University of Alberta

Sedimentology, Ichnology and Mineralogy of the Upper Bahariya Formation, Western Desert, Egypt

by

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Dedicated to my supportive wife Karen,
whose drive and determination has always inspired me.

ABSTRACT

The Upper Bahariya Formation in the Western Desert, Egypt was deposited on a broad tidally influenced mixed siliciclastic-carbonate ramp on the southern margin of the Neotethys seaway. Analysis of twelve cored intervals focusing on the ichnology, sedimentology and the nature of glaucony suggest these strata were deposited in an interdistributary bay prior to a major marine transgression.

The siliciclastic portions of the Upper Bahariya Formation are interpreted as crevasse splay, tidal flat and distributary mouth bar sandstones; while silts and muds are interpreted as interdistributary bay, marsh and overbank levee deposits. The characteristics of autochthonous glaucony and carbonate facies provide evidence of two scales of flooding events.

Analysis of the occurrence and distribution of glaucony within an ichnologic and sedimentologic framework in the Upper Bahariya Formation provides an invaluable tool that enhances the development and understanding of the depositional model.

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Firstly, I would like to thank my supervisor, Dr. George Pemberton. The opportunity that he provided was a once in a lifetime experience that I will never forget. Without his trust in my abilities I may never have had the chance to see the pyramids of Giza, the temples of Luxor and the streets of Amsterdam. I sincerely enjoyed getting to know George over the years, and especially the time we spent in Egypt. My thanks go out to him for providing me with an amazing project, including all the technical resources, financial support and the opportunity to attend and present at a number of conferences, making my graduate experience truly memorable.

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CHAPTER 1: Introduction

1.1 Introductory Remarks

Middle Eastern countries, particularly Saudi Arabia, Iran, and Iraq, have long been recognized as significant contributors in the world's production of hydrocarbons. Egypt also has the potential for developing into an important hydrocarbon producing country, but unfortunately is less recognized. Dolson et al. (2001) noted that since the first discovery of onshore oil in Egypt, over 15.7 billion barrels of oil equivalent in reserves have been found. In the Western Desert of Egypt, there are currently many producing formations, one of which is the Upper Cretaceous Bahariya Formation. Dolson et al. (2001) shows the exceptional production history of the Western Desert in Egypt (table 1). The economic significance of the Bahariya Formation has captured the attention of many exploratory organizations around the world, driving the need for further research on geological interpretations in the area.

This study focuses on the analysis of core from the Cenomanian upper Bahariya Formation. Lithologic, sedimentologic, biologic, and stratigraphic characteristics have been documented and grouped into facies based on observations from the core. Furthermore, it is recognized that stacking patterns and general trends of the facies support characteristic depositional environments, which allow for paleoenvironmental reconstruction.

Wehr et al. (2002) suggested that the upper Bahariya Formation was deposited on a broad, tidally-influenced ramp on the southern margin of the Neotethys sea-way. Thin, sand-poor parasequences, dominated by glauconitic rich clastic lithologies and subordinate carbonate units, correlate regionally and contain lithologic, biologic and sedimentologic properties that are suggestive of a marginal marine setting. Sedimentary structures such as mud doublets, flaser/wavy/convolute bedding, slump structures, small scale ripples, and planar laminations, along with ichnological characteristics such as *Glossifungites* surfaces and a mixture of trace fossils from what appear to be the *Skolithos* and *Cruziana* ichnofacies, suggest deposition in a tidally influenced, relatively low energy, restricted marine setting. Very fine-grained sandstones of the upper Bahariya Formation are interpreted as tidal flat, crevasse splay and distributary mouth bars located in an interdistributary bay environment. Marsh muds and interdistributary bay shales are also common within the bay fill succession. The abundance of autochthonous and allochthonous glaucony throughout the unit allows for supplementary interpretations, including sequence stratigraphic and environmental interpretations.

FIELD	COMPANY	YEAR	DRILLING PROVINCE	MMBOE	BCF GAS	DISCOVERY WELL	AGE	MAJOR TRAP	PRIMARY REFERENCE
BELAYIM MARINE	PETROBEL	1961	GULF OF SUEZ	1593	0.00	BELAYIM M-1	LANGIAN	Structural	Matbouly and Sabbagh, 1996
MORGAN OLD-SOUTH	GUPCO	1965	GULF OF SUEZ	1201	0.00	MORGAN-1	LANGIAN	Structural	Matbouly and Sabbagh, 1996
OCTOBER MAIN	GUPCO	1977	GULF OF SUEZ	848	0.00	GS195-1(OCT-A1)	CRETACEOUS	Structural	Matbouly and Sabbagh, 1996
RAMADAN	GUPCO	1974	GULF OF SUEZ	668	0.00	GS 303-1	CRETACEOUS	Structural	Matbouly and Sabbagh, 1996
SIMIAN	BRITISH GAS	1999	MEDITERRANEAN	416-666	2500-4000	SIMIAN-1	PLIOCENE	Stratigraphic	IHS Energy Group, 1999
BELAYIM LAND	PETROBEL	1955	SINAI	645	0.00	BELAYIM 112-1	SERRAVALIAN	Structural	Matbouly and Sabbagh, 1996
JULY	GUPCO	1973	GULF OF SUEZ	625	0.00	GS 311-1 (J-4)	BURDIGALIAN	Structural	Matbouly and Sabbagh, 1996
SCARAB	BRITISH GAS	1998	MEDITERRANEAN	375-466	2800.00	SCARAB-1	PLIOCENE	Structural	IHS Energy Group, 1999
TEMSAH	MOBIL	1981	MEDITERRANEAN	333-450	2000-2700	EL TEMSAH-2	SERRAVALIAN	Structural	IHS Energy Group, 1999
OBAYEID	OBAIYED	1993	WESTERN DESERT	283-366	1700-2200	OBAYID-3	JURASSIC	Structural	IHS Energy Group, 1999
ROSETTA	BRITISH GAS	1997	MEDITERRANEAN	333-416	2000-2500	ROSETTA-3	PLIOCENE	Structural	IHS Energy Group, 1999
RAS GHARIB	GPC	1938	EASTERN DESERT	357	0.00	RAS GHARIB-3	SERRAVALIAN	Combination	Matbouly and Sabbagh, 1996
SAFFRON	BRITISH GAS	1998	MEDITERRANEAN	333-416	2000-2500	SAFFRON-1	PLIOCENE	Structural	IHS Energy Group, 1999
HAPY	BP AMOCO	1997	MEDITERRANEAN	250-416	1500-2500	HAPY-1	PLIOCENE	Structural	EGPC Records
RAS BUDRAN	SUCO	1978	GULF OF SUEZ	270	0.00	EE 85-1A	CRETACEOUS	Structural	Matbouly and Sabbagh, 1996
BADRI	GUPCO	1987	GULF OF SUEZ	267	0.00	BDR-E-1	SERRAVALIAN	Structural	Matbouly and Sabbagh, 1996
DENISE	IEOC	1995	MEDITERRANEAN	125-150	750-900	DENISE-1	PLIOCENE	Structural	IHS Energy Group, 1999
ABU GHARADIG	GUPCO	1969	WESTERN DESERT	220	586.00	ABU GHARADIG-1	CRETACEOUS	Structural	Hegazy, 1992
BALTIM	IEOC	1993	MEDITERRANEAN	83-133	500-800	BALTIME-1	MESSINIAN	Combination	IHS Energy Group, 1999
ZEIT BAY	SUCO	1980	GULF OF SUEZ	215	0.00	OO 89-1	CRETACEOUS	Structural	Matbouly and Sabbagh, 1996
KHALDA	WEPCO	1971	WESTERN DESERT	213	771.00	KHALDA-1	CRETACEOUS	Structural	Hegazy, 1992
ABU MADI	IEOC	1967	NILE DELTA	209	1254.00	ABU MADI-1	MESSINIAN	Stratigraphic	Moussa and Matbouly, 1994
MORGAN OLD-NORTH	GUPCO	1965	GULF OF SUEZ	200	0.00	MORGAN-1	LANGIAN	Structural	Matbouly and Sabbagh, 1996
SHAMS	REPSOL	1997	WESTERN DESERT	176-250	1000-1500	SHAMS-2X	JURASSIC	Structural	IHS Energy Group, 1999
BED-3	SHELL	1983	WESTERN DESERT	153	847.00	BED 3-1	CRETACEOUS	Structural	Hegazy, 1992
RAS FANAR	SUCO	1978	GULF OF SUEZ	143	0.00	KK 84-1	SERRAVALIAN	Stratigraphic	Matbouly and Sabbagh, 1996
HILAL	GUPCO	1976	GULF OF SUEZ	125-140	0.00	GS 391-1	CRETACEOUS	Structural	Matbouly and Sabbagh, 1996
BAKR	GPC	1958	EASTERN DESERT	135	0.00	BAKR-6	SERRAVALIAN	Structural	Matbouly and Sabbagh, 1996
BED-2	SHELL	1982	WESTERN DESERT	132	792.10	BED 2-1	CRETACEOUS	Structural	Hegazy, 1992
SHOAB ALI	GUPCO	1977	GULF OF SUEZ	110	0.00	ALMA-2	SERRAVALIAN	Structural	Matbouly and Sabbagh, 1996
KANAYES	IEOC	1992	WESTERN DESERT	100-116	600-700	KANAYIS - 5	JURASSIC	Structural	IHS Energy Group, 1999

Table 1 - Giant Oil and Gas Fields of Egypt (Defined as >100 MMBOE). Data are Complete to January 1, 2000 (From Dolson et al., 2001).

An in-depth core study of the sedimentology, stratigraphy and ichnology is vital in the development of depositional models that can be compared and contrasted with modern day analogues. Comparison of a variety of modern depositional environments to the Bahariya Formation, such as the Mississippi river delta and the Volga river delta will provide insight and understanding into the processes involved.

1.2 Study Area

The regional area of study is located south of the Mediterranean coast on the northern reaches of the African continent. The subsurface data utilized in this project is situated in the north Western Desert of Egypt, within the Khalda ridge region (Fig. 1.1). The Khalda Concession is located approximately 100 km south of the Mediterranean coast and approximately 300 km west of Cairo. Within the Khalda Concession, there are four main fields, the Salam, Kenz, Hayat, and Yasser (Fig. 1.2), which are analyzed in this study.

Background data on the Bahariya Formation is limited, especially in the Khalda Concession, and will therefore be analyzed at a much larger scale. Previous studies on the Meleiha area and the Bahariya Oasis serve as a general guideline for data collected and interpreted in the Khalda Concession.

1.3 Regional Tectonics, Paleogeography and Stratigraphy

Tectonic Framework:

The Mesozoic was an era of great tectonic and environmental change in the North African region, as was the case for much of the world. Egypt was subjected to numerous environmental and continental alterations that influenced and shaped coastal areas, as well as created tectonic depocenters. This was especially the case in the north-western regions of Egypt where there were plate motions between the African and Laurasian plates (Sestini, 1984).

Reconstructions of early Mesozoic plate motions suggest that the Mediterranean Sea was closed and southern Turkey was connected to northern Egypt (Morgan, 1990). If reconstructions are correct, then it is estimated that rifting of the Eastern Mediterranean Seaway separating the 'Turkish' (Apulian) microplate from Africa, originated in the early Mesozoic (Morgan, 1990) (Fig. 1.3). At the time of deposition of the Bahariaya Formation, the eastern Mediterranean Sea formed part of the southern reaches of the

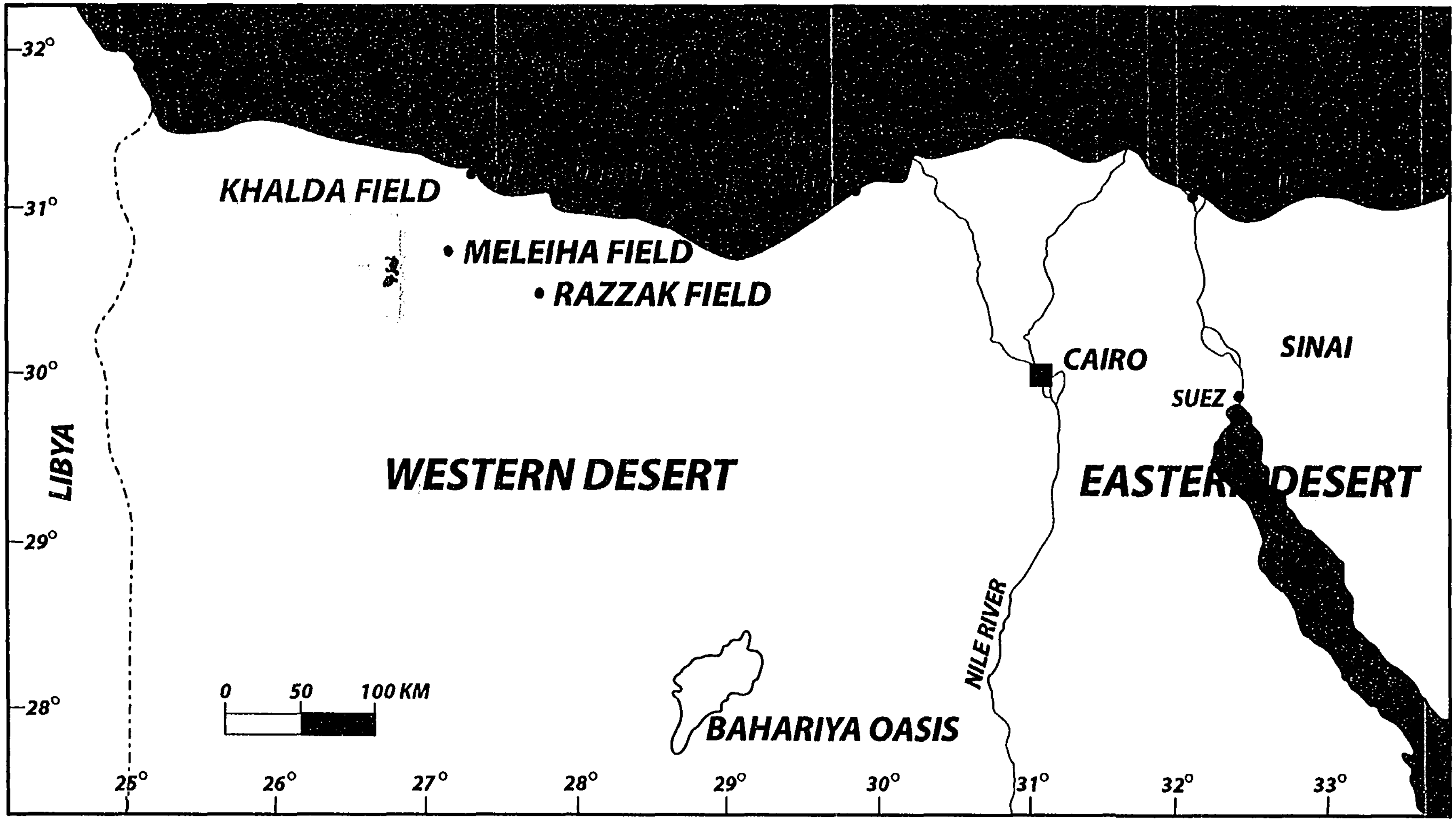

Fig. 1.1 - Map showing the location of the Khalda, Meleiha and Razzak fields and the Bahariya Oasis. (Modified from Abdel-Kireem et al, 1993).

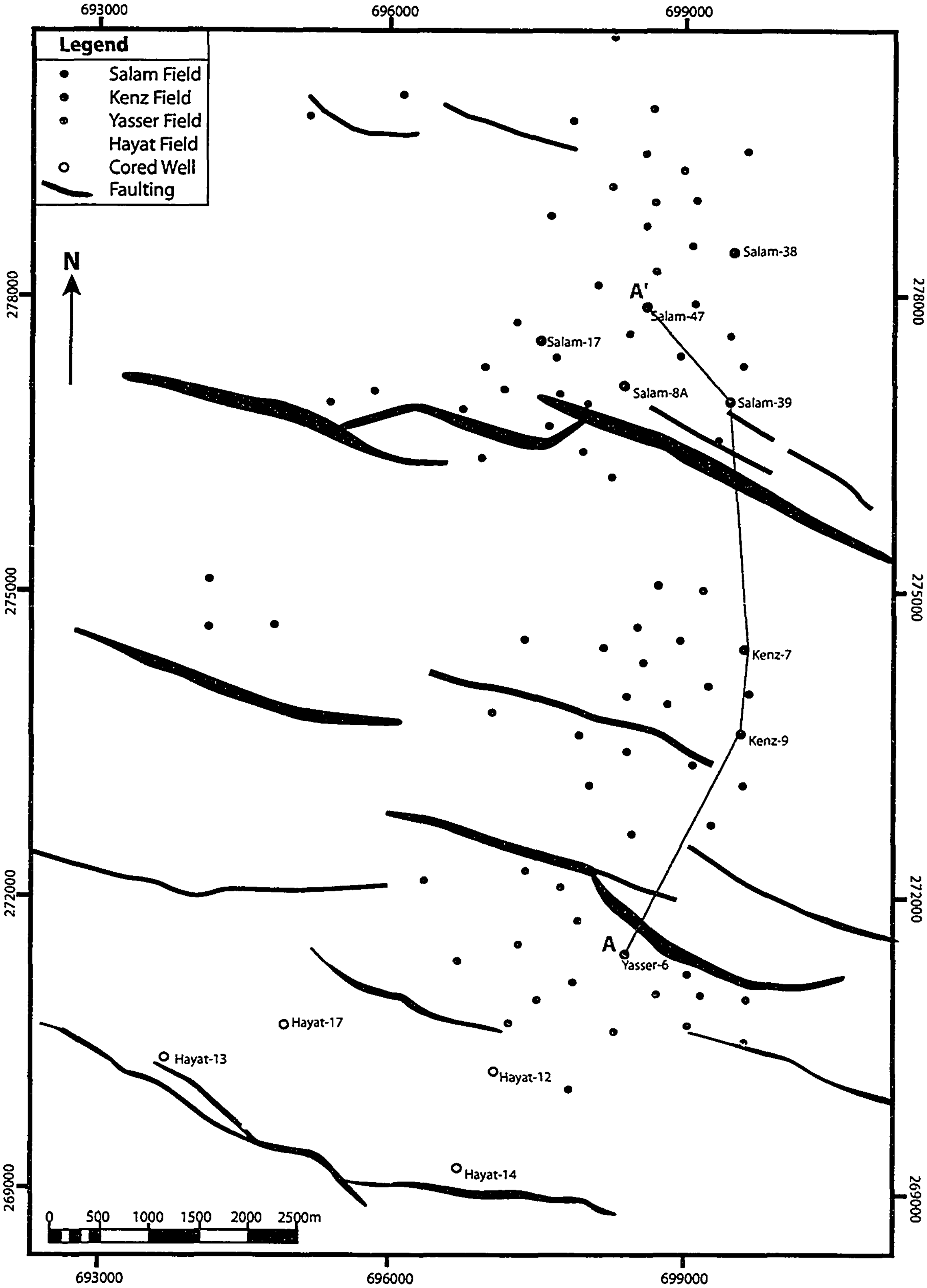

Fig. 1.2 - The Salam, Kenz, Hayat and Yasser fields within the Khalda Concession (Wher, unpublished data)

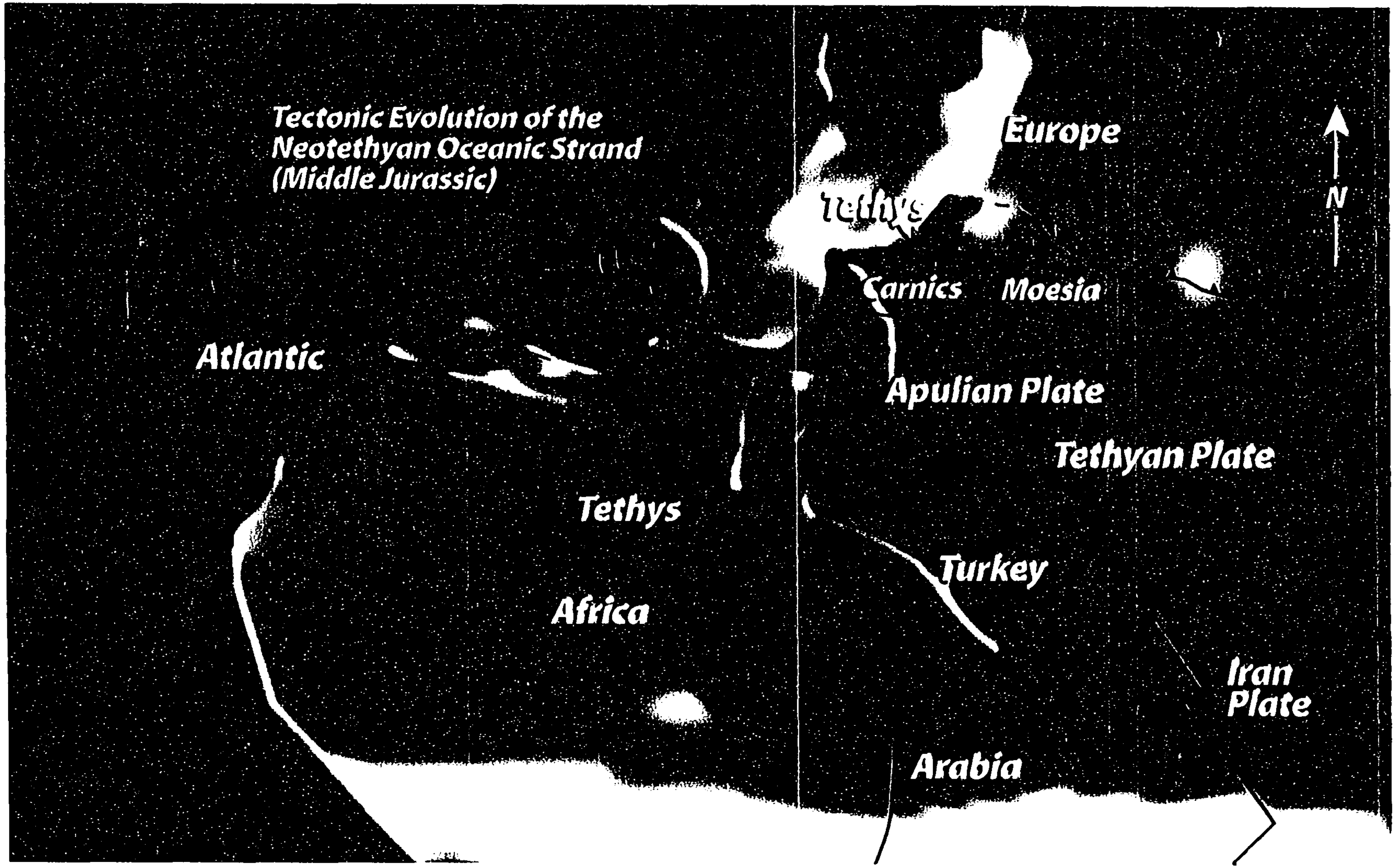

Fig. 1.3 - Tectonic evolution of the Neotethyan oceanic strand in the Middle Jurassic (Modified from Scotese, 2004).

Neotethyan oceanic strand (Sengor et al, 1984). The opening of the Alpine Tethys, or Neotethys, after the destruction of the Paleotethys, occurred concurrently with the opening of the central Atlantic Ocean in early Jurassic time (Meshref, 1990).

Large sinistral shear zones, established in the Jurassic and Cretaceous, developed as a result of up to 2000 km of transcurrent motion between the African and Laurasian plates (Meshref, 1990). Consequently, two main tectonic elements were established: 1) west-northwest trending folds with associated thrust faults and 2) east-northeast trending strike slip faults with left lateral motion (Meshref, 1990). During the late Cretaceous through to the Paleocene, large dextral shear zones were established due to a reversal in plate motion resulting in: 1) east-northeast folding with associated thrust faults and 2) west-northwest strike slip faults with right lateral motion (Meshref, 1990) (Fig. 1.4).

The depositional patterns of many formations in the Western Desert of Egypt are influenced greatly by the aforementioned tectonic forces. The rifting to the north of Egypt, along with the Atlantic rifting to the south, resulted in major extensional tectonics that created depocenters in the interior of northern Africa. Isopach maps demonstrating the depositional thicknesses of the Kharita, Bahariya and Abu Roash formations show trends that can be correlated to the tectonic settings (Meshref, 1990) (Fig. 1.5 a,b,c).

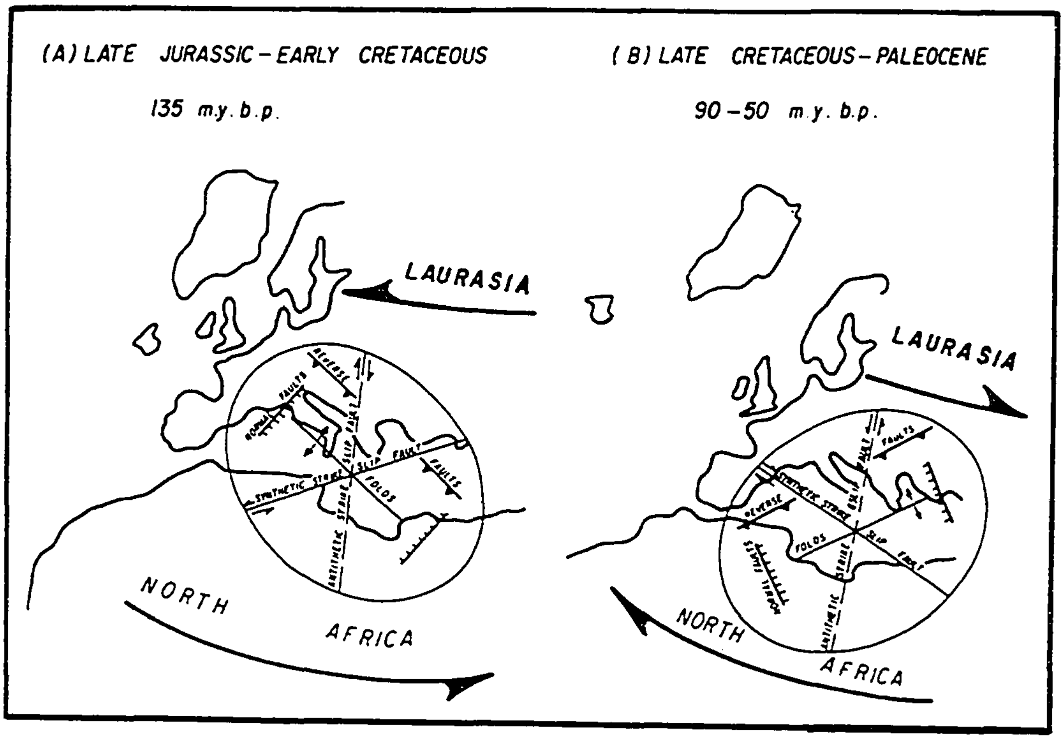

Fig. 1.4 - Transcurrent motion between Africa and Laurasia (From Meshref, 1990 Modified from Smith, 1971).

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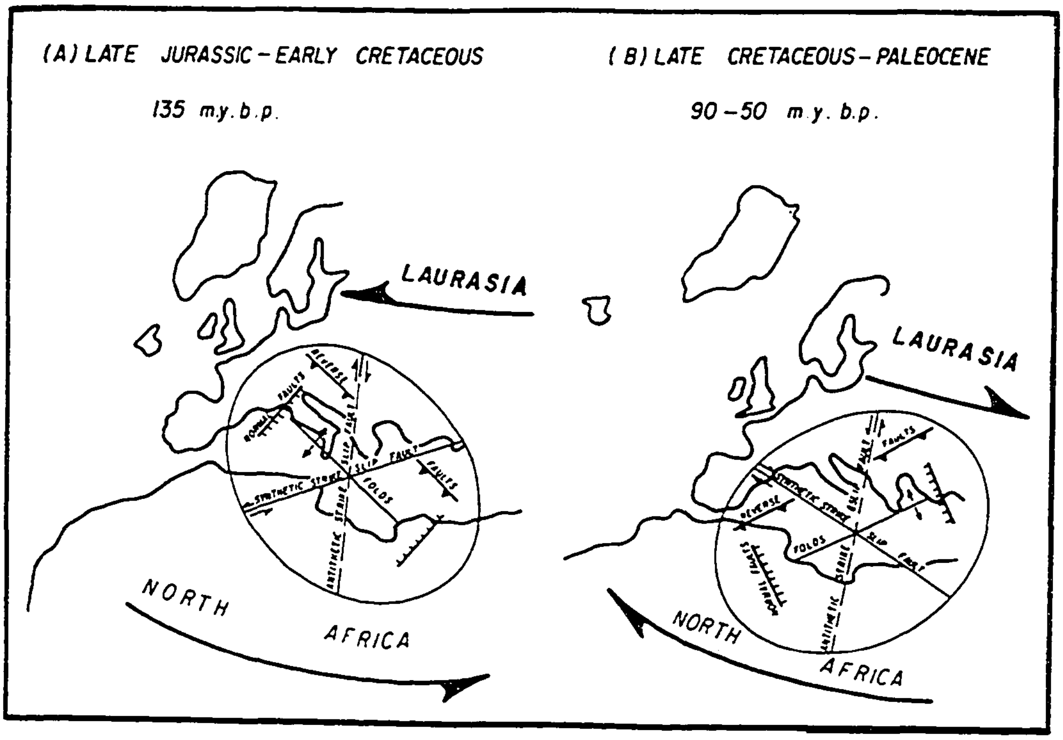

Fig. 1.4 - Transcurrent motion between Africa and Laurasia (From Meshref, 1990 Modified from Smith, 1971).

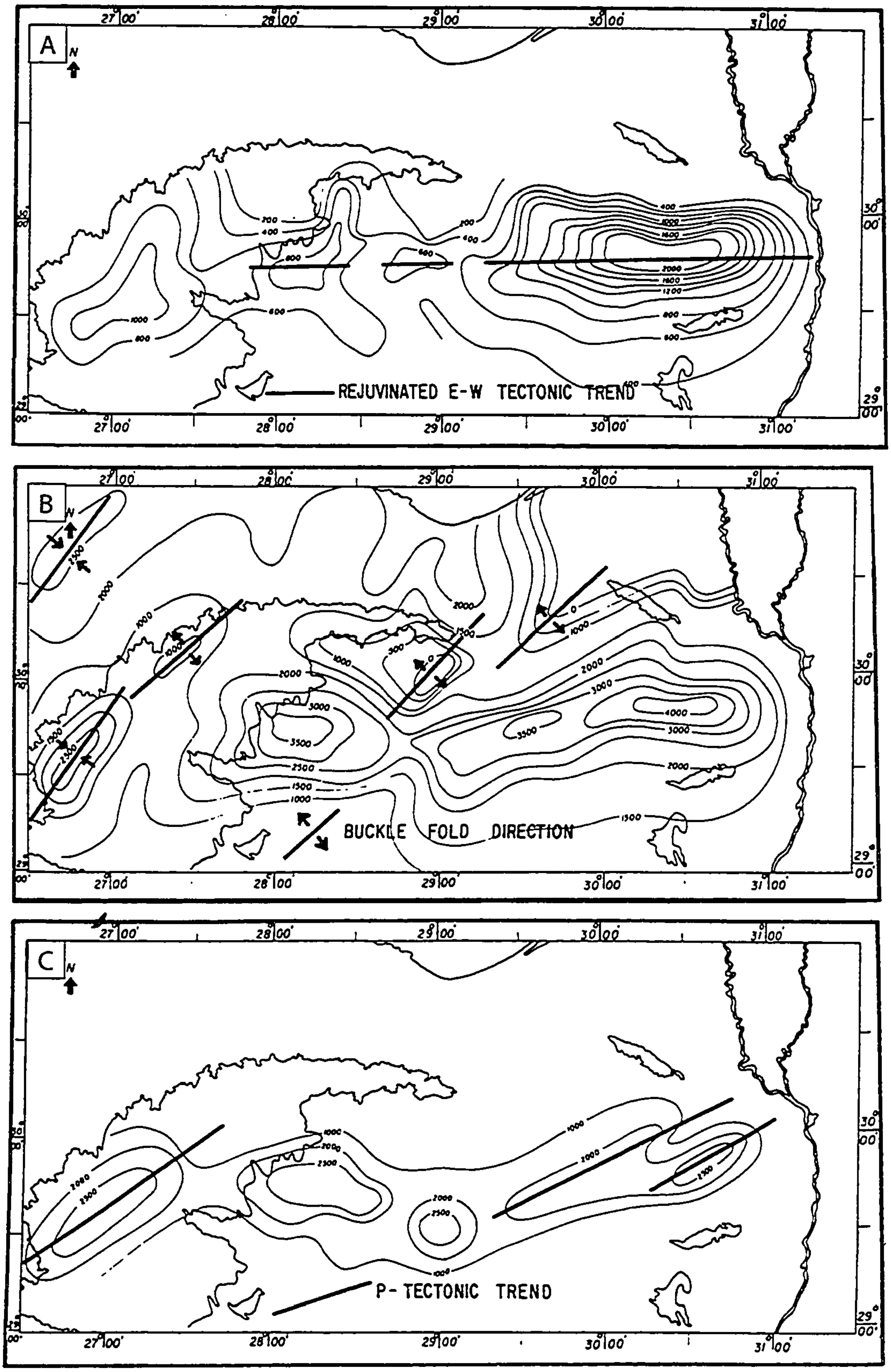

Fig. 1.5 a, b & c - Isopach maps of the **a)** Kharita Formation, **b)** Bahariya Formation and **c)** Abu Roash Formation (From Meshref, 1990).

During the Late Cretaceous, as the African plate moved toward the Eurasian plate, north-south compressive stresses were generated in the Neotethys realm.

Regional Stratigraphy and Paleogeography:

Northern Egypt experienced its first Mesozoic marine inundation in tandem with the opening of the Neotethys and the separation of the Apulian microplate (Hantar, 1990). At this time, most of the north Western Desert was transformed into a shallow open marine environment that stretched laterally along a stable, long-lived platform (Fig. 1.6). It has been proposed that clastic input originated from sources in the east and the south (Hantar, 1990). In some cases, carbonate sedimentation was the dominant process due to a pause in the clastic supply or a distal source area (Hantar, 1990). Evidence for a warm, humid to semi-humid climate exists in deposits of the Nubian strata in the form of extensive floral remains (Klitzsh, 1979). This proposed paleoclimate is consistent with the estimated paleo-latitude of Egypt for this time period, which is just north of the equator.

The Cretaceous stratigraphy of the Western Desert is separated into an upper and a lower unit, coinciding with the boundary between the Upper and Lower Cretaceous (Fig 1.7). The lower unit is dominated by clastic lithologies, while the upper unit is dominated by carbonates. During the Upper Cretaceous, Egypt was experiencing one of the widest encroachments of the sea, which resulted in deposition of a dominantly carbonate section. This sea level change corresponds to a world-wide or eustatic sea level rise (Morgan, 1990). The Bahariya Formation was deposited concordantly with this sea level rise in the early Upper Cretaceous (Cenomanian).

The Bahariya Formation was deposited conformably on top of the Kharita Member, which is Albian to early Cenomanian in age. The Kharita Member is a fine to coarse-grained sandstone with subordinate shale and carbonate interbeds. An increase in the frequency and thickness of the interbeds is apparent in a northwest direction (Hantar, 1990). According to Hantar (1990), the Kharita Member was deposited in a high-energy, shallow marine shelf system. Northern sections appear to be related to deeper water conditions, while reaches of more southerly extent tend to display continental characteristics. The Kharita Member is separated from the overlying Bahariya Formation by a prominant, laterally extensive limestone bed.

The overlying Abu Roash Formation is also conformable to the Bahariya Formation. It is comprised predominantly of limestone with interbeds of shale and sandstone (Hantar, 1990). The formation has been divided into seven members, which

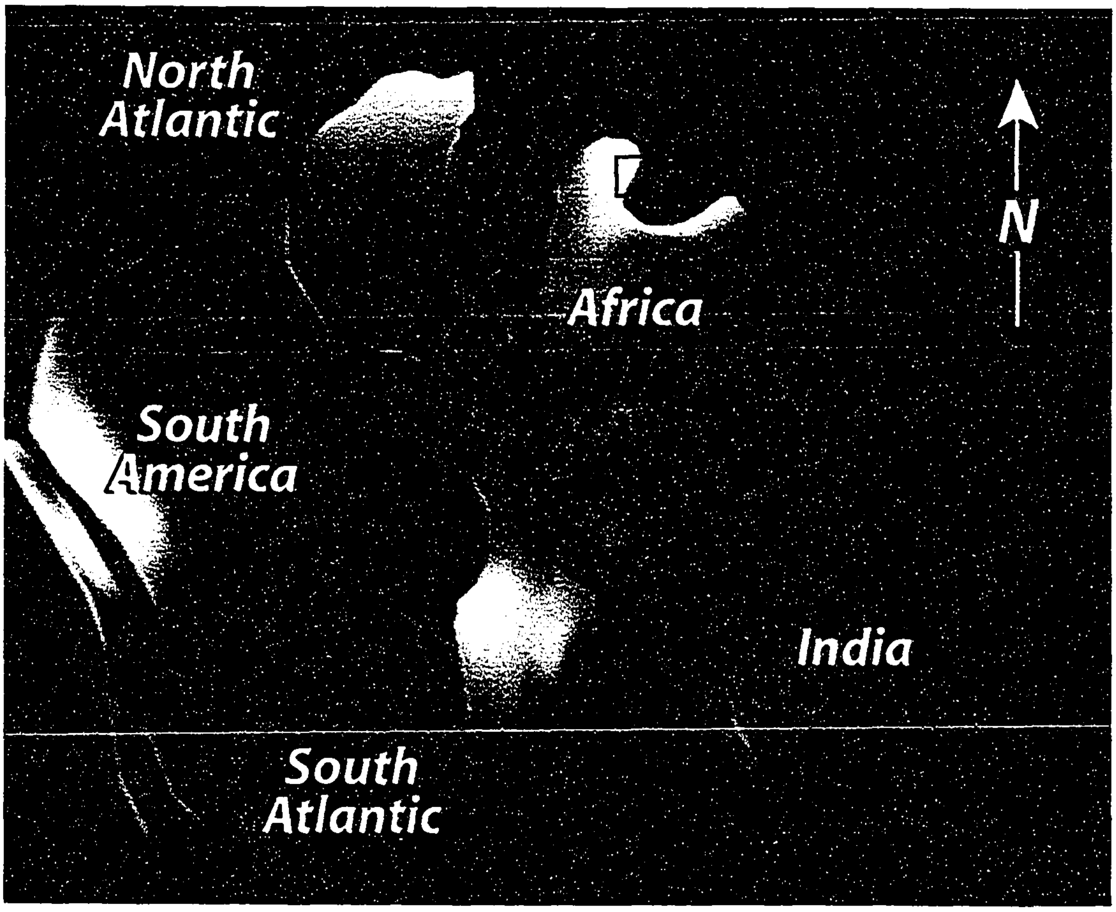

Fig. 1.6 - Schematic diagram showing the paleogeography of the north western desert, Egypt exhibiting large embayments due to a major marine inundation during the Cenomanian (Modified from Scotese, 2004).

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in ascending order are: G, F, E, D, C, B and A. Hantar (1990) suggested that the 'G' member is equivalent to the El Heiz Member of the Bahariya Formation and is of Late Cenomanian age. Members B, D and F have been described as relatively clean carbonates while Members E, C, A and G are largely fine clastics, Turonian to Santonian in age. Throughout the Abu Roash, shales are gray to green in color and are sometimes rich in glaucony and pyrite while the sandstones tend to be fine-grained, with argillaceous and calcareous lithologies. Cryptocrystalline limestones comprise the lithology of the carbonate sections (Hantar, 1990). In northern sections, the contact between the Abu Roash and the Bahariya Formations is easily recognized by the abrupt change from a clastic to a carbonate system.

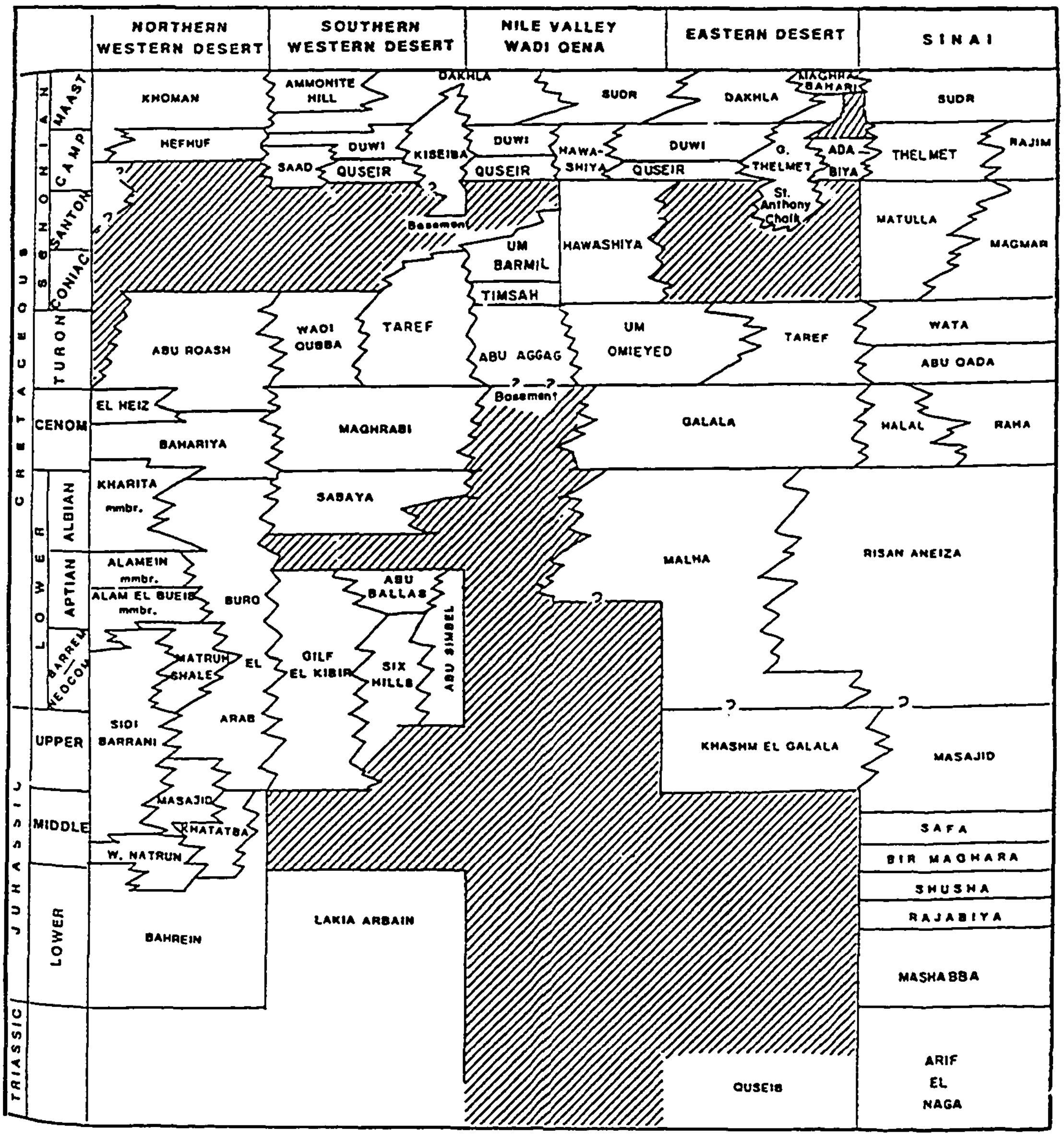

Fig. 1.7 - Stratigraphic correlation of Mesozoic lithostratigraphic units in significant localities (Applicable formations of the lower Cretaceous unit in yellow) (From Kerdany and Cherif, 1990).

1.4 Local Stratigraphy and Paleogeography

Bahariya Formation in the Meleiha Area:

Most of the research that has been conducted on the Bahariya Formation in neighboring fields focuses on the Meleiha field, located approximately 30 km east of the Khalda Concession. Metwalli et al. (2000) separated the Bahariya Formation within the Meleiha field into two main facies associations: 1) a tidal flat and tidal channel facies association and 2) a nearshore, shallow marine facies association. Within the two facies associations, twenty facies were defined based on their gross lithology, sedimentary structures, fossils and biological traces (Fig. 1.8). Metwalli et al. (2000) designated twelve different depositional processes to his facies in order to describe the paleoenvironmental settings of the upper Bahariya Formation. Depositional environments selected to represent the tidal flat and tidal channel facies associations included: tidal channel, sand flat, mixed flat, intertidal zone, marsh-swamp, and mud flat. The nearshore,

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Type and Code	Environment
Tidal Flat and Tidal Channel (FA1)	
Cross-bedded sandstone (Sx)	Tidal channel
Ripples sandstone (Sr)	Sand flat
Heterolithic mud (Hm)	Mixed flat
Heterolithic sand (Hs)	Mixed flat
Bioturbated sandstone (Sbt)	Intertidal zone
Glauconitic sandstone (Sg)	Sand flat
Massive sandstone (Sm)	Sand flat
Laminated sandstone (Sl)	Sand flat
Carbonaceous mudstone (Mc)	Marsh-swamp
Mudstone (M)	Mud flat
Near Shore – Shallow Marine (FA2)	
Fossiliferous mudstone (Mf)	Lagoon
Bioclastic glauconitic sandstone (Sbcg)	Shallow Marine
Bioclastic sandstone (Sbc)	Shallow Marine
Green sands (Gs)	Marine shelf
Sandstone with carbonate nodules (Sln)	Shallow marine
Sandstone with phosphatic clasts (Sph)	Shallow marine (storm lag)
Skeletal limestone (Ls)	Shallow marine
Argillaceous limestone (La)	Near shore (carbonate shoal)
Massive limestone (Lm)	Marine
Nodular limestone (Ln)	Near shore

Fig. 1.8 - Facies code, name, interpreted depositional environment and facies association of the studied cores within the Upper Bahariya Formation, Meleiha area, Egypt (From Metwalli et al., 2000).

shallow marine facies association consists of the following depositional systems: lagoon, shallow marine, marine shelf, shallow marine (storm lag), near shore (carbonate shoal), and marine.

Additional studies of the upper Bahariya Formation in the Meleiha area have established a variety of hypotheses. Kholeif et al. (1986) suggested a depositional setting of a marginal marine to shallow tidal flat setting. Elsheikh (1990) suggested a tidal flat environment grading upwards into a shallow marine shelf. Darahem et al. (1990) subdivided it into 4 units of 9 zones including a range from a subtidal complex to a restricted marine shelf. Salah and Paradisi (1992) described it as a tidal flat and channel fill sand environment. Each of these hypotheses involve environmental conditions that are associated with shallow coastal settings and intertidal deposits.

Bahariya Formation in the Bahariya Oasis:

The upper Bahariya Formation in the Bahariya Oasis has been studied in the greatest detail compared to any other area. The exposure of outcrop and the presence of skeletal remains have drawn the attention of scientists around the world. The Bahariya Oasis is located 320 km southwest of Cairo in the central part of the Libyan Desert. Despite the considerable distance between the Khalda Concession and the Bahariya Oasis, the area presents comparable characteristics to that seen in the study area. The Bahariya Oasis represents a large depression surrounded by escarpments and encompasses an area of about 1800 km^2. The Bahariya Formation forms the floor of the Oasis, and therefore is not fully exposed.

As described by Lacovara et al. (2001), the Bahariya Formation in the Bahariya Oasis has a complex depositional history along a sheltered, low energy, epeiric bight. This open-ended epicontinental sea experienced diminishing energy conditions that allowed for the development of mangrove communities along the coast. Well-established mangrove communities prograded into transgressing seas, while coastal areas lacking mangroves developed small barrier islands, which migrated landward over paralic sediments. As well, the low gradient coastal plain allowed for a wide range of back barrier environments to develop. Thus, deposits of the Bahariya Formation include open-water to lagoonal, tidal flat, mangrove, and tidal channel facies.

A rich fauna of bivalves, gastropods, sharks, bony fish, turtles, crocodyliforms, and plesiosaurs, as well as five dinosaurs including *Spinosaurs, Carcharodontosaurs, Bahariasaurus, Aegyptosaurus* and *Paralititan*, have been recorded in the area. Lacovara (2001) has suggested that the Bahariya Formation may have similar characteristics to the Ten Thousand Island region of the Florida Gulf coast, where the recent (Holocene) transgression over the gently sloping coastal plain has produced an exceptionally wide back barrier environment.

The odd preservation of decapods in close association with dinosaur remains also gives us clues as to some of the depositional characteristics. This unusual occurrence suggests preservation in an environment of rapid burial and quiescent conditions (Schweitzer et al., 2003). It was also noted by Schweitzer et al. (2003) that the tidal couplets in which the crabs were buried indicate an approximate accumulation rate of sediment around 8 mm per tidal cycle or 1.6 cm per day, assuming semidiurnal tides. Slow moving currents were assumed based on the fine grain size, which allows for gentle burial.

Allam (1986) noted that the Bahariya Formation shows a "...gradual transition from fluviatile, cross-bedded and channel sands in the lower part upwards into a laminated shale with small scale ripple bedding and occasional thin fossiliferous ferruginous carbonate beds or sandy limestone of more marine character in the upper part." The lithology of the area appears to be controlled dominantly by its proximity to channels, which are surrounded by dry land and swamps that have abundant vegetation cover (Allam, 1986).

Bahariya Formation in the Khalda Concession:

The Bahariya Formation was deposited on a broad, tidally influenced, ramp margin of the Neotethys. The system represents a complicated interplay between clastic and carbonate deposition that is dated as Late Cenomanian in age (Watkins et al., 2002 and Wehr et al., 2002). Originally, the Bahariya Formation was divided into 3 members, which in ascending order are: the Gebel Ghorabi, Gebel Dist and El Heiz. Dominik (1985) interpreted the depositional environment of each of these members as fluviatile, estuarine, and lagoonal, respectively. The Gebel Ghorabi Member is made up of coarse-grained, cross-bedded, relatively non-fossiliferous sandstone. The Gebel Dist Member consists of fine-grained, well-bedded, ferruginous clastics containing a large number of fossils, including vertebrates in the lower levels and an assortment of oysters and other fossils in the middle and upper levels. The El Heiz is composed of dolomites, sandy dolomites and calcareous grits rich in fossils. There is some discussion as to the equivalent strata of the El Heiz member; in many cases, the Abu Roash 'G' member may be its equivalent (Hantar, 1990).

