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Correlation of the major late Jurassic – early Tertiary low- and highstand cycles of south-west Egypt and north-west Sudan

Abstract The mainly continental deposits of north-west Sudan and south-west Egypt have been correlated with coeval shallow marine and marine deposits in northern Egypt along a north–south running cross-section, based on surface and subsurface data. The palaeodepth curve of northern Egypt illustrates the gradual seal-level rise, reaching its maximum during the Late Cretaceous with conspicuous advances during the Aptian and late Cenomanian. A general highstand is also recorded during the Campanian–Maastrichtian in north-west Sudan. A detailed facies correlation is given for the Aptian and late Cenomanian highstand in western Egypt. The correlation of the Cenomanian Bahariya and Maghrabi formations displays short-term relative sea-level fluctuations. The interpretation illustrates the extensiveness of related erosional processes in the hinterland, partly intensified by temporarily uplift of the Uweinat–Aswan High in the south. Regional uplift and constant erosion took place in south-west Egypt during Coniacian and Santonian times. The regional stratigraphic gaps and uncertain interpretation of the Bahariya Uplift are induced by the influence of the Trans-African Lineament, especially during the Late Cretaceous. Lowstand fluvial sheet sandstones characterized by non-cyclic sequence development and high facies stability occur, especially in the Neocomian and early Turonian. During the Barremian and Albian, fluvial architecture changes to more cyclic fluvial sequences and increasing soil formation, due to increasing subsidence, more humid climatic conditions and the generally rising sea level, culminating in the extensive shallow marine Abu Ballas and Maghrabi formations.

Key words Cretaceous stratigraphy · Subsurface correlation · Low-/highstand cycles · Cratonic sheet sandstones · Regional unconformities · SW Egypt · NW Sudan

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Introduction

During the Cretaceous to Palaeogene, the intra-cratonic area of southern Egypt and northern Sudan was affected by several marine transgressions from northern directions. The early transgressive pulses within the siliciclastic succession of the southern Dakhla Basin are dated as Aptian and late Cenomanian. During Coniacian and Santonian times, non-deposition prevailed in south-west Egypt. The most widespread transgression in the Late Cretaceous started during the Campanian and, although interrupted by minor regressive phases, lasted until the early Eocene. During this transgression phase, which affected northern and southern Egypt, predominantly shales, marls and carbonates were deposited over wide areas.

Micro- and macro-floras have contributed significantly to the subdivision and interpretation of the widespread continental Cretaceous siliciclastic sediments of Egypt and northern Sudan (Klitzsch and Lejal-Nicol, 1984; Lejal-Nicol, 1987; Klitzsch and Wycisk, 1987). The northern Egyptian Cretaceous strata are largely marine, although a strong input of terrestrially derived palynomorphs occurs up to the Cenomanian (Abdel-Kireem et al., 1993). Towards the south, non-marine sediments become increasingly important. In the Dakhla Basin the mainly fluvial Six Hills and Sabaya formations have yielded Barremian and Albian–Cenomanian palynoflora, respectively. The shales of the marine Abu Ballas and Maghrabi formations have been palynologically dated as Aptian and late Cenomanian. A comprehensive documentation of palynological data of the area under discussion has been published by Schrank (1991; 1992). A revision of some Western Desert palynomorph records shows a relatively complete Cretaceous sequence in the Dakhla Basin and a reduced sequence at the Kharga Uplift, where the pre-Aptian Six Hills Formation is directly overlain by the late Cenomanian Maghrabi Formation.

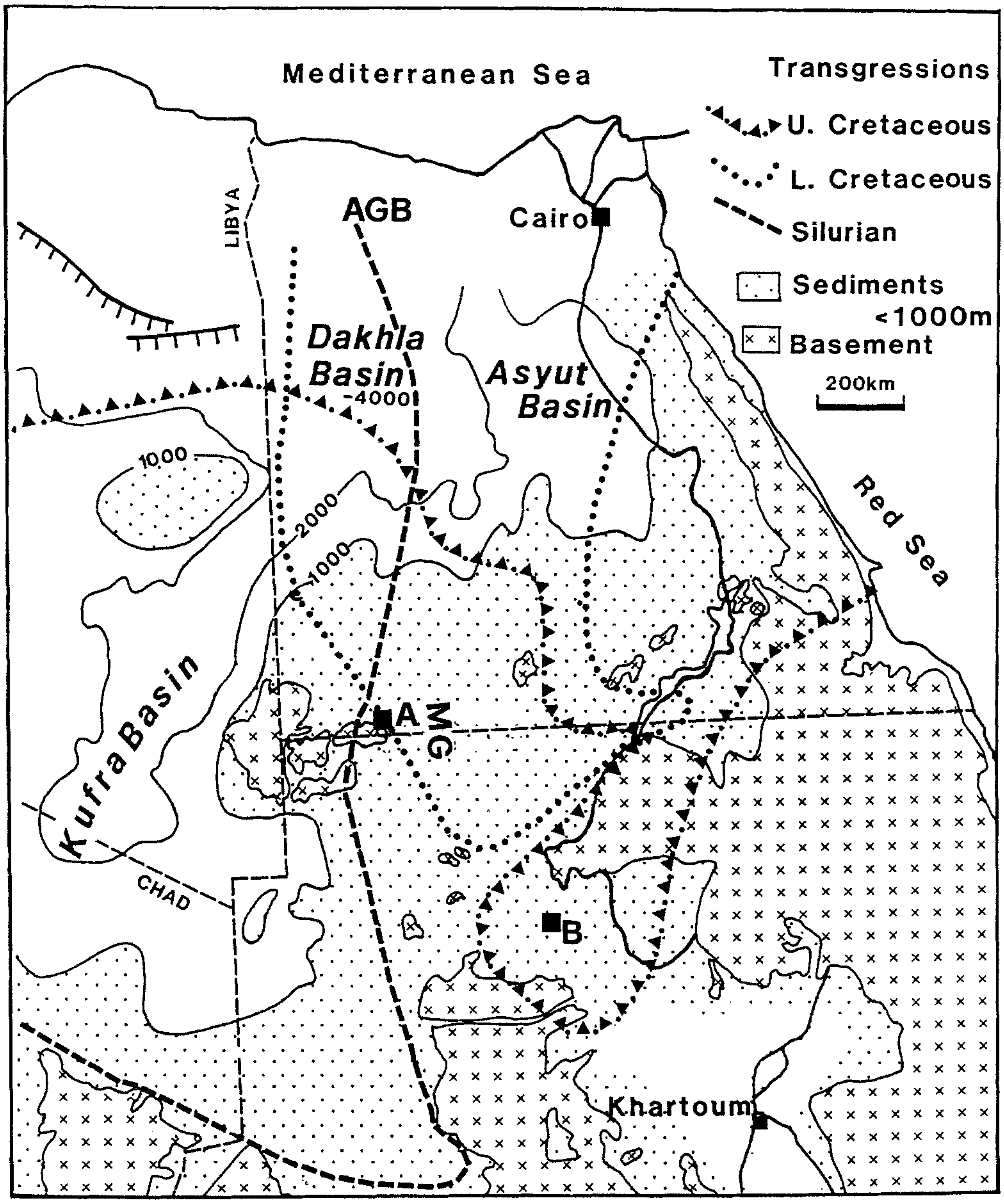

Fig. 1. Distribution of sediment and basement areas on the East Saharan Craton (north-east Africa), including maximum extension of Palaeozoic (Silurian) and Mesozoic (Early and Late Cretaceous) transgressions based on Klitzsch and Wycisk (1987). The indicated area of sediment thickness < 1 000 m includes the complete Phanerozoic stratigrahic sucession. AGB = Abu Gharadig Basin; MG = Misaha Graben. Reference sections: A = Gebel Kamil (Barremian – Turonian); and B = Gebel Abyad (Turonian – Early Eocene).

Palaeogeographical setting

The palaeogeographical setting for the area under discussion is given in Fig. 1. The map includes the configuration of basins and indicates the large areas of low sedimentary preservation potential at the exceptional broad margins of the depocentres, inundated by several transgressions. The main part of the study area belongs to the Dakhla Basin, including the south trending Misaha Graben and in parts the Assiut – Upper Nile Basin in the east, with the Kharga Uplift in between. The east – west oriented Uweinat – Bir Safsaf – Aswan Uplift, close to the Egyptian/Sudanese border, influences the depositional processes of the fluvial systems, as well as the facies distribution of the extended shallow marine intercalations during the Cretaceous. Comprehensive papers of the regional stratigraphy and sedimentology of the area under discussion have been published by Klitzsch et al. (1979), Barthel and Herrmann-Degen (1981), Klitzsch (1986), Hendriks et al. (1987), Klitzsch and Wycisk (1987), Hendriks (1988), Klitzsch and Squyres (1990), Wycisk et al. (1990), and Wycisk (1991; 1993).

