Palaeoenvironmental evolution of the Tunisian carbonate platform margin: Response to global oceanographic and climatic changes (Barremian–Aptian)

Dissertation
for the doctorate degree
of the Department of Geosciences
at the University of Bremen

Submitted by
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Bremen, 2008

Tag des öffentlichen Kolloquiums

04.12.2008

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Preface

The results of this study are documented in 4 separate manuscripts, which are either published or submitted to international journals. The authors contribution to each manuscript is as follows:

1) Microfacies, biostratigraphy, and geochemistry of the hemipelagic Barremian–Aptian in north-central Tunisia: Influence of the OAE 1a on the southern Tethys margin

Authors: Heldt, M., Bachmann, M., Lehmann, J.

Journal: Palaeogeography, Palaeoclimatology, Palaeoecology

Status: published

Own contribution: field work, sedimentologic analysis and interpretation, geochemical interpretation, data on planktonic foraminifers, text, and figures.

2) Absence of a global marine biocalcification crisis during the late Early Aptian Oceanic Anoxic Event 1a

Authors: Heldt, M., Bachmann, M., Lehmann, J., Thielemann, J., Kuss, J., Negra, H., Bey, S.

Journal: Geology

Status: submitted

Own contribution: field work, sedimentologic analysis and interpretation of the Tunisian section, geochemical interpretation of Tunisian data, all data on planktonic foraminifers, integration of Tunisian and Egyptian data, text, and figures.

3) Palaeoenvironmental evolution of a southern Tethys carbonate platform margin: Response to global climate change (Late Aptian of north-central Tunisia)

Authors: Heldt, M., Lehmann, J., Bachmann, M., Kuss, J.

Journal: Sedimentology

Status: under revision

Own contribution: field work, sedimentologic analysis and interpretation, geochemical interpretation, data on planktonic foraminifers, text, and figures.

4) Aptian (Early Cretaceous) biostratigraphy and cephalopods from north-central Tunisia

Authors: Lehmann, J., Heldt, M., Bachmann, M., Negra, H.

Journal: Cretaceous Research

Status: accepted

Own contribution: field work, facies data and interpretation, geochemical data, data on planktonic foraminifers, part of the figures.

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Summary

The Late Barremian–Late Aptian interval was characterised by several major changes in the ocean/climate system related to the onset of the Mid-Cretaceous greenhouse world. North African sedimentary deposits offer excellent archives of the ecological changes on the southern Tethys continental margin during this time interval. In the present phD thesis sedimentology, palaeontology, biostratigraphy, chemostratigraphy, and geochemistry are combined to reconstruct the palaeoenvironmental evolution and sea-level changes of the Tunisian carbonate platform margin. Respect is paid to major palaeoceanographic and palaeoclimatic events including the late Early Aptian Oceanic Anoxic Event 1a (OAE 1a) and two time intervals associated with widespread carbonate platform drowning in the early- and mid-Late Aptian. The last chapter deals with the cephalopod fauna of the platform margin. Results of the detailed regional investigations are compared to global marine palaeoenvironments and discussed in a broad geological context.

CHAPTER 2 focuses on the microfacies, biostratigraphy, $\delta^{13}C$ stratigraphy, and geochemistry of the Hamada Formation at Djebel Serdj, north-central Tunisia. Integrated planktonic foraminifer and $\delta^{13}C$ stratigraphy date the deposits as being Late Barremian–early Late Aptian in age and allows to recognise the late Early Aptian Anoxic Event 1a as well as a time interval associated with major carbonate platform drowning subsequent to the event. The investigated sections are subdivided into 7 facies associations. Each facies association is thought to reflect a different mid- or outer ramp palaeosetting. Changes in the palaeosettings are used to establish a 3rd order sea-level curve which is in accordance with global eustatic curves. Deposits of the OAE 1a are thought to reflect a transgression and eutrophication of the upper water column. The environment at the seafloor was possibly dysoxic during the event. The carbonate production rates were high, which is a remarkable observation considering that the OAE 1a is usually associated with a biocalcification crisis. The Tunisian shelf was possibly affected by unfavourable conditions for primary carbonate producers during the prominent carbonate platform drowning interval subsequent to the OAE 1a.

In CHAPTER 3, the results concerning the deposits around the OAE 1a of the previous chapter are combined with results from a contemporaneous section of the Egyptian Levant platform to estimate the influence of the event on the southern Tethys continental margin. The Egyptian dataset originates from a closely related project of the authors research group. The sections are correlated on the base of biostratigraphy (planktonic foraminifers, larger benthic foraminifers, and ammonites) and $\delta^{13}C$ stratigraphy. Similar to the Tunisian platform (see above), the Egyptian Levant platform was affected by elevated trophic levels during the OAE 1a and the carbonate production rates were high. The discussion focuses on a comparison with global carbonate platform growth. Results suggest that nutrient fluxes during the OAE 1a were rather intermediate than high on the subtropical–tropical shelves and the carbonate production factories mainly intact. A global biocalcification or carbonate platform growth crisis during the event as suggested in previous publications can not be confirmed. The comparison confirms widespread carbonate platform drowning subsequent to the OAE 1a.

CHAPTER 4 deals with the microfacies, biostratigraphy, chemostratigrapy, and geochemistry of the Serdj Formation at Djebel Serdj. Biostratigraphy is based on planktonic foraminifers, larger benthic foraminifers, and ammonites. In combination with $\delta^{13}C$- and $\delta^{18}O$ stratigraphy, a detailed time frame spanning the early Late Aptian–late Late Aptian is established. The combined stratigraphic approach

allows us to recognise a prominent mid-Late Aptian warming phase/platform drowning episode as well as two brief cooling intervals. Four facies units, subdivided into 12 microfacies types, are recognised. Each facies unit is interpreted to reflect a different mid- to inner ramp palaeoenvironment. The occurences of these facies units indicate a progressive shallowing of the sea level, only interrupted by a shortlived deepening in the mid-Late Aptian. This shallowing was caused by tectonical uplift and does not reflect an eustatic signal. The biotic associations suggest a stable oligotrophic water regime throughout the entire investigated time interval. Carbonate platform demise during the warming phase due to nutrification, as reported from many subtropical carbonate platforms, did not occur.

CHAPTER 5 focuses on the taxonomy, biostratigraphy, and palaeoecology of cephalopods collected within the deposits of the Hamada and Serdj Formation at Djebel Serdj and Djebel Slata. Cephalopods are astonishingly rare in the deposits, but occurences are sufficient to date the facies changes and the position of the OAE 1a. The cephalopods are subdivided in 3 groups, which are attributed to facies associations and thus palaeoenvironments deduced from chapters 2 and 4. Results suggest, that the cephalopods lived within the outer to mid-ramp palaeoenvironments and within an inner ramp/lagoon palaeoenvironment. The association of Early Aptian cephalopods shows relations to the central and western Tethys as well as to the Atlantic province. For the Late Aptian, there are similarities with associations of the west and central Tethys as well as South America.

Zusammenfassung

Das späte Barreme–späte Apt war durch große Veränderungen im globalen Ozean/Klimasystem charakterisiert, die in einem engen Zusammenhang mit dem Einsetzen der mittelkretazischen Treibhauswelt standen. Die sedimentären Ablagerungen Nordafrikas bieten für diesen Zeitabschnitt hervorragende Archive der ökologischen Veränderungen auf dem kontinentalen Südrand der Tethys. In der vorliegenden Arbeit werden Sedimentologie, Paläontologie, Biostratigraphie, Chemostratigraphie und Geochemie angewandt, um die Paläoumweltentwicklung und die Meeresspiegelschwankungen auf dem tunesischen Karbonatplattformrand zu erfassen. Besonders berücksichtigt werden hierbei das Ozeanische Anoxische Ereignis 1a (OAE 1a) im späten Frühen Apt sowie zwei Zeitabschnitte im frühen- und mittleren Späten Apt, die mit dem weitverbreiteten Absterben von Karbonatplattformen in Verbindung gebracht werden. Im letzten Kapitel wird die Stratigraphie und Paläobiogeographie der Cephalopoden des tunesischen Karbonatplattformrandes untersucht. Die Ergebnisse der lokalen Untersuchungen werden mit globalen marinen Paläomilieus verglichen und in einem umfangreichen geologischen Rahmen diskutiert.

Im zweiten Kapitel werden die Fazies, Biostratigraphie und organische Geochemie zweier Profile der hemipelagischen Hamada Formation des Djebel Serdj im nördlichen Zentraltunesien detailliert untersucht. Eine kombinierte planktonische Foraminiferen-/δ^{13}C Stratigraphie datiert die Ablagerungen in das Späte Barreme–frühe Späte Apt und erlaubt es, die Positionen des OAE 1a, sowie eines Zeitintervalles assoziiert mit dem verbreitetem Absterben von Karbonatplattformen direkt nach dem OAE 1a, festzulegen. Die untersuchten Profile werden in sieben Faziesassoziationen unterteilt. Jede dieser Assoziationen reflektiert einen unterschiedlichen Lebensraum der mittleren oder äußeren Karbonatrampe. Veränderungen in den Ablagerungsmilieus werden herangezogen, um eine Meeresspiegelkurve der dritten Ordnung zu erstellen. Die Ergebnisse zeigen eine Übereinstimmung mit der globalen eustatischen Meeresspiegelkurve. Die Ablagerungen des OAE 1a zeigen eine Transgression und Eutrophierung der oberen Wassersäule an. Der Lebensraum am Meeresboden war während des Ereignisses möglicherweise dysoxisch. Die Karbonat-Produktionsraten waren bemerkenswert hoch, wenn man bedenkt, daß das OAE 1a gemeinhin mit einer Biokalzifizierungskrise in Verbindung gebracht wird. Der tunesische Schelf war möglicherweise nach dem OAE 1a von ungünstigeren Bedingungen für primäre Karbonatproduzenten betroffen.

Im dritten Kapitel werden die Ergebnisse zum OAE 1a aus dem vorangehenden Kapitel mit Ergebnissen eines zeitgleichen Profiles der ägyptischen Levant Plattform kombiniert, um den Einfluß des Ereignisses auf den kontinentalen Südrand der Tethys einschätzen zu können. Der ägyptische Datensatz stammt aus einem nahe verwandten Forschungsprojekt der Arbeitsgruppe des Autors. Die Profile werden auf der Basis von Biostratigraphie (planktonische Foraminiferen, benthische Großforaminiferen und Ammoniten) und δ^{13}C Stratigraphie korreliert. Die ägyptische Levant Plattform war, ähnlich wie die tunesische Karbonatplattform (siehe oben), von erhöhten Nährstoffgehalten während des OAE 1a betroffen und die Karbonatproduktionsraten blieben hoch. Die Diskussion konzentriert sich auf einen Vergleich mit globalen Karbonatplattformen. Im Gegensatz zu vorherigen Publikationen weisen die Ergebnisse darauf hin, daß die Nährstoffgehalte auf den subtropisch–tropischen Schelfen während des OAE 1a eher von mittlerer Intensität als hoch waren und die Karbonatproduktion intakt. Eine globale Biokalzifizierungs- oder Karbonatplattformkrise während des

Ereignisses kann nicht bestätigt werden. Der Vergleich bestätigt ein weitverbreitetes Absterben von Karbonatplattformen direkt nach dem OAE 1a.

Im vierten Kapitel werden die Fazies, Biostratigraphie und Geochemie dreier Profile der Serdj Formation des Djebel Serdj im nördlichen Zentraltunesien detailliert untersucht. Die Biostratigraphie basiert auf planktonischen Foraminiferen, benthischen Großforaminiferen und Ammoniten. Durch Kombination mit δ^{13}C- and δ^{18}O Stratigraphie kann ein differenzierter Zeitrahmen, der das frühe Späte Apt–späte Späte Apt umfaßt, erstellt werden. Die kombinierte Stratigraphie ermöglicht zusätzlich, ein bekanntes Wärmeinterval/Karbonatplattformabsterbeereignis im mittleren späten Apt festzustellen sowie zwei kurze Abkühlungsintervalle. Insgesamt können 4 Fazieseinheiten, die in 12 Mikrofaziestypen unterteilt werden, unterschieden werden. Jede der Fazieseinheiten repräsentiert ein anderes Paläomilieu der mittleren bis inneren Karbonatrampe. Die Aufeinanderfolge der verschiedenen Fazieseinheiten zeigt eine Verflachung des Meeresspiegels an, nur kurzzeitig unterbrochen von einer Vertiefung im mittleren Späten Apt. Die übergeordnete Verflachung kann tektonischen Bewegungen zugeordnet werden und ist nicht eustatischen Ursprunges. Die biotischen Vergesellschaftungen zeigen stabile oligotrophe Wasserverhältnisse während des gesamten untersuchten Zeitabschnittes an. Ein Absterben der Karbonatplattform aufgrund von erhöhten neritischen Nährstoffgehalten während des Wärmeintervalles trat auf dem tunesischen Schelf nicht auf.

Innerhalb des fünften Kapitels wird die Cephalopoden-Fauna der Hamada und Serdj Formationen des Djebel Serdj und Djebel Slata detailliert untersucht. Cephalopoden sind erstaunlich selten in diesen Ablagerungen zu finden, aber hilfreich, um Faziesveränderungen und die Position des OAE 1a festzulegen. Die gefundenen Cephalopoden werden in drei Assoziationen gruppiert, welche Faziesassoziationen, die aus den Kapiteln 2 und 4 abgeleitet wurden, zugeordnet werden. Die Ergebnisse zeigen an, daß die Cephalopoden in Paläomilieus der äußeren und mittleren Karbonatrampe sowie in der Lagune der inneren Rampe gelebt haben. Die tunesischen Cephalopoden des Frühen Apts zeigen Verbindungen zur zentralen und westlichen Tethys sowie zur atlantischen Provinz. Die Assoziationen des Späten Apt sind Faunen der westlichen und zentralen Tethys sowie Faunen aus Südamerika ähnlich.

CHAPTER 1

Introduction

Mid-Cretaceous sedimentary rocks of the Tunisian carbonate platform cropping out in the southwestern part of Djebel Serdj, close to the village of Beskra.

Introduction

The present thesis deals with the palaeoenvironmental evolution and sea level changes of the Tunisian carbonate platform margin during the Late Barremian–Late Aptian. Special emphasis is put on the sedimentary imprints of prominent palaeoceanographic and palaeoclimatic events, including the late Early Aptian Oceanic Anoxic Event 1a (OAE 1a) and two warming intervals associated with major carbonate platform drowning in the early- and mid-Late Aptian. Furthermore, the cephalopod fauna of the platform margin is investigated in detail. Methods include sedimentology, palaeontology, biostratigraphy, chemostratigraphy, and geochemistry. The samples for the detailed investigations were conducted during two field campaigns in north-central Tunisia in 2005 and 2006. 12 sections at eight different localities, most of them located along Djebel Serdj, were measured in detail with a total length of approximately 2.700 metres. 982 bulk rock samples were prepared for analyses on thin sections and residues of washed material. Geochemical data ($\delta^{13}C$, $\delta^{18}O$, $CaCO_3$, and TOC contents) was obtained from almost 250 bulk rock samples. About 150 macrofossils were prepared for taxonomic determinations. All data sets and samples related to this thesis are stored at Bremen University, Department of Geosciences (Stratigraphy and Sedimentology Research Group, Prof. Dr. J. Kuss and Geosciences Collection, Dr. J. Lehmann).

The following paragraphs give an overview on the Mid-Cretaceous greenhouse world, Oceanic Anoxic Events, and the Mid-Cretaceous carbonate platforms. Furthermore, the investigated palaeoceanographic and palaeoclimatic events of the Late Barremian–Late Aptian are introduced and the regional geological background is described in detail. Finally, the objectives of the thesis are outlined.

1. The Mid-Cretaceous: a time of global changes

1.1. The Mid-Cretaceous greenhouse world

The Mid-Cretaceous period (Aptian to Turonian, 120 to 90 my) is recognised for its exceptional greenhouse climate and major changes in the oceanic environment, e.g. expressed by the occurrence of several Oceanic Anoxic Events (OAEs) (Barron, 1983; Leckie et al., 2002). Substantial evidence for the greenhouse climate include stretched boundaries of the reef line, vast forests in polar regions, and an absence of expanded ice sheets at the poles (Francis and Frakes, 1993; Simo et al., 1993; Harland et al., 2007). Several authors suggested that high levels of atmospheric carbon dioxide (CO_2), perhaps up to 10 times the present level, were responsible for the exceptional warmth (e.g. Barron and Washington, 1985, Beerling and Royer, 2002). The resulting climate was equable with a low pole to equator temperature gradient (Chumakov et al., 1995). The source of the elevated atmospheric CO_2 levels has been attributed to outgassing by increased submarine volcanism, including enhanced spreading along mid-ocean ridges and the formation of large igneous provinces (LIPs) (e.g. Arthur et al., 1985; Larson, 1991). The warm, humid climatic conditions during the Mid-Cretaceous, which reached a temperature maximum during the Cenomanian–Turonian, were accompanied by a long term sea-level rise (Haq et al., 1988; Clarke and Jenkyns, 1999).

However, climatic conditions during the Mid-Cretaceous greenhouse world were far from stable. Several brief cooling and warming phases were superimposed on this period of global warming

(Weissert and Lini, 1991; Price, 2003). These climatic instabilities have been related to variations in atmospheric CO_2 concentrations (e.g. Weissert and Erba, 2004) and subordinately also to the dissociation of methane gas hydrates trapped in marine sediments (e.g. Beerling et al., 2002).

