Karakoram Range (fig.12). As the island moved northwards its velocity decreased to about 2 centimeters per year (Powell, 1979). The Himalayan Orogeny began 48 million years ago when the island finally collided with the Asian mainland, sandwiching the rocks of the Kohistan Island Arc and marine sediments of the Tethys seaway. Crustal buckling of the Indian Shield in central Pakistan creates a ridge of basement rocks called the Kirana Hills. The Kirana Hills divide this region into two large basins, the Upper and Lower Indus basins.

4) Geological Setting

The Kohat-Potohar Basin covers a 36,000 km^2 area in northern Pakistan (Khan et al., 1986), and is bounded by the Margallah Range to the north, the Salt Range to the south, the Surghar Range to the west and the Jhelum Fault to the east (fig.5). The Margallah and Salt Ranges are escarpments associated with the Main Frontal Thrust and Main Boundary Thrust respectively (fig.13). The area between the Khair-E-Murat Ridge and Margallah Range is one of intense tectonic deformation is known as the North Potohar Deformation Zone (NPDZ). This entire basin lies within the Himalayan Fold Belt tectonic zone.

Sedimentation in the Kohat-Potohar Basin began in Cambrian times. These Cambrian formations consist of a thick evaporite succession which includes mainly halite along with minor gypsum and anhydrite. These deposits are notable in this study because these salts provide a decollement surface on which thin skinned faulting has developed. Topographical changes in the basement rock caused by normal faulting give rise to thrusts that propogate along the decollement and create hinterland dipping and foreland dipping duplexes that verge near Khair-E-Murat creating a triangle zone (fig. 14) (Jadoon et al., 1997). Both the Fim Kassar and Khair-E-Murat structures are a result of this deformation.

Figure 10. Map showing movement of Indian subcontinent thorough time (Powell, 1979)

Figure 11. Right: Plate boundary at Shaitan Pari, Indus Kohistan Left: Suture zone at Chalt, Hunza

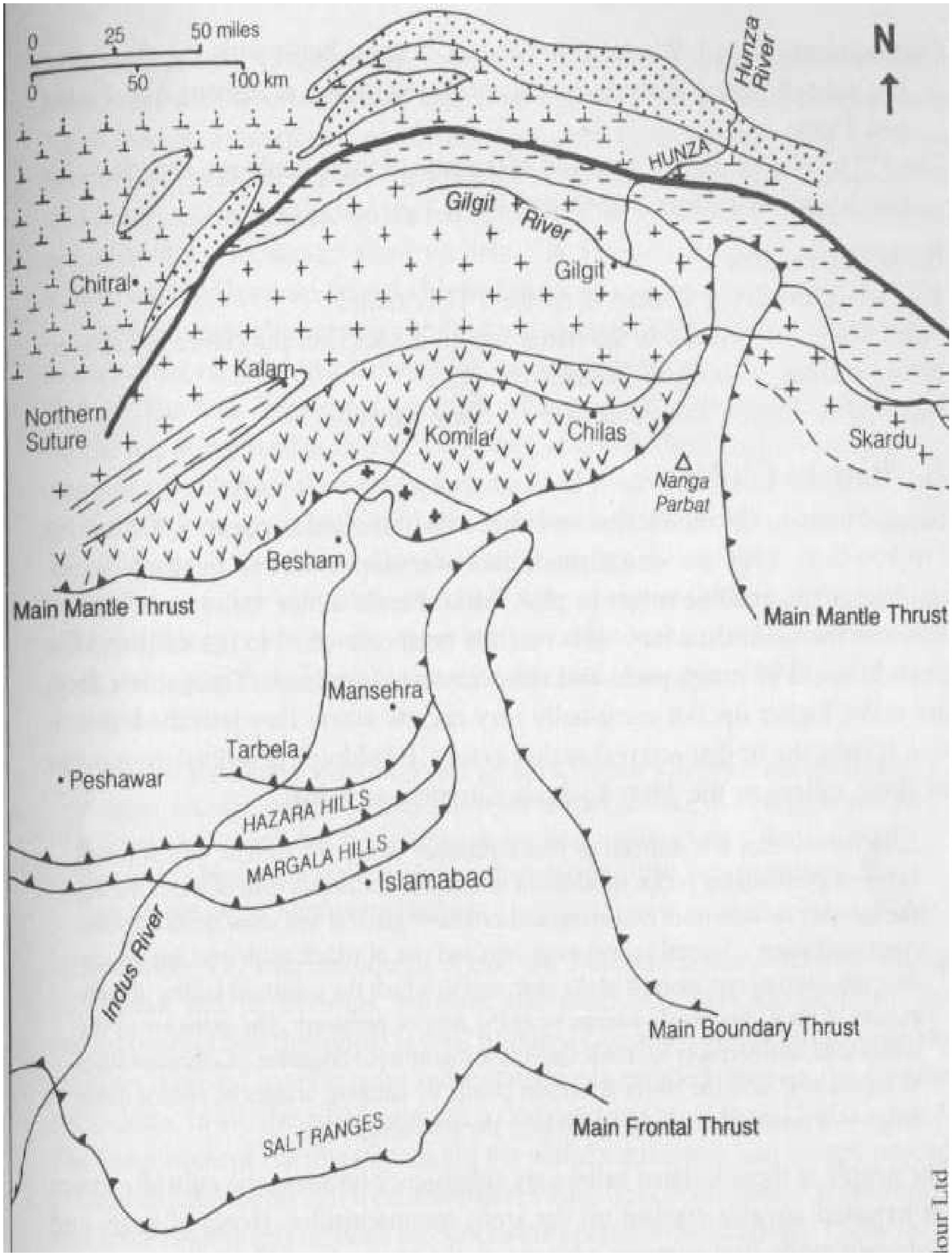

Figure 12. Tectonic map of northern Pakistan (modified from Shaw 1998)

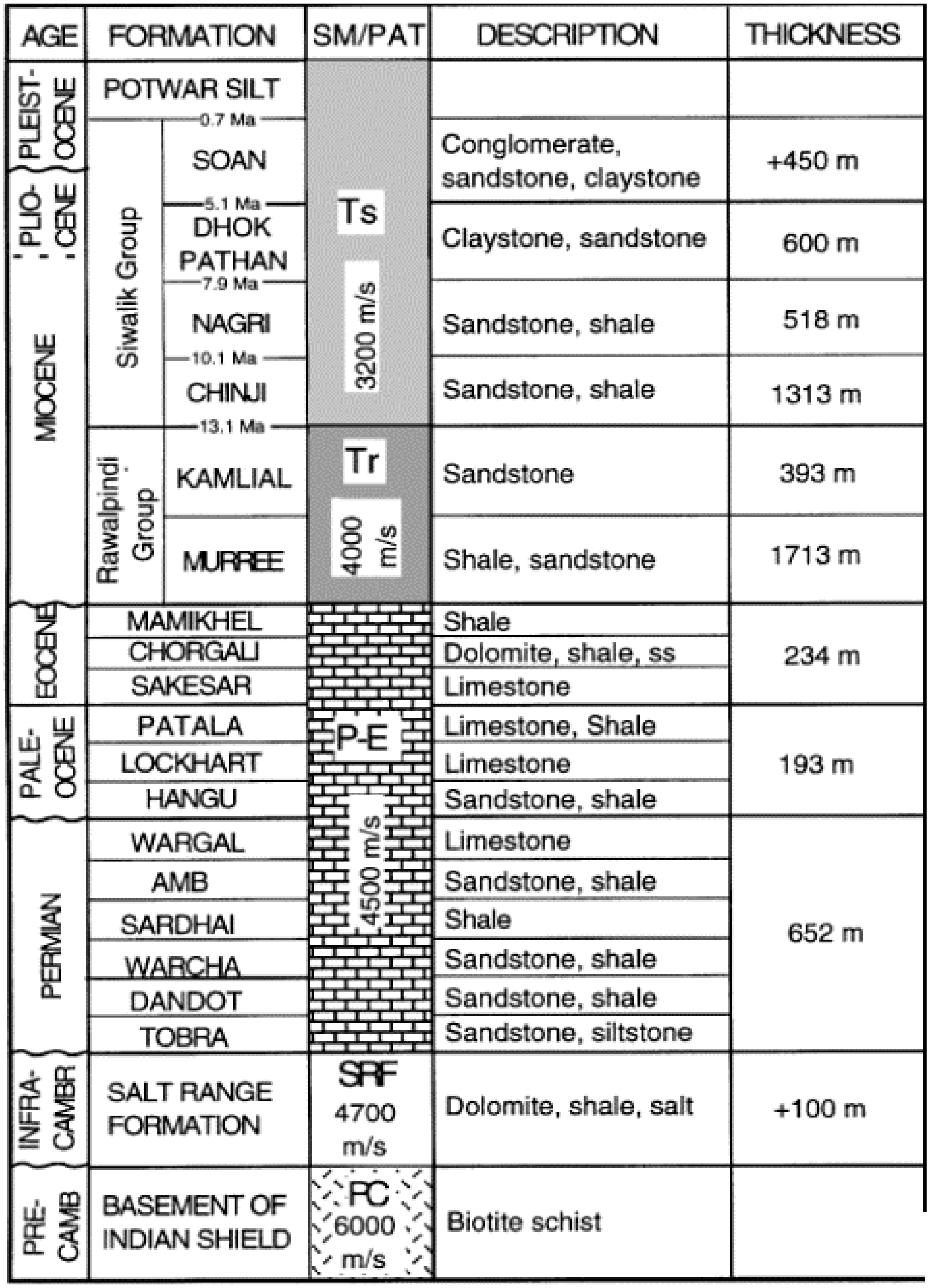

Figure 13. Stratigraphic section of rocks in Kohat-Potohar Basin (reproduced from Jadoon et al., 1997)

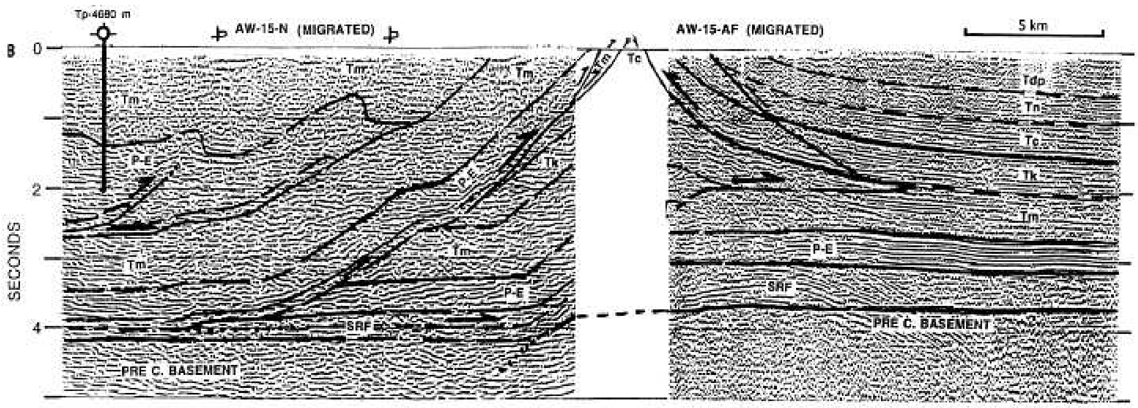

Figure 14. Triangle zone at Khair-E-Murat, seen on seismic (reproduced from Jadoon et al., 1997)

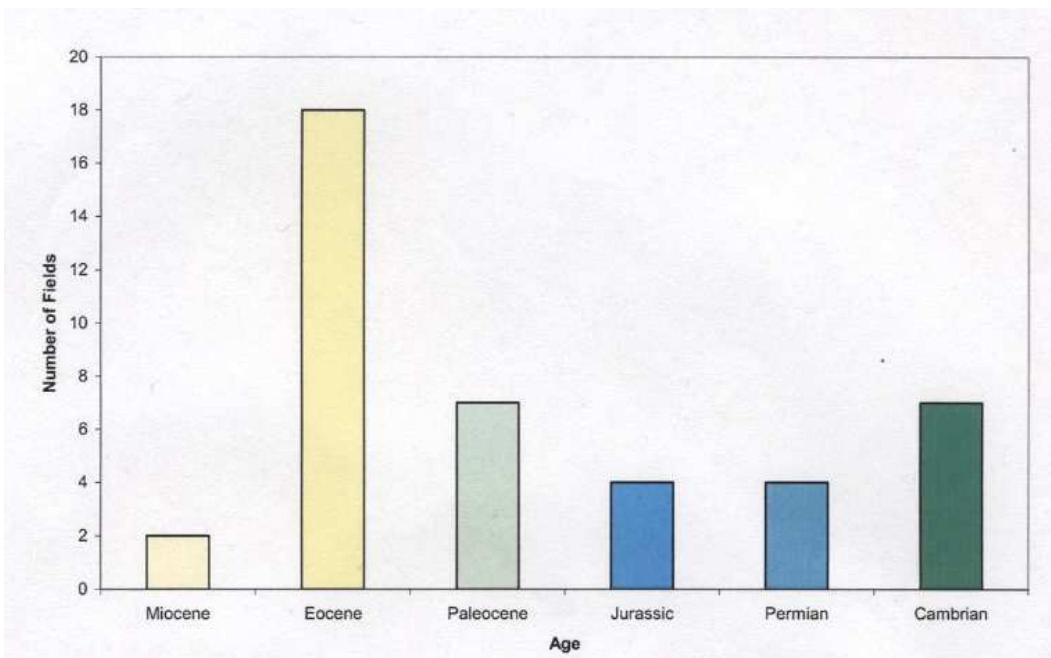

Figure 15. Graph showing distribution of petroleum reservoir ages in the Kohat-Potohar Basin (reproduced from Wandrey et al., 2004)

An unconformity separates Cambrian evaporites from Permian tillites and carbonates. Jurassic carbonates unconformably overly these Permian deposits. The end of the Jurassic is marked by another unconformity. Cretaceous strata are mainly represented by siliciclastics which grade into carbonates in the Tertiary.

Early Cenozoic carbonates were deposited in this basin along the margins of the Tethys Sea. During early Tertiary time vast carbonate platforms extended along the margins of this sea. The Indian subcontinent was at the Equator and paleoclimate was conducive to the proliferation of the carbonate factory.

As the Himalayan Orogeny continued, sediments brought to Tethyan shelves smothered the carbonate factory and these were replaced by a fluvio-deltaic system (Wandrey et al., 2004). A regional unconformity separates these carbonates from younger continental deposits called the Siwaliks.

The Kohat-Potohar Basin has produced 112 million barrels of oil. The reserves for the basin are estimated at 2.4 billion barrels (Khan et al., 1986), and over 70 percent of these are found in Eocene carbonate reservoirs (Wandrey et al., 2004) (fig. 15).

CHAPTER II

REVIEW OF LITERATURE

Very few studies have been published on the Fim Kassar Oil Field or the Paleogene carbonates of the Potohar Plateau. Prior to this thesis no work had been done on the sequence stratigraphy of these Paleogene strata.

The Chorgali Formation was first described by Pascoe (1920) and was described in detail by Jurgan and Abbas (1991). Jurgan and Abbas (1991) measured the Chorgali Formation at the type section and illustrated a stratigraphic section. This section has been lithocorrelated to the composite stratigraphic section created by transecting the Khair-E-Murat Ridge at Chorgali Pass and Galli Jageer Village. Therefore, samples collected and analyzed by Jurgan and Abbas (1991) are useful data that are incorporated into this study (fig. 32). A useful observation made by these workers is that the Chorgali Formation deposits represent a shoaling upwards cycle, which they interpreted as deposition during a regression.

Wells (1983) described the overlying Kuldana Formation in detail. The sedimentological descriptions provided by Wells (1983) were useful in creating a sequence stratigraphic model for this study.

Gingerich (2003) used benthic foraminifera to assign ages to the Kuldana and underlying Chorgali Formation. He then used these ages to correlate the Chorgali and Kuldana deposits with the Haq (1987) global eustacy chart and suggested lowstand conditions. Although this study suggests that the upper Chorgali Formation and the lower Kuldana were deposited during a relative fall in sea-level, the data is more suggestive of a Late Highstand Systems Tract.

The Chorgali and underlying Sakesar formations provide the reservoir for hydrocarbon accumulation at Fim Kassar Field. Production from these tight carbonates is from fractures. There have been several workers (Benchilla et al., 2002; Jadoon et al., 1997) who have investigated the causes, the types, orientation and timing of these fractures. Therefore, this study focuses only on the prediction of these fractures in the subsurface.

CHAPTER III

METHODOLOGY

This study is based on the integration of high resolution lithostratigraphic data from outcrop, wireline logs, seismic, well-cuttings and core collected during two field seasons in the Kohat-Potohar Basin of northern Pakistan.

1) Fieldwork

In 2003 a reconnaissance project was carried out in the Potohar Plateau area to locate good exposures of the Sakesar and Chorgali formations. The formations were identified in the field using the geological map of Pakistan prepared by Bakr and Jackson (1964). These formations are well exposed along the Salt Range and along thrust scarps on the Potohar Plateau. One of these fault scarps forms a ridge known as the Khair-E-Murat Ridge. This ridge trends from northeast to southwest for a length of about 50 kilometers, and juxtaposes Neogene fluvial sediments against Paleogene carbonates. 3 stratigraphic sections were measured and sampled (see fig. 4 for names and locations) along the Khair-E-Murat Ridge (fig. 9), Kuldana type-section, and Shahdara. The best exposure of the Chorgali Formation is located at the type section near Chorgali Pass, which transects the Khair-E-Murat Ridge (fig. 9, fig. 10). Beds were traced laterally and measured using a Jacob staff and brunton. Apparent dips were converted to true dips in beds that were not measured with a Jacob staff. Twenty two beds were measured on a centimeter-scale and field descriptions were noted (Appendix B). These beds are lithostratigraphic and can be easily distinguished from underlying and overlying strata in the field. Fracture patterns and orientations were also observed in the field. Ichnofossils were photographed in the field and samples were collected from each bed for microfossil analysis.

2) Sample Preparation

Samples for this study were collected in the field from the Khair-E-Murat Ridge, Shahdara and Kuldana. Although cuttings were available for study at the Hydcrocarbon Development Institute of Pakistan's core house in Islamabad, these cuttings had been disaggregated. The disaggregation process destroys large benthic foraminifera that are paleobathymmetry diagnostic. Because the identification of these large benthic foraminifera is contingent upon the ability to see them in axial sections under a light microscope, thin sections of all samples were prepared. Fissile or friable samples were first soaked in epoxy overnight before thin section preparation. All sections were cut to a thickness of 30 microns and then observed under a petrographic light under polarized light. Sampled were analyzed for the presence of benthic foraminiferal assemblages to determine paleobathymmetry and apply facies models. The presence of ostracods, pelecypods, dasycladacean algae, bryozoans, and echinoderms was also noted to create field-scale bioevents. Planktonic foraminifera in the sections are the only age-diagnostic taxa preserved in the samples. All samples were also analyzed for calcareous nannoplankton in the micropaleontology labs at the Oil and Gas Training Institute of Pakistan. However, all slides proved to be barren. This is attributed to poor circulation, high salinity and shallow water depth of the sediments. Calcareous supratidal shales were also analyzed for the presence of palynofossils. However the salinity and oxidative environments such as those of the Chorgali Formation are not conducive to the preservation of spores and pollen.

3) Creation of Sequence Stratigraphic Model

This model is based on a mixed carbonate-clastic-evaporite system. Interpretations are based on work done by Handford and Loucks (1993), Evans (1995), Alsharhan and Kendall (2002), Sarg (1988. 1999), Clari et al., (1995) and Schlager (2005). Identification of stacking patterns and key surfaces allows the delineation of systems tracts. Outcrop data is correlated with subsurface data using stacking patterns of strata on wireline logs as well paleontological data. Wireline logs from the Fim 1-X well were tied to the outcrop sequence stratigraphic model using a benthic foraminiferal assemblage. This assemblage is the *Nummulites-Orbitolina* Assemblage which represents the fore bank facies. Key surfaces were identified based on paleobathymmetry data from benthic foraminifera, and ichnofacies.

Although seismic data was available for Fim Kassar, seismic resolution is very low and does not allow sequence analysis. These lines also lacked synthetic seismics and could not be correlated with well or outcrop data. Wireline logs used for this study include Gamma Ray, Spontaneous Potential, Resistivity and Sonic logs.

CHAPTER IV

FINDINGS

1) Sedimentology of the Nammal-Sakesar-Chorgali-Kuldana Sequence

During Middle Eocene times the landmass of India was very close to the Tibetan mainland. A gulf that ran northeast-southwest connected the Tethys Sea between India and Asia with the global ocean (fig. 15). Paleolatitude of the Kohat-Potohar Basin was approximated at 30 degrees north (fig. 16) based on a Kuwait-type sabkha deposits and paleogeographic maps based on magnetic declination of volcanics (Powell, 1979). Based upon coastal waters in the recent Persian Gulf, conditions were probably characterized by high temperatures (20-37^0 C) and salinities (50-75%) (Evans, 1995).

Although the effective reservoir at Fim Kassar Oil Field lies within the Sakesar and Chorgali formations, the Nammal and Kuldana formations are also worth mentioning in this study because the four formations (Nammal, Sakesar, Chorgali and Kuldana) are part of the same depositional sequence in the sense of Vail et al (1977). The Nammal-Sakesar-Chorgali-Kuldana Sequence (NSCKS) was deposited on a ramp which fits the classic models for Tertiary low-latitude carbonate ramps suggested by Buxton and Pedley (1989). These are characterized by slope gradients of less than 1 degree and extend tens to hundreds of kilometers along strike (Buxton & Pedley, 1989). Replete biofacies that include large benthic foraminifera, rhodolithic algae, coralgal patch-reef and gastropod dominated successions characterize these ramps. The sedimentology of samples studied in outcrop and core suggest a restricted gulf with poor circulation. An arid climate also contributed to saline/hypersaline conditions in the Kohat-Potohar Basin. Gastropod communities that are common in many Tethyan ramps of Tertiary age are thus absent in the NSCKS. Consequently cyanobacterial mats are abundant and well preserved (fig. 17). Sedimentology of these formations is discussed below.

A) Nammal Formation

The Nammal Formation gets its name from the Nammal Gorge in the western Salt Range (fig. 4). It is 34 to 130 meters thick and is Early Eocene in age (Bender & Raza, 1995). The lower sections of the Nammal Formation are shale prone, whereas higher up in section limestones are more prominent. Occurrence of the dinoflagellate *Homotryblium tenuispinosum* and nannoplankton such as *Sphenolithus conspicuous* show that the base of Nammal Formation lies in Nannoplankton Zone (NP) 11, middle part in NP 12 and upper part in NP 13 (Bybell & Trail, 1993). The planktonic foraminifera from the Nammal Formation are correlated to the *Morozovella subbotinae*, *M. formosa* and *M. aragonensis* zones and this confirms an early Eocene age derived from dinoflagellates and nannoplankton (Weib, 1988). Microfossil assemblages also show a transition from outer shelf to middle and inner shelf facies (Bybell & Trail, 1993; Weib, 1988).