A synopsis and general outline of the stratigraphy and facies of south-west Egypt and north-west Sudan is given in the facies – time diagram of Fig. 2. In the southern Dakhla Basin, fluvial sedimentation started during Late Jurassic and Early Cretaceous time with the Six Hills and Gilf Kebir formations. The Lower Cretaceous sheet sandstone in particular reflects the eustatic lowstand of the global sea-level curve. Broad areas of the southern Western Desert were covered by the advancing shallow epicontinental sea during the Aptian, documented by shallow marine highstand clastic sediments of the Abu

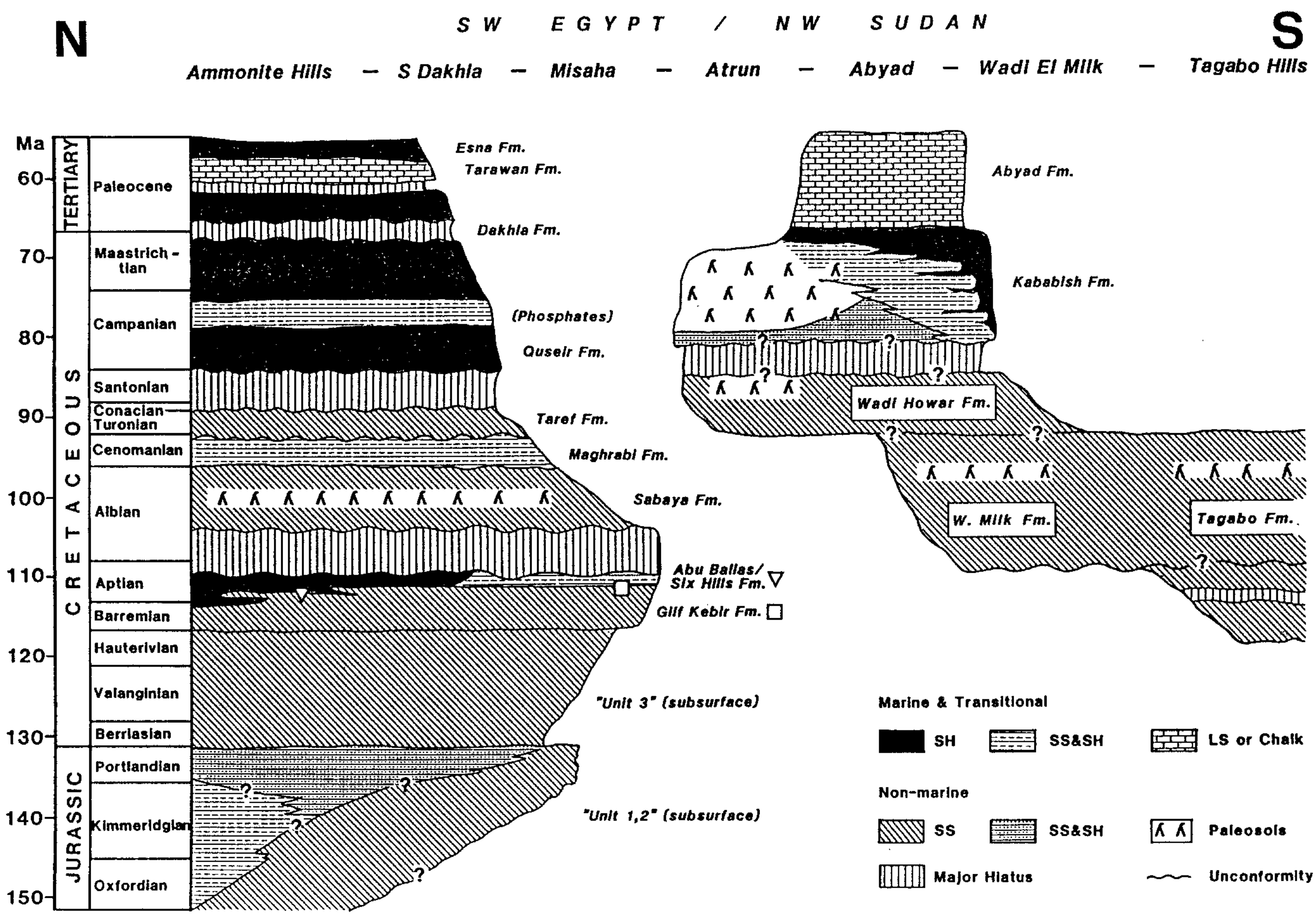

Fig. 2. Time–facies diagram of the Cretaceous of the southern Dakhla Basin (south-west Egypt) and Abyad Basin (north-west Sudan) along a north–south trending cross-section

Ballas Formation. The latter is overlain by the regressive fluvial and floodplain sediments of the Albian–Cenomanian Sabaya Formation. This succession can be linked to the fluvial deposits of the Tagabo and Wadi Milk formations in north-west Sudan. The tidal to estuarine sediments of the Maghrabi Formation reflect only a marginal marine influence of the Cenomanian transgression in the southern Dakhla Basin. Here, subsequent fluvial sedimentation of the Taref Formation took place during Turonian time. This situation grades southward into north-west Sudan, indicated by the extended Wadi Howar Formation.

The environmental reconstruction suggests that during this period uncommon vast alluvial plains sloped northward from northern Sudan for hundreds of kilometres towards the Mediterranean Basin. Streams crossing the plain were mostly fairly small, shallow, straight, and their proximal parts also braided, due to the prevailing semi-arid conditions during the Early Cretaceous. The inter-channel areas were increasingly vegetated by plants as a result of the accelerating wet conditions towards the Late Cretaceous. The mineralogical maturity of the sandstones testifies to rigorous weathering and a long time span for fluvial recycling. Three alluvial plain sequences (the Six Hills, Sabaya and Taref formations), each several hundred metres thick, are separated by thin marine to marginal marine sediments deposited during extensive southward transgressions into Egypt and northern Sudan. It is remarkable that the development of the shallow marine depositional sequences is mainly controlled by: (a) rapidly progressing transgressions, flooding a relatively planar topographic relief with a very low slope; and (b) low subsidence and a negligible sediment supply of mainly clay-free sand. These controlling factors lead to incomplete depositional sequences of amalgamated sand bodies of nearshore and coastal low land successions on the craton. Different aspects of facies recognition of such shallow marine deposits and related sequence stratigraphic applications have been discussed in Wycisk (1992). A continent-wide correlation with emphasis on the non-marine Cretaceous illustrates impressively the extent of the continental portion of the Lower Cretaceous in north-east Africa and Arabia (Mateer et al., 1992).

The so called 'Nubian' lithofacies is characterized by spectacular stacked tabular cross-bedded sandstones and is widespread across North Africa. Former facies interpretations cover a broad spectrum from marine to a eolian depositional environments (see McKee, 1962). A detailed facies interpretation and stratigraphy of the fluvial sandstone sequences deposited mainly on vast