The oceanic circulation pattern in the Mid-Cretaceous were also fundamentally different than those observed in the present ocean. Warm and saline bottom water probably formed in the subtropics–tropics and flowed poleward, transferring heat (e.g. Brass et al., 1982). The ocean surface water currents were characterised by westward flowing, circumglobal currents (Barron, 1987). The Tethys was probably dominated by clockwise gyres (Poulsen et al., 2001). Furthermore, the Mid-Cretaceous is associated with major plate tectonic movements and thus landmass rearrangement, most notably the tectonic evolution of the proto-Atlantic and the concomitant development of the Equatorial Atlantic Gateway during the Cenomanian–Turonian, which had as strong influence on oceanic circulation, climatic, and biogeographic distribution patterns (Wagner and Pletsch, 1999; Poulsen et al., 2003).

1.2. Oceanic Anoxic Events

The specific climatic and oceanographic conditions during the Mid-Cretaceous greenhouse world favoured the occurrence of Oceanic Anoxic Events (OAEs; Fig. 1). These brief episodes of major oceanic perturbations are associated with heightened marine productivity, changes in marine biota (such as dramatic turnover in siliceous and calcareous plankton), accelerated burial of organic matter, and dysoxic to anoxic conditions in deep marine bottom waters (Schlanger and Jenkyns, 1976; Arthur and Sagemann, 1994; Leckie et al., 2002).

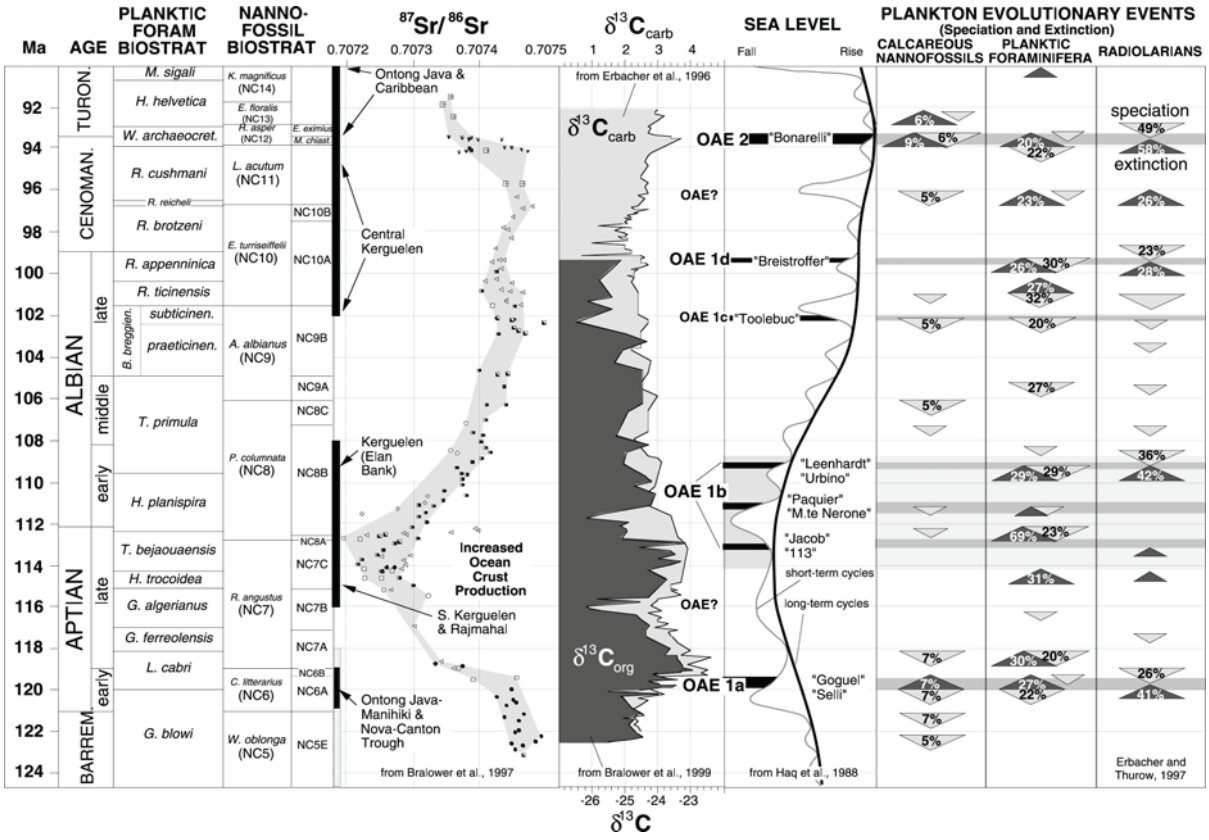

Figure 1: Oceanic Anoxic Events during the Mid-Cretaceous correlated with sea-level changes, biostratigraphy, seawater $^{87}Sr/^{86}Sr$ ratios, $\delta^{13}C$ curves, timing of oceanic plateaus, and plankton evolutionary events. From Leckie et al. (2002).

They are accompanied by positive $\delta^{13}C$ isotopic excursions with peak values of up to 2‰ higher than the background values (Erbacher et al., 1996; Bralower et al., 1999). The two most prominent OAEs are the late Early Aptian OAE 1a and the OAE 2 at the Cenomanian/Turonian boundary. The geological and climatic processes responsible for the occurrence of the OAEs have received much attention during the last 3 decades, but satisfactory explanation has remained elusive. Several authors suggested relationships between OAEs and volcanism, e.g. the formation of the Ontong Java–Manihiki Plateau in the equatorial mid-Pacific is exactly time-equivalent with the OAE 1a (e.g. Bralower et al., 1997; Larson and Erba, 1999; Jones and Jenkyns, 2001). Trace metal peaks coincident with biotic changes and pronounced strontium isotope excursions support this relationship and suggest that marine productivity may have been stimulated by a higher availability of biolimiting metals, such as iron (Sinton and Duncan, 1994; Walczak, 2006).

1.3. Carbonate platforms during the Mid-Cretaceous

The sea-level during the Mid-Cretaceous was 100-200 m higher than today and large areas of the continental shelves were flooded, providing vast space for carbonate platform development in the subtropical–tropical realm (Fig. 2; Haq et al., 1988; Simo et al., 1993; Ziegler et al., 2003). These carbonate platforms were extensively colonised by characteristic biota, including colonial scleractinian corals, rudist bivalves, stromatoporids, larger foraminifers (including orbitolinids) as well as dasycladacean algae and calcareous red algae (Masse, 1992; Kiessling et al., 2003). These photophilic communities were dependant on warm and shallow, nutrient-depleted waters (Hallock and Schlager, 1986; Wood, 1993). The presence of peloids, ooids, and oncolites indicate widespread Bahamian-type environments (Kiessling et al., 2003).

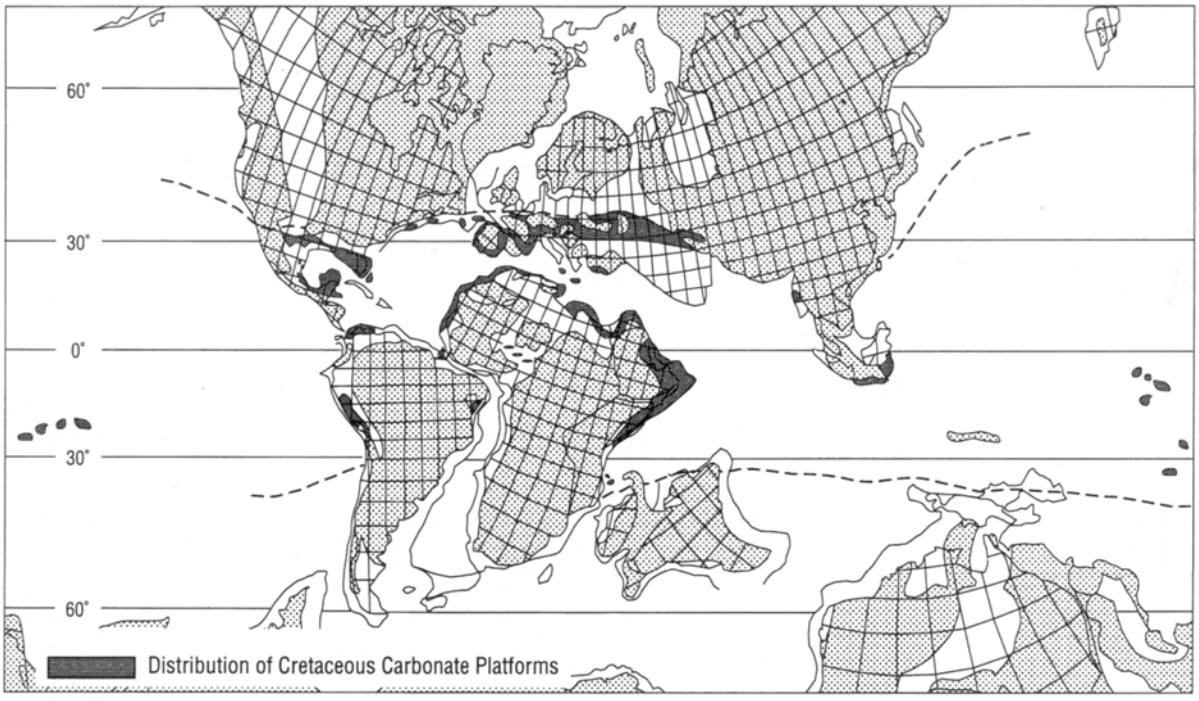

Figure 2: Distribution of Cretaceous carbonate platforms. From Simo et al. (1993).

The carbonate platform evolution during the Mid-Cretaceous was punctuated by a series of drowning events (Weissert et al., 1998; Skelton, 2003). Drowning of a platform, meaning its submergence below the euphotic zone, occurs if its upward growth rate fails to keep pace with rates of subsidence or sea-level rise due to unfavourable conditions for primary carbonate producers, e.g. caused by a nutrification (Schlager, 1981; Hallock and Schlager 1986). Some brief episodes of major carbonate platform drowning possibly corresponded to Oceanic Anoxic Events (Skelton, 2003).

2. Investigated palaeoceanographic and palaeoclimatic events during the Late Barremian–Late Aptian

2.1. The Oceanic Anoxic Event 1a

The OAE 1a (Fig. 3) is the first globally distributed Oceanic Anoxic Event in the Cretaceous and therefore regarded as a major turning point in palaeoceanographic conditions (Leckie et al., 2002). It is associated with heightened marine productivity, increased organic carbon burial, eustatic sea-level rise, and significant changes in neritic–pelagic biotic communities (Haq et al., 1988; Erbacher et al., 1996; Erba, 2004; Luciani et al., 2006). Furthermore, the event is accompanied by pronounced carbon isotope excursions, including a sharp negative $\delta^{13}C$ excursion at its onset and 2 positive excursions during the event (Menegatti et al., 1998; Van Breugel et al., 2007).

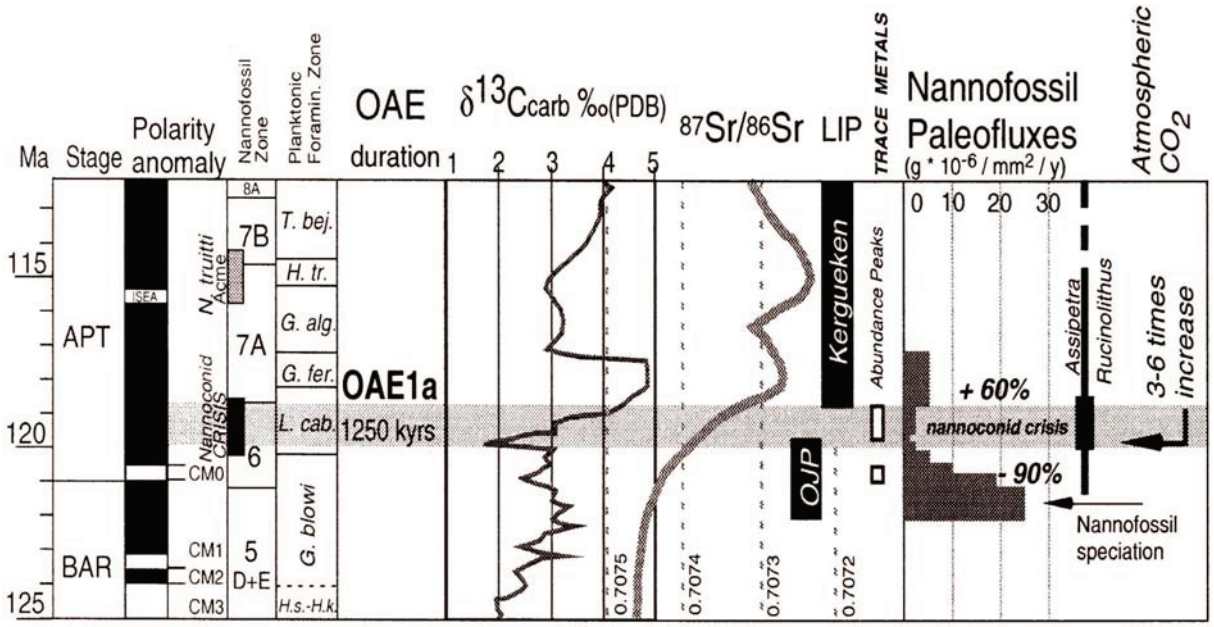

Figure 3: Summary of the major geochemical, oceanographic, climatic, and biotic changes around the late Lower Aptian Anoxic Event 1a. From Erba et al. (2004).

The geologic and climatic background of the OAE 1a is still a matter of debate (chapters 2 and 3). Strontium isotopic excursions and trace metal peaks coincident with biotic changes suggest relationships to increased submarine volcanism in the Pacific Ocean, related to the emplacement of the Ontong Java-Manihiki Plateau (compare Chapter 1.2). The OAE 1a has been often explained by massive additions of volcanogenic CO_2 to the atmosphere, which led to temporarily intensified greenhouse conditions and global humidity increase (e.g. Bralower et al., 1994; Jones and Jenkyns,

2001). Under these climatic conditions, excess nutrient runoff from the continents and increased upwelling could have caused an eutrophication of marine environments (e.g. Menegatti et al., 1998). Erba (2004) notes that this does not explain eutrophic conditions during OAE 1a documented from the remote parts of the oceans. Alternatively, some authors proposed a direct stimulation of marine productivity by hydrothermal input of biolimiting metals during volcanic plateau construction (Larson and Erba, 1999; Walczak, 2006). Furthermore, the OAE 1a is associated with a biocalcification crisis, caused by unfavourable conditions for calcareous plankton in surface waters due to excess nutrients and/or ocean acidification related to excess atmospheric CO_2 concentrations (Wissler et al., 2003; Erba and Tremolada, 2004).

2.2. Carbonate platform drowning events

Two episodes of widespread carbonate platform drowning coupled with global warming pulses have been distinguished in the late Early Aptian–early Late Aptian and mid-Late Aptian (Fig. 4; Weissert and Lini, 1991; Weissert et al., 1998; Herrle and Mutterlose, 2003). Some authors suggested that the onset of the first drowning phase was coincident with the OAE 1a (e.g. Föllmi et al., 2006; Burla et al., 2008). Evidence for the platform drowning episodes comes mainly from carbonate platforms of the subtropical realm, most notably the northern Tethys margin (Weissert et al., 1998; Lehmann et al., 2000; Castro et al., 2006). In recent years, some researchers recognised that carbonate platforms of the southern Tethys realm were not or less affected by drowning (e.g. Immenhauser et al., 2005; Thielemann, 2006; Chaabani and Razgallah; 2006, this study), which raises the question if drowning was rather a subtropical than woldwide phenomenon (chapters 2, 3, and 4). Hypotheses to account for both drowning episodes concentrate on nutrification of shallow marine environments, either by increased coastal runoff and/or by upwelling (Weissert et al., 1998; Föllmi et al., 2006). Furthermore, highly elevated atmospheric CO_2 levels could have supported ocean acidification, which additionally destabilised shallow marine ecosystems (Herrle and Mutterlose, 2003; Wissler et al., 2003, Weissert and Erba, 2004).

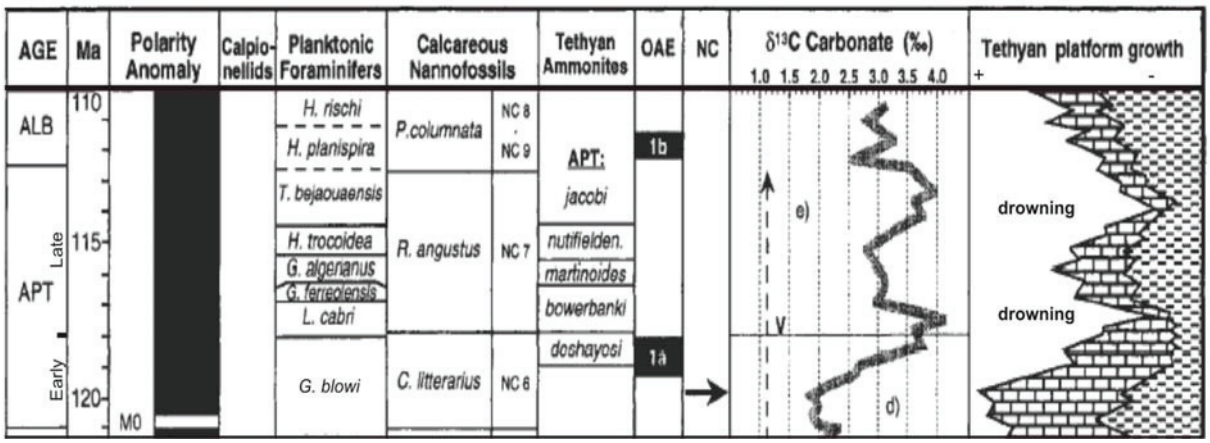

Figure 4: Aptian/Albian Oceanic Anoxic Events, biostratigraphy, geochemistry, and Tethyan carbonate platform drowning. Modified after Weissert et al. (1998).