Figure 16. Paleogeographic map of study area during the Middle Eocene (reproduced from Wandrey et al., 2004)

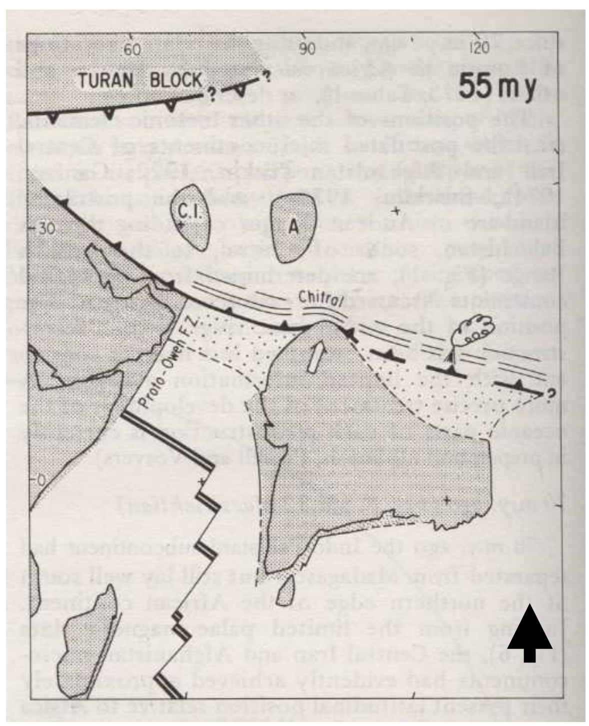

Figure 17. Paleolatitude of Indian Subcontinent during the Middle Eocene (reproduced from Powell, 1979)

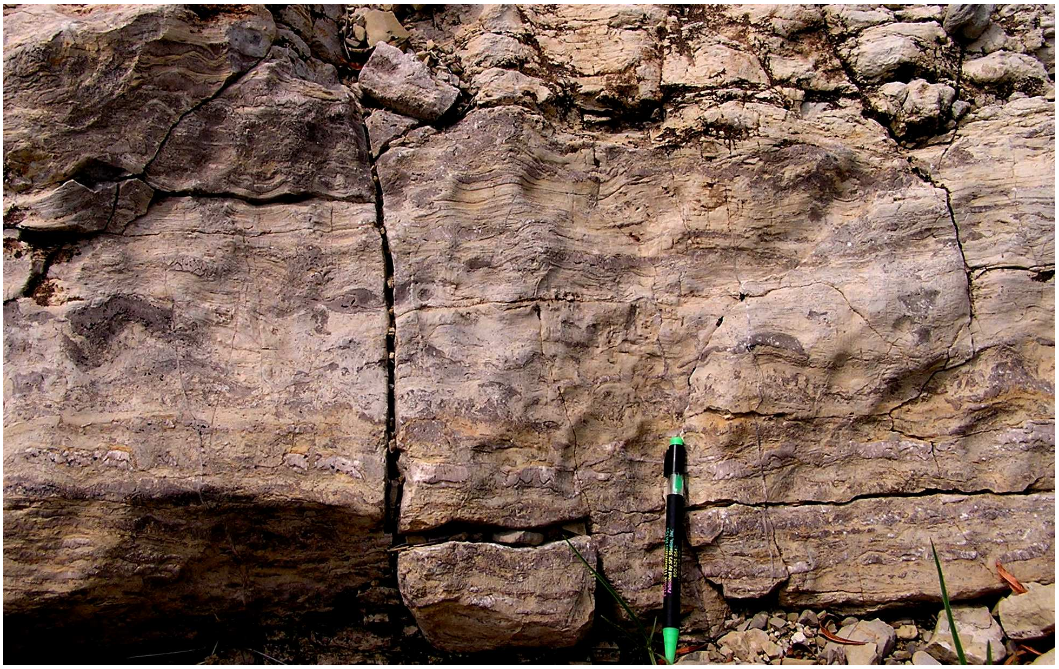

Figure 18. Polygonal cyanobacterial mat from bed 13 at Chorgali Pass, Chorgali Formation Khair-E-Murat Ridge.

Figure 19. Arrows point towards stylolites in a limestone bed of the Sakesar Formation, Chorgali Pass, Khair-E-Murat Ridge.

B) Sakesar Formation

The Sakesar Formation is named after Sakesar Village in the Salt Range where it is well exposed. It is 70 to 300 meters thick and is Early-Middle Eocene in age (Bender & Raza, 1995). The lower Sakesar at Nammal Gorge has yielded nannoplankton characteristic of Nannoplankton Zones 13, 14, and 15 (Bybell & Trail, 1993) of Martini (1971). The formation consists of massive packstones, nummulitic packstones and wackestones with minor shale intercalations. These limestones are grey in color and show stylolites (fig. 18). Porosity in the Sakesar Formation is very low and fractures provide the only mode of permeability. The Sakesar Formation is incredibly rich in benthic foraminifera and also contains fossil echinoids, ostracods, and pelecypods. This allows the application of paleoecological models for Tethyan benthic foraminifera proposed by Gilham and Bristow (1998), Luterbracher (1998), Arni (1965) and Bignot (1972) to the Sakesar depositional system. Based on data from outcrop and core, facies interpretations were developed for the Sakesar Formation. From a more basinal setting and progressing towards the land the facies are:

1. Fore Bank Facies

   These are observed in the core from Fim-2 at a depth of 3012 meters. This interval is characterized by a dark-brown wackestone showing an orbitolinid-nummulitid assemblage (fig 19).

2. Bank Facies

   These were observed in outcrop at Chorgali Pass. They include nummulitic-packstones that show very little transportation of nummulites tests and a distinct linear accumulation. These accumulations are interpreted as concentrations that were

Figure 20. Core interval 3012 meters from Fim-2 showing Nummulitid-Orbitolinid Assemblage.

deposited in nummulites banks (Penney et al., 2005). Nummulites banks are populations of nummulites that grazed on topographic highs and are common in Tertiary Tethyan ramp deposits. They filled the same niche that platform-reefs filled elsewhere (Buxton & Pedley, 1985).

3. Back Bank Facies

The Back Bank is the area next to a nummulites bank in a landward direction. These were observed in the outcrop at Chorgali Pass and include nummulitic packstone accumulations that are interpreted as para-autochtonous wave/current concentrations that were deposited in back-banks (Penney et al., 2005).

4. Shelf Lagoon Facies

These were observed at Chorgali Pass and include wackestones with a Miliolid-Rotalid-Textularinid Assemblage.

C) Chorgali Formation

The Chorgali Formation is named after Chorgali Pass that transects the Khair-E-Murat Ridge near the village of Pind Fateh. The formation consists of massive dolostones,

Figure 21. Sample from Chorgali Formation showing *Glossifungites* (image has been digitally enhanced to show ichnofossils clearly)

Figure 22. Nodular anhydrite in bed 15, Chorgali Formation, Khair-E-Murat Ridge

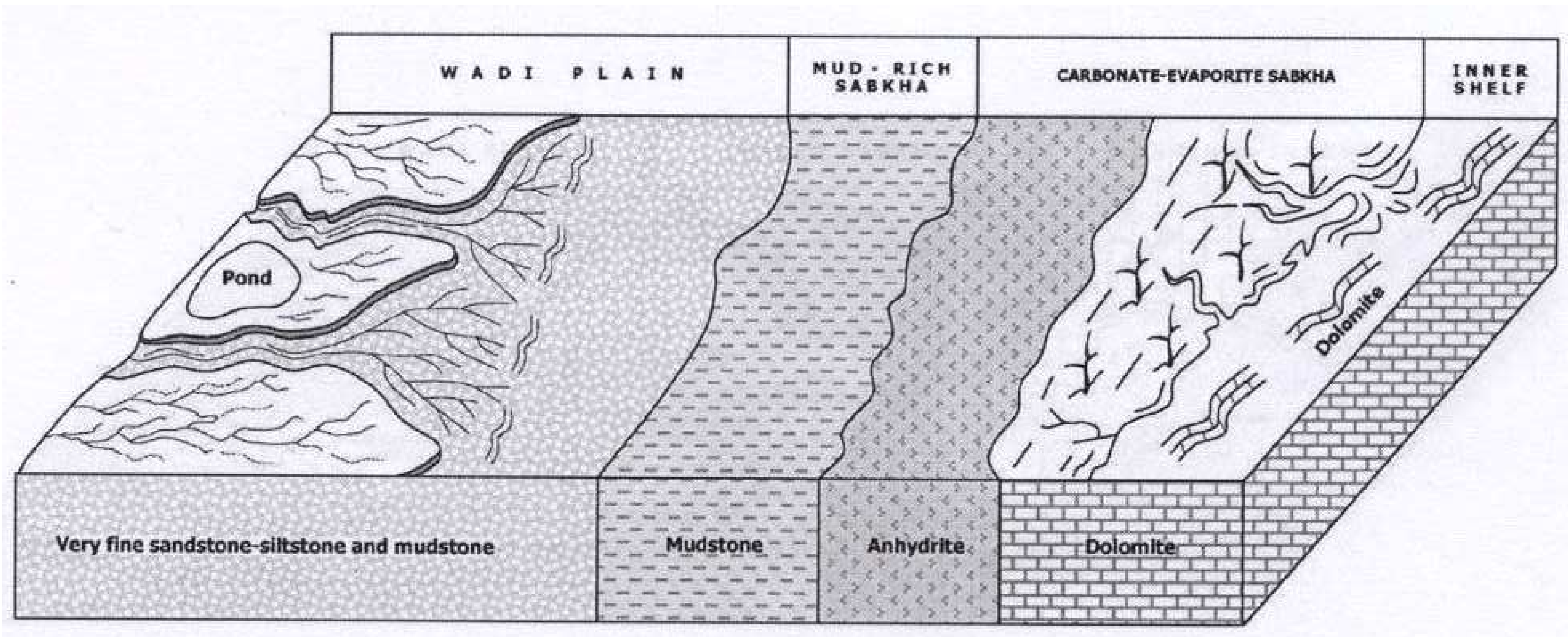

Figure 23. Mud-rich Sabkha model from the Permian Red Cave Formation of Texas (Handford and Fredericks,)

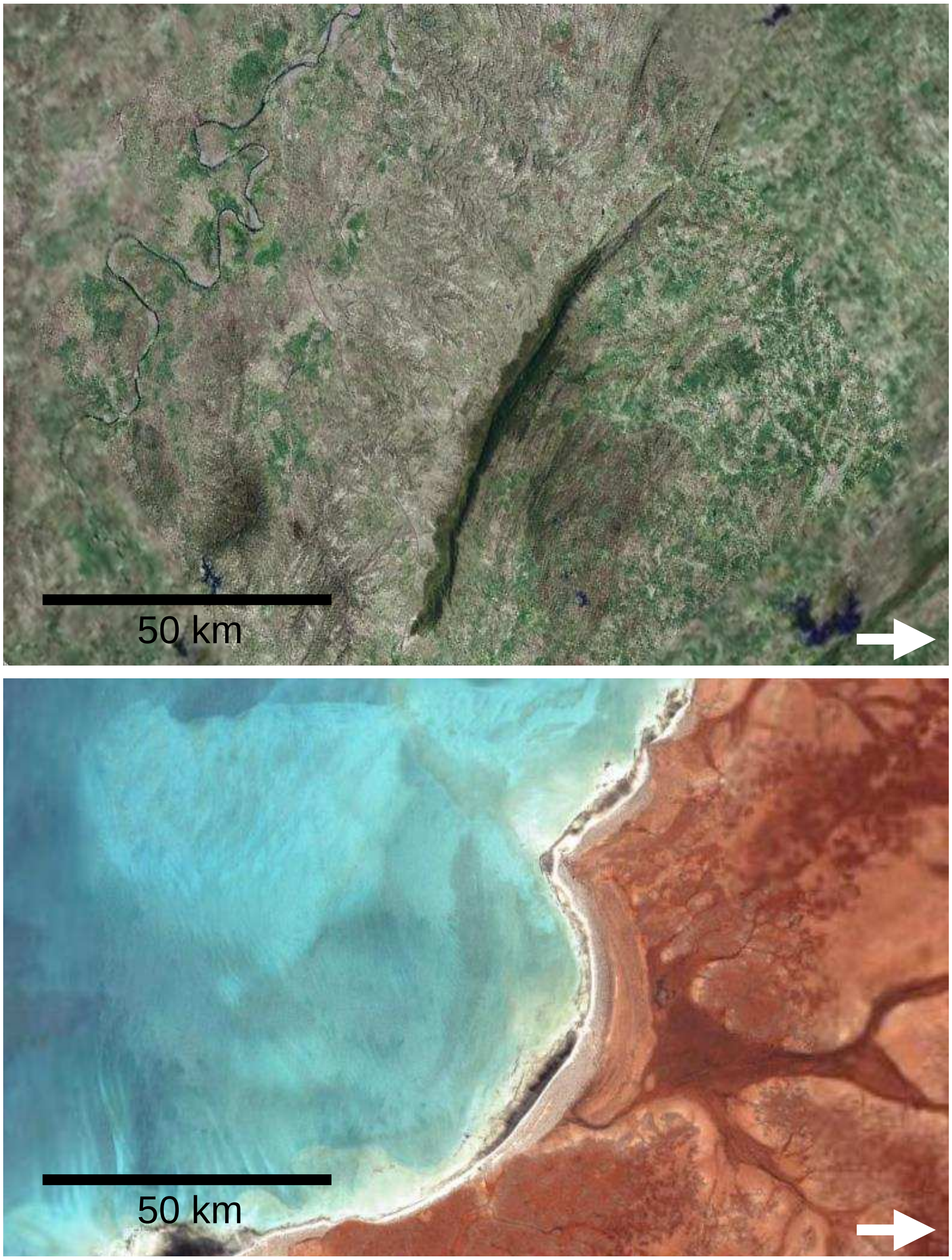

Figure 24. Recent (above) and paleogeographic image (below) of field area based on modern Shark Bay sabkhat.

very fissile varicolored shales, marls, nodular and chickenwire anndydrite, and evaporite collapse breccias . It is 80-90 meters thick (Jurgan & Abbas, 1991) and is early Middle Eocene in age (Gingerich, 2003). There is very little primary porosity and appears as vugs in certain layers (fig. 30). Dolomitization has created porosities up to 25 percent (Malik et al., 1988).

The lithologies of the Chorgali Formation represent a restricted lagoon setting that graded into a mud-rich sabkha and wadi plain (fig. 22). The best modern analog to understand Chorgali deposition would be the Persian Gulf Sabkhat (plural for sabkha).

Sabkhat are found worldwide in semi-arid to arid regions and require certain hydrologic preconditions (Barth & Boer, 2002). These conditions are best developed along the Arabian Peninsula. The term *Sabkha* means 'salt-crusted desert', and this term is used in geology to describe extensive, barren, salt-encrusted and periodically flooded coastal flats as well as inland salt flats. A sabkha is further broken down into a coastal sabkha, inland sabkha and interdune sabkha (Warren, 1991). The three main processes controlling sabkha formation are a) marine coastal b) fluvio-lacustrine and c) aeolian. The Chorgali sabkha appears to be a periodically flooded sabkha. These are flooded on a regular basis, either by high tides or by precipitation in the winter (Barth & Boer, 2002). Storms also inundate the sabkha with lagoonal waters leaving a veneer of marine sediments (Evans, 1995).

Sabkhat throughout the Middle East were analyzed for their similarities to the Chorgali sabkha. Although the sabkha deposits in the Chorgali Formation resemble those of sabkhat in Kuwait, a major component of these sabkhat that is lacking in Chorgali deposits is eolian sands. Typical lithofacies for sabkhat in the Middle East going from basin towards land include a) Lagoonal facies b) Tidal bar or beach ridge facies c) Intertidal cyanobacterial mats d) Supratidal sabkha complex e) Eolian Wadi deposits. Although the lithofacies in the Chorgali Formation match these until the sabkha complex, there are no eolian deposits (Alsharhan & Kendall, 2003). These eolian deposits in the Persian Gulf mainly consist of eolianites and quart rich sandstones. At Chorgali these quartz-rich sand and eolianites are lacking. The absence of eolianites is attributed to the lack of ooids in subtidal deposits. This may be attributed to a lack of wave energy especially if the lagoon was restricted by nummulites banks.

In Shark Bay, Australia there are vast coastal sabkhat and grade into a vast dry low relief plain known as a wadi plain. Ephemeral streams bring in terrigeneous influx of clay and silt sized sediments and create a mud-rich sabkha. The only record of such a sabkha being preserved prior to this study is the Permian Red Cave Formation from the Texas Panhandle (Handford and Fredericks 1980). The facies of the Red Cave Formation (when moving form basin towards land) include a) inner shelf carbonate system b) Sabkha (both continental and coastal) c) Wadi plain system. This system is more mud-rich and is characterized by dolomitic mudstones and pellet wackestones (Handford and Fredericks 1980). Like the Chorgali Formation, gastropods are rare, which allowed the proliferation of cyanobacterial mats. Most importantly the supratidal wadi plain of the Red Cave formation is characterized by red to green mudstones very similar to those of the Chorgali Formation.

Based on this model of mud-rich sabkhat from the Permian of Texas, recent sabkhat of Shark Bay, Australia, and the Persian Gulf, the following interpretation is given for facies preserved in the Chorgali Formation.

1. Subtidal inner lagoon facies

   These were observed in outcrop at Chorgali Pass. Massive grey dolostones inter-bedded with bluish-grey marls represent this facies. Benthic foraminifera mainly include miliolids, but textulariinids and soritids are also present.

2. Intertidal facies

   These include cyanobacterial mats. Kendall et al (2002) have studied cyanobacterial mats in the Persian Gulf and suggest a model that consists of three distinct cyanobacterial mats that can be used to differentiate lower, middle and upper inter-tidal deposits (fig 26, fig 27) . These include the a) cinder zone b) polygonal zone and c) crinkle zone.

   The cinder zone contains lagoonal sands/muds with carbonate hardgrounds. The most distinctive feature of this zone is a layer of peat. This layer is part of bed 13 measured at Chorgali Pass (fig 28). The polygonal zone is characterized by polygonal dessication cracks and is also well preserved in bed 13 (fig 17). The Crinkle zone is characterized by large gypsum crystals and crinkly cyanobacterial mats. This has low preservation potential and is missing from the Chorgali section.

3. Supratidal mud-rich sabkha

Kendall et al (2002) subdivides the supra-tidal sabkha into a) Lower supratidal salt flats b) Middle supratidal salt flats c) Upper supratidal salt flats based upon the occurrence of gypsum, halite, anhydrite and dolomite.

The Lower and Middle supratidal flat, which are characterized mainly by halite, chickenwire annhydrite and gypsum mush, are absent from the sections recorded at Chorgali Pass. The Upper supratidal flat is represented by dolomite that grades into nodular anhydrite. This is seen in bed 15 at Chorgali Pass.

D) The Kuldana Formation

The Kuldana Formation overlies the Chorgali Formation and is Middle Eocene in age. It is named after the village of Kuldana (fig 24) in the Lesser Himalayas and is 20-120 meters in thickness (Gingerich, 2003). The formation consists of 95 percent red mud and 5 percent channel sands (Wells, 1983). The lithologies of the Kuldana are interpreted as a Wadi plain with small ephemeral streams. The best modern analog for this setting is Shark Bay, Australia (fig 23). The Kuldana Formation has produced some of the most spectacular "whale" fossils. Fossils include *Diacodexis pakistanensis*, *Pakicetus inachus* and *Ambulocetus natans*.

Figure 25. Outcrop of Kuldana redbeds at the type section near Kuldana Village.

Figure 26. Fossiliferous limestone samples from Kuldana type locality.

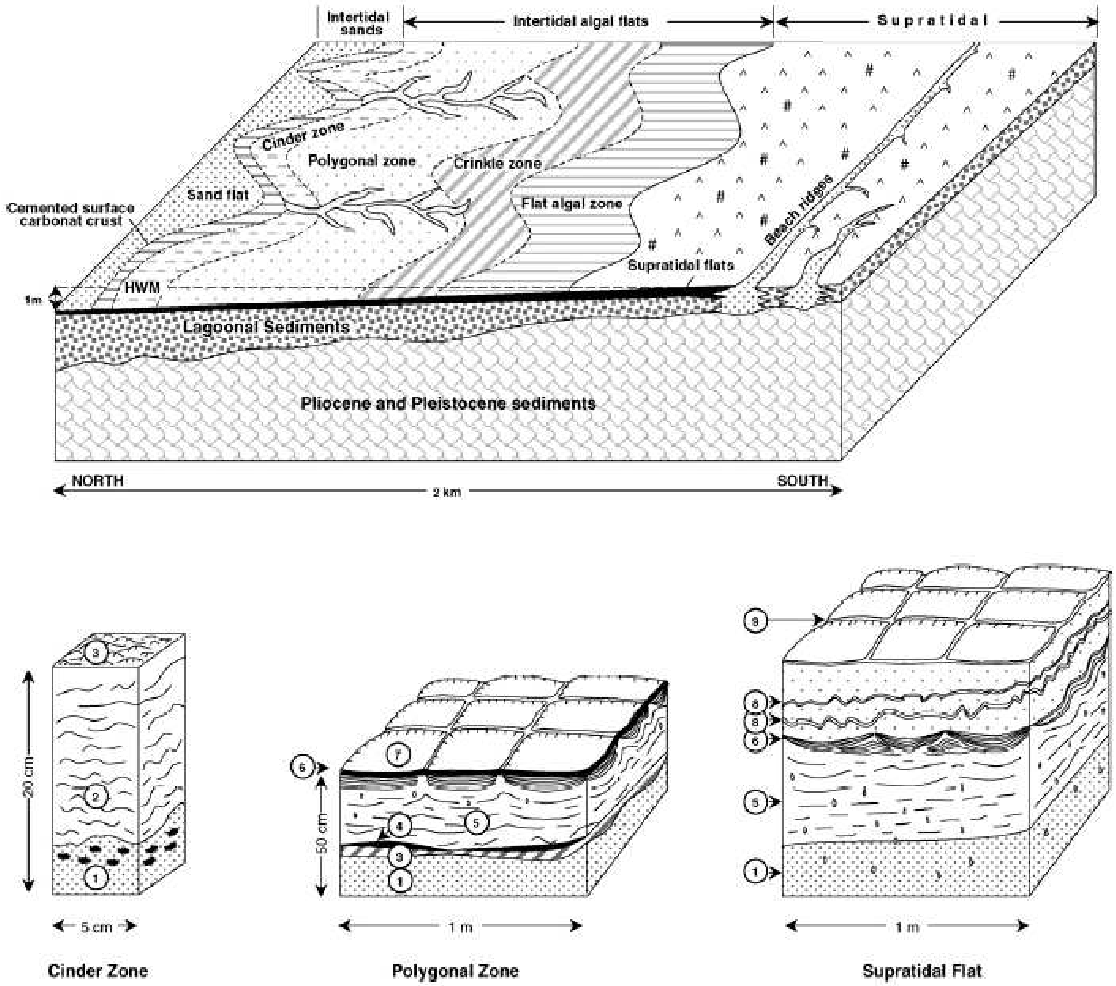

Figure 27. Cyanobacterial mat types from the modern sabkhat of the United Arab Emirates (Alsharhan & Kendall, 2002)

Figure 28. Polygonal (above) and crinkle (below) cyanobacterial mats in the modern Persian Gulf Sabkhat at Khor-Al-Bazam, United Arab Emirates (reproduced from Alsharhan & Kendall, 2002).

Figure 29. Cyanobacterial mats of the cinder zone of bed 13 Chorgali Pass. Grey bands represent dolomite, and yellow represents aragonite.

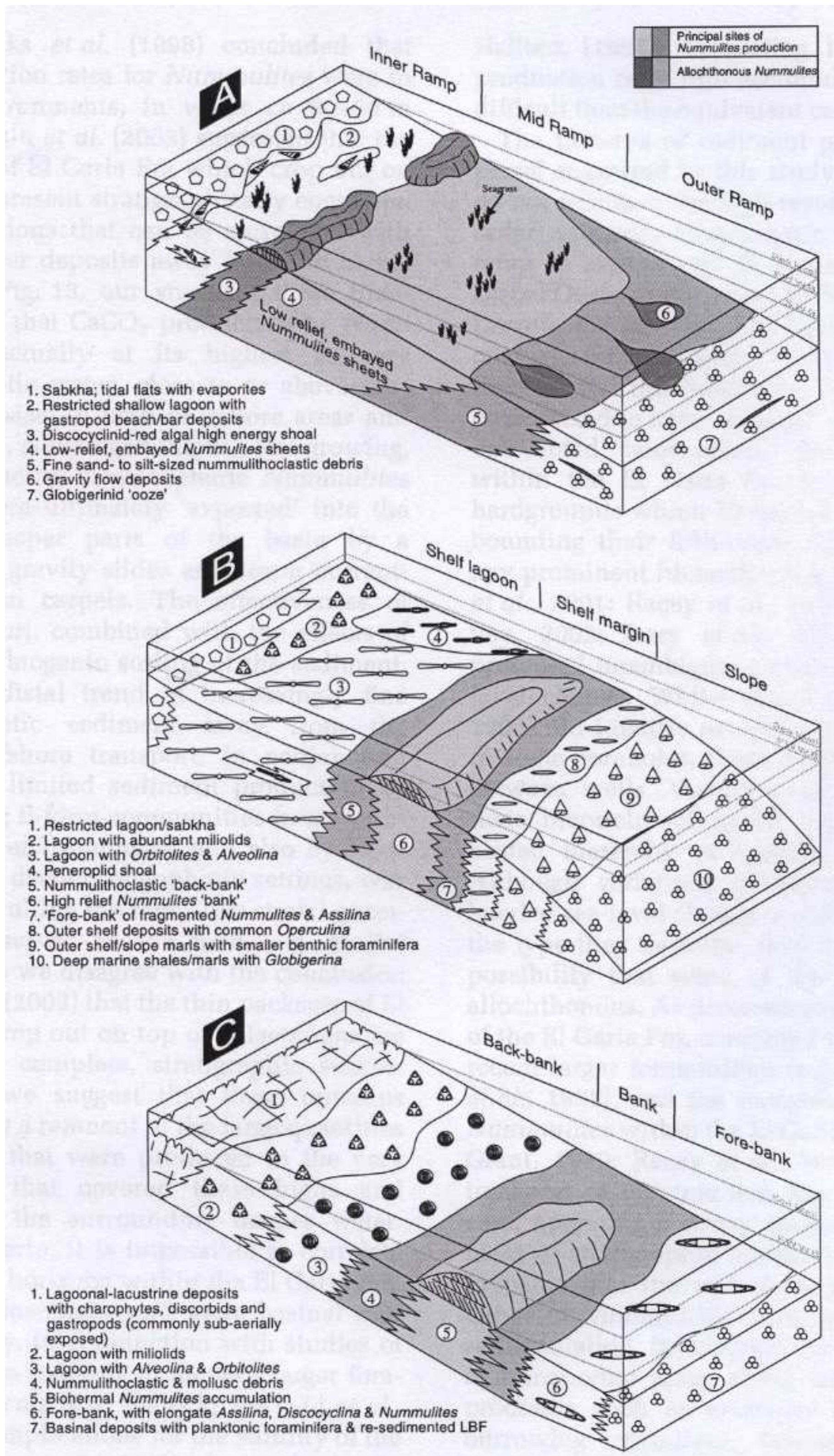

Figure 30. Models of benthic foraminiferal facies. A) Gilham & Bristow, 1998 B) Arni, 1965 C) Bignot, 1972.