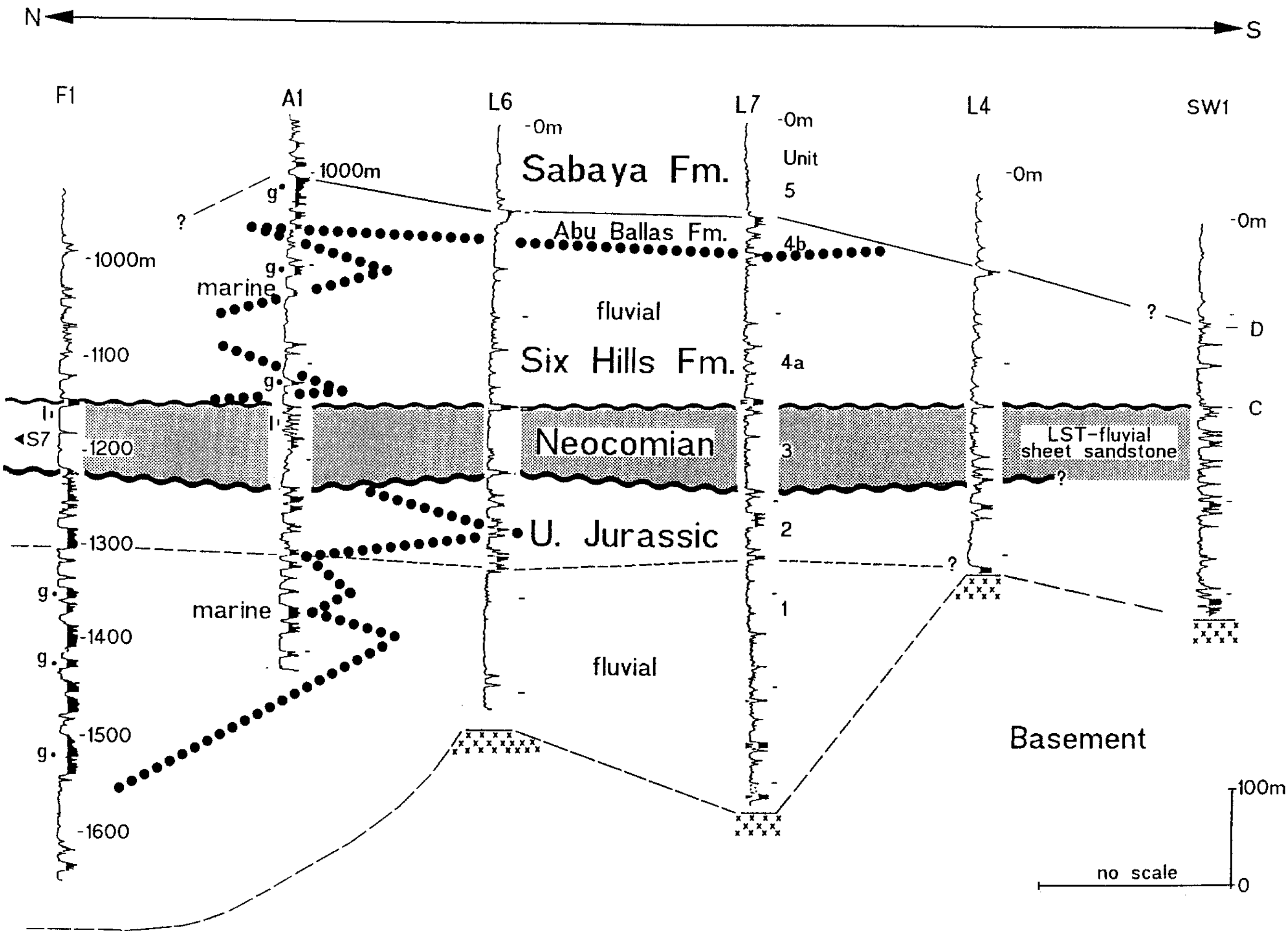

Fig. 3. Subsurface correlation of Late Jurassic and Early Cretaceous lithostratigraphic units based on Wycisk (1987). The conspicuous Neocomian sheet sandstone marks a global lowstand and can be traced for about nearly 800 km from the Misaha Graben (SW 1) in the south to the Dakhla Basin in the north (F 1). The dotted line indicates the approximate position of the shifting palaeo-coastline. Location of wells is given in Fig. 4

alluvial plains have been established since the work of Klitzsch et al. (1979).

The unique aspects of the uncommon fluvial facies compared with most published fluvial models are that the sequence is composed almost entirely of medium- to coarse-grained sandstones, made up of tabular sets of cross-stata 20–100 cm thick, with consistent northern dips. The stream channels were relatively straight, commonly 2–4 m deep and occupied by sand-wave bedforms. In areas of increasing subsidence sandy kaolinitic overbank deposits <2 m thick were deposited, containing small root structures and pedogenic features (Harms, 1979). Comparable palaeogeographical situations are described by Lorenz (1987) for the Messak Sandstone (Late Jurassic–Early Cretaceous) of south-west Libya. Here, much of the Messak was explained adequately using braided river models as well as high sinuousity fluvial systems with related lacustrine and paludal environments.

Late Jurassic–Turonian siliciclastic cycle

Late Jurassic highstand

Jurassic siliciclastics in south and west Egypt give way to carbonates towards the centre of the Mediterranean Basin, with some evaporites to the north and east. The progression of the coast is of decreasing clastic supply with transgression of carbonates. By the late Oxfordian, sandstone deposition had nearly ended and limestone covered most of the eastern Mediterranean Basin (Keeley et al., 1990; Keeley and Wallis, 1991). At the southern rim of the basin in Egypt and Israel there is a deltaic–paralic–lagoonal section with sands derived from the shield. Fluvial sandstones grade northward to a shaly coal-bearing facies, which in turn grades north to marine limestones.

The Late Jurassic shallow marine and coeval continental depositional sequences have been traced towards the south by surface interpretation into the southern Dakhla Basin, via the Misaha Graben into the northern Sudan (Wycisk, 1987; 1991). Based on the latter results, log data from deep water wells in the Misaha Graben are used for a north–south running correlation in Fig. 3. This correlation includes the time-equivalent parts of the wells Ammonite 1 (A 1) and Foram 1 (F 1) near the centre of the Dakhla Basin, as well as coeval sucessions from the

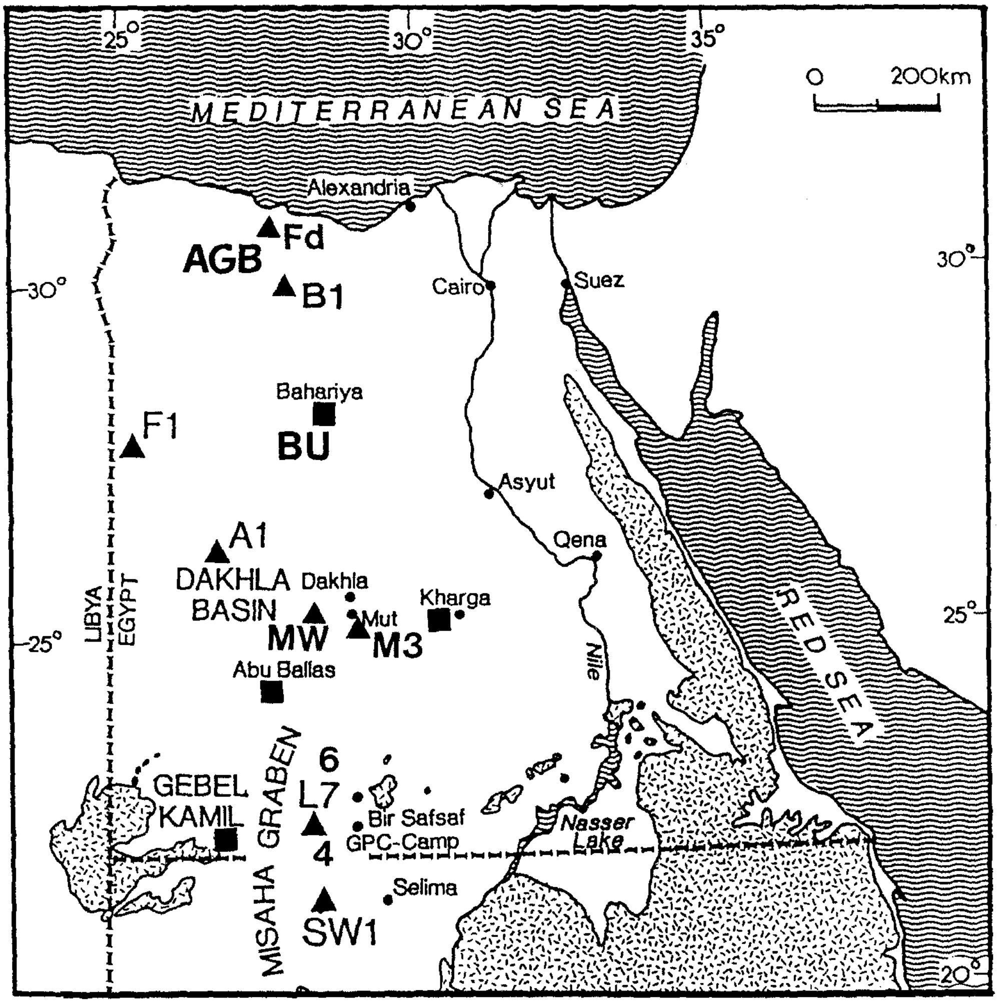

Fig. 4. Location map of reference sections mentioned in the text. Location of deep water wells along a cross-section from south to north: SW1, L4, L7, L6, MW, M3. Oil wells: A1 = Ammonite well 1; F1 = Foram well 1; B1 = Betty 1; Fd = Fadda 1. AGB = Abu Gharadig Basin; BU = Bahariya Uplift; MG = Misaha Graben. Black squares mark position of reference sections mentioned in text

Mut–Kharga–Baris area interpreted in Wycisk (1987). The locations of major stratigraphic sections and subsurface log data used in this paper are given in Fig. 4.

In the study area, the lowermost part of the subsurface sedimentary succession in the Misaha Graben at the Egyptian/Sudanese border is made up of non-cyclic Late Jurassic fluvial sandstone sequences, up to 200 m thick (Fig. 3; units 1 and 2). Mudstone and sandstone beds, originating from shallow marine conditions, follow to the north and can be linked with the Late Jurassic transgression (Keeley et al., 1990). The landward fluvial sandstone wedge in the correlation was caused by vertical block movements at the northern flank of the Uweinat–Bir Safsaf–Aswan Uplift. Here, the basement top shows a vertical displacement of approximately 200 m. Because of the amalgamation of depositional sequences and their reduced thickness towards the south, the correlation of individual lithostratigraphic units becomes increasingly uncertain.