3. Regional geological background

3.1. Tectonic evolution of central Tunisia

Central Tunisia is part of the eastern Atlas domain; it corresponds to a fold thrust belt linking the North African Atlas and the Sicily Apennine chains, called the peri-Mediterranean orogenic arc (Burollet, 1991; Coward and Ries, 2003). The uppermost crust of the eastern Atlas domain is composed of Mesozoic and Cenozoic sedimentary rocks that were deposited in a mosaic of intrashelf basins and then influenced by tectonic deformation with different intensities and styles (Bobier et al., 1991; Bouaziz et al., 2002). At present, this realm essentially consists of NE–SW trending folds, strike-slip faults and diapirism (Ben Ferjani et al., 1990; Bédir et al., 2001).

During large parts of the Mesozoic, from Triassic until Aptian times, central Tunisia was dominated by an extensional tectonic regime related to the NE–SW to N–S opening of the Tethys (Grasso, 1999; Coward and Ries, 2003). This tectonic regime, which affected the entire present North African margin, led to the formation of rifts, tilted blocks, horsts, and grabens (Burollet, 1991; Bouaziz et al., 2002). From Aptian times on, Tunisia was severely affected by diapirism (Jallouli et al., 2005). The combination of salt and extensional tectonics led to an uplift of large parts of central and north Tunisia during the Late Aptian–Early Albian (Ben Ferjani et al., 1990). During the Late Cretaceous and Cenozoic, a series of compressional and extensional regimes related to the northward movement of the African plate affected central Tunisia (Bouaziz et al., 2002; Coward and Ries, 2003). During the Miocene a prominent NW-SE compressional event caused an inversion of older normal faults, reactivated uplifts, and diapirs of Triassic evporites and created most of the folded structures observed today, e.g. also the anticline of Djebel Serdj (Turki, 1977; Bouaziz et al., 2002).

3.2. Palaeogeography of the central Tunisian carbonate platform during the Aptian

During the Mid-Cretaceous, central Tunisia was repeatedly occupied by a broad carbonate platform which evolved between the continental Saharan platform in the south and a Tethys-connected deeper marine basin in the north, called the Tunisian Trough (e.g. Boltenhagen, 1985; Ben Ferjani et al., 1990, Bobier et al., 1991). The Tunisian carbonate platform was part of the tropical carbonate platform system of the southern Tethys continental margin (Kiessling et al., 2003), which included also the Egyptian Levant platform (Chapter 3). The first extended Mid-Cretaceous carbonate platform in Tunisia established during the prominent eustatic sea-level rise of the Early Aptian, which led to an overall enlargement of shallow marine intrashelf basins in North Africa (M`Rabet; 1987; Haq et al., 1988; Dercourt et al., 2000). This Aptian carbonate platform was characterised by some specific palaeogeographic features (for palaeogeographic maps and investigated area see chapters 2 and 4): A stable high (“Kasserine Island”) was located in the eastern part of the platform. A mosaic of islands in the central part of the platform developed due to tectonical uplift in the Late Aptian and divided it into a more or less restricted southern-, and a Tethys-connected northern part. A prominent north-south trending high zone (“North–South Axis”) separated the platform from the tectonically more stable eastern Pelagic Block (Marie et al., 1982; Ben Ferjani et al., 1990; Burollet, 1991).

During the Latest Aptian–Early Albian, large parts of the Tunisian carbonate platform emerged as a consequence of extensional and salt tectonics (compare Chapter 3.1).

4. Overview of research

The purpose of this study is to investigate the Late Barremian–Late Aptian palaeoenvironmental evolution of the Tunisian carbonate platform margin with respect to the sedimentary imprints of prominent palaeoceanographic and palaeoclimatic events. These include the late Early Aptian Oceanic Anoxic Event 1a (OAE 1a) and two time intervals associated with major carbonate platform drowning during the early- and mid-Late Aptian. While the ecological changes during these events on the subtropical shelves, most notably on the northern Tethys margin, are well studied (e.g. Weissert et al., 1998; Föllmi et al., 2006, Yilmaz et al., 2004; Castro et al., 2008), only few data exist from the tropical realm (e.g. the Southern Tethys margin; Immenhauser et al., 2005; Thielemann, 2006; this study). The deposits chosen for the detailed investigations crop out at Djebel Serdj, north-central Tunisia and belong to the Hamada and Serdj formations. They are unusually expanded and thus particularly suitable for high resolution studies. In an integrated approach sedimentology, palaeontology, biostratigraphy, chemostratigraphy, and geochemistry are combined. The objectives of the thesis are summarised in four separate chapters/manuscripts, which are either published or submitted to international journals.

In chapters 2 and 4, biostratigraphy (planktonic foraminifers, larger benthic foraminifers, and ammonites) in combination with $\delta^{13}C$- stratigraphy are used to establish detailed time frames for the investigated deposits. The combined stratigraphic approach allows global correlations and a precise determination of the prominent palaeoevents. Sedimentologic analyses, including facies and microfacies studies, are used to reconstruct the palaeoenvironmental evolution and sea-level changes of the platform margin. The sections are subdivided into facies associations (Chapter 2) or facies units (Chapter 4), which represent different outer- to inner ramp palaeoenvironments. The regional ecological changes during the late Early Aptian OAE 1a and early Late Aptian carbonate platform drowning episode are investigated in Chapter 2. Main objectives focussed in the discussion of this chapter are biotic changes during both events, changes in trophic levels, and questions concerning the carbonate production/preservation during OAE 1a. Chapter 3 exclusively concentrates on a comparison of the results concerning both events with global carbonate platform growth. Main objectives discussed are changes in trophic levels on subtropical–tropical shelves and the influence of the OAE 1a on the neritic carbonate production factories. Results allow to contribute to the discussion on the causes for the event. Ecological changes on the Tunisian shelf during the mid-Late Aptian carbonate platform drowning episode are investigated in Chapter 4. The discussion of this chapter focuses on a comparison with global platform growth during this time interval. Objectives discussed are factors promoting platform growth or decline in different climatic zones and the extent of platform drowning during the mid-Late Aptian. In Chapter 5, the cephalopod fauna of the Tunisian carbonate platform is investigated in detail and compared to other regions. Chapter 6 summarises the previous five chapters and announces topics for future investigations.

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CHAPTER 2

Microfacies, biostratigraphy, and geochemistry of the hemipelagic Barremian–Aptian in north-central Tunisia: Influence of the OAE 1a on the southern Tethys margin

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Published in Palaeogeography, Palaeoclimatology, Palaeoecology

Vol. 261, p. 246–260, 2008

Marlstones of the Hamada Formation cropping out in the central part of Djebel Serdj, close to the village Dechret el Golea. The limestone cliff in the upper part marks the base of the Serdj Formation.

Microfacies, biostratigraphy, and geochemistry of the hemipelagic Barremian–Aptian in north-central Tunisia: Influence of the OAE 1a on the southern Tethys margin

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Abstract

Upper Barremian–lower Upper Aptian hemipelagic deposits of the Hamada Formation in the Djebel Serdj area, north-central Tunisia were studied in detail with regard to microfacies, biostratigraphy, $\delta^{13}C$ stratigraphy, and geochemistry. Our data provide insights into the palaeoenvironmental evolution and sea-level fluctuations of the Tunisian shelf. The unusually expanded deposits consist of mud-, wacke-, and packstones which reflect mid- and outer-ramp depositional environments. Planktonic foraminifer and $\delta^{13}C$ stratigraphy allowed us to establish a detailed time-frame and the recognition of the Lower Aptian Oceanic Anoxic Event 1a (OAE 1a) as well as time-equivalent deposits of shallow-marine carbonate platform drowning. Based on our microfacies studies, we subdivide the studied sections into four genetic intervals: a pre-OAE 1a interval, an OAE 1a and platform-drowning-equivalent interval, and a post-platform-drowning interval. We present a 3rd order sea-level curve for the Tunisian shelf, deriving from the results of our microfacies studies.

Deposits of the OAE 1a in the sections investigated are characterised by bioclastic wacke- and packstones with high abundances of poorly preserved radiolarians and moderately to well preserved planktonic foraminifers, suggesting a transgression and an eutrophication of the upper water column. Scarceness of benthic macrofossils, low abundances of small benthic foraminifers and ostracods possibly suggest dysoxic conditions at the seafloor. Mudstones of the platform drowning time-equivalent deposits, directly overlying the OAE 1a, are partly showing a pronounced drop in carbonate content and are scarce of macrofossils.

Keywords: Aptian; OAE 1a; platform drowning; microfacies

1. Introduction

Marine sediments of the Late Barremian–early Late Aptian interval provide information about significant changes in the ocean/climate system and several major palaeoceanographic and palaeobiological events (e.g. Leckie et al., 2002 and references therein). Especially the late Early Aptian has been focussed by many authors in last and recent years, due to a prominent episode of globally increased organic carbon burial (Oceanic Anoxic Event 1a) (Schlanger and Jenkyns, 1976; Arthur and Schlanger, 1979; Jenkyns, 1980, Arthur and Sageman, 1994; Menegatti et al., 1998; Bralower et al., 1999; Leckie et al., 2002; Erba, 2004), which is associated with increased marine productivity, a sea-level rise, and significant changes in marine flora and fauna (e.g. an appearance of widespread radiolarian blooms and crises in carbonate producing biota) (e.g. Haq, et al., 1988;

Erbacher et al., 1996; Hochuli, 1999; Jenkyns, 1999; Erba, 2004). Geological evidence (e.g. trace metal peaks and pronounced strontium isotope excursions) suggest a direct link of this event with increased submarine volcanism in the Pacific ocean, related to the emplacement of the Ontong Java-Manihiki plateau (e.g. Larson, 1991; Bralower et al., 1997; Larson and Erba, 1999; Jones and Jenkyns, 2001; Jahren, 2002). Many authors suggested, that outgassing of high amounts of CO_2 into the atmosphere was responsible for temporarily intensified greenhouse conditions, which in turn led to several processes (e.g. increased coastal runoff, intensified wind velocities, and upwelling) causing an eutrophication of neritic and pelagic environments as well as distinct perturbations in carbonate production (e.g. Weissert, 1989; Caldeira and Rampino, 1991; Weissert et al., 1998; Jones and Jenkyns, 2001; Weissert and Erba, 2004). It has been critically noted, that these mechanisms alone can not explain the high productivity documented from remote parts of large oceans (Erba, 2004). Another explanation for the OAE 1a is a direct stimulation of marine productivity by hydrothermal input of biolimiting metals (e.g. Fe, Zn) during plateau construction (e.g. Sinton and Duncan, 1997; Larson and Erba, 1999; Walczak, 2006). Furthermore, the results of a study by Heimhofer et al. (2004) suggest that variations in CO_2 concentrations during the OAE 1a have only been of minor importance. These authors found no evidence for major climatic disturbances during OAE 1a in the Vocontian basin, France.

Initially, investigations of the OAE 1a concentrated on pelagic deposits (e.g. Schlanger and Jenkyns, 1976; Jenkyns, 1980; Coccioni et al., 1987; Bréhéret, 1988; Bralower et al., 1994). In more recent years, attention has been also paid to the hemipelagic or shallow-marine time-equivalent deposits (e.g. Jenkyns, 1995; Aguado et al., 1999; de Gea et al., 2003; Immenhauser et al., 2005; Föllmi et al., 2006), which play an important role in understanding the processes leading to the OAE 1a.

In addition, an episode of shallow-water carbonate-platform drowning, which coincides in the initial part with the OAE 1a but lasts up to 4 my (Weissert et al., 1998; Föllmi et al., 2006), is recorded from the northern and southwestern Tethyan margin and from circum-Atlantic regions (e.g. Jansa, 1993; Föllmi et al., 1994; Grötsch et al., 1998; Weissert et al., 1998; Föllmi et al., 2006). Hypotheses to account for this event concentrate on eutrophication of marginal environments either by increased continental runoff and/or by upwelling (e.g. Weissert et al., 1998; Föllmi et al., 2006).

The onset of both events is characterised by a short-lived negative $\delta^{13}C$ excursion, which has been attributed to dissociation of CH_4-hydrates (Jahren and Arens, 1998; Opdyke et al., 1999; Jahren et al., 2001; Beerling et al., 2003). They are followed by pronounced positive $\delta^{13}C$ excursions, which reflect changes in the marine carbon partitioning probably as consequence of nutrient-enhanced productivity (e.g. Menegatti et al., 1998; Weissert et al., 1998; Erba, 2004).

This study focuses on the microfacies, geochemistry, and biostratigraphy of a Late Barremian–early Late Aptian succession cropping out at Djebel Serdj in north-central Tunisia (Fig. 1). The good exposure and expansion of the deposits (330 m) provide the excellent opportunity to study the palaeoenvironmental evolution of hemipelagic, mid- to outer-ramp deposits situated on the southern edge of the Tethyan ocean in detail. Respect is paid to the local sedimentary expression of the OAE 1a, which is more than 45 m thick in the studied area. The main goal of this study is to enhance our knowledge on the largely unknown impact of this event on the southern Tethys margin.

2. Geological setting

Central Tunisia is part of the eastern Atlassic domain; it consists of Mesozoic and Cenozoic sedimentary rocks deposited in several basins. Two major tectonic cycles affected this area, which is characterised by NE–SW trending folds, strike-slip faults and diapirism (Burollet, 1990; Bouaziz et al., 2002). The first tectonic cycle was related to the NE-SW to N-S opening of the Tethys in the Late Permian to Early Cretaceous and led to the formation of rifts, tilted blocks, horsts and grabens by extensional tectonics. The second tectonic cycle was characterised by NW-SE compression in the Cenozoic and caused an inversion of normal faults, reactivated uplifts and diapirs of Triassic evaporites (Ben Ferjani et al., 1990; Grasso et al., 1999; Bouaziz et al., 2002).

During the Late Barremian–early Late Aptian, central Tunisia was dominated by shallow-marine sedimentation in a mosaic of intrashelf basins. A stable high ("Kasserine Island") was located in the eastern part (Fig. 1). Typical deposits of this shallow marine domain are limestones and sandstones (e.g. M`Rabet 1987; Ben Ferjani et al., 1990, Chekhma et al., 1990; Chaabani et al., 1992; Chaabani and Razgallah, 2006). The northern part of Tunisia ("Tunisian Trough") was characterised by basinal sedimentation; typical deposits are claystones and marlstones, partly with intercalations of turbidites (e.g. Turki, 1985; Memmi, 1989, Ben Haj Ali and Ben Haj Ali, 1996).

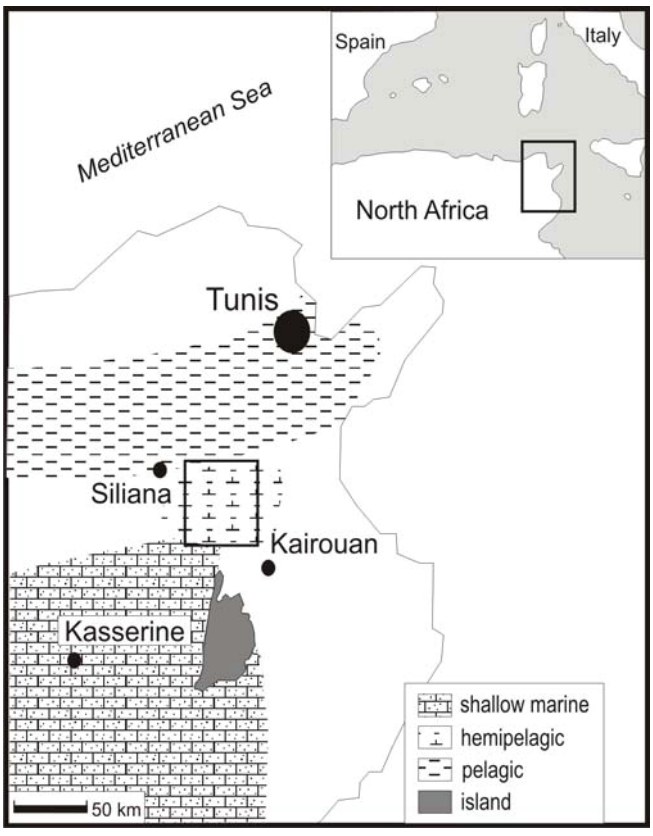

Figure 1: Palaeogeographic map of Tunisia (see upper inlay) for the Lower Aptian. The lower black rectangle marks the studied area (Fig. 2). After Tlatli (1980) and M`Rabet et al. (1987).

The studied area is located about 25km north of Kasserine Island, in a hemipelagic transition zone between the shallow marine domain and the Tunisian Trough (Fig. 1). The deposits investigated are mainly assigned to the 305 m thick hemipelagic Hamada Formation (Fig. 3), which consists of a 82 m

thick limestone/marlstone-alternation dominated lower member, a marlstone-dominated 154 m thick middle member, and a marlstone-dominated 70 m thick upper member. The uppermost part of the studied deposits additionally include the 24 m thick limestones of the lowermost unit (S1) of the Serdj Formation, which is mainly composed of shallow-marine carbonates. Tlatli (1980) introduced lithological units and proposed an Early Aptian to early Late Aptian age for the Hamada Formation and an early Late Aptian age for the base of the Serdj Formation by using planktonic and benthic foraminifers for biostratigraphy.