More recently, the Bahariya Formation is separated into an upper and lower

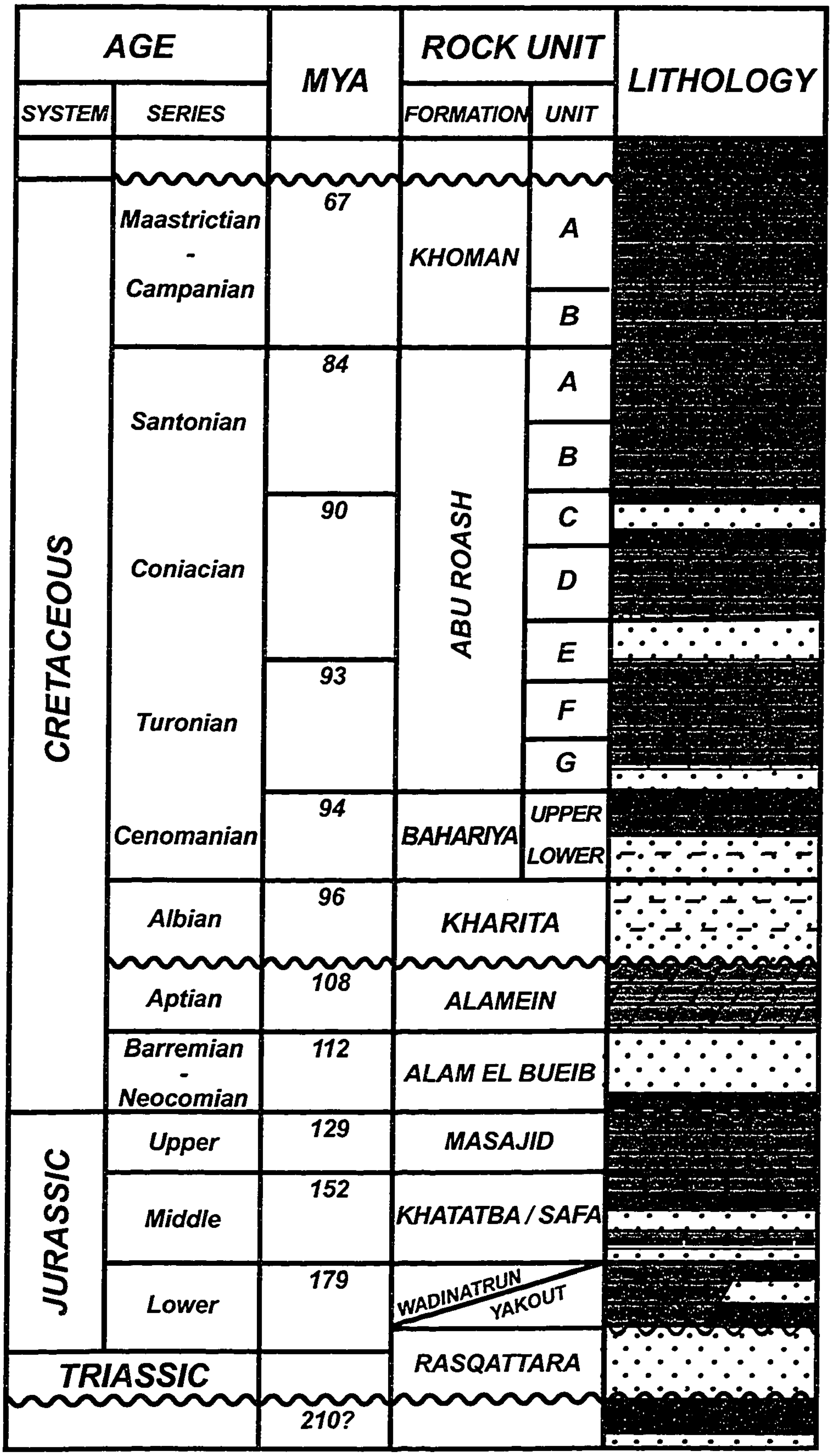

Fig. 1.9 - Stratigraphic nomenclature for the study area, illustrating the interval of investigation (Wher, unpublished data).

member (Wehr et al., 2002; Watkins et al., 2002; and Metwalli et al., 2000) (Fig. 1.9). From detailed core studies combined with regional correlations within the Khalda Concession, Wehr et al. (2002), documented the lower Bahariya Formation to be a relatively sand rich succession of fine to medium-grained sandstone and mudstone. The formation displays sedimentary structures, ichnofacies assemblages, and stratal geometries that indicate deposition in an estuarine to shallow-marine environment with strong tidal influence. Correlations have proven difficult because of the many erosional/onlap surfaces (seen by carbonate cementation and *Glossifungites* trace-fossil assemblages), abrupt lateral facies changes, and the complex diagenetic overprinting. The lower Bahariya Formation has a measured thickness ranging between 400 feet and 800 feet, and has been recognized as the primary reservoir unit in the Khalda Concession.

Wehr et al. (2002) described the upper Bahariya Formation, in the Khalda Concession as a relatively sand poor succession of parasequences that can be correlated regionally. The parasequence boundaries are typified by cemented and burrowed contacts overlain by mudstone. Based on the stratigraphic sequences, sedimentary structures, ichnofacies assemblages and stratal geometries, deposition in a relatively low-energy, restricted marine setting is assumed. Core studies have shown the presence of a heavily vegetated, relatively inactive coastal plain to shallow marine environment, thinly interbedded with shallow marine limestones (Watkins et al., 2002). In the upper 75 feet of the upper Bahariya Formation, very fine-grained sandstones are interpreted as thin bayhead, distributary mouthbar, and shoreface deposits, with rare isolated channel fills (Wehr et al., 2002). The upper Bahariya Formation has a measured thickness of 130 to 300 feet, and is recognized as a secondary producer in the Khalda Concession.

El Beialy (1994) conducted research on the palynological evidence for depositional settings in the Salam field, of the Khalda Concession. El Beialy (1994) found that the sediments of the Bahariya Formation yielded a largely terrestrial microflora and a moderately diverse assemblage of miospores suggesting deposition in a continental environment with proximity to the shoreline. In addition, there is a low diversity assemblage of dinoflagellates, which may be an indication of restricted, brackish water conditions (Batten, 1982; Leckie and Singh, 1991). The palynostratigraphy from the analyzed boreholes have provided the first evidence of the exact age of the Bahariya Formation (El Beialy, 1994). In the nearby Razzak oil field (see Fig. 1.1), El Beialy (1995) studied the palynology in the Bahariya Formation that further supported a depositional setting situated in a shallow marine system dominated by humid conditions.

1.5 Methods and Objectives

This project was undertaken to develop an enhanced depositional model and to improve our understanding of the paleoenvironment represented in the subsurface, upper Bahariya Formation. Interpretations will primarily focus on sedimentary structures, ichnofossil assemblages and stratal geometries as seen in cored intervals. Lithologic and ichnological characteristics were the basis for identifying facies throughout the sections. Ichnology served as a primary tool in determining valid depositional models used in the paleoenvironmental reconstruction and interpretation of the system. As well, mapping and regional correlations from the available log suites have assisted in environmental interpretations.

Data was processed from twelve intervals totaling approximately 305 m (1000 ft) of core. All twelve cored intervals were originally logged in imperial measurements and were assessed at a resolution of approximately 2.5 cm (1 inch), with emphasis placed on recording the gross lithology, physical sedimentary structures, biogenic sedimentary structures and grain size. As well, photographs were taken at increments of approximately 30 cm (1 ft) of core.

Available log suites were calibrated using the information collected from cored intervals. The calibrated log suites were then used for correlations, which enabled the construction of local stratigraphic interpretations and assisted in the establishment of depositional models and isopach sand maps.

The objectives mentioned above are covered in chapters two through five. Chapter 2 gives complete descriptions and interpretations of Facies A - K. Chapter 3 incorporates a more detailed description of Facies F (glaucony rich silty sandstone) and addresses the relevance of observed characteristics displayed by the glauconitic material. *Glossifungites* assemblages in the upper Bahariya Formation are then discussed in Chapter 4, providing a clear distinction between two types of processes in the formation of the *Glossifungites* assemblages in both siliciclastic and mixed carbonate-siliciclastic environments. Finally, Chapter 5 addresses three different facies associations, relationships to modern day systems and describes a possible depositional model that is consistent with the vertical stacking patterns observed. Chapter 6 summarizes the pertinent information discussed in all previous chapters.

CHAPTER 2: Facies Descriptions and Interpretations

2.1 Introduction

Within the Khalda Concession, cores were logged from the upper Bahariya Formation documenting observations on lithologic, sedimentologic and ichnologic characteristics. Based on these characteristics, several distinct units were identified and separated into eleven facies (Table 2). These facies were separated into three facies associations: Facies Association 1 (Facies A, B, D, H, I and J) is characterized by low energy, distal interdistributary bay deposits, Facies Association 2 (Facies A, C, E and G) is characterized by higher energy, proximal interdistributary bay deposits, and Facies Association 3 (Facies B, F and K) is identified as offshore muds, limestone and a condensed section containing highly evolved autochthonous glaucony. A facies association is defined as a grouping of genetically related facies utilized in the identification of depositional systems. A detailed discussion on each of the facies associations can be found in Chapter 5. The following section documents the non-genetic observations and discusses possible depositional environments responsible for their development. All core logs can be found in Appendix A.

2.2 Facies A (FA): Silty Sandstone

Description:

Facies A is the most widespread unit within the study area. It occurs in all the logged wells and is found at any horizon. There are three sub-facies associated with FA (A1, A2 and A3) defined by their constituent sedimentology, ichnology and lithology (Fig. 2.1, 2.2 & 2.3).

Generally, FA ranges in thickness from 16 cm to as much as 3 m. Lithologic characteristics include grain sizes that range from lower very fine sandstone to upper fine sandstone with variable silt and mud content. Colors range from light tan to medium gray, depending on the relative proportions of grain sizes and other constituents that are present. Lithologic constituents typically consist of varying amounts of quartz grains, organic debris, shell material, siderite clasts and glaucony with calcite cement and siderite staining. The organic debris within FA generally occurs as small grains (sand sized) or large fragments (2.5 – 5.3 cm) that have been coalified. Shell material is usually disarticulated, whole or fragmented and concentrated at discrete horizons. Siderite

Facies	Descriptive Name	Physical Sedimentary Structures	Biogenic Sedimentary Structures	Depositional Environment	
FA1	Bioturbated Silty Sandstone	Planar Laminations & Load Structures	Te, Di, Sk, Ch, Pl, Pa, Th	Tidal Flat	Tidal Flat Sands
FA2	Silty Sandstone w/ Lag	Scoured Base & Graded Bedding	-		Tidal Creek Lag
FA3	Convolute Silty Sandstone	Convolute Bedding	-		Tidal Flat (Proximal to Source)
FB1	Shelly Limestone	-	Di, Sc, Pl, Pa, Th, Te	Marine Bay Carbonate	
FB2	Silty/Sandy Limestone				
FB3	Micritic Limestone				
FC	Clean Sandstone	Massive Scoured Base w/ Lag (Common)	Ar, Sk	Crevasse Splay Distributary Mouth Bar	
FD	*Helminthopsis* Dominated Silty Sandstone	Planar Laminations (Rare) Scoured Base w/ Lag (Common)	He, Th, Te, Pl, Pa	Marine Bay	
FE1	Current Rippled Sandstone	Asym. Rip. & Climbing Rip.	Te, Lo, Sk, Pl, Pa, Ar	Crevasse Splay Delta Front	Proximal Delta Front
FE2	Flaser Bedded Sandstone	Flaser Bed.			Delta Front
FE3	Wavy/Planar Laminated Mud & Sand	Wavy & Planar Laminated & Syneresis Cracks			Distal Delta Front
FF	Glaucony Rich Silty-Sandstone	-	As, Te, Sc, Rh, Th	Condensed Section, Offshore	
FG	Organic Rich Sandstone	Planar Laminations (Rare) Convolute Bedding Scoured Base w/ Lag (Rare)	Th, Pl, Pa, Te	Crevasse Splay Distributary Mouth Bar	

Table 2. Table of facies observed in the upper Bahariya Formation (Continued on page 20).

FH	Carbonateous Shale	Planar Laminations	-	Interdistributary Bay
FI	Rooted Green Mudstone	Planar Laminations (Rare) Asymmetrical Ripples (Rare) Calcreate Nodules	Ps, Sk, Roots	Natural Levee and Marsh
FJ	Green Mudstone	Planar Laminations (Rare)	Ar, Sk, Pl	Interdistributary Bay
FK	Shale	Mottled	-	Offshore Shale

Table 2 ***(Cont.).*** Table of facies observed in the upper Bahariya Formation. Key to abbreviated ichnogenera: Ar: *Arenicolites,* As: *Asterosoma,* Ch: *Chondrites,* Di: *Diplocraterion,* He: *Helminthopsis,* Lo: *Lockeia,* Pa: *Palaeophycus,* Pl: *Planolites,* Rh: *Rhizocorallium,* Sc: *Scolicia,* Sk: *Skolithos,* Te: *Teichichnus,* Th: *Thalassinoides.*

clasts are sub-angular and possess a deep maroon color. Localized glauconitic material within FA has a wide range of development, from dark green to lighter green individual grains. When present, glaucony is relatively sparse (<10% by volume), however in most examples of FA it is absent.

Primary sedimentary structures are usually disrupted or absent due to biological reworking and soft sediment deformation expressed as loading, degassing and dewatering structures. Rare, locally preserved primary structures include black organic or silty gray laminae that are planar laminated and typically found in pairs. Isolated symmetrical and asymmetrical ripples have been identified. Commonly, organic debris is associated with shell fragments and /or siderite clasts overlying sharp and possibly erosive contacts within FA. These shell fragments are aligned horizontally, usually concave up, and grade upward into smaller fragments with fewer shells, siderite clasts and organic material.

The ichnological characteristics associated with FA include small, simple forms representative of one or two ichnotaxa. Trace fossils typically include a predominance of *Teichichnus,* with minor *Diplocraterion, Skolithos, Chondrites, Planolites, Palaeophycus* and *Thalassinoides.* In many instances, difficulty arises in distinguishing bioturbate textures from soft sediment deformation, which decreases the ability to identify specific ichnotaxa. The degree of bioturbation is variable between sub-facies, thus will be discussed in greater detail within each sub-facies description.

FA is commonly found conformably or unconformably underlying FC or FG, and unconformably underlying FD or FE. FA is also commonly observed overlying FB and interfingering with FH and FI.

Sub-Facies A1 (FA1): Bioturbated, Silty Sandstone with Soft Sediment Deformation

Description:

Sub-facies A1 is the most common unit within FA and throughout the entire study area. It is generally 16 cm to 0.9 m in thickness and can be correlated between most wells. It is commonly truncated by overlying Facies E, C or D. High abundance of bioturbation and small-scale soft sediment deformation characterize Sub-facies A1 (Fig. 2.1 a, b, c & d). Sedimentary structures include common planar laminations and minor ripples, along with very common load structures. Sub-facies A1 is light gray to medium gray in color and locally contains pale green and/or dark green grains of glaucony (<10% by volume).

The ichnotaxa present in this sub-facies contains the most diverse suite of biological activity within FA. Burrows are dominated by small (0.5 - 1 cm) *Teichichnus*, with minor development of small *Diplocraterion, Skolithos, Chondrites, Planolites, Palaeophycus* and *Thalassinoides*.

Sub-Facies A2 (FA2): Sharp Based, Silty Sandstone With Lag Deposits

Description:

This unit demonstrates a more limited range of occurrence in comparison to Sub-facies A1. It is generally confined to the base or the middle of FA and is not correlatable between wells. Sub-facies A2 ranges in thickness from 8 cm to 0.6 m and can occur multiple times in a single succession of FA. It is characterized by an increased grain size relative to Sub-facies A1 (Fig. 2.2 a), and the presence of shell fragments and siderite clasts (Fig. 2.2 b , c & d). Grain size ranges from upper very fine to upper fine sandstone and has variable silt and clay content. Examples of this unit are generally light tan/gray to medium gray in color and are typically associated with black specks of organic material and large wood clasts. A general fining upward trend throughout the unit commonly overlying a scoured surface at the base, is characteristic in many of the examples. Variable amounts of glauconitic material are present and range from pale green to medium green individual grains.

Biological traces have not been identified within any Sub-facies A2 intervals.

Sub-Facies A3 (FA3): Convolute, Silty Sandstone

Description:

Sub-facies A3 occurs in all wells within the study area. This sub-facies comprises the large-scale soft sediment deformation that occurs within FA (Fig. 2.3). Convolute bedding occurs in a grain size range from lower very fine sandstone to upper fine sandstone. Furthermore, Sub-facies A3 is usually light tan to medium gray in color and ranges in thickness from 8 cm to 45 cm. In some cases, there is a high degree of organic material highlighting the laminations and/or variable amounts of silt and clay. Sub-facies A3 also contains minor amounts of glauconitic material that ranges from pale green to dark green individual grains. This Sub-facies is commonly found in close proximity to facies C, G and E, and is commonly found at the top of FA.

Ichnological behaviors are not observable within this Sub-facies because of the

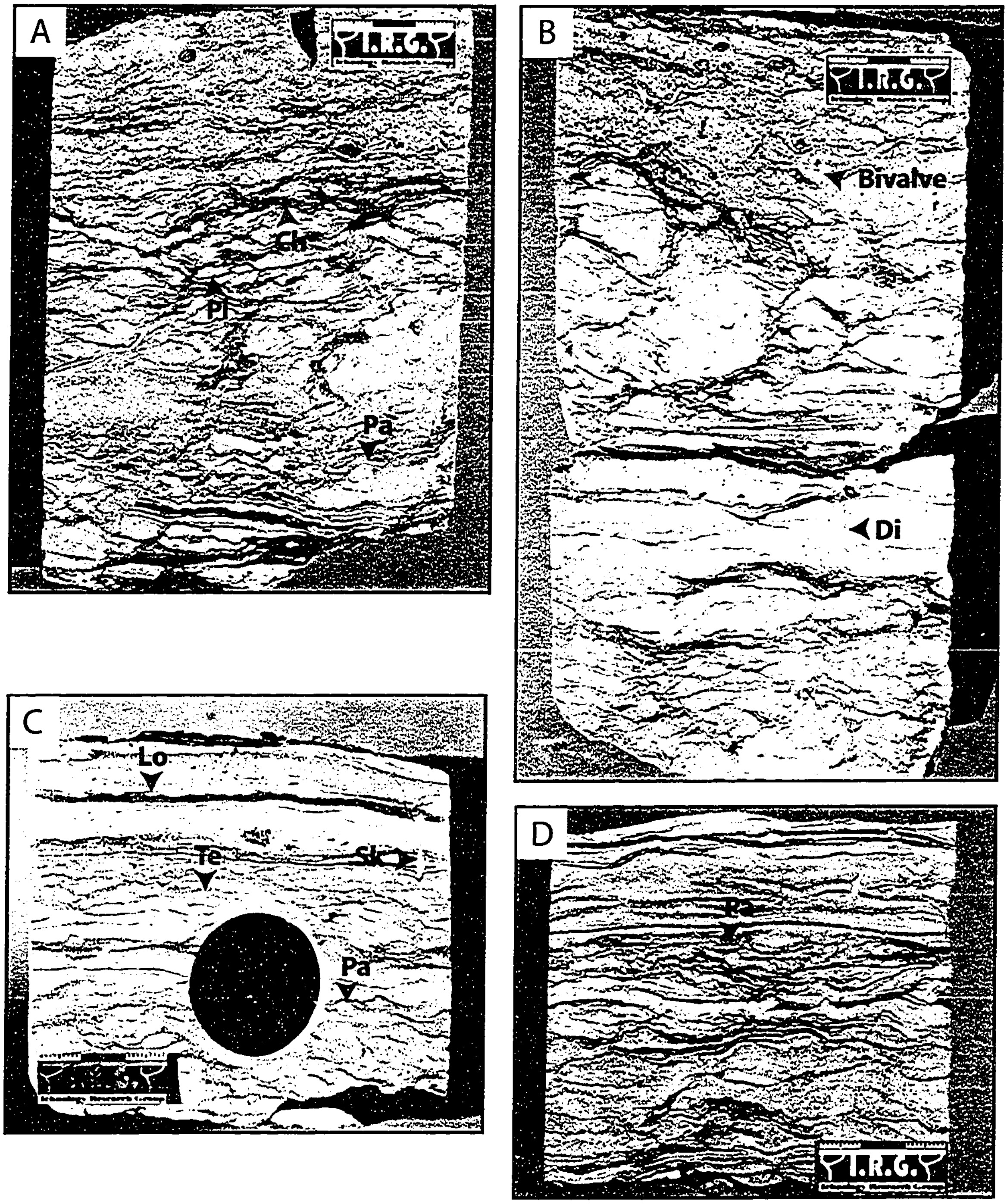

Fig. 2.1 - Bioturbated Silty Sandstone (Sub-facies A1): All pictures show evidence of soft sediment deformation. **(A)** Trace fossils *Chondrites* (Ch), *Palaeophycus* (Pa) and *Planolites* (Pl) (Salam 47, depth 5881 ft (1793 m)); **(B)** *Diplocraterion* (Di) and bivalve shell fragments (Salam 47, depth 5863 ft (1788 m)); **(C)** *Skolithos* (Sk), *Palaeophycus* (Pa), *Teichichnus* (Te) and *Lockea* (Lo) (Salam 17, depth 5821 ft (1775 m)); **(D)** *Palaeophycus* (Pa) and remnant planar laminations (Salam 47, depth 5837 ft (1780 m)).

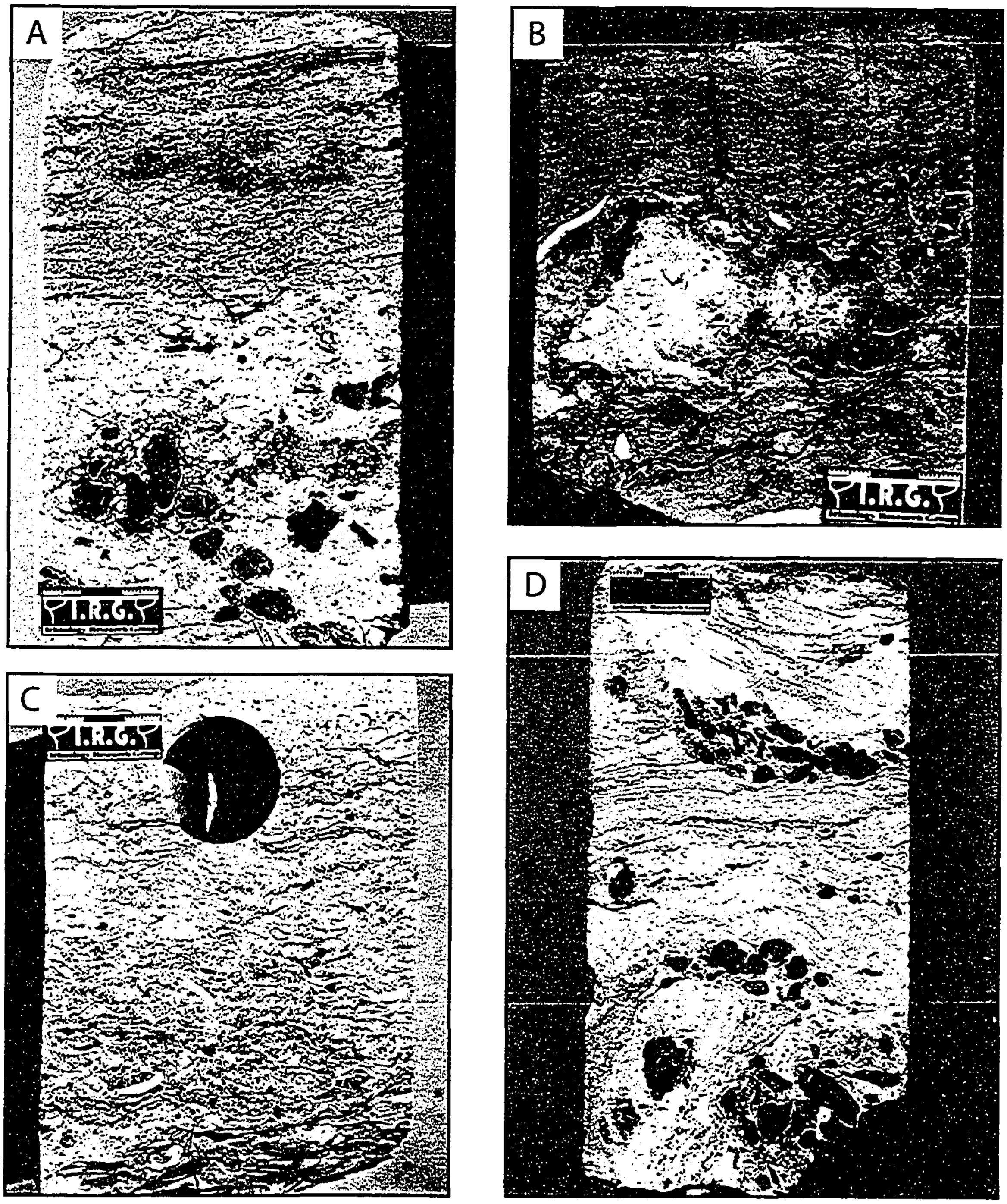

Fig. 2.2 - Silty Sandstone with Lag Deposits (Sub-facies A2): All pictures show siderite clasts and other lag material. **(A)** Normal graded bedding (Salam 8, depth 5779 ft (1762 m)); **(B)** Organic and shell lag material (Salam 17, depth 5804 ft (1770 m)); **(C)** Normal graded shell deposit (Salam 17, depth 5802 ft (1765 m)); **(D)** Soft sediment deformation in lag deposit (Hayat 12, depth 6122 ft 1866 m)).

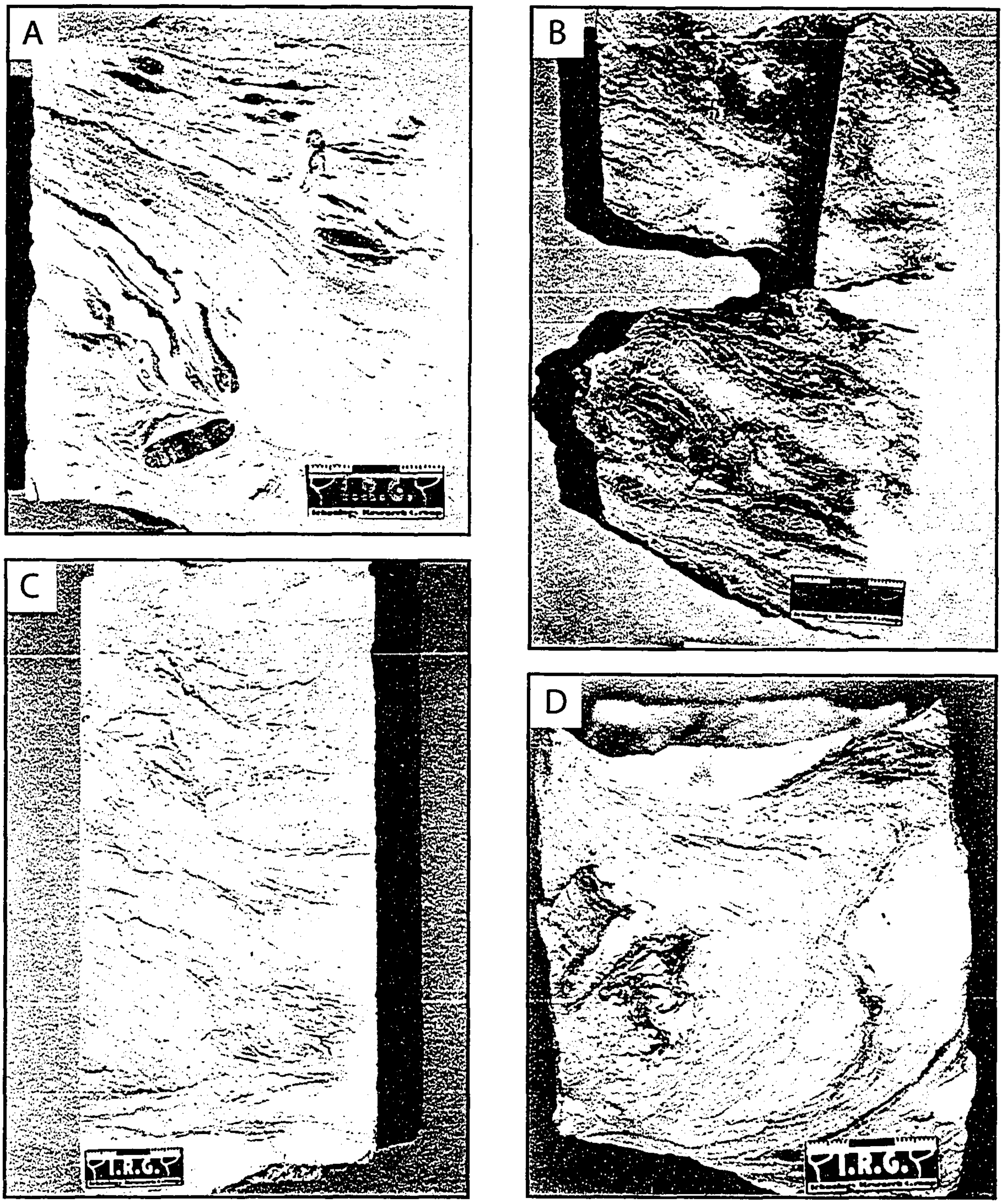

Fig. 2.3 - Convolute Silty Sandstone (Sub-facies FA3): All pictures show evidence of convolute bedding (*ie.* dewatering structures). **(A)** Small amount of siderite clasts (Hayat 17, depth 5989 ft (1826 m)); **(B)** Slightly more organics (Yasser 6, depth 5906 ft (1801 m)); **(C)** (Salam 47, depth 5832 ft (1778 m)); **(D)** (Salam 38, depth 5909 ft (1802 m)).

large-scale sediment disruption. Thus, this unit is typically devoid of any visible trace fossils.

Interpretation: Facies A (Tidal Flat, Intertidal Zone)

Tidal flats are depositional environments that occur in estuaries, lagoons, bays, or behind barrier islands and other sand bars (Reineck and Singh, 1973). Requirements for deposition of tidal flats include a gently dipping coast, a measurable tidal range in an area of abundant sedimentation, and the absence of strong wave action (Reineck and Singh, 1973). Tidal flats are situated most commonly within the intertidal zone, as well as within the sub-tidal and supra-tidal zones (Reineck and Singh, 1973). The tidal flat is often found as an elongate sediment body parallel to the shoreline for hundreds of kilometers and area with an average width of seven to ten kilometers (Reineck and Singh, 1973). Over this span of deposition, migration of tidal channels, tidal creeks and river estuaries may result in cross cutting relationships. In some cases, subaqueous levees may form that are exposed as sand flats during low tides (Reineck and Singh, 1980)

Facies A is deposited as the result of a relatively low energy depositional environment that is situated some distance from a fluvial source in an interdistributary bay setting. The interpreted system involves a weak but active marine influence that reworks and redistributes the available sediments over a large lateral extent. The redistribution of grains is interpreted as a function of tidal processes in a micro to meso-tidal environment. Deposition rates are relatively high resulting in dewatering and loading structures throughout the study area. The low diversity and high abundance of simple ichnological structures, along with small dimunitive forms, suggests a restricted brackish body of water that may be located at or near the limits of a marine transgression (Pemberton et al., 2001). Within this facies, the moderate occurrence of minor scoured surfaces followed by coarser grained material and layers of shell fragments suggest the presence of tidal channels or tidal creeks cutting into the surrounding tidal flat environment. Large-scale convolute bedding that occurs at or near the top of the facies implies an upward increase in energy and depositional rates present within parasequences.

FA demonstrates many of the characteristics observed within tidal flat environments; however, it is difficult to separate the unit into intertidal and subtidal divisions. Weimer et al. (1982) observed that the intertidal zone makes up most of the tidal flat environment while the subtidal areas are the most likely to be preserved. Consequently, FA likely contains both intertidal and subtidal deposits. The lack of sedimentary structures and identifiable ichnotaxa makes the task of separation difficult, if not unrealistic. However, the available information allows us to make other relevant interpretations.

The thickness of tidal flat deposits are said to be proportional to the tidal range (Weimer, et al., 1982). Ignoring the extent of compaction on the deposited sediments, a maximum thickness for Sub-facies A1 was measured to be approximately 1 m. A 1 m tidal flat deposit supports a micro-tidal environment. Disregarding the amount of compaction is not advisable in most cases. However, assuming that approximately 30% compaction occurred, the total thickness would only increase from 1 m to 1.3 m; thus, the thickness is not notably affected and the micro-tidal interpretation stands.

Tidal creeks are identified by sharp-based (scoured) surfaces, underlying relatively coarse-grained sediments with shell debris and locally abundant mud clasts. Asymmetric ripples provide evidence of unidirectional sediment transport. In general, tidal creeks are not appreciably burrowed, contain abundant plant fragments and develop a fining upwards deposit (Weimer, et al., 1982). These characteristics have all been observed in FA. Tidal creeks within the area have a maximum thickness of about 0.6 m suggesting a channel depth of approximately 0.6 m based on Weimer, et al. (1982). The limited depth of these channel deposits supports an interpretation of smaller distributaries such as tidal creeks as opposed to larger tidal channels.

Deposits of the tidal flat (FA) are largely disrupted by soft sediment deformation due to the relatively high sedimentation rates. The high degree of clay and silt-sized particles mixed with very fine-grained sandstone allows for a high pore water pressure, which is trapped until compactional forces are exerted. During compaction, dewatering structures develop, which distort primary sedimentary structures leaving only a few depositional clues. Localized planar laminations with alternating mud and sand layers give the appearance of double mud draping. The limited examples of these tide-dominated structures are not conclusive but provide further support for a tide-influenced environment. Additional support includes the presence of marine-derived sediments. FA contains pale green and/or dark green individual glauconitic grains as a result of transport of allochthonous grains from an offshore environment through tidal action and/or possible storm activity, depositing the material within the alternating layers of mud and sand.

The deposits within the tidal flat include sediments transported from both marine and fluvial sources. The proximity of FA to a significant fluvial source allows for minor grain size variation within FA, and more noticeably a diminished abundance of clay and silt particles. In many cases, FA grades into FC as the energy of the environment increases (more proximal). Commonly, Sub-facies A3 (convolute, silty sandstone) occurs at the top of the tidal flat immediately below facies C, G or E as higher sedimentation rates allowed for more significant water escape structures to develop. Concentrations of fine carbonaceous detritus found alternating with sand layers suggest periodic fallout of suspended material. This suspension settling possibly occurred during periods of slack current flow, such as at high or low tide (*eg.* Weimer, et al., 1982). The organic material within FA is sourced from fluvial environments that have been in contact with areas of vegetation and results in a gradation to FG (Organic rich sandstone) as the deposits become increasingly proximal.

The brackish assemblage of trace fossils is interpreted from the presence of mixed *Skolithos* and *Cruziana* ichnofacies dominated by small *Teichichnus,* with the rare occurrences of small *Diplocraterion, Skolithos, Chondrites, Planolites, Palaeophycus* and *Thalassinoides.* Brackish deposits of the intertidal flat are typically abundant in bioturbation with traces that are diminutive and incorporate various vertical and horizontal shafts (Gingras et al., 1999). The identification of these brackish water deposits is important because they often help us recognize the change from continental to marine settings and tend to occur at or near the limits of marine transgressions (Pemberton et al., 2001).

2.3 Facies B (FB): Limestone

Description:

FB occurs in most wells at regular intervals and displays a common occurrence in northern sections of the study area. There are three Sub-facies (B1, B2 and B3), which are all distinguished and defined by the lithologic characteristics (*eg.* carbonate *vs.* clastic influence), allochems and ichnology (Fig. 2.4 , 2.5 & 2.6).

Thicknesses generally range from 16 cm to 0.6 m and in some cases to as much as 1.5 m. Interval spacing generally ranges from 3.0 m to 6.0 m but can vary. There is a tendency for increased abundance and consistency of spacing for FB in the more northernly studied wells, such as in the Salam field. Colors are usually a light gray or white to medium gray with a rare pale green background. Individual dark green grains of glaucony are also present, locally. Lithologically, FB is dominated by a micritic limestone matrix with varying amounts of clastic material, shell material and organics. Shell material has been broken down into general classifications, based on both hand samples and thin sections, and include dominantly disarticulated bivalve skeletons, gastropods, ostracods and rare foraminifera.

The ichnological characteristics within FB include the presence of *Diplocraterion* (rare), *Scolicia, Planolites, Palaeophycus, Thalassinoides* and *Teichichnus*.
The abundance and type of burrowing organisms varies within each Sub-facies. *Thalassinoides* burrows, witch appear to have been passively infilled with shell material that was subsequently dissolved, are common within FB.

FB is commonly associated with FH, FI or FD, or on top of FC, G or E. Also, this unit displays a gradational relationship with FF at the top of all the wells in the study area.

Sub-Facies B1 (FB1): Shelly Limestone

Description:

This sub-facies is found in most of the wells throughout the study area. It consists of a micritic calcite matrix, abundant shell material (*eg*. bivalves and gastropods; up to 80% by volume) and a variable amount of siliciclastic components (Fig. 2.4). The shell material is commonly disarticulated and occurs as local concentrations in thin layers, as burrow infill (usually in *Thalassinoides*), or dispersed throughout massive units. As well, the shell material dominantly consists of one or two species including bivalves and/or gastropods, which range in size from 7 mm to 5.3 cm. In many cases, the shell material is dissolved leaving the rock with a vuggy texture and a higher porosity. Commonly, this unit is associated with an organic lag at its base and minor amounts of siderite throughout.

Visible bioturbation is generally rare to moderate, with passively shell infilled *Thalassinoides* as the most common trace fossil.

Sub-Facies B2 (FB2): Limestone with Clastic Influence

Description:

Sub-facies B2 is found throughout the entire study area in all of the wells. This sub-facies is the most prevalent within FB and can range in thickness from 0.3 cm to 1.5 m. This sub-facies comprises a micritic calcite matrix mixed with a significant portion of siliciclastic material (Fig. 2.5). Colors generally range from white to medium gray, with minor amounts of pale green. Clastic material ranges in grain size from silt to lower very fine-grained sandstone. In most cases, the calcite matrix and clastic material are amiscible causing a mottled appearance that locally resembles ichnological activity. Siderite staining is also common within this unit.

In some instances, bioturbation may be high and include traces such as *Diplocraterion, Thalassinoides, Palaeophycus* and *Planolites*. Burrows are often filled with very fine-grained sandstone, and in some cases they are sharp-walled and passively infilled.

Sub-Facies B3 (FB3): Micritic Limestone

Description:

Sub-facies B3 is found throughout the study area in only a limited number of wells. Thicknesses are generally small ranging between 8 cm and 0.3 m. This sub-facies is dominated by a micritic calcite matrix, very minor amounts of siliciclastic material and rare shell-material (Fig. 2.6). A smooth light gray/white to medium gray typifies the color range for this unit. Siderite staining is common and found in localized layers.

The homogeneous nature of this unit makes the identification of trace fossils difficult. The ichnology is sparse and is typically comprised of minor occurrences of *Thalassinoides* burrows.

Interpretation: Facies B (Marine Bay Carbonate)

As interdistributary bays reach their maximum limit of infilling, crevasse channels (see section 2.4, 2.6 and 2.8) wane and become inactive (Coleman and Prior, 1982). This drop in clastic sediment influx partially provides the necessary controls required for the production of carbonates (James and Kendall, 1992). The decrease in terrigenous material allows the filled, or partially filled, interdistributary bay to undergo rapid subsidence followed by the inundation of marine waters developing a marine bay (Coleman and Prior, 1982).

Prior to renewed freshwater flooding via crevasse channels, if conditions are suitable, a carbonate factory can become active in the bay. This quiet area, protected from wave energy, allows for the development of a micritic limestone. Minor amounts of fresh water may be introduced into the system by periodic over-bank flooding creating a slightly brackish environment. The biota present in this type of system are generally low in diversity but high in abundance (Jones and Desrochers, 1992). It is also common for

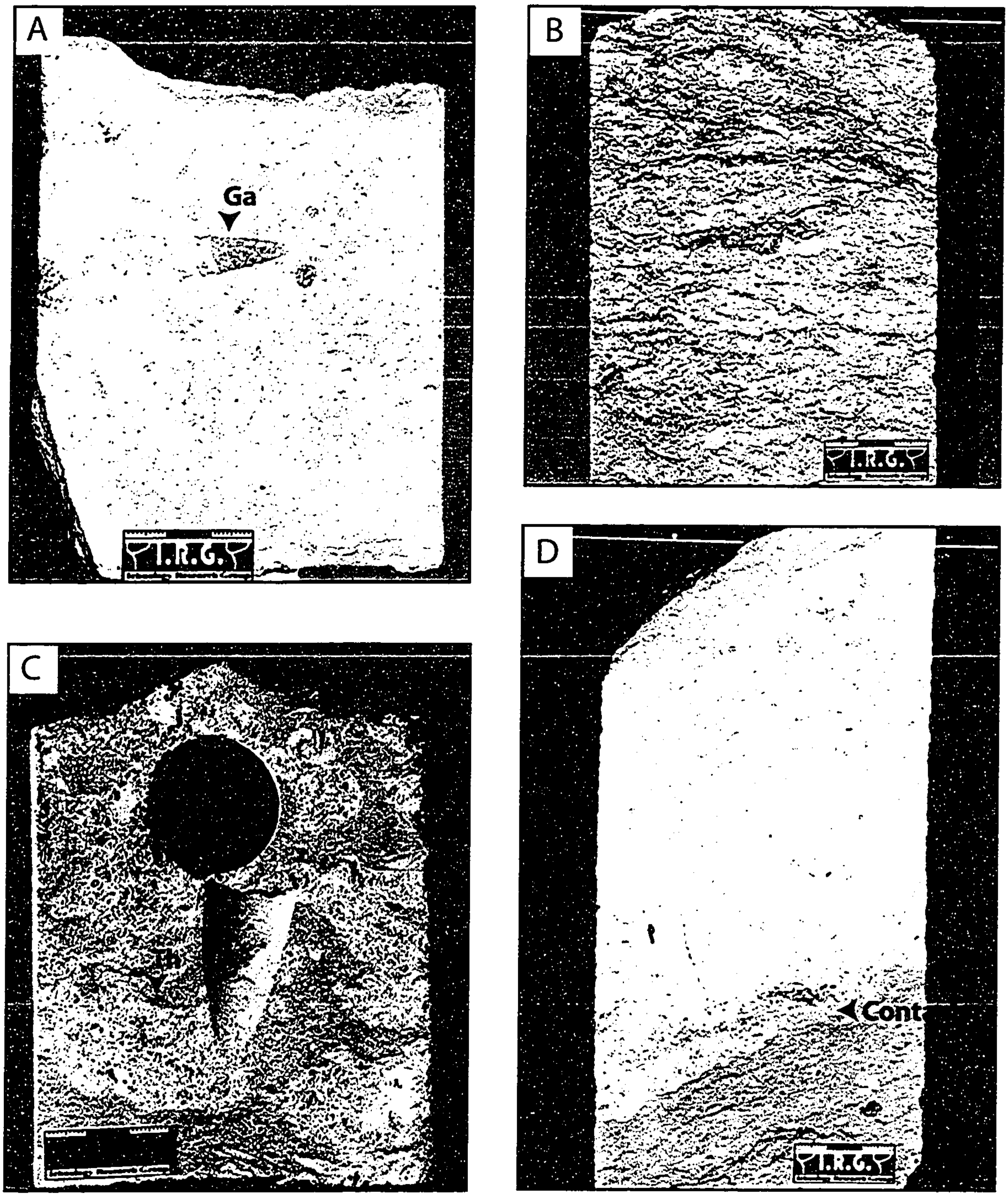

Fig. 2.4 - Shelly Limestone (Facies B1): All pictures show a high abundance of shell material. **(A)** High abundance and low diversity of shell material (gastropods (Ga)) (Salam 8, depth 5793 ft (1766 m)); **(B)** Domanantly bivalve material; Sharp contact to underlying facies A (Salam 47, depth 5869 ft (1789 m)); **(C)** Passively infilled *Thalassinoides* with dissolved shell material (Salam 38, depth 5864 ft (1788)); **(D)** Sharp contact with underlying Facies A (Salam 47, depth 5880 ft (1793 m)).

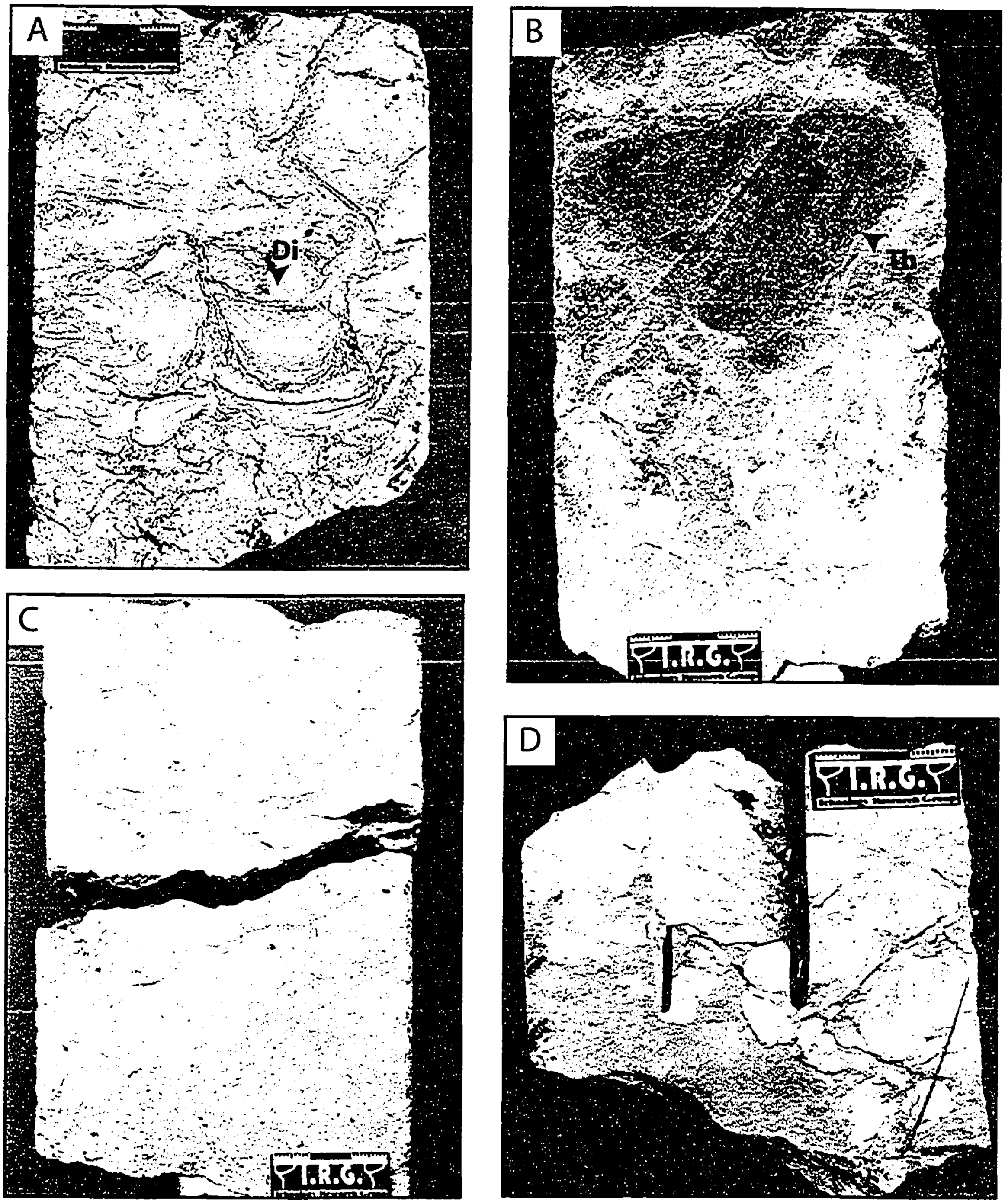

Fig. 2.5 - Silty/Sandy Limestone (Sub-facies B2): All pictures show a high variability of clastic influence. **(A)** *Diplocraterion* (Salam 38, depth 5901 ft (1799)); **(B)** Passive infill of dissolved shell material in *Thalassinoides* (Th) (Salam 47, depth 5829 ft (1777 m)); **(C)** Large clastic influence; Possibly deformed burrows such as *Planolites, Thalassinoides* and *Teichichnus* (Salam 38, depth 5929 ft (1808 m)); **(D)** Siliciclastic influence; Possibly deformed *Planolites* and *Thalassinoides* (Salam 47, depth 5841 ft (1781 m)).