Neocomian lowstand

Lower Cretaceous sandstones onlapped an erosion surface over nearly the entire shelf area in northern Egypt. The major hiatus comprises the Berriasian to Lower Hauterivian in the Fadda 1 well (Omran et al., 1990). Fluvial and deltaic sandstones derived from the shield prevailed over most of the present land areas and grade northward to marine sandstones, shale and carbonates. During the Barremian and early Aptian, the sea level rose. Transgressive carbonates, such as the Alamein Dolomite in northern Egypt, overlie the older shale and sandstone in most of the Middle East and North Africa, and a limestone platform developed during the middle Aptian. A sea level fall followed, culminating the first major cycle of the Cretaceous. The synchronism of the Cretaceous events over the circum-Arabian region is described by Harris et al. (1984), Alsharhan and Nairn (1986, 1988) and Flexer et al. (1986).

In south-west Egypt, the Late Jurassic strata are overlain by an extensive sheet sandstone (unit 3, Fig. 3), displaying a few upward fining sequences and a continuous lateral facies development. This conspicuous lowstand sheet sandstone can be traced in the subsurface for nearly 800 km a north–south direction. The unit attains a nearly constant thickness of around 100 m in the Misaha Graben and towards the centre of the Dakhla Basin. It wedges out towards the Kharga Uplift in the east and is missing in the Kharga–Baris area. A Neocomian age can be assumed for this conspicuous

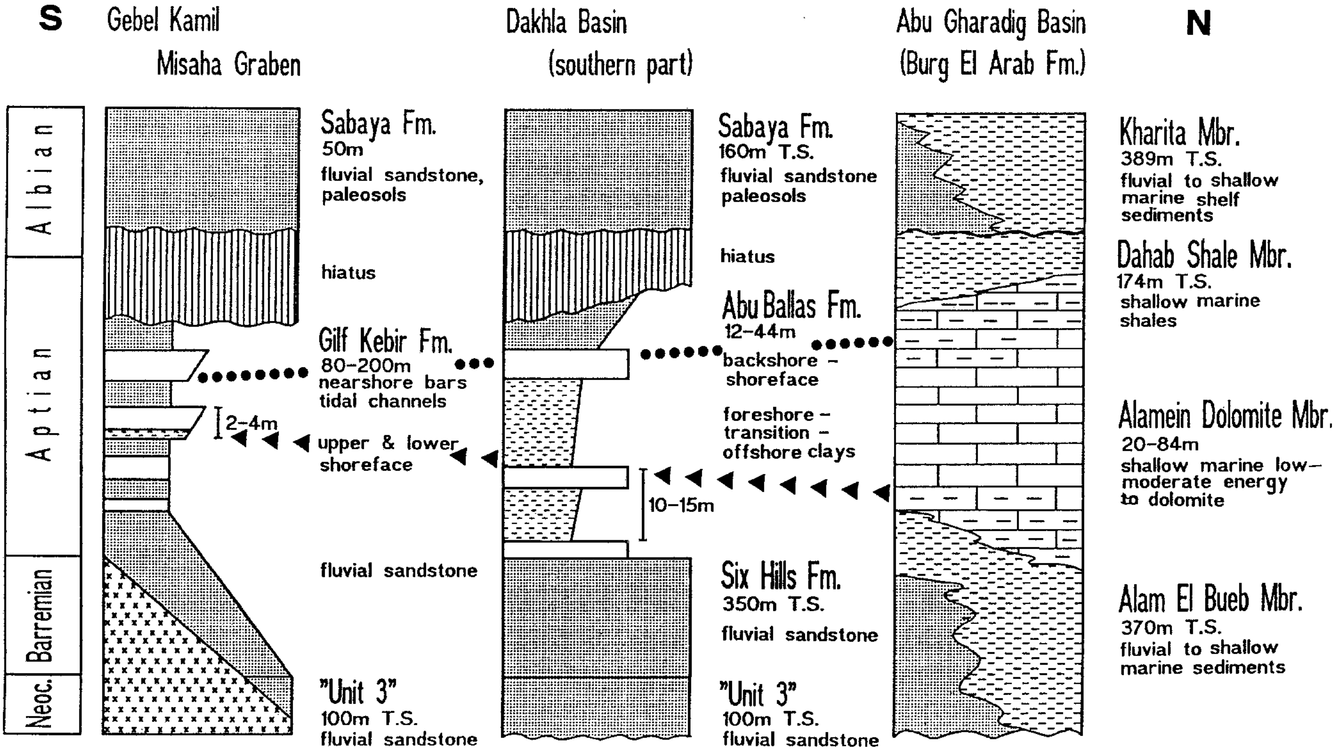

Fig. 5. Facies correlation chart of the Aptian Abu Ballas Formation and coeval deposits in the southern Dakhla and Abu Gharadig Basins based on Hendriks and Kallenbach (1986), Hantar (1990), Omran et al. (1990), Ibrahim (1986, 1992), and Wycisk (1990). Vertical extension not to scale

lithostratigraphic unit on the basis of log correlation and palynological evidence (Wycisk 1987).

The sheet sandstone corresponds stratigraphically in parts with the outcropping Gilf Kebir Formation (Late Jurassic to Early Cretaceous). The Gilf Kebir Formation contains fine- to medium-grained, cross-bedded fluvial sandstone sequences with silt and shale intercalations. East and south-east of Gilf Kebir, the upper part of the formation interfingers with sediments of the mainly marine Abu Ballas Formation of Aptian age. Coeval fluvial sediments of the Gilf Kebir Formation have been recognized in north-west Sudan, proved by an assemblage of plant remains of an Early Cretaceous, probable Barremian age (Wycisk et al., 1990).

Towards the centre of the Dakhla Basin, the contemporaneous Six Hills Formation unconformably overlies the basement rocks of Precambrian age and consists of medium- to coarse-grained fluvial sandstones. Conglomeratic layers are minor and the number of palaeosol horizons increases in the upper part of the sedimentary succession due to the increasing subsidence of the sedimentary basin. The thickness of the formation at the type area at Six Hills is of the order of 450 m. The Six Hills Formation is unconformably overlain by the shallow marine Aptian Abu Ballas Formation and interfingers to the west and south-west with the Gilf Kebir Formation.

In the subsurface of the area studied, the sedimentary succession is identified as unit 4 (Fig. 3) and interpreted as the equivalent of the Six Hills and Abu Ballas formations of the southern Dakhla Basin and the Gilf Kebir Formation in the surroundings of Bir Misaha and Gebel Kamil areas towards the Gilf Kebir Plateau. Palynological investigations by Schrank (1987) from El Masara Well 1 a proved a Barremian age for the Six Hills Formation (unit 4 a).

Aptian highstand

Spreading of the Eastern Mediterranean Basin reached a maximum in the middle Cretaceous. The northern part of the Arabian platform was a passive margin on which a carbonate shelf developed. In Egypt, downwarps, graben and horsts that had originated in the Jurassic or Early Cretaceous became prominent in the Albian and Cenomanian. Many structures fit a pattern of regional right-lateral shear (Kelly and Wallis, 1991). Based on microfloras and -faunas from subsurface investigations of the northern Western Desert of Egypt, Ibrahim (1986; 1992) and Abdel-Kireem et al. (1993) gave a depositional and palaeoenvironmental model for the Aptian Alam El Bueib Formation (in parts) and Alamein Formation which suggests nearshore marine to inner shelf environmental conditions. Numerous terads of *Classopolis* indicate that their parent plants predominate on the adjacent coastal marshes.