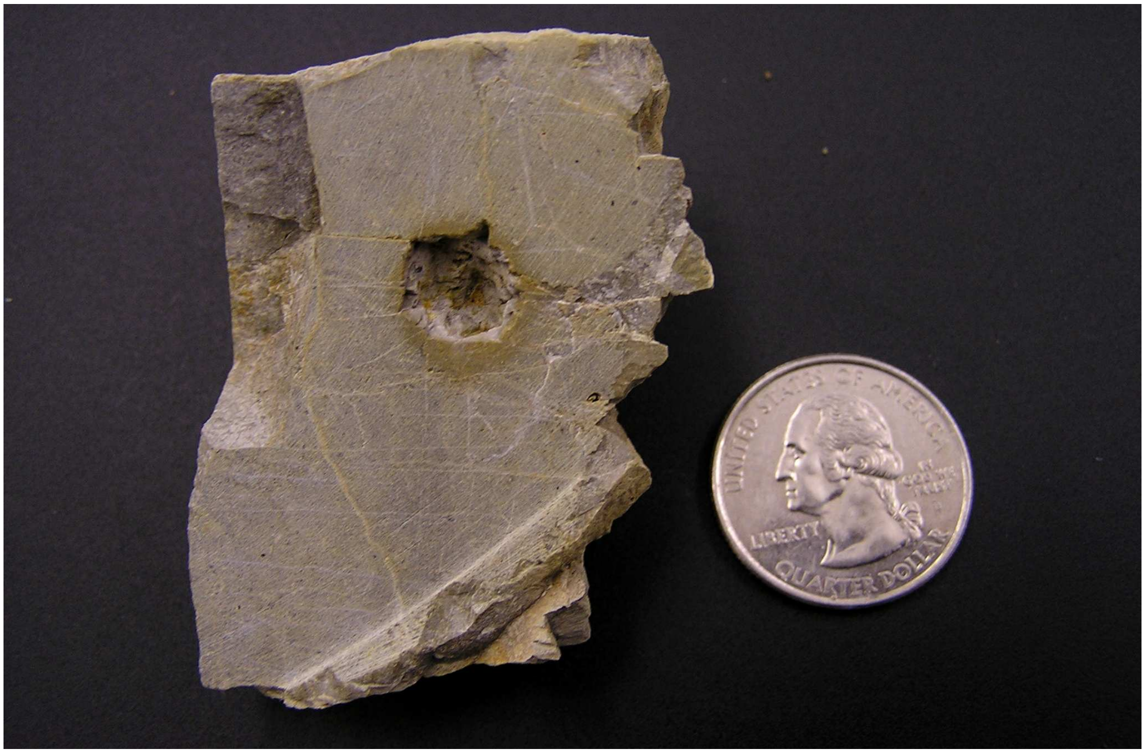

Figure 31. Vug in bed 9 of Chorgali Pass, Chorgali Formation, Khair-E-Murat Ridge

Figure 32. Channel conglomerate at Galli Jageer Village. Naveed and Aslam provide scale.

The Kuldana Formation is important in the present study for two reasons. First, it supports the mud-rich sabkha model proposed here for the Chorgali Formation. Second, the mudstones of the Kuldana Formation provide a good seal for hydrocarbon entrapment in the underlying Chorgali Formation.

2) Sequence Stratigraphic Modeling

A sequence stratigraphic model is presented here to predict the occurrence of fracture prone beds which form payzones within the dolostones of the Chorgali Formation. Because the effective reservoir at Fim Kassar Oil Field only produces from Sakesar and Chorgali Formations, this model focuses on the recognition of key surfaces, stacking patterns and systems tracts for these formations only. This model is illustrated in Figure 33.

Jurgan and Abbas (1991) interpreted the Chorgali Formation as being deposited during a “general regression.” Gingerich (2003) used benthic foraminifera from the Chorgali Formation to date these carbonates and then correlated them with the Haq et al (1987) global eustacy chart. By correlating the Haq (1987) global eustacy chart with ages derived from benthic foraminifera he established that the Chorgali and overlying Kuldana formations were deposited during a global lowstand (Gingerich, 2003).

This study shows that the upper part of the Chorgali and the overlying Kuldana were indeed deposited during a relative drop in sea-level. But these sediments are believed to be part of a late (falling stage) Highstand Systems Tract and not a Lowstand Systems Tract as suggested by Gingerich (2003).

A) Identification of sequence boundaries

Two sequence boundaries are recognized in the Eocene strata of the Kohat-Potohar Basin. These are discussed below.

Sequence Boundary 1

This separates the Late Paleocene Patala Formation from the overlying Early Eocene Nammal Formation. This boundary is recognized on the basis of paleontological data.

Haq (1971) sampled the Patala Formation at Nammal Gorge and suggested that the formation contained *Discoaster multiradiatus* Zone of Hay et al (1967), making it equivalent to NP 9. The presence of the dinoflagellate *Apectodinium homomorphum* also provides a Late Paleocene age for the Patala Formation (Edwards, 1993). Frederikson et al (1993) used spores and pollen and also established a similar age.

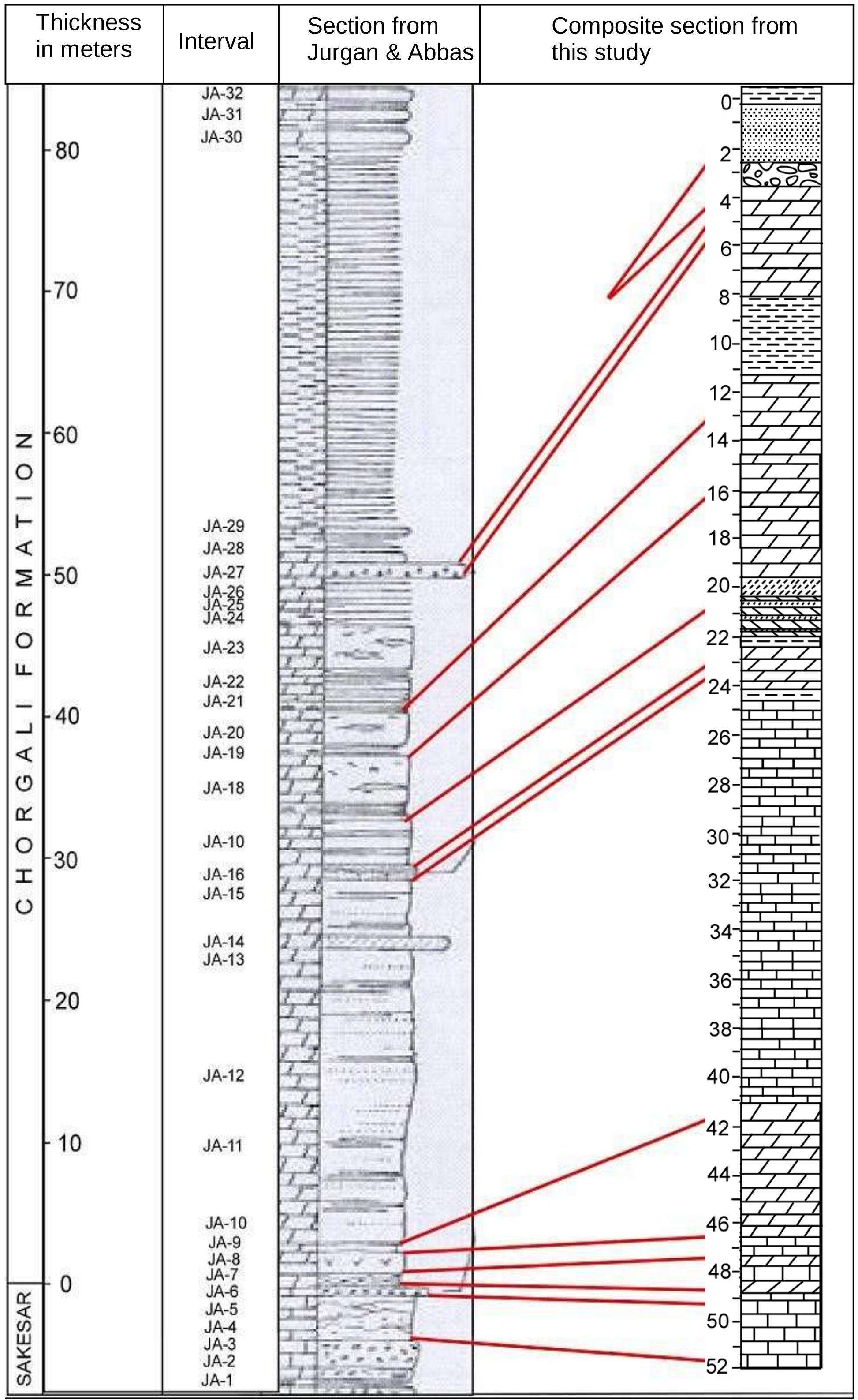

Figure 33. Lithocorrelation between composite stratigraphic section measured for this study and the section measured by Jurgan and Abbas (1991)

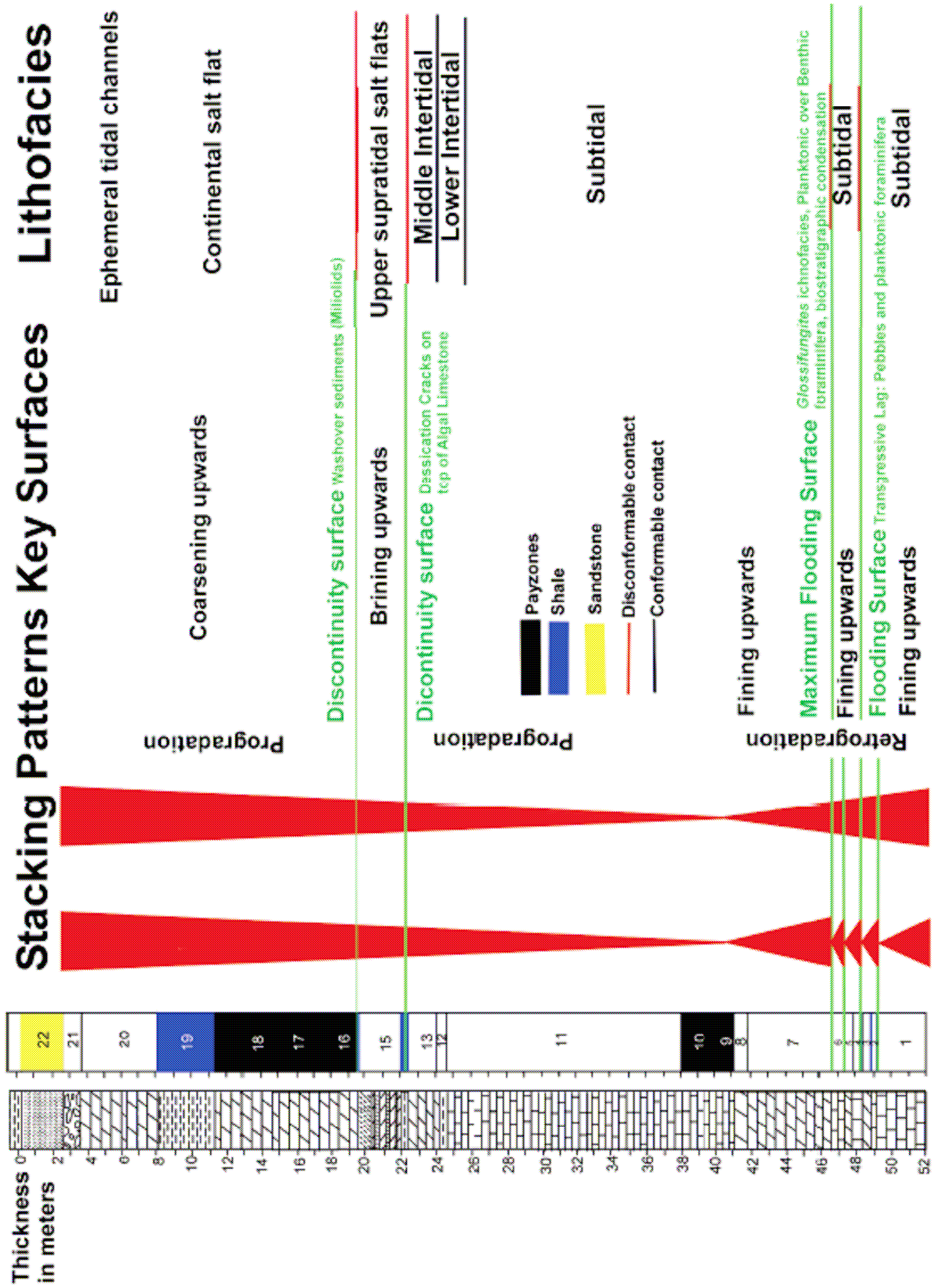

Figure 34. Sequence stratigraphic model showing the Sakesar-Chorgali reservoir

the overlying Nammal has also been dated using calcareous nannoplankton, dinoflagellates and planktonic foraminifera. On the basis of these fossils the Nammal Formation is assigned an Early Eocene age. The absence of NP Zone 10 suggests a significant hiatus at the Patala-Nammal boundary (Bybell & Trail, 1993). The sequence boundary is dated between 54 and 52 ma and thus the hiatus is about 2 million years.

There is also an important bioevent at the sequence boundary. The boundary is marked by the sudden disappearance of all large benthic foraminifera that are found in the Patala Formation (Weib, 1988).

Sequence Boundary 2

This boundary separates the Middle Eocene tilted strata of the Kuldana Formation from the overlying fluvial mudstones and sandstones of the Oligocene-Miocene Rawalpindi Group. The boundary is marked by an angular unconformity which appears as toplap on seismic lines. Unfortunately continental deposits of the Rawalpindi Group contain no microfossils that can provide reliable dates. The Rawalpindi Group does contain rare crocodilian fossils and fossil suids such as *Anthrachotherium lahirii* which are found in Late Oligocene strata elsewhere. This boundary dated at approximately 40-45 ma.

These sequence boundaries bind the Nammal, Sakesar, Chorgali and Kuldana Formations into a sequence in the sense of Mitchum et al (1977). This is a first order sequence that spans an interval of approximately 17 million years.

B) Stacking patterns and key surfaces

The sequence stratigraphic model presented here is based upon outcrop work done on the Khair-E-Murat Ridge between the villages of Galli Jageer and Pind Fateh. Stratigraphic sections measured here combined to create a composite section. This section was then lithocorrelated with the stratigraphic section illustrated in Jurgan and Abbas (1991) (fig. 32). Each lithologic bed in the field area was measured on a centimeter scale and samples were taken at the base of each bed. These samples were processed for microfossils to delineate lithofacies. Abnormal lithofacies associations were noted and paleobathymmetry across such surfaces was determined using benthic foraminifera.

Emphasis is placed on the recognition Discontinuity Surfaces (DS) that Clari et al (1995) define as: "a surface which separates younger from older sedimentary rocks where evidence based on geometric, diagenetic, or biostratigraphic criteria, enables to infer a break in sedimentation, of whatever length." The author uses this term to describe unconformable surfaces in supratidal facies. In the absence of abundant microfossils it is hard to recognize flooding surfaces which can be recognized by the presence of deeper water faunas over shallow water faunas. Unlike flooding surfaces, discontinuity surfaces can develop both in submarine and subaerial environments (Clari et al., 1995). Evidence for discontinuity surfaces can be superposition of facies contrasting Walther's Law and therefore suggesting a prolonged break in sedimentation (Clari et al., 1995). The term flooding surface (FS) is only used where there is strong evidence for an abrupt shift in facies towards land. Another surface that is important in this model is the Omission

Surface (OS). These are defined by Bromley (1975, 1990) and Clari et al (1995) as discontinuity surfaces that correspond to ancient firmgrounds.

Given below is a discussion of parasequences and the surfaces used to delineate their boundaries.

Parasequence set A

This set contains three upwards fining parasequences and indicates retrogradation/ backstepping of parasequences. This is interpreted as a landward shift in facies that was the result of a relative rise in sea-level. These parasequences are part of a Transgressive Systems Tract.

1. Parasequence 1

This is a fining upwards parasequence, contains bedset 1 and represents subtidal lithofacies based on benthic foraminifera.

2. Flooding Surface

There is a flooding surface between beds 1 and 2. The evidence for this is a disconformable contact and the presence of deeper water (planktonics) over shallower water fauna.

3. Parasequence 2

This is a fining upwards parasequence, contains bedset 3 and represents subtidal lithofacies based on benthic foraminifera.

4. Flooding Surface

This is indicated by a transgressive lag that includes pebbles and shell hash along a disconformable contact.

5. Parasequence 3

This is a fining upwards parasequence, contains bedset 4 and 5 and represents subtidal lithofacies based on benthic foraminifera.

6. Flooding Surface

This is between beds 5 and 6 and is recognized by a disconformable contact and abundance of deeper water faunas over shallow water faunas.

7. Flooding Surface/Omision surface

This is recognized by *Glossifungites* ichnofacies (*Thalassinoides*) which is interpreted as a carbonate firmground that was flooded during a relative shift in facies towards land (fig 20).

Progradational strata

These are coarsening upwards and show a general shoaling upwards trend and signify progradation. This progradation is attributed to a decrease in accommodation space caused by rates of sedimentation exceeding rates of subsidence. These strata were deposited during a normal/depositional regression.

The first of these is a brining upwards succession. Dolomite beds are intercalated with anhydrite beds, higher up in the parasequence the anhydrite beds become thicker with a thinning in dolomite beds. These parasequences are often capped by a gypsum or anhydrite unit. Such meter-scale brining upwards successions are characteristic of highstand systems tracts in mixed carbonate-evaporite systems (Sarg, 2001). They are a result of sub-tidal to supratidal deposition on restricted shelves in broad evaporitic lagoons (Sarg, 1988). The presence of miliolid foraminifera in this parasequence is evidence of storm wash-over deposits.

1. Discontinuity Surface

   This surface is marked by the absence of the Lower and Middle supratidal salt flat facies.

C) Systems Tracts

Systems tracts are delineated in this study using a) stacking patterns of parasequences b) key surfaces (sequence boundaries, condensed sections, discontinuity surfaces, flooding surfaces, and omission surfaces).

1. Transgressive Systems Tract

   This is represented by the Sakesar Formation. Bybell & Trail (1993) presumed an unconformity at the boundary of the Nammal and Sakesar formations. However because of the scarcity of nannoplankton in the Sakesar Formation, this unconformity cannot be dated by absolute means. The author interprets this boundary as a Transgressive Surface that separates the underlying Lowstand Systems Tract from the overlying Transgressive Systems Tract. This interpretation in based on the recognition of stacking patterns of limestones (exposed in outcrop, and stacking patterns observed in wireline Logs) and the position of other key surfaces.

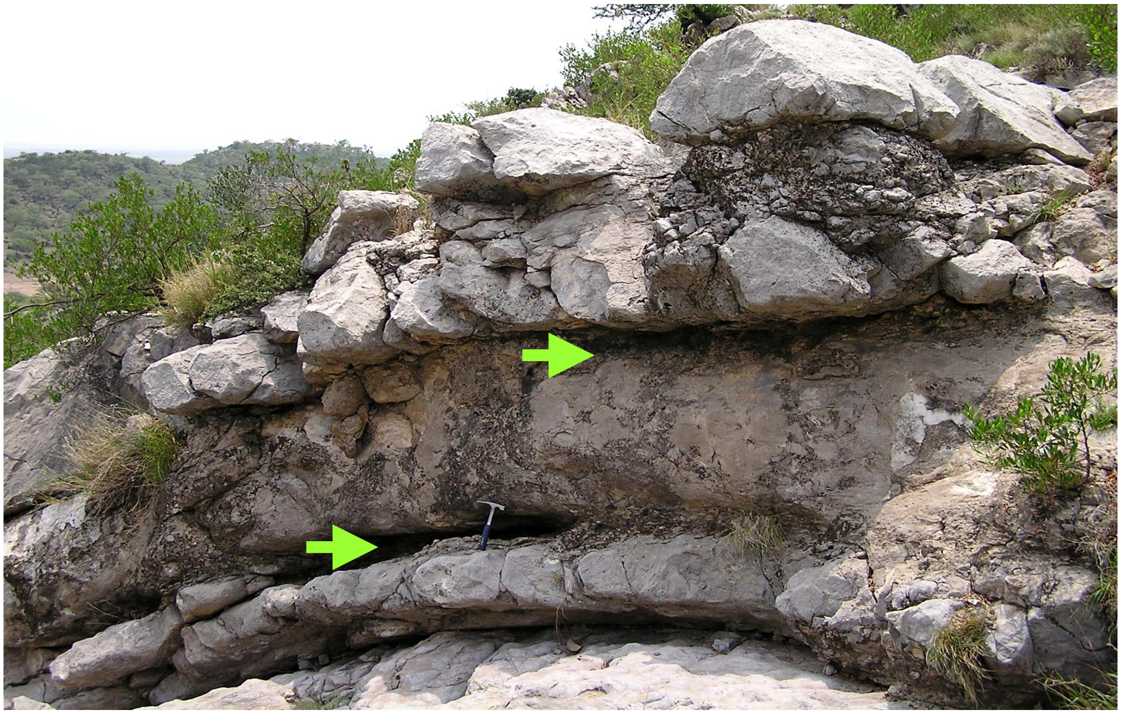

Figure 35. Flooding surfaces at Chorgali pass, Khair-E-Murat Ridge.

Figure 36. Upwards coarsening parasequence of the late Highstand Systems Tract, Chorgali Pass, Khair-E-Murat Ridge

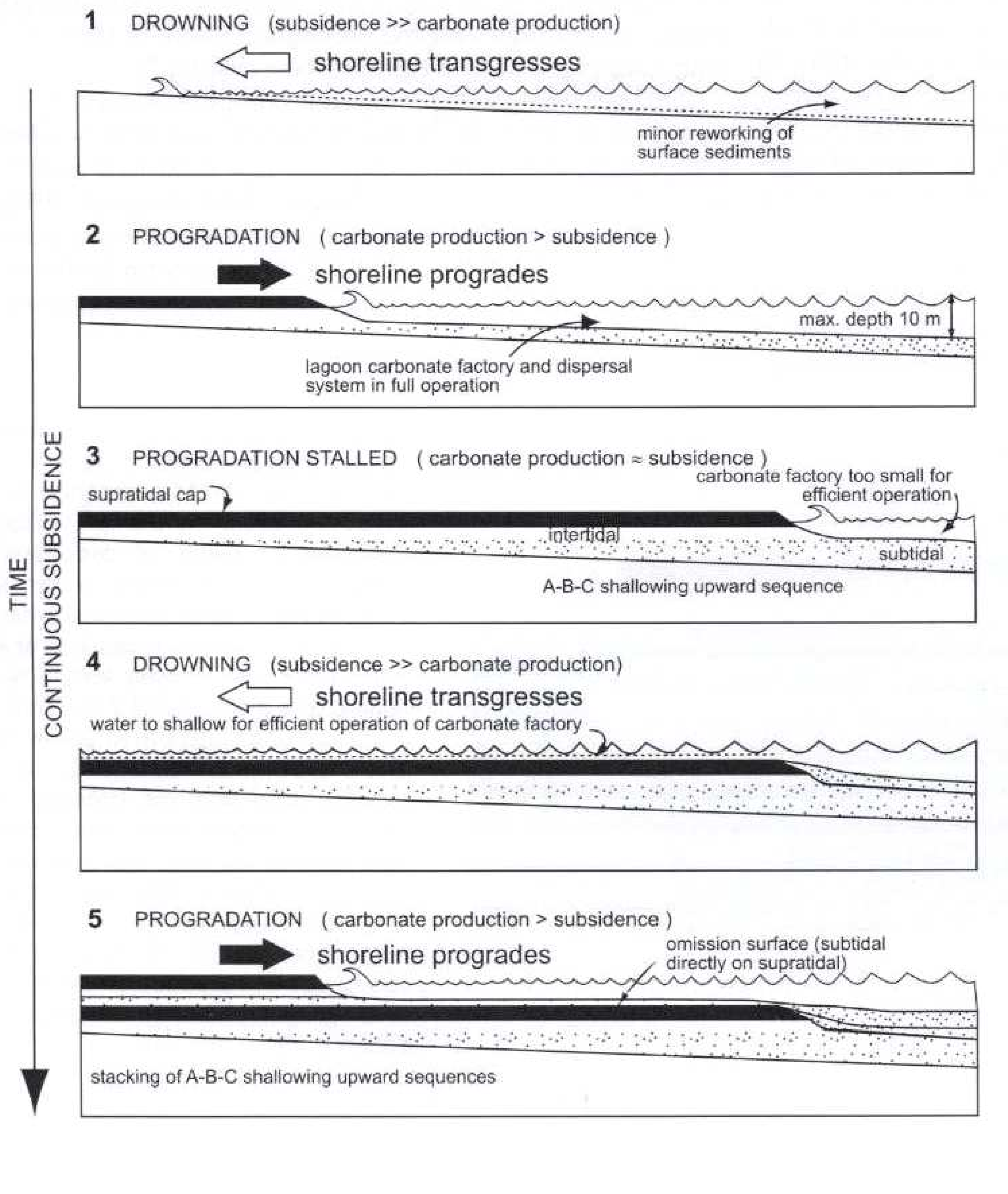

Figure 37. Ginsburg's autocyclic model of sedimentation (Ginsburg, 1971; Shinn, 1983; Schlager, 2005)

Figure 38. Linear accumulation of nummulitid tests in the Kuldana Formation at Shahdara

Figure 39. Limestone stringer in the Kuldana Formation at Shahdara

Upwards fining stacking patterns showing retrogradation only occur during a relative shift in marine facies towards land (Posamentier & Vail, 1988; Van Wagoner et al., 1990). Such parasequences were observed in the Chorgali Pass section at the Khair-E-Murat outcrop.