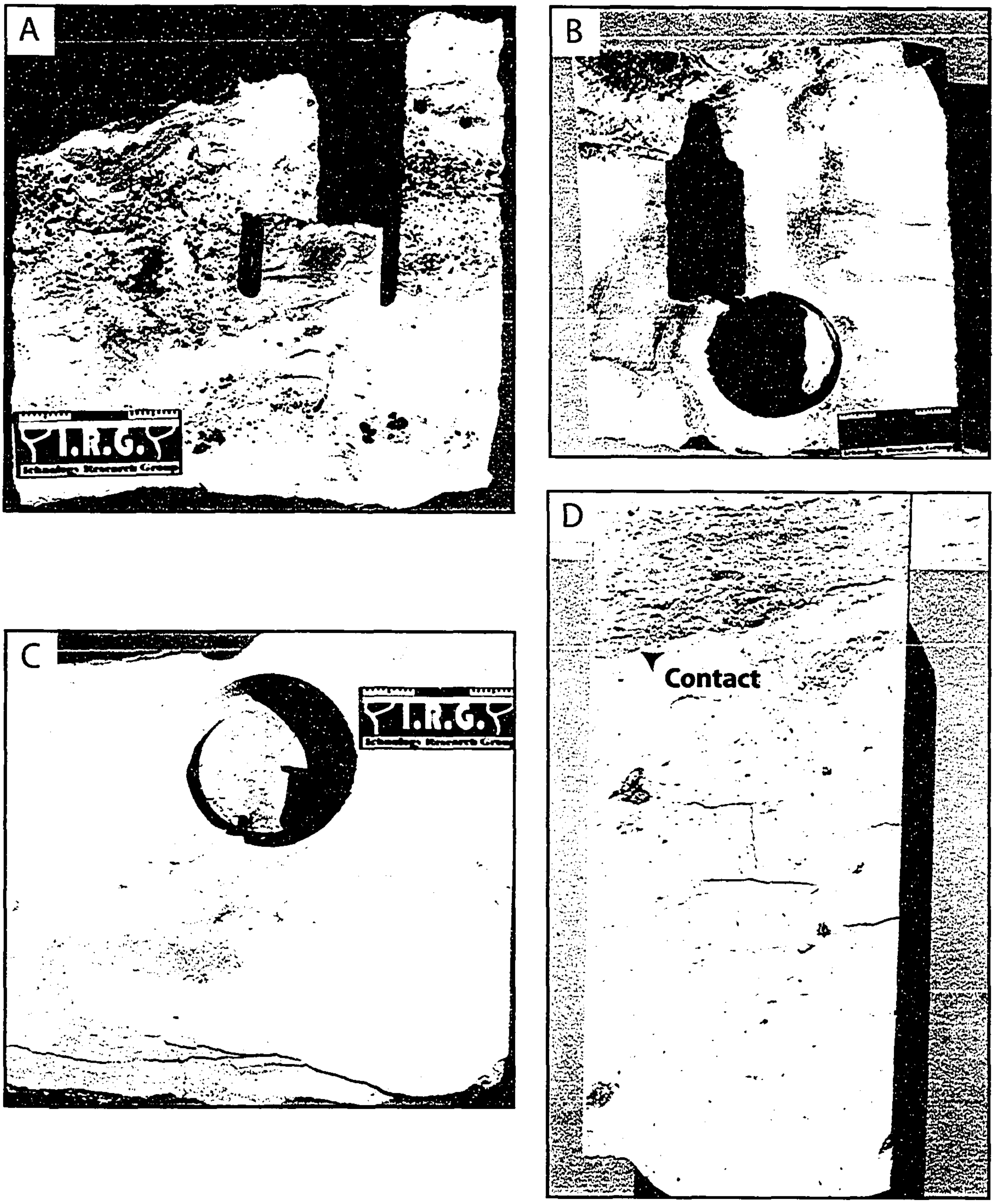

Fig. 2.6 - Micritic Limestone (Sub-facies B3): All pictures display a low abundance of siliciclastic influence. **(A)** Passively infilled burrows with organic debris (Salam 47, depth 5844 ft (1782 m)); **(B)** Color variation in micritic material may be a result of burrowing (*Thalassinoides*) (Salam 38, depth 5863 ft (1788 m)); **(C)** Uniform micritic lithology (Salam 17, depth 5772 ft (1760 m)); **(D)** Micritic limestone underlying Facies A; Possibly burrowed contact (Salam 39, depth 5846 ft (1782 m)).

restricted environments to contain ostracods, and in some cases foraminifera. A variable amount of clastic material will be present with a wide range in grain sizes due to the communication between the adjacent distributary through over-bank flooding.

The occurrence of FB at the top of cleaning-upward cycles provides support for a decrease in clastic influx and increase in subsidence resulting in inundation of marine waters. The micritic nature of the limestone suggests a restricted, quiescent environment, which is further supported by the presence of a low diversity biota where individual species occur in high abundances.

The behavioral characteristics of biological traces in this facies also suggest a lower energy environment dominated by deposit feeders. The *Thalassinoides* ichnotaxon is commonly found in low diversity, brackish water suites (Pemberton et al., 2001). In many cases, *Thalassinoides* occurs as passively infilled, unlined structures suggesting a substrate that is at least firm during colonization (Pemberton et al., 2001). The *Glossifungites* ichnofacies in siliciclastic systems is typically associated with erosional dislocations suggesting exhumation of previously buried deposits. These previously buried deposits are commonly compacted and dewatered resulting in a firmer substrate. In carbonate environments, firm and hard substrates may develop more frequently without the need for burial, compaction and dewatering. According to James and Kendall (1992), carbonate sediments are frequently cemented on the sea floor contemporaneously with deposition. This process allows for the presence of *Glossifungites* assemblages under conditions that are typically not expected (See Chapter 4).

2.4 Facies C (FC): Clean Sandstone

Description:

FC tends to occur at regular intervals throughout the study area in most of the wells. This facies occurs at or near the top of cleaning-upward packages that repeat at regular intervals and are correlatable across the study area. The regularity of repetition is equivalent to that mentioned for FB (*ie.* repetition every 3.0 m to 6.0 m).

Thicknesses for FC typically range from 0.3 m to 0.9 m. Lithologic characteristics include grain sizes that are slightly larger than the bulk of FA, varying between upper very-fine and upper fine with little or no silt or mud content. This well sorted facies ranges in color from light to medium tan and consists dominantly of quartz grains. The unit contains minor amounts of transported material such as shell fragments, bone fragments and organic material consisting of wood fragments and other small grains.

There is a high degree of variability in the cement content, which allows for the presence of hydrocarbon in some of the more porous units (Fig. 2.7 b). The base of this facies is commonly sharp and overlain by lags of coarse sand and organic material. Furthermore, this facies is generally massive in appearance and does not display sedimentary structures clearly (Fig. 2.7 a, b & c). However, rare sedimentary structures are observed, including planar laminations and wave/current ripple laminations consisting of silt and/or organics, and often show a low-angle dip. Dewatering structures are also commonly visible in areas of preserved laminations and in massive units producing cement pillars (Fig. 2.7 a).

The ichnological contents of FC are consistently very rare throughout the study area. Those burrows that are present, consist of vertical shafts and U-shaped structures that are lined, representing *Skolithos* and *Arenicolites* respectively.

FC is commonly found underlying FB, H, I or FD and overlying FA. This facies can also be found in close association with FE and G.

Interpretation: (Crevasse Splay, Distributary Mouth Bar)

Crevasse splays are over-bank deposits adjacent to major distributary channels, beyond the natural levee, and are a result of flooding. Flood inundation over the natural levee is not continuous along all portions of the main distributary, which allows for discrete breaks and crevasse splay lobes to prograde over the lows during a single flood event (Coleman, 1976). Distributary mouth bars are sand bodies formed near the seaward limit of a distributary channel (Reineck and Singh, 1980). The coarsest sediment is deposited in the distributary mouth bar as a result of a decrease in current velocity and consequently the carrying capacity of the distributary, as the water leaves the channel (Bhattacharya and Walker, 1992; Reineck and Singh, 1980). Often, there is little or no scouring evident at the base of these sequences (Coleman and Prior, 1982).

Sedimentation rates in this sub-environment are exceptionally high; sufficiently higher then at any other sub-environment associated with any deltaic-like process (Reineck and Singh, 1980). Sediments may be subject to continuous reworking by stream currents, tidal processes and/or wave action. Depositional parameters such as these allow for the presence of both sand and silt within the distributary mouth bar environment. If sedimentation rates are sufficiently high, a massive sandstone package may be deposited. These sands may also contain thin laminations of plant debris and wood fragments (Reineck and Singh, 1980). Common sedimentary structures include both wave and current ripple bedding (Reineck and Singh, 1980). As a result of the high rates of sedimentation, it would not be uncommon to preserve dewatering structures in

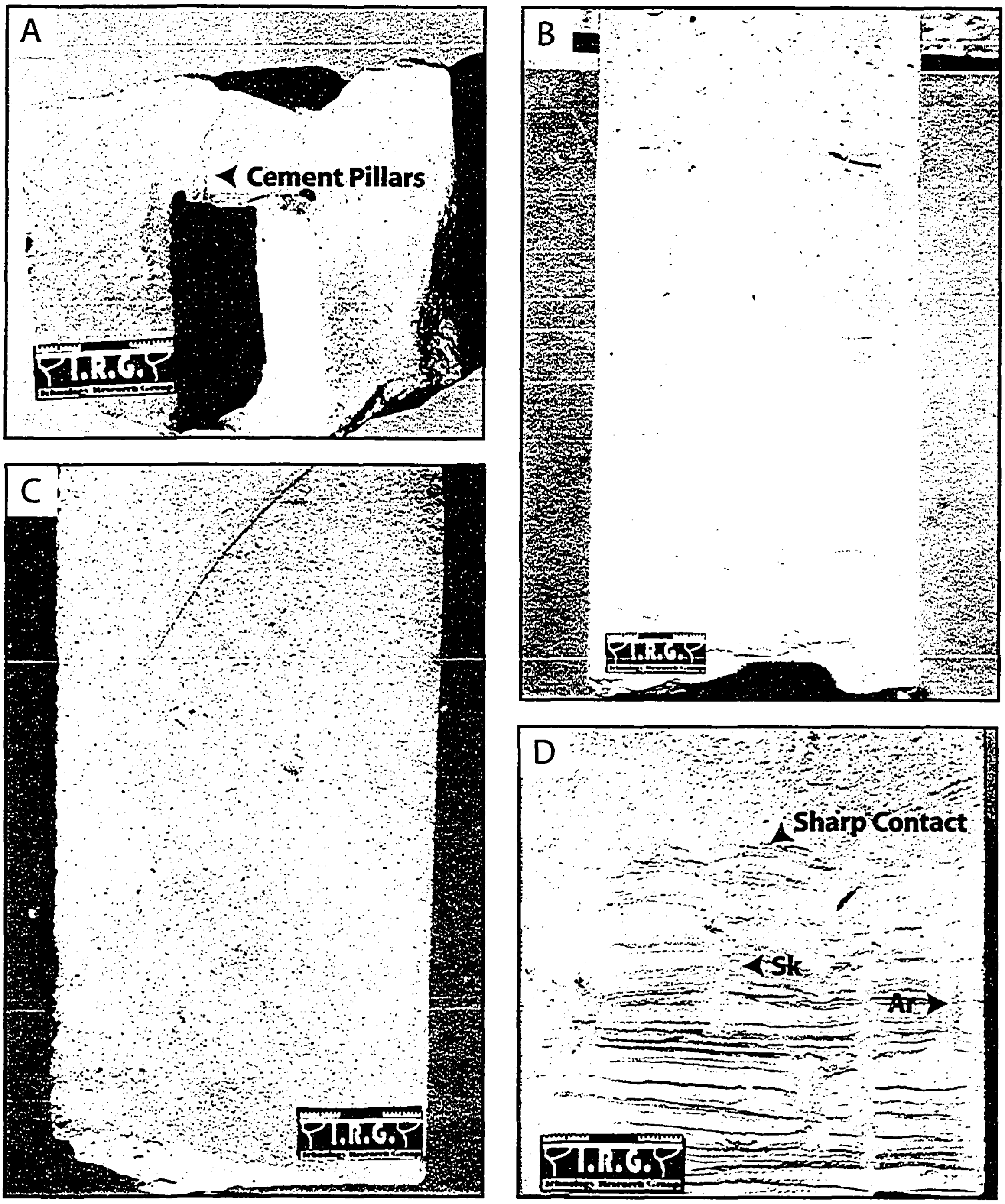

Fig. 2.7 - Clean Sandstone (Facies C): Pictures show little or no silt or clay content within Facies C. **(A)** Vertical cement pillars from dewatering (Salam 47, depth 5829 ft (1777 m)); **(B)** Variable amounts of cementing (Kenz 7, depth 6055 ft (1846 m)); **(C)** Massive sandstone (Yasser 6, depth 5941 ft (1811)); **(D)** Passively infilled *Skolithos* (Sk) and *Arenicolites* (Ar); Facies C overlying Facies E (sharp contact) (Kenz 7, depth 6077 ft (1853 m)).

the distributary mouth bars causing disruption of laminated deposits.

FC was deposited in a relatively high-energy environment that was situated proximal to a fluvial discharge. The sharp-based contact to underlying units is interpreted to be the basal extent of the distributary and introduction of the high-energy current flow. The overall absence of sedimentary structures within FC is a result of the rapid sedimentation of sand in a short period of time. The rare occurrence of symmetrical and asymetrical ripples can be attributed to current activity from the distributary channel and wave activity within the basin. Rare silt laminations deposit during periods of high-energy basinal processes such as at high-tide. On many occasions, FC is associated with a variable abundance of plant debris and wood fragments that are rapidly buried in the massive sand. In a few examples, FC develops large-scale contorted bedding that is interpreted as the result of dewatering.

The behavioral characteristics associated with the ichnology of this system provide additional support for the interpretation of a distributary mouth environment. The presence of both the *Arenicolites* and the *Skolithos* ichnogenera suggest an occurrence of the *Skolithos* ichnofacies. This ichnofacies generally develops in relatively high levels of wave or current energy and typically in clean, well-sorted, loose or shifting particulate substrates (Pemberton et al., 2001). These characteristics are commonly associated with bars and spits with stratification features such as gently seaward dipping laminae (Pemberton et al., 2001).

2.5 Facies D (FD): *Helminthopsis*-Dominated Silty Sandstone

Description:

FD is rare throughout the study area. This unit varies in thickness from 8 cm up to 0.6 m and is described as a light tan to medium gray unit with grain sizes ranging from silt to lower very-fine sandstone. Iron staining or sideritized layers are common with a moderate abundance of pyrite. FD is commonly associated with FH, I and B. Also, this facies commonly overlies FA with a scoured surface and a lag deposit, on top of a passively infilled burrow network. Commonly, there is a high degree of bioturbation, which disrupts most primary sedimentary structures except for some rare planar laminations (Fig. 2.8).

The dominant presence of *Helminthopsis* in this unit give it a particularly characteristic appearance, clearly distinguishing it from others of a similar grain size and/or color. *Helminthopsis* is associated with rare *Thalassinoides* and *Teichichnus*.

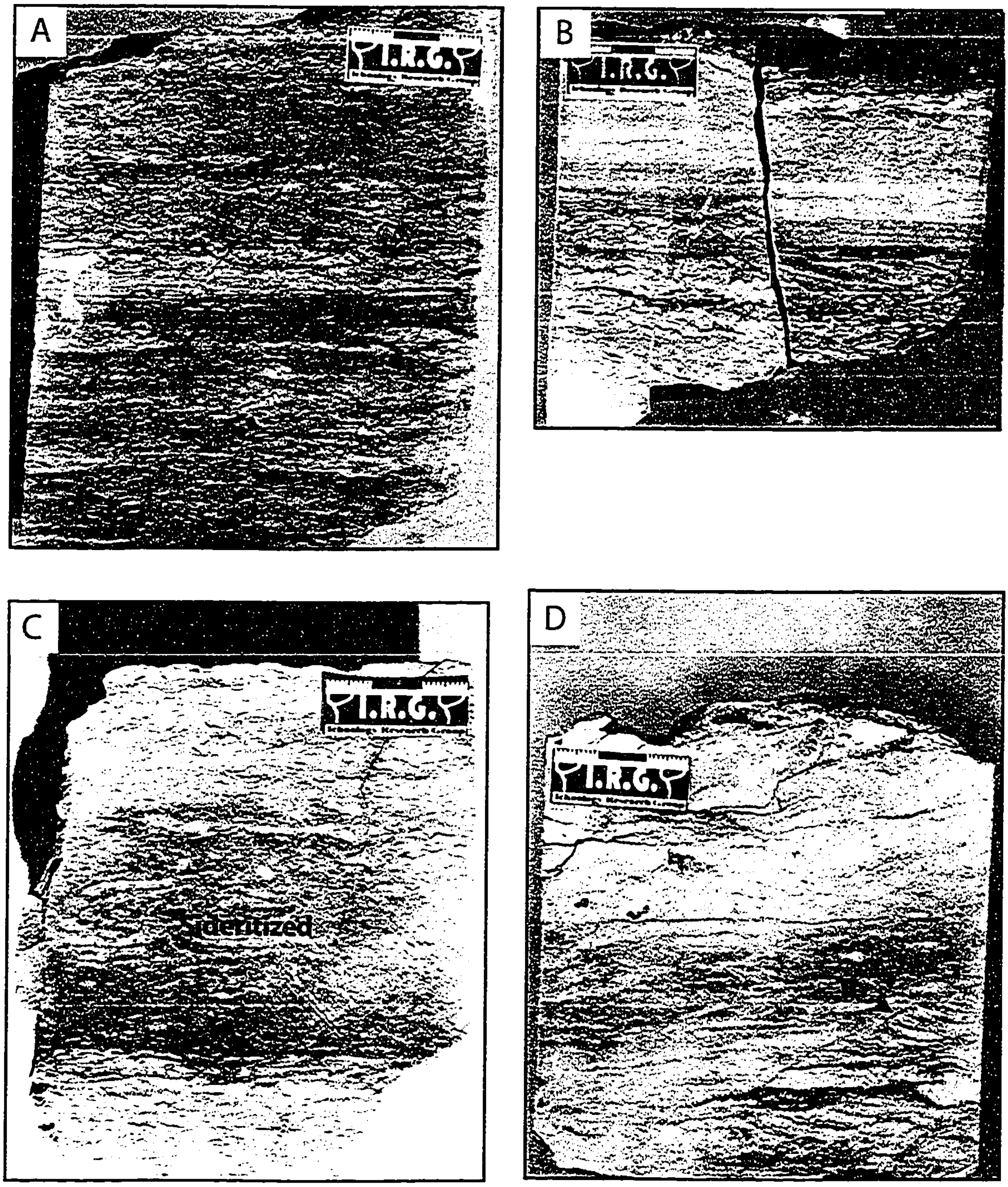

Fig. 2.8 - Helminthopsis Dominated Silty Sandstone (Facies FD): Pictures show a dominance of *Helminthopsis* (He). **(A)** (Salam 47, depth 5872 ft (1790 m)); **(B)** (Salam 47, depth 5872 ft (1790 m)); **(C)** Siderite staining (Yasser 6, depth 5959 ft (1817 m)); **(D)** *Teichichnus* (Te) (Salam 38, depth 5918 ft (1804 m)).

Interpretation: Facies D (Marine Bay)

FD, in most respects, displays a lithologic appearance that is similar to FA. The distinctive characteristic of this facies is the presence of *Helminthopsis*, which replaces the brackish water suite observed in FA.

The fine-grained nature of this unit suggests a very low energy environment. The close association of FD with FH and B supports a slightly deeper water origin, possibly within more fully marine waters then FA. *Helminthopsis* is a common element of the distal *Cruziana* ichnofacies and proximal *Zoophycos* ichnofacies on a normal marine shallow shelf (Pemberton et al., 2001). It also occurs in low energy, fine-grained bay environments (Pemberton et al., 2001). Restricting fresh water influence into an open bay and then flooding the system with fully marine waters would sufficiently change the behavioral characteristics of the ichnofauna to match those of FD.

In addition, FD is commonly found overlying lag deposits and scoured surfaces associated with *Glossifungites* assemblages. The style of burrowing and taking into account the other factors that have been discussed, implies the presence of a possible transgressive surface of erosion. This event most likely indicates a minor or major flooding surface separating parasequences or parasequence sets.

2.6 Facies E (FE): Laminated Muddy Sandstone

Description:

This facies is one of the most recognizable units in the study area due to the clear development of sedimentary structures. This unit is easily correlated between wells and generally occurs at regular horizons. FE is present in most of the wells and appears to show an abundance near the middle of the study area (*eg*. Kenz and Yasser fields). FE consists of three Sub-facies (E1, E2 and E3), which are defined based on the sedimentary structures that they contain, and their constituent silt, mud and sand content (Fig. 2.9, 2.10 & 2.11).

FE varies in thickness from 16 cm up to 1.2 m with the dominant grain size ranging from silt to upper fine sandstone along with minor clay laminations. The proportion of mud and silt within the unit is one of the distinguishing factors between sub-facies. The color of the unit ranges from pale green/gray to medium gray interfingered with dark gray or black laminations. Laminations are defined by silt, mud and/or fine-grained organic material interbedded with sand. Sedimentary structures include wavy bedding, flaser bedding, asymmetrical ripples, symmetrical ripples, planar laminations, rhythmic laminations, mud cracks, convolute bedding and climbing ripples. Furthermore, the base of FE is commonly sharp and erosive.

Sub-facies E1 is distinguished from E2 and E3 by the presence of asymmetrical ripples, climbing ripples and the dominance of sand sized particles (Fig. 2.9). Sub-facies E2 is distinguished by the presence of mud preserved within troughs of ripples (flaser bedding). This unit is also characterized by the dominance of sand sized particles (Fig. 2.10). Lastly, Sub-facies E3 contains thicker laminations of mud interfingered with sand laminations displaying wavy bedding, symmetrical ripples and planar laminations, which tend to develop mud drapes that commonly occur in pairs (Fig. 2.11).

The ichnological components include rare *Teichichnus, Lockea, Skolithos, Siphonichnus, Planolites, Palaeophycus* and *Arenicolites*. On many occasions, the burrowing infill is remineralized to pyrite.

FE is most commonly overlain by FG, C or A and underlain by FB, H or I. In most cases, FE is erosionally disconformable with the underlying units and is conformable with those lying above.

Interpretation: Facies E (Crevasse Splay "Delta Front")

As was described for FC, a crevasse splay is an over-bank deposit adjacent to a major distributary channel produced as a result of flooding. Flooding, via discrete breaks in the natural levee, allow for the progradation of crevasse splay lobes over the lows within the bay (Coleman, 1976). These coarsening-upward units resemble a mini-delta (Horne et al., 1978). In many respects, crevasse splays have sedimentary structures, biological activity and lithologic characteristics similar to the progradational front of a delta (*ie.* delta front). For the purposes of this paper the term "delta front" will be used in reference to the progradational front of the crevasse splay sands. In this system the delta front is deposited where the sediments of the distributary mouth bar interact with basinal processes and its associated sediments. Often, the coarser-grained delta front deposits sink into the underlying muddy prodelta sediments causing compaction and mud diapirs to form (Moore, 1966; Reineck and Singh, 1973). This process may lead to the development of contorted bedding within the delta front deposits. Another factor resulting in contorted bedding in delta front originates from gas-heave structures as a result of the production of carbon dioxide from the underlying prodelta deposits (Moore, 1966). Water escape structures may also contribute to the development of these structures. In vertical succession, delta front sediments may grade into sandy channel and natural

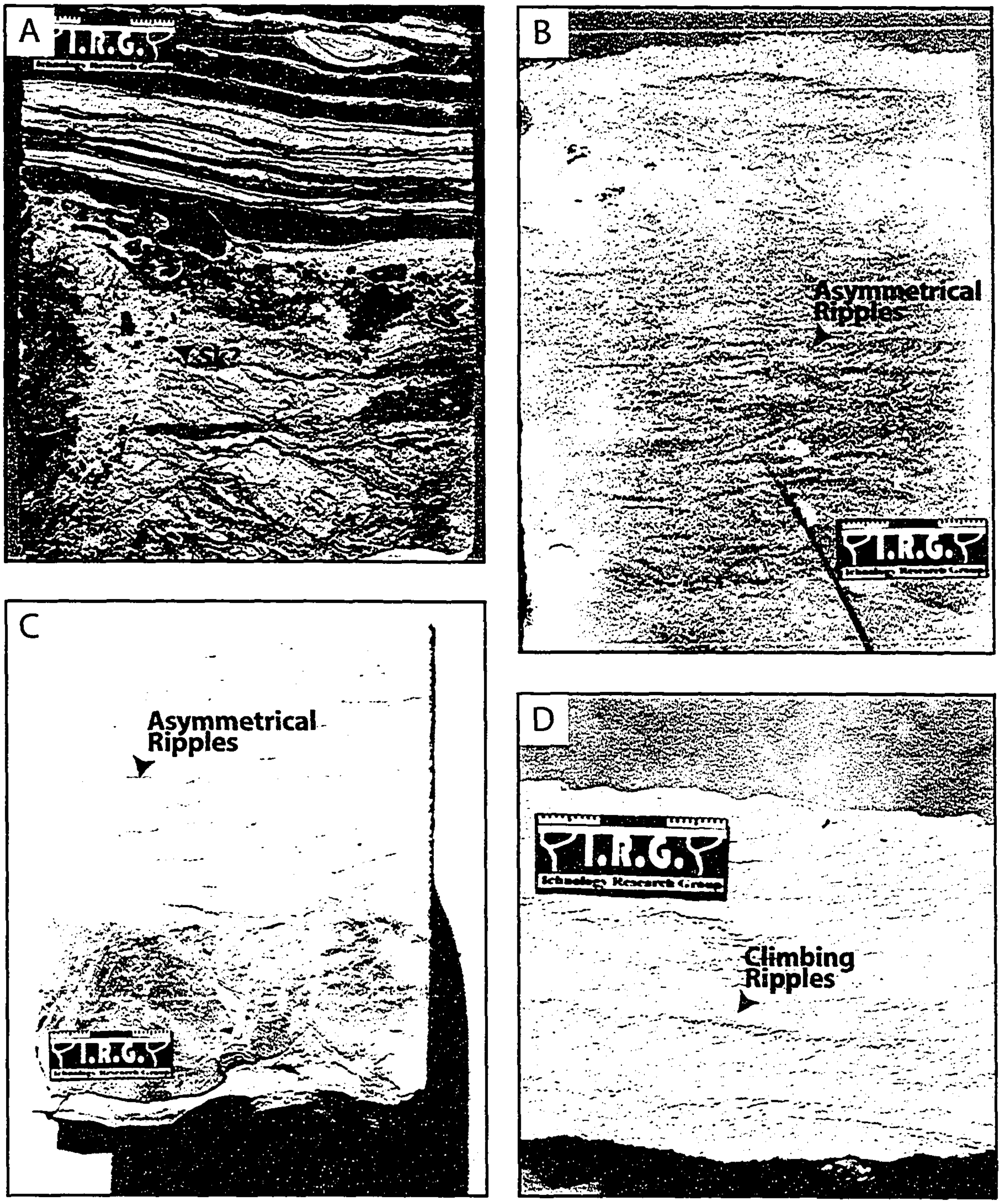

Fig. 2.9 - Current Rippled Sandstone (Sub-facies E1): Pictures show a dominance of sandstone and asymmetrical ripples. **(A)** Scoured contact between underlying Facies A and overlying Facies E producing a *glossifungites* burrow; *Skolithos* (Sk) (Yasser 6, depth 5914 ft (1803 m)); **(B)** (Salam 47, depth 5840 ft (1780 m)); **(C)** (Kenz 9, depth 6070 ft (1851 m)); **(D)** Climbing ripples (Kenz 7, depth 6100 ft (1860)).

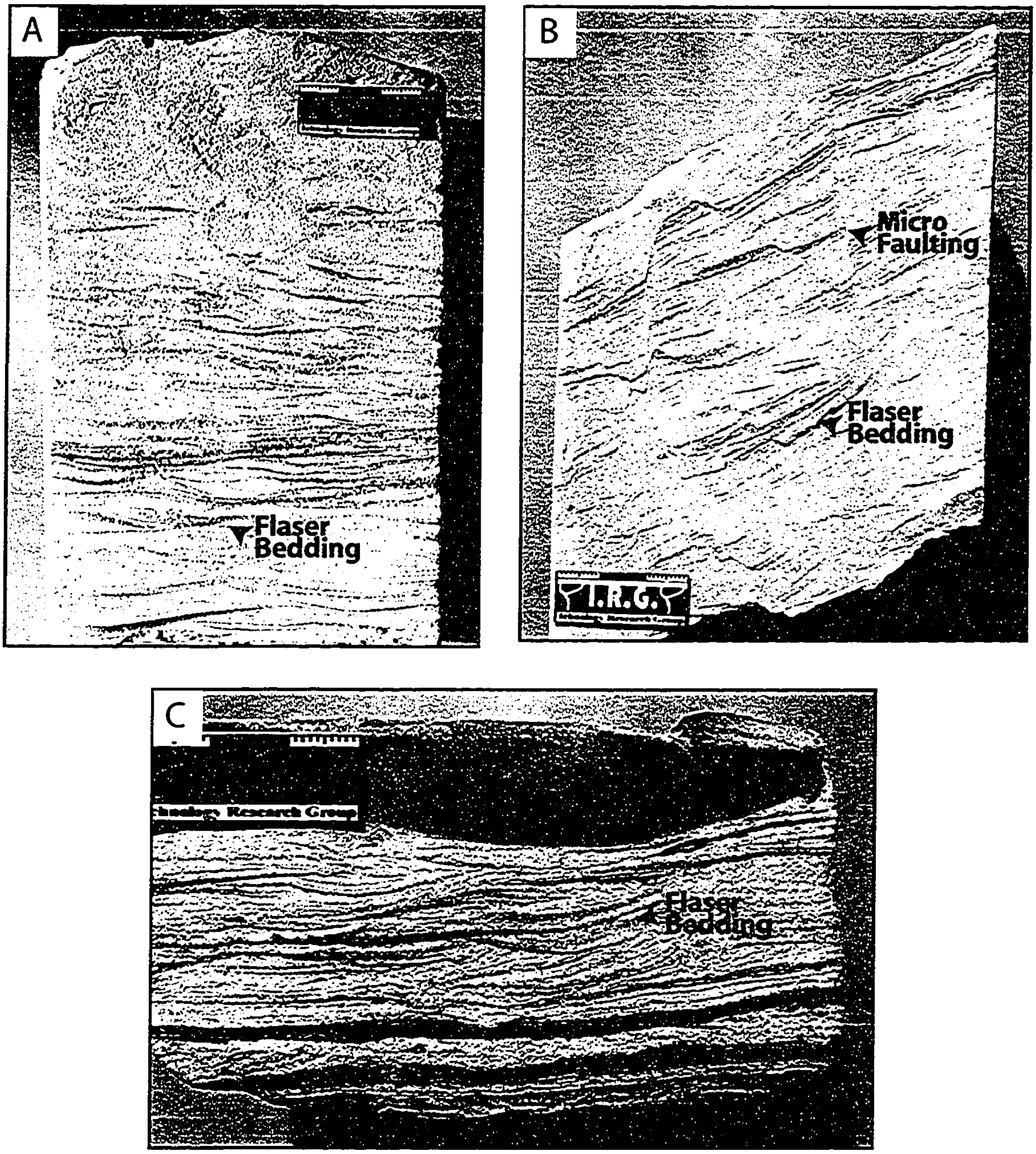

Fig. 2.10 - Flaser Bedded Sandstone (Sub-facies E2): Pictures show a dominance of sandstone and mud preserved in troughs (flaser bedding). **(A)** (Salam 38, depth 5865 ft (1788 m)); **(B)** Micro faulting (Kenz 7, depth 6102 ft (1860 m)); **(C)** (Kenz 9, depth 6070 ft 1851 m)); **(D)** (Salam 39, depth 5849 ft (1783 m)).

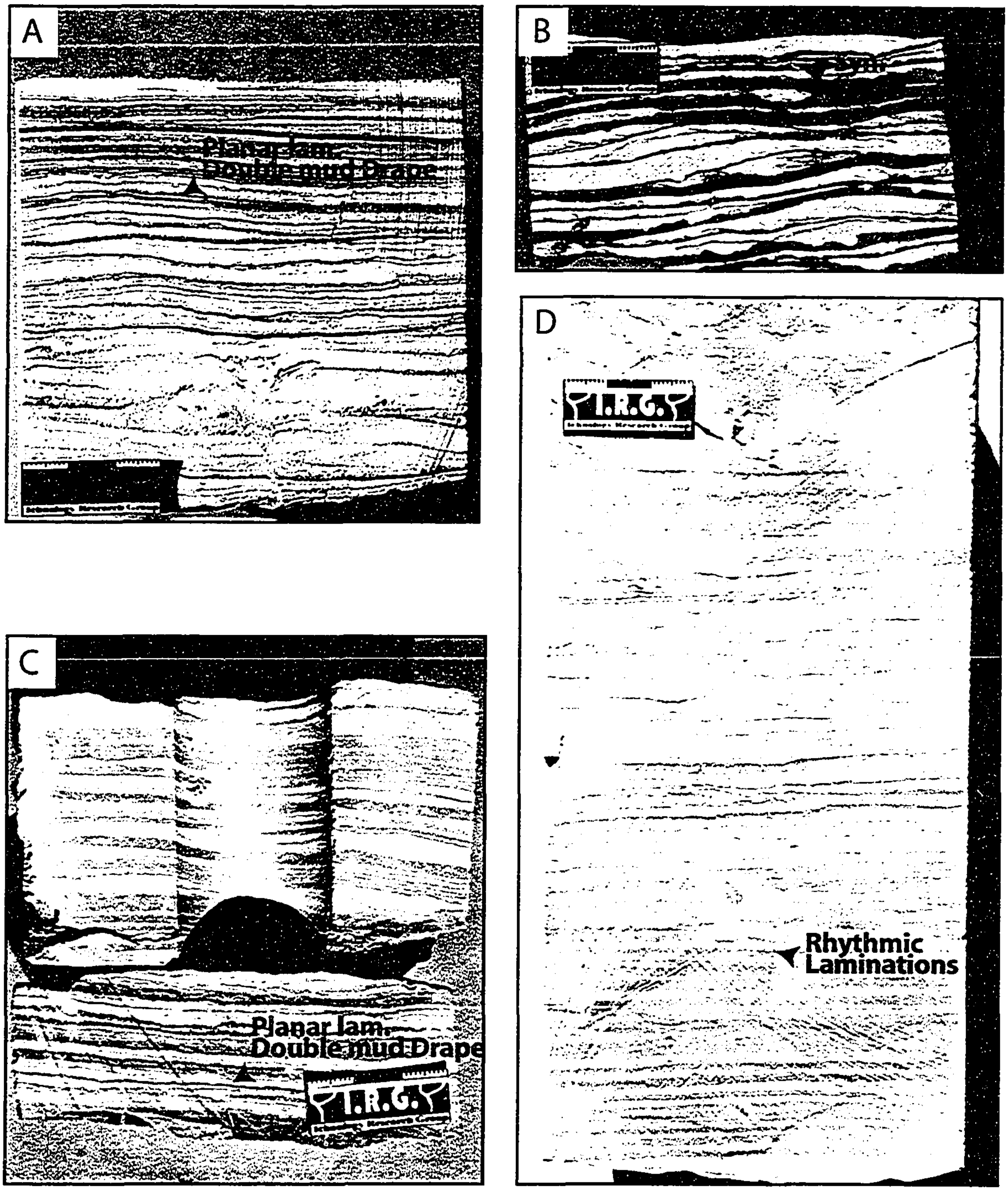

Fig. 2.11 - Wavy/Planar Laminated Mud and Sandstone (Sub-facies E3): Pictures show a mixture of sandstone and mud interfingering as planar laminations and wavy bedding. **(A)** Double mud draping (Salam 38, depth 5867 ft (1789 m)); **(B)** Synaeresis crack (Hayat 12, depth 6086 ft (1855 m)); **(C)** (Yasser 6, depth 5913 ft (1803 m)); **(D)** Rhythmic laminations (Kenz 7, depth 6105 ft (1861 m)).

levee deposits, which grade laterally into delta plain and marsh deposits (Reineck and Singh, 1973). This type of deposit exhibits an interaction between river discharge, wave reworking and bay sedimentation in the distal to intermediate bar area (Elliott, 1974). Vertical successions through crevasse splay deposits demonstrate an upward gradation from symmetrical ripples and clay drapes to asymmetrical ripples as the splay progrades into channel-dominated settings (Elliott, 1974).

FE displays an abundance of silt, mud and/or organic material laminated with sandstone particles. The bimodal distribution of grains and segregated laminations of sand and finer grained material suggests two sediment sources. These characteristics support the mixing of a distributary mouth bar with other bay fill processes in the delta front environment.

The vertical succession attributed to laterally adjacent environments within the delta front, suggested by Reineck and Singh (1973), is recognizable in the Upper Bahariya core. Here, the delta front deposits (FE) commonly grade laterally into bay shales (FH) and tidal flat sands (FA) and often grade laterally into marsh deposits and natural levee deposits of FI (rooted green muds).

Further support for a delta front interpretation involves the presence of a number of sedimentary structures. Synaerisis cracks were observed in all the sub-facies of FE and provide support for the mixing of fresh and saline waters. Sub-facies E1 contains sedimentary structures such as current ripples and climbing ripples, which are an indication of high sedimentation rates attributed to the proximal delta front environment. According to Coleman (1976), climbing ripples are a common occurrence within deposits of the delta front deposits. The base of FE has been observed as an erosional contact. Sub-facies E2 incorporates slightly more distal deposits, when compared to Sub-facies E1, and is still dominated by sandstone particles but demonstrates flaser bedding. This type of deposit is formed due to the added presence of bay processes to the current energy of the crevasse channel. Sub-facies E3 integrates a higher mud content with double mud drapes, symmetrical ripples and wavy bedding placing it in a slightly more distal position compared to Sub-facies E1 and E2. Reworking of the crevasse sand by wave processes produces symmetrical ripples (Elliott, 1974), while tidal processes lead to double mud draping. Elliott (1974), suggested that multi-directional ripple laminations in the bar facies were recorded as a result of the complex interaction of current and wave processes, which may explain the presence of wavy bedding.

2.7 Facies F (FF): Glaucony

See chapter 3 for a detailed discussion on the observations made and interpretations derived for FF.

2.8 Facies G (FG): Organic-Rich Sandstone

Description:

FG occurs in most of the wells across the study area; however, this facies is minor and comprises an insignificant portion of the core, but is easily correlatable. This is a fairly distinctive facies, as a result of an abundance of incorporated wood fragments (Fig. 2.12).

The thickness of FG varies between 30 cm and 60 cm. Grain sizes range from upper very-fine sandstone to lower fine sandstone. Samples vary in color from a medium gray to a dark gray depending on the size and abundance of organic material. The wood fragments typically comprise 5% to 30% of the rock and are aligned horizontally, parallel to layers. The wood fragments are coalified and 3 mm to 3 cm in length. Sedimentary structures such as planar laminations, are typically disrupted by bioturbation or soft sediment deformation causing contorted bedding.

Burrowing tends to be moderate to high and includes *Planolites, Palaeophycus, Thalassinoides* and *Teichichnus*. Traces are usually filled with a lighter, less organic material and in some cases have been remineralized to pyrite.

FG has a common association with FC and/or FE and is generally found overlying FA. This unit is also commonly found underlying FB or H.

Interpretation: Facies G (Crevasse Splay, Distributary Mouth Bar)

Building on the discussion of a crevasse splay in FC and FE, highly organic sands can be deposited due to episodic fluctuations during flood stages. Bay-like environments are typically encircled by extensive areas of vegetation (Fisk, 1960; Morgan, 1970), which may provide organic material for deposition within the crevasse splay. Flooding via crevasse splays may encounter large amounts of vegetation in the vicinity of the levee breach and transport it to proximal areas, where it is quickly buried. In vertical sections, as deposits become more proximal to fluvial sources within a bay fill environment, layers of organic trash are commonly deposited (Coleman and Prior, 1982). The base

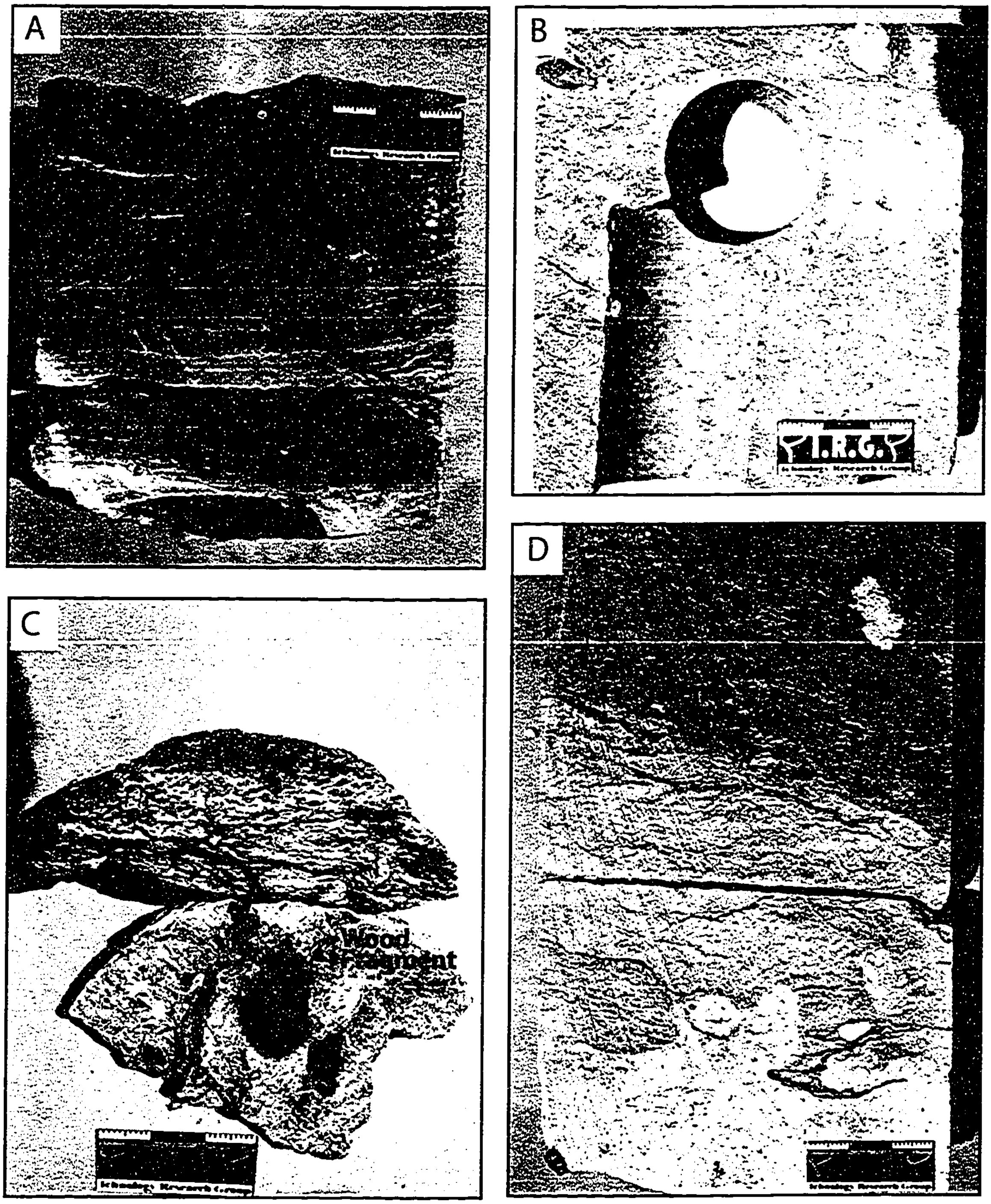

Fig. 2.12 - Organic-Rich Sandstone (Facies G): Pictures show a relatively high abundance of organic material. **(A)** (Yasser 6, depth 5905 ft (1800 m)); **(B)** (Hayat 13, depth 5906 ft (1801)); **(C)** Coalified wood fragment (Yasser 6, depth 5904 ft (1800 m)); **(D)** Wood fragments aligned parallel with laminations (Hayat 17, depth 5944 ft (1812 m)).

of distributary mouth bars are commonly composed of pebble lag deposits and/or coal spars, which represent compressed pieces of wood or bark (Horne et al., 1978). Thin laminations of plant debris and wood fragments are also often present within parts of the distributary mouth bar deposits (Reineck and Singh, 1980).

FG was deposited in a similar process as FC. The well-sorted sands of this facies were deposited by a distributary mouth bar system. The abundance of organic material is a result of flooding into vegetated areas, incorporation of organics, transport via crevasse channels, and finally deposition in the distributary mouth bar environments. Contorted bedding is a common feature found within these deposits due to the local slumping of sediments, dewatering or the degassing of the underlying prodelta deposits.

The ichnological assemblage of this unit differs from that of FC because of the availability of organics. This facies is dominated by deposit feeding traces rather than suspension feeding traces as was the case for FC. Typical ichnotaxa include *Palaeophycus, Teichichnus* and *Thalassinoides*. *Teichichnus* is produced by deposit feeding organisms that migrate upward to keep pace with sedimentation and is commonly found in bay facies characterized by brackish water (Pemberton et al., 2001). *Thalassinoides* is commonly found in lower diversity, brackish-water suites (Pemberton et al., 2001) suggesting a restricted bay environment for FG.

2.9 Facies H (FH): Carbonaceous Shale

Description:

FH commonly occurs in all wells across the study area. This unit appears at multiple horizons within each cored interval, resulting in difficulty of correlations.

Grain size varies for this facies from dominantly mud to dominantly silt, altering the texture from blocky to fissile. The organic content can be as high as 60% by volume, but is typically 5-10%. This unit exhibits a medium gray to black color, occurs in thicknesses that range from 16 cm to 1.2 m and may contain sedimentary structures such as planar laminations (Fig. 2.13).

Due to the fissility of this unit, the identification of trace fossils is not possible.

FH is associated with all facies but is most commonly found in relationship with Facies B, D, A and I. There is a close relationship between FH and J, represented as a gradation between the two units.

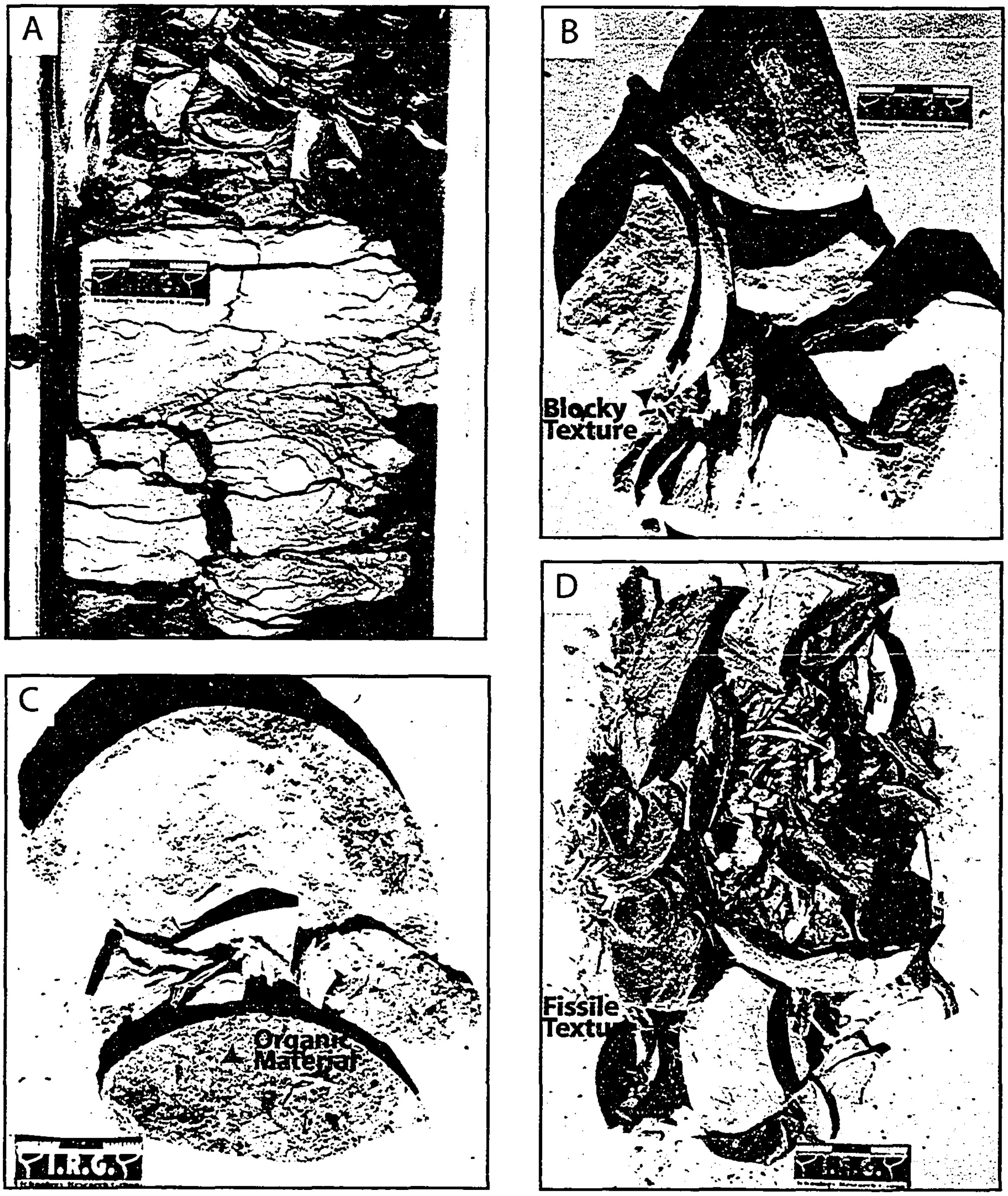

Fig. 2.13 - Carbonaceous Shale (Facies H): Pictures show variability in the amount of organic material and texture of the shale. **(A)** (Salam 38, depth 5926 ft (1807 m)); **(B)** Blocky texture (Yasser 6, depth 5909 ft (1802 m)); **(C)** Organic material along bedding planes (Yasser 6, depth 5930 ft (1808 m)); **(D)** Fissile texture (Hayat 17, depth 5930 ft (1808 m)).

Interpretation: Facies H (Interdistributary Bay Shale)

Interdistributary bays are defined as areas between distributary channels, irrespective of whether the bays are completely open to the sea, partially open, or entirely closed (Coleman, 1964). During initial stages of bay infilling, flooding occurs as sheet flows over the channel levees allowing fine grained suspended sediment to be deposited over the entire bay (Elliott, 1974). Coarse sediment is confined to bay margins (Elliott, 1974) allowing the finer-grained material to blanket the center of the bay. In later stages of bay infilling, crevasse splays may develop. As a crevasse system begins to prograde, the finer-grained material is found in more distal deposits away from the splay sands. In many examples, an abundance of pyrite is seen replacing plant material and other organic matter (Coleman and Prior, 1982).

A depositional origin is difficult to assign to FH. Black, organic shales have been documented in central estuaries, interdistributary bay fills and in marine environments. The difficulty arises in differentiating and recognizing the characteristics that separate these depositional systems.