In the eastern part of Egypt, late Aptian – early Cenomanian carbonates from Gebel Maghara (Kuss and Schlagintweit, 1988) have been discussed in relation to the development of the south-western continuation of the

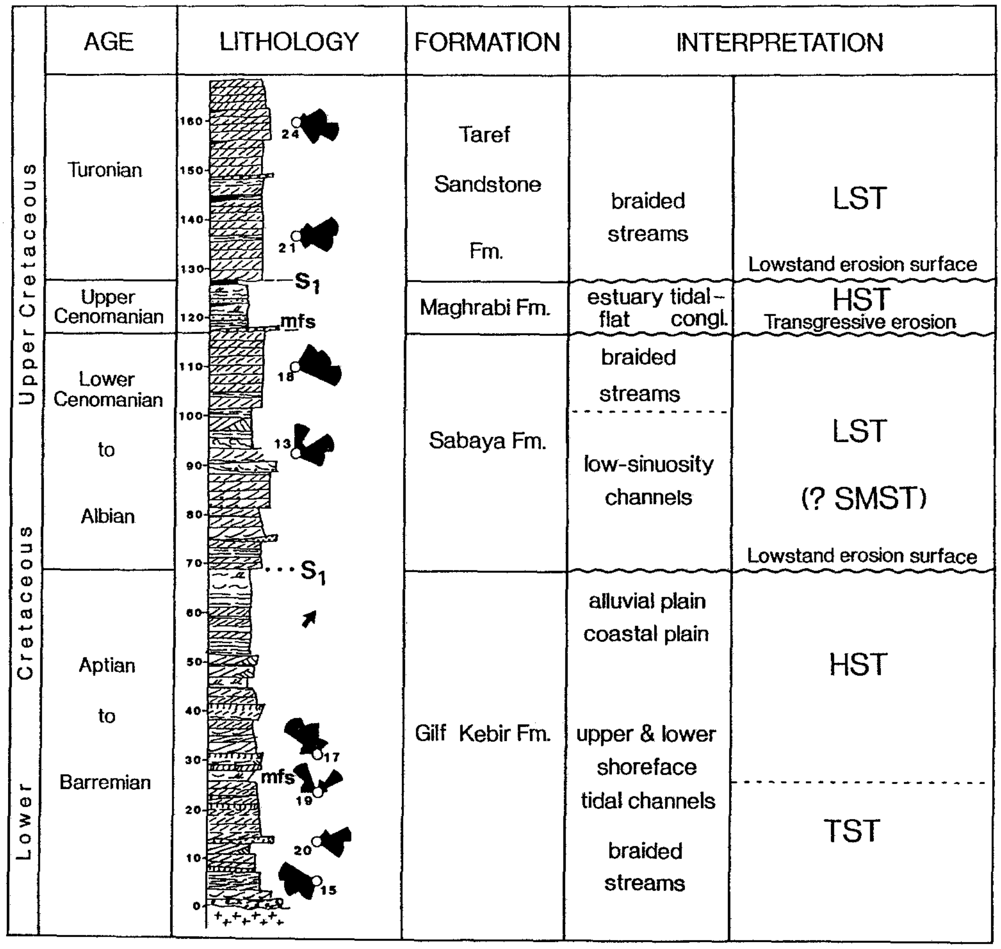

Fig. 6. Reference section of the Lower and Upper Cretaceous at Gebel Kamil, near the Egyptian – Sudanese border. The stratigraphic succession shown comprises Barremian to Turonian continental and shallow marine deposits and their related sequence stratigraphic interpretations. Further explanations are given in the text

equivalent Aptian sediments in the Dakhla Basin. In the latter, Böttcher (1982) investigated a rich Aptian fauna and flora in the Abu Ballas Formation, which has been formed in the transitional fluvial/shallow marine environment of a shallow epicontinental sea. The shallow marine deposits indicate a wide ingression of an unusual extent within south-west Egypt and north-west Sudan, compared with the less extensive onlapping of the following Cretaceous sequence.

The stratigraphic sequence of the Abu Ballas Formation in the south-east Dakhla Basin documents a retrograding and prograding shoreline shift, due to the sea-level change of the Aptian sea. The depositional sequence consists of silty and sandy deposits of a marginal marine facies (Fig. 5) and ranges from sub-environments of backshore to offshore transition zone (Hendriks and Kallenbach, 1986). The shallow marine deposits accumulated on the western slope of the Kharga Uplift bounding the Dakhla Basin towards the east. At many locations east and north-east of the type locality towards the Abu Tartur escarpment, the formation is topped by thick palaeosol sequences of several metres, which are linked with the very late highstand position of falling sea level.

In the subsurface of the area studied, the Abu Ballas Formation corresponds to unit 4b in the subsurface correlation (Fig. 3). The data suggest an extended open and marginal marine shaly intercalation within the southern part of the Dakhla Basin. The logs indicate a continuously increasing thickness of the unit from approximately 100 m in the south to a maximum of 250 m in Well Ammonite 1 towards the north (Figs 3 and 4).

The extent of the Aptian shoreline, close to the Sudanese border, is recorded in the Gebel Kamil section equivalent nearshore and fluvial sequences (Fig. 5), which represent here the uppermost part of the Gilf Kebir Formation. A detailed description of the depositional sequence is given in Wycisk (1990). The coarsening-upward sequences of lower and upper shoreface deposits form an retrogradational parasequence set, indicating the transgressive systems tract within the section (Fig. 6). The subsequent highstand systems tract is represented by a clearly developed and strongly bioturbated lower to upper shoreface sequence with the maximum flooding surface at their silty base. In the uppermost part of the formation, progradational and upward-fining coastal lowland sequences characterize the late highstand situation of the Aptian sea.

An extension of the Aptian sea south of the Uweinat – Aswan Uplift is documented by trace fossil-bearing nearshore sandstones south-east of Gebel Kissu. Nearshore deposits of most probably Aptian age found in the vicinity of El Fasher been discussed in Wycisk et al. (1990).

Albian to early Cenomanian lowstand

In the Western Desert, fluvial and deltaic depositional environments continued through the Albian into the early Cenomanian. Palynological data from the Qattara region in north-west Egypt prove the strong terrestrial influx of the enduring shallow marine conditions of the Burg El-Arab Formation in the Abu Gharadig Basin (Ibrahim, 1992; Abdel-Kireen et al., 1993). The short-term Early Cenomanian regression was followed by the extensive Late Cenomanian transgression, coinciding with the establishment of vast carbonate platform environments, which can be traced from Egypt across the Sinai to Jordan (Kuss, 1992).

The stratigraphic succession grades southward into the broad continental lowstand sequence of the Albian to early Cenomanian Sabaya Formation in the southern Dakhla Basin. The fine- to coarse-grained fluvial deposits are predominantly tabular and through cross-bedded and occasionally include conglomeratic intercalations. The fluvial architecture indicates straight and low sinuosity channels. Sandy and silty overbank deposits are rare. In the upper part of the formation, which attains a thickness of 160 m in the reference area, mottled palaeosols commonly occur within the floodplain deposits. Whereas the strata in general conformably to slightly unconformably overlie the Abu Ballas Formation, there is evidence of major erosion in the type section area (Hendriks and Kallenbach, 1986). The contact with the overlying Maghrabi Formation is mainly erosive.

In the subsurface of the southern Dakhla Basin, the outcropping succession is identified as unit 5 (Fig. 3). The top of unit 5 is dated by palynoflora of late Albian to early Cenomanian age (Schrank, 1987). The unit increases in thickness from 150 m south of Kharga towards the centre of the Dakhla Basin to nearly 500 m at Well Ammonite 1.

The southernmost outcrop of the Sabaya Formation is exposed in the Gebel Kamil section (Wycisk, 1990). The fluvial dominated lowstand systems tract starts above a sharp lowstand erosional surface with pebbly medium- to coarse-grained, weak kaolinitic channelized sandstones, which are tabular and through cross-bedded (Fig. 6). The upper part of the formation consists of unique medium-grained sandstones, showing stacked small-scale tabular cross-bedding with single, horizontally stratified sets. The development and architecture of the fluvial sequences of the Sabaya Formation reflect here a decreasing level of transport energy. The gradual facies change from low sinuosity to braided river systems reflects decrease of the palaeo-gradient and can be linked to the rising sea level in the north. Northwards to the centre of the Dakhla Basin, this formation grades laterally from a braided river to a more low sinuosity fluvial environment with broad overbank deposits and soil formation.

The Tagabo and Wadi Milk formations represents in north-west Sudan proximal upstream deposits within the vast alluvial plain during the Albian – early Cenomanian and describe the major part of the outcropping Cretaceous (Wycisk et al., 1990; Wycisk, 1991). The Tagabo Formation (Northern Darfur, El Fasher-Malha area) consists of non-cyclic braided river deposits at the base, followed by fining upward cycles of low sinuosity rivers and kaolinitic overbank deposits. Eastward, the equivalent Wadi Milk Formation (Gebel Nagashush, Wadi Milk area) shows medium- to coarse-grained sandstone sequences by low sinuosity rivers. Conspicuous lateral facies changes within the fluvial-lacustrine environment and the evolution of the fluvial depositional style show a close relationship with the given structural control, due to the subsidence patterns of the narrow and deep graben structures of the Humar Basin and their prolongation (Wycisk et al., 1990; Bussert, 1993). An Early Cretaceous and perhaps Late Jurassic age for the underlying rift sediments can be assumed.

Late Cenomanian highstand

The upper Aptian to Turonian cycle in the southern Mediterranean Basin began with clastic sediments and culminated in an emergent carbonate platform. The most extensive shelf limestone is of late Cenomanian and early Turonian age, coinciding with a global sea-level highstand, followed by a sea-level fall in the late Turonian (Flexer et al., 1986). Carbonates with some anhydrite covered nearly the entire basin region by the late Cenomanian. A carbonate platform developed from Sinai northeastward as far as south-eastern Turkey. The platform culminated in barrier reefs with rudistids along the platform edge in Israel and Lebanon (May, 1991).