Kendall and Schlager (1981) suggested that under normal conditions carbonates in a TST go through three distinct phases a) start-up phase b) catch-up phase and c) keep-up phase. However in systems were conditions are less favorable for carbonate production Sarg (1988) suggests that TST only show catch-up deposition. Highly saline conditions during the deposition of the TST in the NSCKS retarded carbonate production and this has resulted in a thin TST. This catch-up deposition is characterized by early submarine cementation and mud-rich parasequences.

2. Highstand Systems Tract (HST)

The HST is represented by the Chorgali and Kuldana Formations. The evidence for this lies in the stacking patterns of parasequences and position of key surfaces relative to parasequences. The parasequences show an aggradational and progradational stacking pattern and this is interpreted as a relative stillstand. Progradation observed in the field is not attributed to a forced regression caused by a eustatic fall, but instead to a depositional regression.

Prior to this study, limestone stringers in the Kuldana Formation were noted by Jurgan and Abbas (1991) and Wells (1983). However the cause of these stringers was not discussed in detail. In the section measured by Jurgan and Abbas (1991) at Chorgali Pass, limestone beds in the upper Chorgali are interpreted as being deposited in freshwater ponds in a supratidal flat. This interpretation is based upon the presence of Characean oogonia, which according to Schlager (2005) are a reliable indicator of brackish to freshwater conditions. The transition from supratidal to terrestrial facies occurs between beds 21 and 22. Bed 22 is a matrix supported channel conglomerate that grades upwards into a lithic wacke. This poorly sorted graded bed is interpreted as being deposited by an ephemeral stream in bankfull discharge. Overlying this unit are green to red shales very similar to those described by Handford and Fredericks (1980) from the mud-sabkha complex of the Texas panhandle. Higher up in the Kuldana are these limestones stringers that have abundant large nummulites which suggest subtidal deposition. These were studied in the field at the Kuldana type locality (fig 24) and near the village of Shahdara (fig 39) The presence of these stringers in the Kuldana Formation along with the progradation of supratidal facies in the Upper Chorgali Formation can be explained using Ginsburg's autocyclic model of sedimentation (Ginsburg, 1971; Shinn, 1983; Schlager, 2005).

This model assumes steady subsidence on a seaward dipping platform and depth-dependant carbonate production. Production at supratidal flats is assumed to be near-zero and high in the shallow-marine lagoon. The cycle began with rapid transgression and lagoon formation. This phase is represented by non-dolomitized skeletal packtstones of the Sakesar Formation. Sediment production was slow at first (start-up phase), and then sped up (catch-up phase). Because of saline conditions in this lagoon the catch-up phase is more dominant in the NSCKS. This caused sediment to migrate landwards (retrogradation) and lagoon fills up to the tidal flats. Because of this decrease in accommodation these flats began to prograde. This progradation of tidal flats constantly reduced carbonate production as productive lagoon floor was replaced by non-productive tidal flats. Progradation stopped when the lagoon had become too small to support further growth of tidal flats. At this stage the system stagnated until subsidence lowered the nummulites banks on the seaward side of the flats and this was followed by a rapid transgression that deposited poorly cemented nummulitic packstones over supratidal redbeds (fig 24, fig 25). The author believes that a forced regression led to the development of SB 2 between the Kuldana Formation and overlying Rawalpindi group strata.

3) Reservoir Characterization

The effective reservoir for Fim Kassar Oil Field lies within the confines of the Sakesar and Chorgali Formations. Porosity and permeability in this reservoir are a function of dolomitization and fracturing, respectively.

Payzones in this study are defined as economically producible layers within the reservoir of interest. Therefore to isolate payzones, it is important to understand the processes of dolomitization and reservoir compartmentalization as they apply to Sakesar and Chorgali Formations at Fim Kassar.

A) Sabkha dolomitization

Dolomitization in mixed carbonate-clastic-evaporite systems is a function of meteoric and groundwater fluid interactions in the sabkha. There are four processes that influence dolomitization in a periodically flooded sabkha:

1. Flood recharge
Flooding of the sabkha surface by storm-driven lagoonal waters (Butler, 1969)

2. Capillary evaporation
Evaporation of the water from saturated near-surface sediments (Evans, 1995)

3. Evaporative pumping
Draw-up of water from underlying lagoonal and eolian sediments (Hsu & Sneider 1973; McKenzie et al., 1980)

4. Seepage Refluxion
Flushing of large volumes of magnesium rich brine downwards through calcareous sediment (Boggs, 2001).

These processes lead to precipitation of aragonite and gypsum and production of diagenetic minerals (celestite, magnesite, and dolomite). Evaporation in the intertidal zone creates a saturation of calcium and magnesium ions and this leaves a high concentration of gypsum in cyanobacterial mats. At 60^0 C gypsum dewaters and turns to anhydrite, giving off calcium ions (Boggs, 2001). The Mg/Ca ratio in normal seawater is 5:1, but in such hypersaline conditions it can be as high as 10:1. These calcium ions bond with magnesium and carbonate to produce dolomite. Dolomite also replaces aragonite mud and pelleted mud but does not affect stouter skeletal grains (Evans, 1995). According to field studies conducted by Kendall et al. (2002) on the Khor-al-Bazam sabkha of the modern UAE, a hardground forms in the intertidal region. This hardground becomes cemented by either calcite or gypsum and forms a seal between underlying subtidal sediments with marine waters and overlying supratidal flats with saline brines. This seal separates the zone of dolomitization above from a zone of very little dolomitization below.

Because of hypersalinity and consequent decrease in fauna, there is a scarcity of skeletal grains in the Chorgali Formation. This explains the dolomitization of Chorgali

Formation sediments and the lack of dolomitization in the coarser skeletal packstones of the underlying Sakesar Formation.

However grain size alone does not predict the occurrence of dolomitized beds. According to a detailed study conducted by Montanez and Read (1992) on the dolomites of the Ordovician Knoxville Group of Tennesse, dolomitization is also a function of relative sea-level changes. 80% of all cycles found in regressive intervals in this group are dolomitized whereas only 56% of all cycles found in transgressive intervals are dolomitized. Read and Montanez (1992) also noted that dolomitization was closely-related to the proportion of tidal-flat to subtidal facies. The ratio of tidal flat to subtidal facies has an inverse correlation with cycle thickness. Cycles associated with tidal flats are thinner (avg = 1.6 m) versus cycles associated with subtidal facies (avg = 4.1 m).

To summarize, beds showing the highest degree of dolomitization would be thin intertidal to supratidal beds (avg = 1.5 m), that are associated with upwards coarsening parasequences deposited during the regressive (falling stage) HST.

B) Fracturing of reservoir

Fim Kassar produces hydrocarbons from dolomitized fractured beds. Fractures do not cross bed boundaries as suggested by models of fracturing in anticlines proposed by Nelson (1985) and Nurmai (1991). Fieldwork done on the Khair-E-Murat Structure show that fractures run in certain beds and not in others, and a highly fractured bed may lie against another non-fractured bed of similar apparent lithology. Fracture occurrence in these beds seems to be a function of rheology and not structure (fig 35). The occurrence of fracture prone beds in this structure is random. This model is very similar to the Kilve

Anticline of southern England (fig. 2). Seismic resolution for Fim Kassar Oil Field is around 40 meters, and this is insufficient to recognize fractures on Fim Kassar seismic lines. These fractures do appear in fracture logs and in FMIs. However their prediction between wells and elsewhere in the field is problematic. According to a detailed study performed by Benchilla et al., (2002) on fractures on the Khair-E-Murat Structure there are two distinct fracture patterns. Bed Parallel Stylolites (BPS) run parallel to bedding plane and Tectonic Stylolites (TS) run perpendicular to bedding planes. Thus fractures observed on the Khair-E-Murat structure are not a function of sedimentary unloading associated with uplift and exposure. We can therefore assume that the buried Fim Kassar structure which is composed of the same lithologies (Sakesar and Chorgali Formations), and that has gone through the same tectonic deformation as the Khair-E-Murat Structure (the two structures are less than 30 kilometers apart) will have fractures with similar orientation and pattern. Therefore a carbonate sequence stratigraphic model was created and payzones fingerprinted for the Fim Kassar structure using the Khair-E-Murat as an analog.

Jadoon et al (2002) also noted that thin beds are more fracture prone than thick massive beds. Benchilla (2002) noted that the most fracture prone beds are located in the uppermost sections of the Chorgali Formation.

C) Reservoir Compartmentalization

Although the Sakesar and Chorgali Formations are predominantly massive limestones and dolomites, shales and anhydrite beds provide baffles. Highstand evaporites are economically important because they provide a lateral and top seal to hydrocarbon reservoirs (Sarg, 2001). As Highstand parasequences aggrade and prograde, the evaporite lithofacies build seaward and eventually cover most of the shelf region. This architecture puts evaporites overlying porous HST reservoirs. Since the thin beds of intertidal and supratidal association are more prone to dolomitization (Montanez & Read, 1992) and are more fracture prone (Jadoon, 2002; Benchilla, 2002) we can predict that these beds will be found in the falling-stage parasequences of the HST.

In the study area bed 15 is a 2.18 meter thick anhydrite layer that would act as a baffle to the migration of hydrocarbons. Faulting and consequent fracturing of this layer provides migration pathways for hydrocarbons into beds 16, 17 and 18. These beds are overlain by a 3.33 meter thick layer of shale that would prevent beds 20, and 21 from being charged.

Based upon these data, two payzones are identified within the Sakesar and Chorgali formations. The criteria used for the selection of payzones includes, a) porosity b) occurrence of macrofractures c) the presence of a baffle or seal that would promote entrapment of hydrocarbons, and d) a minimum thickness of 3 meters (10 feet).
These payzones are described below:

Payzone 1

Formation: Chorgali Formation

Beds: 9,10

Thickness: 2.92 meters

Porosity type: bed 9 has fenestrate porosity, channel porosity, styloporosity and moldic porosity. Bed 10 has vugs

Macrofractures were observed in the field at Chorgali Pass, Khair-E-Murat Ridge in bed 10.

Payzone 2

Formation: Chorgali Formation

Beds: 16, 17, 18

Thickness: 8.32 meters

Porosity type: bed 16 has channel porosity (see Appendix A, Plate 19), bed 17 has fenestrate and fracture porosity, and bed 18 has fracture porosity

Macrofractures were observed in the field at Chorgali Pass, Khair-E-Murat Ridge in bed 16.

Although beds 20 and 21 show macrofractures, they lie above a thick (3.33 meters) bed of shale and are not in communication with underlying hydrocarbon bearing strata.

4) Identification of bioevents

Five field-scale bioevents were identified in this study. These are easy to recognize and would be useful in correlation of future wells in Fim Kassar Field. These bioevents are described below:

1. The *Lockhartia-Alveolina-Nummulites-Daviesina-Assilina* Strict Overlap Assemblage Fossilzone.

This is defined as the thickness of strata between the lowest co-occurrence and highest co-occurrence of every one of the specified taxa (Walsh, 2000). This bioevent was identified in Bed 6 of the Chorgali Formation at Chorgali Pass.

2. *Oribitoides tissoti* Abundance Zone

This zone is characterized by quantitatively distinctive maxima of a relative abundance of *Orbitoides tissoti* (Article 52, NACSN, 1983). This bioevent was identified in Bed 8 of the Chorgali Formation at Chorgali Pass.

3. HO_k of *Assilina*

This is the highest known occurrence of *Assilina* in the Chorgali Formation in the vicinity of Fim Kassar Field. This bioevent was identified in Bed 10 of the Chorgali Formation at Chorgali Pass.

4. HO_k of Miliolids

This is the highest known occurrence of miliolids in the Chorgali Formation in the vicinity of Fim Kassar Field. This bioevent was identified in Bed 11 of the Chorgali Formation at Chorgali Pass.

5. HO_k of Ostracods

This is the highest known occurrence of ostracods in the Chorgali Formation in the vicinity of Fim Kassar Field. This bioevent was identified in Bed 17 of the Chorgali Formation at Chorgali Pass.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Sequence boundaries of the Nammal-Sakesar-Chorgali-Kuldana Sequence are dated between 52 and 37 ma respectively based on paleontological data. The depositional environment of the reservoir rocks of the Sakesar and Chorgali formations represent (going from basin towards land): Fore Bank Facies, Bank Facies, Back Bank Facies, Shelf Lagoon Facies, Subtidal Inner Lagoon Facies, Intertidal Facies, Supratidal mud-rich Sabkha Facies.

Two payzones are recognized which include beds 9, 10 and 16, 17 and 18, based on the occurrence of porosity and macrofractures. The structure shows small scale mechanical stratigraphy in the sense that some layers are more prone to fracturing than others. Integrating observations of macrofractures in field with data from thin sections shows a strong correlation between carbonate matrix and fracturing. Beds that are rich in Microspar matrix fracture whereas those with dolomitic matrix show very little fracturing. The reservoir is compartmentalized by beds of anyhdrite and shale. The occurrence of dolomitic beds is in the highest part of the stratigraphic section which includes progradational parasequences of the Highstand Systems Tract. These beds (16, 17, 18) show good porosity and are fractured.

Based upon sequence stratigraphic modeling done in this study the following recommendations are made for future drilling in Fim Kassar Field:

1. The probability of penetrating fractures through vertical drilling is very low. This activity should be avoided. All future wells in this field should be horizontal because directional drilling in fracture prone beds would be a lot more efficient (Fig 3). The author recommends drilling for payzone 1 and payzone 2 using directional drilling.

2. Using Perf-Drill® is a very efficient way of drilling directional wells in fractured reservoirs. It would work very well for the Sakesar-Chorgali reservoir. The only drawback to this system is that cuttings are produced as “flakes” which will preserve benthic foraminifera in 3D and would require resin preparation for their identification. Visit (http://www.perf-drill.com/) for details.

3. Cuttings acquired from Fim Kassar and other fields perforating the Sakesar-Chorgali carbonates should not be disaggregated. This process works well for deeper water sediments that contain planktonic fauna. However in the shallow hyper-saline depositional environment of the Sakesar and Chorgali formations, the only forms preserved are benthic foraminifera. These are identified by observing their axial sections in petrographic slides which cannot be prepared from disaggregated samples.

4. 3D seismic for Sakesar-Chorgali carbonates will be of limited value and is not recommended as hydrocarbon production in this reservoir is a function of fracture occurrence. These fractures are beyond the resolution of seismic.

5. A well-site geologist with basic knowledge of microfossils would be needed in-order to successfully biosteer horizontal wells. An identification key to lithologies and microfossils of payzones was created in this study. It shows what cuttings should look like as long as the drill-bit is perforating the payzone. Tips on microfossil preparation and identification for successful biosteering are also given.

The author hopes that this study will be useful not only to OGDCL geologists and engineers, but geoscientists working towards enhanced recovery from fractured reservoirs worldwide.

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APPENDICES

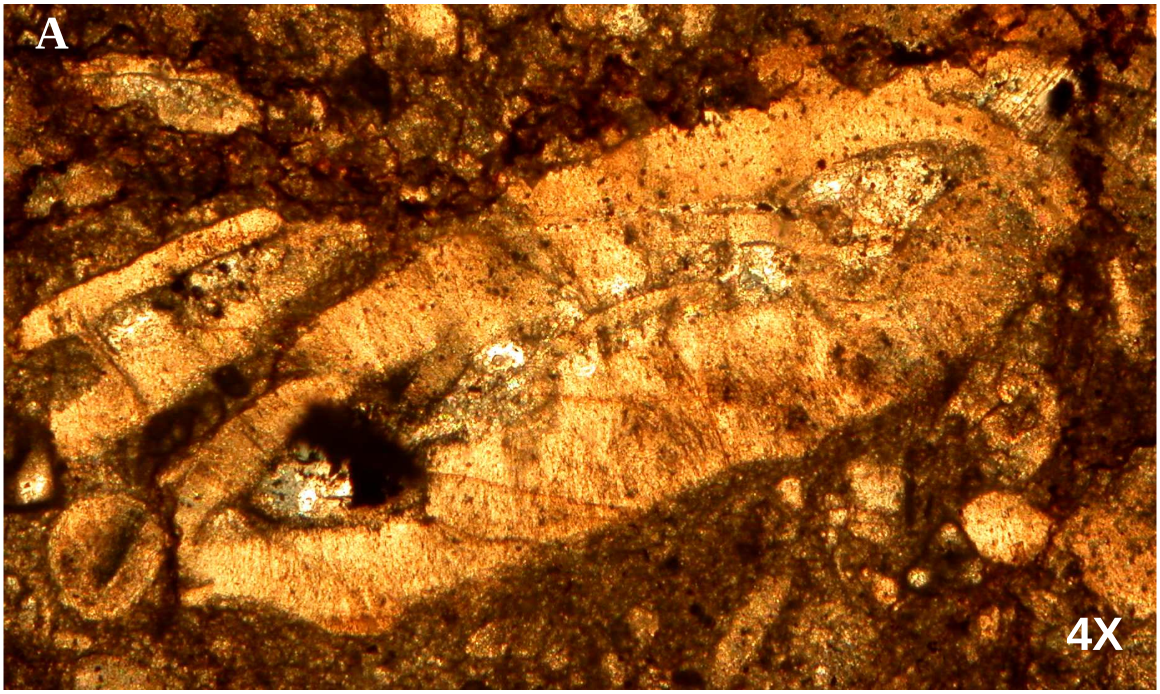
APPENDIX A

Petrographic Images of samples

PLATE 1

Bed 1: Skeletal packstone of the Sakesar Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Axial section of *Assilina. sp*
B. Axial section of *Assilina. sp*


A
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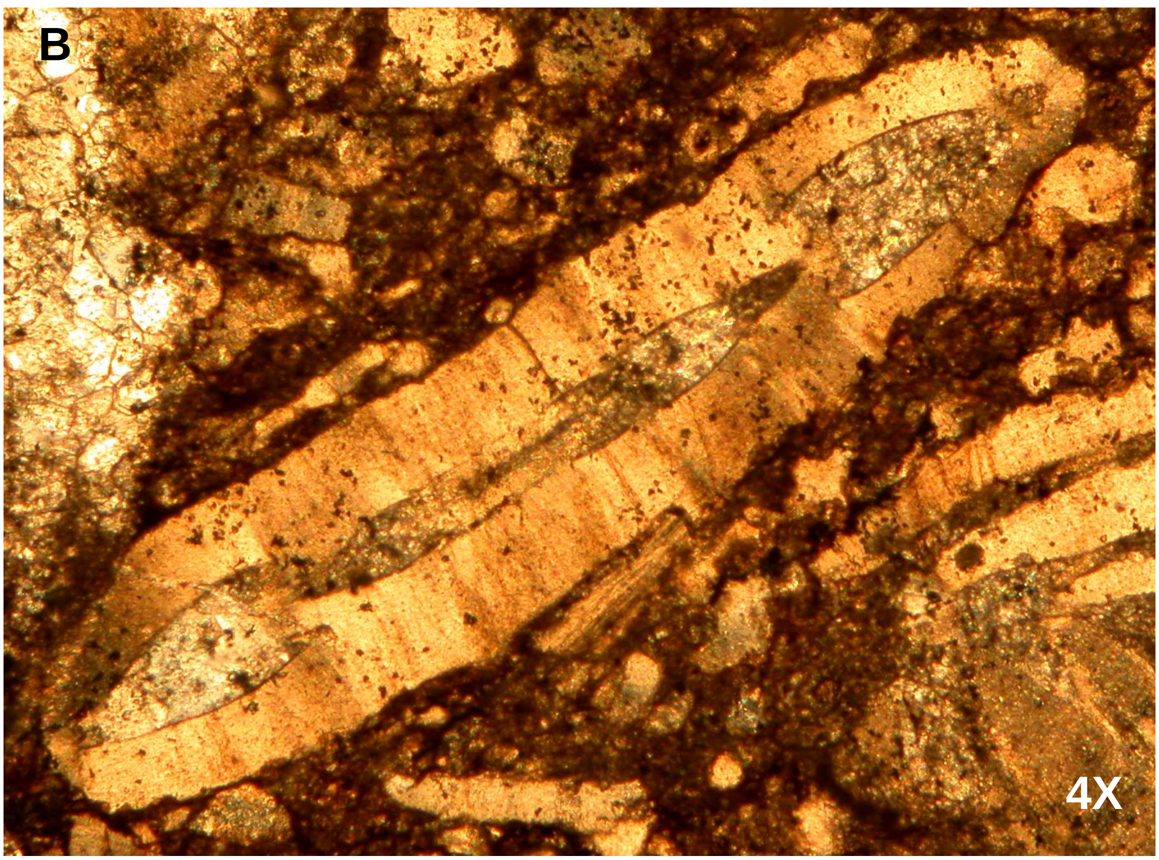
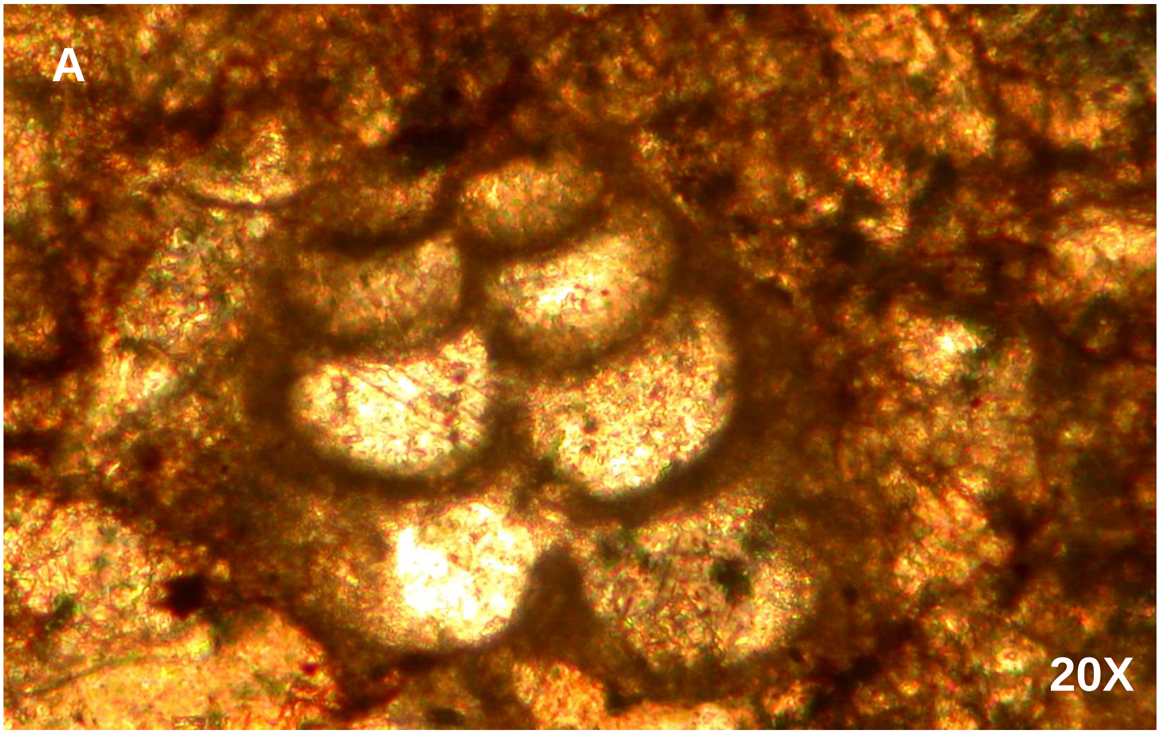