The fine-grained nature of the shale indicates a very low energy environment located a reasonable distance from a depositional source. Deposition of organic rich shale is favored when the surface water productivity is high and/or terrestrial plant material is transported basinward in high abundance (Reading and Collinson, 1996). The close association of FH with FD, J and B suggests a relatively deeper water environment when compared to depositional parameters associated with other bay fill deposits. This facies appears to be most prevalent at the base of cleaning upward sequences connected to a flooding event separating possible parasequences within a bay-fill setting. Also, FH can interfinger with deposits of FI (marsh muds) and FA (tidal flat sands), which are concordantly forming along the fringes of the bay fill environment.

2.10 Facies I (FI): Rooted Green Mud

Description:

Facies I occurs in most of the wells in the study area at only a few horizons. Thicknesses for FI typically range from 15 cm up to 90 cm. Lithologic characteristics typically include a pale or medium green background deposit composed of clay-sized particles and variable amounts of silt and sand-sized particles. Petrographic analysis permitted identification of silt-sized quartz grains and an abundance of pale green clay matrix. The pale green clay matrix shows evidence of alteration; however, limited sampling makes any conclusive analysis impossible. The samples ranged in relative proportions of matrix from 15% to 50% and quartz from 35% to 85% by volume. An abundance of iron-stained roots are present at many horizons, along with common development of calcrete nodules (Fig. 2.14). Rarely preserved sedimentary structures include planar laminations and asymmetrical ripples. Core samples display blocky to fissile textures with a high degree of variability in the cement content. Sideritized layers are common throughout the study area.

Burrowing is common in this facies, but specific traces are difficult to identify because of a lack of contrast in lithologic constituents. Rare development of vertical shafts, both branched and unbranched, have been identified as *Psilonichnus* and *Skolithos*, respectively.

FI is commonly found on top of crevasse splay sands such as Facies C, E and G and can also be found ontop of tidal flat sands of FA.

Interpretation: Facies I (Natural Levee and Marsh Muds)

Natural levees are ridges that lie parallel and adjacent to distributaries along the length of a channel. As a result of the river stage periodically rising above these ridges, coarser sediments are deposited along its flanks. In some examples, levee deposits will exhibit various kinds of current ripples and ripple bedding (Reineck and Singh, 1980). More often, sedimentary structures are intensively burrowed by plants and animals completely disrupting the host sediments (Reineck and Singh, 1980). Natural levees are often found in interdistributary bay environments associated with marsh deposits (Reineck and Singh, 1980; Coleman, 1976). Marsh deposits are low tracts of periodically inundated land supporting non-woody plants such as grasses, reeds and rushes (Coleman, 1976). These deposits are located adjacent to levee deposits and generally approximate the mean high tide level (Coleman, 1976). As interdistributary bays are periodically infilled with clastic sediment, coarsening upward sequences are often capped with marsh muds (Coleman, 1976; Elliott, 1974). The top of the sequence is characterized by highly rooted structures, representing a build-up to sea level and colonization by marsh plants (Coleman, 1976). Fine clastic clays are brought in by periodic flooding over the natural levee into an otherwise organic rich region (Coleman, 1976). Where marshes and swamps are well drained, the organic content is often very low (Reineck and Singh, 1980). In these situations deposits are mainly clay with isololated silt lenses commonly containing nodules of $CaCO_3$ (Reineck and Singh, 1980).

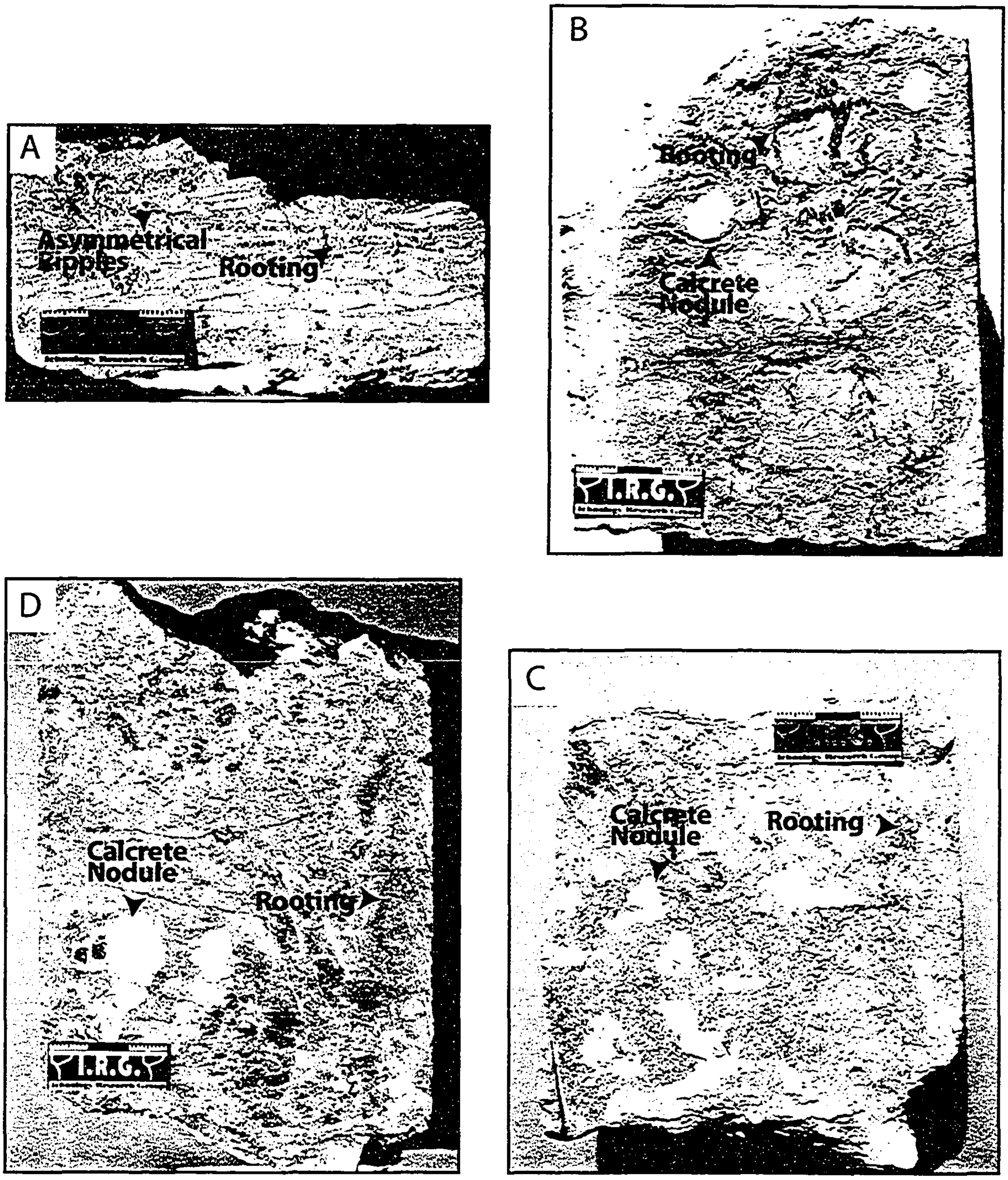

Fig. 2.14 - Rooted Green Mudstone (Facies I): Pictures show a pale green clay matrix. **(A)** Asymmetrical ripples with sideritized roots (Salam 17, depth 5824 ft (1776 m)); **(B)** Calcrete nodules and sideritized roots (Yasser 6, depth 5909 ft (1802 m)); **(C)** Calcrete nodules and sideritized roots (Yasser 6, depth 5930 ft (1808 m)); **(D)** Calcrete nodules and sideritized roots (Hayat 17, depth 5930 ft (1808 m)).

A pale green clay matrix is found within a number of different facies, but most commonly within FI (rooted green mudstone). There is no conclusive evidence confirming the presence of any glauconitic material within the pale green mudstone because of its fine-grained nature. A more probable interpretation for the green color is associated with the chemical alteration due to the formation of paleosols. Evidence for this interpretation includes the presence of rooting and calcrete nodules in many of the samples and additional data gathered by other authors. El Beialy (1994) found the sediments of the Bahariya Formation yielded a largely terrestrial microflora and a moderately diverse assemblage of miospores suggesting deposition in a continental environment with proximity to the shoreline. Generally, finer sediments such as fine sand, silt, and small amounts of clay tend to accumulate on levees (Moore, 1966). Typically the primary sedimentary structures are destroyed by later modifications such as burrows and calcareous or ferruginous nodule formation (Moore, 1966).

The presence of *Psilonichnus* is further support for emergent to near-emergent conditions, such as a supra-tidal environment. If this interpretation is correct the pale green muds may be interpreted as levee and/or marsh deposits in the supra-tidal zone, which are colonized by plants allowing for the development of preserved roots. In temperate areas, the supra-tidal environment accumulates interlaminated clays and silts, in which the laminae are extensively disrupted by rootlets, nodule growth and bioturbation (Reineck, 1967). The lack of organic material is also support for a well-drained marsh environment. According to Weimer et al. (1982), the preservation of roots is a relatively common occurrence in the supra-tidal zone and the rare presence of laminations and bioturbation within this facies is a characteristic of the uppermost inter-tidal zone and the supra-tidal zone (Weimer et al., 1982). The natural levee often merges imperceptibly into the flanking marshes, whose vegetation tends to encroach upon the levee (Weimer et al., 1982). As a result of this gradual transition it is often difficult to distinguish between marshes and levee deposits.

2.11 Facies J (FJ): Green Mud

Description:

Facies J is present throughout the study area at multiple horizons. Thicknesses for FJ range from 16 cm up to 2 m. Lithologic characteristics are very similar to those of FI, displaying a pale or medium green background composed of clay-sized particles with variable amounts of silt and sand (Fig. 2.15). Petrographic analysis reveals silt-sized quartz grains and an abundance of pale green clay matrix. FJ is differentiated from FI by the absence of iron stained roots and calcrete nodules. Iron staining is still present throughout the facies, both in nodule form and in layers. Rare bivalve shells and minor amounts of organic material are locally associated with pebble lags. Sedimentary structures such as planar laminations are rarely preserved and lithologic textures are typically blocky. Calcite cement content within this facies is variable.

Burrowing in this facies is difficult to identify due to the homogeneous nature of the sediments. Small *Skolithos, Planolites* and *Arenicolites* occur in rare abundance. Burrows are commonly accentuated by iron staining.

FJ displays a very close relationship to FH and FI and can be found interfingering with FA. It commonly overlies FB at the base of cleaning upward packages.

Interpretation: Facies J (Interdistributary Bay Muds)

As was described for FH, an interdistributary bay is defined as low areas between distributary channels, irrespective of whether the bays are completely open to the sea, partially open, or entirely closed (Coleman and Gagliano, 1964). Fine-grained sediment is deposited over the entire bay due to flooding of channel levees and sediment input from the adjacent marine environment. During later stages of bay infilling, crevasse splays are developed, allowing fine-grained deposits to be transported to distal areas. In deeper and quieter parts of the bay, a reducing environment may be present allowing for alteration of the deposits.

A low energy environment is interpreted for FJ due to the fine-grained nature of the core samples. Alteration of the clay particles to a pale green color suggests a setting where reducing conditions are prevalent, such as in a central restricted bay environment. The close association of FJ to other low energy facies such as FH (bay shale) provides further support for this type of environment. Additionally, the common occurrence of FJ and FH directly above FB (marine carbonate) at the base of cleaning upward successions, is further support for a relatively deeper and/or restricted setting within an interdistributary bay.

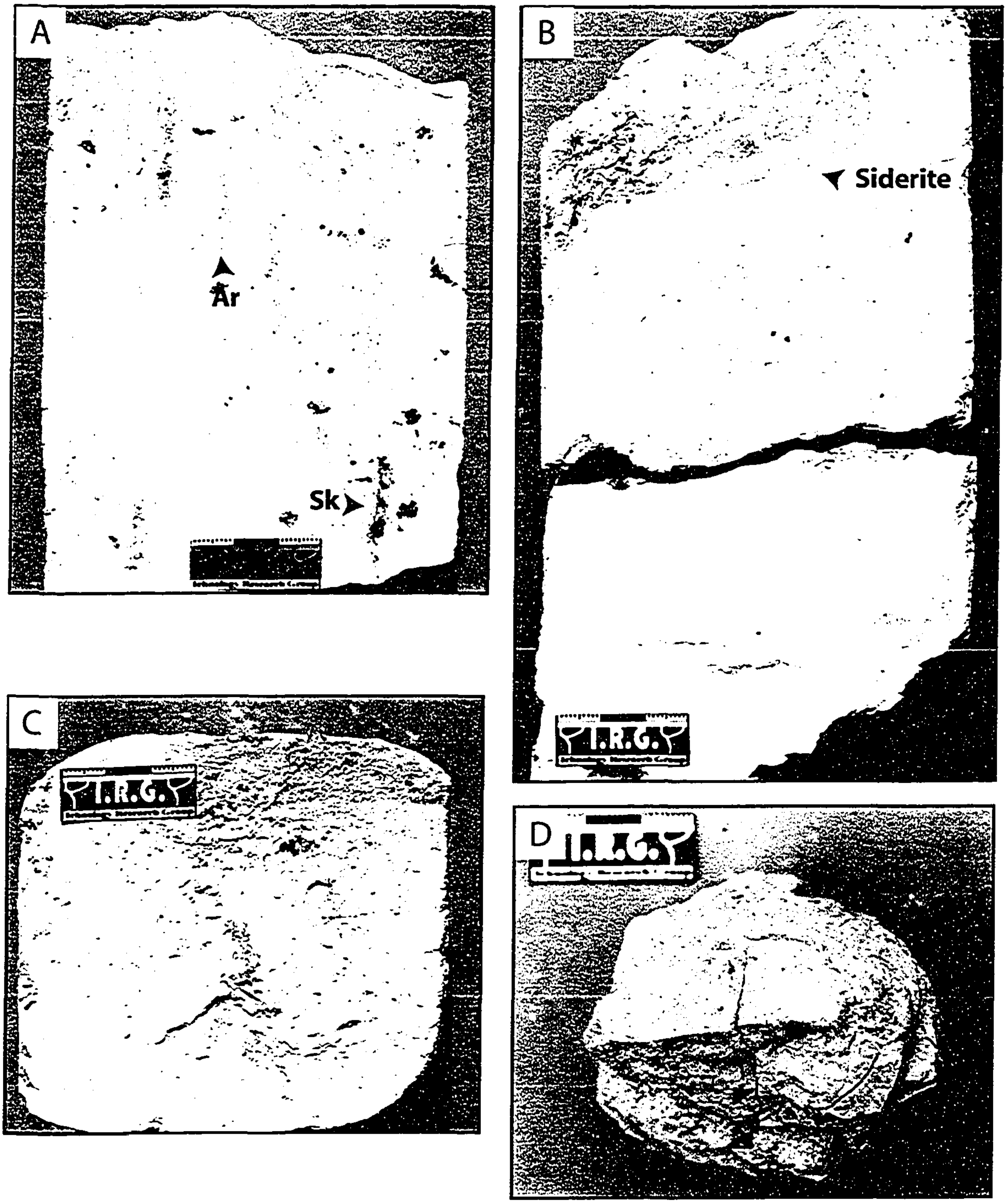

Fig. 2.15 - Green Mudstone (Facies J): All pictures illustrate the presence of green mud. **(A)** Trace fossils *Arenicolites* (Ar) and *Skolithos* (Sk) (Hayat 12, depth 6104 ft (1860 m)); **(B)** Siderite layer (Salam 38, depth 5935 ft (1809 m)); **(C)** (Kenz 9, depth 6042 ft (1842 m)); **(D)** Blocky texture (Salam 38, depth 5935 ft (1809 m)).

2.12 Facies K (FK): Shale

Description:

Facies K occurs near the top of all wells across the study area. Correlation of this facies is relatively simple due to its limited vertical occurrence and lateral extensiveness.

Characteristics of Facies K are similar to the carbonaceous shale described in FH. Grain size varies from dominantly mud to dominantly silt, changing the texture of the core from blocky to fissile (Fig. 2.16). One of the only distinguishing lithologic features that separate FK from FH is the absence of carbonaceous material. Color ranges from medium gray to black and is typically 30 cm to 1 m in thickness. Sedimentary structures include rare planar laminations that are accentuated by the cleavage of the core.

Due to the low cohesive nature of this unit, trace fossil identification was not possible in most intervals. Rare intact samples show a mottled appearance that suggests complete reworking by biological organisms.

Facies K is most commonly found at the top of every core interfingering with deposits of FF and FB.

Interpretation: Facies K (Offshore Shale)

Shale and/or mud is common in offshore environments due to quiet water conditions. Ancient siliciclastic offshore settings are commonly dominated by mud facies (Johnson and Baldwin, 1986), where primary sedimentary structures are often destroyed through bioturbation (Fraser, 1989). Muds are generally sourced from extrabasinal environments such as rivers (Fraser, 1989), where they are transported to the offshore zone, located below fair-weather wave base and above storm-weather wave base.

Facies K is a difficult unit to separate out and assign a specific environmental interpretation based on lithologic constraints alone. FK is interpreted largely on its stratigraphic position and common association to adjacent facies. Due to the fact that FK occurs in close proximity to an offshore, condensed section containing glauconitic material (FF) and marine carbonates (FB), a depositional environment of deeper marine origin is identified. The fine-grained nature of this deposit is supportive of the low energy conditions commonly present in the offshore environment. Shales of this type commonly form in laterally extensive blanket type deposits over large epicontinental areas as a result of eustatic rises in sea level (Johnson and Baldwin, 1986). The occurrence of abundant bioturbation, noted as the mottled appearance, is further support for a fully marine environment.

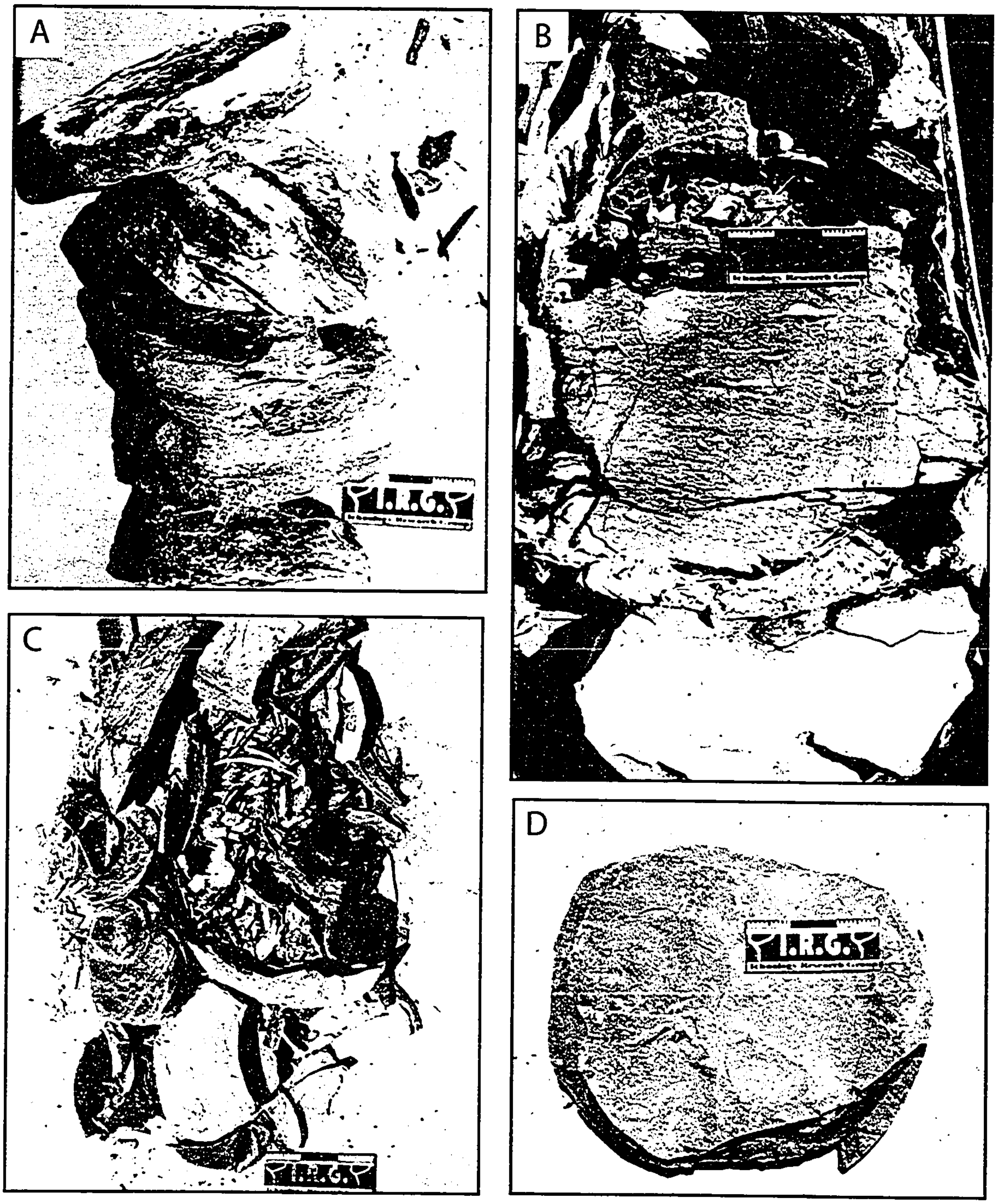

Fig. 2.16 - Shale (Facies K): All pictures illustrate the fissile nature of this facies. **(A)** (Salam 17, depth 5780 ft (1762 m)); **(B)** Mottled texture (Salam 39, depth 5824 ft (1776 m)); **(C)** (Hayat 17, depth 5931 ft (1808 m)); **(D)** (Kenz 7, depth 6041 ft (1842 m)).

CHAPTER 3: Glaucony

3.1 Introductory Remarks and Objectives

The Bahariya Formation has an abundance of glaucony throughout the upper and lower sections. This chapter deals with the significance and applicability of glaucony to interpretations of sequence stratigraphy and depositional environments. Topics such as terminology, uses, and relevance of glaucony will be discussed in order to inform the reader and to guide interpretations in later chapters. Observations regarding the glaucony within the upper Bahariya Formation will be discussed including an in depth description of the petrographic characteristics and electron microprobe data acquired. A brief discussion will be made concerning the origin of all glauconitic material within the formation.

3.2 Definition and Use of Terms

Background Information:

For the past half century, glauconite has been a well-known term relating to both an individual mineral as well as a group of minerals that occur in depositionally similar environments. Glauconite is an iron-rich variety of the clay mineral illite, with varying amounts of an expandable clay mineral, montmorillonite (Gundu Rao, 1986). A variety of different materials such as clay, colloidal silica, fecal pellets, volcanic glass fragments, micas, pyroxenes, quartz and calcite may serve as the starting medium for source material prior to the diagenisis or formation of the glauconite mineral(s) (Takahashi, 1939). Almost any type of mineral particle can provide an effective substrate for authigenesis of glauconitic clay minerals (Odin and Matter, 1981). There are however, mineral grains that tend to alter more quickly and are therefore more favorable for the glauconization process. Initial substrates that contain carbonate and/or kaolinite material tend to be more favorable for the formation of glauconitic minerals (Odin and Matter, 1981).

Odin and Letolle (1980) redefined the terminology used to describe the depositional facies corresponding to the sand-sized, green glauconitic grains because of the continuing confusion that surrounds the definition of glauconite. Glauconite has been interchangeably used to describe both a group of green minerals that occur in a depositionaly similar environment as well as a specific individual green micaceous mineral (Odin and Matter, 1981). Regardless of their mineralogical structure, the 2:

1 and 1:1 layered potassium-poor and iron-rich dioctahedral and trioctahedral minerals containing a high Fe^{3+}/Fe^{2+} ratio has recently been categorized and separated into the glaucony and verdine groups, respectively.

Verdine:

Verdine is visually indistinguishable from glaucony but can be easily identified by its mineralogical structure and chemical composition as there is significantly less K_2O than in glaucony (Amorsi 2003). Verdine generally forms in warmer tropical conditions, with water temperature near or greater than 25°C. As well, verdine is more abundant at shallower depths (15 to 60 m) than glaucony, and incorporates individual green minerals such as bathierine, and chamosite (Amorsi, 2003). Verdine is particularly abundant in estuarine environments or immediately offshore from fluvial deltas.

Glaucony:

Glaucony represents the depositional, as well as diagenetic facies in which glauconitic minerals occur. The Glaucony facies includes end members of glauconitic smectite and glauconitic mica (glauconite), which typically form in low energy conditions with slow sedimentation rates characteristic of the outer margin on the continental shelf and upper slope (Odin and Matter, 1981). The optimal conditions for glauconization are those of semi-confinement to a microenvironment with an interface between the oxidizing seawater and slightly reducing interstitial water (Odin and Matter, 1981; Amorosi, 2003; Stonecipher, 1999). It is important to note that glaucony precursors are required to remain at or near the depositional surface for extended periods of time, with temperatures generally below 15°C. The setting requires that the individual grains are repeatedly exhumed and shallowly buried by active bottom currents (Amorosi, 1995; Stonecipher, 1999). Typical depths required for formation of glaucony range in the order of 50 to 500 m, with a particular abundance between 200 and 300 m depth (Odin and Matter, 1981).

Over the years, glaucony has proven to be a particularly useful tool in directing and assisting the development of many depositional models and sequence stratigraphic interpretations. It has become apparent that glaucony is capable of providing ample information on sequence stratigraphy if the variations in its abundance, physiochemical properties, and spatial/temporal characteristics are carefully documented (Amorosi, 1995; Stonecipher, 1999). Glaucony grains must be separated into their characteristically similar groups in order to understand their genetic origin.

The distribution of glaucony within specific units is of primary importance in aiding sedimentological interpretations. Thickness of glaucony-bearing units, vertical variations (upward increasing or decreasing trends) and estimates of the relative abundance of glaucony will assist in providing an appropriate depositional model (Amorosi, 1995).

Since the beginning of the 20th century, glaucony has shown to be one of the most reliable indicators of slow sedimentation rates in marine settings (Goldman, 1922; Hadding, 1932; Heim, 1934; Amorosi, 2003). It has also been regarded by most scientists as diagnostic of the transgressive systems tract (TST). As studies have progressed over the years, it has become evident that the separation of in-situ and transported glaucony is extremely important. This recent understanding has led to the separation of glaucony into the allochthonous (parautochthonous and detrital) and autochthonous categories (Fig. 3.1). Together, allochthonous and autochthonous glaucony can occur at virtually any sequence stratigraphic level in varying abundances and maturity. Allochthonous glaucony can be distinguished from autochthonous glaucony by a number of characteristics: 1) the association of non-marine deposits, 2) the selective spatial distribution of grains, 3) the high degree of sorting and roundness, and 4) the absence of fractures in evolved samples (Amorosi, 2003). Remobilization of the in-situ glaucony by high-energy activity such as storm reworking, tidal currents, wave action, or by subaerial exposure of the shelf is likely to lead to either a parautochthonous or a detrital origin (Amorosi 2003). It is important to identify the origin of reworked grains of glaucony. The grains may have been transported from an intrasequential (parautochthonous) adjacent location, or from a transported extrasequential (detrital) location of a different stratigraphic level. A variety of environments that are poorly suited for the formation of glaucony, such as nearshore, lagoonal, estuarine, incised valleys, and turbidite systems, may contain minor to large amounts of transported glaucony. Detrital versus parautochthonous grains can be distinguished in two ways: 1) radiometric dating of the samples and 2) comparing the compositional attributes of the glaucony to the presumed sources (Amorosi, 2003).

Odin and Matter (1981) broke down the evolution of glaucony into four stages: nascent, slightly evolved, evolved and highly evolved (Fig. 3.2). Differentiation of the four stages can be determined in two ways: 1) on the basis of potassium content, with nascent glaucony showing a K_2O = 2% to 4%, slightly evolved K_2O = 4% to 6%, evolved K_2O = 6% to 8%, and highly evolved K_2O > 8% (Fig.3.3) and 2) on the shade of green within the sample, with the nascent and slightly evolved stages showing a pale to light green color, and the evolved to highly evolved stages showing a green to dark green color. The darker green, or more highly evolved glaucony grains, statistically

	SPATIAL CHARACTERISTICS	TEMPORAL CHARACTERISTICS	PROPOSED TERMINOLOGY	SYNONYMS
GLAUCONY	AUTOCHTHONOUS (IN PLACE)	INTRASEQUENTIAL	AUTOCHTHONOUS	AUTHIGENIC, IN SITU
	ALLOCHTHONOUS (TRANSPORTED)	INTRASEQUENTIAL	PARAUTOCHTHONOUS	PERIGENIC
		EXTRASEQUENTIAL	DETRITAL	ALLOGENIC, REWORKED

Fig. 3.1 - Classification of glaucony by spatial versus temporal characteristics (From Amorosi, 1995)

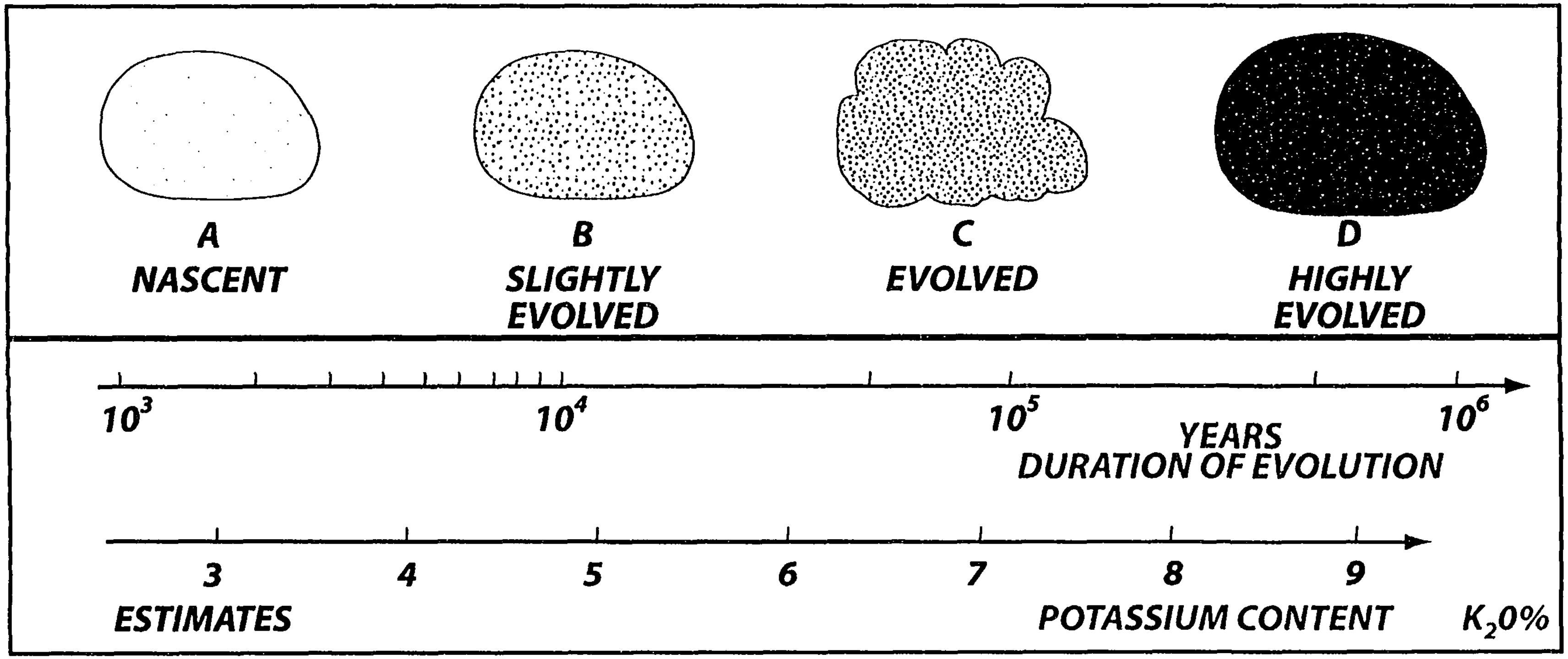

Fig. 3.2 - Stages of development in the glauconization of a granular substrate: a) nascent; b) slightly evolved; c) evolved; d) highly evolved (Odin and Fullagar, 1988).

GLAUCONY	MATURITY	K_2O CONTENT	MINERALOGICAL	PARAMAGNETIC SUSCEPTIBILITY	COLOR
NASCENT	LOW	<4%	SMECTITE	LOW	PALE GREEN
SLIGHTLY EVOLVED	MODERATE	4-6%		MODERATE	LIGHT GREEN
EVOLVED	HIGH	6-8%		HIGH	GREEN
HIGHLY EVOLVED	VERY HIGH	>8%	MICA (GLAUCONITE)	VERY HIGH	DARK GREEN

Fig. 3.3 - Classification of glaucony at different stages of evolution (From Amorosi, 1995).

demonstrate a higher specific gravity (Odin and Matter, 1981). During evolution of the grains from nascent to highly evolved, the volume of the grain becomes more pronounced in the interior then on the exterior, which leads to an evolved sample with a bulbous and cracked habit. This characteristic fracturing and bulbous habit may eventually be filled and smoothed over if the environmental conditions remain suitable for the glauconization process (Amorosi, 2003). In the event that glauconization does continue, grains may develop a characteristic rim that encrusts the entire surface with a slightly less evolved (*ie.* lower K_2O content) glauconitic material (Lamboy and Odin, 1975). In this scenario, the glaucony will appear to have been transported and rounded forming a smooth surface, when in actuality, it is truly a highly evolved autochthonous grain.

At any point during its evolution, the glauconization process may be halted if the environmental conditions become unsuitable (Odin and Fullagar, 1988). Stability in the formation of glauconite may falter depending on two main factors. Sea level change is an important process, which can expose grains to a more oxidizing environment if a drop in sea-level occurs or if there is phosphatization during transgression. The other factor involved in disruption of the glauconization process is burial of the grains (Stonecipher, 1999). Grains buried up to 1 m depth still have potential to undergo glauconization, while anything below will halt the evolutionary process (Stonecipher, 1999). Since prolonged contact with seawater is required, the maturity of glaucony is a general guide to the duration of non-deposition before burial. Thus, the extent of the hiatus can be approximated using the K_2O content of the sample. An evolved sample of glaucony with a K_2O content of 7% may indicate a hiatal pause of approximately 10^4 to 10^5 yrs, while a highly evolved sample with a K_2O content of >8% may suggest a hiatal pause of approximately 10^6 yrs (see Fig. 3.2) (Odin and Fullagar, 1988).

3.3 Glaucony: Sequence Stratigraphic Application

General Application:

If proper care is taken to evaluate the above characteristics of glaucony, a useful sequence stratigraphic analysis can be performed. Otherwise, the presence of glaucony tells us very little and is not recommended as an interpretive tool (Amorosi, 1995). The role of glaucony in sequence stratigraphy had not been analyzed in detail until Amorosi (1993); who was one of the first researchers to illustrate how the distribution, maturity, and genetic attributes of glaucony can result in useful information for sequence stratigraphic analysis. Past research has shown that glaucony can occur at any

	Sequence Stratigraphic Location	Host Deposit	Origin	Maturity
HST	Upper part of parasequence	High-energy shelf deposits	P	Low to very high
	Lower part of parasequence	Low-energy shelf deposits	A	Low to moderate
CS	Maximum flooding surface	Top of marginal-marine sand-stones	A	High to very high
	Uppermost TST-lowermost HST	Hardgrounds	A	High to very high
	Uppermost TST-lowermost HST	Outer-shelf to slope deposits	A	High to very high
TST	Ravinement surface	Transgressive sheet sandstones	P, A, D	Variable
	Incised valley fill	Estuarine deposits	P,D	Variable
	Upper part of parasequence	High-energy shelf deposits	P	Low to moderate
	Lower part of parasequence	Low-energy shelf deposits	A	Low to high
LST	Shelf margin wedge	Offshore-marine deposits	A,P	Low to moderate
	Shelf margin wedge	Coastal-belt deposits	D	Variable
	Proximal lowstand wedge	Coastal-belt deposits	D	Variable
	Lowstand fan complex	Deep-water turbidites	D	Variable

P = Parautochthonous; A= Autochthouous; D=Detrital

Fig. 3.4 - Conceptual framework of glaucony distribution in depositional sequences and expected features of glaucony (Amorosi 1995).

stratigraphic level; however, differentiation of its occurrence within the lowstand systems tract (LST), highstand systems tract (HST), and transgressive systems tract (TST) can be made (Fig. 3.4).

Low Stand Systems Tract (LST):

The sequence boundary underlying the LST in a type 1 sequence is characterized by incision into the previously deposited topsets (alluvial plain, coastal plain and/or shelf deposits of the previous sequence) as a consequence of base level fall (Emery and Myers, 1996). Sediment is carried to a common point of deposition (the previously deposited highstand clinoform slope) resulting in slope instability and large-scale slope failures creating submarine fans (Emery and Myers 1996) (Fig. 3.5). The subaerial exposure of the shelf in a type 1 sequence presents unfavorable conditions for the formation of autochthonous glaucony. However, detrital glaucony is commonly found in deep-water turbidites in the lowstand fan complex and/or in coastal belt and estuarine sand deposits of the proximal lowstand wedge (Amorosi, 1995). This can only occur if previously deposited and buried glaucony-bearing units are exposed during the incision event.

In the LST of a type 2 sequence, sea-level does not retreat beyond the offlap break, thus the outer part of the shelf is not subaerially exposed. Consequently, the

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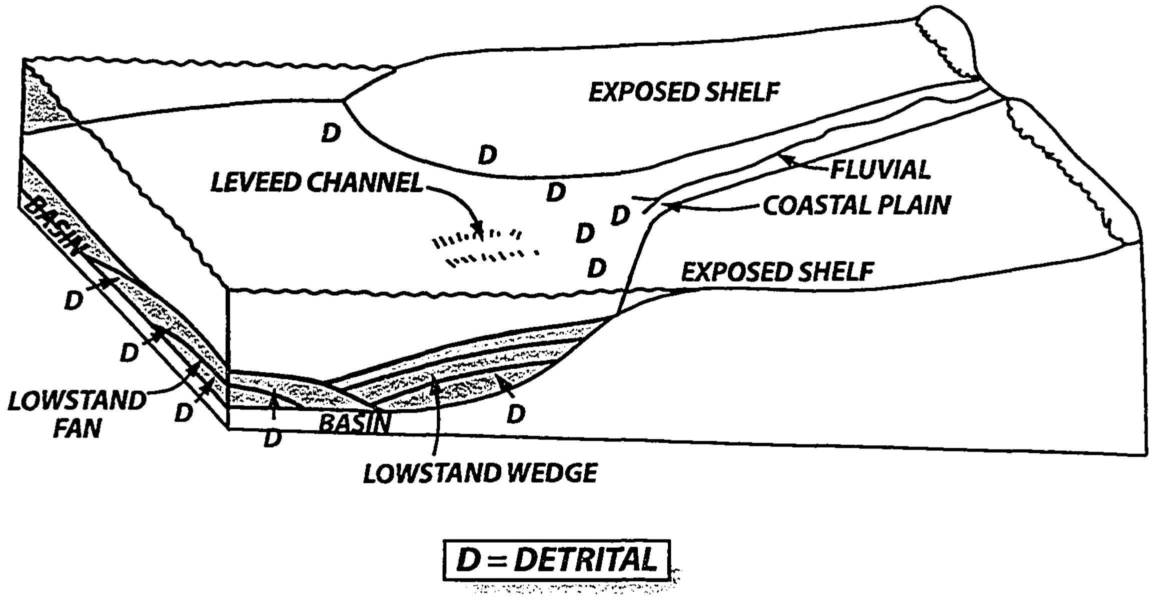

Fig. 3.5 - Distribution of glaucony in the low stand systems tract (Modified from Stonecypher 1999).

occurrence of both autochthonous and allochthonous (intrasequential and extrasequential) glaucony may be found together in sedimentary traps such as a coastal plain or in paralic environments including lagoonal and/or foreshore/shoreface deposits (Walker and Bergman, 1993). Autochthonous glaucony is thought to occur in offshore marine deposits on omission surfaces at the base of parasequences in a progradational/aggradational parasequence set (Amorosi, 1995).

Transgressive Systems Tract (TST):

The TST is characterized by base level rise that increases at a faster rate than the rate sediment is supplied to the basin, which increases accommodation space (Emery and Myer, 1996). This undersupply of sediment, together with relative sea-level rise, allows for flooding of previously exposed sections and favorable conditions for the production of autochthonous glaucony (Amorosi, 1995) (Fig. 3.6). The *maximum flooding surface* (MFS) marks the end of the systems tract, and is the point at which the rate of topset accommodation volume decreases to a level consistent with sediment supply (Emery and Myer, 1996).

An abundance of glaucony is found at the top (near the MFS) or at the boundary between the TST and the HST (Stonecypher, 1999). This however, does not negate the

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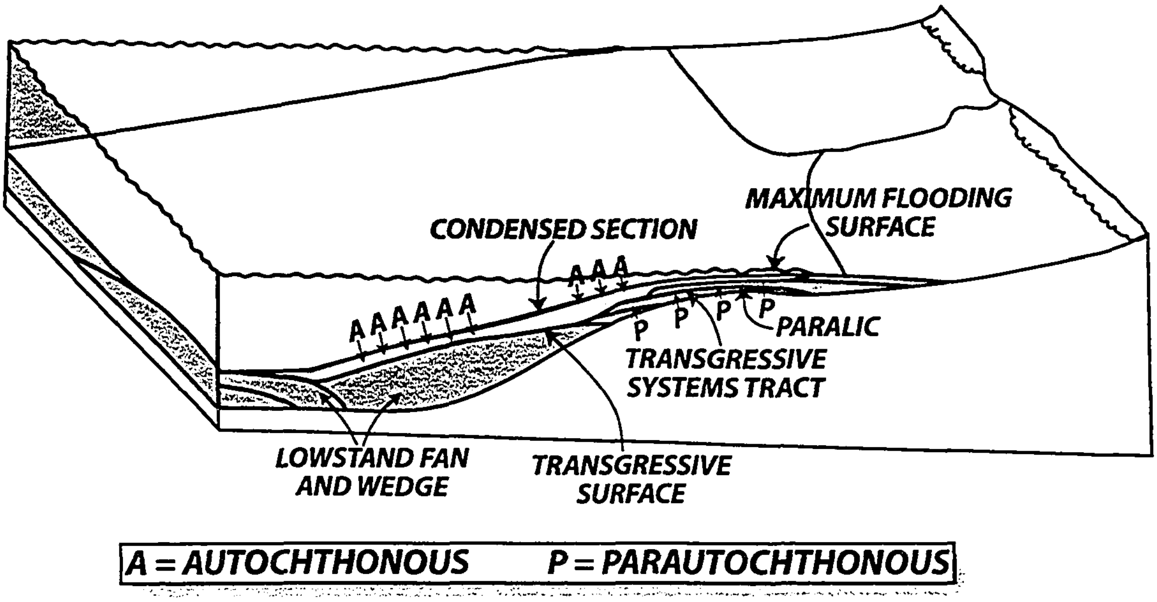


Fig. 3.6 - Distribution of glaucony in the transgressive systems tract (Modified from Stonecypher 1999).

possibility of glaucony occurring throughout the TST. The maturity and concentration of glaucony generally shows an upward increase throughout the TST (Amorosi, 1995), suggesting more favorable conditions and a higher probability of preservation near the top. Marine flooding surfaces throughout the TST mark the boundary between parasequences, and are possible autochthonous glaucony-bearing horizons (Amorosi, 1995). These marine flooding surfaces occur at the top of each parasequence, which are generally shoaling-upward cycles within a backstepping, retrogradational parasequence set (Amorosi, 1995). The sediment that occurs congruently with glaucony will generally be fine-grained and characterized by omission surfaces on the tops of burrowed coarse-grained deposits (Amorosi, 1995).

The occurrence of parautochthonous glaucony in higher-energy deposits is a result of remobilization in shallow marine settings by waves, tides, and storm energy. In this case, where glaucony is present in the upper portion of parasequences, it is assumed that the grains have been winnowed landward or seaward, before the completion of its evolution. This results in glaucony of low to moderate maturity (Amorosi, 1995). Glaucony in the TST, particularly in the lower portions, can therefore be interpreted as either autochthonous or allochthonous in origin because of their common occurrence. On the other hand, in the upper portion of the TST, as maturity of glaucony increases towards the MFS, an autochthonous origin can be established with more confidence.

Condensed Section (CS):

Glaucony is commonly reported as a major constituent of condensed sections (CS) (Loutit et al., 1988). The CS is the distal expression of the maximum flooding surface MFS of the TST (see Fig. 3.6). It is characterized by deposition with low sediment supply rates and the development of condensed facies including glauconitic, organic rich and/or phosphatic shales, or pelagic carbonates (Emery and Myers, 1996). The separation of the TST and the highstand systems tract (HST) by the MFS allows for a wide spread CS on the drowned shelf and deep basin due to sediment starvation (Emery and Myers, 1996). It is important to note that the presence of a CS is not indicative of a MFS. The CS can also be commonly found as a less extensive facies at minor flooding surfaces between parasequences.

The rapid relative sea-level rise that occurs at the start of the CS, and gradually decreases until the top of the TST, produces a depositional setting that is conducive for glauconization. As sea-level rises, sediment is trapped in more landward areas allowing for the development of authigenic glaucony with higher concentrations and highly evolved grains compared to the lower portions of the TST (Amorosi, 1995). The lithologies frequently associated with glaucony in a CS include an abundance of planktonic and benthic microfossils, phosphate grains, and organic debris (Emery and Myers 1996; Amorosi, 2003). In addition, these lithologies are commonly reported to be intensively burrowed, homogeneous outer-shelf and slope deposits (Odin, 1975 and 1985). The CS incorporates most of the autochthonous, dark green, evolved and highly evolved glaucony (Amorosi, 1995). Prolonged breaks in sediment accumulation within stratigraphically condensed intervals may include up to 90% autochthonous glaucony (Amorosi, 2003). Rhythmic fluctuations in abundance of glaucony are typical, and the maximum concentrations occur at the base of a cycle, decreasing upward (Amorosi, 2003).

Highstand Systems Tract (HST):

The HST is deposited overlying the MFS and prior to the sequence boundary of the successive sequence. The HST is deposited when the rate of sediment supply exceeds the rate of creation of accommodation space, and represents a decelerating rate of relative sea-level rise (Emery and Myers, 1996). The increase in sediment supply gives rise to initial aggradation succeeded by progradation of the topset-clinoform (Emery and Myers,

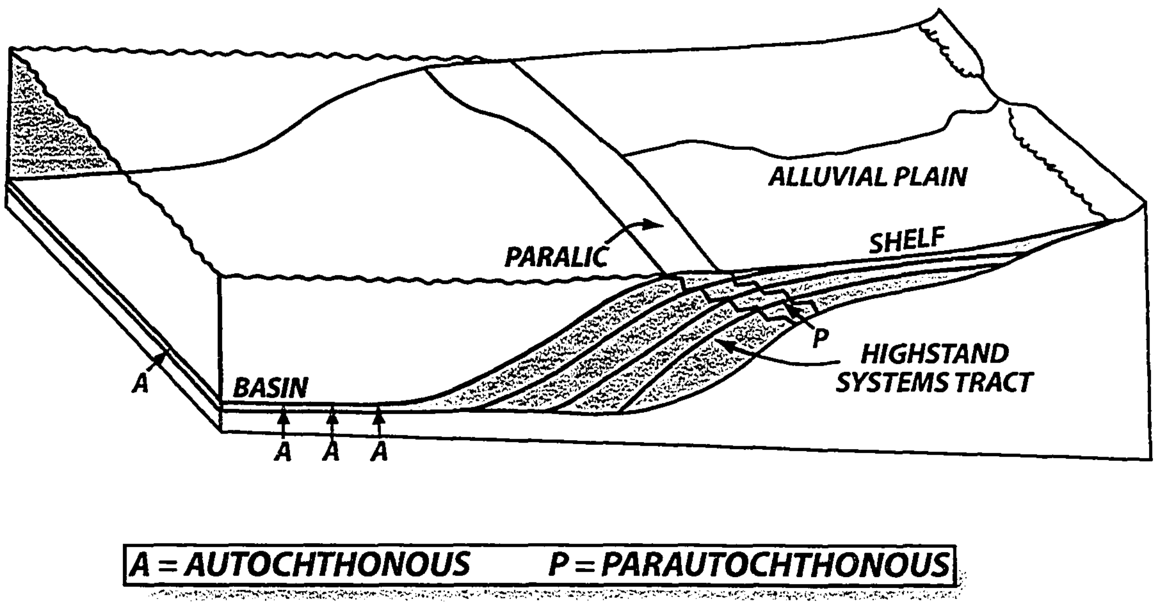


Fig. 3.7 - Distribution of glaucony in the high stand systems tract (Modified from Stonecypher 1999).

1996); therefore justifying the rarity of glaucony reported within this systems tract (Amorosi, 1995). This rarity is explained by the increasing sediment supply, which allows for an unfavorable setting for the glauconization process.

Glaucony present within this systems tract may be of autochthonous or parautochthonous origin (Fig. 3.7). Lower parts of the HST may contain minor amounts of authigenic glaucony, if there are local areas with low clastic influence. These glauconitic grains are associated with fine-grained outer shelf deposits in lower portions of parasequences or at the top of shoaling-upward sequences, marking the final stage in production of authigenic glaucony within a sequence (Amorosi, 1995). Autochthonous glaucony will display an upward decrease in abundance and maturity, distinguishing the HST from the TST (Amorosi, 1995). Furthermore, parautochthonous glaucony, of low to moderate maturity, may be associated with cross-bedded arenites deposited by bars and sand waves (Amorosi, 1995). Where as highly evolved glaucony may be interpreted as the reworking of underlying units such as the CS (Amorosi, 1995).

3.4 Glaucony in the Upper Bahariya Formation

Introduction:

The upper Bahariya Formation contains a large abundance of glauconitic material throughout its stratigraphy. Nearly all the facies defined may incorporate at least a small portion of either allochthonous or autochthonous glaucony. One facies in particular, Facies F (FF), incorporates a large abundance of glaucony and is a laterally extensive, correlatable unit across the study area. The significant abundance of glaucony in FF makes the upper Bahariya Formation an exceptional candidate for the study of the various characteristics glauconitic material may illustrate.