The deposition of the local Cenomanian succession probably took place in shallow marine water of the inner to middle shelf as a result of progressive phases of the marine transgressions. The micropalaeontological record of the individual basins, e.g. the Matruh and Abu Gharadig Basin, reflect an independent development of their palaeo-depth curves (Abdel-Kireem et al., 1993). The reconstructed short-term sea-level fluctuation in the Bahariya Formation of the Abu Gharadig Basin (Betty I) by Ibrahim (1986) indicates three regressive and two transgressive cycles during the Cenomanian, as shown in Fig. 7. This development can be connected laterally to the south with the related facies development and increasing erosional processes in the hinterland (Uweinat – Bir Safsaf – Aswan Uplift. As indicated in Fig. 7, three regressive and two transgressive short-term cycles of decreasing lateral extent can be connected within the Bahariya Formation in a north – south direction.

The stratigraphic section of the Bahariya Formation (Bahariya Oasis) has been subdivided by Dominik (1985) from bottom to top into three members with a revised stratigraphic range of late Cenomanian (Fig. 7). The Gebel Ghorabi Member consists mainly of fluvial sandstones which crop out within the Bahariya depression only around the anticlines. The Gebel Dist Member is an estuarine sequence, which is strongly affected by tides. Numerous marine fish and terrestrial vertebrates are derived from the inner estuarine system. Different species of the ammonites *Neolobites* occur in the thin shallow

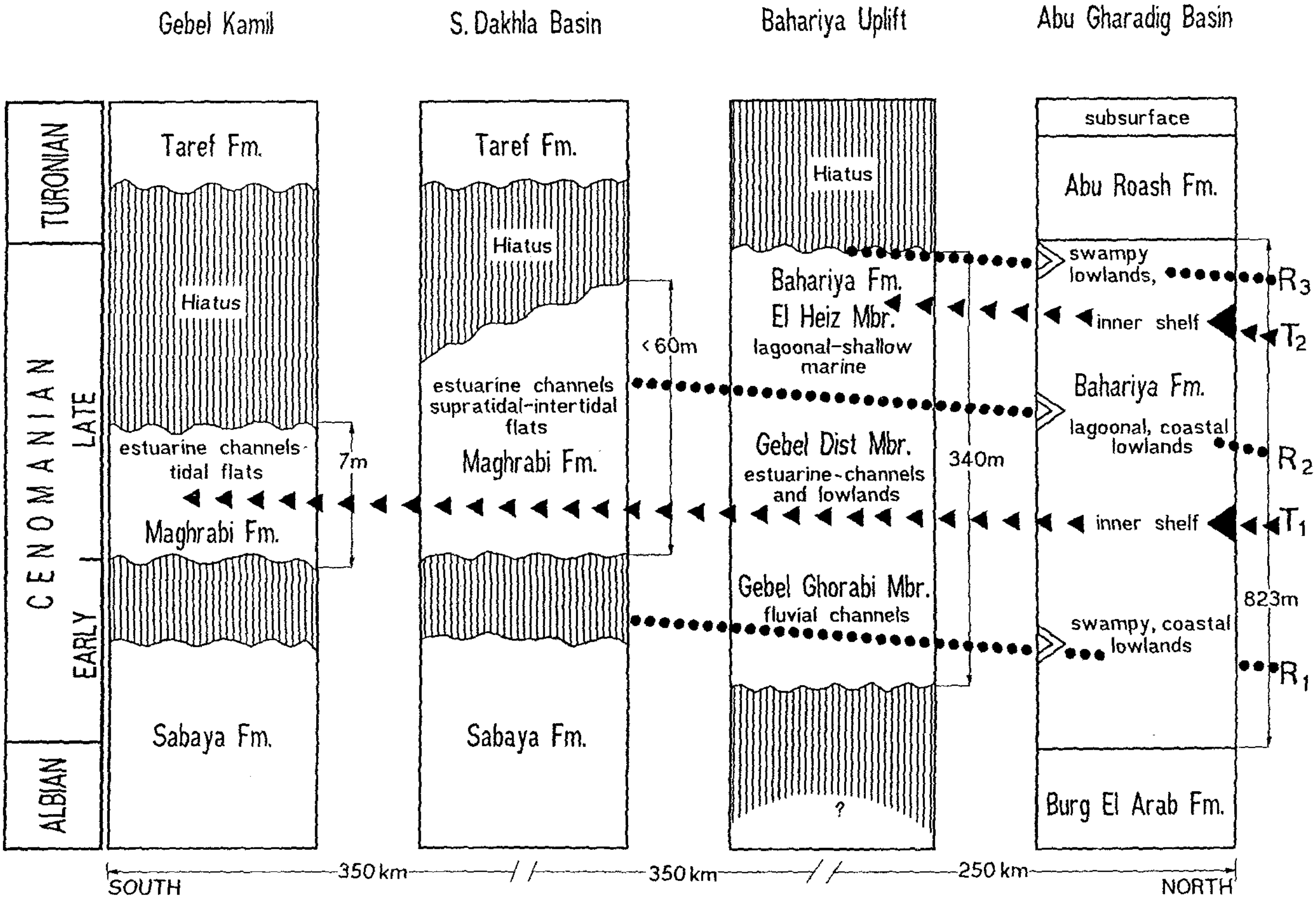

Fig. 7. Facies correlation chart of the Cenomanian Bahariya and Maghrabi formations displaying short-term relative sea-level fluctuations. T 1 marks the major transgressive peak, which reached the Gebel Kamil area near the Sudanese border. The regressive facies associations in the northern part of the basin can be linked to erosional processes R 1 below or R 2, R 3 above the transgressive sequences T 1, T 2, respectively. This interpretation illustrates for the first time the large extent of related erosional processes in the hinterland, partly intensified by temporarily uplift of the Uweinat – Aswan High in the south. Stratigraphic data from Dominik (1985), Hendriks (1986), Wycisk (1990) and Abel-Kireem et al. (1993)

marine intercalations of the Gebel Dist Member and prove a late Cenomanian age. It is best developed in the northern parts of Bahariya around Gebel Dist. The El Heiz Member finally represents the lagoonal to supratidal part, formely separated as El Heiz from the Bahariya Formation. The gradual regression in the latter member started after the short peak of the late Cenomanian transgression.

Further south, the Cenomanian Maghrabi Formation (60 m) consists of massive grey claystone successions, intercalated with siltstone and sandstone beds, originating in a more marginal than open marine environment (Fig. 7). In the type area near Kharga, the formation can be divided into eight distinctive sedimentary facies originating from supradital, intertidal and subtidal provenance; they characterize a tidal flat environment for this region, repeatedly eroded by meandering estuarine channels (Hendriks, 1986). The marginal marine sedimentation of the Maghrabi Formation terminates with an intensified accumulation of sandy detritus from the rivers in the south, indicating strong erosion in the hinterland. These deposits document a progradation of the shoreline due to the gradual regression of the sea during a late highstand.

The southernmost reference section of the Cenomanian Maghrabi Formation is located at Gebel Kamil (Figs 6 and 7). The formation overlies unconformably the Sabaya Formation, with a thin transgressive erosional conglomerate. Here, the formation attains a thickness of 8 – 10 m and is made up of fine-grained sandstone with shale intercalations. The major facies of horizontal bedding and ripple cross-lamination reflect low energy transport conditions of a mixed estuarine and tidal flat environment. The occurrence of less frequent agglutinated foraminifera indicate a Cenomanian age (Klitzsch and Wycisk, 1987). The erosional surface at the base of the subsequent lowstand deposits of the Taref Formation (Turonian) is clearly pronounced in the section.

Early Turonian lowstand

During the early Turonian, a remarkable short fall of sea level took place in southern Egypt and shallow marine shelf conditions in the middle part of the Abu Roash Formation are restricted to the northern Western Desert (Abdel-Kireem et al., 1993).

In the southern Western Desert, cross-bedded fluvial channel sediments, partly conglomeratic, are found, especially at the base of the Turonian Taref Formation. The strata mainly originate from a fluvial environment, but weak marine nearshore deposits have also been described from the Kharga area. The thickness of the type section at Gebel Taref north of Kharga reach approximately 40 m, thickening basinward to the west. The areal distribution of this formation reaches from the Kharga area westward to the southern foreland of Ammonite Hills and north of Gilf Kebir and Abu Ras Plateau towards the Libyan border.

The southernmost location of the Taref Formation is exposed at Gebel Kamil. Here, the Taref Formation (lowstand systems tract) overlies the Maghrabi Formation (highstand systems tract) with a sharp erosional base (Fig. 6). The stratigraphic sequence represents the uppermost part of the Gebel Kamil section and is made up of unique, non-cylic medium- to coarse-grained sandstones with small-to large-scale tabular cross-bedding and some shaly sandstone intercalations. The low sinuosity to predominant braided fluvial environment is characterized by migrating, straight-crested megaripples, indicating broad rivers and a low topographic relief. The major palaeocurrent direction indicates an eastward sediment transport because of the local regional uplift of the Uweinat – Aswan High (Wycisk, 1990).