B
4X

PLATE 2

Bed 1: Skeletal packstone of the Sakesar Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Axial section of miliolid
B. Axial section of *Assilina laminosa* (left) and *Nummulites atacicus (right)*

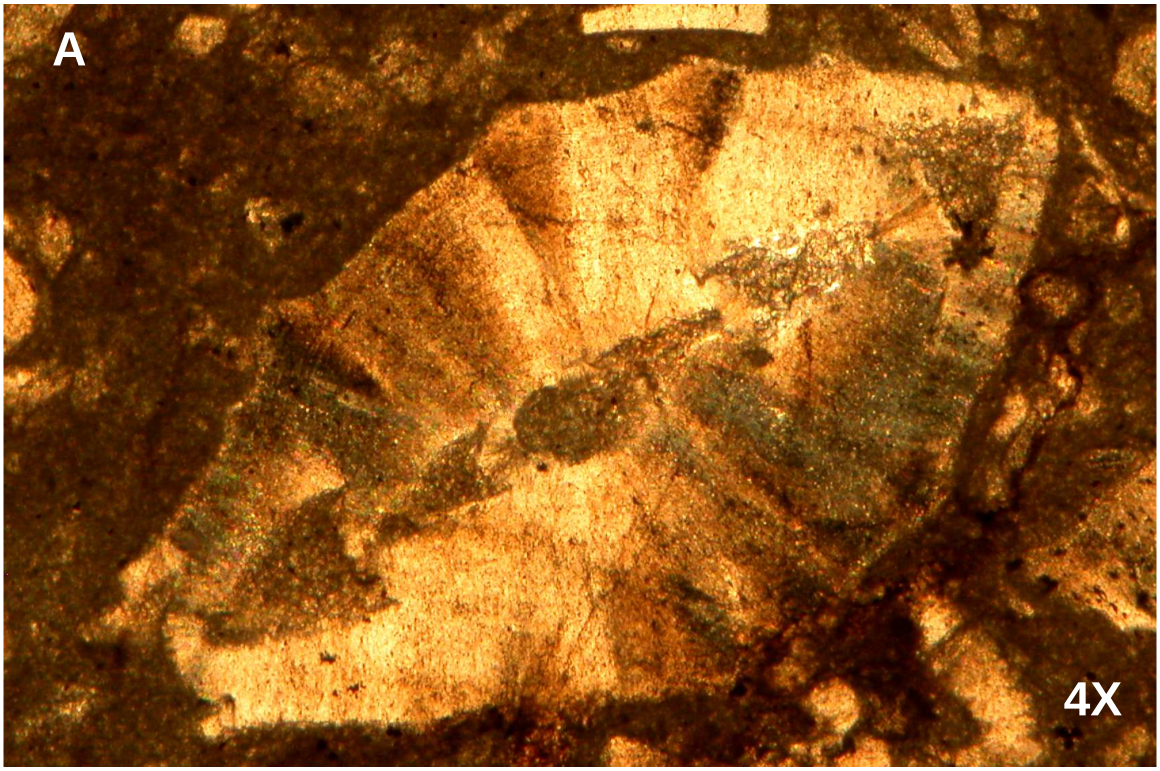

A
20X


B
4X

PLATE 3

Bed 2: Skeletal wackestone of the Sakesar Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Axial section of *Asslina laminosa*
B. Axial section of *Assilina postulosa*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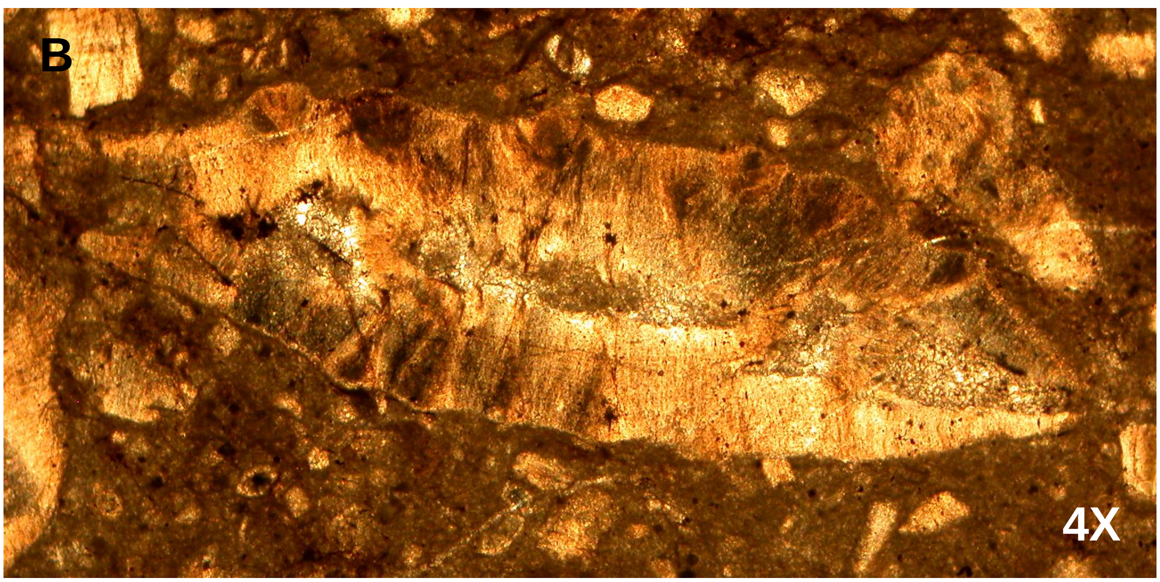
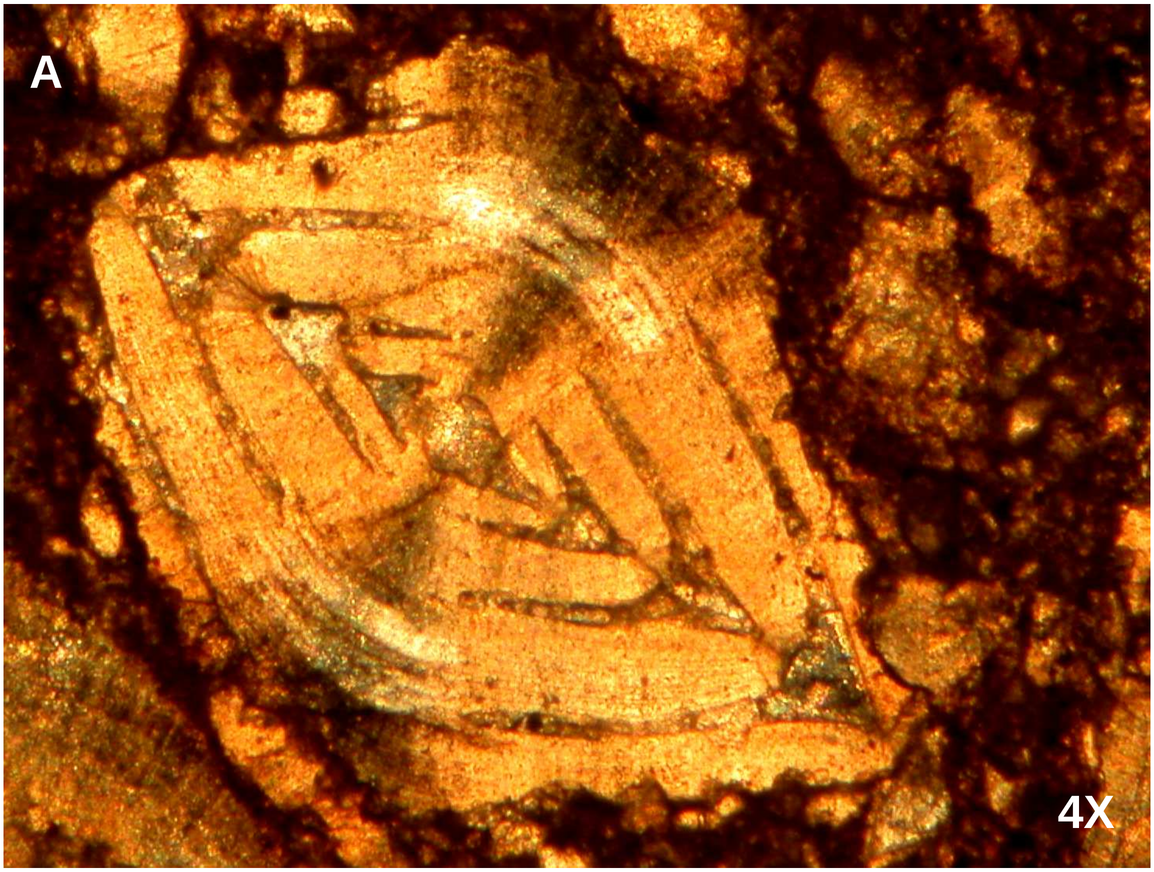

B
4X

PLATE 4

Bed 2: Skeletal wackestone of the Sakesar Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Axial section of *Nummulites burd*
B. Medial section of Asteroid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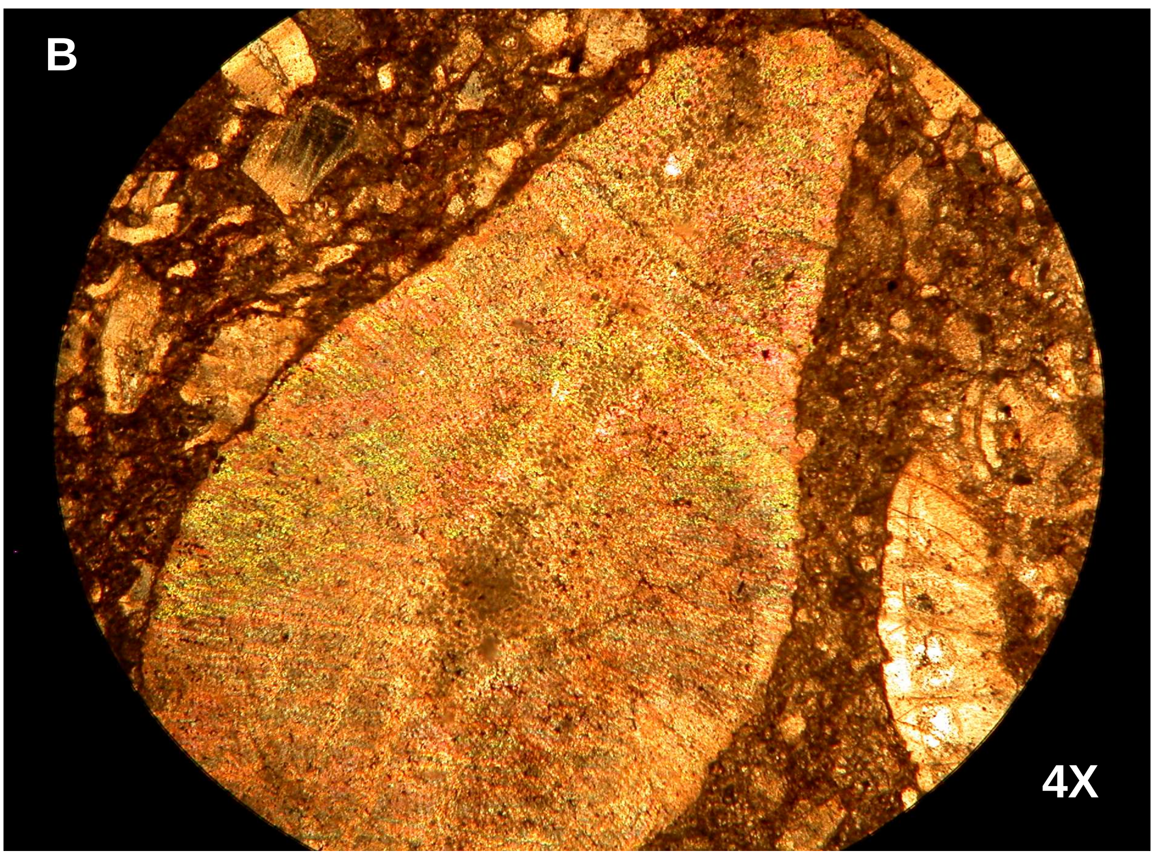

B
4X

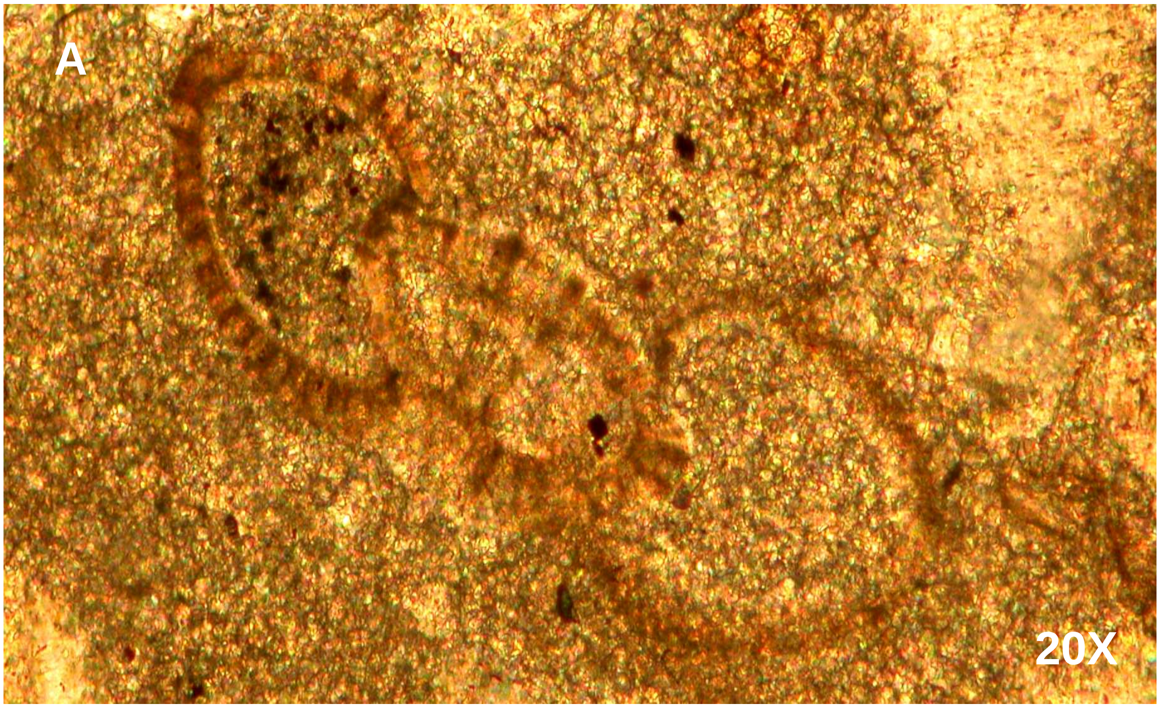
PLATE 5

Bed 2: Skeletal wackestone of the Sakesar Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Axial section of *Planorotalites sp*

Bed 3: Dolomitic packstone of the Sakesar Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

B. Axial section of *Nummulites increscens*


A
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B
20X

PLATE 6

Bed 3: Dolomitic packstone of the Sakesar Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Axial section of *Assilina placentula (top) Assilina plana*
B. Axial section of *Nummulites globulus*

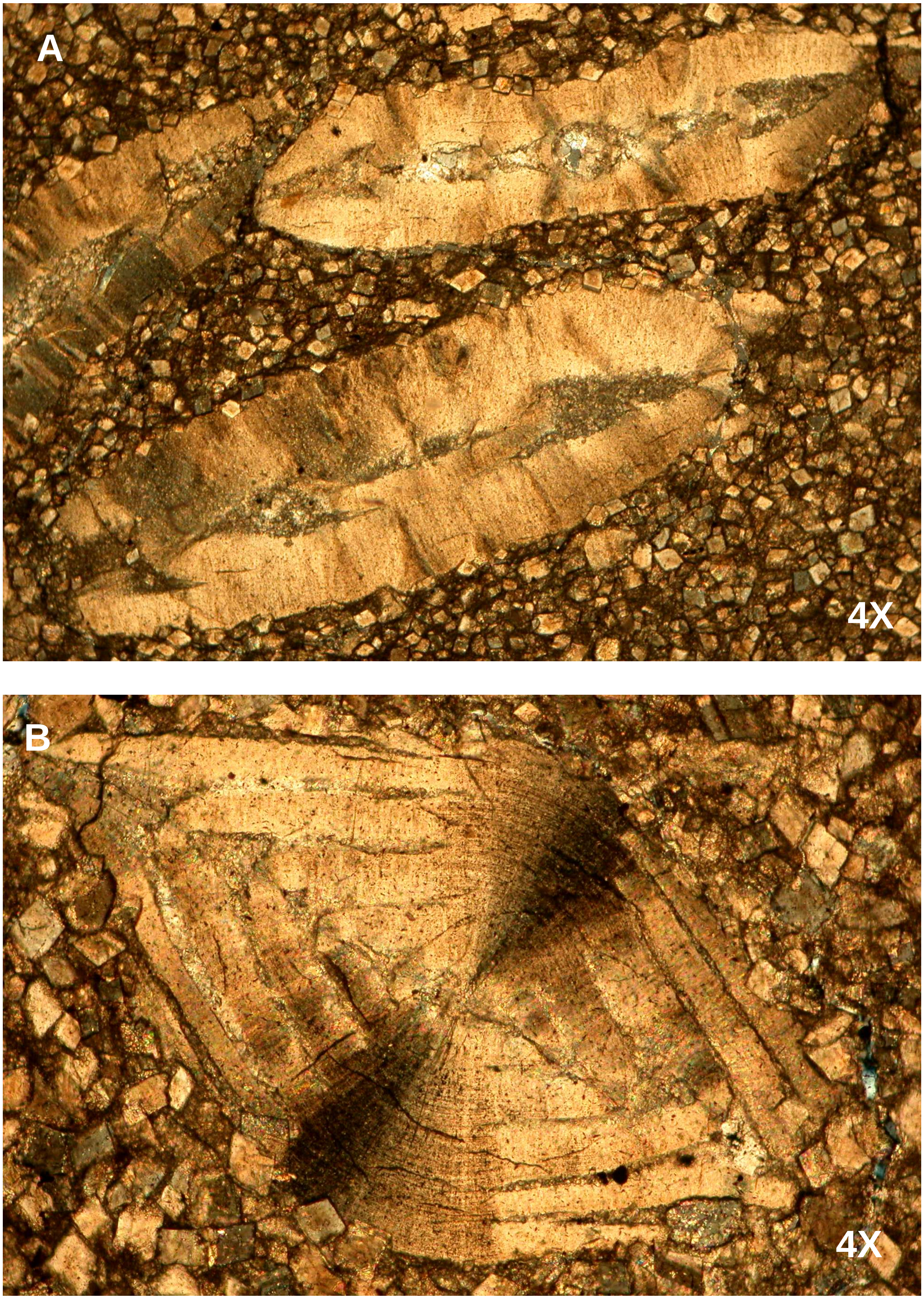
A
4X
B
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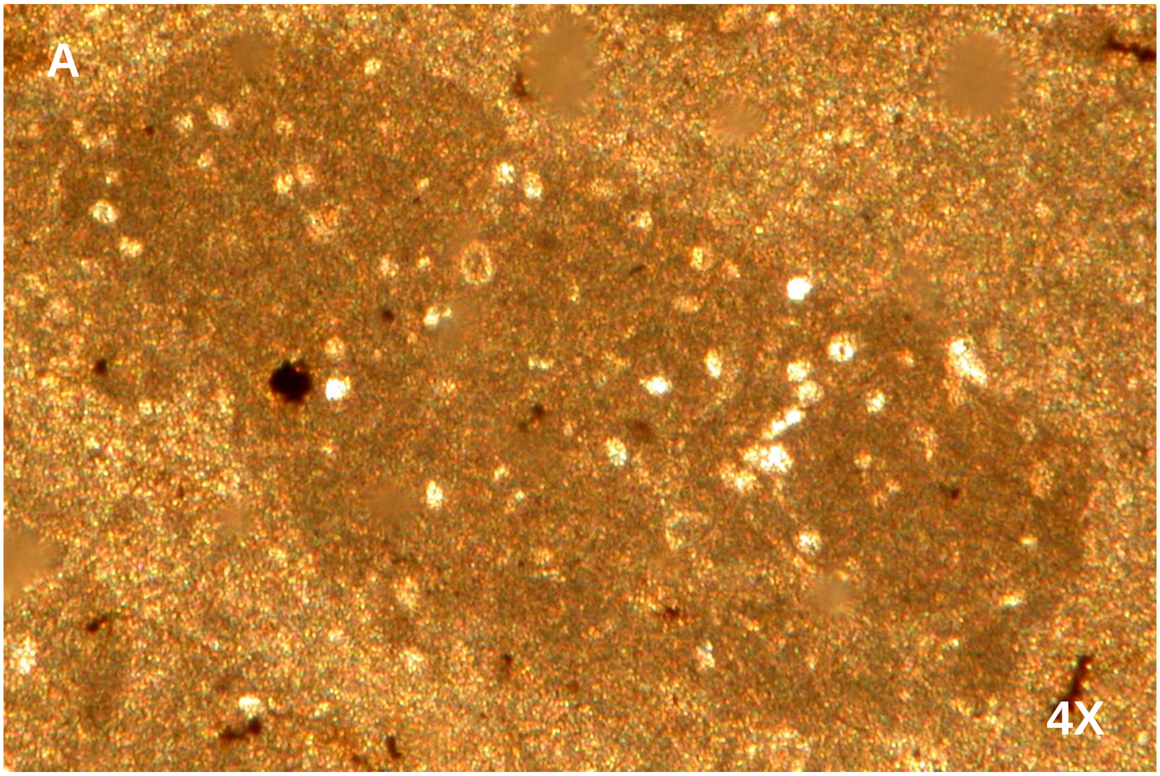
PLATE 7