3. Materials and methods

The study is based on two sections (A and B; 60 m and 270 m thickness, respectively) located in the Djebel Serdj region (Fig. 2). The sections were choosen for their good exposure and low tectonic overprint. A composite section is shown in Fig. 3.

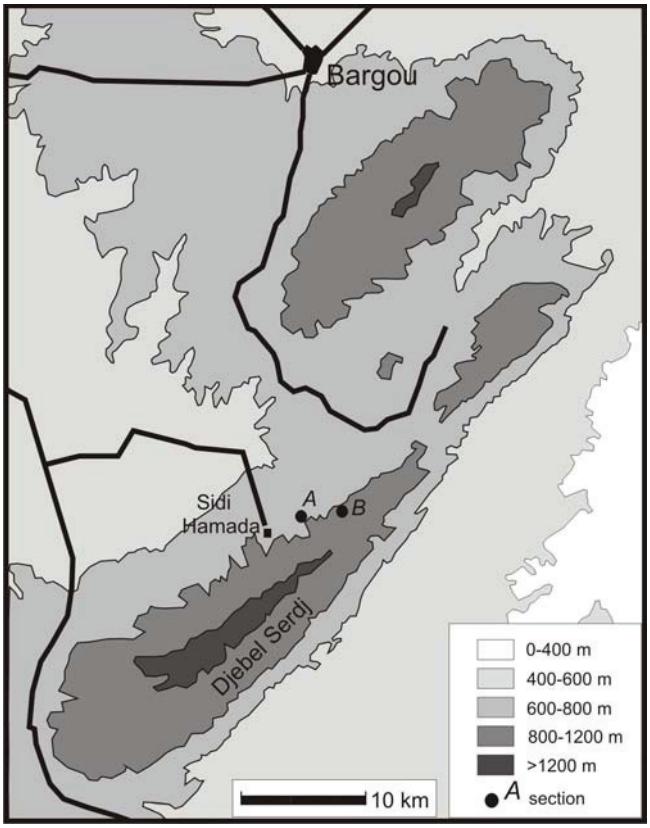

Figure 2: Map of the Djebel Serdj area with locations of the sections investigated.

Our detailed microfacies, biostratigraphical, and geochemical study presented in this paper is based on 145 samples (Fig. 3). In the lowermost part of the section and throughout the OAE 1a the spacing of samples was <1 m, whereas the homogenous marlstones in the upper part of the section were sampled at 2 to 10 m intervals. One-hundred fourteen thin sections were prepared from indurate samples (marlstones, limestones and siltstones). Thirty-one marlstone samples were disaggregated in clay dispersion (Rewoquat) and subsequently washed through sieves of 630, 100, 63, and 20 micron-screen. In both thin sections and washed samples, we determined microfacies composition and

rounding of components. Depositional textures, relative abundances, and sorting of components were determined in thin sections. Relative abundances were obtained by using percentage estimation charts (e.g. Flügel, 2004). Components with abundances below 20% of the thin-section surface area are classified in: rare (few individuals), common (few individuals–10%), and abundant (10–20%). Abundances higher than 20% are plotted as percentages. Field observations and the results of the microscope analyses are summarized in 7 facies associations (A–G).

Biostratigraphy is based on planktonic foraminifers, which were picked from residues of washed material (60–100 specimen each sample). Taxonomic classifications, based mainly on shell texture and morphology, refer to Verga and Premoli Silva (2002) and Premoli Silva and Sliter (2002). The planktonic foraminifer zonal scheme is based on the standard low-latitude zonal schemes of Premoli Silva and Sliter (1999).

Carbon isotope data, additionally used for stratigraphy, has been obtained from 50 bulk rock samples which were measured in the RCOM, Bremen with a Finnigan MAT 251 mass spectrometer (accuracy +/- 0.07‰). The $\delta^{13}C$-curve is divided into segments, as invented by Menegatti et al. (1998) for time-equivalent deposits in the pelagic Roter Sattel and Cismon sections (Swiss Préalps and southern Alps of northern Italy). These segments, C1-C8, are often applied as a chronostratigraphic tool in global successions (e.g. Bralower et al., 1999; Luciani et al., 2001; de Gea et al., 2003; Immenhauser et al., 2005). They include: an increase in $\delta^{13}C$ values (C1 segment), followed by a decrease (C2) and a $\delta^{13}C$ minimum (C3), a significant increase in values (C4), a stable interval (C5), followed by a further increase (C6), then variable, but overall high values (C7), followed by decreasing $\delta^{13}C$ values (C8).

The $CaCO_3$ content of 130 samples (Fig. 3) was derived from the measurement of C_{total} with a Leco CNS-200 elemental analyzer (accuracy +/- 0.05%). The TOC content of the same samples was measured with a Leco CS-125 analyzer (accuracy +/- 0.02%). The measurements were carried out in the Alfred Wegener Institute, Bremerhaven.

4. Geochemical data and carbon isotope stratigraphy

4.1. $CaCO_3$ content

The carbonate content of the composite section ranges from 0 to 91% (Fig. 3).

Values fluctuate considerably between 0 to around 70% in the marlstone/limestone alternation forming the first 45 m of the succession. Low values reflect the occurrence of siltstone beds. Values between 70 to 80% characterise the overlying marlstone/limestone alternation and limestone dominated deposits between 45 and 87 m. The marlstones between 87 and 142 m show a distinct decline in $CaCO_3$ content, two minima of 30.7% and 42.7% are observed at 116 and 140 m. Values at around 60 to 70%, rarely up to 90% characterise the overlying marlstone and limestone deposits (from 142 to 305 m) until the uppermost, limestone dominated part of the succession, where the $CaCO_3$ content rises up to over 90% (from 305 to 315 m).

4.2. TOC content

The total organic carbon (TOC) content of the composite section is generally low, values range from 0.1% to 1.1% (Fig. 3). Samples in the lower 55 m of the succession contain less than 0.2% TOC. The

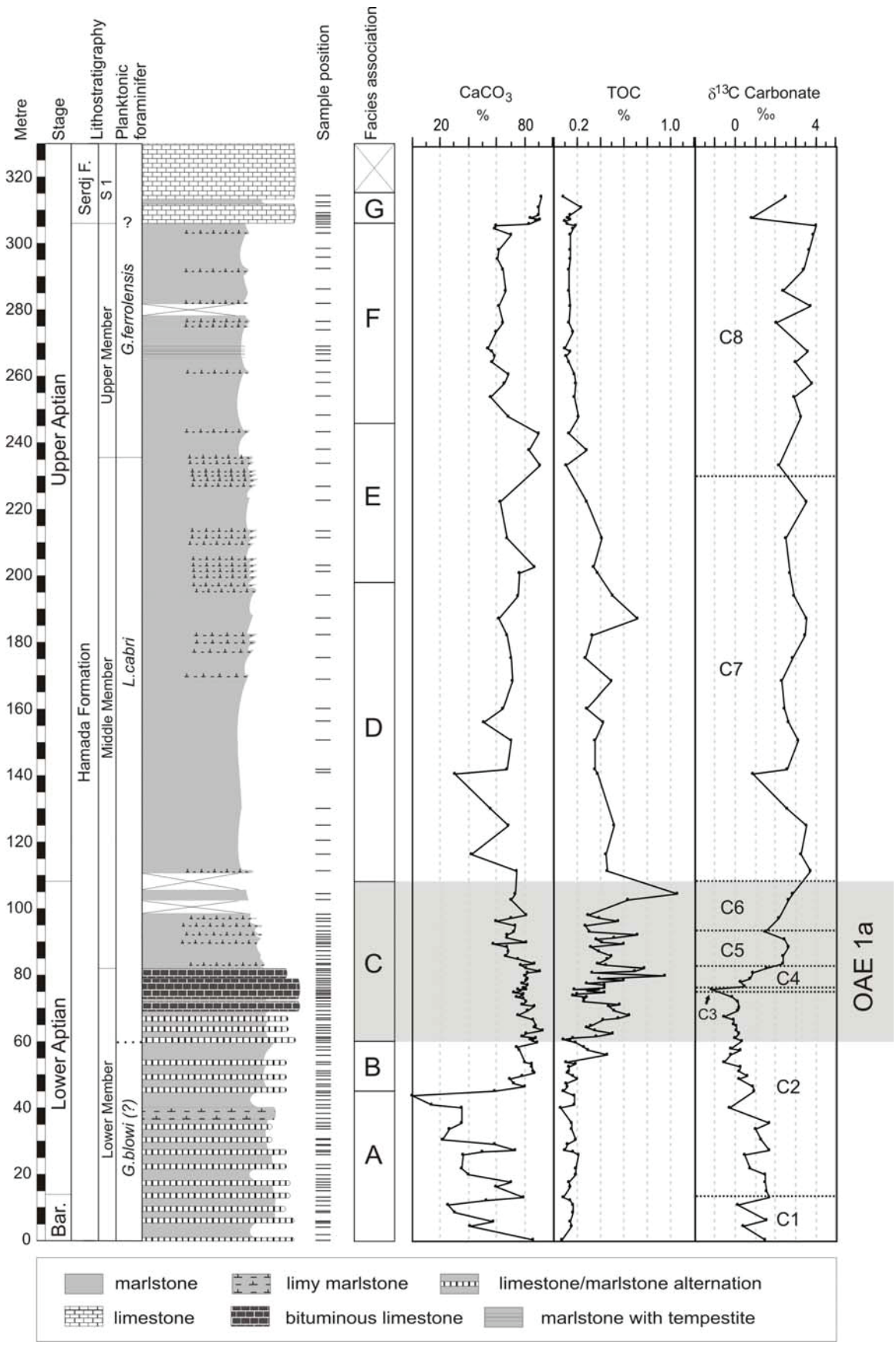

Figure 3: Composite section of Djebel Serdj with geochemistry and biostratigraphy. The shaded area marks the OAE 1a interval. Based on two sections (A=1–60 m, B=60–330 m). For locations see Fig. 2.

deposits between 55 and 108 m are characterised by fluctuations in values between 0.2 and 0.6%. A TOC maximum is reached at 105 m with 1.1%. The deposits from 108 to 218 m show values between 0.3 and 0.5%, exceptionally 0.7% at 187 m. The TOC content gradually decrease from 218 to 265 m, followed by moreless constant values between 0.1 and 0.2% in the uppermost part of the studied section (from 265 to 315 m).

4.3. Carbon isotope ratio and -stratigraphy

$\delta^{13}C$ values of the Serdj section range between -1.2‰ and 4‰.

Our $\delta^{13}C$-curve of the studied section (Fig. 3) exhibits excursions, which closely correlate with those described by Menegatti et al. (1998) and other authors for Upper Barremian–lower Upper Aptian deposits worldwide (e.g. Jenkyns, 1995; de Gea et al., 2003; Takashima et al., 2004; Immenhauser et al., 2005). We exclude a strong diagenetic overprint of the deposits and attribute a Late Barremian–Early Aptian age for the Hamada Formation. This age is additionally confirmed by the results of our biostratigraphic studies on planktonic foraminifers (see chapter 5).We divide the $\delta^{13}C$-curve into 8 segments (Fig. 3) as suggested by Menegatti et al. (1998) (see chapter 3). From the base of the section upwards, the changes in $\delta^{13}C$ values are characterised as follows:

The lowermost part of the section (first 14 m) shows fluctuating values between 0.1 and 1.7‰ (C1 segment). It is followed by an overall negative shift with fluctuations in values (C2). A $\delta^{13}C$ minima is observed at 75 m (C3, -1.2‰). A positive excursion (C4) characterises the deposits between 75 and 83 m. It is followed by an interval with moreless stable $\delta^{13}C$ values (C5, 83–92 m) around 2.4‰ and a second positive shift (C6) between 92 and 111 m. Fluctuating, but predominantly high positive $\delta^{13}C$ values (ranges from 0.9 to 3.5‰) characterise the deposits between 111 and 228 m (C7). The upper part of the succession is characterised by fluctuating values between 0.81 and 4‰ (C8, 228–315 m). In coeval Tethyan successions, the whole C8 segment is marked by a pronounced negative shift (e.g. Menegatti et al., 1998; Weissert et al., 1998; de Gea et al., 2003).

5. Bio- and isotope stratigraphy

The biozonation of the Djebel Serdj composite section is based on planktonic foraminifers, which are present in the largest part of the studied succession. Their tests are recrystallised and moderately to well preserved. Zonal markers are missing in the lower part of the section (first 120 m). Here, $\delta^{13}C$-stratigraphy (see chapter 4) allow a global correlation and the tentative definition of the corresponding standard foraminifer zone (Fig. 3). From the base upward three biozones were identified (Figs. 3 and 4):

Globigerinelloides blowi (?) Zone (from 0 to 60 m): Defined as interval from the first occurrence of *G. blowi* to the first occurrence of *L. cabri*, following Premoli Silva and Sliter (1999). The zone was not identified by the use of planktonic foraminifers since *G. blowi* and other marker species are absent. Isotopic data (C1 to C3 segment) clearly define this part of the studied interval as being the uppermost part of the *G. blowi* planktonic foraminifer zone (e.g. Erba et al., 1999; Luciani et al., 2001; de Gea et al., 2003). Low diversity planktonic foraminifer assemblages are represented by hedbergellids and gorbachikellids. The upper boundary of the zone coincides with the onset of the OAE 1a interval (Premoli Silva and Sliter, 1999).

Leupoldina cabri Zone (from 60 to 235 m): Defined as acme zone of the nominal taxon, which can be applied at larger scale, then comprising the OAE 1a in the lowermost part (Premoli Silva and Sliter, 2002). We use this zone as total range zone, because rare specimen of *L. cabri* already appear during the OAE 1a interval.

Hedbergellids are the most common planktonic foraminifers in this biozone, accompanied by rare to common occurrences of leupoldinids (mainly *L. pustulans pustulans* and *L. cabri*), rare globigerinelloidids and rare gorbachikellids. Single large specimens of *G. ferrolensis* appear in the middle of this biozone (Fig. 4). The genera *Leupoldina* and *Gorbachikella* disappear at the upper boundary of the zone (Fig. 4). $\delta^{13}C$ data (C3–C7 segment) confirm a correlation with the *L. cabri* biozone.

Globigerinelloides ferrolensis Zone (from 235m, the upper boundary is not defined): Partial range zone of *G. ferrolensis* from the last occurrence of *L. cabri* to the first occurrence of *G. algerianus*, according to Premoli Silva and Sliter (1999). Planktonic foraminifer assemblages in the *G. ferrolensis* Zone are dominated by hedbergellids, accompanied by rare large specimen of *G. ferrolensis*.

The scarcity of planktonic foraminifers in the uppermost part of the studied section prevents the identification of the planktonic foraminifer zone. $\delta^{13}C$ isotope data does not provide further stratigraphic information due to irregular isotopic values in most part of the C8 segment compared to other sections (see chapter 4).

6. Depositional environments

Seven facies associations have been distinguished (A–G) on the base of main components, textures, macro-, and microfossil associations as well as lithological variations observed in the outcrops. Figure 3 shows the the ranges of the facies associations in our composite section. An overview of their characterisation and environmental interpretation is presented in Table 1. Relative abundances of selected components are illustrated in Fig. 4. A sea-level curve (Fig. 4) was established by using changes in the depositional settings (Fig. 4). From base to top, the facies associations are as follows:

6.1. Facies association A: Silty bioclastic wackestone and packstone containing planktonic and small benthic foraminifers and ostracods, limestone/marlstone alternation (Fig. 5/A)

The 45 m thick facies association A is dominated by rhythmically alternating cm to dm thick olive green to grey marlstone and grey marly limestone beds. Grey to brownish marlstone (4–5 m thick) is intercalated in the lowermost and uppermost part. Few siltstone beds occur in the upper part. Bioturbation, thick lamination, and very thin bedding of marlstone is observed sporadically. Calcareous nodules appear in the lowermost part. Macrofossil assemblages in the first 25 m consist of rare to common echinoids (mainly *Toxaster*), brachiopods (Rynchonellida), bivalves (such as oysters), and gastropods. The upper 20 m are devoid of macrofossils.