Owing to the increasing transport conditions of the coeval fluvial systems in north-west Sudan, the Wadi Howar Formation (Turonian – Santonian) consists predominantly of medium- to coarse-grained fluvial sandstones, attributed to more channelized low sinuosity and braided river systems (Wycisk et al., 1990). In the type area, the Wadi Howar Formation rests unconformably on basement and towards the south at Wadi Milk this formation unconformably overlies the Wadi Milk Formation. On the southern rim of the Abyad Plateau, the palaeosols of the Wadi Howar Formation are erosively overlain by the transgressive nearshore sediments of the Kababish Formation. The clear erosional base above the well developed lateritic paleosol mark an important regional unconformity at the base of the Kababish Formation. A weak shallow marine influence in the upper part of the Wadi Howar Formation can be linked with the shallow marine incursion in the Aswan area (southern Egypt) of Coniacian time.

Campanian to lower Eocene shale–carbonate cycles

The Late Cretaceous and Early Tertiary were dominated by plate convergence and its effects on the platform. On the platform, older lines of tectonic activity became activ anew. Senonian beds are thin to missing on uplifts and show multiple levels of onlap and angular unconformities from Syria to the Western Desert of Egypt, as May (1991) summarized. The Eastern Mediterranean Mesozoic basin, which had been an integral structure since the Triassic, was broken into a complex of lesser grabens and downwarps (Keeley and Wallis, 1991). In Egypt, the Abu Gharadig and nearby basins follow trends established in the Jurassic or Early Cretaceous and renewed by regional right shear. The complex structural evolution and basin-fill, based on drillhole data and seismic records, has been described by Bayoumi and Lofty (1990). The vertical distribution of the palynomorphs and planktonic foraminifera of the Cenomanian – Maastrichtian succession from the Kahraman 1 Well (Abdel-Kireem et al., 1993) proves the existence of a regional hiatus between the Santonian and Campanian in the northern Western Desert as a result of the absence of upper Santonian deposits. In the Abu Gharadig 18 well, a hiatus between the Santonian and Maastrichtian is recognized due to the absence of upper Santonian to Campanian strata.

During the Late Cretaceous highstand, transgressions repeatedly flooded the contemporaneous coastal plains of the southern Dakhla Basin and parts of the Uweinat – Aswan High in the south and advanced into the northern Sudan towards the Abyad Basin (Klitzsch, 1986; Barazi and Kuss, 1987). The new major transgressive cycle starts in the southern Dakhla Basin in the Campanian (Fig. 2), indicated by fluvial and tidal sediments of the Quseir Formation (= Mut Formation), which is overlain by the phosphate-bearing Duwi-Formation of early Masstrichtian age. The deeper shelf deposits of the Maastrichtian/Palaeocene sea covered larger areas of Egypt, resulting in widespread shales and marls of the Dakhla Formation. The open marine deposits of the Dakhla partly assume a sandy facies of the Ammonite Hill Member, which is described along the north-western rim of the Dakhla Basin (Luger, 1988 a; 1988 b).

Towards the south-east of the Dakhla Basin, the fluvio-deltaic sediments of the Kiseiba Formation laterally replace the Quseir and Duwi formations as well as the Maastrichtian part of the Dakhla Formation. The Cretaceous/Tertiary boundary falls within the shales of the Dakhla Formation in the southern Dakhla Basin, which has been discussed in detail by Luger (1988 a). Recent studies were focused on the environmental interpretation and biostratigraphic studies of the basin facies, including their nearshore equivalents (Dominik, 1985; Luger, 1988 b; Hendriks et al., 1987; Hendriks, 1988).

The Campanian to Maastrichtian Kiseiba Formation laterally replaces the Quseir and Duwi formations and the Maastrichtian part of the Dakhla Formation in the south-eastern Western Desert. The type section is located at the escarpment of Bir Kiseiba and the thickness of the stratigraphic succession is around 150 m and may exceed more than 300 m, including the Shab and Shagir Member (Hendriks et al., 1987). The sedimentary sequence is made up of fine-grained sandstone, flaser and small-scale cross-bedded with shaly silt- and sandstone intercalations. Bone beds and phosphatic beds occur in different positions of the section. The sediments originate from different deltaic and shallow marine sedimentary sub-environments and can be assigned to several transgressive and regressive cycles (Hendriks, 1988).

In northern Sudan, the coeval Kababish Formation of Campanian – Maastrichtian age overlies unconformably the Wadi Howar Formation with a clear transgressive

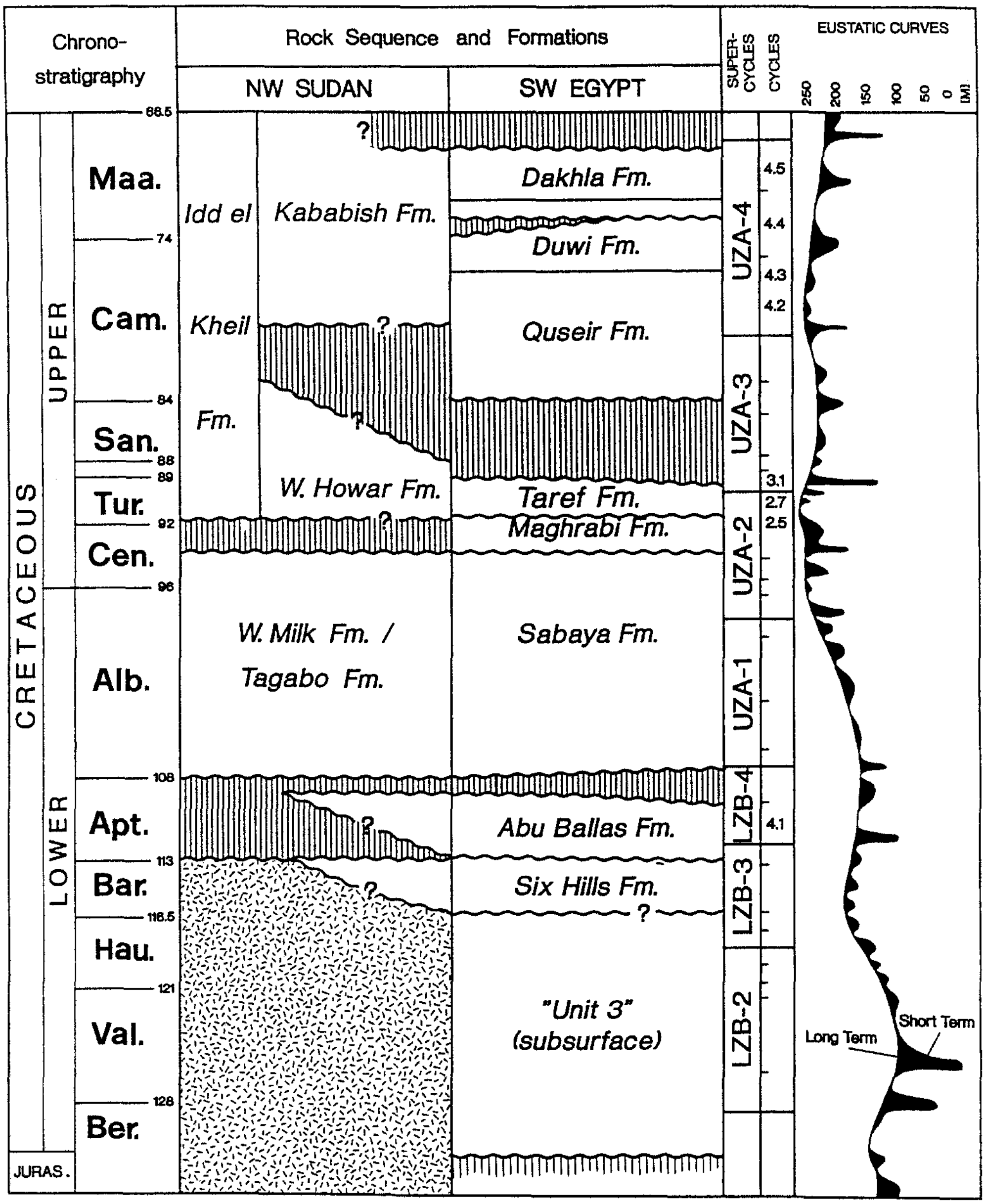

Fig. 8. Lithostratigraphic chart of the Cretaceous succession comparing the situation of south-west Egypt and north-west Sudan, including an update of formation boundaries and major unconformities, which can be linked in general to the global eustatic curve of Haq et al. (1987)

nearshore sequence. The formation represents a continental to transitional marine depositional environment with different fossils of invertebrates, trace fossils and plant remains (Barazi, 1985). Towards the south, this facies grades into the fluvio-lacustrine deposits of the Idd el Kheil Formation. Owing to the structural situation, the formation shows significant lateral facies changes of a nearshore to backshore environment of a wave-dominated coast with coeval fluvio-lacustrine sediments and palaeosols on the landside. In the El Atrun area, the Kababish Formation consists of up to 70 m of superimposed hydromorphic palaeosols from ancient coastal plains (Wycisk et al., 1990). The small-scale sequences of the described Kababish Formation indicate an aggradational parasequence set, which tends to be progradational in the upper part of the formation. Until now, an exact allocation to the individual Campanian and Maastrichtian transgressive events has not been possible.