Bed 4: Peloidal wackestone of the Sakesar Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Intraclast
B. Miliolid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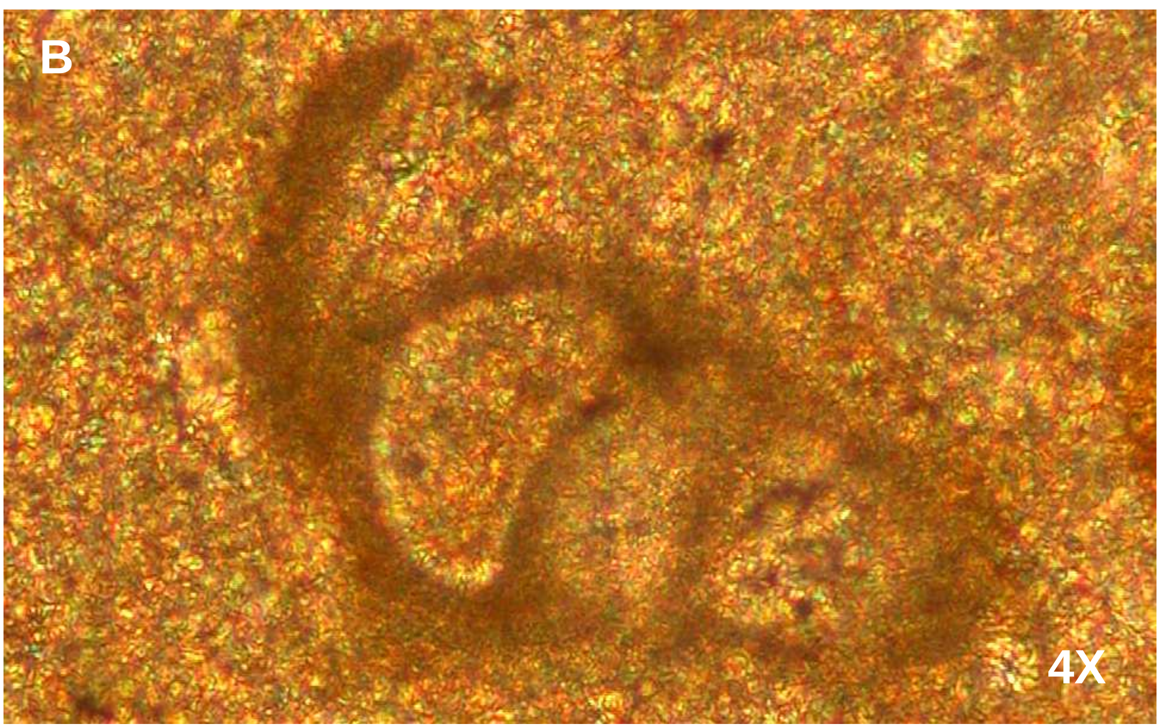
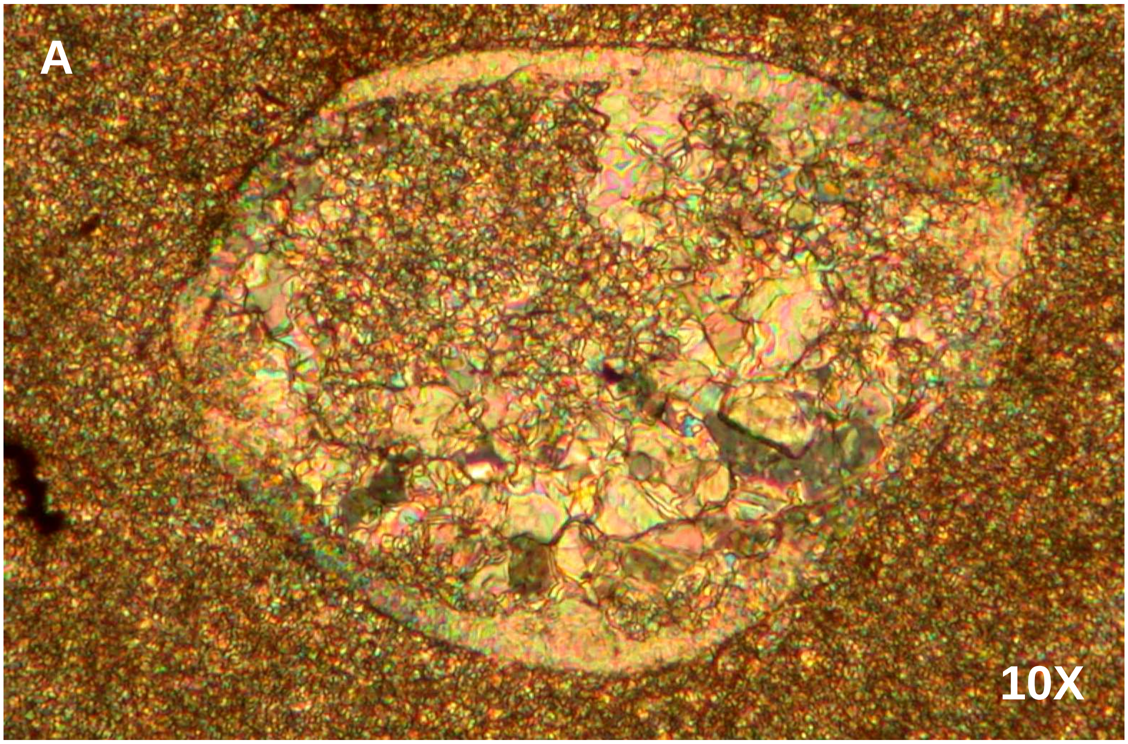

B
4X

PLATE 7

Bed 4: Peloidal wackestone of the Sakesar Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Axial section of an ostracod
B. Axial section of ostracod shell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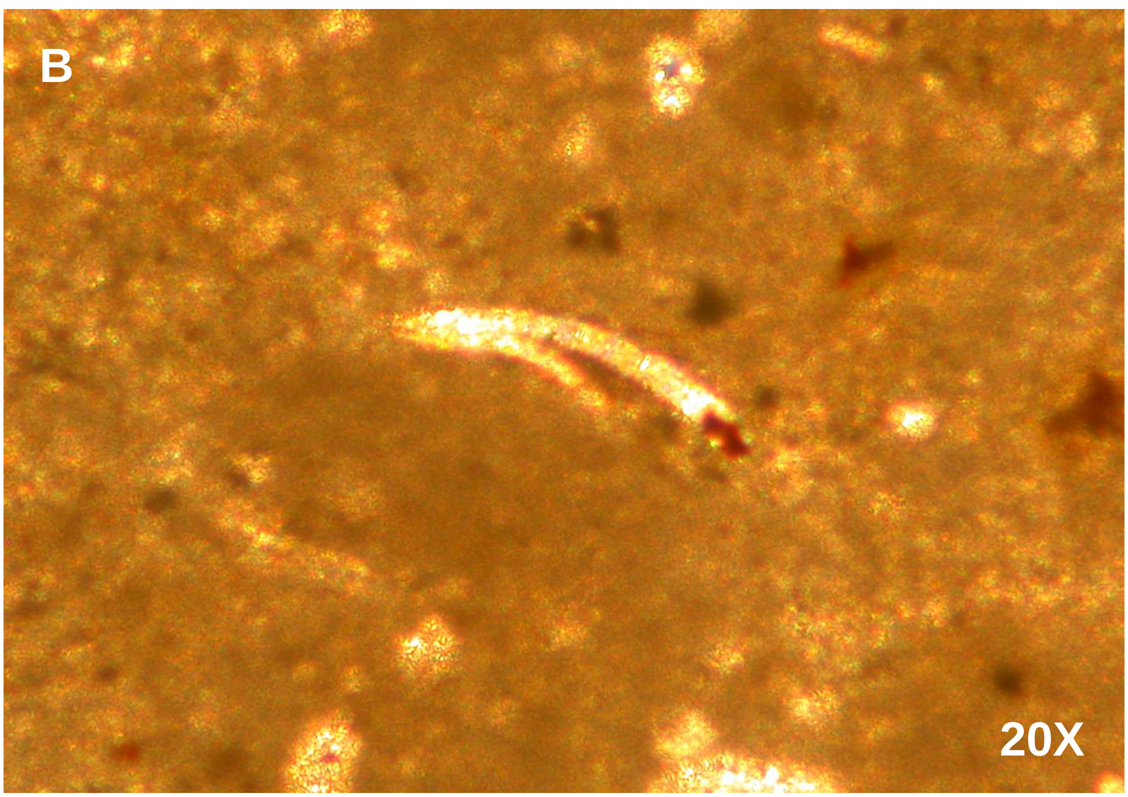
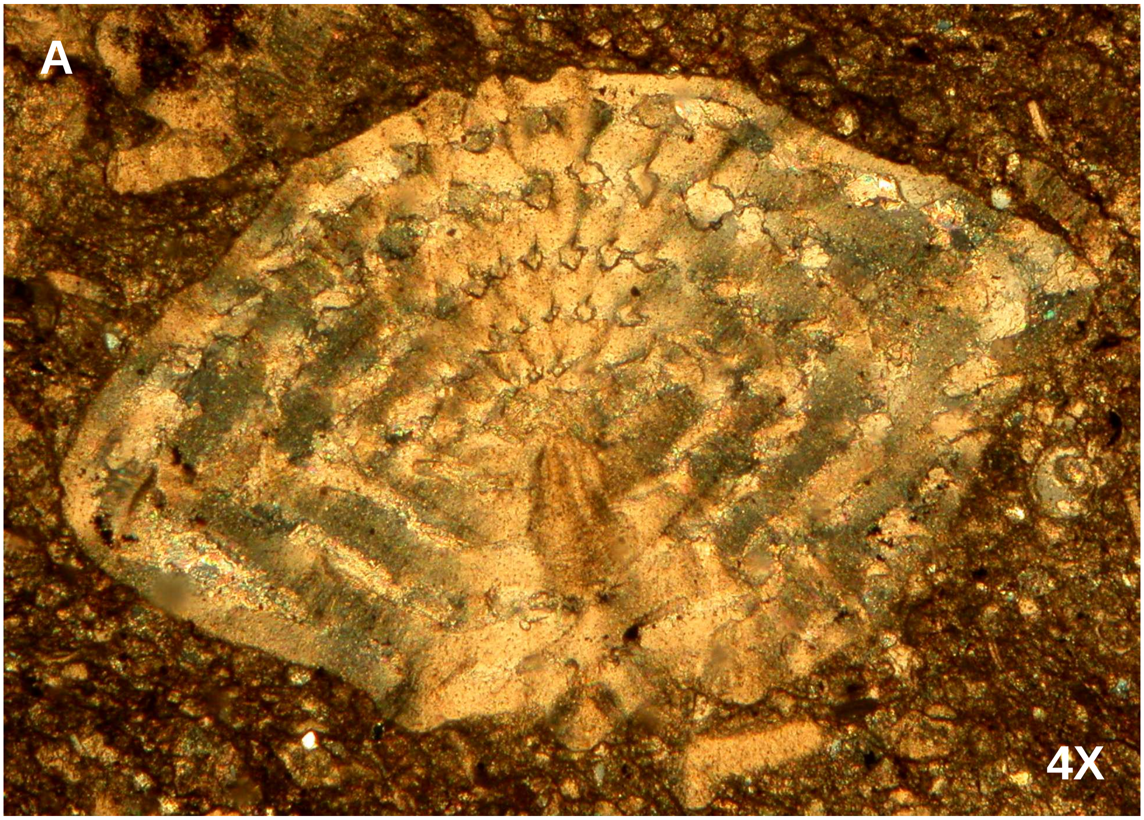

B
20X

PLATE 8

Bed 5: Skeletal wackestone of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge.

A. Axial section of *Nummulites burdigalensis*
B. Axial section of *Nummulites sp*


A
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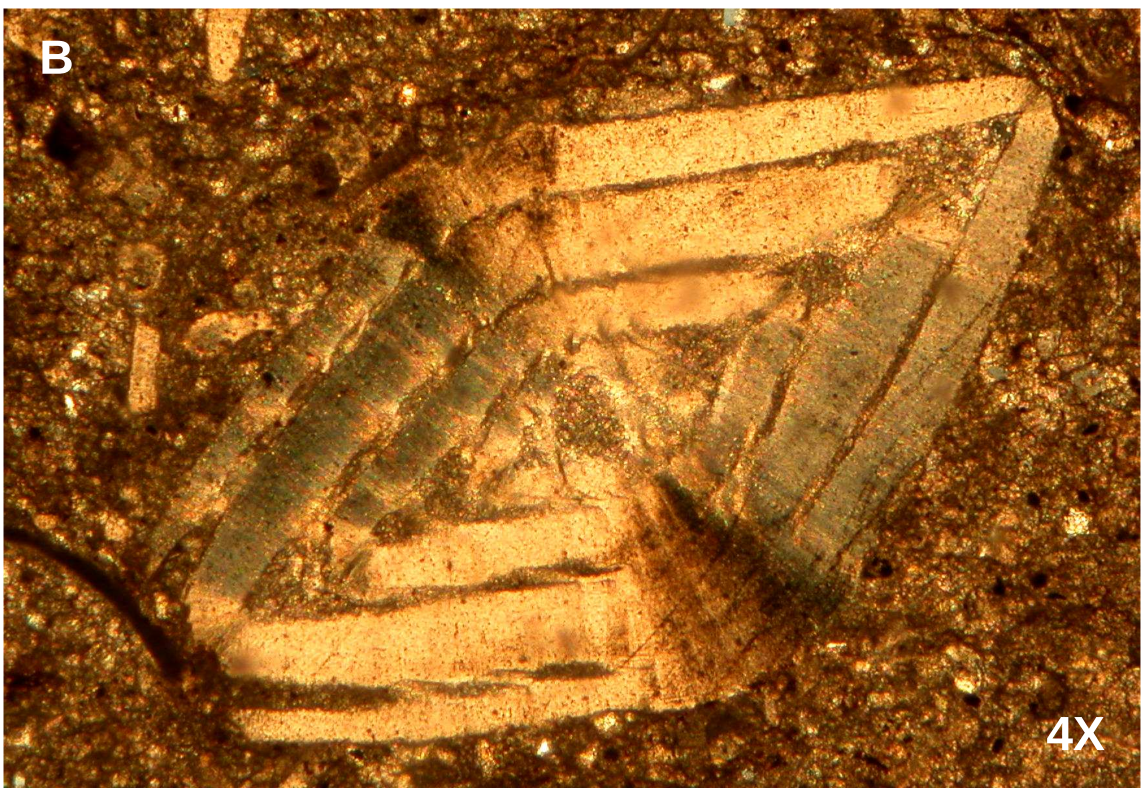
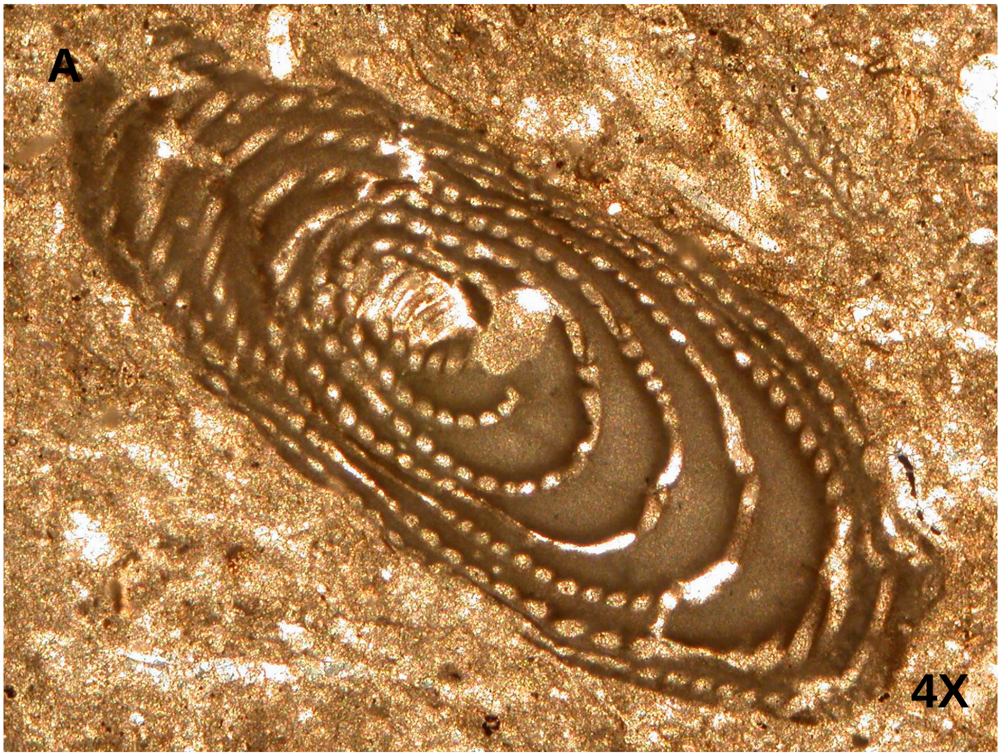

B
4X

PLATE 9

Bed 6: Skeletal packstone of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge.

A. Axial section of *Alveolina (Flosculina) sp*
B. Median section of *Alveolina (Flosculina) sp*


A
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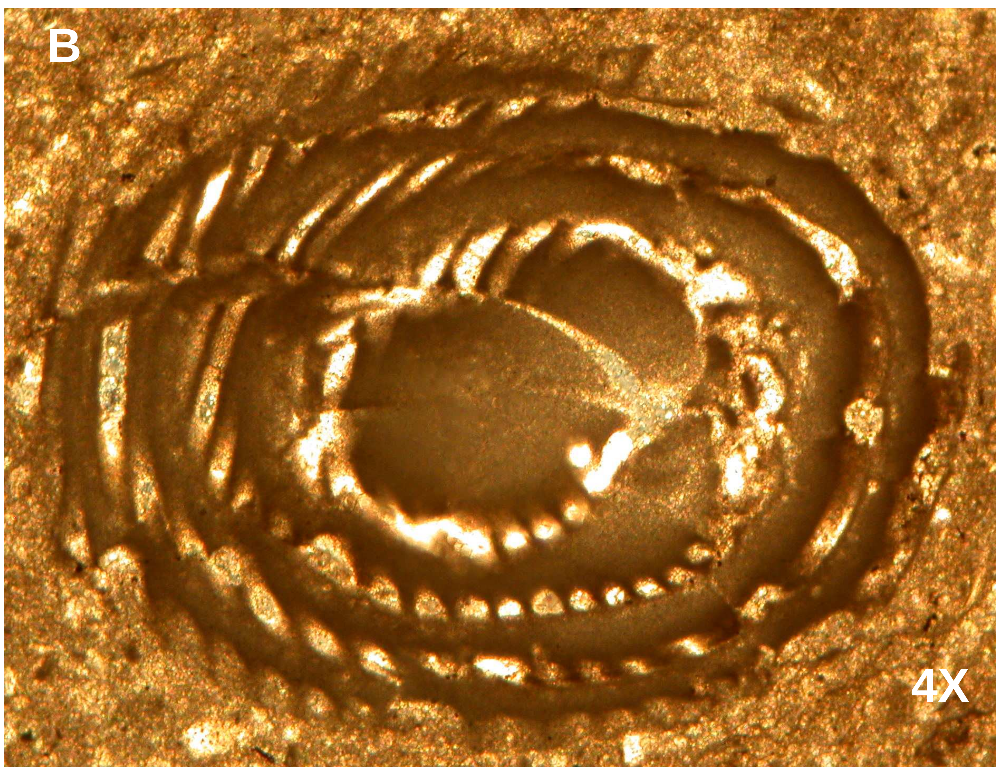
B
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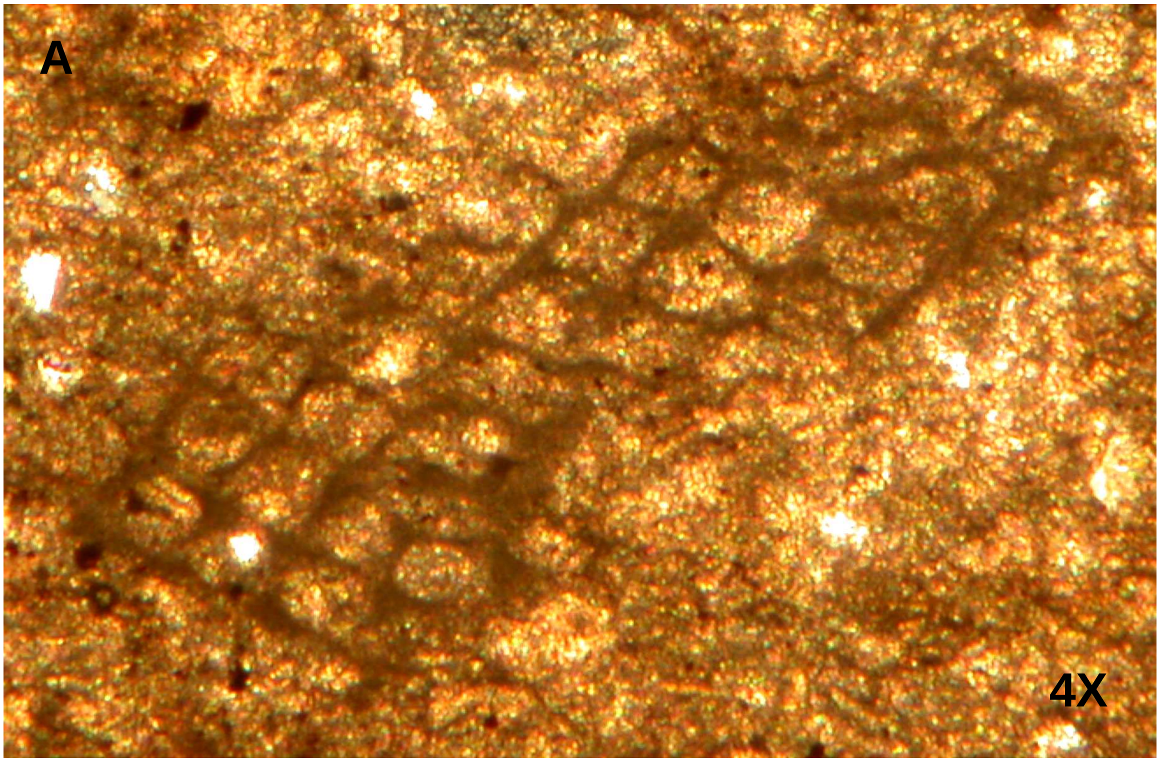
PLATE 10

Bed 6: Skeletal packstone of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Bryozoan
B. Echinoderm spine


A
4X

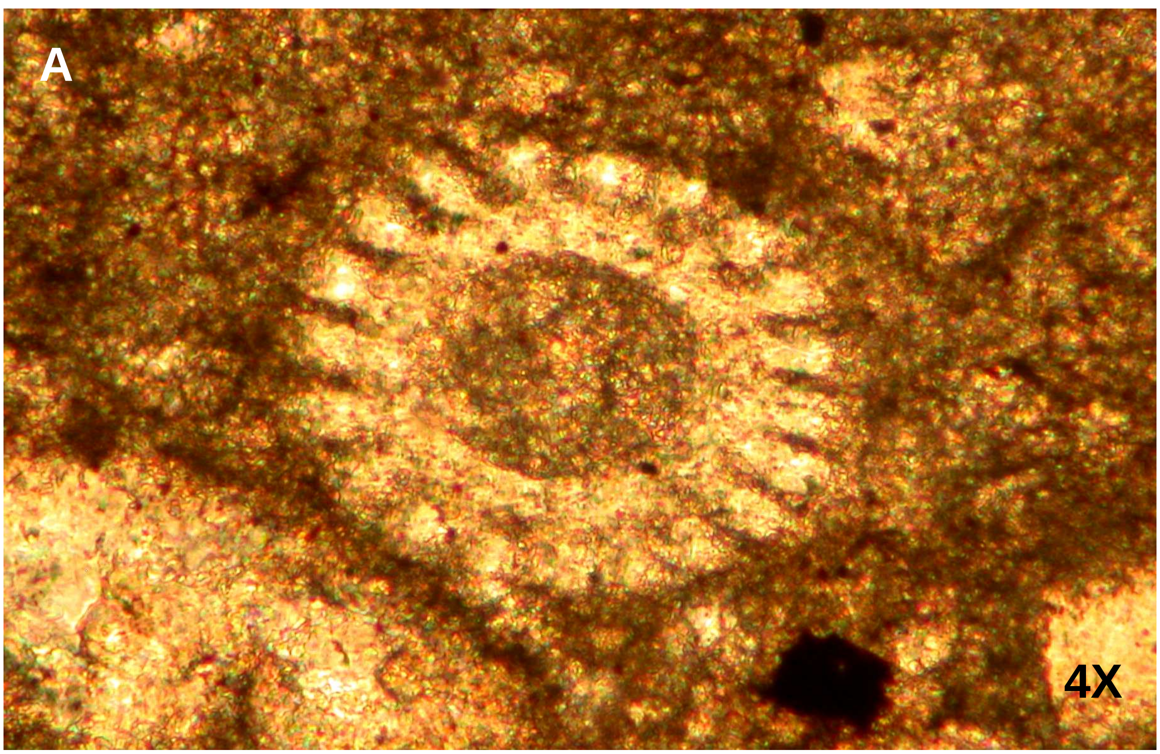
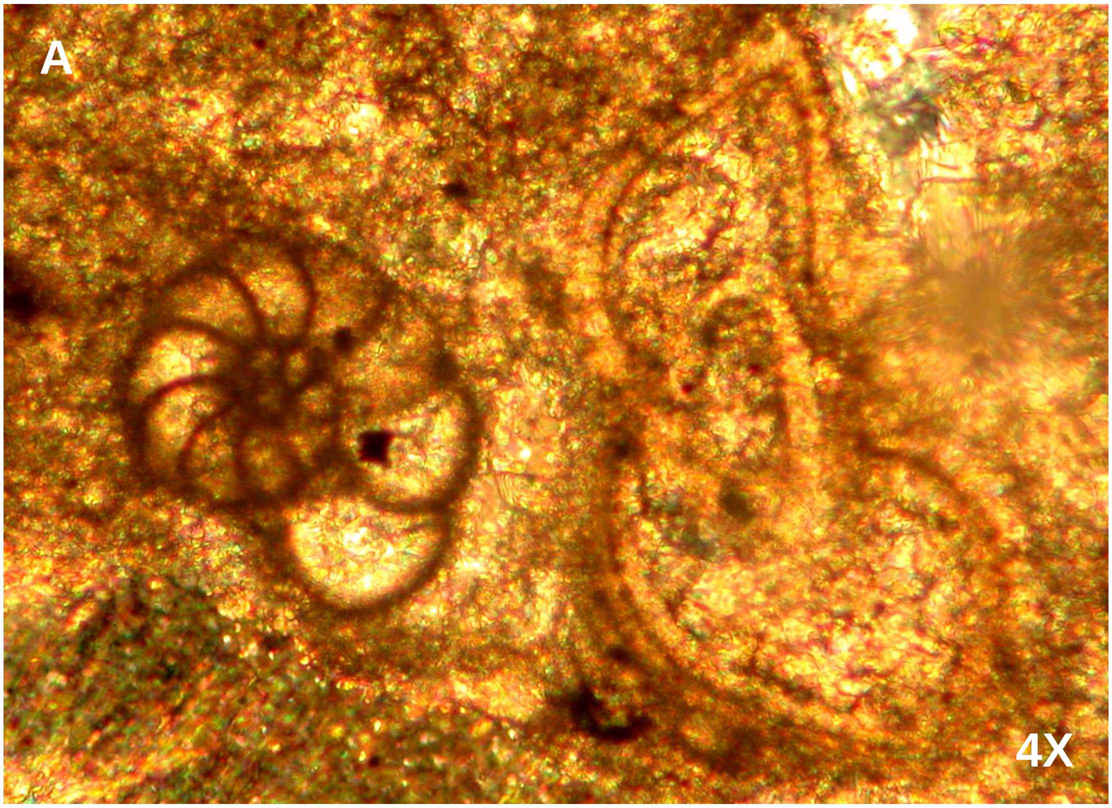