Bioclasts in the thin sections mainly consist of fine-grained skeletal detritus and smaller sized (mainly <1 mm, maximum 3–5 mm) fragmented shells. In the first 27 m, planktonic foraminifers (small hedbergellids and gorbachikellids), small benthic foraminifers (mainly *Protomarssonella praeoxycona*, *Patellina subcretacea,* and *Ataxophragmiides*), and ostracods are common, but scarce in the upper part. Larger shells (bivalves and gastropods), echinoderm fragments, echinoid spines, and small

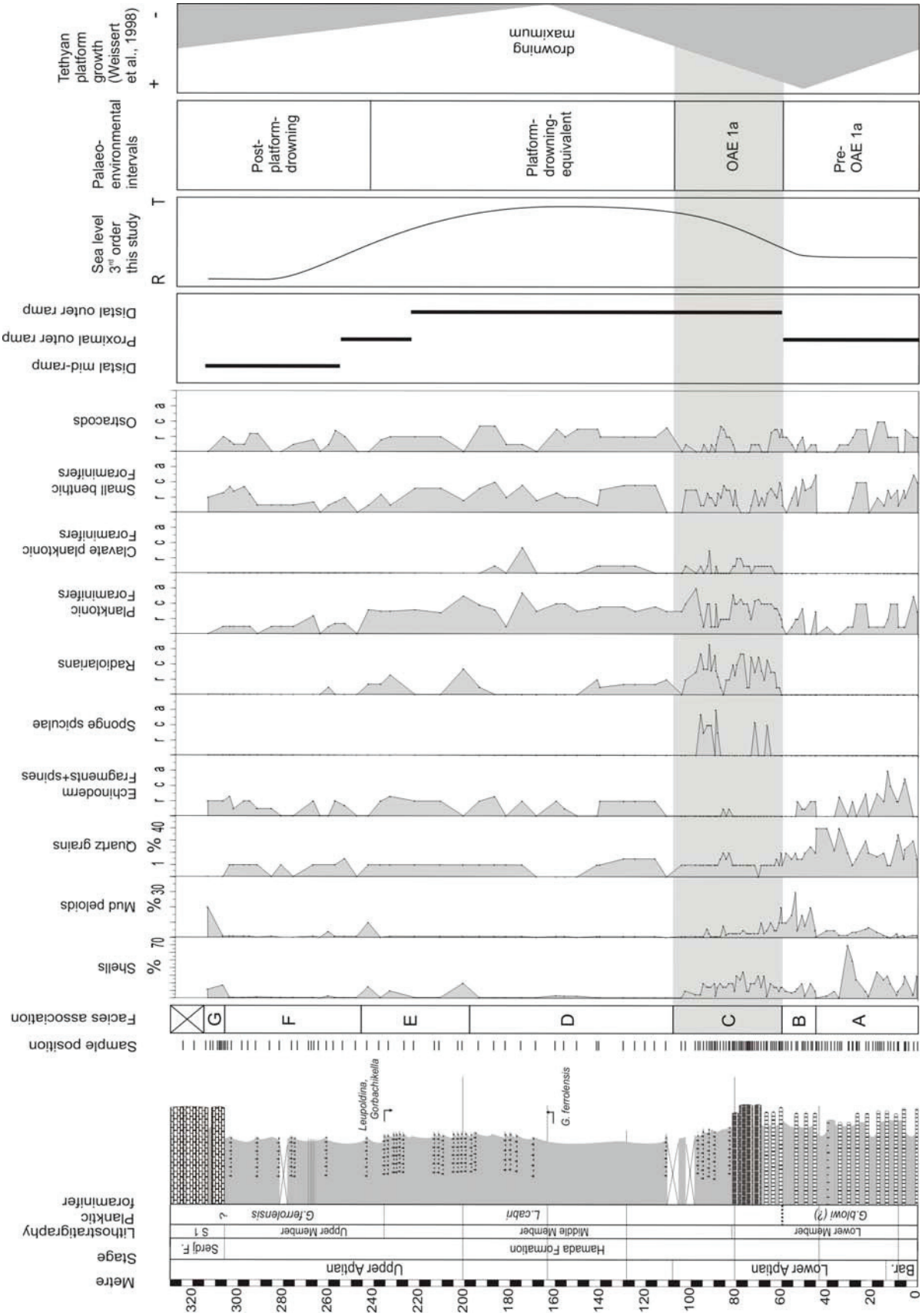

Figure 4: Composite section of Djebel Serdj with components, depositional settings, sea-level changes, and palaeoenvironmental intervals. Abbreviations: r=rare, c=common, a=abundant; R=Regression, T=Transgression. The abundances of components are estimated (see chapter 3). The shaded area marks the OAE 1a interval. For the description of the lithology see Fig. 3.

Facies association		Lithology	Microfacies / Macrofossils	Environmental interpretation
A	**silty bioclastic wacke- and packstone** containing planktonic, small benthic foraminifers, and ostracods	rhythmically alternating marlstone and limestone siltstone beds appear in the upper part nodular bedding, thick lamination and very thin bedding are observed sporadically	**Components:** fine-grained skeletal detritus, small shells, quartz grains, planktonic and small benthic foraminifers, ostracods, and other components **Macrofossils:** echinoderms, brachiopods, bivalves, gastropods, shells **Sorting/rounding:** poorly to moderately sorted, angular to subrounded shapes	proximal outer ramp (low-energy setting) seafloor temporarily influenced by bottom currents
B	**bioclastic to peloidal packstone** containing planktonic, small benthic foraminifers, and quartz grains	rhythmically alternating limy marlstone and limestone nodular bedding is common in the lower part, thick lamination occurs sporadically	**Components:** fine-grained skeletal detritus, small shells, mud peloids, planktonic and small benthic foraminifers, quartz grains, and other components **Macrofossils:** brachiopods, echinoids, bivalves, gastropods, shells **Sorting/rounding:** poorly to moderately sorted, angular to subrounded shapes	proximal outer ramp (low-energy setting) oxic conditions at the seafloor
C	**bioclastic wacke- and packstone** containing radiolarians, planktonic foraminifers, and sponge spiculae	alternating marlstone and limestone, bituminous limestone, marlstone nodular bedding and thin to thick lamination are observed sporadically	**Components:** fine-grained skeletal detritus, small shells, radiolarians, planktonic foraminifers, sponge spiculae, subordinated small benthic foraminifers, ostracods, and other components **Macrofossils:** ammonites, bivalves, gastropods, shells **Sorting/rounding:** poorly sorted / angular shapes orientation of bioclasts in the bedding plane	distal outer ramp (low-energy setting) meso- to eutrophic environment in the upper water column possibly dysoxic conditions at the seafloor seafloor influenced by bottom currents
D	**mudstone** containing planktonic, small benthic foraminifers, and ostracods	marlstone, intercalations of limy marlstone beds nodular and thin bedding are observed sporadically	**Components:** fine-grained skeletal detritus, small shells, planktonic and small benthic foraminifers, ostracods, and other components **Macrofossils: -** **Sorting/rounding:** poorly sorted / angular shapes	distal outer ramp (low-energy setting)
E	**mudstones and bioclastic wackestone,** containing planktonic, small benthic foraminifers, and ostracods	marlstone, intercalations of limestone beds nodular bedding and thick lamination occurs sporadically	**Components:** fine-grained skeletal detritus, small shells, planktonic and small benthic foraminifers, ostracods, and other components **Macrofossils: -** **Sorting/rounding:** poorly sorted / angular shapes	distal to proximal outer ramp (low-energy setting)
F	**mudstone** containing small benthic foraminifers	marlstone, intercalations of limy marlstone beds rare nodular bedding silty limestone beds with hummocky cross-stratification are intercalated in the middle part	**Components:** fine-grained skeletal detritus, small shells, small benthic foraminifers,subordinated planktonic foraminifers, ostracods, and other comp. **Macrofossils:** oysters in the uppermost part **Sorting/rounding:** poorly sorted / angular shapes	distal mid-ramp (low-energy setting) deposition between fair-weather wave base and storm wave base
G	**bioclastic to peloidal wackestone** containing shells	limestone beds marlstone is intercalated in the upper part nodular bedding is common	**Components:** mud peloids, fine-grained skeletal detritus, small shells, small benthic foraminifers, larger shells, and other components **Macrofossils:** oysters and shells at the base **Sorting/rounding:** poorly sorted / angular shapes	distal mid-ramp (low-energy setting)

Table 1: Facies associations, lithology, microfacies, and palaeoenvironmental interpretation of the Serdj section. The ranges of the facies associations in our composite section are plotted in Figs. 3 and 4.

gastropods are common in the whole succession. Additional rare faunal elements are worm-tube fragments, remains of bryozoans, small indistinct calcispheres, larger benthic foraminifers, such as *Choffatella*, and predominantly reworked orbitolines. Rounded cortoids with traces of microboring and bahamite peloids are present to common in few samples. Mud peloids and small mud intraclasts are rare. Most thin sections exhibit high amounts of quartz grains (<0.2 mm). All components are poorly to moderately sorted. In a couple of thin sections, a parallel orientation of bioclasts in the bedding plane has been observed. Fragmented bioclasts exhibit angular, subordinate subangular, and rounded shapes. Quartz grains exhibit angular shapes.

6.1.1. Interpretation

The diverse normal marine macro- and microfossil assemblages, which include planktonic organisms, and the muddy textures of the deposits suggest open marine conditions. Sorting and rounding of components indicates low-energy deposition. The occasional orientation of bioclasts in the bedding plane suggests an influence of bottom currents at times. The presence of rounded cortoids with traces of microborings, which are commonly associated with shallow-marine environments (e.g. Flügel, 2004), indicate transport from shallow-marine domains of the Tunisian platform. We suggest a proximal outer-ramp depositional environment with a strong detrital influx.

6.2. Facies association B: Bioclastic to peloidal packstone containing planktonic and small benthic foraminifers and quartz grains, limestone/marlstone alternation (Fig. 5/B)

Facies association B (8 m thick) consists of rhythmically alternating grey limy marlstone and grey limestone-beds (bedded at cm to dm scale) in the lower part and grey limy marlstone (7 m thick) in the upper part. Nodular bedding due to bioturbation is common in the lower part. Thick lamination and thin bedding of marlstone can be observed sporadically in the entire succession. The lower part of the deposits is characterised by high abundances of benthic macrofossils, especially well preserved brachiopods (Rynchonellida, Terebratulida) and echinoids (mainly *Toxaster*), common bivalves (such as oysters), gastropods, and large shells whereas poorly preserved ammonites (such as *Deshayesites*, *Pseudohaploceras*) and nautilids (*Heminautilus sanctaecrucis*) are rare. The upper part contains no macrofossils.

The biogenic assemblage in the thin sections is mainly composed of fine-grained skeletal detritus and smaller sized fragmented shells (predominantly <1 mm). Planktonic foraminifers (small hedbergellids and gorbachikellids) and small benthic foraminifers (mainly *Protomarssonella praeoxycona* and *Patellina subcretacea*) are rare to common. Echinoderm fragments are common. Few samples contain rare ostracods, echinoid spines, worm tube fragments, calcispheres of unknown origin, *Choffatella*, and small mud intraclasts. Rare rounded cortoids with traces of microborings and bahamite peloids are limited to the lowermost part of the deposits. Mud peloids often constitute a substantial part of the groundmass, their boundaries are often unclear in the micritic matrix. Quartz grains (<0.3 mm) are common in the lower part of the succession but become scarce in the upper part. All components are poorly to moderately sorted. The shapes of fragmented bioclasts are angular to subrounded. Sparite is present in some thin sections.

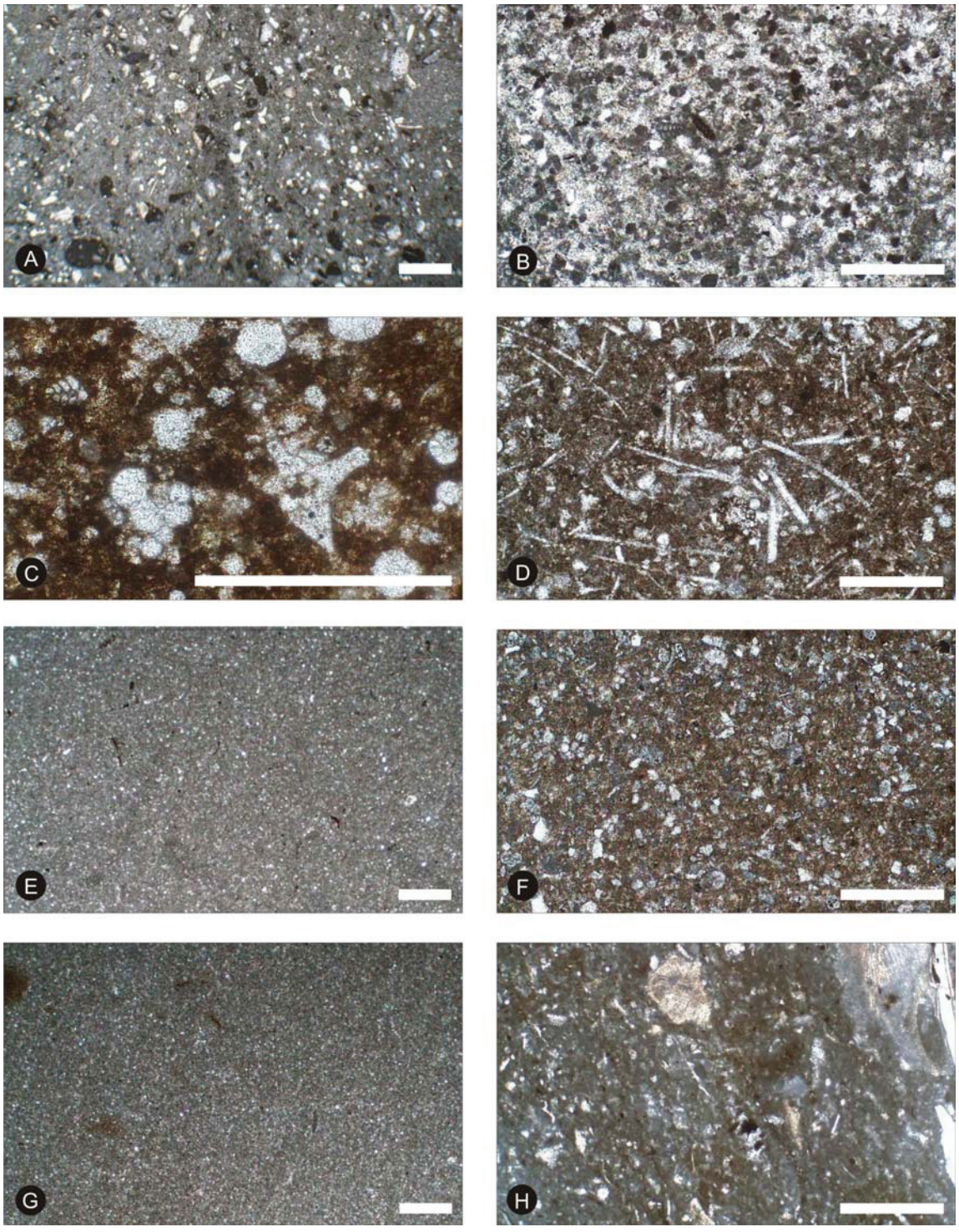

Figure 5: Microfacies of the Serdj section. The scale is 1mm for all images. (A) Facies association A, silty bioclastic wackestones and packstones containing planktonic and small benthic foraminifers and ostracods. (B) Facies association B, bioclastic to peloidal packstones containing planktonic and small benthic foraminifers and quartz grains. (C) Facies association C, bioclastic wackestones and packstones containing radiolarians, planktonic foraminifers, and sponge spiculae. A hedbergellid is seen in the lower left and a planktonic foraminifer of the genus *Leupoldina* in the lower right. (D) Facies association C, bioclastic wackestones and packstones containing radiolarians, planktonic foraminifers, and sponge spiculae. (E) Facies association D, mudstones containing planktonic and small benthic foraminifers and ostracods.(F) Facies association E, mudstones and bioclastic wackestones containing planktonic and small benthic foraminifers and ostracods. (G) Facies association F, mudstones containing benthic foraminifers. (H) Facies association G, bioclastic to peloidal wackestones containing shells.

6.2.1. Interpretation

The diverse normal marine macro- and microfossil assemblages including planktonic organisms and the muddy textures suggest open marine conditions. Sorting and rounding of components suggest low-energy deposition. Facies association B differs from facies association A in slightly less diversified faunal associations, higher abundance of macrofossils, higher abundance of mud peloids, and a lower quartz content. High abundances of brachiopods and echinoids in the lower part of the succession suggest oxic conditions on the seafloor. A decrease in quartz content and absence of cortoids in the upper part could be related to a more distal deposition. We assume a proximal outer-ramp depositional environment for the lower part of the succession and a more distal outer-ramp depositional environment for the upper part.

6.3. Facies association C: Bioclastic wackestone and packstone containing radiolarians, planktonic foraminifers, and sponge spiculae, limestone and marlstone (Fig. 5/C–D)

Facies association C (45 m thick) consists of alternating grey marlstone and limestone (7 m thick), partly rhythmically bedded dark grey bituminous limestone (15 m thick), and grey, partly splintery marlstone (23 m thick) with intercalations of grey limy marlstone beds. The uppermost part of the facies association is only partially exposed. All deposits are predominantly bedded at dm scale (rarely cm scale) and partially thin to thick laminated. Calcareous nodules are very rare. Macrofossils are scarce with the exception of two beds enriched in poorly preserved ammonites (*Pseudohaploceras*). Apart from these beds, only rare poorly preserved ammonites, rare gastropods, rare bivalves (such as oysters), and some larger fragmented shells have been observed.

The biogenic assemblage in the thin sections is composed of varying amounts of fine-grained skeletal detritus, indistinct small sized fragmented shells (mainly <1 mm), common to abundant calcified radiolarians and planktonic foraminifers (mainly hedbergellids, rarely globigerinelloidids, leupoldinids, and other clavate forms). Radiolarian species can not be identified due to recrystallisation and dissolution. Sponge spiculae occur in highly variable amounts (absent to abundant). Additional biogenic elements are rare to common small benthic foraminifers (such as *Protomarssonella praeoxycona*) and ostracods. Echinoderm fragments, echinoid spines, calcispheres of unknown origin, small mud intraclasts, and mud peloids are very rare. Quartz grains (<0.2 mm in diameter) are very rare to rare. Fine grained skeletal detritus and fragmented bioclasts are poorly sorted and exhibit angular shapes. Quartz grains are angular to subangular shaped. Parallel orientation of bioclasts in the bedding plane is a common feature in the deposits, especially in planktonic foraminifer and radiolarian rich layers.

6.3.1. Interpretation

Facies association C is thought to represent the local sedimentary expression of the OAE 1a. The pronounced increase in abundance of planktonic foraminifers compared to facies association A and B and appearance of high abundance of radiolarians suggest a change in the nutrient conditions in surface water and deepening, since no changes in preservation states have been observed. We suggest a deposition in a distal outer-ramp palaeoenvironment with low detrital input. Sorting and rounding of components indicate low-energy deposition. The seafloor was often influenced by bottom

currents, as indicated by common orientation of bioclasts in the bedding plane. Scarce benthic macrofossils, low abundances of small benthic foraminifers and ostracods possibly suggest a dysoxic environment at the seafloor.