Methods:

Samples of glauconitic materials were cut into thin sections for petrographic and electron microprobe analysis. Descriptions from hand samples, thin section work and microprobe analysis are discussed and evaluated based on three characteristics: 1) spatial and temporal relationships, 2) physiochemical properties and 3) abundance of glauconitic material. A depositional and stratigraphic framework is developed from the glaucony analysis in conjunction with observations and interpretations on surrounding facies.

The electron microprobe was used to determine the weight percent of the following elemental oxides: CaO, MgO, Na_2O, FeO, K_2O, SiO_2 and Al_2O_3. Approximately twenty thin sections (2.5 x 4.4 cm) were made from the upper Bahariya core. Out of the twenty thin sections, ten were polished, put through an ultrasonic bath and carbon coated in preparation for analysis on the Jeol JXA-8900 electron microprobe at the University of Alberta. Glaucony grains and green clay matrix were analyzed using a beam diameter of 10 µm, 15 keV gun potential, 10 nA beam current and regressed using a ZAF correction. For additional analytical conditions used, see Table 3 and 4.

Description (Hand Sample):

Observations and descriptions of glaucony in the study area have been prepared from hand samples, petrographic analysis and electron microprobe data for FF. Thorough analysis was performed to gain a greater understanding of the nature of the glauconitic material that is abundant throughout most of this facies.

Facies F is the most identifiable unit and most consistent marker throughout the

Table 3. Conditions used for microprobe analysis.

Element	Crystal	Accelerating Voltage	Count Time (sec)	
			Peak	Back
Ca	PET	15	20	10
Mg	TAP	15	20	10
Na	TAP	15	10	5
Fe	LIFH	15	15	5

Table 4. Standards used for microprobe analysis.

Element	Standard	Curr.(A)	Detection Limits (ppm)
CaO	kaersuitite	1.00E-08	266.9
MgO	kaersuitite	1.00E-08	233.0
Na2O	kaersuitite	1.00E-08	278.8
FeO	fayalite	1.01E-08	307.8
K2O	biotite	1.00E-08	181.5
SiO2	biotite	1.00E-08	397.0
Al2O3	biotite	1.00E-08	224.8

entire study area. Facies F is found at the top in every well and is also developed as a correlatable unit across the middle of three cores. Dark green glauconitic grains comprise between 50 and 95% of this facies, except in rare cases where clastic material introduced into the system decreases the glauconitic material to < 5% (Fig. 3.8). Grains range in size from upper very fine sandstone to medium sandstone. Sedimentary structures are non-existent within this facies, thus, it exhibits a massive appearance. The unit ranges in thickness from 0.3 m to 2.1 m and commonly has a sharp-based dislocation to the underlying units. Siderite is not common in the unit, but is observed locally. There is a very common occurrence of large bivalve shells throughout the facies, which range in size from 3 mm to 4 cm (Fig. 3.8 d). The shell material varies in abundance from 5 to 30% by volume and is both articulated and disarticulated. Disarticulated shell fragments are locally concentrated into high abundance layers, but also preserved as more disseminated layers where the shell material is scattered in a random pattern. Locally, there is an association of bone fragments and phosphate grains with the shell fragments. In units of low glauconitic content a silty sandstone is present displaying a high abundance of burrowing.

Trace fossils within this unit tend to be slightly more robust then in other facies and include *Asterosoma*, *Teichichnus*, *Palaeophycus*, *Scolicia*, *Rhizocorallium* and *Thalassinoides* (Fig. 3.8 b & c). Trace fossils are visible due to a light gray infilling, which is void of glaucony. The massive character of the glaucony makes it very difficult to identify any other ichnological traces. Beneath every occurrence of FF there is a burrowed erosive surface that is mappable between cored intervals and in some cases, displays a passively infilled assemblage (Fig. 3.8 a). The burrows can penetrate as deep as 1.2 m and contain glauconitic material that was piped down into the burrow network. This burrowing behavior exhibits sharp walled, passively infilled networks created by ichnotaxa such as *Thalassinoides*.

The erosive nature of FF allows for any facies to lie immediately below the dislocation. However, there is a significant relationship between FF and FB showing a considerable gradation between the two (Fig. 3.8 c). Facies F also shows a commonality with FK (offshore shale).

Description (Thin Section):

In thin section the glaucony grains of FF tend to be moderately to well sorted and range in size from 50 to 300 μm (lower very-fine sandstone to medium sandstone). Most grains are egg shaped and are zoned with a dark green core (approximately 95%

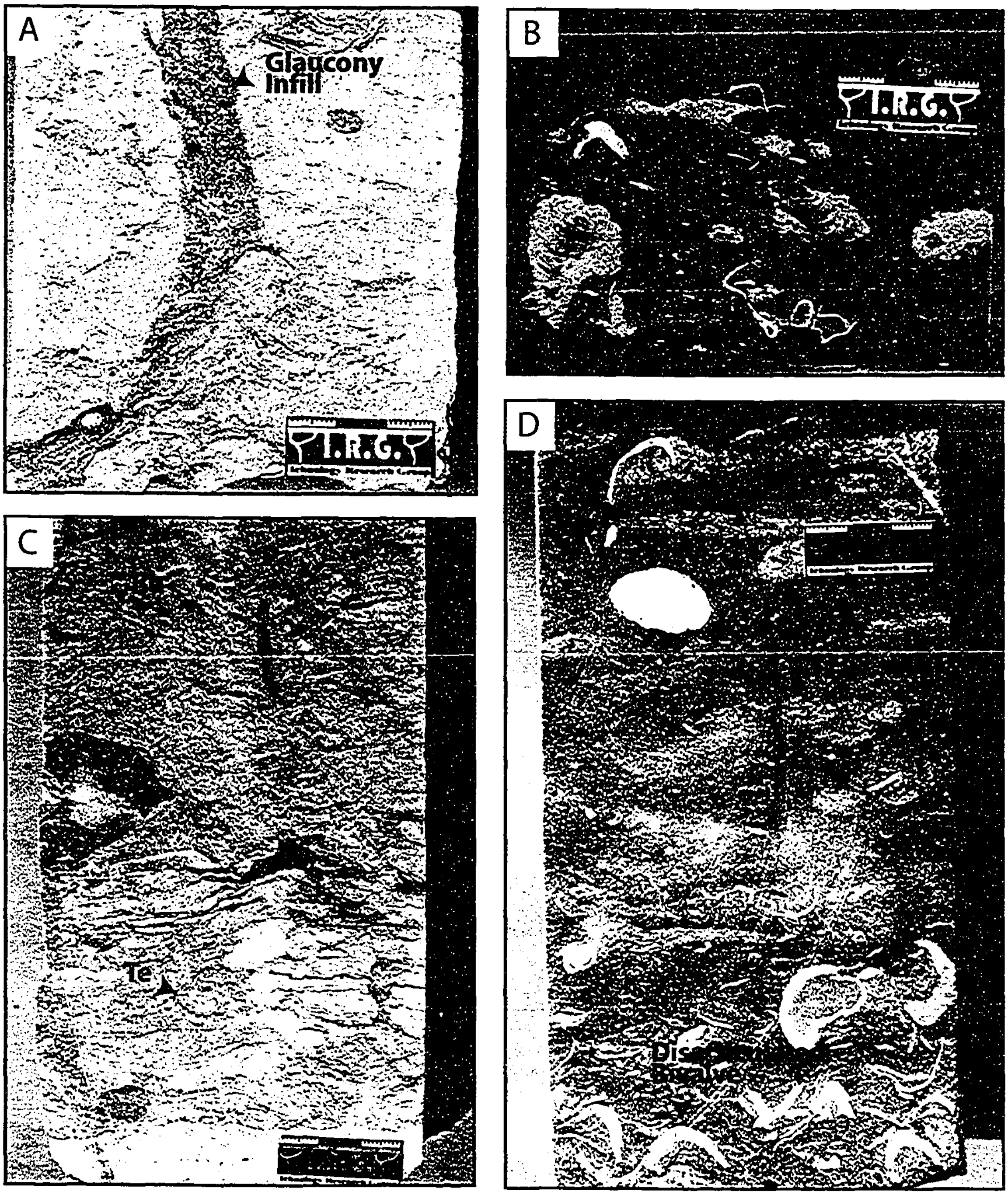


Fig. 3.8 - Glaucony Rich Silty Sandstone (Facies F): Pictures show a variable amount of glaucony. **(A)** Passively infilled burrow with glaucony located beneath TSE (Hayat 13, depth 5962 ft (1818 m)); **(B)** Robust *Teichichnus* (Te) and *Asterosoma* (As) (Salam 17, depth 5793 ft (1766 m)); **(C)** Low glaucony content in a silty-sandstone containing *Rhizocorallium* (Rh), *Palaeophycus* (Pa) and *Teichichnus* (Te) (Hayat 12, depth 6072 ft (1851 m)); **(D)** Large disarticulated and fragmented bivalve shells (Salam 38, depth 5859 ft (1797 m)).

of the grain) and a lighter green rim (approximately 20 μm) (Fig. 3.9 a & b). The dark green core often shows an irregular and sometimes sub-angular shape, while the rim is sub-rounded to rounded. In some cases, the core contains fractures that penetrate into its center allowing the pale green rim to infill the fractures. Other glauconitic grains have shown to be more irregular in shape with no defined rim (Fig. 3.10 a & b). These grains are generally a paler green color and are splotchy or striped in appearance. All of the glauconitic grains appear to be composed of aggregates of smaller crystals. Each of the grains has interference colors that are masked by the natural green color of the glaucony grain. Mineralogical components of FF include up to 60% quartz, 30 to 80% glaucony, 5 to 10% shell and bone fragments and <5 to 10% clays and cement. Quartz grains are generally smaller and more angular then the glaucony grains, and are poorly sorted. The large bivalve shells within FF commonly display small borings through the shell material.

Other facies, such as FA, contain minor amounts of glauconitic material that illustrate similar petrographic characteristics, such as grains ranging in size from 50 to 300 μm and evidence of rims. Differences arise with the poorly developed rims, which in some cases only encrust a portion of the grain. Some samples may also be a lighter green in color and have no rim at all. The pale green matrix is too fine grained to make any petrographic interpretations that are reliable.

Description (Electron Microprobe):

Probing of the rimmed glaucony grains of FF (Fig. 3.10 e & f) revealed a decrease in the K_2O content from the center to the periphery of the grains. The K_2O content in the core ranged from as high as 7.9% to as low as 5.1% and averages around 7.2%. Unfortunately, the probe was unable to obtain consistent readings on the K_2O content of the rims because of the width of electron beam required to analyze these samples. The few measurements that where obtained from the glaucony rims appear to be slightly lower in K_2O content (approximately 0.2% lower).

The more irregular grains of FF returned data showing a range in K_2O from 6.8% to as low as 6.1% with an average around 6.5%. In some samples (*eg.* FI and FJ), a pale green matrix (clay) was observed and analyzed using the probe. However, the analysis was inconclusive because the grains were too small for the width of electron beam used.

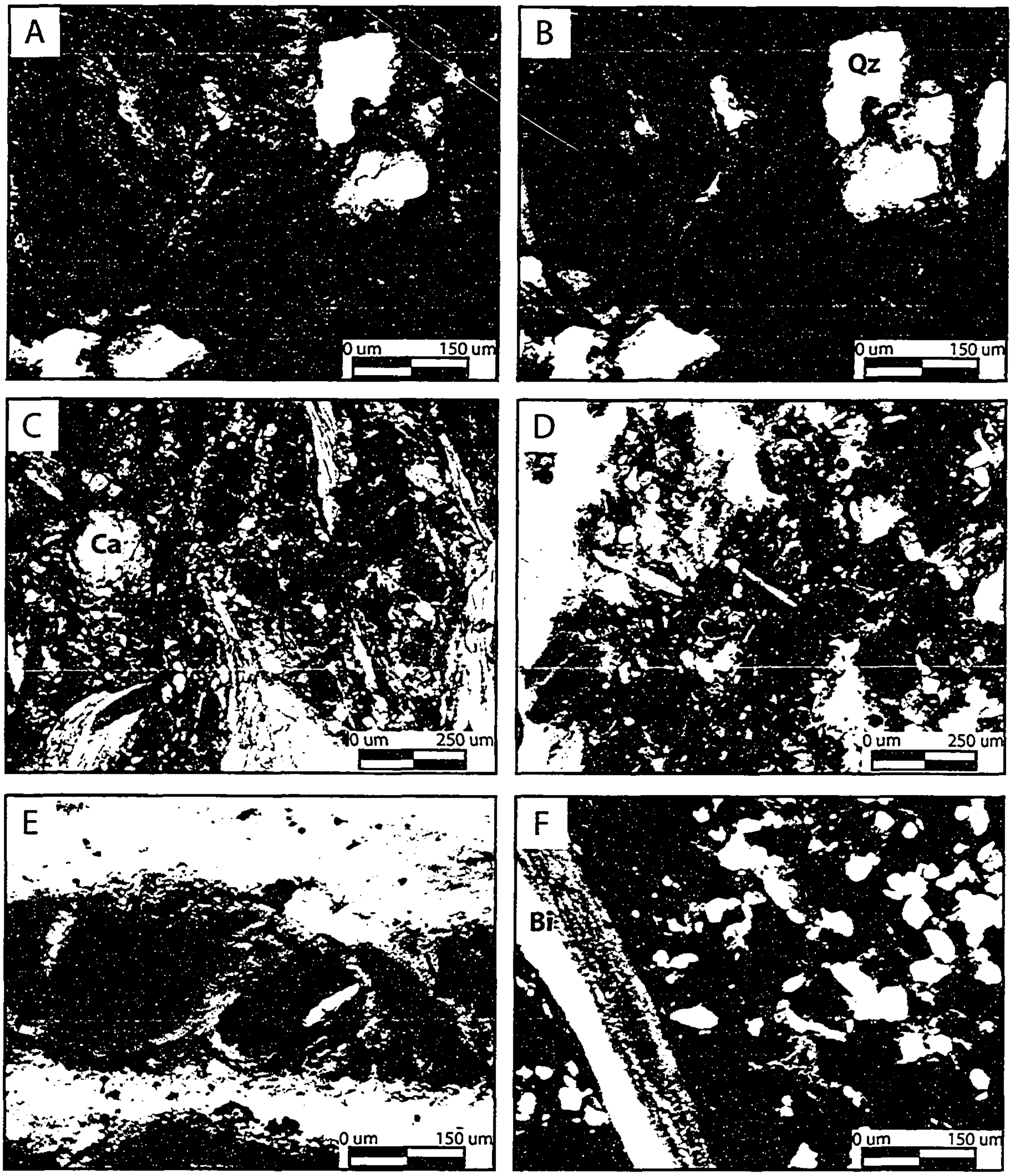


Fig. 3.9 - Rimmed Glaucony (Facies F): All thin sections show rimmed glaucony grains, quartz grains (Qz), shell fragments and calcite cement (Ca). **(A)** Glaucony grains in cross-polarized light (xpl); Each grain appears to be comprised of an aggregate of smaller crystals; interference color is masked by the natural green color (Yasser 6, depth 5897 ft (1798 m)); **(B)** Same as A but in plain polarized light (ppl) (Yasser 6, depth 5897 ft (1798 m)); **(C)** Typical appearance of FF in (xpl) (Yasser 6, depth 5886 ft (1794 m)); **(D)** General appearance of facies F in (ppl) (Yasser 6, depth 5886 ft (1794 m)); **(E)** Glaucony in (ppl) (Yasser 6, depth 5886 ft (1794 m)); **(F)** General appearance of FF in (xpl); Bivalve shell (Bi) (Yasser 6, depth 5897 ft (1798 m)).

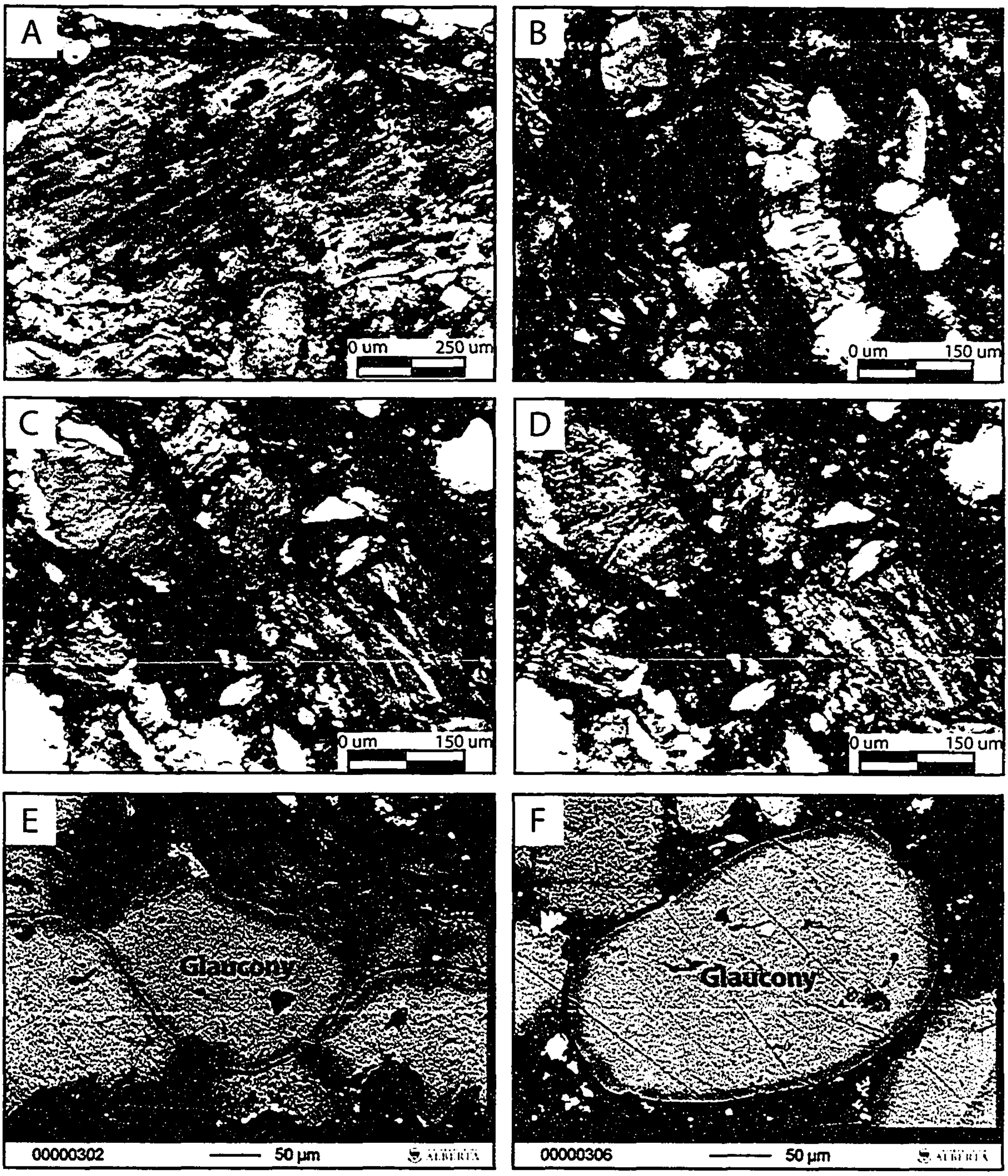


Fig. 3.10 - Irregular Glaucony (Facies F): Thin sections A-D show irregular glaucony grains, quartz grains (Qz) and a clay matrix (Mx); thin sections E and F are pictures from the micro-probe. **(A)** Glaucony grain in (ppl) (Yasser 6, depth 5886 ft (1795 m)); **(B)** Pale green glaucony is filling in fractures (ppl) (Salam 17, depth 5784 ft (1763 m)); **(C)** Glaucony in (ppl) (Salam 17, depth 5784 ft (1763 m)); **(D)** Glaucony in (xpl) (Salam 17, depth 5784 ft (1763 m)); **(E & F)** Rimmed glaucony; darker shade of grey illustrates lower K_2O content.

Interpretation:

In order to interpret the genetic origin of glauconitic material an understanding of the following three principles must be made: 1) spatial and temporal characteristics, 2) physiochemical properties and 3) abundance of glauconitic grains. Based on these observations, two strong processes of glaucony genesis are interpreted.

Evolved to Highly Evolved Autochthonous Glaucony; Facies F (Condensed Section, Offshore):

The smooth rims that encrust the glauconitic grains have been interpreted by Lamboy and Odin (1975) as evidence of long-term conditions favorable for glauconization. The encrusting and filling of a bulbous and cracked core with slightly less evolved glauconitic material usually occurs in the fourth and final stage of evolution. According to Odin and Fullagar (1988), a K_2O content of approximately 7.2% suggests a hiatal pause on the order of approximately 10^5 years. This extended period of non-deposition provides support for the autochthonous origin of glaucony and illustrates a quiescent fully marine environment with low sedimentation rates.

The more irregular lighter green glauconitic grains followed a slightly different path of glauconization but are still autochthonous in origin. These samples returned a K_2O content of approximately 6.5% suggesting a hiatal pause around 5×10^4 years. In most cases, the grains show a bulbous and cracked habit, which has not been fully encrusted. The slight difference in the physiochemical evolution and geometry of the grains is attributed to a different precursor grain, which was introduced to the system at a later time.

The high abundance of glauconitic material and its association with fully marine indicators such as *Asterosoma* burrows and robust *Teichichnus* further support an autochthonous origin. There is evidence, in some instances, that suggest a minor transport component of the glauconitic material. Amorosi and Centieo (1997), suggested that an abundance of grain sizes <100 μm could be a result of fragmentation due to mechanical breakdown of larger grains during transport. The amount of glauconitic grains <100 μm in FF is insignificant, suggesting that if transport did occur it was on a minor scale.

The consistent thickness, lateral extensiveness, association with FB (limestone), association with phosphate grains and a number of other characteristics of FF indicate a probable depositional environment of a condensed section (CS). Comparing the thickness as well as the position to underlying facies, it can be assumed that the CS formed as the distal expression of the maximum flooding surface (MFS) in the offshore environment. The occurrence of low abundant glaucony units is the result of periodic inundation of clastic material due to events such as storm activity. The erosive surface at the base of the condensed section, which often forms a *Glossifungites* ichnofacies, is defined as a transgressive surface of erosion (TSE). The occurrence of a correlatable section of FF mid-way up of three cored intervals is possibly a CS associated with a major marine flooding surface separating parasequence sets. A K_2O content of approximately 6.5% was measured within this CS suggesting a smaller scale depositional hiatus when compared to the glaucony associated with the MFS.

Nascent Autochthonous Glaucony:

A pale green clay matrix is found within a number of different facies but most commonly in FI (rooted green mudstone) and FJ (green mudstone). Unfortunately, there is no conclusive evidence confirming the presence of glauconitic material within these units due to its fine grained nature and the inability to recover usable data from thin section work or the electron microprobe. The lack in supporting evidence allows for several different interpretations to be applied.

In many cases, the pale green mudstone occurs in close proximity to FB (Limestone). This relationship may suggest a minor flooding event that chokes off sedimentation for a period of time allowing for a short depositional hiatus to occur. The length of hiatus, based on the color of the grain, may have been on the order of 10^3 to 10^4 yrs. It has also been noted that substrate grains <50 μm do not provide an adequate surface for the complete evolution of glauconitic minerals (Amorosi and Centineo, 1997), suggesting that the length of hiatus, after Odin and Fullagar (1988), may not be accurate. If this interpretation is correct, then the presence of FI and/or FJ may be an indication of minor flooding surfaces separating parasequences.

Another possible interpretation and a more likely environment may not have a relation to the glauconization process at all. The pale green color may be linked to chemical alteration that occurs during the development of paleosols and other alterations due to reducing conditions. Evidence for this interpretation includes the presence of rooting and calcrete nodules in many of the samples and proximity to other interdistributary bay environments. If this interpretation is correct the pale green muds may be interpreted as overbank levees or marsh muds that are periodically colonized by plants allowing for the development of roots and muds that form in restricted central bay environments.

Evolved Parautochthonous Glaucony:

The presence of autochthonous glaucony in any system allows for the potential of parautochthonous glaucony. If an appropriate mechanism of transport is available, adjacent facies may contain minor to significant amounts of remobilized glauconitic material. In a few occurrences, an abundance of evolved to highly evolved glaucony is associated with facies of a more landward origin (*eg.* FA). These units contain glauconitic material because of the available transport mechanisms such as tidal processes and possible storm activity. Thus, transportation of the material occurs from an original fully marine location (possibly a CS) into a more landward environment (interdistributary bay).

A small number of thin sections were cut from surrounding facies that did not appear to have any appreciable amounts of glauconitic material. On closer examination up to 5% (or slightly more) of the facies was made up of individual grains of glaucony. These grains have an appearance very similar to the autochthonous evolved to highly evolved grains but are typically more bulbous and irregular in shape. The encrusting rim is usually no longer present and the total weight percent of potassium is slightly lower (approx. 5.4%). This information suggests that these grains were worked landward before the completion of their evolution. The mechanism of transport for these grains is likely related to tidal action or storm activity. Evidence can be seen for these processes within the surrounding facies that were logged within the upper Bahariya Formation.

In a few cases, a large abundance of evolved to highly evolved glaucony is associated with fining upward units characterized by abundant shell fragments. These beds may represent storm activity that reworked glauconitic material from a fully marine location (possibly a CS) into a more landward environment. Thin sections were not cut from these horizons so a proper petrographic analysis could not be performed and probe data could not be collected.

3.5 Summary

Glaucony can be one of the most reliable indicators of slow sedimentation rates in marine settings, if analyzed properly. The mere presence of glaucony tells us very little as to what processes were involved and may provide misleading information if caution is not used. Additional information such as the spatial, temporal and physiochemical properties of glaucony must be gathered and carefully analyzed in order to make valid interpretations. If these steps are taken, glaucony is a potentially powerful tool for basin analysis and sequence stratigraphic interpretation.

In differentiating the various types of glauconitic grains and placing them into their characteristically identifiable groups, such as: 1) nascent, slightly evolved, evolved and highly evolved, 2) autochthonous and allochthonous (parautochthonous and detrital), and 3) intrasequential and extrasequential glaucony, an emphasis can be placed on their origin and possible interpretation. In review:

1) *Autochthonous* glaucony will be present throughout the TST, and more rarely in the lower portions of the HST, as it is associated with open-marine deposits. The abundance and maturity will show an initial increase within the TST, followed by a subsequent decrease, which relates to the lower portion of the HST. This type of glaucony is commonly found and expected at the MFS, which will exhibit the most highly evolved glaucony in the stratigraphic column.

2) *Parautochthonous* glaucony is expected in higher energy conditions especially depositional environments dominated by storm lags, tides, and wave processes. Common occurrences are associated with the TST and HST, while minor amounts may be found within the LST. The higher energy environment is less conducive for glauconization and therefore usually has a lower abundance and a maturity ranging from low to moderate.

3) *Detrital* glaucony is commonly associated with the lowstand wedge of the LST. It may also occur within the lower portions of the TST if conditions are favorable. The abundance and maturity of the glaucony is controlled entirely by its erosional source, which can be anything from highly evolved to nascent and low to high in abundance.

In applying some of the above noted indicators, the presence of glaucony in the upper Bahariya Formation allows for improved interpretations (Fig. 3.8). The upper Bahariya Formation contains variable amounts of glaucony, which exhibit a variety of characteristics. Three possible interpretations were developed based on the presence and the observable characteristics of glauconitic material. The pale green mudstone incurred inconclusive data as to the origin of the green color. Based on the lithologic and biologic associations discussed in Chapter 2 the more probable interpretation is that the green color is not related to the glauconization process; instead it is the result of chemical alteration in a marsh environment. The dark green autochthonous glauconitic material at the top of every core is interpreted as the distal expression of the MFS in a condensed section. The formation of this glauconitic material took place over a long and geologically significant period of time. Many of the deposits below this condensed section contain variable amounts of pale to medium green parautochthonous glaucony, which is transported from deeper water systems that are favourable for the glauconization process. In opposition to the autochthonous glaucony, the parautochthonous glaucony

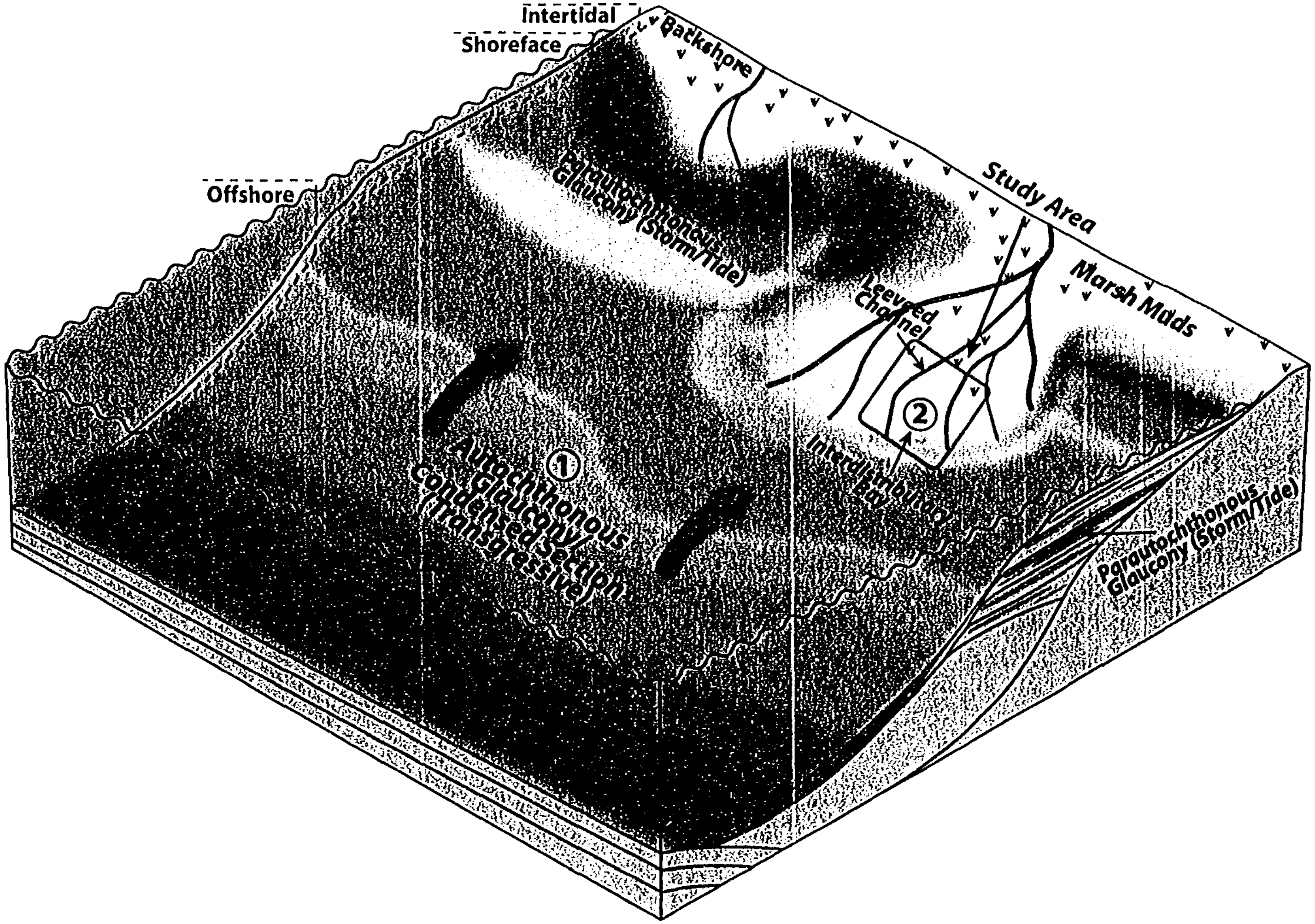


Fig. 3.11 - Environmental interpretation of glauconitic material in the upper Bahariya Formation. 1) Offshore highly evolved autochthonous glaucony in a condensed section, which eventually transgresses over the interdistributary bay, 2) Study area containing interdistributary bay fill successions and parautochthonous glaucony.

was reworked into a more landward location before it had a chance to fully evolve. As a result the physiochemical properties tend to incorporate a lower percentage of potassium and have a larger range in the depositional environments in which they can be found.

CHAPTER 4: *Glossifungites* Ichnofacies in a Mixed Carbonate Siliciclastic Environment

4.1 Introduction

The *Glossifungites* ichnofacies has proven to be a consistent tool in delineating key stratal surfaces and in contributing to the coherency of depositional facies in many siliciclastic environments. Unfortunately, this model has had very little exposure to mixed carbonate siliciclastic environments and is likely to hinder the interpretation of the system unless there is due care and understanding of the data. This section addresses the variations observed between *Glossifungites* assemblages in siliciclastic and mixed carbonate-siliciclastic environments.

The upper Bahariya Formation was formed in a mixed carbonate-siliciclastic environment and displays multiple examples of the *Glossifungites* assemblage. For this reason, the upper Bahariya Formation will serve as a subsurface example that will demonstrate the differences in the stage development of the *Glossifungites* assemblage in both siliciclastic and mixed environments. The general occurrence and stage development of the *Glossifungites* assemblage in clastic depositional conditions will be discussed and reviewed in order to provide a comparative model for their development in a mixed environment. Firstly, a brief overview of carbonate cementation in shallow depositional environments will be discussed to gain a basic understanding and a general framework.

4.2 Carbonate Cementation

Carbonate cementation in any type of environment is problematic when discussed in fine detail. The scope of this section is not to discuss these finer points but to gain a general understanding of the processes involved in the precipitation of cements in marginal marine to fully marine environments.

Precipitation of cements in shallow marine waters is widespread and common throughout recent depositional settings; however, in certain situations this process does not lead to lithification (Bathurst, 1975). Bathurst (1975) also noted that partial cementation may occur between grains that are too mobile for the slow development of an adhesive contact between grains. It stands to reason that if deposited grains of siliciclastic material are subject to low energy environments, such as an omission surface, the grains may partially fuse together producing a semi-consolidated or cohesive substrate. There are many different mechanisms that initiate the diagenetic process of

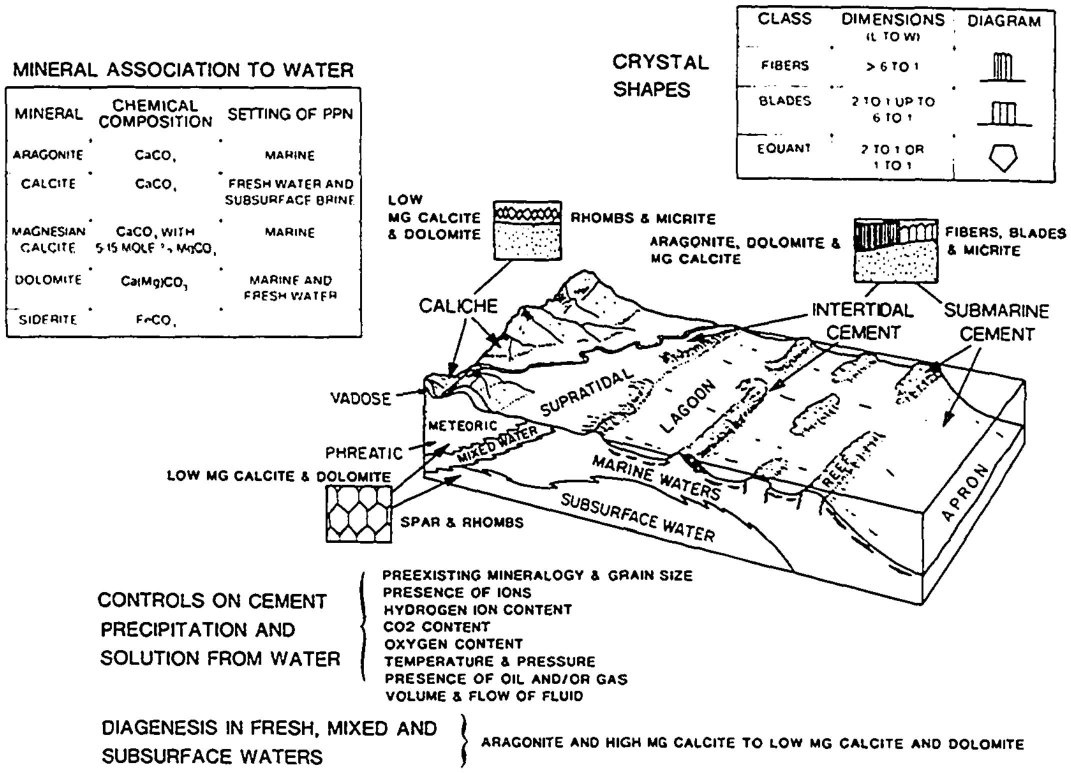


Fig. 4.1 - Patterns in carbonate cementation for various diagenetic environments. (From Harris et al., 1985).

carbonate precipitation. There is also a multitude of depositional environments that can support the various mechanisms of cementation (Fig. 4.1). Within each of these diagenetic systems there are a few commonalities that can be observed. A permeable host rock and a mechanism to flush waters through the system is a requirement in transporting the necessary constituents to the point of precipitation. Tidal pumping, hydrostatic head, thermal expansion, smectite to illite conversion and shale compaction are a few of the driving forces that allow regional movement of waters through the system (Harris et al., 1985).

In fully marine environments, deep water cementation may occur in areas of low sedimentation (Harris et al., 1985), such as a condensed section in a maximum flooding surface. On the opposite end of the spectrum, cementation can also occur in shallow water settings such as intertidal and supratidal environments. In these zones cementation may occur due to sediment bypass causing an omission surface, or because of mixing of two separate and chemically distinct bodies of water (Bathurst, 1975). If each of the bodies of water is saturated with $CaCO_3$ and has different values of P_{CO_2}, then there is a potential of precipitating a substantial amount of $CaCO_3$ (Bathurst, 1975). Sea level fluctuations are one of the dominant factors when dealing with the degree of

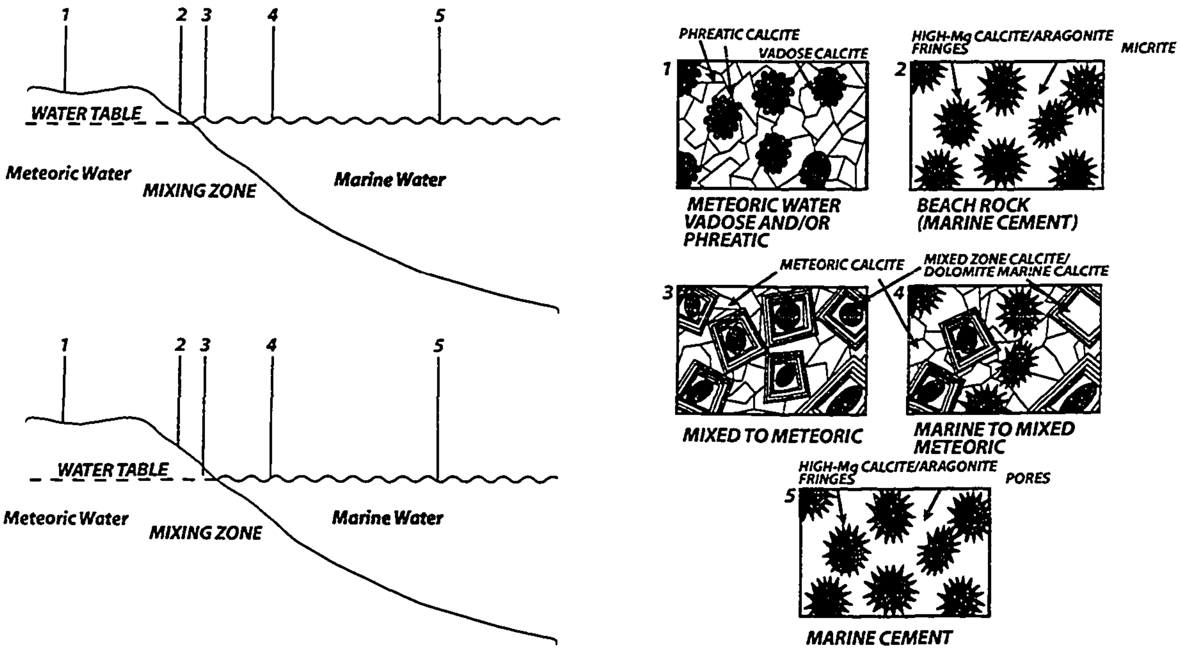


Fig. 4.2 - The effect of sea level fluctuations on carbonate cementation. (Modified after Morad, 1998).

mixing between meteoric and marine waters. Therefore, sea level variations are also a contributing factor to the pattern of carbonate cementation (Fig. 4.2) and are the result of allocyclic or autocyclic processes. These processes can be identified by the regional extent of cementation. Another contributing factor to the degree of mixing and position of the transition zone of meteoric and fresh waters is the annual and climatic variations in rainfall that occur (Harris et al., 1985). An enhancement of precipitation in mixing waters may also be attributed to an increase in alkalinity due to oxidation of organic matter and methane (Harris et al., 1985).

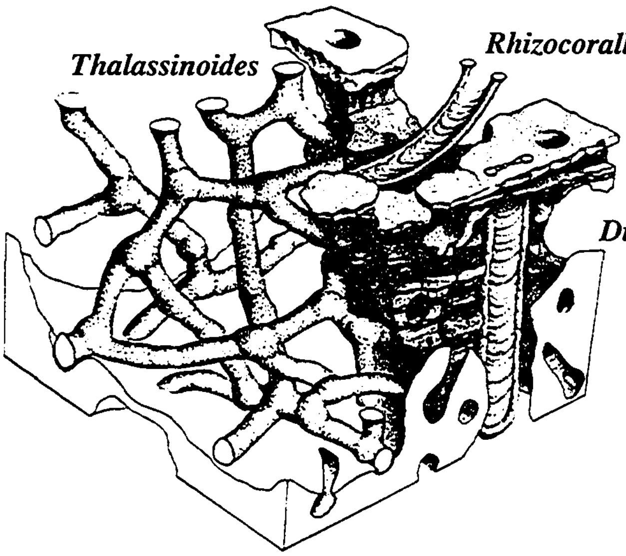
4.3 General Characteristics of the *Glossifungites* Ichnofacies

As documentation of the *Glossifungites* ichnofacies has been biased toward the siliciclastic end member, a general review on the particulars is essential. It is important not to confuse the characteristics of the *Glossifungites* ichnofacies in siliciclastic environments with the fundamental properties that define its occurrence.

The *Glossifungites* assemblage has the potential to occur in most depositional environments because of the relatively wide environmental constraints imposed upon it. Perhaps the only constraint dictating the potential establishment of the *Glossifungites* assemblage is the development of a firm, unlithified, substrate that is made available for

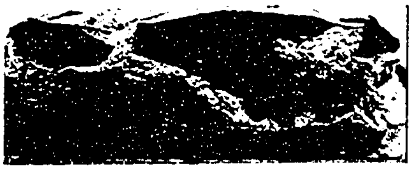
GLOSSIFUNGITES ICHNOFACIES

Semi-cohesive Substrates



Detail of modern *Glossifungites* Ichnofacies, St. Catherine's Island, Georgia.

Upper surface of exhumed mud.



Modern shrimp burrow in exhumed salt marsh mud, infilled with beach sand

1. **Vertical, cylindrical, tear- or U-shaped dwelling burrows.**
2. **Protrusive spreiten burrows resulting from animal growth**
3. **Suspension feeders or animals that leave the burrow to feed.**
4. **Low diversity but individual structures may be abundant.**
5. **Burrow walls may display scratch marks.**

Fig. 4.3 - Fundamental characteristics of the *Glosssifungites* ichnofacies. (From Pemberton et al., 2001).

recolonization. The stable and cohesive nature of the substrate allow for sharp walled and unlined domiciles that are passively infilled during post omission sediment accumulation (Fig. 4.3). Trace fossils are typically robust and deep penetrating (20-100cm), with burrow shafts ranging in diameter from 0.5 - 1.0cm (Pemberton, et al., 2001). Organisms that make use of these firm substrates construct permanent domiciles, which tend to display vertical to subvertical dwelling structures of suspension feeders and animals that leave the burrow to feed, such as *Diplocraterion, Skolithos, Psilonichnus, Arenicolites*, and firmground *Gastrochaenolites* (Pemberton and Frey, 1985). The characteristic firmness of the *Glossifungites* substrate functions as a deterrent for intrastratal deposit feeding organisms; however, horizontal dwelling structures of deposit feeders such as *Rhizocorallium, Thalassinoides, Spongeliomorpha* and *Zoophycos* have all been observed in various locations (*eg.* MacEachern and Burton, 2000). The presence of cylindrical, U or tear shaped pseudo borings and sparsely to densely branching dwelling burrows are common as well as protrusive spreiten in few cases as a result of animal growth (Pemberton and Frey, 1985). Burrowed surfaces tend to exhibit low diversity, but commonly display an abundance in individual structures (Pemberton, et al., 2001)

4.4 *Glossifungites* Ichnofacies in a Siliciclastic Environment

Substrate-controlled ichnofacies such as the *Glossifungites* by their very nature, break down the principal components of the depositional system into comprehensible subsets. In most clastic depositional systems, the *Glossifungites* ichnofacies forms in sediment that is buried, compacted, dewatered and erosionally exhumed. Dewatering is a result of burial and compaction (Pemberton and Frey, 1985) leading to a volume loss in pore spaces and forcing water to migrate to areas of lower lithostatic pressure. If the exposed firm substrate is recolonized the surface is a *Glossifungites* surface. The erosional exhumation may result due to a variety of processes including channel migration, valley incision, meandering tidal channels, coastal erosion, erosive shoreface retreat and submarine channels (Pemberton et al., 2001). These examples demonstrate the potential of an erosional dislocation to form in either sub-aerial or sub-marine environments; but recolonization is assumed to occur in the marine realm (Pemberton et al., 2001). After colonization of the exhumed surface has occurred, sedimentation resumes allowing for passive infilling of the burrowed network. The accessibility of the firm substrate to burrowing organisms indicates that a depositional hiatus has occurred between the erosional event and continued sedimentation of the overlying unit. Therefore, the presence of recolonization is evidence for an omission surface. This process can be broken down into four stages: 1) deposition, burial and possible development of a softground ichnofacies, 2) erosion and exhumation, 3) recolonization during depositional hiatus (omission) and 4) continued sedimentation and the possible development of a new softground ichnofacies (Fig. 4.4). By observing the trace-fossil assemblages associated with the first, third, and fourth stages, a genetic understanding of the erosional discontinuity demonstrated at stage two can be formulated.

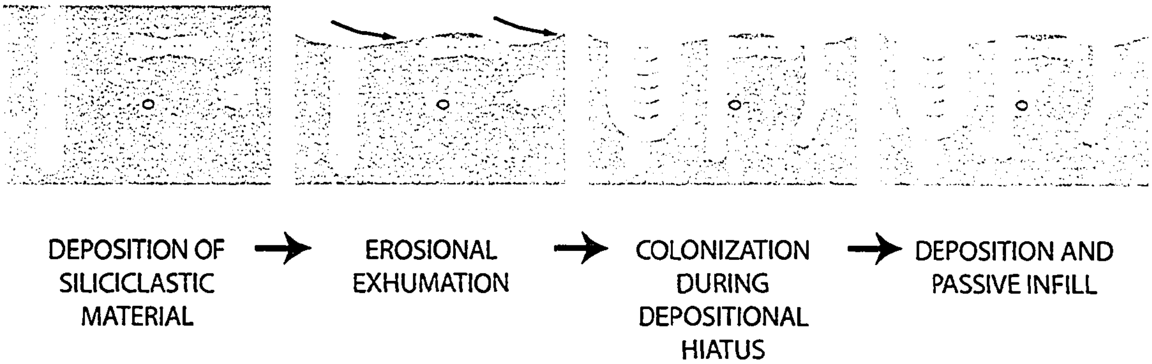


Fig. 4.4 - The stage development of the *Glossifungites* ichnofacies in siliciclastic environments. (Modified after Pemberton et al., 2001).

4.5 *Glossifungites* Ichnofacies in a Mixed Carbonate Siliciclastic Environment

In a mixed carbonate-siliciclastic environment the firm substrates hosting the *Glossifungites* ichnofacies develops under a different set of parameters than in a purely siliciclastic system. Early cementation is one recognizable process for the increase in substrate coherency and firmness allowing for possible recolonization by a *Glossifungites* assemblage. Utilizing this new process facilitates the conceptualization and further development of the *Glossifungites* ichnofacies to incorporate a wider variety of depositional parameters.

As was addressed by Bromley (1975), firm or hardground development in a carbonate setting may be the result of erosional exhumation or non-depositional breaks associated with submarine cementation at the sediment water interface. The development of the *Glossifungites* ichnofacies in a mixed system can be broken down into four stages: 1) deposition of siliciclastic or carbonate grains and colonization of the pre-omission suite, 2) early cementation caused by omission (sediment bypass) or freshwater influx resulting in a firm substrate, 3) recolonization by the *Glossifungites* assemblage during omission and 4) continued sedimentation causing passive infilling and colonization of the post-omission suite (Fig. 4.5). Unfortunately, the passive infilling of open domiciles becomes difficult to recognize in this type of scenario because of the conformable nature and minor environmental change that can occur. The absence of an erosive contact and the possibility of conformable deposition drastically alters the usual perception associated with the *Glossifungites* ichnofacies. Stratigraphic interpretations may not be as prevalent and more emphasis may be placed on local depositional constraints and characteristics within the system.

It is important to note that the *Glossifungites* assemblage in mixed carbonate-siliciclastic environments may still give indication of key stratal surfaces but the more common occurrence suggests changes on a more autocyclic scale. The relationship between the pre-omission, omission and post-omission suites are of significant importance in determining if environmental alterations have occurred during hiatus.