A
4X

PLATE 11

Bed 6: Skeletal packstone of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Axial section of *Daviesina. sp*
B. Median section of *Alveolina (Flosculina) sp*


A
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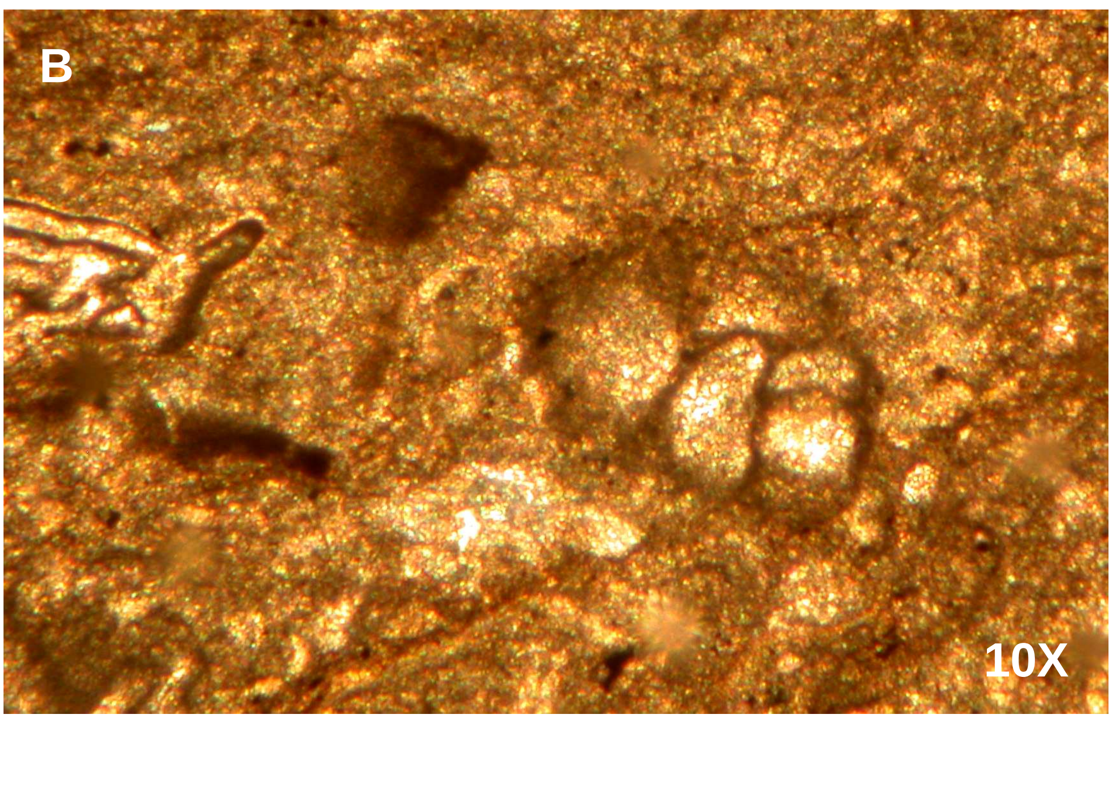
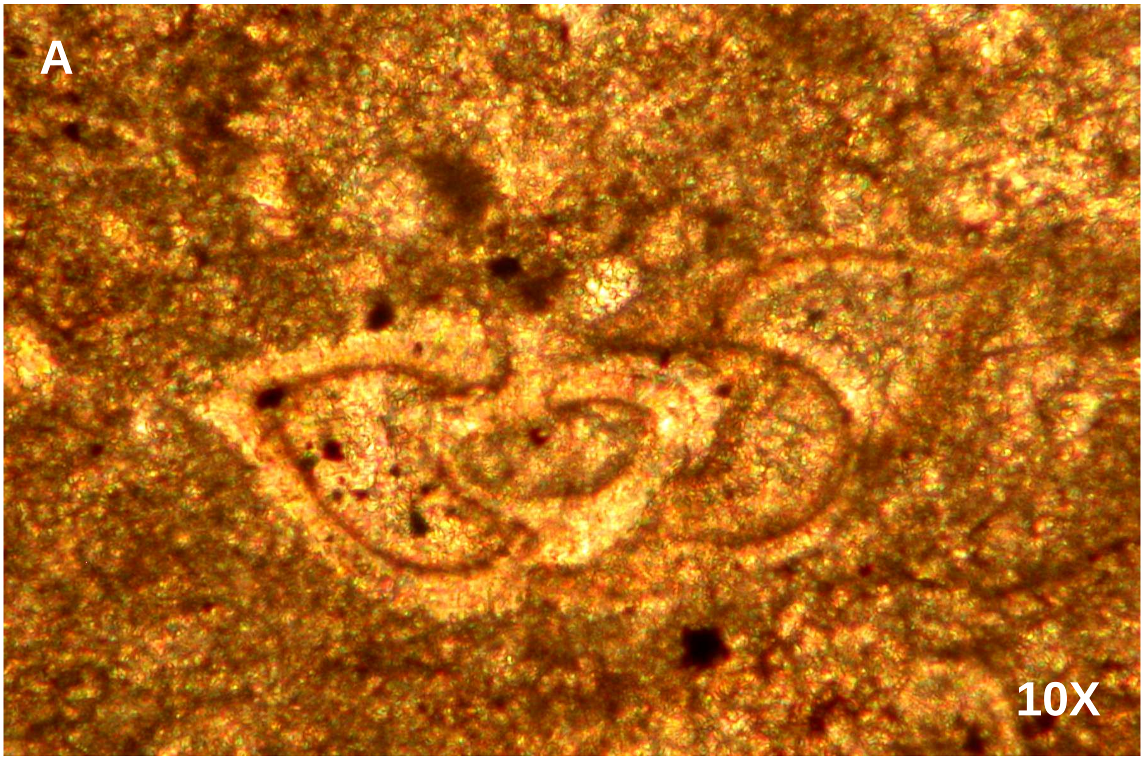

B
10X

PLATE 12

Bed 6: Skeletal packstone of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Medial section of *Globanomalina sp*
B. Axial section of Barnacle


A
10X

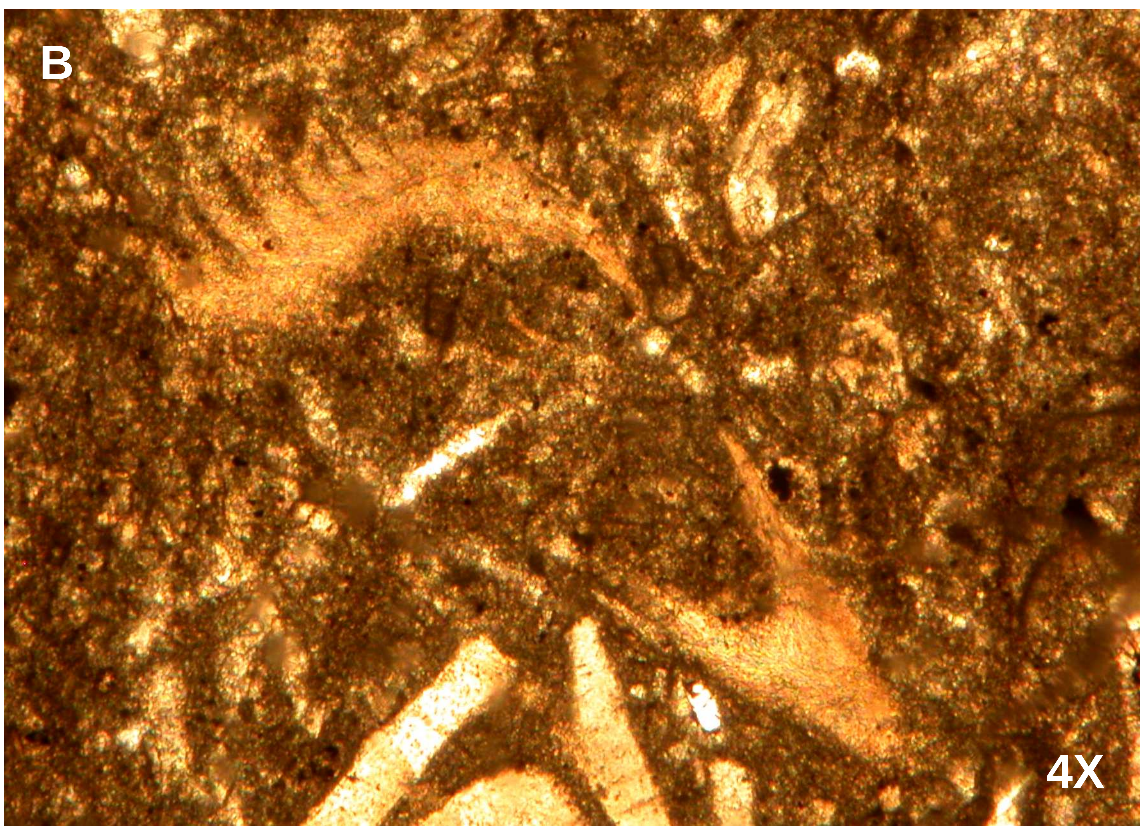

B
4X

PLATE 13

Bed 6: Skeletal packstone of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Axial section of *Lockhartia heimei*
B. Median section of *Miliolid*

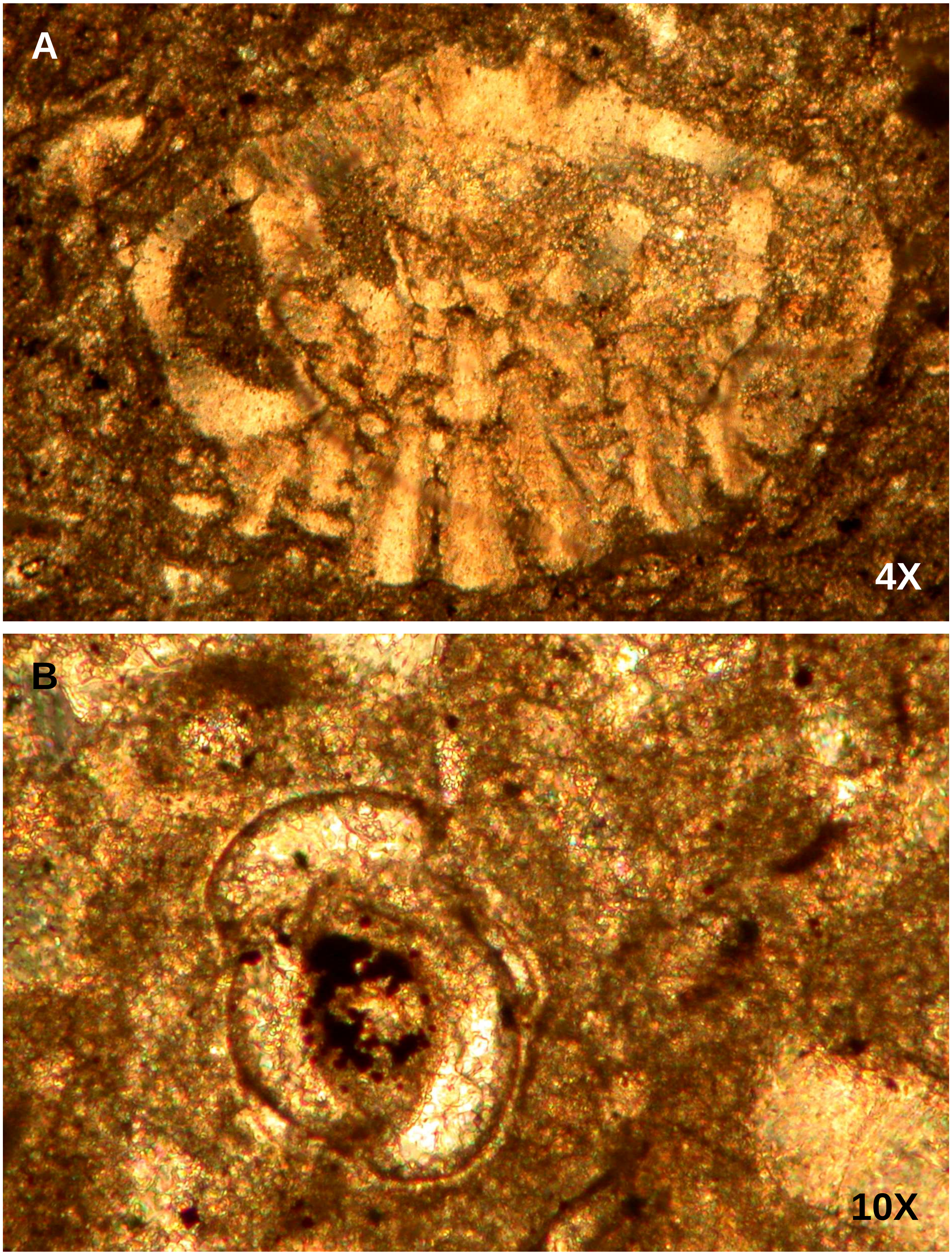
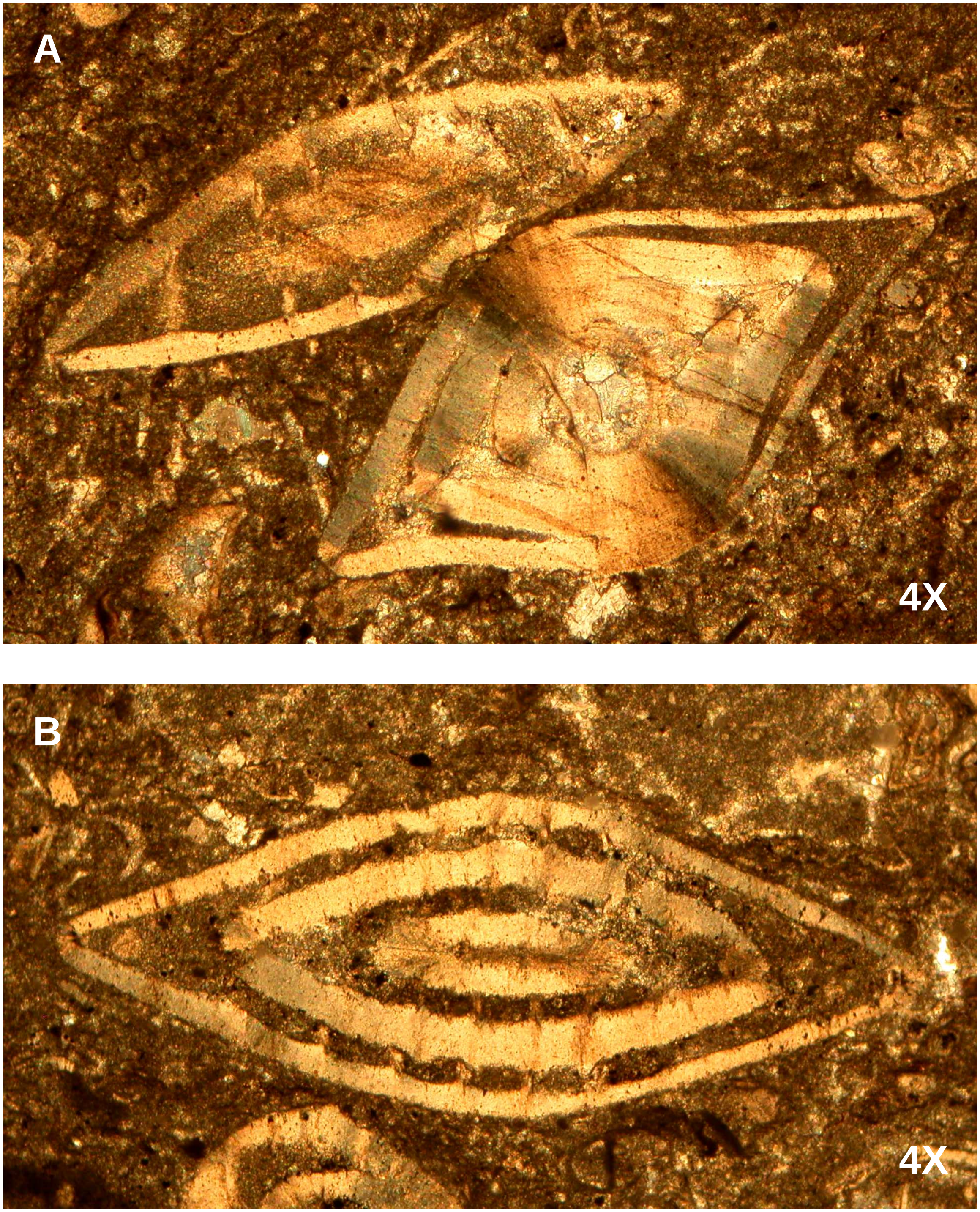

A
4X
B
10X

PLATE 14

Bed 6: Skeletal packstone of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Axial section of *Nummulites globulus* (bottom) and *Nummulites atacicus* (top)
B. Axial section of *Nummulites atacicus*



A
4X
B
4X

PLATE 15

Bed 6: Skeletal packstone of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Medial section of algae.
B. Medial section of an octocoral


A
4X

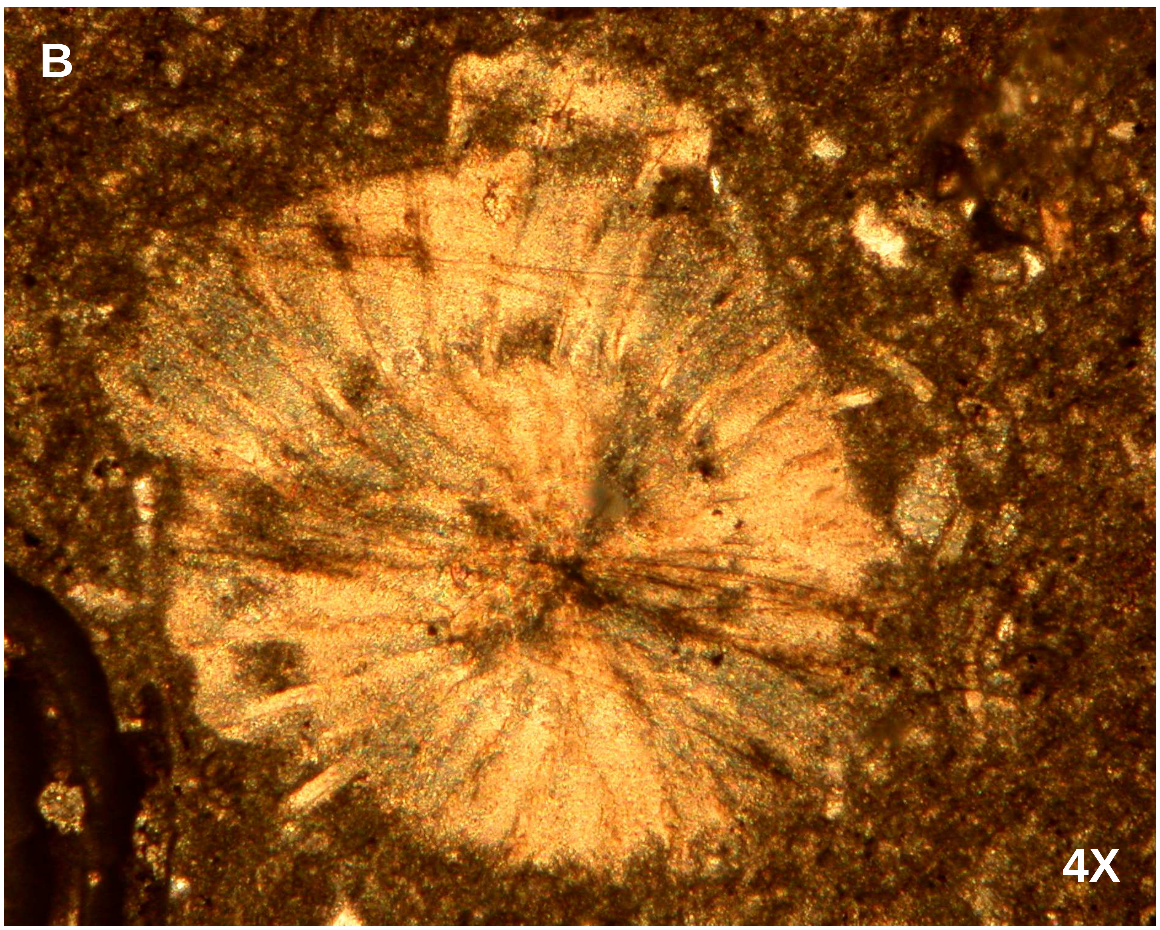

B
4X

PLATE 16

Bed 6: Skeletal packstone of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Axial section of *Nummulites sp.*

Bed 17: Micrite of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

B. Fenestrate porosity


A
4X

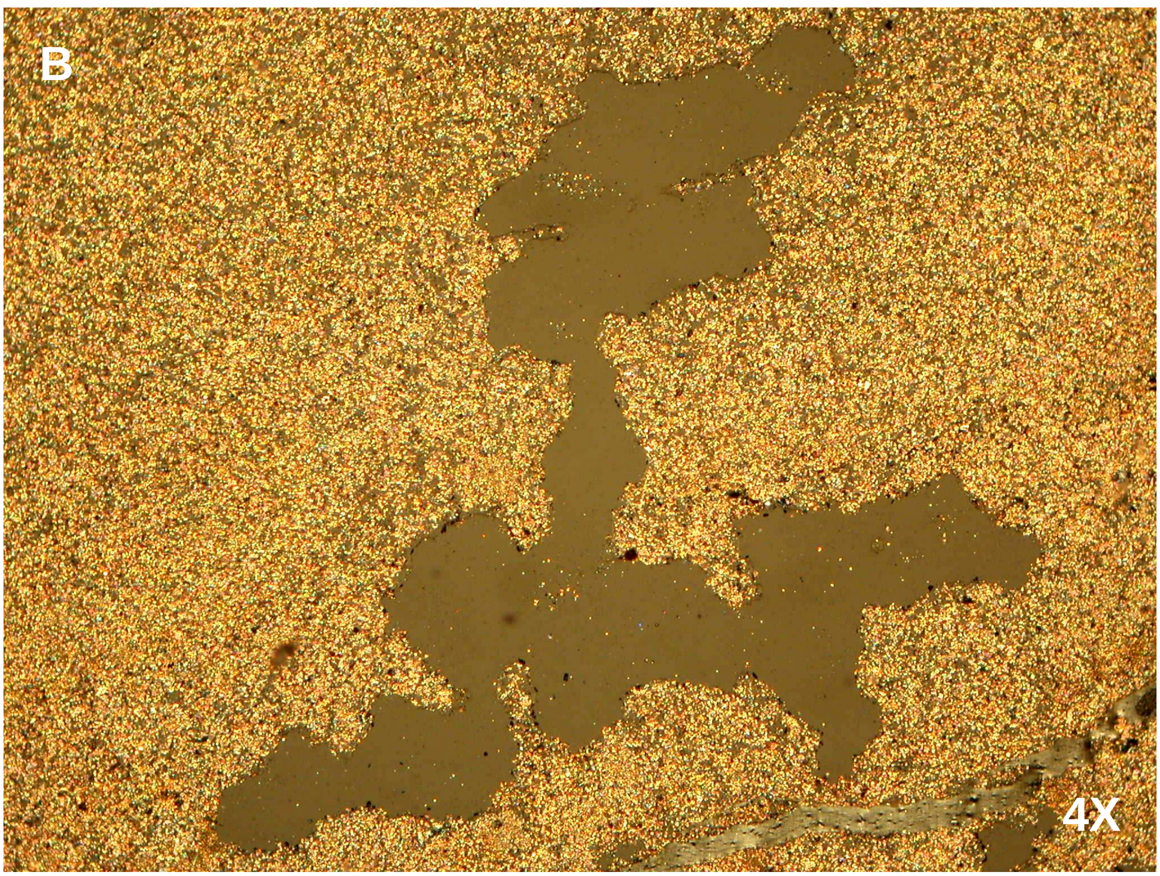

B
4X

PLATE 18

Bed 8: Peloidal-skeletal wackestone of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Conjugate fractures