6.4. Facies association D: Mudstone containing planktonic and small benthic foraminifers and ostracods, marlstone (Fig. 5/E)

Facies association D comprises 95 m grey, mainly structureless, sometimes splintery marlstone. Few limy marlstone beds (0.2–1 m thick) appear in the uppermost part of the deposits. No macrofossils have been observed and bioturbation is rare.

Bioclasts in the thin sections mainly consist of rare to common fine grained skeletal detritus and smaller sized fragmented shells (mainly <1 mm), rare to common planktonic (mainly hedbergellids) and small benthic foraminifers (such as *Dorothia* and *Gavelinella*), as well as rare to common ostracods. Clavate planktonic foraminifers are rare, except for one thin interval near the boundary to the overlying facies association E when leupoldinids become abundant before the genus disappears completely. Echinoderm fragments and spines, radiolarians, small calcispheres, and mud peloids can be additionally recognised among the scarce components of the sequence. The sediment contains scarce quartz grains (<0.1 mm). Fragmented bioclasts and mud peloids are poorly sorted and exibit angular shapes.

6.4.1. Interpretation

The muddy texture of these deposits, the poorly sorting and rounding of bioclasts and presence of plankton suggest an open marine depositional environment. Distinct similarities of this facies with the basinal facies described from the Tunisian Trough (northern Tunisia; Tlatli, 1980) suggest further deepening and possibly sea level highstand. We assume a low-energy distal outer-ramp depositional environment with low detrital input. High abundances of leupoldinids have been interpreted as an adaptive response to low oxygen levels in the upper water column by some authors (e.g. Boudagher-Fadel et al., 1997; Premoli Silva et al., 1999). Thus, the interval with increase in abundance of leupoldinids might reflect a significant change in palaeoenvironmental conditions.

6.5. Facies association E: Mudstone and bioclastic wackestone containing planktonic and small benthic foraminifers and ostracods, limestone and marlstone (Fig. 5/F)

Facies association E is represented by 45 m of grey, sometimes splintery marlstone with common intercalations of dm-scale limestone beds. Nodular bedding or thick lamination is observed sporadically. Macrofossils are missing.

The biogenic assemblage in the thin sections is characterised by fine grained skeletal detritus, small sized fragmented shells (mainly <1 mm), common planktonic foraminifers (mainly hedbergellids), rare to common small benthic foraminifers (such as *Dorothia* and *Gavelinella*), and ostracods. Additional bioclasts are echinoderm fragments and spines, rare radiolarians, and few calcispheres. Mud peloids are predominantly rare. Quartz grains (<0.1 mm) are very scarce. Components are poorly sorted, fragmented bioclasts exhibit angular, rarely subangular shapes.

6.5.1. Interpretation

Facies association E differs from facies association D predominantly in the occurrence of numerous limestone beds and higher contents of shells. The overlying deposits of facies F are characterised by mid-ramp deposition, which suggests a shallowing for facies association E. We suggest a distal to proximal outer-ramp low-energy depositional environment with little detrital input.

6.6. Facies association F: Mudstone containing small benthic foraminifers, marlstone (Fig. 5/G)

Grey, splintery marlstone with few intercalations of limy marlstone beds (beds at dm-scale) which exhibit a total thickness of 60 m characterise facies association F. Nodular- and thin bedding is rarely observed. Few intercalations of small and sharp bedded yellow silty limestone beds (0.02–0.1 m thick) with hummocky cross-stratification or thin lamination are observed in the middle part (265–269 m). The deposits are devoid of macrofossils, only few oysters appear in the upper part.

Bioclasts in thin sections are mainly rare to common fine grained skeletal detritus and small sized fragmented shells (mainly <1 mm). Small benthic foraminifers (such as *Praedorothia hyperconica*, *Protomarssonella praeoxycona* and *Spiroplectinella gandolfi*) are rare except for the uppermost 10 m, where they are common. Ostracods and planktonic foraminifers (dominated by *Hedbergella*) are scarce. Further biogenic components are test fragments of echinoids and spines. Radiolarians are limited to rare specimens in the lowermost part of the succession. Mud peloids and quartz grains (<1 mm) are very rare to rare. Components are poorly sorted, fragmented bioclasts exhibit angular shapes.

6.6.1. Interpretation

The occurrence of storm related features (hummocky cross-stratification) suggest a depositional environment between fair-weather wave base and storm wave base with low detrital input. We assume a low-energy distal mid-ramp depositional environment.

6.7. Facies association G: Bioclastic to peloidal wackestone containing shells, limestone (Fig. 5/H)

Facies association G consists of 10 m of massive grey to brownish limestone beds (bedded at dm to m-scale) which are commonly nodular bedded. 1.5 m of brown marlstone with wackestone textures are observed in the upper part of the succession. Some oysters and large shells have been observed in the lower part. The studied sequence is the lower part of a massive cliff (30 m thickness), composed of limestone which is bedded at dm to m scale.

The microfacies is characterised by varying amounts of mud peloids (rare to abundant), fine grained skeletal detritus and small sized shells (generally <1 mm). The boundaries of the peloids are often not recognizable. Larger shell fragments of bivalves and gastropods are common. Small benthic foraminifers, planktonic foraminifers, calcispheres, worm-tube fragments, echinoderm test fragments and spines are rare. Small mud intraclasts occur in a few samples. Quartz grains are rare to absent (diameter < 1 mm). Some thin sections exhibit sparite. The sorting of the components is poor, fragmented bioclasts are angular, rarely subangular shaped.

6.7.1. Interpretation

Facies association G is characterised by low-energy deposition. Due to the scarceness of plankton we suggest a deposition in a distal mid-ramp environment.

7. Discussion

7.1. Biostratigraphy and $\delta^{13}C$ stratigraphy

Our integrated planktonic foraminifer and $\delta^{13}C$ stratigraphy dates the Hamada Formation at Djebel Serdj as late Late Barremian–early Late Aptian in age. The subdivision of the composite section by using the standard low latitude planktonic foraminifer biozones (Figs. 3 and 4) (*G. blowi*, *L. cabri,* and *G. ferrolensis* Zone; Premoli Silva and Sliter, 1999) modifies and extends the biostratigraphic framework of Tlatli (1980), who interpreted the deposits as being Early Aptian–early Late Aptian in age. The position of the Lower/Upper Aptian boundary, which was formerly located at the base of the *G. ferrolensis* Zone (base of the upper member of the Hamada Formation; Tlatli, 1980), is now set on top of the OAE 1a in the lower part of the *L. cabri* Zone, in the lower part of the middle member of the Hamada Formation. The new position follows common use (e.g. Menegatti et al., 1998; Luciani et al., 2001; Bellanca et al., 2002).

Overall, the trends in $\delta^{13}C$ values in the Serdj composite section are consistent with other records worldwide, but the absolute values are generally 0,5–1,5‰ lower relative to some pelagic sections, e.g. sections from the Alpine Tethys (Menegatti et al., 1998) or from the Vocontian Basin (Herrle et al., 2004). The greatest discrepancy is observed in the C2 and C3 segment. The lighter values in general might be related to the hemipelagic setting of the Serdj section, thus being influenced by $\delta^{12}C$ enriched coastal water-masses.

The stratigraphical range of the OAE 1a in the studied section differs from some other investigations (e.g. Menegatti et al., 1998; de Gea et al., 2003; Föllmi et al., 2006). To date, authors apply different criteria to define the onset of the event. Menegatti et al. (1998) defined the OAE 1a chemostratigraphically as the interval ranging from the base of the the C4 segment to the C6/C7-segment boundary, even if organic carbon-rich sediments crop out below. Some authors adapted the segments, but choosed a part within the C2 segment or the C3 segment as onset (e.g. Bralower et al., 1999; Luciani et al., 2001; Bellanca et al., 2002; Danelian et al., 2004). Within these segments, significant changes in marine flora and fauna are already observed, e.g. an increase in abundance of radiolarians, a crisis of nannoconids, and eutrophication induced changes in shallow-water platform communities (e.g. Erba, 1994; Weissert et al., 1998; Danelian et al., 2004; Erba, 2004; Föllmi et al., 2006). In the Serdj section, a significant change in microfacies composition occurs in the upper part of the C2 segment. Here, radiolarians and planktonic foraminifers suddenly increase in abundance, indicating a transgression and eutrophication of the upper water column (see chapter 6.3). Therefore, the OAE 1a in the Serdj section is thought to range from the upper part of the C2 segment to the C6/C7-segment boundary.

7.2. Sea level changes

A 3rd-order sea level curve for the Tunisian shelf (Fig. 4) was established by using changes in the depositional settings (chapter 6). Our sea-level curve closely correlates with the global curve of Haq et

al. (1988) and the curve of Haq and Qahtani (2005) for the Arabian platform. Therefore, the sea level changes on the Tunisian shelf are interpreted to reflect global sea-level changes and are not related to local tectonics. Microfacies data in the lower part of the Serdj composite section suggests a transgression, which started shortly before OAE 1a in the upper part of the *Globigerinelloides blowi* biozone. A sea level highstand possibly extends over most part of the *Leupoldina cabri* Zone, followed by a regression in the transition interval to the *Globigerinelloides ferrolensis* Zone. A transgression and sea level highstand associated with the *Globigerinelloides blowi–Globigerinelloides ferrolensis* Zones has been discussed in several other papers (e.g. Erbacher et al., 1996; Weissert et al., 1998; Jones and Jenkyns, 2001; Föllmi et al., 2006). It has been related to enhanced coastal nutrification during the OAE 1a by significantly expanding the areas of shallow banks and inland seas, thus increasing the area receiving large terrestrial nutrient influxes (e.g. Schlanger and Jenkyns, 1976; Jones and Jenkyns, 2001).

7.3. Palaeoenvironmental evolution of the Tunisian shelf

Our microfacies analyses in combination with field observations provide information on the palaeoenvironmental evolution and sea-level fluctuations of the Tunisian shelf during the Late Barremian–early Late Aptian interval. While Tlatli (1980) interpreted the deposits of the Hamada Formation predominantly as being basinal deposits, our new data suggest a deposition in mid- to outer-ramp palaeoenvironments (see chapter 6). We suggest to subdivide the palaeoenvironmental evolution into four intervals (Fig. 4): 1) a pre-OAE 1a interval, 2) an OAE 1a interval, 3) a platform-drowning-equivalent interval, and 3) a post-platform-drowning interval. These intervals are discussed below with respect to the local sedimentary expression of the OAE 1a.

7.3.1. Pre-OAE 1a

The pre-OAE 1a interval comprises the lowermost part of the studied section (facies associations A and B) and is characterised by bioclastic wacke- and packstones which are interpreted as low-energy proximal outer-ramp deposits (see chapters 6.1 and 6.2). A moderate to high siliciclastic content especially in the upper part of facies association A probably originate from weathering on the stable uplift in the south (“Kasserine Island”, M`Rabet et al., 1987). High abundance of benthic macroorganisms in the lower part facies association B indicates oxic seafloor-conditions. A decrease in detrital influx and decline in transported shallow water platform components (cortoids) possibly indicates the onset of the transgression, which is commonly associated with the OAE 1a (see chapter 7.2).

7.3.2. OAE 1a

The deposits of facies association C, which are thought to represent the OAE 1a interval (see chapter 6.3), are characterised by bioclastic wacke- and packstones and are interpreted as distal outer ramp low-energy facies deposited under transgressive conditions. By comparison with other investigations, our studies on the microfacies of the event confirm some main observations, but also highlight some differences.

High abundance of radiolarians (Fig. 4) during the event are in agreement with previous studies on OAE 1a related deposits in pelagic successions (e.g. Erba et al., 1999; Premoli Silva et al., 1999; Danelian et al., 2002; Marsaglia, 2005). Recent radiolarian-rich deposits predominantly accumulate under areas of high fertility conditions in surface water, especially under upwelling conditions in which required nutrients and dissolved silica are provided (Racki and Cordey, 2000). Cretaceous radiolarian-rich deposits related to OAE 1a are also most probably indicative of high nutrient concentrations, because the increase in radiolarian abundance coincides with additional productivity-indicators (such as enhanced accumulation rates of organic matter, composition of nanno- and microfossil assemblages) (e.g. Erbacher et al., 1996; Jenkyns, 1999; Premoli Silva et al., 1999; Erba, 2004). An unusual observation is the co-occurrence of radiolarians and moderately to well preserved planktonic foraminifers (Fig. 4) during most part of the OAE 1a in the Serdj section. Both show similarities in their distribution pattern (Fig. 4). In pelagic successions, planktonic foraminifers are often scarce or absent and poorly preserved across the OAE 1a interval (e.g. Coccioni et al., 1992; Cobianchi et al., 1999; Premoli Silva et al., 1999; Marsaglia, 2005) and characteristically out of phase with radiolarian abundance (e.g. Coccioni et al., 1992; Cobianchi et al., 1999; Luciani et al., 2001). The temporary absence and poorly preservation of calcareous plankton in pelagic successions has been related to shoalings of the CCD as consequence of high productivity (e.g. Weissert et al., 1985; Bralower et al., 1994; Bralower et al., 2002; Danelian et al., 2002), and/or unfavorable conditions for calcareous plankton in surface waters (e.g. Cobianchi et al., 1998; Erba, 2004*)*.

Planktonic foraminifer assemblages during the event at the Serdj section are mainly provided by hedbergellids (see chapter 6.3), which have been also described for the OAE 1a from many other localities (e.g. Cobianchi et al., 1999; Premoli Silva et al., 1999; Luciani et al., 2006). Hedbergellids have been interpreted as being adapted to meso- to eutrophic conditions in the upper water column, they were probably capable of tolerating significant fluctuations in temperature, salinity, nutrients, and oxygen (e.g. Coccioni et al. 1992; Premoli Silva and Sliter, 1999; Luciani et al., 2001). Globigerinelloidids are very scarce within the planktonic foraminifer assemblage in the studied section, which is consistent with results from some other localities (e.g. Cobianchi et al., 1999; Premoli Silva et al., 1999, Luciani et al., 2006). This genus has been related to oligo- to mesotrophic conditions in surface waters (e.g. Coccioni et al., 1992; Premoli Silva et al., 1999). Leupoldinids, which are a consistent component of planktonic foraminifer assemblages in some other Tethyan hemipelagic or pelagic successions (e.g. Luciani and Cobianchi, 1994; Aguado et al., 1999; Premoli Silva et al., 1999) are also scarce in the studied section during OAE 1a. This group has been often interpreted as indicator for eutrophic conditions and low-oxygen levels in the upper water column (Boudagher-Fadel et al., 1997; Premoli Silva et al., 1999, Coccioni et al., 2006). Considering that ecological behaviour of Cretaceous planktonic foraminifera is still inadequately understood, planktonic foraminifer assemblages in combination with high abundance of radiolarians suggest meso- to eutrophic conditions in the upper water column of the studied area and possibly higher oxygen levels in comparison to pelagic palaeoenvironments.

Low abundance of benthic foraminifers in the Serdj section, which is a common feature in deposists of the OAE 1a interval (e.g. Coccioni et al., 1992; Premoli Silva et al., 1999; Cobianchi et al., 1999;

Luciani et al., 2001), in combination with low abundance of ostracods and scarceness of benthic macroorganisms possibly indicate a dysoxic milieu at the seafloor.

The carbonate content of the OAE 1a interval in the studied section ranges from around 80% in the lower half of the OAE 1a to around 65% in the upper half (Fig. 3). Several pronounced drops in values, which have been described from coeval pelagic sucessions (e.g. Menegatti et al., 1998; Bralower et al., 1999), are missing at Djebel Serdj. Furthermore, some pelagic successions are even partially or entirely devoid of carbonate (e.g. Baudin, 1998; Danelian et al., 2002). These observations in pelagic sections have been related to shoalings of the CCD or unfavourable conditions for carbonate producing organisms in surface water, as already mentioned in relation with the temporary absence and poorly preservation of planktonic foraminifers. Shoalings of the CCD would have not affected carbonate sedimentation in the hemipelagic Serdj area, thus explaining the high carbonate content as well as high abundance of planktonic foraminifers. The hemipelagic Cau section (SE Spain, Aguado et al., 1999) also shows predominantly high abundance of planktonic foraminifers. A lower nutrient content in the upper water column favored by carbonate producing biota can not be excluded as reason for the observations at Djebel Serdj, but seems to be less probable considering the richness in radiolarians (up to 20% of thin-section surface-area), which is consistent with pelagic sections.

Another explanation for the high carbonate content in the Serdj section, especially in the lower half of the OAE 1a (around 80%), could be carbonate export from shallow-marine areas with still-active shallow-water carbonate production. Shallow water platform components (cortoids) in the lowermost part of the section (facies association A and B) indicate the studied area being adjacent to the shallow-marine domain of the Tunisian platform. Recent studies on shallow-marine successions in Oman and Egypt (Immenhauser et al., 2005; Thielemann, 2006) document an uninterrupted carbonate production during the event. We suggest that the pronounced perturbation of carbonate production during OAE 1a, as discussed by several authors for neritic as well as pelagic environments (e.g. Weissert et al., 1998; Wissler et al., 2003; Weissert and Erba, 2004; Föllmi et al., 2006), did not affect the southern Tethys margin or at least not to the same extent.