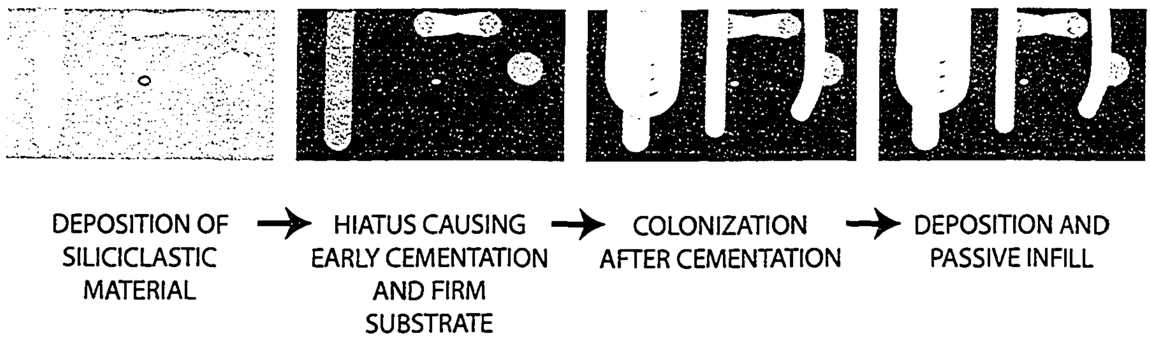


Fig. 4.5 - The stage development of the *Glossifungites* ichnofacies in mixed carbonate-siliciclastic environments. (Modified after Pemberton et al., 2001).

4.6 Descriptions of the *Glossifungites* Ichnofacies in the Upper Bahariya Formation

Type 1:

The type 1 *Glossifungites* assemblage generally occurs with an erosive dislocation from the overlying units (Fig. 4.6). The erosional contact is commonly recognized under lag deposits of iron stained nodules or shell hash (Fig. 4.6 c) that has been deposited following the recolonization of the omission surface. The coarser grained material can be seen in the passively infilled omission suite, which is characterized by burrows ranging

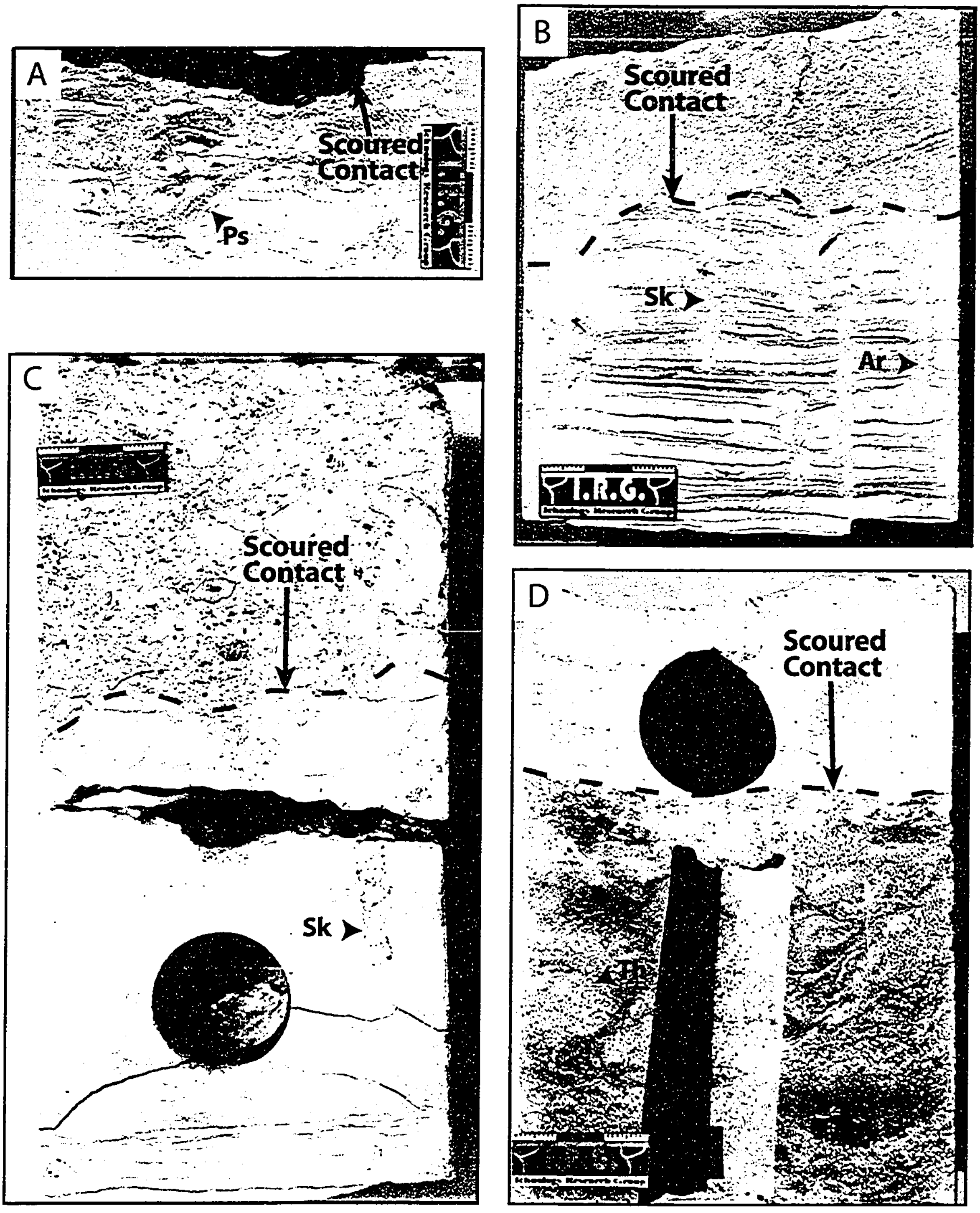


Fig. 4.6 - Type 1 *Glossifungites* Ichnofacies: All pictures show evidence of scouring and exhumation of a firm substrate that is later burrowed. **(A)** *Psilonichnus* (Ps) that has been passively infilled with glaucony (Hayat 17, depth 5993 ft (1827 m)); **(B)** *Skolithos* (Sk) and *Arenicolites* (Ar) that are passively infilled with the overlying unit (Kenz 7, depth 6077 ft (1853 m)); **(C)** *Skolithos* (Sk) that is passivly infilled with shell material from the overlying unit (Salam 38, depth 5871 ft (1790 m)); **(D)** *Thalassinoides* (Th) that is passively infilled with dissolved ooids (Salam 17, depth 5838 ft (1780 m)).

from horizontal *Thalassinoides* to vertical *Skolithos, Arenicolites* and *Psilonichnus*. The omission suite burrows are characterized by sharp walled and unlined domiciles low in diversity (generally one or two ichnogenera) and vary in abundance. The pre-omission and post-omission suites exhibit tracefossils and lithologies that are case dependant and will not be discussed in this section.

The observations made in regards to the type 1 *Glossifungites* assemblage are recognized with certainty as the typical occurrence of the *Glossifungites* in a siliciclastic environment. The coarse passively infilled burrow and scoured contact reveal a facies dislocation, which exposed firm substrates that were subsequently recolonized and buried.

Type 2:

In the type 2 *Glossifungites* assemblage a sharp but conformable contact may be observed between the pre-omission and post-omission suites. The contact can be especially difficult to recognize due to the minor environmental changes that can occur during omission (Fig. 4.7). Burrow infill ranges from coarse shell material or calcite rich muds to fine, possibly micritic, calcite cements. The ichnogenera include a dominance of *Thalassinoides*, *Arenicolites,* and *Skolithos,* which have a tendency to occur in close proximity to calcite rich units such as limestones and highly cemented very fine-grained sandstones and mudstones. In accordance with the type 1 *Glossifungites* assemblage, the burrows of the omission suite are characterized by sharp walled, unlined domiciles that are low in diversity (one or two ichnogenera) and vary in abundance. In some instances, the documented burrowing in the upper Bahariya Formation occurred in micritic limestone making the differentiation between the *Glossifungites* and *Trypinites* ichnofacies very difficult. Cross cutting of grain material is not observed, forcing the assumption of firm ground rather then hard ground burrowing. Further discussion of this topic is not in the scope of this project and will not be dealt with in any more detail. Variability in the pre-omission and post-omission suite of tracefossils and lithologies, as in the type 1 *Glossifungites,* are also case dependant and will not be discussed in this section.

Documentation of the type 2 *Glossifungites* assemblage illustrates the common occurrence of early cementation in a mixed carbonate siliciclastic environment such as the upper Bahariya Formation. The absence of an erosional dislocation between the pre-omission and post-omission suites and the nature of passively infilled material demonstrates the conformable progression and stage development of the *Glossifungites* assemblage in a mixed environment.

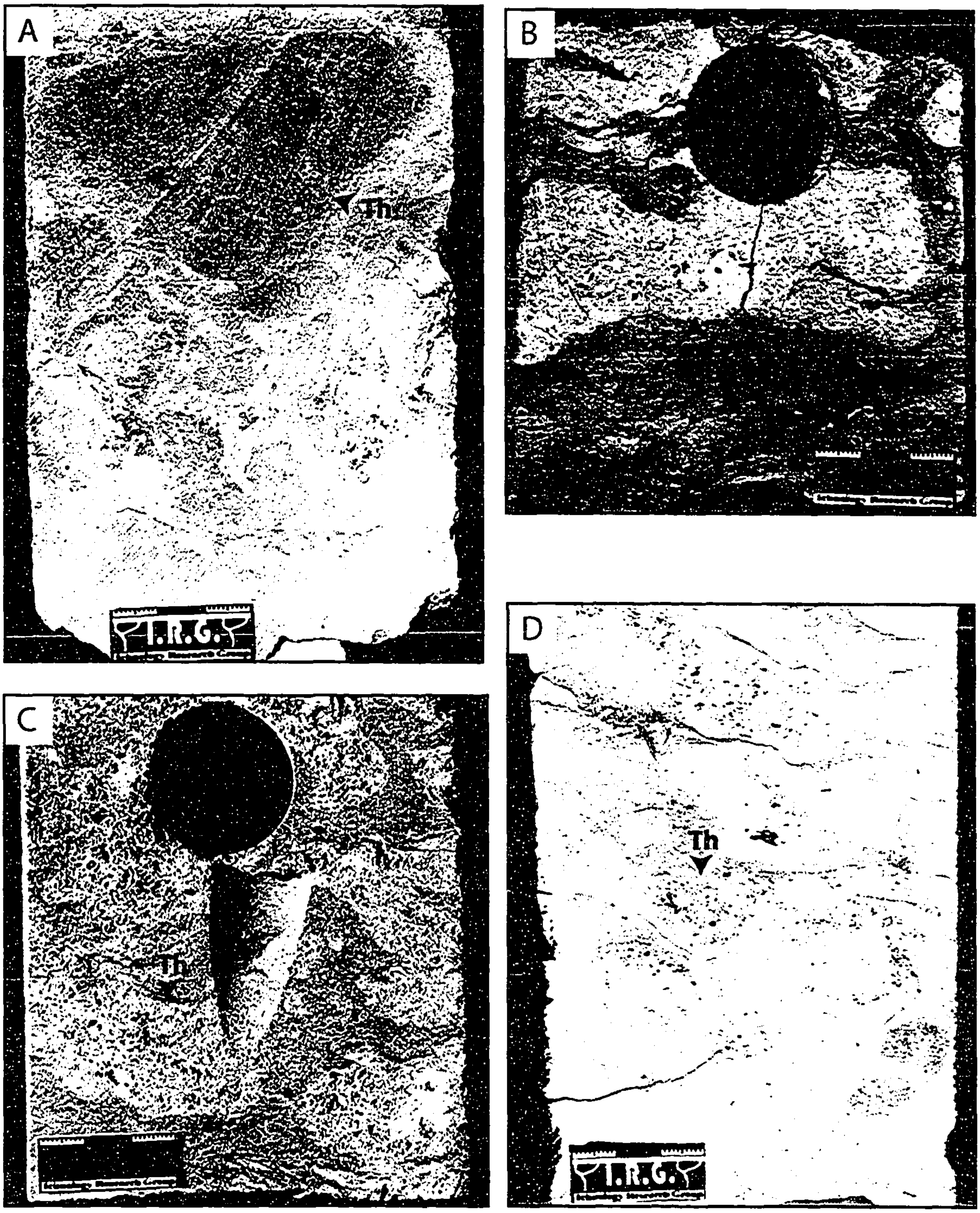


Fig. 4.7 - Type 2 *Glossifungites* Ichnofacies: All pictures show evidence of passively infilled *Thalassinoides* (Th) with no indication of erosional exhumation. Burrows are infilled with a partially dissolved shell material and are surrounded by a calcite rich lithology. **(A)** Some hydrocarbon staining is visible in the burrow due to an increase in porosity and permeability. (Salam 47, depth 5828 ft (1777 m)); **(B)** (Hayat 17, depth 5938 ft (1810 m)); **(C)** (Salam 38, depth 5864 ft (1788 m)); **(D)** (Yasser 6, depth 5918 ft (1804 m)).

4.7 Discussion

Within the upper Bahariya Formation there is a clear division between two distinctly different types of *Glossifungites* assemblages. Each of these assemblages represents burrowing into a firm unlithified substrate that has experienced a period of omission. The first, and most widely understood occurrence deals with a surface that has undergone burial, compaction, dewatering, erosional exhumation and recolonization during an omission. This type of *Glossifungites* surface has proven to be a consistent tool in delineating key stratal surfaces in the Western Canadian Sedimentary Basin and will continue to do so in clastic environments. The second type is far less recognized due to its infrequency, but is no less important to understand. The occurrence of early cementation followed by an omission surface leads to a *Glossifungites* assemblage that does not necessarily represent a stratigraphic discontinuity. As shown in examples from the upper Bahariya core, environmental interpretations are based strictly on the relationship of the pre-omission, omission and post-omission suites and may not display any relevant information on sequence stratigraphic processes. Identification of conformable units, and thus the absence of an erosive contact, coinciding with the pre-omission, omission and post-omission suites allow for the separation of stratigraphically significant *Glossifungites* assemblages from those of a more autocyclic influence.

CHAPTER 5: Discussion and Depositional Model of the Upper Bahariya Formation

5.1 Introduction

In order to evaluate and develop a depositional model for the upper Bahariya Formation the separation of facies associations, significant surfaces and a comparison to modern day analogues is necessary. A variety of pictures, illustrations and cross-sections have been put together and are discussed in the following sections. Satellite photographs of modern day crevasse splay environments are analyzed and briefly discussed as possible analogues for the upper Bahariya Formation. Isopach maps of sands in the Khalda field were produced from core and wire line data present in the Salam, Kenz, Yasser and Hayat fields. These maps were then used as a comparison to modern day systems. Following this discussion, a four stage depositional model will be presented allowing for a more detailed look at the scale of cycling found in each of the logged intervals. As part of each stage of the depositional model, a 3-D sediment distribution diagram is proposed. The four depositional stages include: 1) initial interdistributary bay development, 2) flooding of distributary channel causing discrete breaks along the adjacent levee resulting in crevasse splay deposits, 3) complete or partial filling of interdistributary bay by crevasse channels allowing the breached levee to be rebuilt and become inactive, and 4) rapid subsidence of interdistributary bay initiating inundation of marine waters. The presence of parasequences will be discussed and illustrated for the upper Bahariya succession, providing an overall understanding of events leading to the TSE located beneath the glaucony rich unit (FF) found near the top of every core. A brief explanation of the characteristics associated with the presence of glaucony are then discussed providing a general interpretation for the behavior of sealevel in this setting.

5.2 Facies Associations and Cross-section

As mentioned in Chapter 2, the upper Bahariya consists of three facies associations. Cross-section A - A' (Fig. 5.1) displays the relationship between each individual facies in the low energy, distal interdistributary bay Facies Association 1 (Facies A, B, D, H and I), the high energy, proximal interdistributary bay Facies Association 2 (Facies A, C, E and G) and the offshore to shelf deposits of Facies Association 3 (Facies B, F and K).

Facies Association 1 incorporates five facies, each of which characterize low energy distal environments as discussed in Chapter 2. Facies A is interpreted as tidal flat deposits and is commonly associated with marsh muds (FI), marine bay carbonates (FB), marine bay siltstones (FD), bay muds (FJ) and bay shales (FH). During early stages of interdistributary bay infilling a quiescent environment exists, allowing for fine-grained deposits such as FJ and FI to settle out of suspension. In some cases, if the environmental conditions are suitable, FB may form in central parts of the bay instead of FJ and/or FI. Along the fringes of the interdistributary bay, the coarsest sediment is reworked into tidal flats (FA), where eventually marsh muds (FI) may form if significant exposure occurs. Later, during higher energy stages of interdistributary bay infilling, prograding sands of the crevasse splay may transport fine-grained material, such as FJ and FH, to distal portions of the bay. Lower energy deposits are eventually prograded over by crevasse splay delta fronts and distributary mouthbars of the higher energy Facies Association 2.

Facies Association 2 incorporates four facies, one of which also occurs within Facies Association 1. This facies association is typically found at the top of cleaning upward sequences, but is also present intermittently in lower parts of the cleaning upward package. It is characterized by higher energy, coarser grained deposits that are proximal to the crevasse splay system. Facies E (delta front) is the most distal facies within this association and typically occurs immediately above tidal flat (FA), bay shales (FH) and bay muds (FJ). In vertical succession, FG and FC of the distributary mouth are typically found above and interfingering with FE and FA. Facies A occurs in both Facies Associations 1 and 2, and commonly displays convolute bedding when associated with the latter due to high rates of sediment supply.

Facies Association 3 consists of three facies, each of which occur in a deeper marine setting, implying a genetic dislocation from both Facies Associations 1 and 2. This association transpires at the onset of the MFS above a TSE where deposits of glaucony rich silty-sandstones (FF) are formed in a CS. FK (offshore shale) is found blanketing FF over the entire study area and eventually begins to interbed with FB (marine carbonates) and FF further up the succession.

A south - north oriented cross-section containing five cored intervals along the A-A' line (see Fig. 1.2) is illustrated in figure 5.1. Correlations are based on facies associations and separated where necessary by flooding events (FB & FD) to help highlight the cyclical pattern. Wells integrated into the section include Yasser 6, Kenz 9, Kenz 7, Salam 39 and Salam 47. The datum utilized in this cross-section is the base of a minor marine flooding surface, which occurs across a large portion of the study area and has been given the designation "UB-FS20" (Wehr, Personal Communication). A number of other minor flooding surfaces designated by Wehr have been used on this cross-section and in following figures. Cleaning upward packages, facies associations and significant

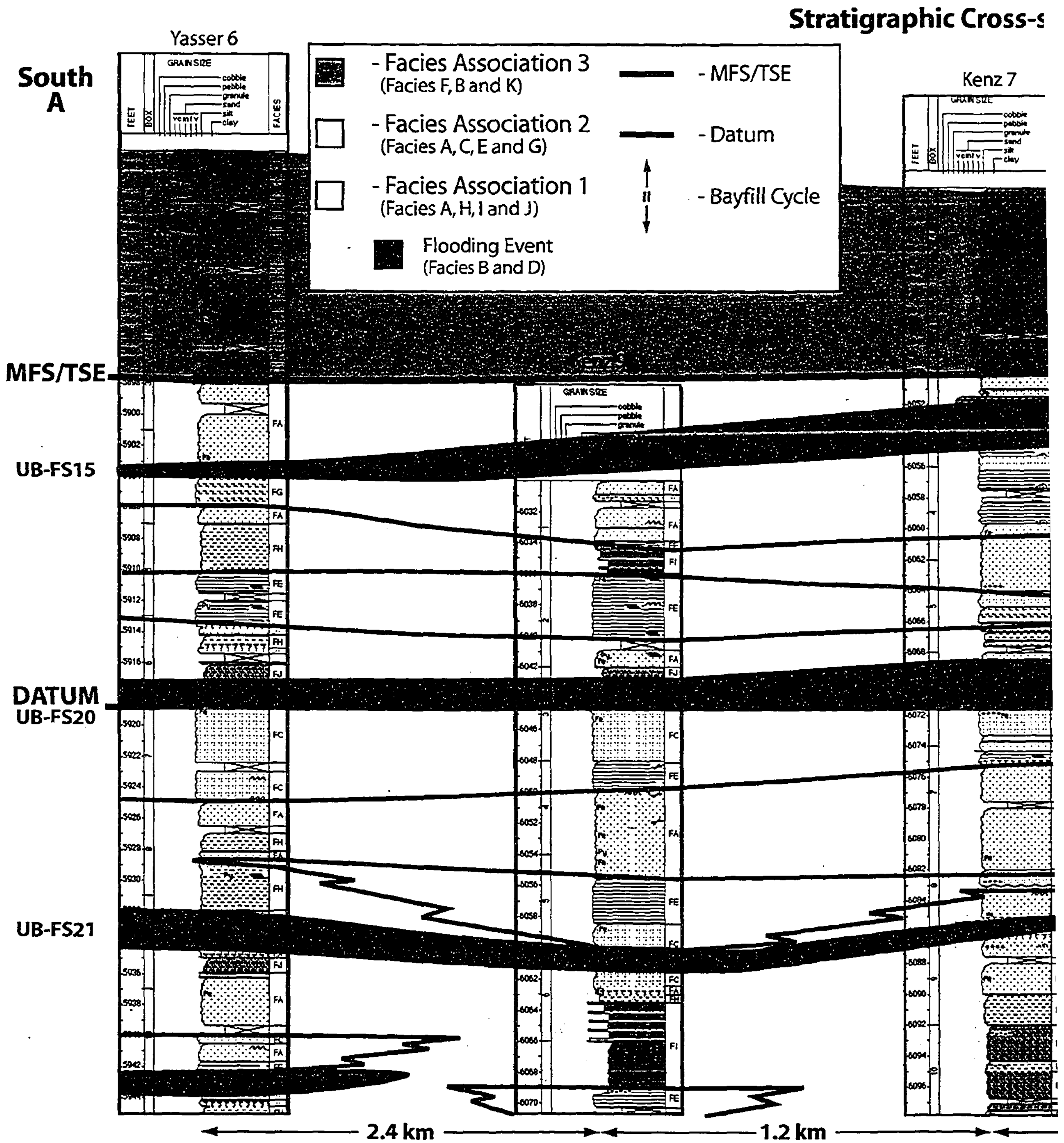
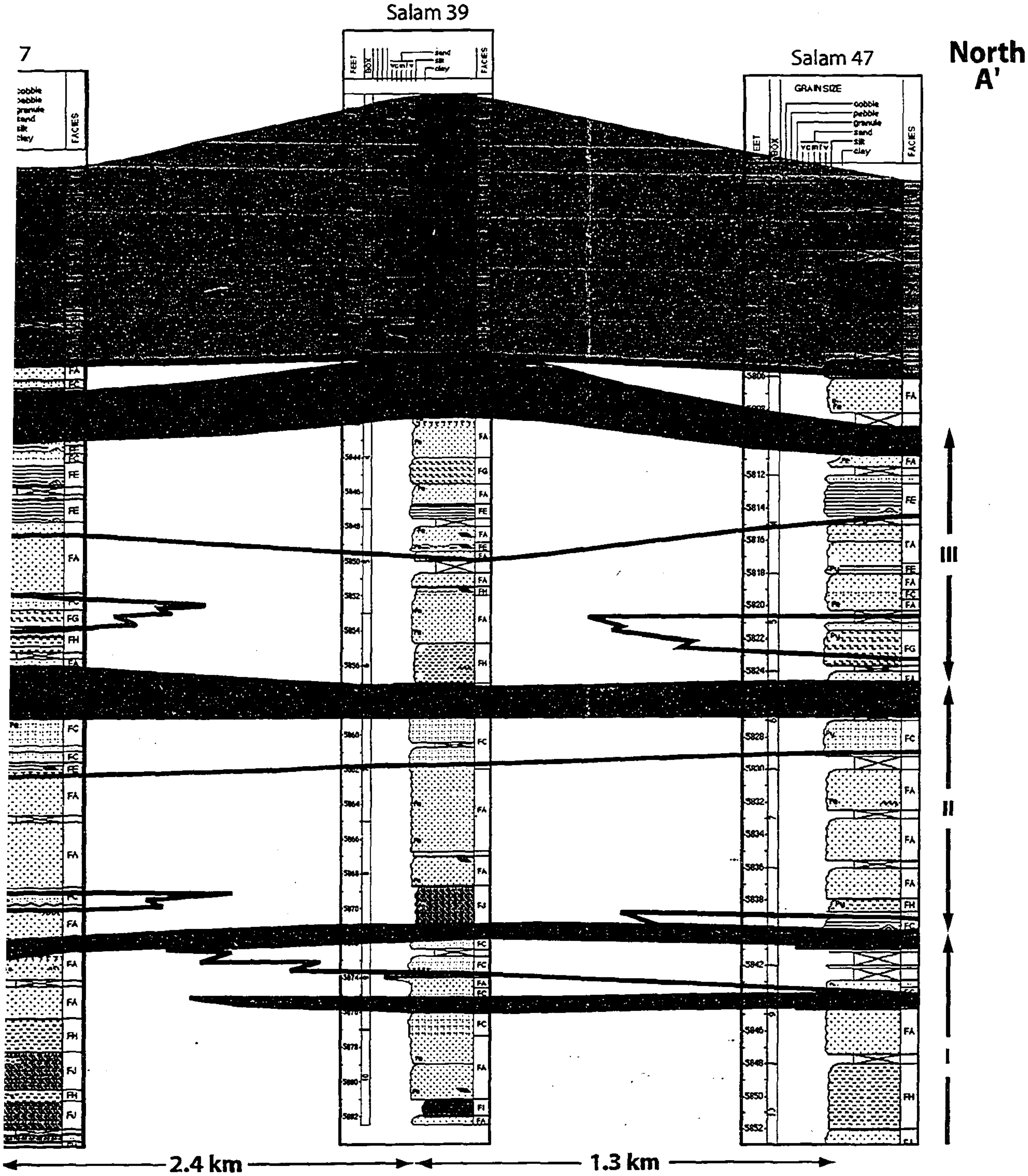


Fig. 5.1 - Stratigraphic cross-section A - A'. See text for a detailed description of cross-section characteristics. Loc

ss-section A - A'



ics. Location of cross-section is shown in Fig. 1.2. See Appendix A for litholog symbols.

surfaces are displayed on the section. The cross-section exhibits two full parasequences and a partial at its base. Each successive parasequence provides evidence of a general upward thickening of flooding events, as well as an increase in carbonate material (FB) to the north of the section. This information, along with the knowledge that the top of the cross-section is capped with deeper marine deposits, suggests deposition in the transgressive systems tract.

5.3 Comparison to Modern Day Crevasse Splay Environments

The study and comparison of modern day systems is essential in understanding the possible geographic distribution of facies. By mapping thicknesses of specific facies within the study area a palaeogeographic interpretation can be produced. Figures 5.2 and 5.3 are sand trend maps produced over the Khalda field within the UB-FS21 to UB-FS20 sequence. This interval of interest represents one complete cycle, illustrating the filling of an interdistributary bay by overbank and crevasse splay deposits. Sand thicknesses obtained from twelve cored intervals were used to calibrate wire line data throughout the study area. Approximately eighty wells were used from the Salam, Kenz and Yasser fields to produce maps of splay sand and total sand thicknesses. The Hayat field was excluded from the mapping process due to the lack of cycle bounding units (*ie.* rare flooding surfaces were observed).

Map 1 (isopach of splay sand) was constructed using Facies C, E and G as the desired sand intervals (Fig. 5.2). Sands of this map range in thickness to as much as 10 ft (3 m). Two possible sources of deposition can be interpreted on the eastern border of the study area and a third may be present on the western edge. A lobate structure is apparent, suggesting deposition at the terminal end of a channel deposit. Based on previous interpretations in earlier chapters, the lobate structure is likely the result of crevasse channels bifurcating within the interdistributary bay. In the southwestern quadrant of the map area (Hayat field) the wells become increasingly dominated by bay muds (FJ), marsh muds (FI), tidal flats (FA) and bay shales (FH). The absence of observable flooding surfaces and the increased abundance of Facies Association 1 suggests a more distal environment (*ie.* distal to crevasse splay deposits of Facies Association 2). Variations in the thickness of the sand are dependant on the proximity to the source of deposition. Thicknesses of < 1 ft (< 30 cm) are sites of low or no accommodation space, or are distal from the crevasse splay mouth. The thickest areas are proximal to the crevasse mouth environment and generally represent increased accommodation space.

Map 2 (isopach of total sand) was constructed using Facies C, E, G and A as the

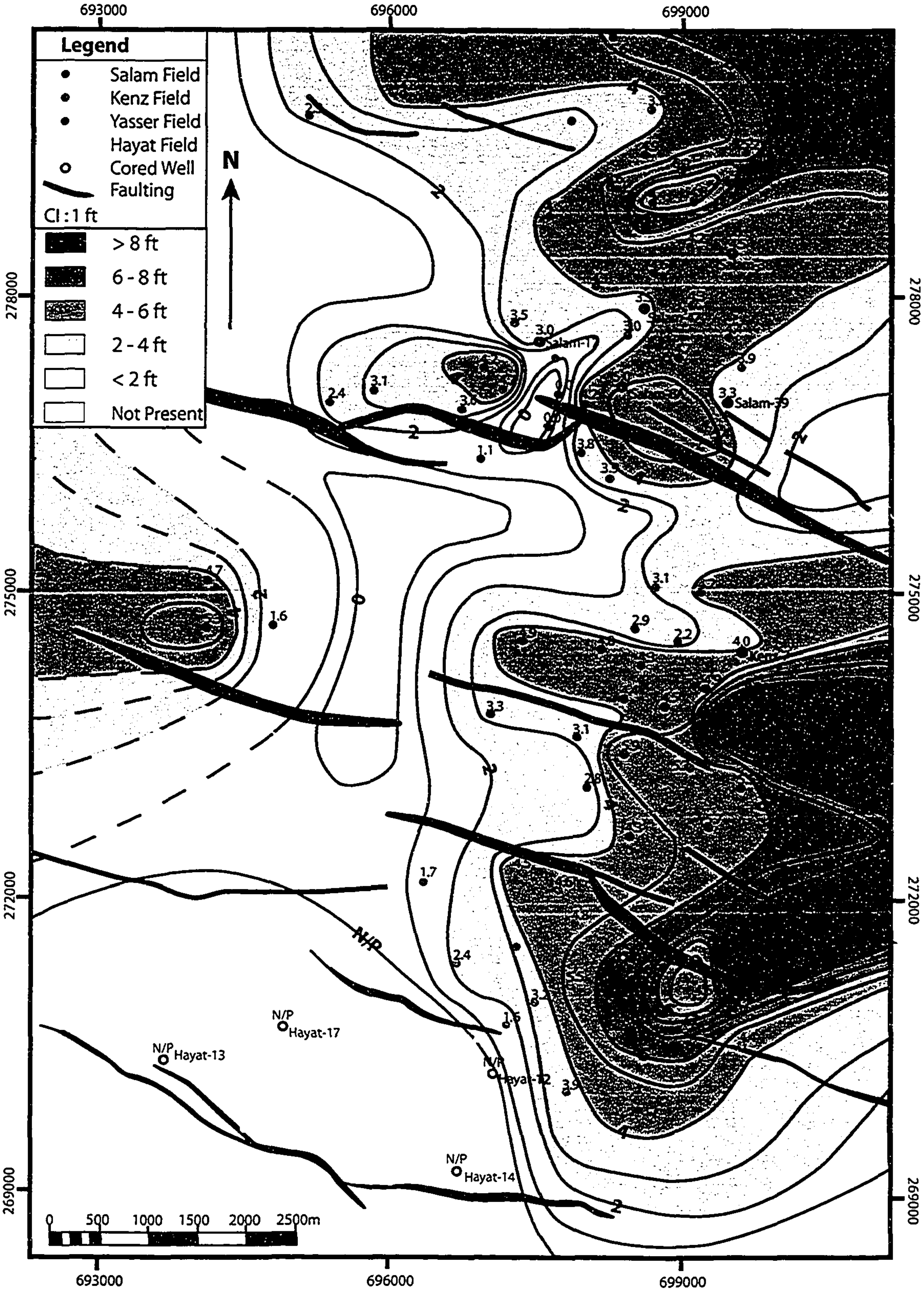


Fig. 5.2 Isopach Map 1: Crevasse splay sand thickness map, which displays disrete lobes of splay deposits in the UB-FS21 and UB-FS20 sequence.

desired sand intervals (Fig. 5.3). Thicknesses of sand range from < 6 ft (1.8 m) to as much as 13 ft (3.9 m). Increased thicknesses are associated with the accumulation of sand by the aforementioned splay deposits, as well as reworking of sand into tidal flats. Two possible sources of deposition along the eastern edge of the study area are still apparent and a third site is likely present along the western margin, as is the case of the splay sand isopach map. In contrast to the splay sand map, the total sand isopach tends to show a slightly less lobate configuration due to the smearing of sand into tidal flats (FA) along the fringes of the bay as a result of tidal processes. Supporting evidence that builds on this theory is the presence of sand in areas where there is little or no sand in the splay sand map. The fringes of the Hayat field show thin sand packages, which are distal to the presumed source and provide evidence for distal deposition of Facies Association 1. This distribution of sand suggests that the edge of the Hayat field is located at the distal edge of the interdistributary bay and provides reason for the lack of flooding surfaces in the area (*ie*. Hayat field is in a more landward location).

Finding modern day analogs for a system involving all the characteristics mentioned for the upper Bahariya Formation is difficult to accomplish. To simplify, an interdistributary bay with crevasse splay deposits is a more realistic analogue. Figures 5.4 a & b are satellite images of the Volga River delta and the Mississippi River delta, respectively. Each of these examples comprise main distributary channels that have been breached, allowing for the formation of crevasse splays in the adjacent bay environment. In both cases, multiple levee breaches occur along the same distributary allowing for the development of several point sources within the same interdistributary bay. A common characteristic in both systems is the strong bifurcating tendency of all crevasse splay deposits creating a lobate sand body. The Mississippi River delta is an adequate illustration for visualizing some of the possible sub-environments of the upper Bahariya Formation. Although the Mississippi delta is a wave-dominated environment, the interdistributary bay is still connected to the open marine through a channel system. In a tide-dominated environment, such as the upper Bahariya Formation, these channels are described as tidal channels and would act as conduits for marine waters during periods of high tide. In a tide-dominated setting, tidal flats, marsh muds and overbank levee deposits would be found adjacent to tidal channels and on the fringes of the interdistributary bay.

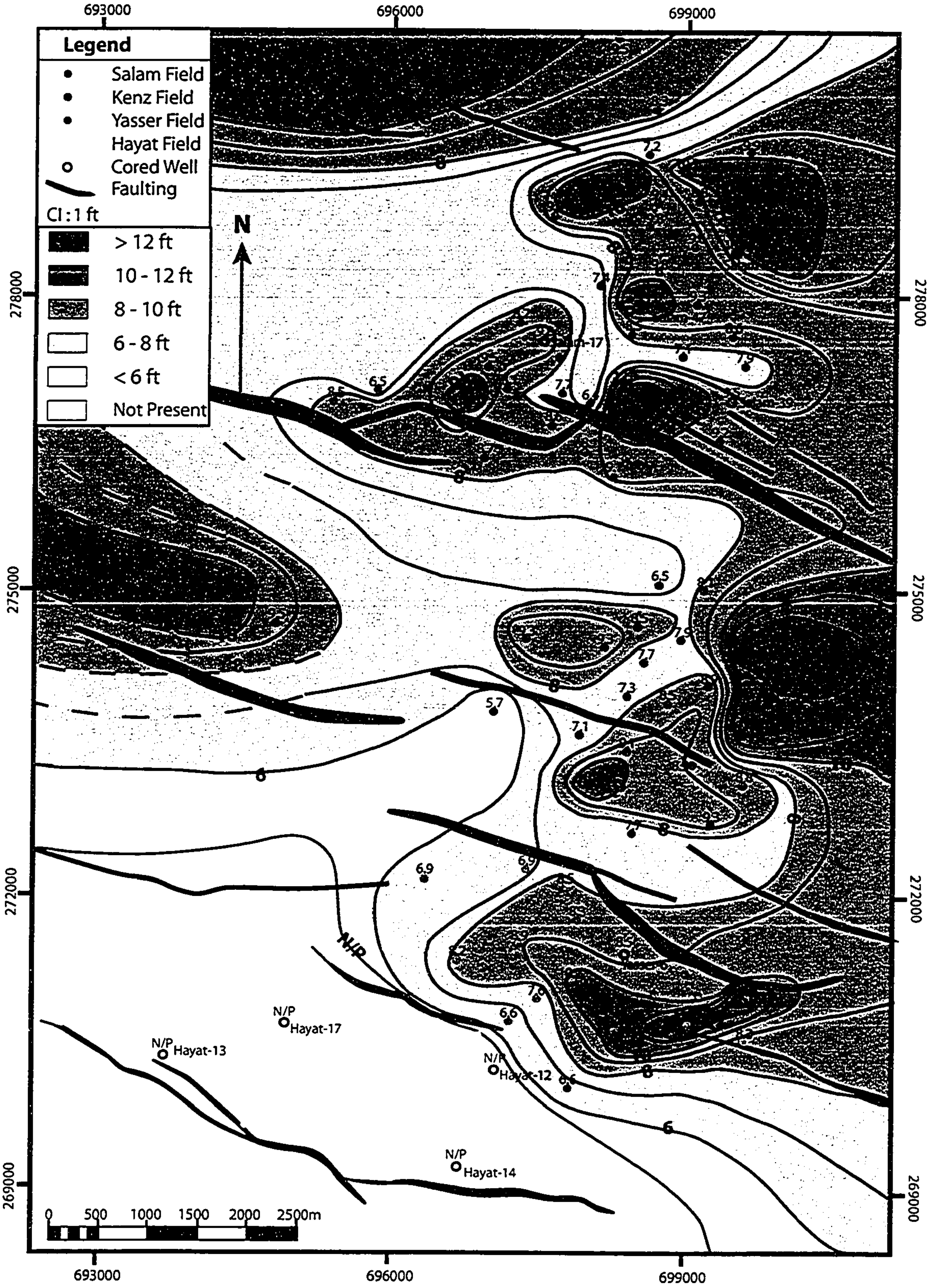


Fig. 5.3 Isopach Map 2: Gross sand thickness map, which displays the distribution of sand within the UB-FS21 and UB-FS20 sequence.

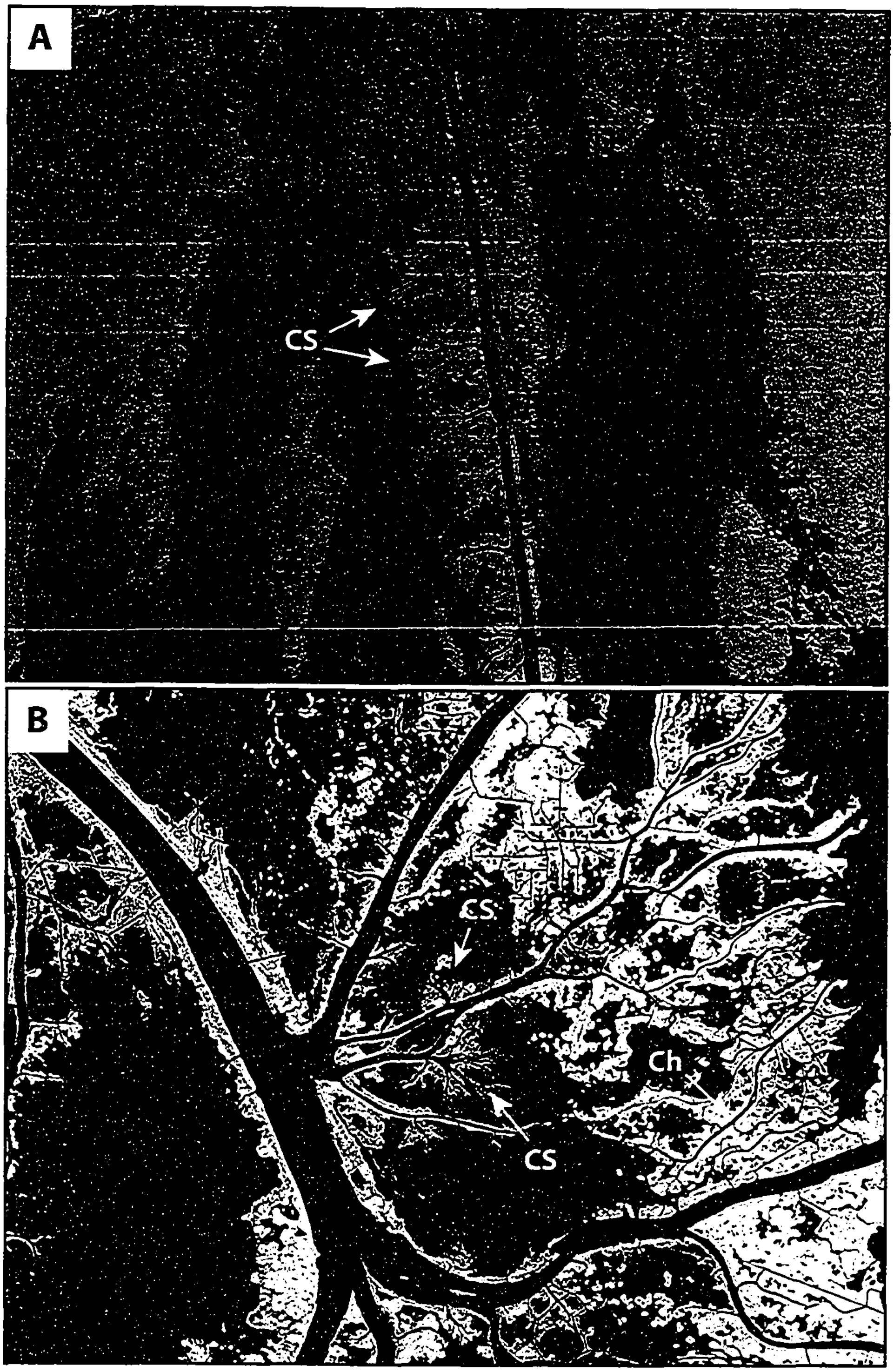


Fig. 5.4 Modern crevasse splays (CS) within interdistributary bays of the delta plain environment. **A)** Crevasse splays witin the delta of the Volga River (NASA website, 2004); **B)** Crevasse splays within the delta of the Mississippi River; channel systems (Ch) connect the interdistributary bay to open marine waters (NASA website, 2004).

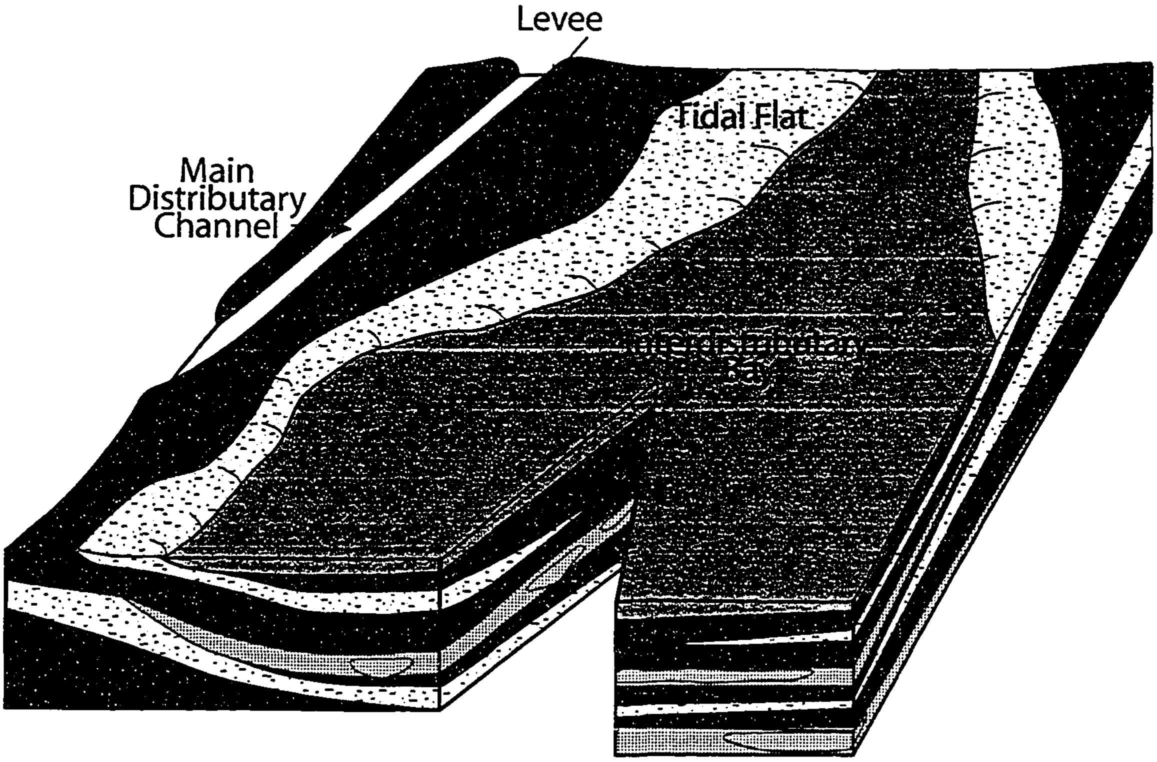


Fig. 5.5 Stage 1: Initial interdistributary bay development (Modified from Horne et al., 1978).

5.4 Stage 1: Initial Interdistributary Bay Development

The lower delta plain is made up of distributary channels and a multitude of other depositional environments. It is defined as the area where river and marine processes interact; thus, it is constrained by the low tide mark and the upper limit of tidal influence (Coleman and Prior, 1982). The numerous deposits found between distributaries comprise a large percentage of the lower delta plain and can be summed up, in a general sense, as bay fill environments. An interdistributary bay is defined as an open body of water within an active delta, which may be completely surrounded by marshes or distributary levees, but are commonly partially opened to the sea or connected to it by small tidal channels (Coleman, 1976). The bay fill environment comprises the largest percentage of the lower delta plain and commonly incorporates tidal channels, overbank splays (natural levees), interdistributary bays, crevasse splays, marshes and swamps (Coleman and Prior, 1982). In tide dominated environments, the bay passes shorewards into tidal flats (Van Andel, 1967; Morgan, 1970) (Fig. 5.5).

During early stages of development, interdistributary bays receive sediment from marine waters due to tidal currents transporting fine-grained material into the bay (Arndorfer, 1973). Sediment is also received from overbank flooding by adjacent distributary channels along the fringes of the bay with minor amounts deposited in the central basin (Arndorfer, 1973; Gould, 1970). Flooding leads to the buildup of levee deposits (FI), marsh environments (FI) and eventually contributes to central parts of the bay, where the deposits are reworked by tidal processes adding to tidal flats (FA) and central bay muds (FH and FJ) (Gould, 1970). Through the flooding events, the lower delta plain is able to keep pace with continued subsidence and maintain its near sealevel position (Gould, 1970). The fine grain deposits from the overbank floods are commonly homogenized by burrowing activity (as seen in Facies I) (Coleman et al., 1964). In essence, interdistributary bays become settling basins for sediments that have been washed over the natural levees (Reineck and Singh, 1980).

During this period, all bay fill sub-environments, such as marsh and levee muds, tidal flat sands, bay muds and bay shales, show an interfingering relationship (Facies Association 1). Overall, the setting is a very low energy system characterized by fine-grained material. Tidal processes and overbank flooding are the dominant transport mechanisms for sedimentation in this environment.

5.5 Stage 2: Flooding of Distributary Channel Causing Discrete Breaks Along the Adjacent Levee Resulting in Crevasse Splay Deposits

Crevasse splay deposits are a major contributor in the filling of interdistributary bay environments. They are defined as natural breaks in levees of distributary channels providing a conduit for sediment transport into the bay. The breaks occur as a result of periodic flooding, which is not uniform along all portions of the bank (Coleman, 1976). Eventually a break in the major distributary channel forms, gradually increasing in size with every subsequent flooding event (Coleman and Prior, 1982). Following the initial breach the channel may be abandoned; after multiple flooding events, if the breach is significantly deep, continual flow may result between flood times (Elliott, 1974) (Fig.5.6).

The high-energy environment of a crevasse splay system involves the deposition of coarser-grained deposits at the limit of crevasse channels in the form of distributary mouth bars (FC and FG). During high-energy influxes, such as flooding of the distributary channel, deposits at the distributary mouth bar are coarse structureless sands. Frequently, the onset of these floods occur over marsh deposits (FI) or in areas of abundant plant growth and other organic material. The crevasse channel picks up the vegetation and carries it along with organic material that is already part of its bed-load and transports it to the distributary mouth or beyond (FG). Adjacent to the distributary

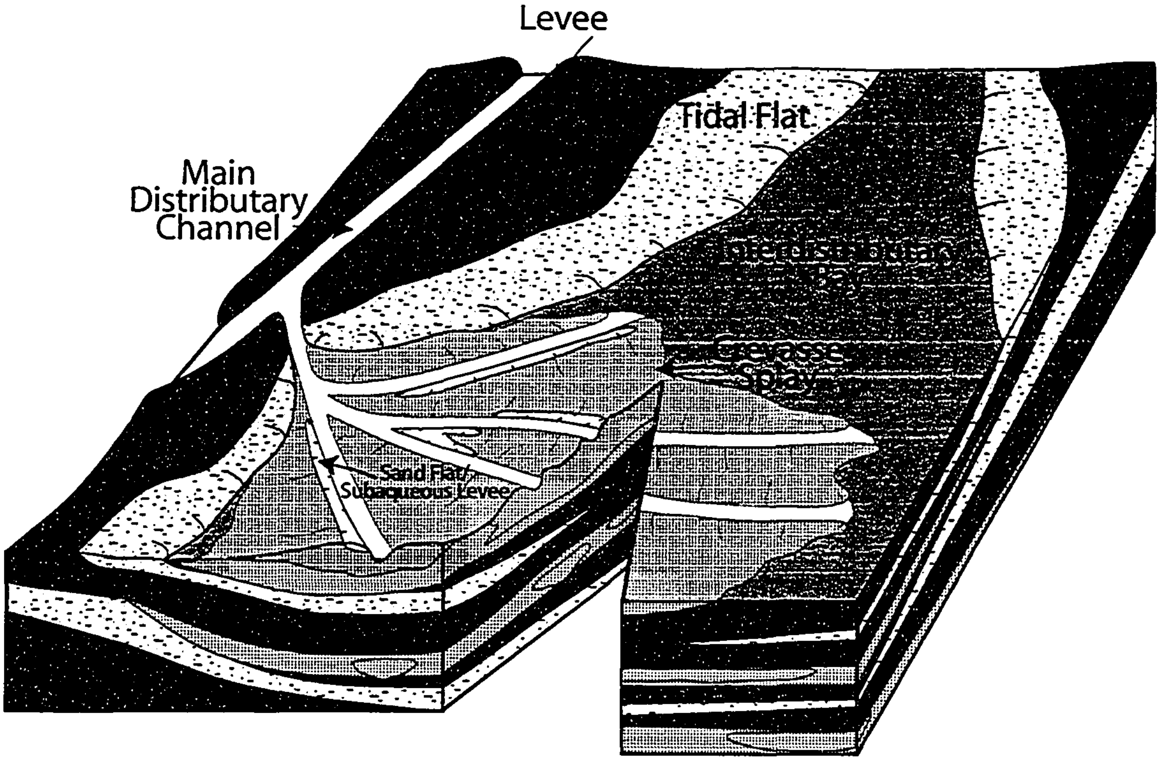


Fig. 5.6 - Stage 2: Flooding of distributary channel causing discrete breaks along the adjacent levee resulting in crevasse splay deposits (Modified from Horne et al., 1978).

mouth, basinal processes within the bay, such as tidal currents, interact with the deposits producing an interlamination of sands and silts/muds (FE). These deposits prograde into more central bay regions, displaying characteristics similar to delta front environments. Sharp or erosive-based contacts beneath the prograding delta front are a common occurrence (Elliott, 1974) and can be associated with mud clasts and pebble lags. Thicker splay deposits may result in emergence and ponding (Elliott, 1974), leading to the development of sand flats (FA) in tide-dominated settings.