B. Left lateral fault cuts through Orbitolinid test

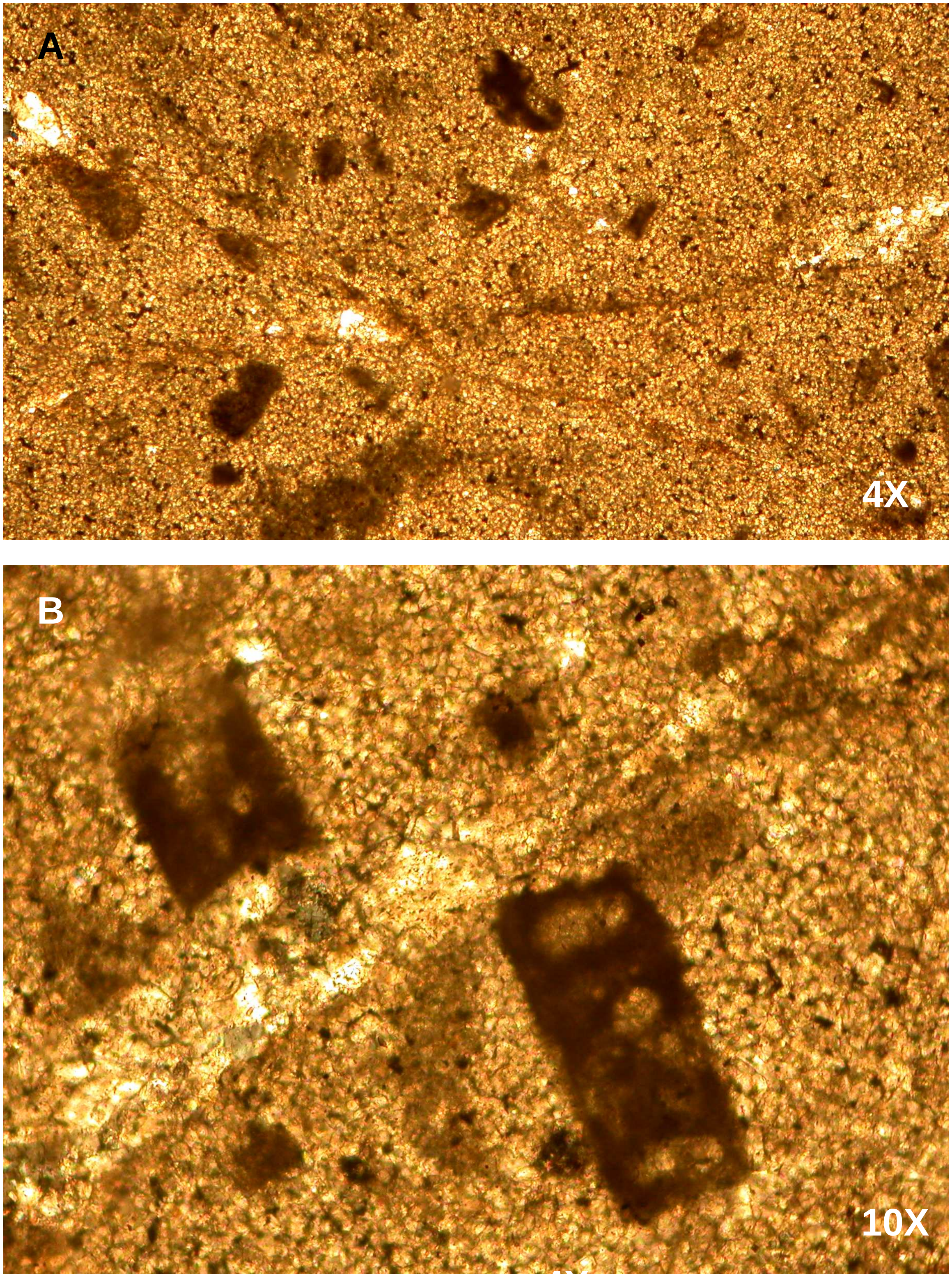

A
4X
B
10X

PLATE 19

Bed 8: Dolomitized peloidal-skeletal packstone of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Axial view of *Oribitoides tissoti*
B. Medial view of *Orbitoides tissoti*

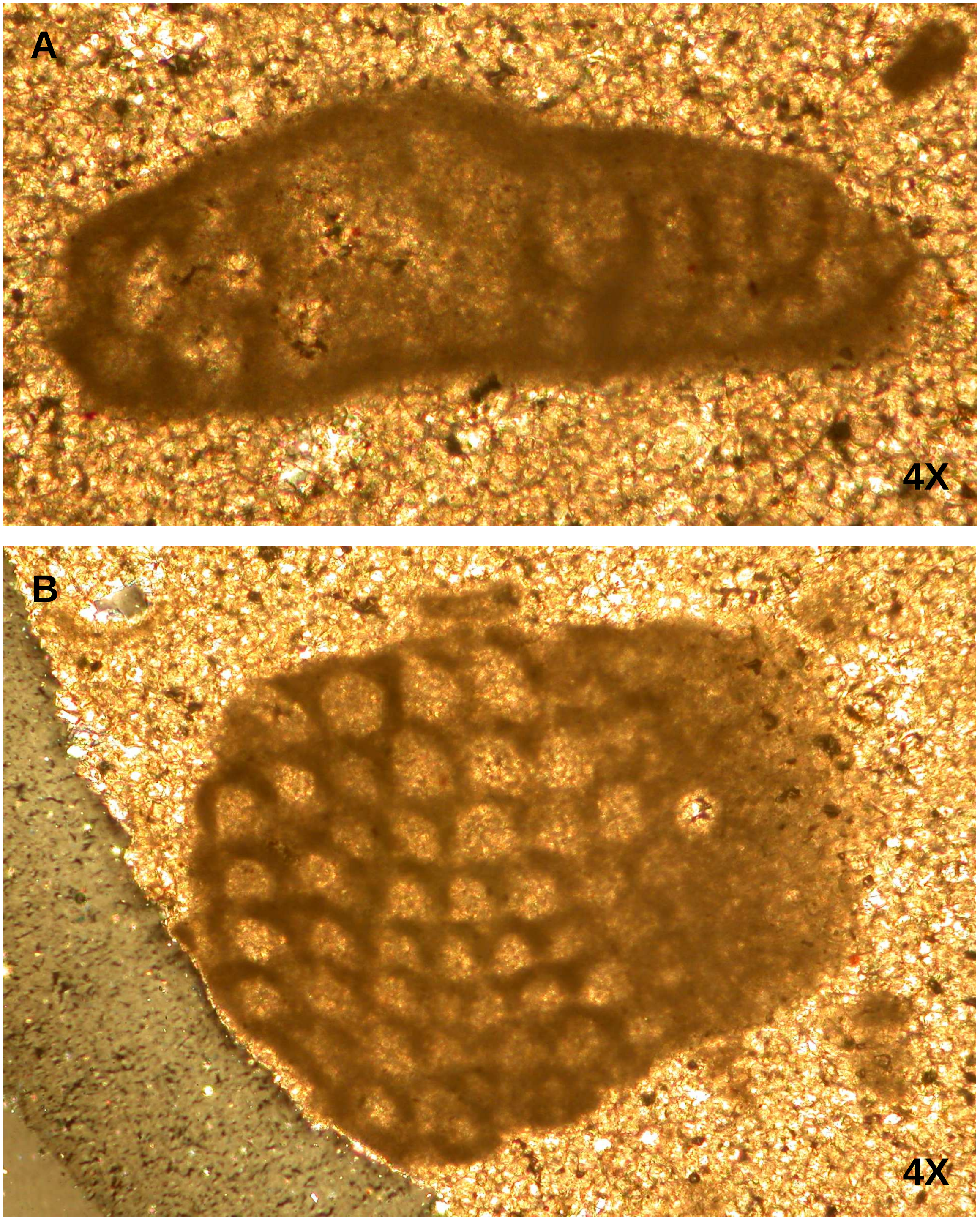

A
4X
B
4X

PLATE 19

Bed 9: Peloidal wackestone of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Channel porosity
B. Fenestrate porosity

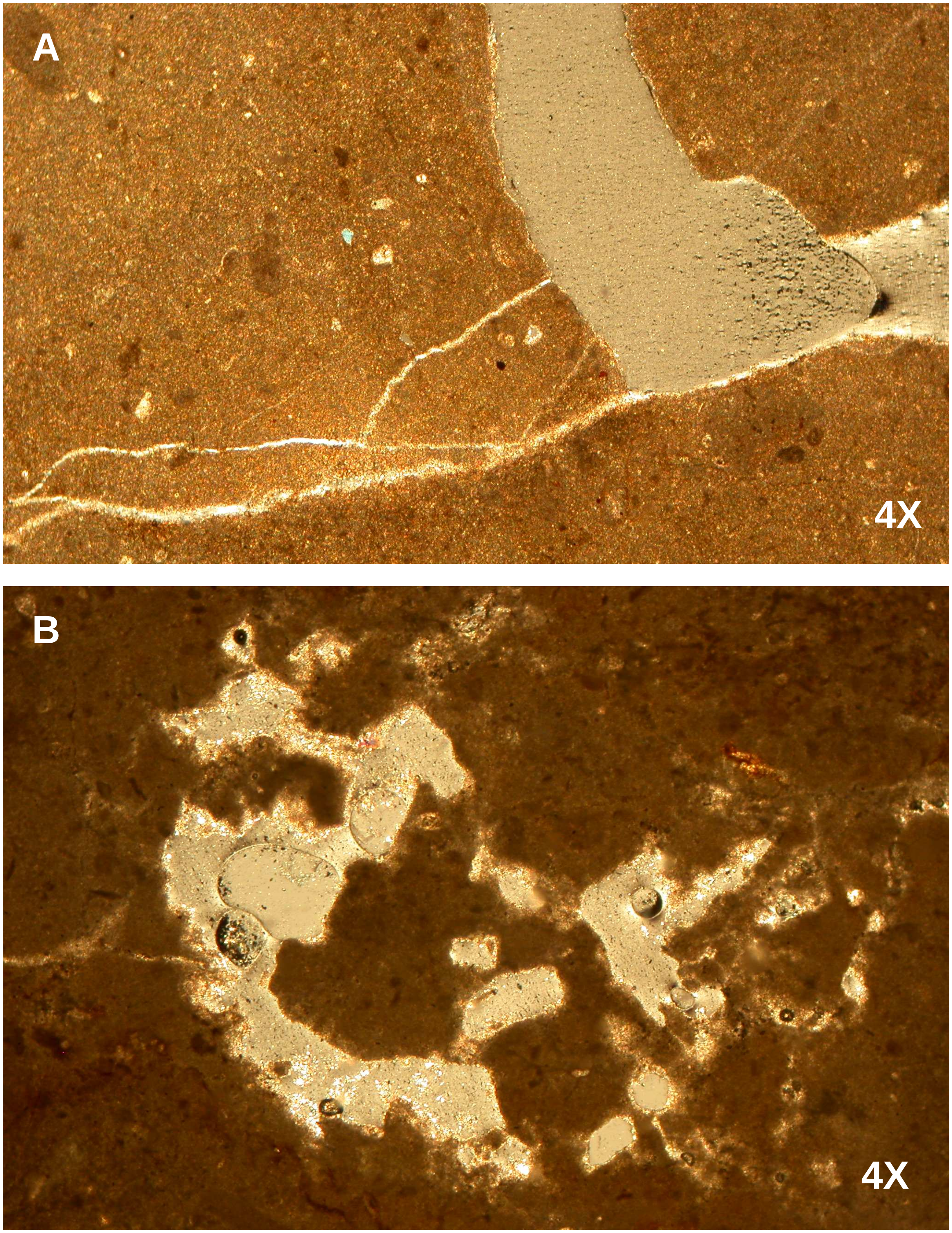

A
4X
B
4X

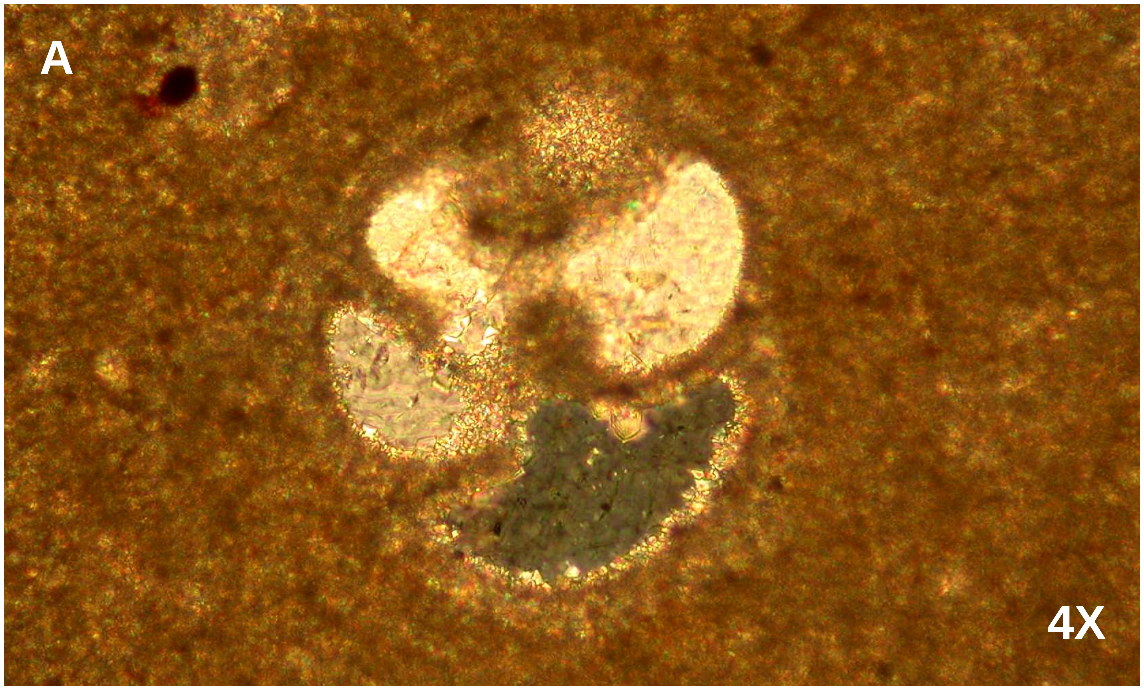
PLATE 20

Bed 9: Peloidal wackestone of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. Moldic porosity in Miliolid

Bed 10: Skeletal wackestone of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

B. Axial section of *Assilina postulosa*


A
4X


B
4X

PLATE 21

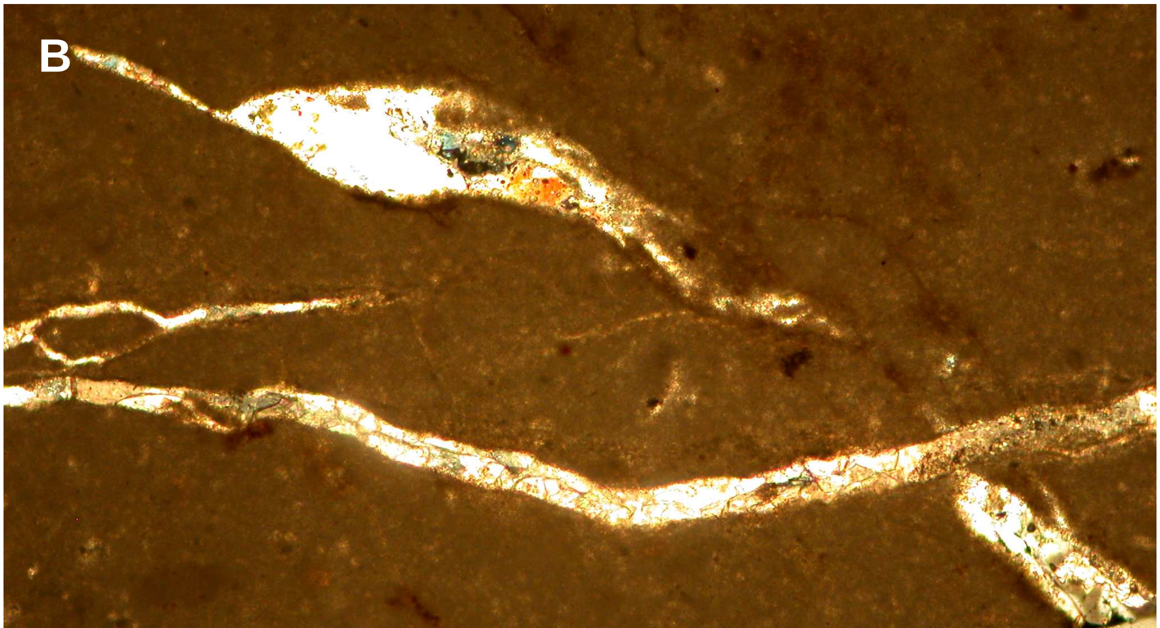
Bed 10: Skeletal wackestone of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

A. *Assilina sp.*

Bed 11: Peloidal wackestone of the Chorgali Formation, collected from Chorgali Pass, Khair-E-Murat Ridge

B. Stylolites


A
4X


B
4X

APPENDIX B

Data

Bed	Thickness in meters	Upper Contact	Lithology	Munsell	Color	Bedform/Structures
1	2.42	Disconformable, Pebble Lag	Biomicrite	2.5Y 6/3	Light yellowish brown	Massive, upwards fining
2	0.33	Disconformable, Foram Lag	Dolomite with Chickenwire anhydrite	2.5Y 5/3	Gray	Massive, upwards fining
3	0.35	Sharp, Pebble Lag	Dolomite	2.5Y 4/2	Light Olive brown	Massive, upwards fining
4	0.37	Sharp	Dolomite with Chickenwire anhydrite	5Y 6/1	Gray	Massive, upwards fining
5	0.45	Gradational	Biomicrite	2.5Y 7/3	Pale yellow	Massive, upwards fining
6	0.78	Sharp	Biomicrite	5Y 6/2	Light olive gray	60 cm aggradational laminasets
7	4.48	Sharp	Micrite	2.5Y 7/3	Light olive brown	Thick laminasets, aggradational
8	1.92	Sharp	Micrite	2.5Y 7/2	Light Gray	Thick laminasets, aggradational
9	0.47	Sharp	Micrite	2.5Y 7/3	Pale yellow	Thin laminasets
10	2.45	Sharp	Micrite	2.5Y 8/2	Pale yellow	Thin-medium laminasets
11	13.0	Sharp	Dolomite	5Y 8/1	White	Thick laminasets
12	1.5	Sharp	Marl	2.5Y 6/4	Light yellowish brown	Thick laminasets
13	1.61	Disconformable	Stromatolite	2.5Y 8/2	Pale yellow	Very fine organic laminae
14	0.06	Sharp	Dark Shale	2.5Y 6/2	Light Brownish grey	Coarsening upwards laminasets
15	2.18	Sharp	Annhydrite	2.5Y 8/1	White	Nodular
16	1.18	Sharp	Micrite	2.5Y 5/1	Gray	Massive
17	3.94	Sharp	Micrite	2.5Y 7/3	Pale yellow	Coarsening upwards laminasets
18	3.2	Sharp	Micrite	2.5Y 7/4	Pale yellow	Coarsening upwards laminasets
19	3.33	Gradational	Very fissile oxidized shale	5Y 5/3	Olive	No apparent bedding
20	4.64	Sharp	Dolomite	?		Massive
21	0.9	Gradational	Poorly sorted matrix supported conglomerate	2.5Y 4/3	Olive brown	Massive
22	2.42	Gradational	Fine grained lithic wacke	2.5Y 3/2	Very dark grayish brown	Parallel

Table 1. Field data collected from Chorgali Pass, Khair-E-Murat Ridge. (NOTE: Lithologies for carbonates were described in greater detail after analysis of thin sections)

Bed	**Lithology**	**Foraminifera**	**Others**
1	Skeletal packstone	*Assilina laminosa, A. sp, Nummulites atacicus,* miliolids	
2	Skeletal wackestone	*Assilina laminosa, A postulosa, Nummulites burd,* planktonics	Echinoderms
3	Dolomitic packstone	*Nummulites increscens, Assilina placentula, Assilina plana, Nummulites globulus*	
4	Peloidal wackestone	Miliolids	Ostracods
5	Dolomitic Skeletal wackestone	*Nummulites burdigalensis, Nummulites sp*	Echinoderms
6	Skeletal packstone	*Alveolina sp, Daviesina sp,*miliolids, planktonics, *Lockhartia heimei, Nummulites globulus , Nummulites atacicus, Nummulites sp*	Bryozoans, echinoderms, octocoral, ostracods
7	Dolomitic mudstone	Barren	
8	Dolomitic Peloidal-skeletal wackestone	*Oribitoides tissoti*	
9	Peloidal wackstone	Miliolids	
10	Skeletal wackstone	*Assilina postulosa, Assilina sp.*	
11	Peloidal wackestone	Miliolids	
12	Dolomitic mudstone	Barren	
13	Cyanobacterial boundstone	Barren	
14	Dolomitic mudstone	Barren	
15	Anhydrite	Barren	
16	Dolomitic mudstone	Barren	
17	Dolomitic mudstone	Barren	Ostracods
18	Dolomitic mudstone	Barren	

Table 2. Paleontological data from petrographic sections (the same samples were analyzed for Calcareous Nannoplankton as well and were barren).

Bed	Porosity Type	Macrofractures	Matrix
1	none		Microspar
2	none	fractured	Microspar
3	vugs		Coarsely crystalline dolomite
4	styloporosity		Microspar
5	styloporosity		Partially dolomitized with Microspar
6	none		Microspar
7	none		Coarsely crystalline dolomite
8	none		Medium crystalline dolomite
9	fenestrate porosity, channel porosity, styloporosity, moldic porosity		Microspar
10	vugs	fractured	Microspar
11	none	fractured	Microspar
12	vugs		Micro crystalline dolomite
13	none		Sand grains interbedded with dolomite
14	none		Medium crystalline dolomite
15	none		Annhydrite
16	channel porosity	fractured	Finely cystalline dolomite
17	fenestrate porosity, fracture porosity		Medium crystalline dolomite
18	fracture porosity		Microcrystalline dolomite

Table 3. Relationship between matrix, porosity and fractures in beds.

VITA

Ali Raza Jaffri

Candidate for the Degree of

Master of Science

Thesis: ENHANCED RECOVERY FROM A FRACTURED RESERVOIR USING HIGH IMPACT BIOSTRATIGRAPHY: A CASE STUDY FROM THE FIM KASSAR OIL FIELD, PAKISTAN

Major Field: Geology

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Experience: Received over $20,000 in research grants as an undergraduate, gave several presentations at professional meetings; worked full-time and put self through college; started company that takes clients to the Himalaya for mountaineering; currently working on PhD.

Professional Memberships: American Association of Petroleum Geologists, Society for Sedimentary geology, Society of Exploration Geophysicists, North American Micropaleontological Society.

Name: Ali Jaffri Date of Degree: July, 2006

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: ENHANCED RECOVERY FROM A FRACTURED RESERVOIR USING HIGH IMPACT BIOSTRATIGRAPHY: A CASE STUDY FROM THE FIM KASSAR OIL FIELD, PAKISTAN

Pages in Study: 125 Candidate for the Degree of Master of Science

Major Field: Geology

Scope and Method of Study: The purpose of this study was to integrate several data sets to solve a geologic problem. The problem investigated was how fractured carbonate reservoirs can be exploited successfully. This was accomplished by identifying the style of fracturing, then isolating fracture prone beds, and then creating a sequence stratigraphic model that would predict the occurrence of these beds in the subsurface.

Findings and Conclusions: The Fim-Kassar anticline is analogous to the Khair-E-Murat anticline as both are composed of the Sakesar and Chorgali Formations. Both structures show small-scale mechanical stratigraphy in the sense that some layers are more prone to fracturing than others. Layers that are composed of microspar matrix are more prone to fracturing than layers that have dolomitic matrix. From basin towards land the following six lithofacies were recognized: Forebank facies, Bank facies, Back-bank facies, Subtidal inner lagoon facies, Intertidal facies, Supratidal facies. Two distinct payzones were recognized on the basis of porosity and fracture occurrence. An identification key was created for well-site geologists such they can biosteer the drill-bit keeping it within the confines of the payzones.