The TOC values during the OAE 1a interval in the Djebel Serdj section (between 0.2% and 1%) (Fig. 3) are very low in comparison to Tethyan pelagic sections (e.g. Menegatti et al., 1998; Danelian et al., 2002), which show values of up to 8% or more. Low values (about 0.8%) are also observed in the hemipelagic Cau section, SE Spain (Aguado et al., 1999), which was affected by a high subsidence rate, too. These authors interpreted the low contents as a being result of terrigenous dilution. The overall low values in the Serdj section can also be explained by dilution (here by terrigenous input and carbonate sedimentation), considering the extraordinary high sedimentation rate in the studied section.

7.3.3. Platform-drowning-equivalent

The platform-drowning-equivalent interval (Fig. 4) is characterised by mudstones and bioclastic wackestones (facies associations D and E) which are interpreted as low-energy distal outer-ramp facies deposited during further transgression, possibly sea-level highstand and regression (see chapters 6.4 and 6.5). Facies association D is time-equivalent with the maximum of the early Late Aptian shallow-carbonate-platform drowning (Fig. 4; Weissert et al., 1998). The corresponding

deposits are characterised by mudstones in the Serdj section, being partly poor in $CaCO_3$ content and nearly devoid of macrofossils.

Studies on time equivalent shallow-marine deposits on the Tunisian platform (e.g. Chekhma et al., 1990; Chaabani et al., 1992; Chabaani and Razgallah, 2006) does not add information on regional ecological changes in this time interval, because biostratigraphic markers for high resolution studies are missing in central Tunisian shallow-marine successions and $\delta^{13}C$ curves have not yet been established.

A small interval at the upper boundary of facies association D, which shows an increase in abundance of planktonic foraminifers of the genus *Leupoldina*, is probably related to a temporary change in palaeoenvironmental conditions. High abundances of leupoldinids have been interpreted as an adaptive response to low oxygen levels in the upper water column, as discussed for the OAE 1a interval (facies association C). The interval in the upper part of the *Leupoldina cabri* Zone has not been described elsewhere, and therefore it is interpreted to reflect a local event.

7.4. Post-platform-drowning

Mudstones and bioclastic wackestones of facies association F and G (see chapters 6.6 and 6.7) are interpreted to reflect the post-platform-drowning interval (Fig. 4). The deposits are predominantly characterised by low-energy deposition. Storm related features (hummocky cross-stratification) within facies association F indicate the establishment of a mid-ramp facies as consequence of a regression. The mid-ramp deposition probably prevails until the uppermost part of the studied section.

8. Conclusions

The Upper Barremian–lower Upper Aptian deposits of the Hamada Formation in the Djebel Serdj area, north-central Tunisia have provided excellent opportunity to study the evolution of a hemipelagic mid- to outer-ramp palaeoenvironment situated on the southern edge of the Tethyan ocean in detail. Altogether, four palaeoenvironmental intervals are subdivided: 1) a pre-OAE 1a interval, 2) an OAE 1a-interval, 3) a platform-drowning-equivalent interval, and 4) a post-platform-drowning interval. The results of the detailed microfacies, biostratigraphy, $\delta^{13}C$ stratigraphy, and geochemistry analyses concerning the OAE 1a confirm main observations in comparison to pelagic successions, but also highlight some differences. Our microfacies analyses show, that in the hemipelagic setting of the Tunisian shelf, the severe palaeoenvironmental perturbation related to the OAE 1a led to radiolarian blooms, which is consistent with results from pelagic successions worldwide. By interpreting high abundance of radiolarians as high fertility indicator, this study confirms the high-productivity model for the OAE 1a. Transgressive conditions during the event, which have been described by several other authors, can also be confirmed for the studied section. High abundance of moderate to well preserved planktonic foraminifers and a high carbonate content during OAE 1a is an unusual observation in comparison to pelagic successions, which can be most probably explained by a better preservation. Considering the palaeobathymetry of the section, the studied area would have not been influenced by shoalings of the CCD, which probably led to intensified carbonate dissolution during pelagic sedimentation. The unusual high carbonate content at Djebel Serdj could be additionally related to carbonate export from shallow-marine areas of the Tunisian platform. Recent studies on shallow

marine successions of the southern Tethys margin suggest a high carbonate production during the event.

Time-equivalent deposits of the maximum of shallow-marine carbonate platform-drowning were identified on the base of biostratigraphy and $\delta^{13}C$ stratigraphy. They are represented by macrofossil-poor mudstones, deposited during further transgression and possibly sea level highstand.

Acknowledgements:

We are grateful to Hedi Negra and Saloua Bey (both University of Tunis) for joining and supporting the fieldwork. M. Segl measured the $\delta^{13}C$ content and R. Bätzel prepared the thin sections. David Fischer and Patric Simundic helped in the laboratory (all University of Bremen). Benjamin Slotnick (San Diego State University) corrected the English. Furthermore, we would like to thank the reviewers, Jochen Erbacher and an anonymous reviewer, for their helpful comments and suggestions.

This project was supported by the DFG (German Research Foundation, project no Ba-1571-11).

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CHAPTER 3

Absence of a global marine biocalcification crisis during the late Early Aptian Oceanic Anoxic Event 1a

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Submitted to

Geology

Marlstones and limestones of the Hamada Formation cropping out south of Sodga village in the northeastern part of Djebel Serdj. The prominent limestone bed in the upper part of the picture marks the onset of the OAE 1a interval.

Absence of a global marine biocalcification crisis during the late Early Aptian Oceanic Anoxic Event 1a

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Abstract

Oceanic Anoxic Events (OAEs) are geologic time intervals characterised by accelerated burial of organic matter, which led to a widespread, in some cases even global deposition of black shales. The first globally distributed of these events, the late Early Aptian Oceanic Anoxic Event 1a (OAE 1a), has been related to high primary productivity caused by global ocean eutrophication. A carbonate production crisis during the event has been proposed to explain a general decrease in abundance of pelagic carbonate-secreting micro- and nannofossils in favour of radiolarians and organic-walled dinoflagellates. Furthermore, the OAE 1a has been related to a widespread breakdown of neritic carbonate production. A detailed sedimentology, geochemistry, and biostratigraphy study of two carbonate platform successions in Egypt (platform interior) and Tunisia (platform edge) provides new information on growth conditions for carbonate platforms during the event on the southern Tethys continental margin. Results suggest an absence of broad perturbations in the carbonate production factory, as indicated by high carbonate contents and high abundances of carbonate-secreting biota within both successions. Both platforms were affected by elevated trophic levels. A comparison with other late Early Aptian carbonate platforms suggests, that intact neritic carbonate production factories during the event were more widespread than previously suggested. Nutrient levels on the shelves were probably rather intermediate than high. A carbonate platform growth crisis during OAE 1a was mainly restricted to the northeastern Atlantic and northern Tethys margin.

Our results are not in accordance with a global biocalcification crisis during OAE 1a and vast eutrophic regimes on subtropical–tropical shelves. Furthermore, they suggest that intensified greenhouse conditions and subsequent processes generally associated with the OAE 1a, such as higher average global precipitation rates, accelerated chemical weathering, increased coastal runoff, intensified wind velocities, and upwelling were less intense than previously suggested and can not explain eutrophic surface water conditions in pelagic palaeoenvironments. Additionally, our results weaken the hypothesis of global changes in oceanic seawater *p*H due to massive additions of volcanogenic CO_2 to the atmosphere.

Keywords: Aptian, Oceanic Anoxic Event 1a, carbonate platforms, biocalcification crisis, global climate change

1. Introduction

The mid-Cretaceous period (Aptian–Turonian) is associated with an exceptional greenhouse climate, increased ocean crust production, intense submarine volcanism, and an overall rising sea-level. The global warming has been attributed to high levels of atmospheric greenhouses gases, especially volcanogenic carbon dioxide (CO_2). A brief episode (approximately 0.4–1 myrs) of black shale deposition and possibly further intensified greenhouse conditions, called the Oceanic Anoxic Event 1a (OAE 1a), was superimposed on this period of global warming in the late Early Aptian (Schlanger and Jenkyns, 1976; Bralower et al., 1994; Erba, 2004). The OAE 1a is the first globally traceable of a series of anoxic events in the Mid-Cretaceous, being especially characterised by heightened marine productivity coupled with distinct changes in biotic communities, accelerated burial of organic matter, and dysoxic to anoxic conditions in deep marine bottom waters (Arthur and Sagemann, 1994; Leckie et al., 2002). These OAEs are accompanied by positive $\delta^{13}C$ isotopic excursions with peak values of around 2‰ higher than the background values (Leckie et al., 2002). The OAE 1a is additionally accompanied by a prominent negative isotopic excursion at its onset, possibly related to a sudden release of methane hydrates (Jahren and Arens, 1998). Trace metal peaks during OAE 1a and pronounced strontium isotope excursions suggest a direct link to temporarily increased submarine volcanism in the Pacific ocean (Ontong-Java “superplume” eruption; Larson and Erba, 1999). Massive additions of volcanogenic CO_2 to the atmosphere could have led to elevated atmospheric temperatures and subsequent processes (such as increased average precipitation rates, increased coastal runoff, intensified wind velocities, riverine and/or upwelling-induced nutrification), which caused an eutrophication of marine environments and thus unfavourable conditions for primary carbonate producers (Bralower et al., 1994; Weissert et al., 1998; Jones and Jenkyns, 2001). Hydrothermal input of biolimiting metals related to the submarine volcanism could have further intensified oceanic eutrophication (Sinton and Duncan, 1994; Larson and Erba, 1999). Additionally, elevated CO_2 levels are predicted to have caused an increase in the partial pressure of CO_2 (pCO_2) in the surface ocean, thus seawater possibly became more acidic (Wissler et al., 2003; Erba and Tremolada, 2004). Carbonate platform growth could have been greatly reduced due to all aforementioned processes, leading to a widespread drowning during late Early Aptian eustatic sea-level rise (Weissert et al., 1998; Wissler et al., 2003; Föllmi et al., 2006; Burla et al., 2008). However, some of the hypotheses to account for the OAE 1a are still highly controversial. Heimhofer et al. (2004) negates major terrestrial vegetation and pCO_2 changes associated with the event. Ando et al. (2008) suggests, that intensified greenhouse conditions were restricted to the onset of the OAE 1a only and the event itself was mainly accompanied by a cooling trend.

In order to test the hypothesis of a global carbonate platform growth crisis and to evaluate changes in neritic trophic levels, we studied two carbonate platform sections from the southern Tethys continental margin (Egypt and Tunisia) on the base of sedimentology, biostratigraphy, and geochemistry. The results are compared to other investigations on carbonate platforms of low- and mid-latitudes and discussed in the aforedescribed climatic and oceanographic context to contribute to the discussion on the causes for the event.

2. Geological setting and methods

2.1. Geological setting

We studied Latest Barremian–late Early Aptian successions at the Raghawi mountain in northern Sinai, Egypt and Serdj mountain in north-central Tunisia. During the mid-Cretaceous, both areas were covered by carbonate platforms (Levant and Central Tunisian carbonate platforms), which were part of the broad innertropical platform system along the southern Tethys continental margin. The limestones, marlstones, claystones, siltstones, and sandstones(Fig. 1) of the Raghawi mountain belong to the deltaic–marine Rizan Aneiza Formation. The deposits are thought to reflect palaeoenvironments of the carbonate platform interior to outer ramp (Bachmann et al., subm.). The marlstones and limestones of the Serdj mountain (Fig. 2) belong to the Hamada Formation, which has been ascribed to the edge of the Central Tunisian carbonate platform. These deposits have been interpreted to reflect an outer ramp palaeoenvironment (Heldt et al., 2008). The Tunisian as well as the Levant platform were located close to rivers/deltaic systems.

2.2. Methods

The study is based on field observations, microfacies analyses, biostratigraphy, $\delta^{13}C$ stratigraphy, $CaCO_3$, and TOC analyses. The microfacies was investigated in thin sections and residues of washed material. Abundances of macro- and microfossils were estimated. The biostratigraphic control in the Egyptian section is based on well preserved larger foraminifers (orbitolines). Biostratigraphy in the Tunisian section is based on recrystallised, moderately to well preserved planktonic foraminifers occurring nearly within the entire succession. $\delta^{13}C$ values were measured on bulk rock samples. The $\delta^{13}C$ curve is divided into segments as suggested by Menegatti et al. (1998) for time-equivalent pelagic deposits in the Swiss Préalps and southern Alps of northern Italy. They include: an increase in $\delta^{13}C$ values (C1 segment), followed by a decrease (C2) and a $\delta^{13}C$ minimum (C3), a significant increase in values (C4), a stable interval (C5), followed by a further increase (C6), then variable, but overall high values (C7).

The combination of biostratigraphy and carbon isotope data allows us a determination of the OAE 1a and precise correlations with global sedimentary records. $\delta^{18}O$ values were not further considered because of possible diagenetic alteration.

3. Results

3.1. Bio- and chemostratigraphic correlation

Orbitoline species (*Palorbitolina lenticularis*, *Praeorbitolina cormyi*, and *Orbitolina (Mesorbitolina) parva)* in the Egyptian section were compared to the zonal scheme of Bachmann and Hirsch (2006). Planktonic foraminifer assemblages in the Tunisian section allowed to define the *Leupoldina cabri* Zone, comparable to the standard low-latitude zonal scheme of Premoli-Silva and Sliter (1999). The Early Aptian/Late Aptian boundary occurs in the upper part of the succession (Figs. 1 and 2). Furthermore, ammonites in both sections were used for a dating (Hamama and Gabir, 2001; Heldt et al., 2008).

The biostratigraphical data supported by the $\delta^{13}C$ stratigraphy suggests a Latest Barremian–late Early Aptian age for the Tunisian section and a late Early Aptian age for the Egyptian deposits. The OAE 1a

was determined due to pronounced isotopic excursions (C2–C6), corresponding to globally observed patterns (e.g. Menegatti et al., 1998; Bralower et al., 1999; Burla et al., 2008). Authors apply different criteria to define the onset of the event. Menegatti et al. (1998) defined the OAE 1a chemostratigraphically as the interval ranging from the base of the C4 segment to the C6/C7-segment boundary, even if organic carbon-rich sediments crop out below. In contrast, we agree with Bralower et al. (1999), Bellanca et al., (2002), and Danelian et al., (2004) choosing an interval within the upper part of the C2 segment as onset (e.g.), because significant changes in marine flora and fauna are already observed, including a general increase in abundance of radiolarians, a crisis of nannoconnids, and eutrophication induced biotic changes on the northern Tethys shelf (Erba, 1994; Föllmi et al., 2006; Heldt et al., 2008).

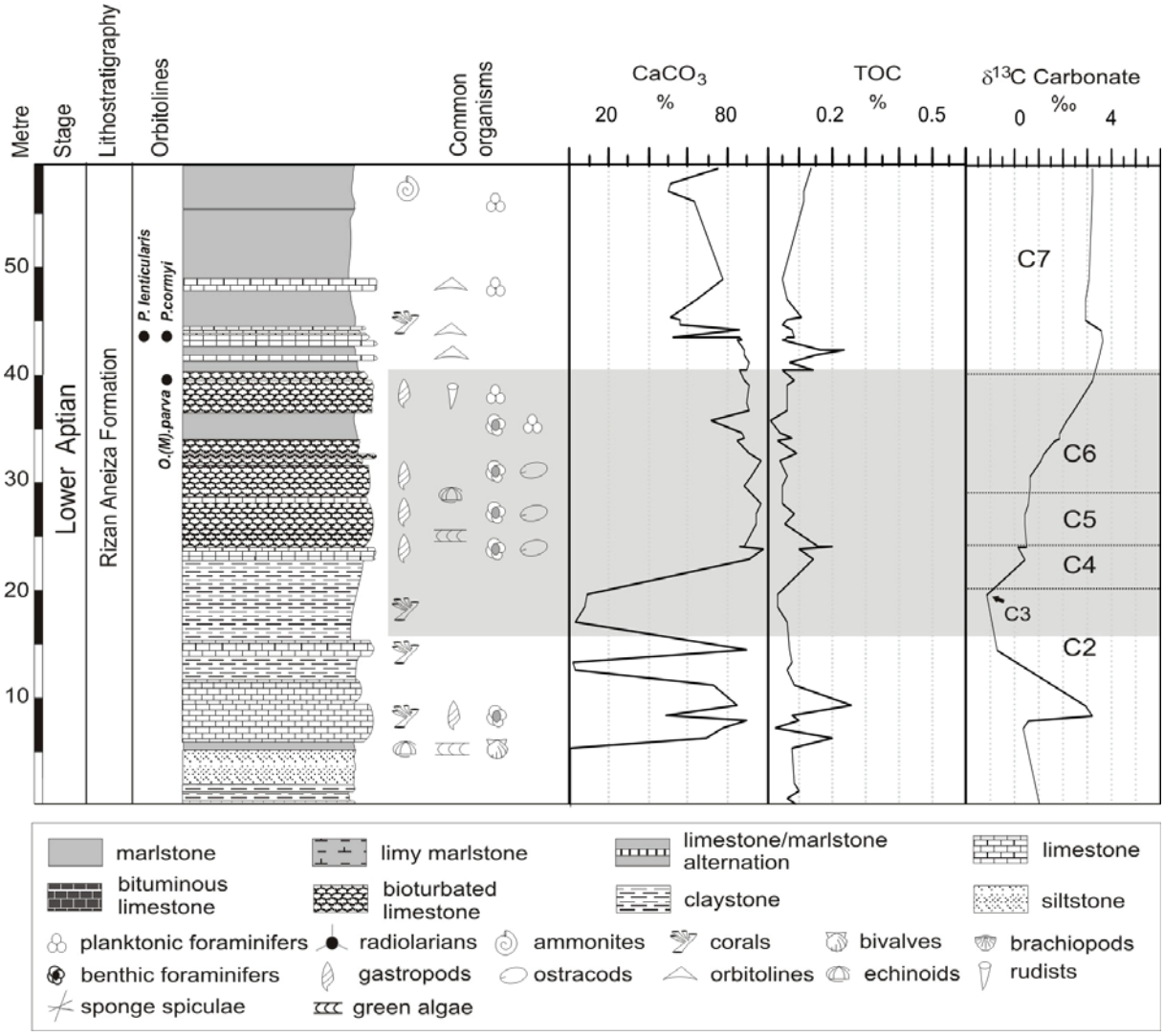

Figure 1: Section of the Egyptian Levant carbonate platform with lithology, biostratigraphy, common macro- and microfossils, geochemistry, and $\delta^{13}C$ stratigraphy. The shaded area marks the OAE 1a.