High sedimentation rates produce deposits that have high pore water content. During compaction, while sediments are soft, pore water pressure becomes too great, forcing water up through overlying units. As a result, convolute bedding is common and can be seen in much of the core studied. As the crevasse splay progrades over organic bay shales, gas-heave structures may also develop due to the release of CO_2. Among the deformation structures within bay fill environments, convolute bedding is most abundant (Reineck and Singh, 1980).

Environments associated with the initial breaching of the levee include proximal deposits such as distributary mouth bars (FC and FG), delta front sands (FE), tidal flat sands (FA), and distal deposits such as central bay shales (FH) central bay muds (FJ), tidal flats (FA), as well as marshes and natural levees (FI).

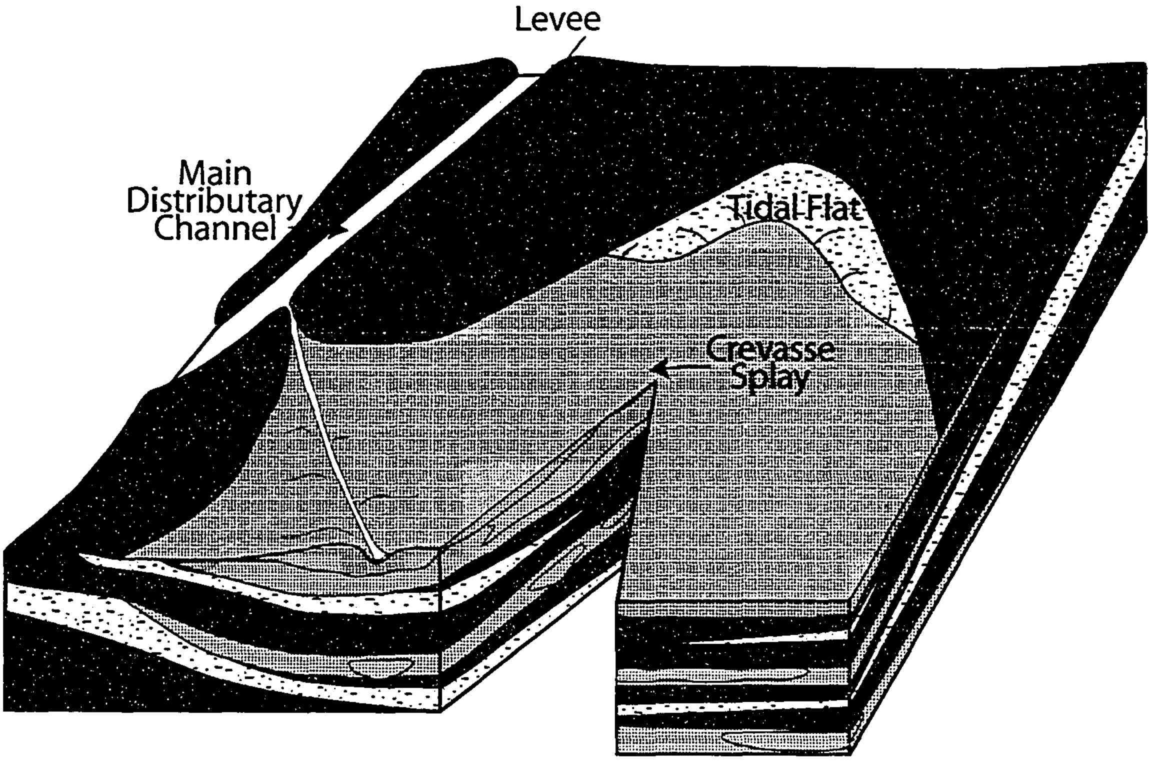


Fig. 5.7 - Stage 3: Complete or partial filling of interdistributary bay by crevasse channels allowing the initial levee breach to be rebuilt and become inactive (Modified from Horne et al., 1978).

5.6 Stage 3: Complete or Partial Filling of the Interdistributary Bay by Crevasse Channels Allowing the Breached Levee to be Rebuilt and become Inactive

During this stage, the crevasse splay has provided enough sediment to completely or partially fill the interdistributary bay. The crevasse splay remains active until it builds up to the point of flood level and the breach in the natural levee wanes and becomes inactive (Coleman, 1976) (Fig. 5.7).

Prior to the build up of levee deposits the interdistributary bay shoals, due to constant infilling of sediment, and a higher energy environment is produced. Coarser-grained material is deposited across a wide lateral extent capping the bay fill with clean sandstone. The top of each bay fill cycle comprises distributary mouth bar deposits (FC) and delta front sands (FE), and will commonly be capped with marsh deposits (FI) (Reineck and Singh, 1980) if the sediment is sub-aerially exposed prior to marine transgression. The typical depth of an interdistributary bay is approximately 1 - 4 m (Elliott, 1974), representing a relatively limited thickness for bay fill cycles. Lower delta plain deposits are dominated by these coarsening-upward sequences, have a total thickness ranging from 15 to 55 m and stretch laterally from 8 to 117 km (Elliott, 1974).

In most lower delta plain settings the main channels are straight with little tendency to migrate laterally resulting in rare point bar deposits (Horne et al., 1978). This tendency allows for bay fill deposits to occur with little interference or cross cutting by distributary channels.

In areas distal to the breached levee, finer grained deposits such as bay shales (FH) bay muds (FJ), tidal flat sands (FA) and marsh muds (FI) are present (Horne, 1978). A higher degree of preservation of these lower energy deposits may occur in upper portions of the bay fill cycle if only a partial filling of the bay occurs.

5.7 Stage 4: Rapid Subsidence of Interdistributary Bay Initiating Inundation of Marine Waters

After crevasse splay abandonment, the weight of deposited sediment within the interdistributary bay causes relatively rapid subsidence and eventual inundation by marine waters. If subsidence rates of the bay are significantly large, the marine waters will encroach rapidly overtop of the subsiding delta, allowing for shallow water marine deposits to directly overly the regressive delta deposits with no observable reworking taking place (Coleman and Prior, 1982). The inundation recreates an environment that is similar to the initial interdistributary bay where quiet water conditions are present with very little sediment influx (Fig. 5.8).

If the water chemistry of the inundating water falls within certain parameters the development of a carbonate factory may occur. The presence of limestone (FB) in the upper Bahariya Formation can be loosely attributed to the onset of flooding at the top of bay fill sequences. *Glossifungites* assemblages are a common occurrence within these flooding events due to the partial lithification of carbonate grains relatively shortly after deposition.

If water chemistry of the inundating seawater does not have the appropriate requirements for the development of carbonate deposits, another marine deposit will occur in its place. The environment will be a quiescent setting, variably between brackish and marine waters. The development of the *Helminthopsis* ichnotaxon in very fine-grained sandstone or siltstone (FD) may be present if overbank flooding of fresh water is minimal and a more marine water chemistry is present. As this facies transgresses over top of the subsiding bay an erosive base may develop, exposing compacted and dewatered sediments. The firm substrate is then made available for recolonization by burrowing organisms, producing a *Glossifungites* ichnofacies on a TSE.

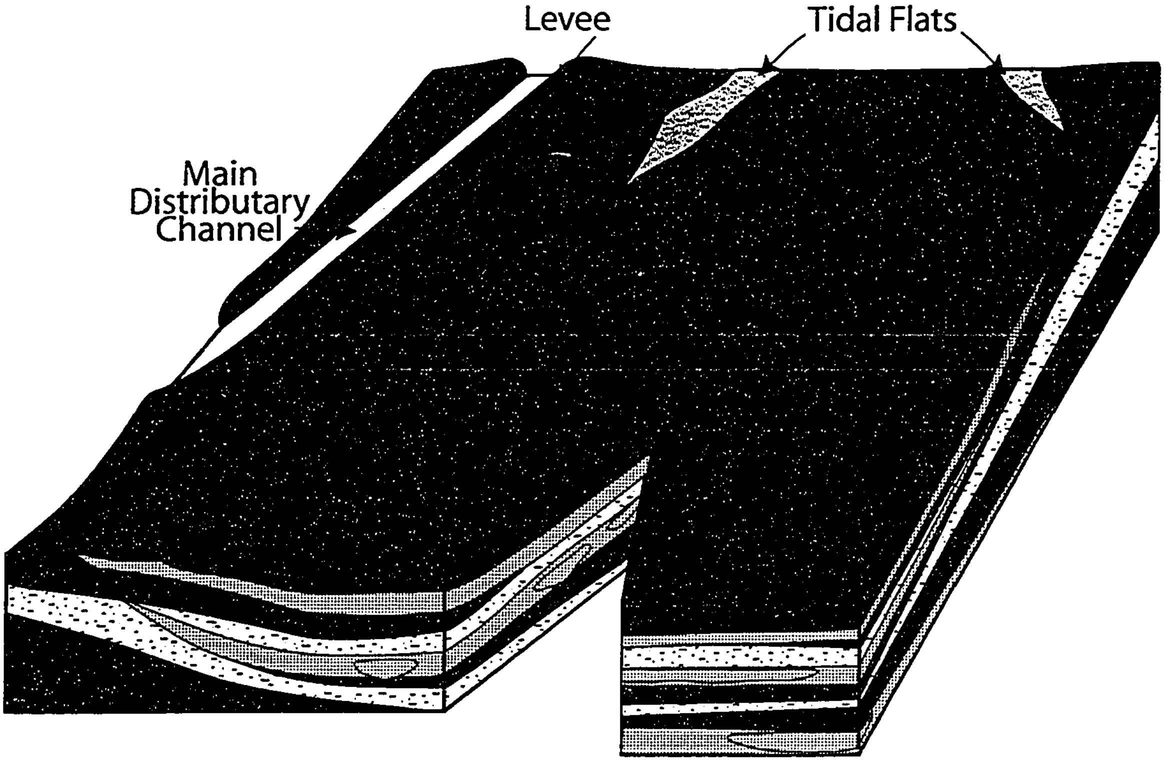


Fig. 5.8 - Stage 4: Rapid subsidence of interdistributary bay initiating inundation by marine waters (Modified from Horne et al., 1978).

In areas distal to the bay-marine water connection (*ie.* closer to the main distributary channel; toward Hayat field), Facies A, H, I and J may preferentially form due to the lack of water circulation into far reaches of the bay and/or clastic influx from overbank flooding. These deposits are laterally equivalent to marine carbonates (FB) in a more basinward direction (*ie.* Salam, Kenz and Yasser fields).

5.8 Repetition of Bay Fill Sequences and the Maximum Flooding Surface

The upper Bahariya Formation is crudely arranged into regular upward-coarsening units that display an upward-shoaling facies succession separated by thin units representing deepening. This trend is recognized and defined by Emery and Myers (1996) in sequence stratigraphic terms as parasequences. Van Wagoner et al. (1990) defined parasequences as relatively conformable successions of genetically related beds or bodies bounded by marine flooding surfaces and their correlative surfaces.

Salam 39 (depth 5873 – 5854 ft) and Salam 17 (depth 5832 – 5810 ft) are two type sections in the Khalda field displaying a typical coarsening upward cycle observable in most interdistributary bay fill sequences of the upper Bahariya Formation (Fig. 5.9). A marine flooding surface comprised of carbonate sediments (FB) or other relatively deeper deposits (FD) develop the base of each sequence initiating each cycle. Fine-grained bay muds (FJ), tidal flats (FA) and bay shales (FH) commonly clean upward into cleaner sand deposits of the crevasse splay environment (*eg*. Facies C, E and G). This trend is repeated throughout the core and displayed as a vertical stacked succession of bay fills (Kenz 7, Depth 6085 – 6051 ft) (Fig. 5.10).

The highly evolved glauconitic material (FF) representing a CS drapes over all the bay fill deposits and has no genetic relationship to the underlying units. Onset of the CS represents a significant deepening event laterally equivalent to the maximum flooding surface. The base of the CS is a TSE and in many areas a *Glossifungites* ichnofacies is developed. At this stage, seawater rises to its maximum landward extent and remains for an extended period of time allowing for glauconitic material to evolve in an area of low sedimentation. Continued deepening results in the development of offshore shale (FK) and carbonates (FB), which initially interfinger and eventually become the dominant deposit.

5.9 Future Work

The limited number of core available within the study area impedes the outcome and interpretation of the upper Bahariya Formation to a subjective explanation. Increased well control (especially logged core) would drastically improve and strengthen the environmental interpretations made in this study. Additionally, increasing the size of the study area would be beneficial in order to identify adjacent environments present in the rock record. Assuming the above interpretation is correct, a main distributary channel would be expected, possibly on either side of the study area. From an exploration point of view, locating the channel sands of this type of environment would be extremely advantageous in delineating possible new reservoir potential.

By increasing the well control within the study area, a more detailed analysis of parautochthonous glaucony can be performed. The recognition of increasing/decreasing abundances and changes in physiochemical properties of the glauconitic material within parasequences and parasequence sets would enable a more defined stratigraphic framework to be developed. An X-ray diffraction analysis would also provide additional support on the evolution of glauconitic material and may provide information on the pale green clay matrix, which the electron microprobe could not resolve.

Further support for the timing and interpretation of early cementation and firmground

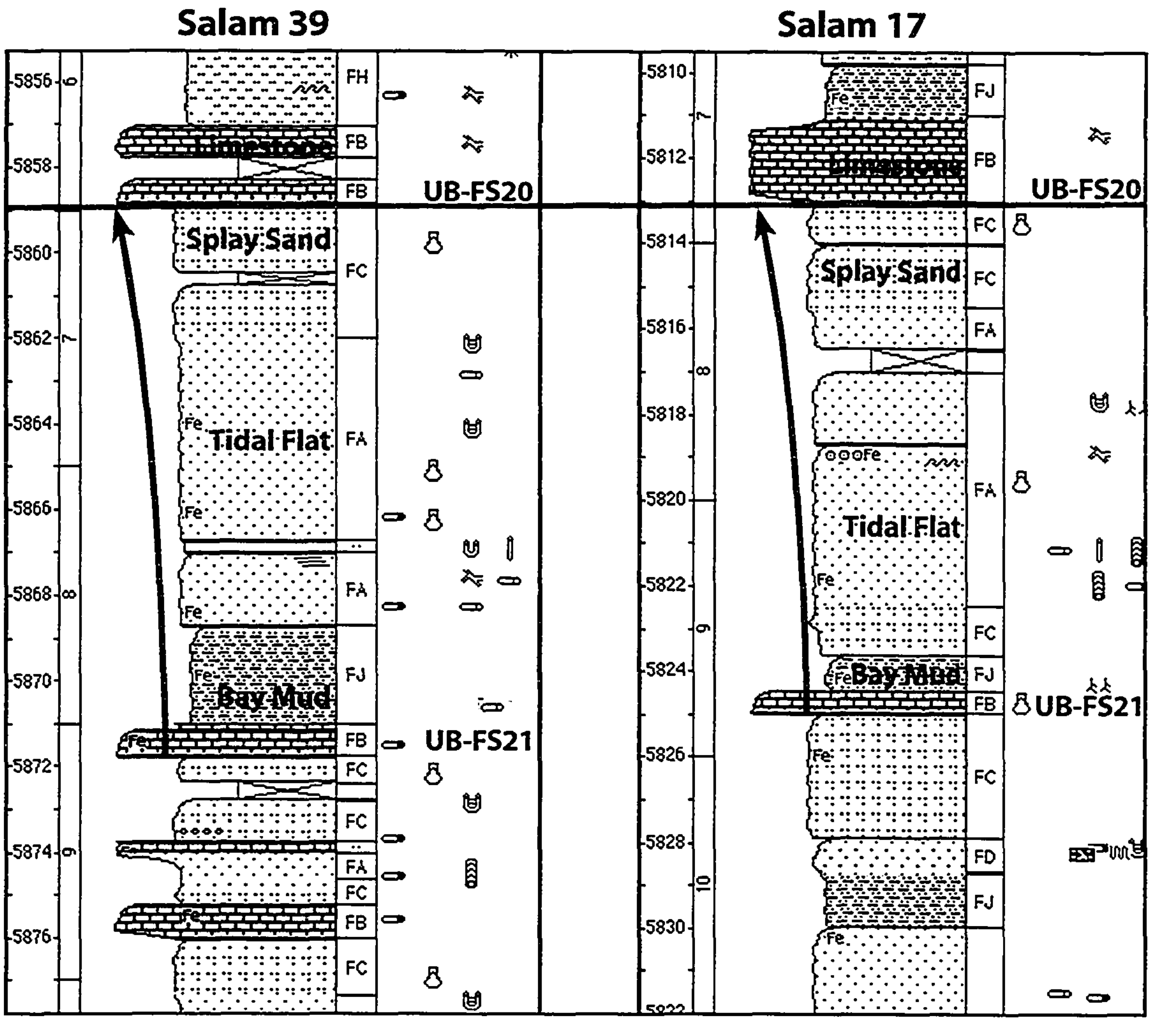


Fig. 5.9 - Typical bay fill cycle for Salam 39 (depth range, 5878 - 5855 ft) and Salam 17 (depth range, 5832 - 5810 ft) between the UB-FS21 and UB-FS20 surfaces; both wells show a general cleaning upward trend from silts or lower very fine sand of the bay and tidal flat environment to upper very fine sand of crevasse splay deposits, which are then flooded by marine waters producing carbonate lithologies; for legend see Appendix A.

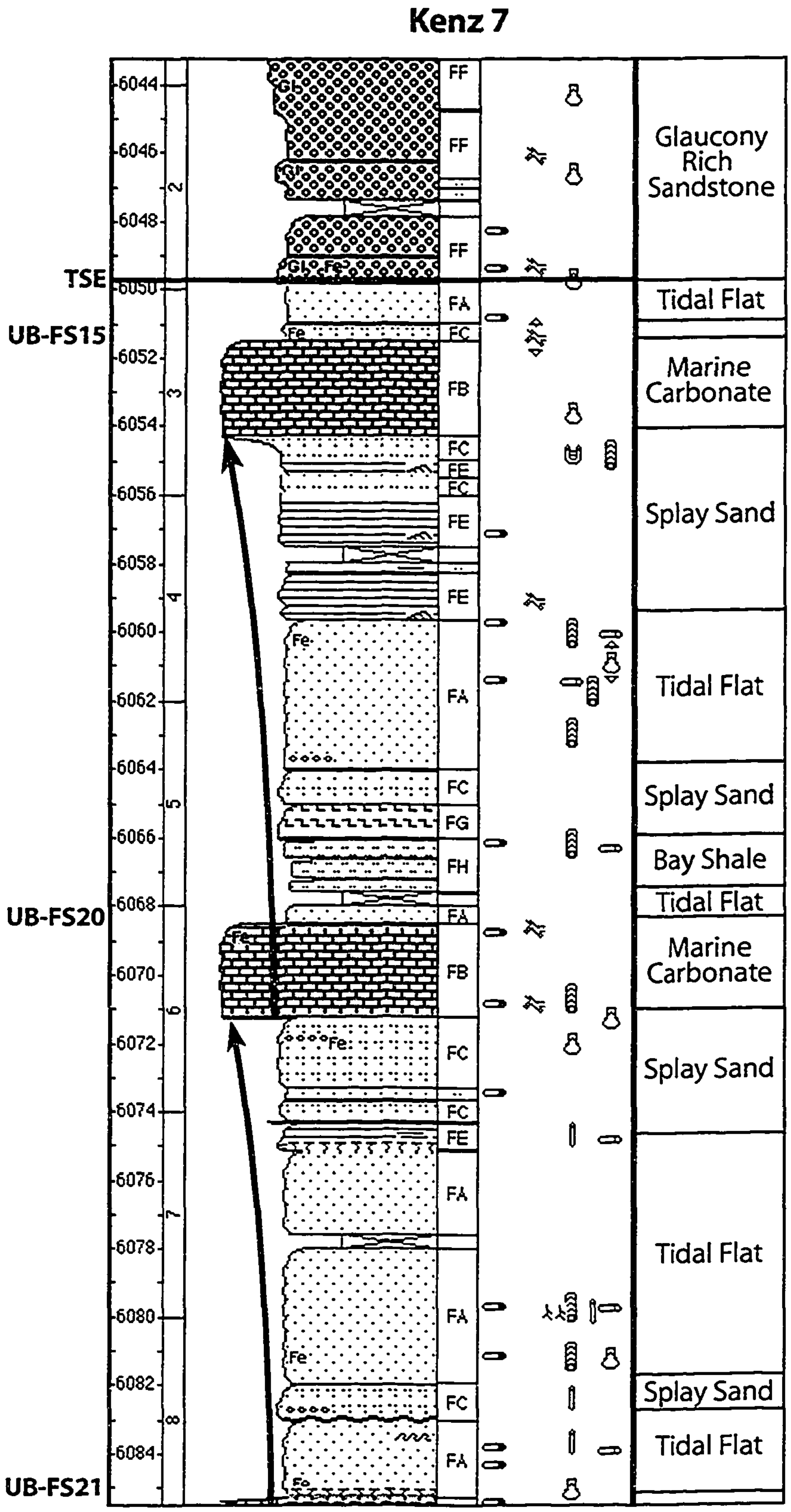


Fig. 5.10 - Stacking of successive bay fill cycles for the Kenz 7 well (depth, 6085 - 6044 ft) including the UB-FS21 to UB-FS20 sequence, as well as the UB-FS20 to UB-FS15 sequence; for legend see Appendix A

development, allowing for a *Glossifungites* assemblage to form, is of utmost importance. The limited number of core studied within this project, as well as limited access to the data (located in Egypt), was not conducive for a detailed study of this sort. In order to prove the working hypotheses and the present understanding of this depositional environment, a petrographic analysis on multiple samples will need to be performed.

A detailed study involving the temporal relationship of cementation and burrowing can be ascertained through comprehensive observations made on samples of core, providing further proof of firmground burrowing. It is also important to gain an understanding of the environmental implications associated with the genesis of the carbonate cement. Understanding the depositional setting that the carbonate cements formed under (*ie.* mixing zone, shallow marine omission surface, or deep marine cementation) will greatly advance the preliminary research presented in this study. In addition, an overall understanding of the genetic origins of the pre-omission and post-omission suites associated with the *Glossifungites* assemblages will improve the understanding of the processes involved in creating these surfaces.

CHAPTER 6: Conclusions

6.1 Conclusions

1. Eleven facies (FA – FK) have been described and separated in to three facies associations. The facies associations have been interpreted as: low energy, distal interdistributary bay fill deposits (Facies A, B, D, H, I and J) of Facies Association 1, high energy, proximal interdistributary bay fill deposits (Facies A, C, E and G) of Facies Association 2, and as the low energy offshore deposits (Facies B, F and K) of Facies Association 3.

2. Glaucony is found throughout the upper Bahariya Formation in deposits of tidal flat sands, flooding surfaces (limestone) and near the top of every core in a condensed section. Parautochthonous glaucony ranges in its physiochemical composition from nascent to highly evolved and was transported by means of tidal processes or storm activity. Autochthonous glaucony ranges in its physiochemical composition from evolved to highly evolved and is the result of low sedimentation rates in a condensed section following the onset of a major marine transgression.

3. *Glossifungites* assemblages are found on numerous occasions throughout the upper Bahariya Formation under two different depositional settings. The type 1 *Glossifungites* assemblage is associated with the typical progression found in most siliciclastic environments. Burrowing of this type occurs in sediment that is buried, compacted, dewatered and erosionally exhumed allowing for the recolonization of a firm unlithified substrate that is later buried upon resumed sedimentation. The type 2 *Glossifungites* assemblage is associated with the poorly understood burrowing of a mixed carbonate siliciclastic environment. Development of this type is the result of deposition of siliciclastic or carbonate grains, which are partially lithified through early cementation, followed by burrowing in a firm unlithified substrate that is then passively infilled with resumed sedimentation.

4. The upper Bahariya Formation is summed up in a four stage depositional model: 1) initial interdistributary bay development, 2) flooding of a distributary channel causing discrete breaks along the adjacent levee resulting in crevasse splay deposits, 3) complete or partial filling of interdistributary bay by crevasse channels allowing the breached levee to be rebuilt and become inactive, and 4) rapid subsidence of interdistributary bay initiating inundation of marine waters. This model repeats throughout the upper Bahariya Formation as parasequences and is eventually capped by a glaucony rich condensed section, offshore shales and marine limestone. The base of the condensed section represents a transgressive surface of erosion for the maximum flooding surface.

REFERENCES:

Abdalla, A. and El-Bassyouni, A. 1985. Primary Sedimentary Structures and Sedimentary Environment of the Bahariya Formation "Lower Cenomanian", Bahariya Oasis, Egypt. The Geological Survey of Egypt and Mining Authority, Cairo, Egypt, Vol. XV.

Abel-Kireem, M., Samir, A., Ibrahim, M. and Schran, E. 1993. Cretaceous Palaeoecology, Palaeoclimatology and Paleeogeography of the Northern Western Desert of Egypt. *In*: Geoscientific Research in Northeast Africa; Preceedings of the International Conference. A.A. Balkema. Rotterdam, Netherlands.

Allam, A. 1986. A Regional and Paleoenvironmental Study on the Upper Cretaceous Deposits of the Bahariya Oasis, Libyan Desert, Egypt. Journal of African Earth Sciences, Great Britain, Vol. 5, No. 4.

Amorosi, A. 1993. Ineret des Niveaux Glauconieux et Volcano-Sedimentaires en Stratigraphie: Exemple de Depots de Bassins Tectoniques Miocenes des Apennins et Comparaison Avec Quelques Depots de Platte-forme Stable (Ph.D. thesis). Memoires des Sciences de la Terre no. 93-12, Universite Pierre et Marie Curie, Paris, p. 195.

Amorosi, A. 1995. Glaucony and Sequence Stratigraphy: A Conceptual Framework of Distribution in Siliciclastic Sequences. Journal of Sedimentary Research, Vol. B65, No. 4, p. 419-425.

Amorosi, A. 2003. Gaucony and Verdine, *In*: Middleton, G, Micheal, C, Mario, C, Laurence, H, and Frederick, L, (eds.). Encyclopedia of Sediments and Sedimentary Rocks, (Encyclopedia of Earth Sciences Series), Kluwer Academic Publishers, Dordrecht/Boston/London, p. 331-333.

Amorosi, A. and Centineo, M. 1997. Glaucony from the Eocene of the Isle of Wight (Southern UK); Implications for Basin Analysis and Sequence Stratigraphic Interpretation. Journal of the Geological Society of London, Vol. 154, Part 5, p. 887-896.

Arndorfer, D. 1973. Discharge Patterns in two Crevasses in the Mississippi River Delta. Marine Geology, Vol. 15, p. 269-287.

Bathurst, R. 1975. Carbonate Sediments and Their Diagenesis. Elsevier Scientific Publishing Company, Amsterdam Oxford New York, Second Enlarged Edition, p. 361-457.

Batten, D. 1982. Palynofacies, Palaeoenvironments and Petroleum. Micropaleontology, Vol. 1, p. 111-125.

Bhattacharya, J. and Walker, R. 1992. Deltas, *In*: Walker, R. and James, N. (eds.). Facies Models, Response to Sea Level Change. Geological Association of Canada, p. 157-177.

Bromley, R. 1975. Trace Fossils at Omission Surfaces, *In*: Frey R. (ed.). The Study of Trace Fossils. Springer-Verlag, New York, p. 399-428.

Coleman, J. 1976. Deltas: Processes and Models of Deposition for Exploration. Continuing Education Publication Company, Inc, Champaign, IL 61820, USA, p. 102.

Coleman, J. and Gagliano, S. 1964. Cyclic Sedimentation in the Mississippi River Deltaic Plain. Transactions of the Gulf Coast Association of Geological Societies, Vol. 14, p. 67-80.

Coleman, J. and Prior, D. 1982. Deltaic Environments of Deposition. *In*: Scholle, P. and Spearing, D. (eds.). Sandstone Depositional Environments. The American Association of Petroleum Geologists Tulsa, Oklahoma 74101, USA, p. 139-178.

Collinson, J. 1969. The Sedimentology of the Grindslow Shales and Kinderscout Grit: A Deltaic Complex in the Namurian of Northern England. Journal of Sedimentary Petrology, Vol. 39, p. 194-221.

Darahem, M. Paradisi, C. and Moinard, L. 1990. Evaluation of the Bahariya Formation from High Resolution Logging. 10th EGPC Exploration Production Seminar, p. 290-315.

Dolson, J., Shann, M., Matbouly, S., Harwood, C., Rashed, R. and Hammouda, H. 2001. The Petroleum Potential of Egypt. *In*: Downey, M., Threet, J. and Morgan, W. (eds.). Petroleum Provence of the Twenty-first Century, American Association of Petroleum Geologist., Mem. 74. p. 453-461.

Dominik, W. 1985. Stratigraphie und Sedimentologie (Geochemie, Schwermineralanayes) der Oberkreide von Bahariya und ihre Korrelation zum Dakhla Becken (Western Desert, Agypten). Berl. Geowiss., Abh. 62(A), p. 1-173.

El Beialy, S. 1994. Palynological Evidence for the Age and Depositional Environment of the Cretaceous Bahariya Formation. Northwestern Desert, Egypt, Bull. 47.

El Beialy, S. 1995. Datation and Palaeoenvrionmental Interpretation By Microplankton and Miospore Assemblages of the Razzak Oil Field Sediments, Western Desert, Egypt. Geobios, Vol, 28, 6, p. 663-673.

Elliott, T. 1974. Interdistributary Bay Sequences and their Genesis. Sedimentology, Vol. 21, p. 611-622.

Elsheikh, M. 1990. Reservoir Geology of the Bahariya Formation in the Melehiha Development lease. 10th EGPC Exploration Production Conference, p. 15.

Emery, D. and Meyers, K. 1996. *In*: Emery, D. and Myers, K. (eds.). Sequence Stratigraphy. Blackwell Science, p. 1-297.

Fisk, H. 1960. Recent Mississippi River Sedimentation and Peat Accumulation. International Congress on Carboniferous Stratigraphy and Geology, p. 187-199.

Fraser, G. 1989. Clastic Depositional Sequences: Processes of Evolution and Principals of Interpretation. Prentice Hall Advanced Reference Series, p. 253-305.

Gingras, M., Pemberton, S., Saunders, T. and Clifton, H. 1999. The Ichnology of Modern and Pleistocene Brackish-water Deposits at Willapa Bay, Washington; Variability in Esturine Settings. Society of Economic Paleontologists and Mineralogists, Vol. 14, p. 352-374.

Goldman, M. 1922. Basal Glauconite and Phosphate beds. Science, Vol. 56, p. 1-6.

Gould, H. 1970. The Mississippi Delta Complex. *In*: Morgan, J. and Shaver, R. (eds.). Deltaic Sedimentation Modern and Ancient. Special Publication, Society of Economic Palaeontologists and Mineralogists, Tulsa, No. 15, p. 3-30.

Gundu Rao, C. 1986. Glaoconite and Oil Exploration. *In*: Srivastava, R. (ed.). Current Trends in Geology, Glauconite: Form and Function. Today and Tomorrow's Printers and Publishers, New Deli, Vol. 10, p. 57-60.

Hadding, A. 1932. The Pre-Quaternary rocks of Sweden. Glauconite and Glauconitic Rocks, Lunds Geologisk-Mineralogiska Institution. Meddelanden, Vol. 51, p. 175.

Hantar, G. 1990. North Western Desert. *In*: Said, R. (ed.). The Geology of Egypt. A.A. Balkema, Rotterdam, Nertherlands.

Harris, P., Kendall, C. and Lerche, I. 1985. Carbonate Cementation - A Brief Review. *In*: Schneidermann and Harris, P. (eds.). Carbonate Cemnts. Society of Economic Paleontologists and Mineralogists, Special Publication No. 36, p. 79-95.

Heim, A. 1934. Stratigraphische Kondensation. Ecologae Geologicae Helvetiae, Vol. 27, p. 272-383.

Horne, J., Ferm, J., Caruccio, F. and Baganz, B. 1978. Depositional Models in Coal Exploration and Mine Planning in Appalachian Region. Bulletin of American Association of Petroleum Geology, Vol. 62/12, p. 2397-2411.

James, N. and Kendal, A. 1992. Introduction to Carbonate and Evaporite Facies Models. *In*: Walker, R. and James, N. (eds.). Facies Models, Response to Sea Level Change. Geological Association of Canada, p. 265-275.

Johnson, H. and Baldwin, C. 1986. Shallow Siliciclastic Seas. *In*: Reading, H. (ed.). Sedimentary Environments and Facies, Second Edition. Blackwell Science Publications, p. 229-282.

Jones, B. and Desrochers, A. 1992. Shallow Platform Carbonates. *In*: Walker, R. and James, N. (eds.). Facies Models, Response to Sea Level Change. Geological Association of Canada, p. 277-301.

Kerdany, M. and Cherif, O. 1990. Mesozoic. *In*: Said, R. (ed.). The Geology of Egypt. A.A. Balkema, Rotterdam, Nertherlands.

Kholeif, W., Work, J. and Sanad, S. 1986. Meleiha, its History and its Significance. 8th EGPC Exploration Production Seminar, Cairo, p. 14.

Kireem, A., Samir, A., Ibrihim, M. and Shrank, E. 1993. Cretaceous Palaeoecology and Palaeogeography of the Northern Western Desert of Egypt. *In*: Thorweile, U. and Schandelmeier, H. (eds.). Geoscientific Research in Northeast Africa; Proceeding of the International Conference, A. A. Balkema. Rotterdam, Netherlands, p. 375-380.

Klitzsch, E. 1979. Zur Geologie des Gilf Kebir Gebietes in der Ostsahara. Clausthaler Geol., Abh. 30 p. 113-132.

Lacovara, K., Smith, J., Smith, J. and Lamanna, M. 2001. Coastal Depositional Environments Along the Cretaceous Tethys Seaway of Egypt. Geological Society of America Annual meeting, Marine/Coastal Science (Posters), Session No. 80.

Lamboy, M. and Odin, G. 1975. Nouveaux Aspects Concernant les Glauconies du Plateau Continental Nord-Ouest Espagnol. Revue de Geographic Physique et de Geologie Dynamique, Vol. 17, p. 99-119.

Leckie, D. and Singh, C. 1991. Esturine Deposits of the Albian Paddy Member (Peace River Formation) and Lowermost Shaftesbury Formation, Alberta Canada. Journal of Sedimentary Petrology, Vol. 61, p. 825-849.

Loutit, T., Hardenbol, J., Vail, P. and Baum, G. 1988. Condensed Sections: The Key to Age Detirmination and Correlation of Continental Margin Sequences. *In*: Wilgus, C., Hastings, B., Kendall, C., Posamentier, H., Ross, C. and Van Wagoner, J. (eds.). Sea-Level Changes: An Integrated Approach, Society of Economic Paleontologists and Mineralogists, Special Publication, No. 42, p. 183-213.

MacEachern, J. and Burton, J. 2000 Firmground Zoophycos in the Lower Cretaceous Viking formation, Alberta: A Distal Expression of the Glossifungites Ichnofacies. Palaios, Society for Sedimentary Geology, Vol. 15, p. 387-398.

Meshref, W. 1990. Tectonic Framework. *In*: Said, R. (ed.). The Geology of Egypt. A.A. Balkema, Rotterdam, Nertherlands.

Metwalli, H., Saad, M. and Ali, T. 2000. Effect of Depositional Environments on Reservoir Capacity of Upper Bahariya Formation, Meleiha Oilfields, North Western Desert, Egypt. Journal of the Sedimentological Society of Egypt, Vol. 8a.

Moore, D. 1966. Deltaic Sedimentation. Earth Science Reviews, Elsevier Publishing Company, Amsterdam, Vol. 1, p. 87-104.

Morad, S. 1998. Carbonate Cementation in Sandstones; Distribution Patterns and Geochemical Evolution. *In*: Morad, S. (ed.). Carbonate Cementation in Sandstones; Distribution Patterns and Geochemical Evolution. Special Publication of the International Association of Sedimentologists, Vol. 26, p. 1-26.

Morgan, J. .1970. Depositional Processes and Products in the Deltaic Environment. *In*: Morgan, J. and Shaver, R. (eds.). Deltaic Sedimentation Modern and Ancient. Special Publication, Society of Economic Palaeontologists and Mineralogists Tulsa, Vol. 15.

Morgan, P. 1990. Egypt in the Framework of Global Tectonics. *In*: Said, R. (ed.). The Geology of Egypt. A.A. Balkema, Rotterdam, Nertherlands.

NASA website, (2004): http://zulu.ssc.nasa.gov/mrsid

Odin, G. 1975. De Glauconiarum: Constittione, Origine, aetateque (Unpublished Theses d'etat). Universite Pierre et Maie Curie, Paris, p. 280.

Odin, G. 1985. Significance of Green Particles (Glaucony, Berthierine, Chlorite) in Arenites. *In*: Zuffa, G, (ed.). Provenance of Arenites, D. Reidel Publishing Company, Dordrecht, Holland, Vol. 148, Series C, p. 279-307.

Odin, G. and Letolle, R. 1980. Glauconization and Phosphatization Environments; a Tentative Comparison. *In*: Bentor, Y. (ed.). Marine Phosphorites; Geochemistry, Occurrence, Genesis. Society of Economic Paleontologists and Mineralogists, Special Publication No. 29, p. 227-237.

Odin, G. and Matter, A. 1981. De Glauconiarum Origine. International Association of Sedimentologists, Vol. 28, p. 611-641.

Odin, G. and Fullagar, P. 1988. Geological Significance of the Glaucony Facies. *In*: Odin, G. (ed.). Green Marine Clays, Amsterdam, Elsevier, p. 295-332.

Pemberton, S. G. and Frey, R. 1985. The Glossifungites ichnofacies: Modern Examples from the Georgia Coast, U.S.A. *In*: Curran, H. (ed.). Biogenic Structures: Their Use in Interpreting Depositional Environments. Society of Economic Paleontologists and Mineralogists, Special Publication No. 35, p. 237-259.

Pemberton, S.G., Spila, M., Pulham, A., Saunders, T., MacEachern, J., Robbins, D. and Sinclair, I. 2001 Ichnology and Sedimentology of Shallow Marginal Marine Systems, Ben Nevis and Avolon Reservoirs, Jeanne d'Arc Basin. Geological Association of Canada, Vol. 15, p. 190-219.

Reading, H. and Collinson, J. 1996. Clastic Coasts. *In*: Reading, H. (ed.). Sedimentary Environments, Third Edition. Blackwell Science Ltd., p. 154-231.

Reineck, H. 1967. Layered Sediments of Tidal Flats, Beaches, and Shelf Bottom of the North Sea. *In*: Lauff, G. (ed.). Estuaries, Am. Assoc. Adv. Sci., Pub., Washington, DC., p. 191-206.

Reineck, H. and Singh, I. 1973. *In*: Reineck, H. and Singh, I. (eds.). Depositional Sedimentary Environments, With Reference to terrigenous Clastics. Springer Verlag, New York Heidelberg, Berlin, p. 439.

Reineck, H. and Singh, I. 1980. *In*: Reineck, H. and Singh, I. (eds.). Depositional Sedimentary Environments, With Reference to terrigenous Clastics. Springer Verlag, New York Heidelberg, Berlin, p. 439.

Salah, M. and Paradisi, C. 1992. Analysing Depositional Environments in Bahariya Formation Using High Resolution Electrical Image Data. 11th EGPC Exploration Production Conference, Vol. 2, p. 295-309.

Schweitzer, C., Lacovara, K., Smith, J. Lamanna, M., Lyon, M. and Attia, Y. 2003. Mangrove-dwelling Crabs (Decapoda: Brachyura: Necrocarcinidae) Associated With Dinosaurs From The Upper Cretaceous (Cenomanian) Of Egypt. Journal of Paleontology, Vol. 77.

Scotese, C, website (2004): http://www.scotese.com.

Sengor, A., Yilmaz, Y. and Sungurlu, O. 1984. Tectonics of the Mediterranean Cimmerides: Nature and Evolution of the Western Termination of Palaeo-Tethys. *In*: Dixon, J. and Robertson, A. (eds.). The Geological Evolution of the Eastern Mediterranean. Geological Society Special Publication, No. 17, p. 77-112.

Sestini, G. 1984. Tectonic and Sedimentary History of the NE African Margin. *In*: Dixon, J. and Robertson, A. (eds.). The Geological Evolution of the Eastern Mediterranean. Geological Society Special Publication, No. 17, p. 161-175.

Smith, A. .1971. Alpine Deformation and the Oceanic areas of the Tethys, Mediterranean and Atlantic. Bulletin Geological Society of America., Vol. 82, p. 2039-2070.

Stonecipher, S. 1999. Genetic Characteristics of Glauconite and Siderite: Implications for the Origin of Ambiguous Isolated Marine Sandbodies. Socetiy of Economic Paleontologists and Mineralogists, Special Publication, No. 64, p. 191-204.

Takahashi, H. 1939. Synopsis of glauconitization in Recent Marine Sediments, Bulletin of American Association of Petroleum Geologists, Vol. 23, Part 1.

Van Andel. 1967. The Orinoco Delta. Journal of Sedimentary Petrology, Vol. 37, p. 297-310.

Van Wagoner, J., Mitchum, R., Campion, K. and Rahmanian, V. 1990. Siliciclastic Sequence Stratigraphy in Well Logs, Cores and Outcrop: Concepts for High Resolution Correlation of Time and Facies. American Association of Petroleum Geologists Methods in Exploration Series, Tulsa, Vol. 7, p. 55.

Walker, R. and Bergman, K. 1993 Shannon Sandstone in Wyoming: A Shelf-Ridge Complex Reinterpreted As Lowstand Shoreface Deposits. Journal of Sedimentary Petrology, Vol. 63, No. 5, p. 839-851.

Watkins, C., Metters, S., Fenton, J., Menshawy, Z., Ahmed, A. and Yule, J. 2002. The Sedimentology and Stratigraphic Framework of the Bahariya Formation, Western Desert, Egypt. American Association of Petroleum Geologists International meeting, Cairo, Egypt (Abstract Volume unpaginated).

Wehr, F., Youle, J. and Pemberton, G. 2002. Sequence Stratigraphy and Sedimentology of the Bahariya Formation, Khalda Concession, Western Desert, Egypt. American Association of Petroleum Geologists, International meeting, Cairo, Egypt, (Abstract Volume unpaginated).

Weimer, R., Howard, J. and Lindsay, D. 1982. Tidal Flats and Associated Tidal Channels, *In*: Scholle, P. and Spearing, D. (eds.). Sandstone Depositional Environments, The American Association of Petroleum Geologists Tulsa, Oklahoma 74101, USA, p. 191-245.