The ferruginously mottled, kaolinitic silty sandstone shows massive bedding and reflects a predominating monocyclic soil formation, in contrast with the unconformity bounded lateritic soils on top of the Wadi Howar Formation. The Kababish Formations is ?conformably overlain by the dolomite and limestone of the Gebel Abyad Formation of Palaeocene – Eocene age, originating from supratidal, tidal flat and lagoonal environments (Barazi and Kuss, 1987). A hiatus at the Cretaceous/Tertiary boundary, as south-east Egypt, can only be assumed.

Relative sea-level changes

In western Egypt and north-west Sudan, relative sea-level changes during the Cretaceous lead to three major transgressive – regressive sedimentation cycles on the

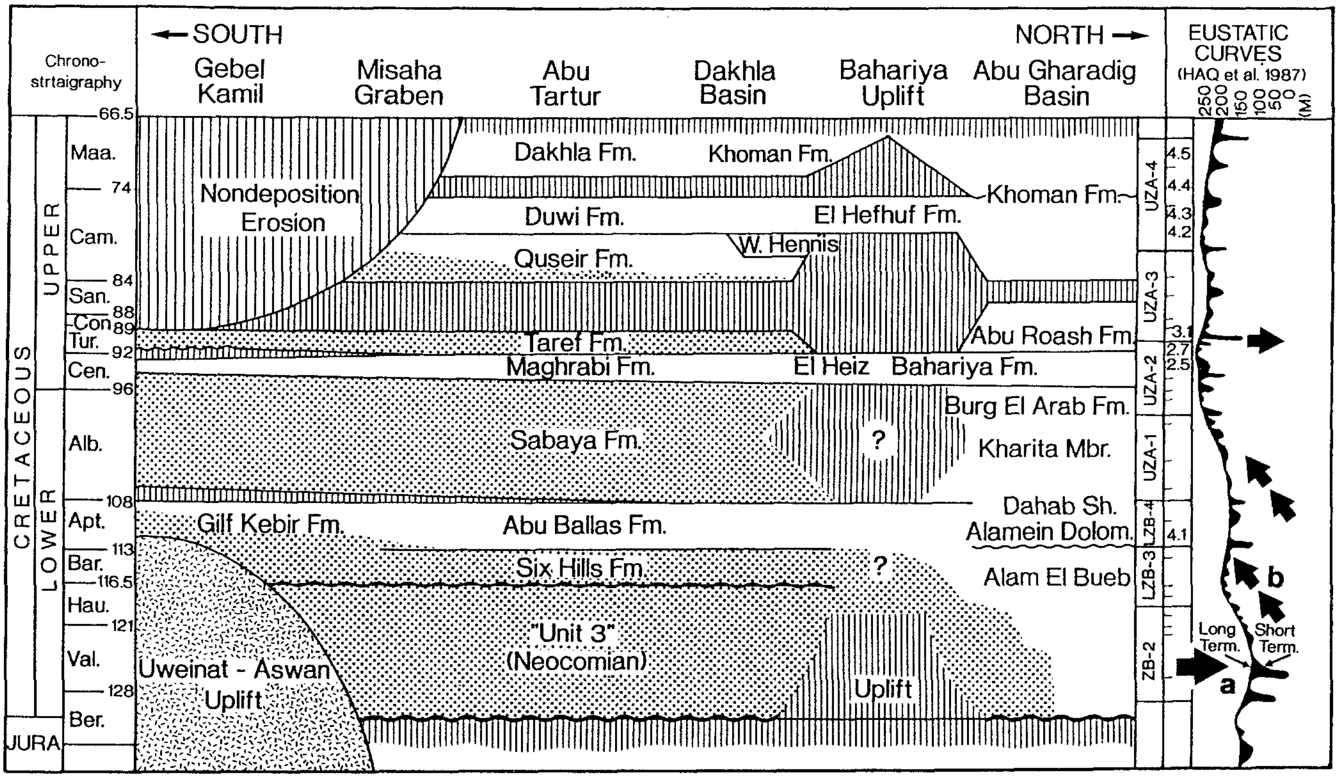

Fig. 9. Generalized correlation chart and facies – time diagram of the Cretaceous in western Egypt along a north – south cross-section displaying changes of fluvial (stippled) and marine – shallow marine (blank) environments in relation to the global eustatic curve of Haq et al. (1987). The position of regional unconformities is indicated by vertical hatching. The consequences of the Uweinat – Aswan Uplift in the southern Dakhla Basin and the influence of the Trans-African Lineament at the Bahariya Uplift are clearly indicated. Fluvial lowstand sheet sandstones characterized by non-cyclic sequence development and high facies stability occur in the Neocomian and early Turonian (a). During the Barremian and Albian, fluvial architecture changes to more cyclic fluvial deposits and increasing soil formation (b), due to increasing subsidence, more humid climatic conditions and the generally rising sea level, culminating in the extensive shallow marine Abu Ballas and Maghrabi formations. Further details are given in the text. Stratigraphic data from northern Egypt and Abu Gharadig Basin: Ibrahim (1986; 1992), Hantar (1990), Omran et al. (1990) and Abdel-Kireem et al. (1993)

northern margins of the craton (Figs 8 and 9). These cycles are the Neocomian – Aptian, the Albian – early Cenomanian/Turonian, which are mostly terrigenous sediments, and the Campanian to early Eocene, which are basin marls, marly chalks and platform carbonates. The cycles are separated by major regional unconformities: the Aptian – Albian and Cenomanian-Turonian boundaries. The intensity of erosion was triggered in south-west Egypt by uplift movements of the east-west striking Uweinat – Aswan High. Regional uplift and erosion took place in south-west Egypt during the Coniacian and Santonian. The regional stratigraphic gaps and uncertain interpretation on the Bahariya Uplift are induced by the influence of the Trans-African Lineament, especially during the Late Cretaceous (Fig. 9).

The palaeo-depth curve of the northern Egyptian Cretaceous illustrates the gradual sea-level rise, reaching its maximum during the Late Cretaceous with conspicuous advances during the Aptian and late Cenomanian (Fig. 9). In south-east Egypt extensive transgressions are documented in the late Turonian, late Campanian and early Maastrichtian. A general highstand is also recorded during the Campanian – Maastrichtian in north-west Sudan. Major lowstands occur in the Neocomian, Barremian, Albian – early Cenomanian and early Turonian. The most prominent and extensive lowstand sheet sandstone of Neocomian age can be linked with the global eustatic low, whereas the Turonian lowstand deposits are related to a short-term fall of sea level. The fluvial architecture of both lowstand sequences is affected by an increasing slope gradient which was affected in parts by the Uweinat – Aswan Uplift and a general low subsidence, which causes a lateral and vertical stacking and high facies stability of fluvial channels. As pointed out by Wescott (1993), rivers may adjust to lowered base levels and changes in slope by modifying channel patterns during eustatic lowstands. Therefore, not all lowstands produce type 1 sequence boundaries, which explains the situation in the southern Dakhla Basin. During the Neocomian, the prevailling semi-arid to arid climatic conditions support the mobility of sediment in fluvial depositional systems, due to reduced soil-forming processes and limited vegetation.

The Barremian and Albian lowstands, Six Hills and Sabaya Formation, respectively, are characterized by the presense of overbank deposits and related fluvial systems in the Dakhla Basin. The increasing soil-forming processes are related to the more humid climatic conditions and a higher preservation potential due to the increasing subsidence of the sedimentary basin. It can be assumed that the fluvial architecture is also affected by the rising sea level of the extended subsequent transgressive sequences such as the Abu Ballas and Maghrabi formations.

The major transgressive – regressive events and related unconformities deduced from the surface and subsurface continental stratigraphic succession of south-west Egypt and north-west Sudan show a comparable development to neighbouring ares. The cycles are comparable with cycle descriptions in the Eastern Desert of Egypt, Sinai, Israel and Jordan (Flexer et al., 1986; Luger and Schrank, 1987; Luger and Gröschke, 1989; Kuss, 1992) and even correspond with those from more remote regions such as Saudi Arabia, reflecting major fluctuations of the Cretaceous sea level (Harris et al., 1984, Alsharhan and Nairn, 1986, 1988, 1990; Alsharan and Kendall, 1991; Le Nindre et al., 1990; Lewy, 1990).

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