APPENDIX A: CORE LOGS

LEGEND

LITHOLOGIES

Silty Sandstone	Glaucony Rich Silty Sandstone	Green Mudstone
Carbonaceous Shale	Organic Rich Sandstone	Limestone
Shale	Clean Sandstone	*Helminthopsis* Dominated Silty Sandstone
Rooted Green Mudstone	Laminated Muddy Sandstone	Lost Core

CONTACTS

Sharp	Erosional	Firmground

PHYSICAL STRUCTURES

Current Ripples	Oscillatory Ripples	Climbing Ripples
Planar Bedding	Low Angle Bedding	Flaser Bedding
Wavy Parallel Bedding	Convolute Bedding	Sysaeresis Cracks

LITHOLOGIC ACCESSORIES

Pebbles/Granules	Sid Siderite	Gl Glauconite
Py Pyrite	Fe Ferruginous	Rip Up Clasts
Coal Fragment	Wd Wood Fragments	

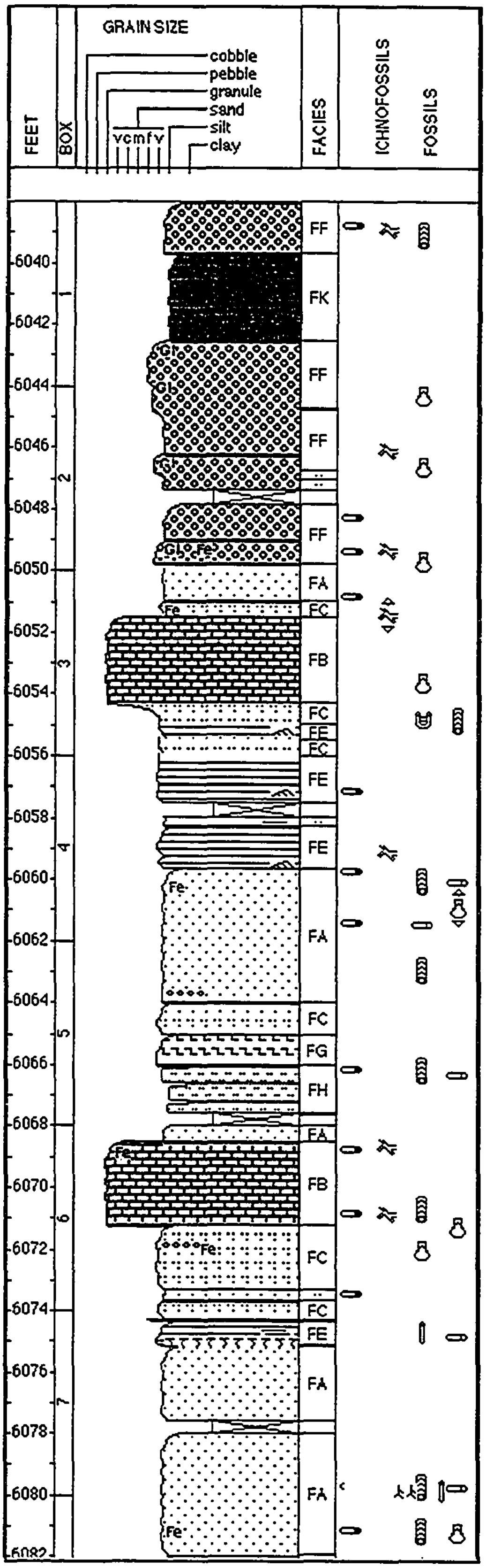
TRACE FOSSILS

Rootlets	*Skolithos*	*Planolites*
Palaeophycus	*Diplocraterion*	*Arenicolites*
Rhizocorallium	*Bergaueria*	*Asterosoma*
Thalassinoides	*Chondrites*	*Teichichnus*
Helminthopsis		

FOSSILS

Fish Remains	Cephalopods	Gastropods
Palecypods	Bone Fragments	

Kenz 7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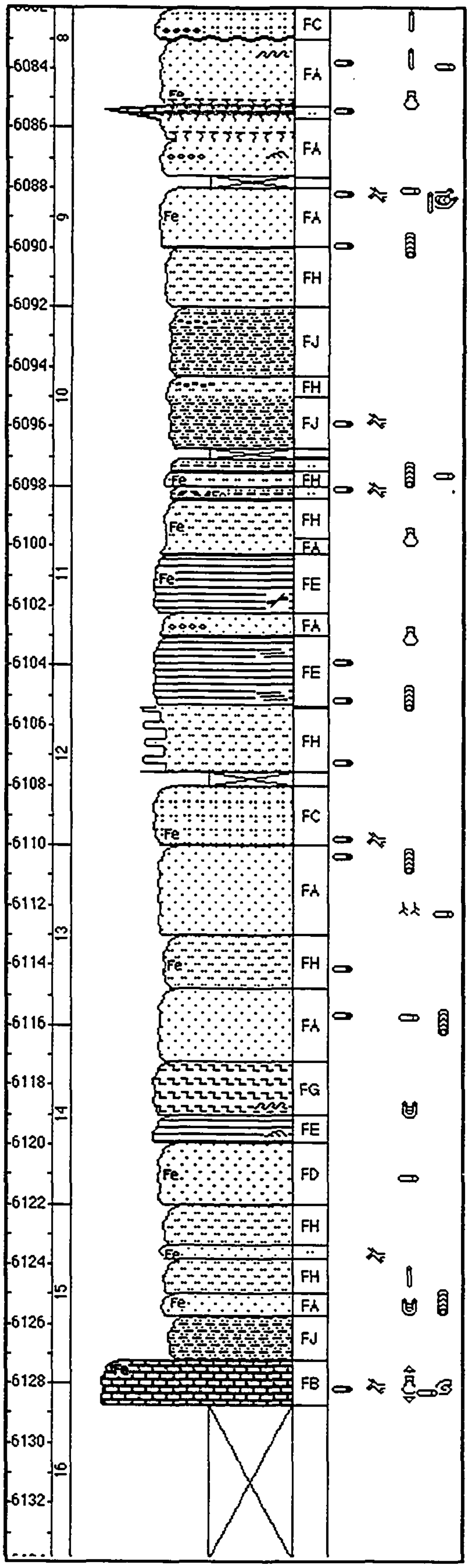

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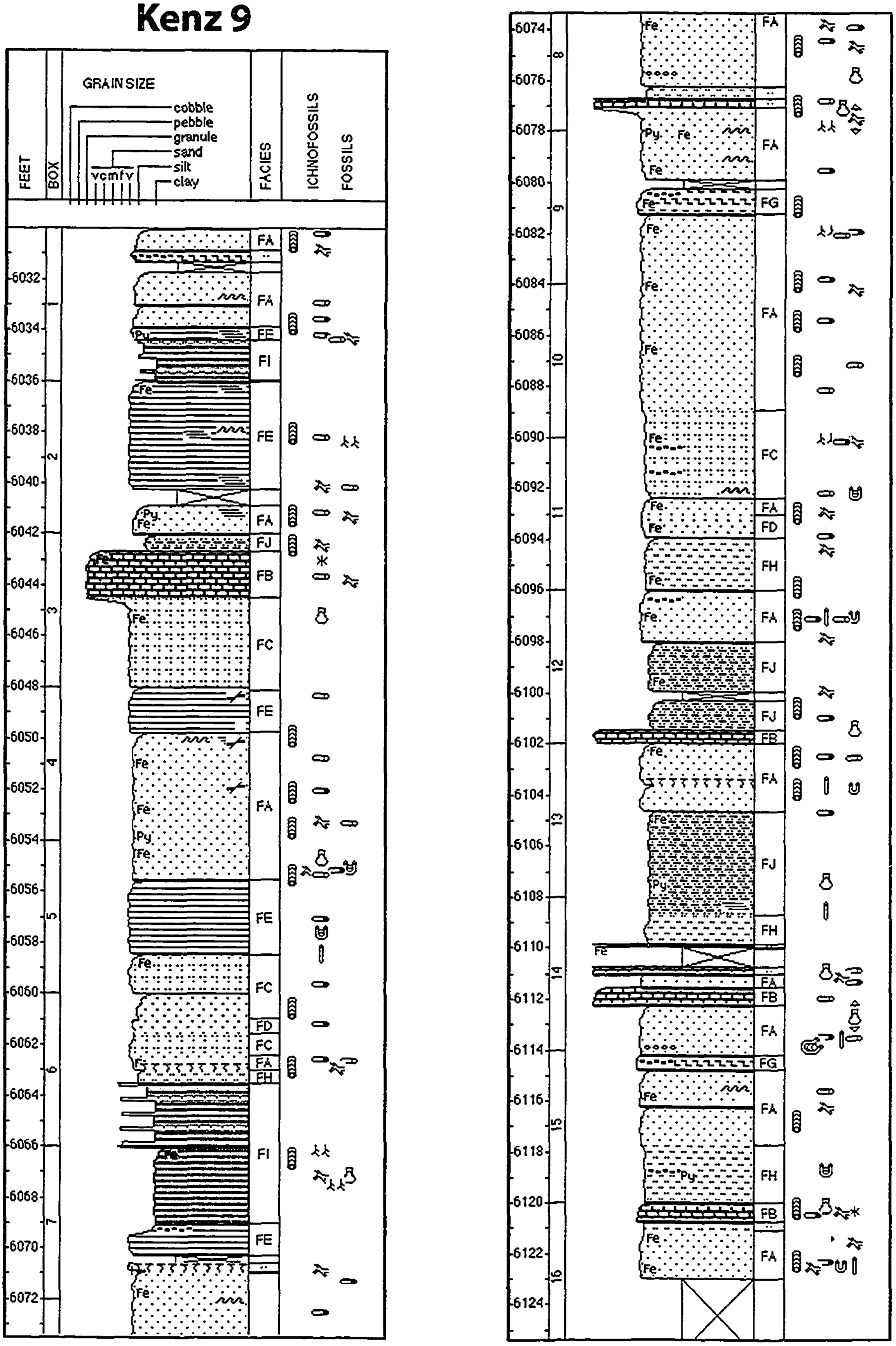
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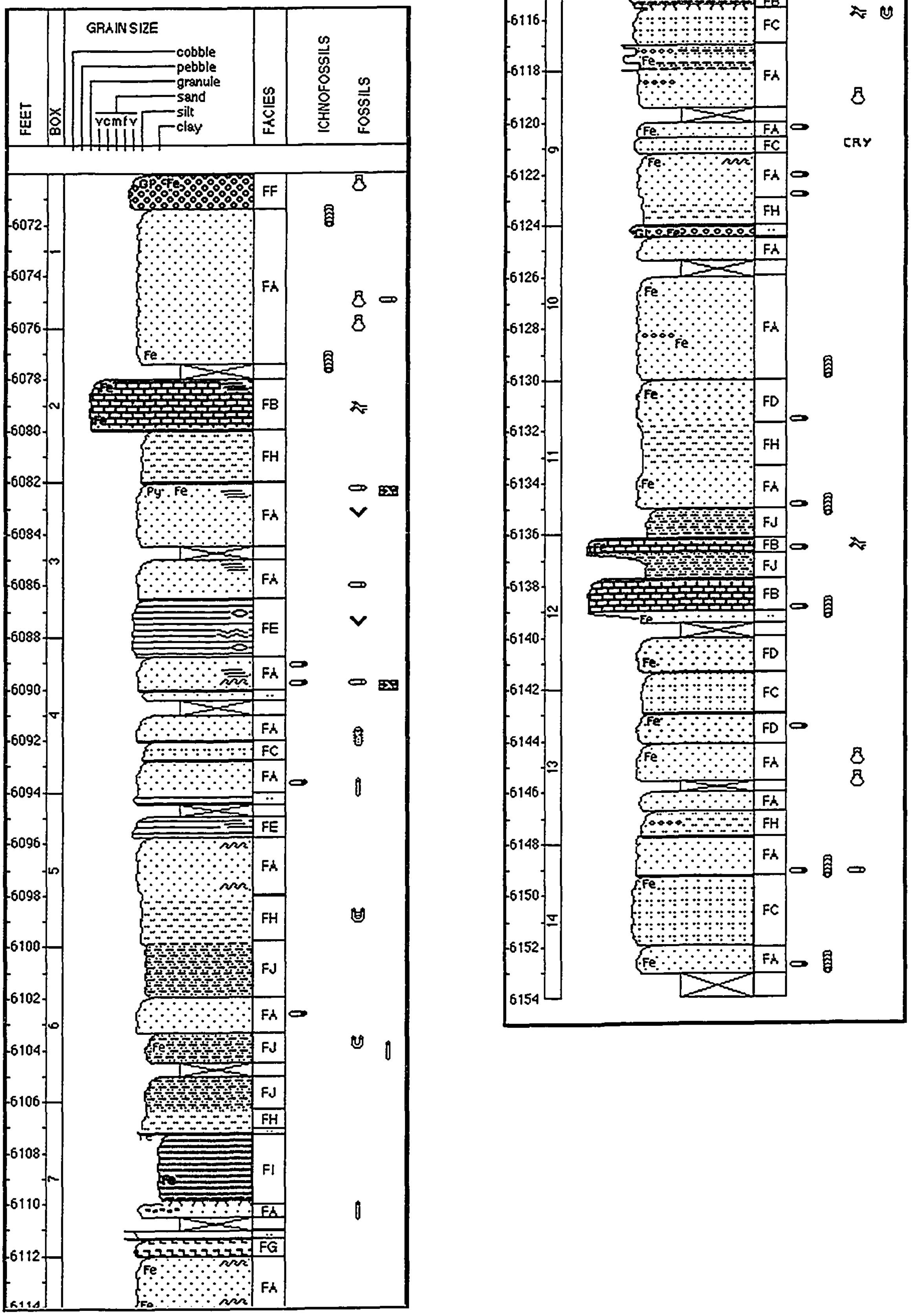
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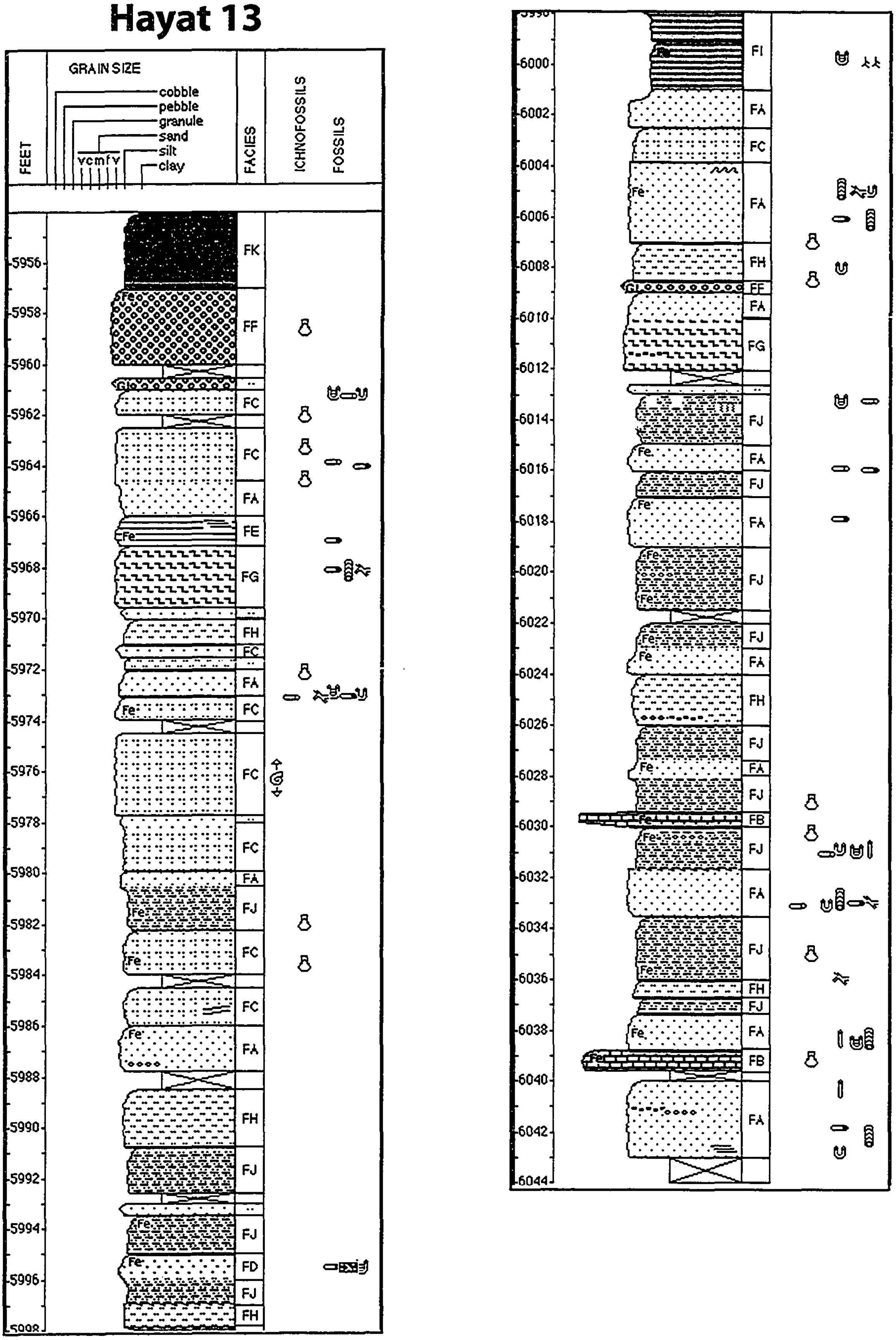
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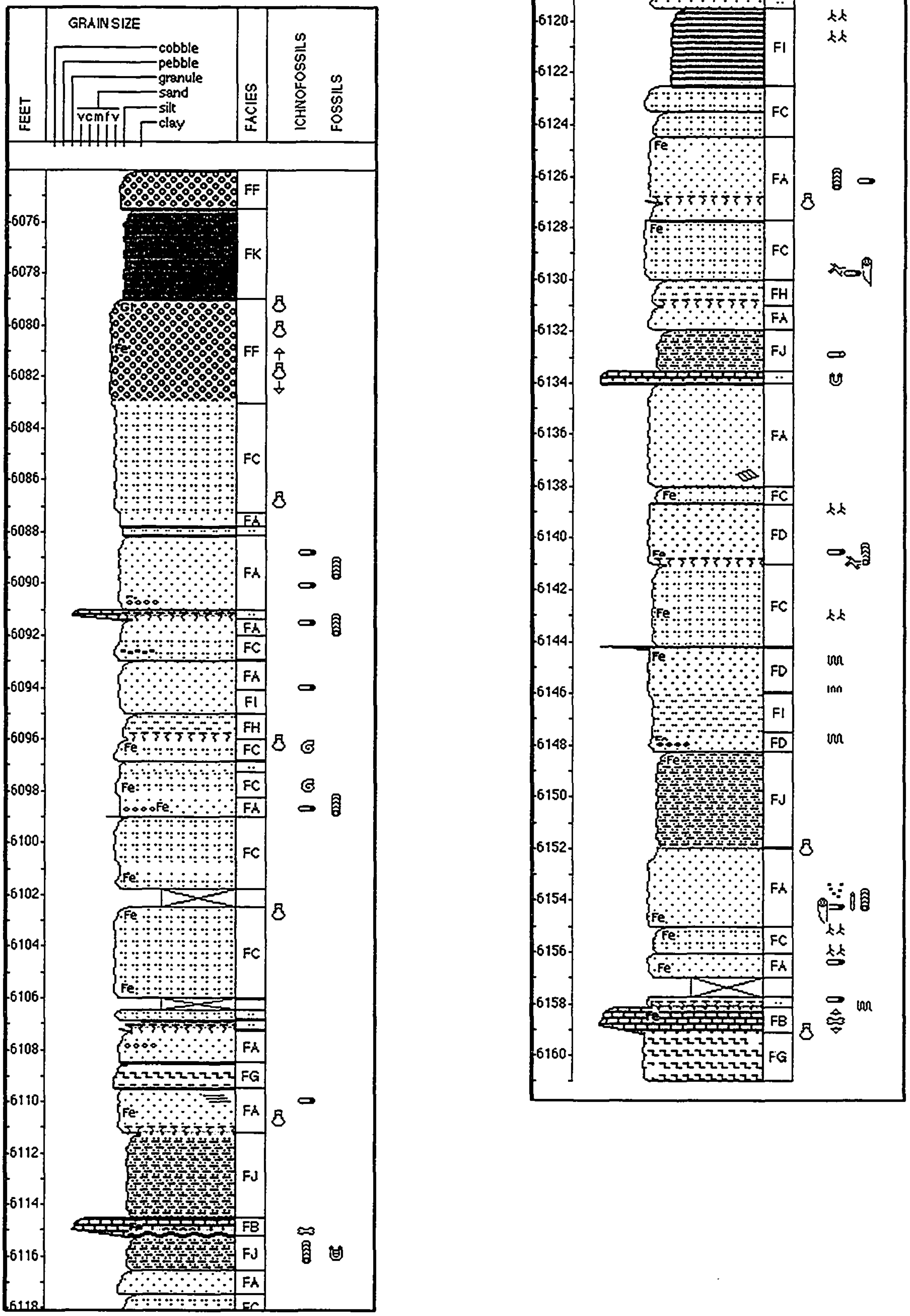
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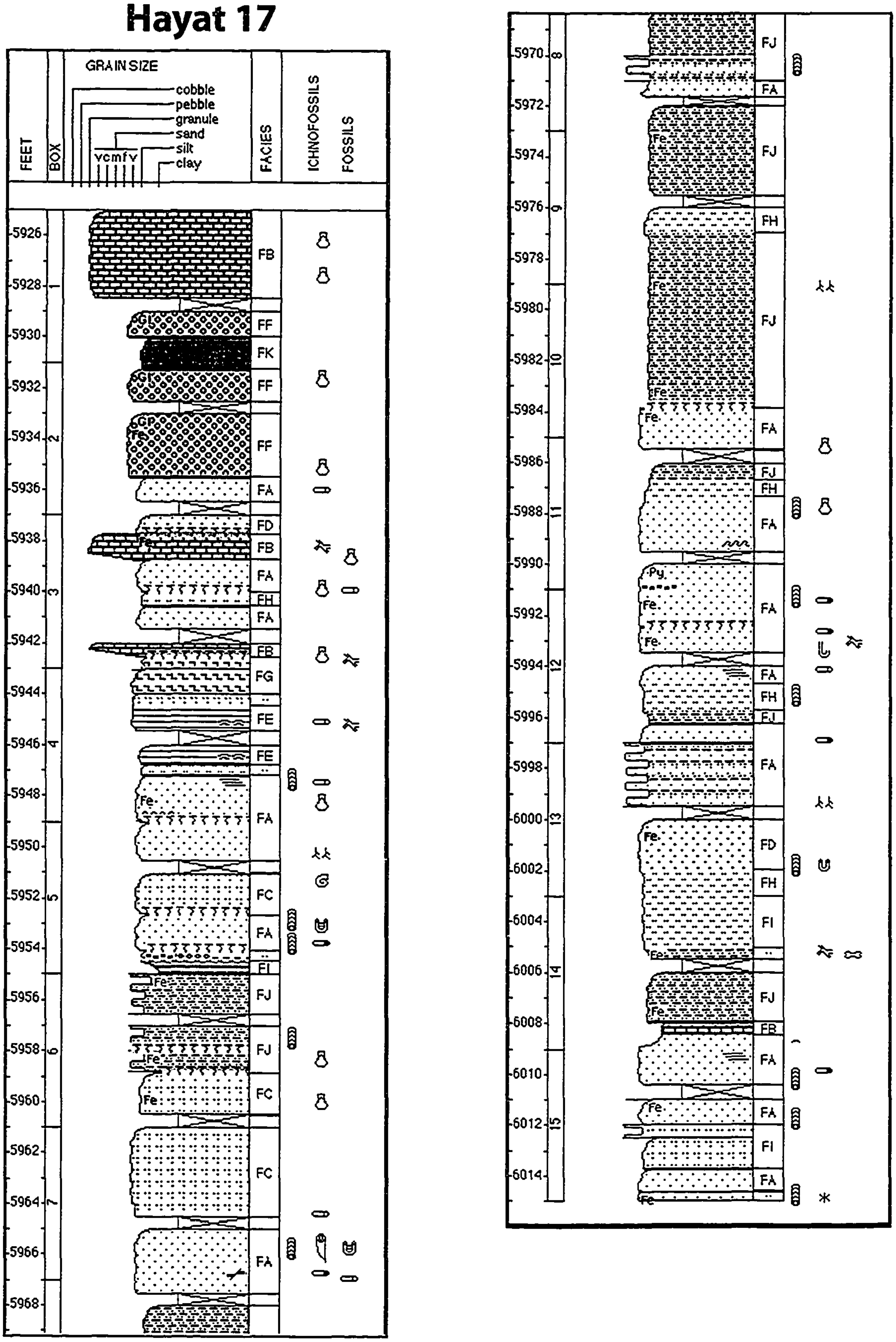
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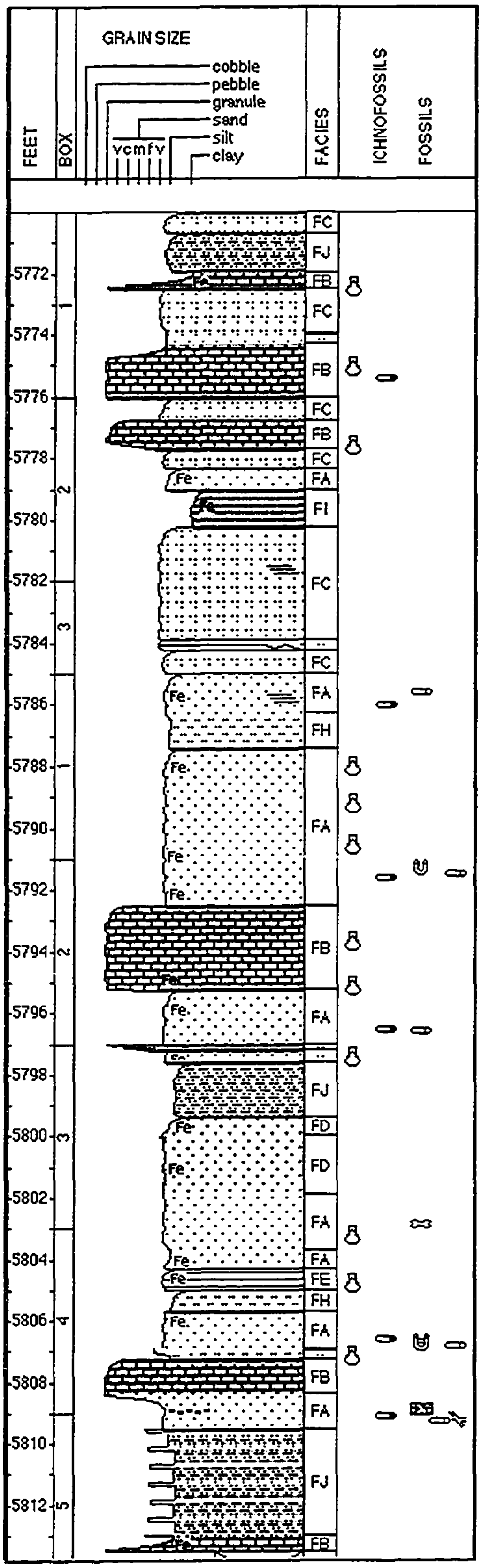
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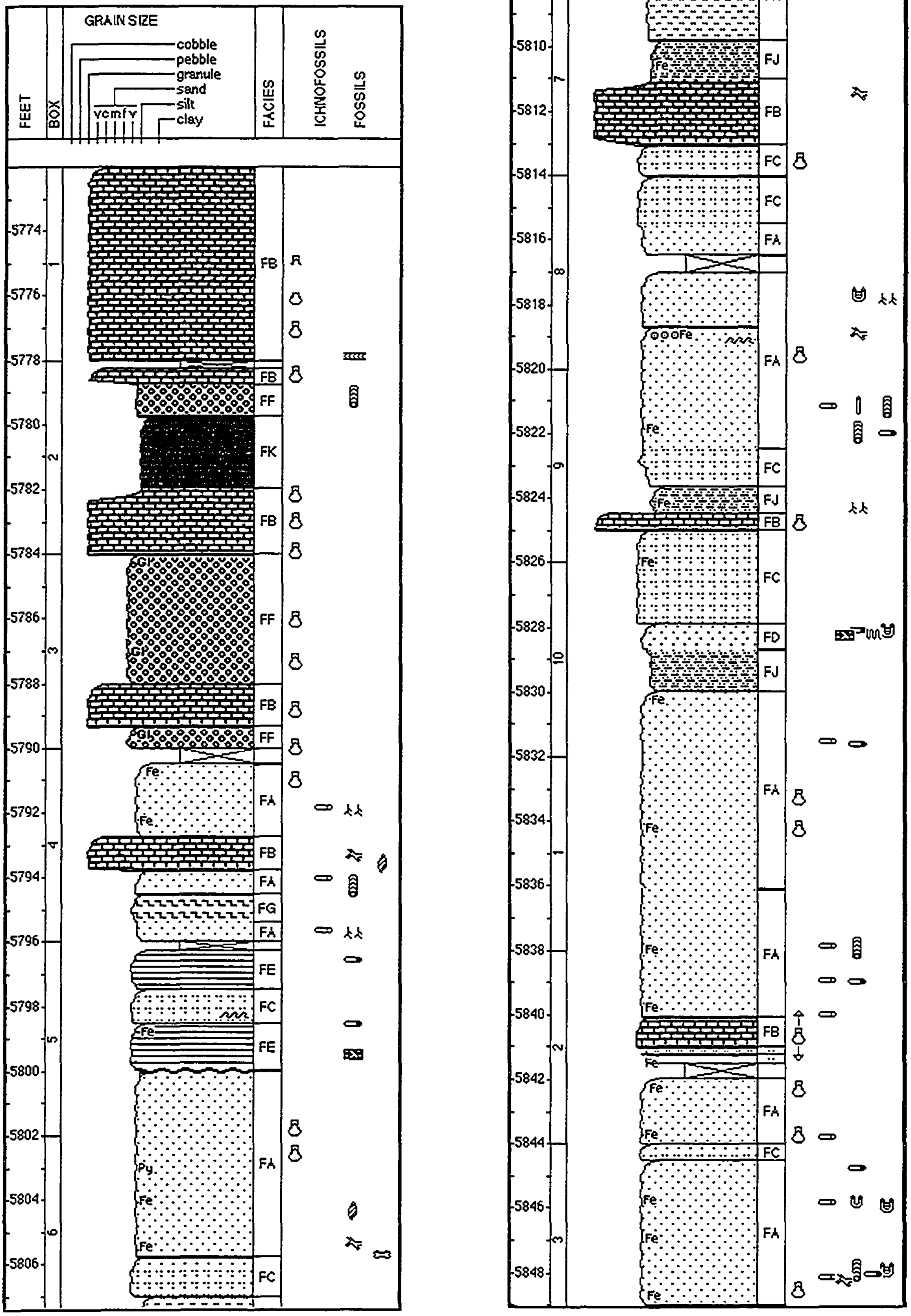
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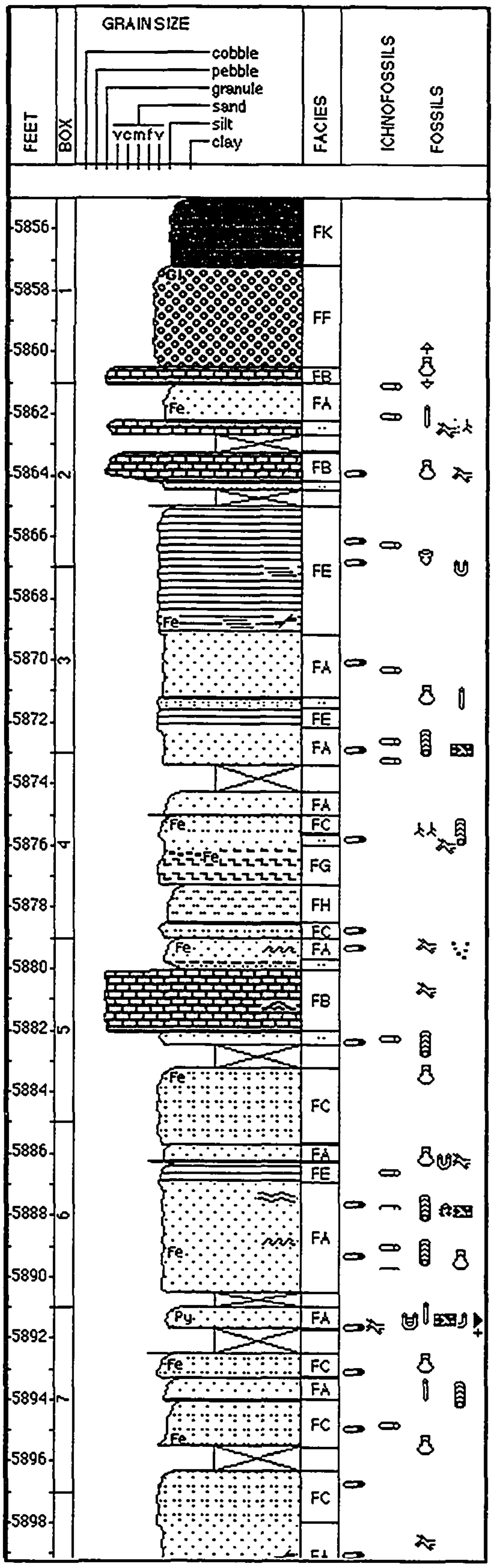
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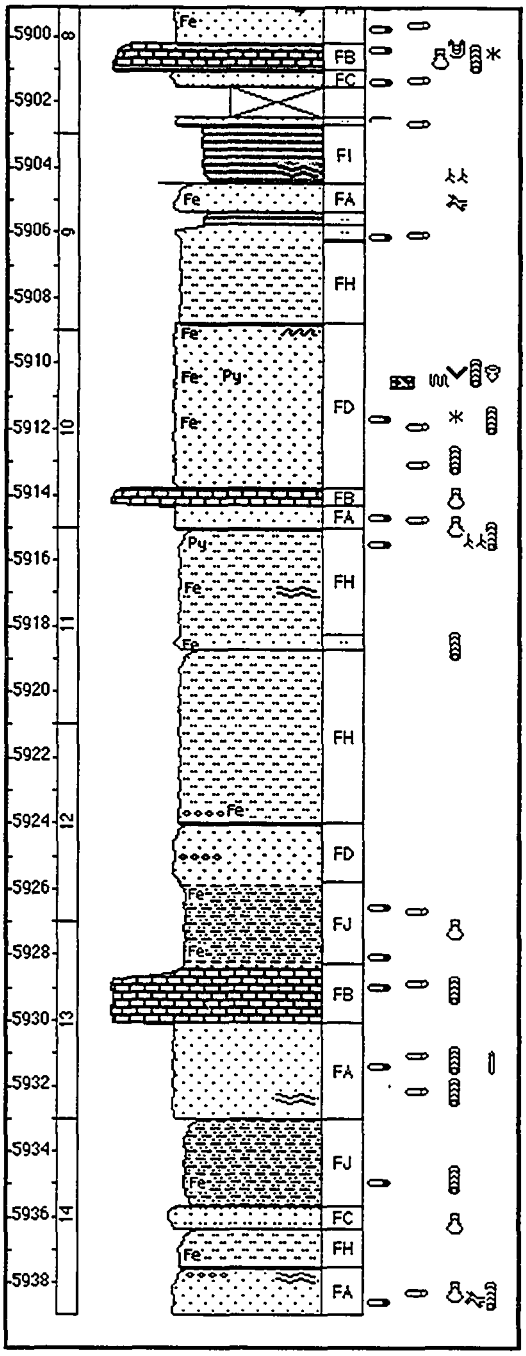

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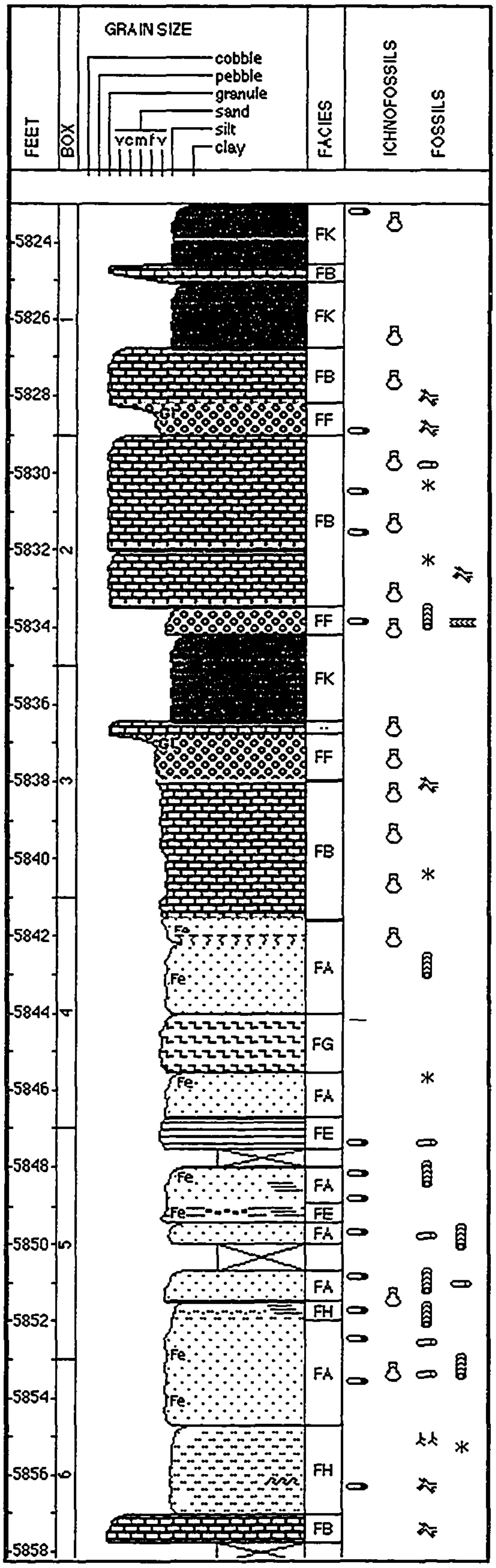
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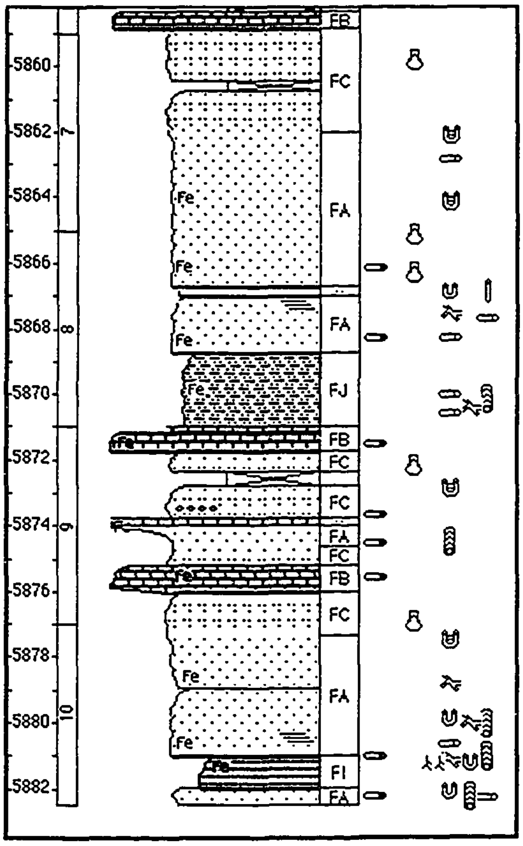
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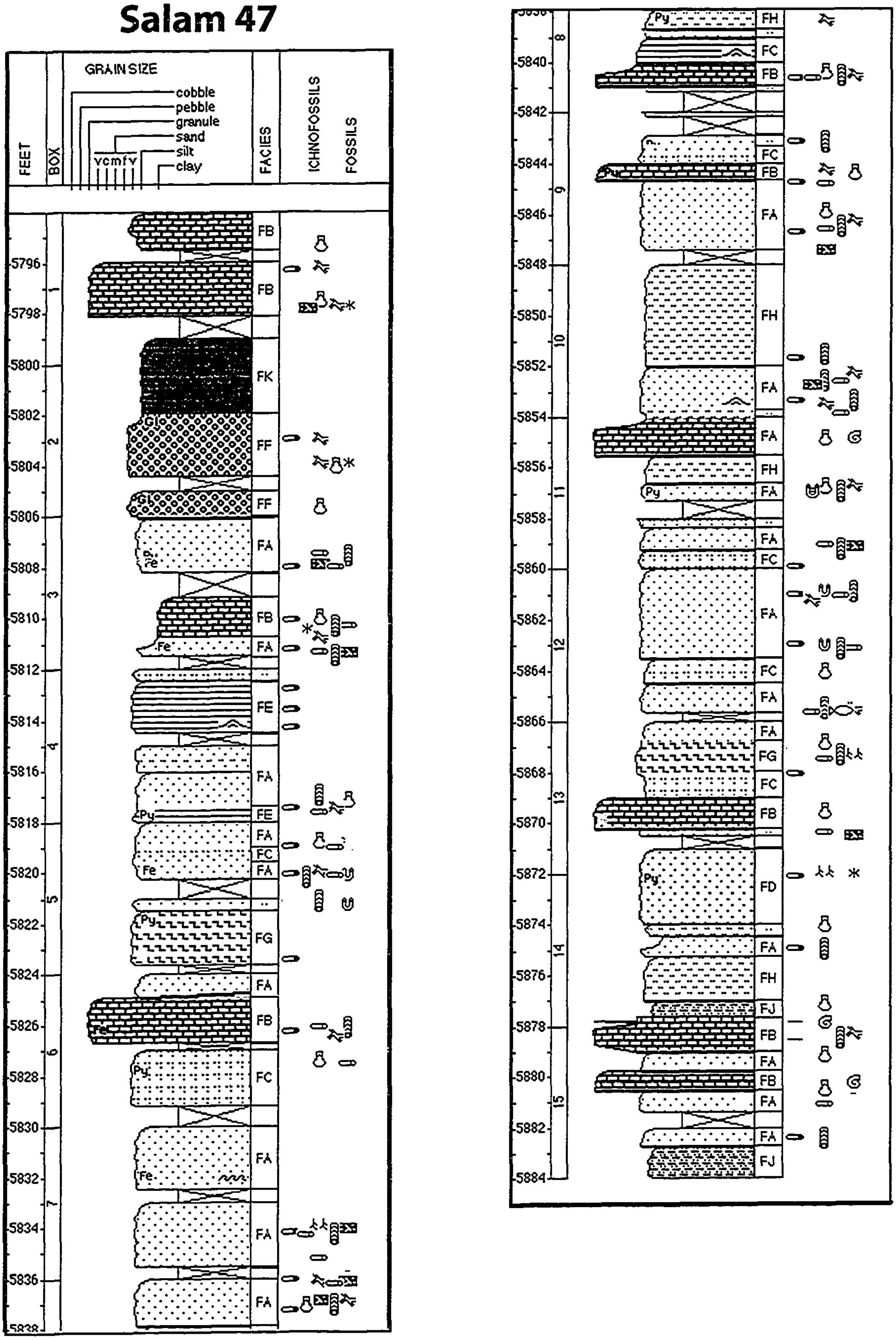
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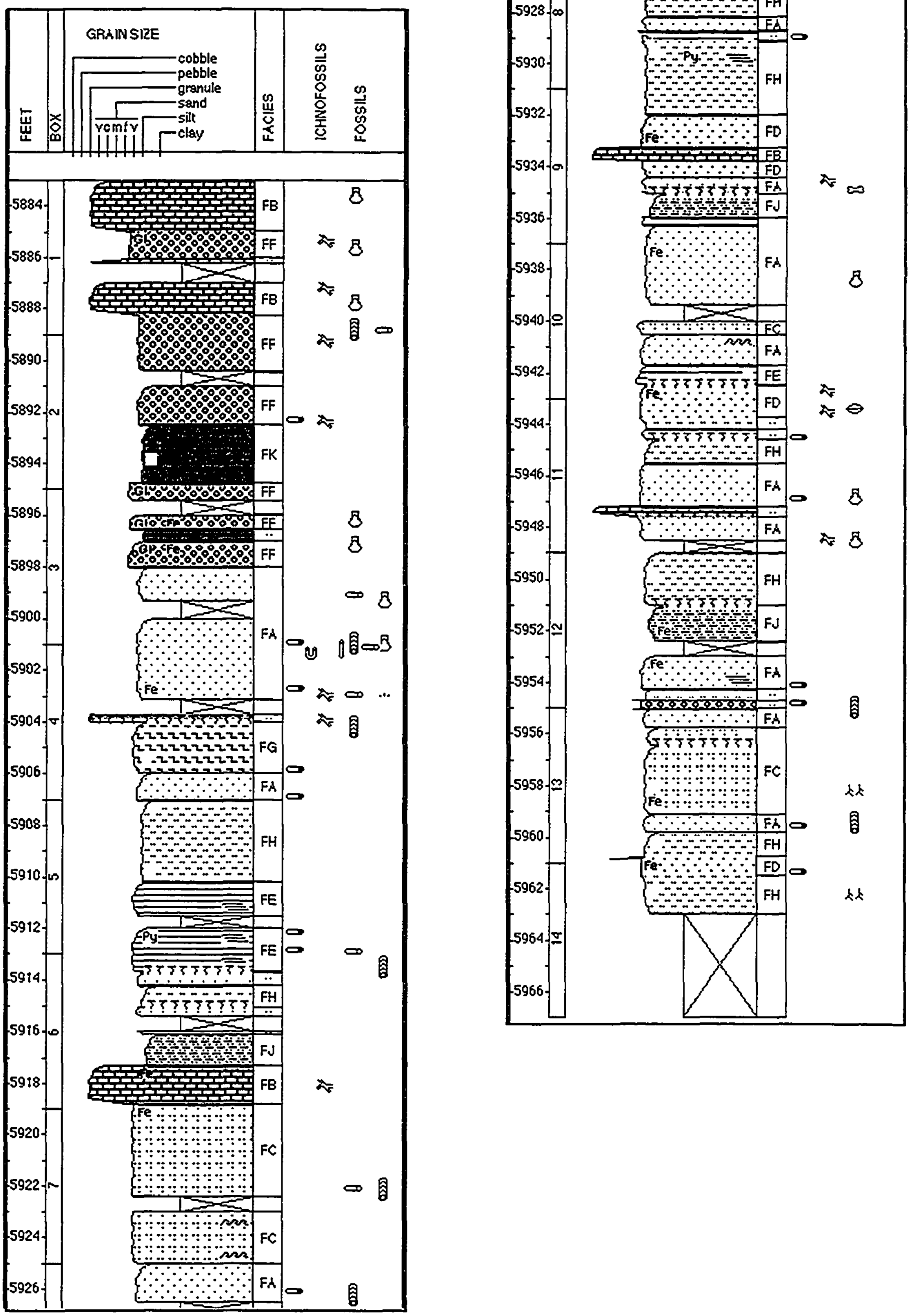
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APPENDIX B: PROBE DATA

Elemental Weight Percent										
Grain #	SiO_2	Al_2O_3	CaO	MgO	FeO	Na_2O	K_2O	Total	Estimated OH-	Comments
1	50.60	10.99	0.36	3.56	18.46	0.01	7.65	91.71	8.29	Salam17_5784 Core
1	51.00	11.21	0.35	3.71	18.25	0.06	7.70	92.28	7.73	Salam17_5784 Core
1	50.93	11.09	0.37	3.63	18.55	0.05	7.52	92.15	7.85	Salam17_5784 Core
1	52.07	11.35	0.35	3.69	18.13	0.04	7.38	93.00	7.00	Salam17_5784 Core
1	49.62	11.71	0.26	3.43	16.79	0.10	7.42	89.34	10.66	Salam17_5784 Rim
2	51.64	14.73	0.53	3.18	15.12	0.10	6.93	92.23	7.77	Salam17_5784 Core
2	48.68	14.79	0.53	2.86	15.76	0.14	6.66	89.41	10.59	Salam17_5784 Core
2	48.44	14.75	0.61	2.98	16.71	0.19	6.72	90.40	9.60	Salam17_5784 Core
3	51.01	14.96	0.47	3.22	14.80	0.09	6.47	91.01	8.99	Salam17_5784 Core
3	52.92	14.60	0.37	3.24	14.49	0.03	6.77	92.43	7.58	Salam17_5784 Core
4	51.89	13.77	0.60	3.34	15.89	0.01	6.79	92.37	7.64	Salam17_5784 Core
4	49.11	12.95	0.38	3.08	13.91	0.50	6.56	86.48	13.52	Salam17_5784 Core
5	50.91	11.60	0.27	3.71	18.03	0.11	7.49	92.11	7.89	Yasser6_5897 Core
5	51.82	11.99	0.32	3.73	17.45	0.07	7.39	92.78	7.22	Yasser6_5897 Core
5	51.18	11.91	0.32	3.60	17.52	0.18	7.35	92.05	7.95	Yasser6_5897 Core
5	50.43	11.83	0.38	3.63	17.70	0.10	7.39	91.45	8.55	Yasser6_5897 Core
6	48.40	13.05	0.31	3.55	18.17	0.13	7.04	90.66	9.35	Yasser6_5897 Core
6	49.22	13.60	0.33	3.64	17.86	0.17	7.13	91.94	8.06	Yasser6_5897 Core
6	48.60	13.20	0.39	3.62	18.45	0.14	7.08	91.47	8.53	Yasser6_5897 Core
6	47.56	13.15	0.41	3.77	19.60	0.12	6.66	91.26	8.74	Yasser6_5897 Core
6	44.19	11.63	0.14	3.89	20.71	0.37	5.86	86.79	13.21	Yasser6_5897 Rim
7	50.12	14.21	0.39	3.39	16.40	0.17	7.09	91.78	8.23	Yasser6_5897 Core
7	51.12	14.68	0.28	3.51	15.85	0.09	7.21	92.73	7.27	Yasser6_5897 Core
7	50.89	14.54	0.32	3.49	16.49	0.18	6.92	92.83	7.18	Yasser6_5897 Core
8	50.28	12.10	0.37	3.85	16.92	0.01	7.38	91.00	9.00	Yasser6_5897 Core
8	50.93	11.73	0.35	3.92	17.28	0.12	7.48	91.81	8.19	Yasser6_5897 Core
8	51.56	11.64	0.36	3.90	17.44	0.10	7.30	92.31	7.69	Yasser6_5897 Core
8	51.53	11.52	0.36	3.86	17.54	0.08	7.37	92.26	7.74	Yasser6_5897 Core
8	49.54	10.66	0.18	3.85	16.99	0.18	7.26	88.65	11.35	Yasser6_5897 Rim
9	48.99	11.79	0.35	3.89	18.28	0.13	7.46	90.90	9.10	Yasser6_5897 Core
9	49.13	12.47	0.32	3.82	18.62	0.17	7.13	91.66	8.34	Yasser6_5897 Core
9	47.07	12.73	0.40	4.19	19.52	0.15	6.69	90.74	9.26	Yasser6_5897 Core
9	45.47	13.66	0.41	4.17	20.97	0.09	6.02	90.78	9.22	Yasser6_5897 Core
9	47.12	12.23	0.42	4.07	19.94	0.09	6.62	90.49	9.51	Yasser6_5897 Rim
10	50.49	15.45	0.46	3.23	14.54	0.12	6.51	90.79	9.21	Yasser6_5833 Core
10	51.10	15.75	0.56	3.50	14.84	0.12	6.78	92.65	7.35	Yasser6_5833 Core
10	47.66	15.01	0.27	3.04	13.40	0.18	6.45	86.01	13.90	Yasser6_5833 Rim
11	52.45	13.26	0.38	3.52	16.84	0.07	7.02	93.54	6.46	Yasser6_5855 Core
11	50.22	12.89	0.35	3.49	17.78	0.08	6.96	91.78	8.22	Yasser6_5855 Core
11	48.04	14.17	0.39	3.63	17.85	0.02	6.39	90.49	9.51	Yasser6_5855 Core
11	45.53	14.89	0.45	3.69	19.98	0.07	5.47	90.08	9.92	Yasser6_5855 Core
12	50.72	16.99	0.64	2.95	13.97	0.04	6.55	91.88	8.13	Salam17_5833 Core
12	49.75	17.21	0.27	2.81	12.24	0.14	6.66	89.09	10.91	Salam17_5833 Rim
13	54.96	20.01	0.72	3.36	10.48	0.09	6.26	95.88	4.12	Salam17_5833 Core

Grain #	SiO2	Al2O3	CaO	MgO	FeO	Na2O	K2O	Total	Estimated OH-	Comments
13	51.89	19.47	0.73	3.18	10.00	0.00	6.12	91.39	8.61	Salam17_5833 Rim
14	49.98	18.86	0.23	2.54	8.78	0.12	6.24	86.76	13.25	Salam17_5833 Rim
15	47.98	19.20	0.71	2.65	9.83	0.13	6.33	86.84	13.16	Salam17_5833 Core
15	49.23	17.89	0.27	2.73	9.64	0.08	6.22	86.05	13.95	Salam17_5833 Rim
16	52.42	19.13	0.81	3.09	10.26	0.09	6.48	92.26	7.74	Salam17_5833 Core
18	47.35	14.57	0.09	3.11	15.88	0.24	5.66	86.90	13.10	Salam17_5848 Core
18	45.78	15.27	0.09	3.11	15.41	0.27	5.11	85.04	14.96	Salam17_5848 Core
19	51.60	11.33	0.25	3.98	17.13	0.12	7.82	92.23	7.77	Yasser6_5886 Core
19	51.98	11.10	0.29	4.10	17.16	0.06	7.79	92.49	7.51	Yasser6_5886 Core
19	51.75	11.48	0.27	4.05	17.26	0.10	7.90	92.81	7.19	Yasser6_5886 Core
19	52.04	11.52	0.36	4.14	17.04	0.13	7.73	92.94	7.06	Yasser6_5886 Core
19	52.13	11.81	0.31	4.02	16.58	0.17	7.69	92.72	7.28	Yasser6_5886 Rim
20	51.75	12.17	0.53	4.13	16.55	0.05	7.61	92.78	7.22	Yasser6_5886 Core
20	51.91	12.83	0.60	4.01	16.15	0.07	7.24	92.81	7.19	Yasser6_5886 Core
20	51.84	12.47	0.45	4.22	16.30	0.09	7.51	92.88	7.12	Yasser6_5886 Core
20	51.90	13.23	0.63	3.92	15.69	0.10	7.24	92.71	7.29	Yasser6_5886 Core
20	51.24	13.49	1.03	3.88	14.48	0.08	7.02	91.20	8.80	Yasser6_5886 Rim
21	52.01	12.99	0.41	3.94	15.77	0.06	7.57	92.74	7.26	Yasser6_5886 Core
21	52.70	12.76	0.44	4.01	16.08	0.01	7.35	93.53	6.47	Yasser6_5886 Core
21	52.42	13.33	0.43	3.83	15.47	0.09	7.25	92.81	7.19	Yasser6_5886 Core
21	52.10	13.23	0.38	3.87	15.70	0.10	7.10	92.48	7.52	Yasser6_5886 Core
21	49.82	12.01	0.15	3.67	15.36	0.01	7.27	88.38	11.62	Yasser6_5886 Rim
22	52.27	12.23	0.32	3.89	16.18	0.07	7.33	92.30	7.70	Yasser6_5886 Core
22	52.30	12.06	0.42	4.17	16.57	0.07	7.57	93.16	6.85	Yasser6_5886 Core
22	52.69	12.01	0.37	4.03	16.58	0.11	7.55	93.43	6.57	Yasser6_5886 Core
22	52.47	11.84	0.47	4.12	16.37	0.11	7.49	92.86	7.14	Yasser6_5886 Core
22	51.24	11.77	0.30	3.82	15.79	0.06	7.47	90.45	9.55	Yasser6_5886 Rim
23	51.99	12.62	0.34	4.08	16.02	0.08	7.46	92.59	7.41	Yasser6_5886 Core
23	52.60	12.30	0.33	4.25	16.19	0.10	7.45	93.23	6.77	Yasser6_5886 Core
23	52.68	12.99	0.48	3.91	15.68	0.06	7.41	93.21	6.79	Yasser6_5886 Core
23	52.91	12.74	0.39	3.82	16.02	0.12	7.33	93.34	6.66	Yasser6_5886 Core