3.2. Biota, $CaCO_3$, and TOC values around the OAE 1a

Deposits of the Egyptian section are characterised by bioclastic wacke- and packstones, marlstones, claystones, siltstones, and orbitoline floatstones (Fig. 1). Common macrofossils of the pre-OAE 1a

interval are colonial corals, echinoids, and gastropods. Skeletal grains in thin sections include bivalves, gastropods, and echinoderm fragments, benthic foraminifers, ostracods, remains of green algae, coral fragments, and planktonic foraminifers. Macrofossils of the syn-OAE 1a interval are mainly large gastropods and echinoids. Common biotic components in thin sections are gastropod fragments, remains of green algae, echinoderm fragments, ostracods, benthic foraminifers, and planktonic foraminifers. Macrofossils in the post-OAE 1a interval are scarce. Thin sections contain orbitolines, indistinct shell fragments, remains of colonial corals, and planktonic foraminifers.

$CaCO_3$ values vary between 0 and 97% (Fig. 1) with highest values during the OAE 1a. A pronounced drop in carbonate content is coincident with the negative carbon isotope spike. The TOC values are generally low, ranging from 0 to 0,25% (Fig. 1).

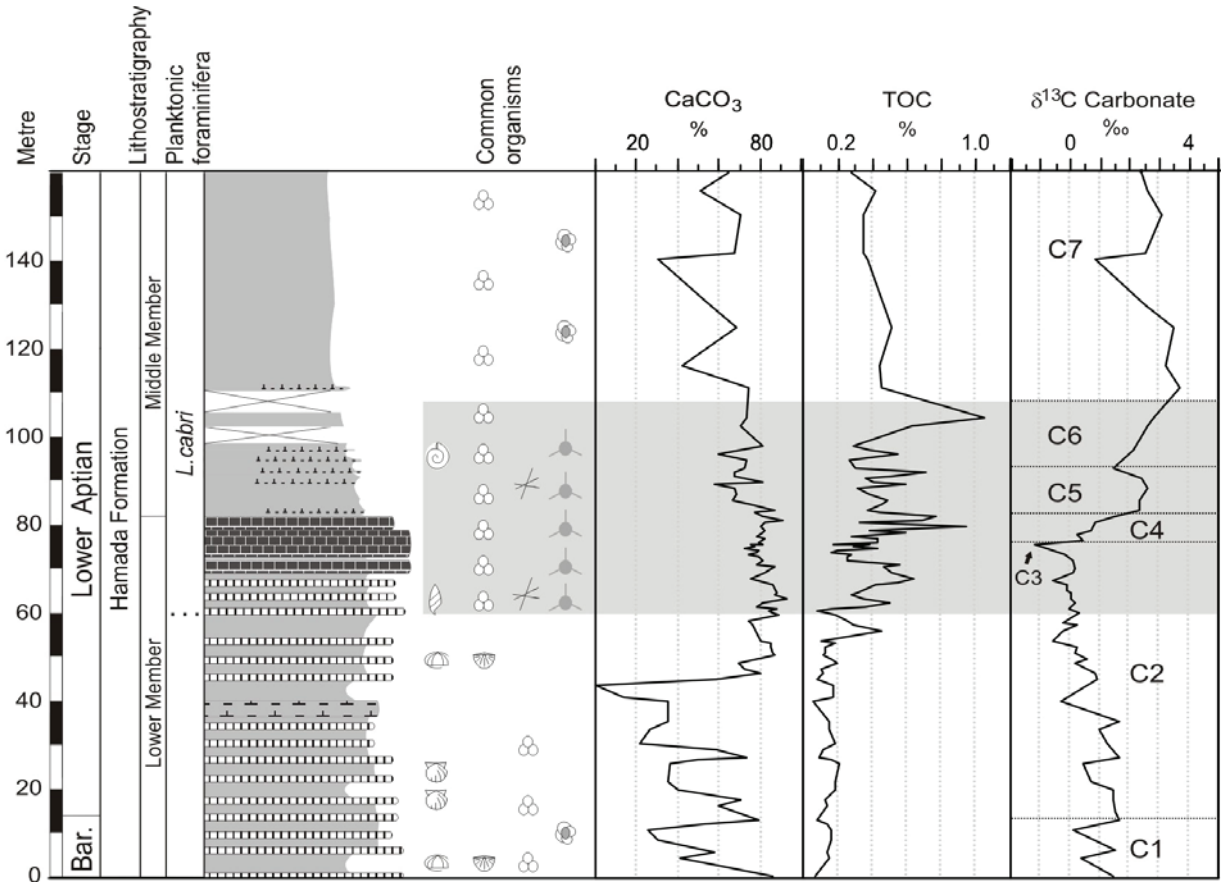

Figure 2: Section of the Central Tunisian carbonate platform with lithology, biostratigraphy, common macro- and microfossils, geochemistry, and $\delta^{13}C$ stratigraphy. The shaded area marks the OAE 1a.

The deposits of the Tunisian section mainly consist of bioclastic to peloidal wacke- and packstone and marlstone (Fig. 2). The pre-OAE 1a deposits are partly rich in macrofossils, especially echinoids and brachiopods. Skeletal grains in thin sections include bivalve and echinoderm fragments, planktonic foraminifers, benthic foraminifers, ostracods, remains of bryozoans, and others. The syn-OAE 1a deposits are poor in macrofossils, while planktonic foraminifers, and radiolarians dominate in thin sections. Additional biota are benthic foraminifers, ostracods, and sponge spiculae. Thin sections of the macrofossil-poor post-OAE 1a deposits mainly contain indistinct shell fragments, planktonic foraminifers, benthic foraminifers, and ostracods. $CaCO_3$ values of the succession range between 0

and 91% with significant drops below and above the event (Fig. 2). A $CaCO_3$ minimum below the OAE 1a is due to the occurrence of a small siltstone bed. TOC values vary between 0.1 to 1.1% with maxima during the OAE 1a (Fig. 2). Siltstones or limestones with higher abundances of quartz grains are restricted to the pre-OAE 1a deposits in both successions.

4. Discussion and Coclusions

The high carbonate content and high abundance of carbonate-secreting biota within both investigated successions suggest an intact carbonate production factory during the OAE 1a on the northafrican continental margin. Only a shortlived drop in carbonate content in the Egyptian section coincident with the upper part of the C2–C4 segment (Fig. 1) could be related to deteriorated conditions for primary carbonate producers. This time interval is marked by the onset of widespread disturbances in marine palaeoenvironments related to the OAE 1a (Erba, 2004). It is characterised by a strong decrease in abundance of the rock-forming nannoconids in pelagic successions and the onset of a carbonate platform drowning phase on the northern Tethys shelf (Erba, 1994; Föllmi et al., 2006; van Breugel et al. 2007).

Both investigated sections reflect biotic changes during OAE 1a due to elevated trophic levels. The biotic assemblage in the Egyptian section, dominated by benthic grazers (gastropods and echinoids) and calcareous green algae, corresponds well to typical mesotrophic associations described by several authors (e.g. Mutti and Hallock; 2003). Colonial corals, indicative of low nutrient levels, become scarce during the event. The mass occurrence of radiolarians, the planktonic foraminifer assemblages, and 2–3 times elevated TOC contents in the Tunisian succession have been related to meso- to eutrophic conditions in surface waters and higher primary productivity (Heldt et al., 2008).

Our results are in accordance with other investigations on carbonate platforms of the southern Tethys realm, suggesting predominately high carbonate production rates and rather intermediate than high nutrient levels. The interior to external parts of the Bahamian-type carbonate banks north of the North African continental margin (Apulia, Gavroro, and Tauride carbonate platforms; locations 2, 3, 4 in Fig. 3) were predominately characterised by intact carbonate factories under oligotrophic to mesotrophic water conditions. Platform drowning has been reported from one locality on the Apulia platform only (location 17 in Fig. 3). Occurrences of shallow marine *Lithocodium-Bacinella* buildups and orbitoline-rich deposits coincident with the OAE 1a in Oman (locations 6 and 7 in Fig. 3) have been related to mesotrophic water conditions.

A comparison to investigations on global subtropical–tropical shelf regions apart from the southern Tethys realm highlights, that the carbonate production factory during OAE 1a was also intact in the Gulf of Mexico (Lehmann et al., 2000 and personal communication; locations 8 and 9 in Fig. 3) and on the southern South American margin (location 10 in Fig. 3), which rules out the hypothesis that favourable conditions for neritic carbonate-secreting biota were a regional phenomenon restricted to the southern Tethys realm (Wissler et al., 2003; Burla et al., 2008). Widespread carbonate platform drowning during OAE 1a and highly elevated trophic levels have been particularly reported from the northeastern Atlantic and northern Tethys margin (e.g. locations 13, 14, 15; 16 in Fig. 3). Nevertheless, some carbonate platforms and their edges in these realms were also less affected by environmental perturbations, as indicated by orbitoline-rich deposits during the event in the Lusitanian

or Vocontian regions (location 11 and 12 in Fig. 3), or calcareous microfossil-rich deposits on the edge of the Prebetic platform (location 14 in Fig. 3). Global comparisons further suggest that deteriorated conditions for neritic carbonate producers were possibly more widespread subsequent to the OAE 1a than during the event. Carbonate platforms in the Gulf of Mexico or on the northern Tethys margin were affected by a post OAE 1a-drowning (Weissert et al., 1998; Lehmann et al., 2000) and deposits of the Central Tunisian and Levant platforms show pronounced drops in carbonate content and a decline in abundance of macro- and microfossils (Figs. 1 and 2).

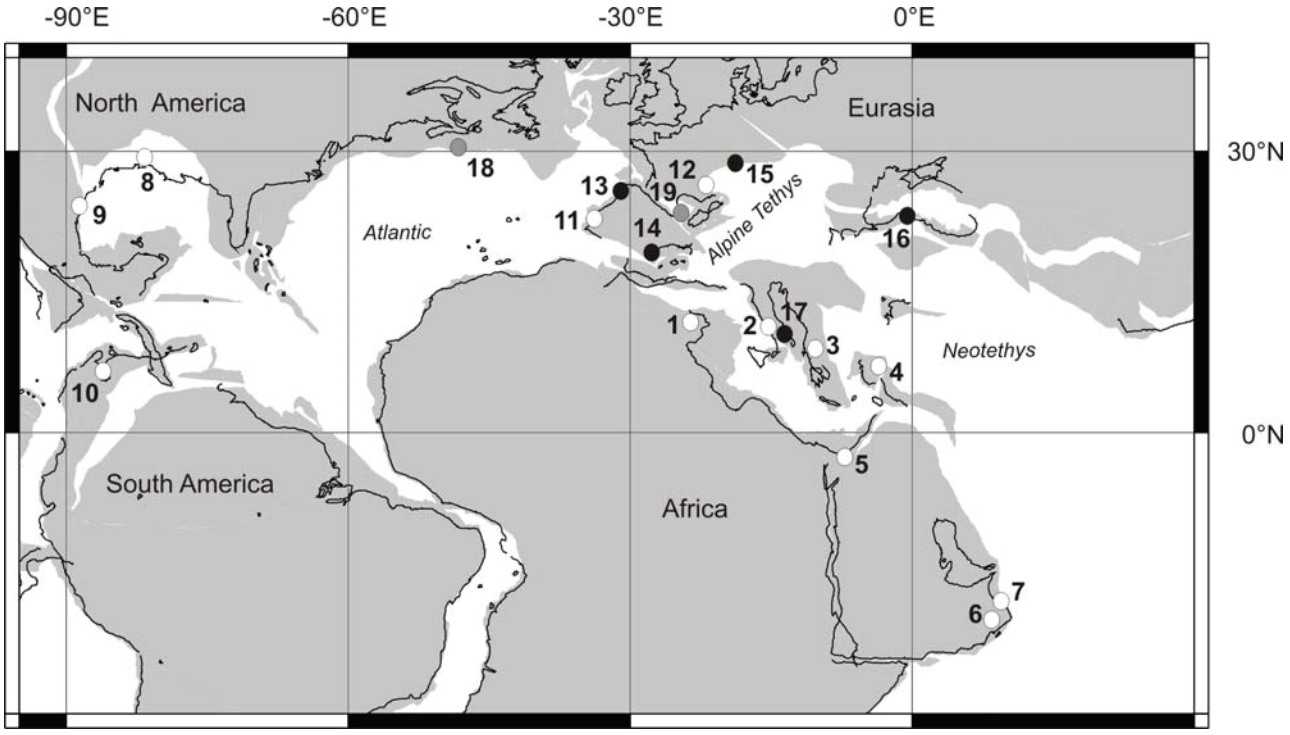

Figure 3: The impact of the OAE 1a on carbonate platforms. White circles mark platforms which were characterised by high carbonate production rates during the event (1-Central Tunisian Platform, 2-Apulia Platform, 3-Gavroro Platform, 4-Tauride Platform, 5-Levant Platform, 6 and 7-Arabian Platform, 8-north rim Gulf of Mexico, 9-Cupido Platform, 10-Maracibo Platform, 11-Lusitanian region, 12-Vocontian region). Black circles indicate carbonate platform drowning (13-North Cantabrian region, 14-Prebetic region, 15-Helvetic region, 16-Pontide Platform, 17-Apulia Platform). Grey circles indicate carbonate platforms with uncertain age determinations of drowning (18-Scotian region, 19-Provence region). For references see supplementary data.

In contrast to predominately high neritic carbonate contents, deeper marine OAE 1a-related deposits are often partially or entirely devoid of carbonate (e.g. Coccioni et al., 1992; Danelian et al., 2004, Erba, 2004). Some authors suggested shallowings of the Carbonate Compensation Depth (CCD) to explain this observation (e.g. Weissert et al., 1985; Heldt et al., 2008). Other authors proposed reduced biocalcification rates in surface waters either related to CO_2-driven ocean acidification (Wissler et al., 2003; Weissert and Erba, 2004; Erba and Tremolada, 2004) or to highly elevated trophic levels (Coccioni et al., 1992; Cobianchi et al., 1998; Erba, 2004). However, CO_2-induced changes in water chemistry should have also lowered biocalcification rates on the shelves, which can not be confirmed in the present study.

Altogether, our results are not in accordance with a global carbonate production crisis during OAE 1a, vast eutrophic regimes on subtropical–tropical shelves, and a widespread carbonate platform drowning phase. We suggest that intensified greenhouse conditions and subsequent processes associated with the event, such as increased average precipitation rates, increased coastal runoff, intensified wind velocities, riverine and/or upwelling-induced nutrification, must have been generally less intense than previously suggested or were only of regional importance. We found no evidence for increased terrigenous runoff in both sections investigated, although the platforms were located in proximity of rivers. A recent publication from the northern Tethys margin even suggests an absence of climatic changes associated with the OAE 1a (Heimhofer et al., 2004). Ando et al. (2008) restricts intensified greenhouse conditions to the onset of the OAE 1a only.

Our results strengthen the hypothesis of oceanic eutrophication by hydrothermal input of biolimiting metals related to the construction of the Ontong Java–Manhiki plateau (Larson and Erba; 1999; Erba, 2004), because it could explain best the discrepancy between high trophic levels in pelagic regimes (e.g. Hochuli, 1999; Erba, 2004) and rather intermediate nutrient levels on many shelves. Biolimiting metals could have reached surface waters by hydrothermal event plumes (Vogt, 1989). They could have been distributed in global pelagic regimes by surface currents in a few thousand of years and could have been also carried to varying extent onto the carbonate platforms during the eustatic sea-level rise associated with the OAE 1a, by upwelling, and water exchange processes between the platform interiors and open ocean.

Acknowledgements

We thank C. Scheibner (Bremen) for stimulating discussions.

This project was supported by the DFG (German Research Foundation, project no. Ba-1571-11).

Rerefences:

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Supplementary data

Fig. 1. Literature: 1-this study; 2-internal part: Ferreri et al., 1997, external part: Luciani et al., 2006; 3-Grötsch et al., 1998 and personal communication; 4-Yilmaz et al., 2004; 5-this study, 6-Immenhauser et al., 2005; 7-Pittet et al., 2002; 8-Yurewicz et al., 1993; 9-Lehmann et al., 2000; 10-Vahrenkamp et al., 1993; 11-Burla et al., 2008; 12-Hunt and Tucker, 1993; 13-Wilmsen, 2005; 14-internal part: Castro et al., 2006, external part: Aguado et al., 1999; 15-Föllmi et al., 2006; 16-Yilmaz et al., 2004; 17-Graziano, 1999, 18-Jansa, 1993; 19-Masse, 1993

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CHAPTER 4

Palaeoenvironmental evolution of a southern Tethys carbonate platform margin: response to global climate change (Late Aptian of north-central Tunisia)

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Submitted to

Sedimentology

Sedimentary deposits of the Serdj Formation cropping out in the central part of Djebel Serdj, close to the village of Sidi Hamada. The lowermost limestone cliff represents the base of the Serdj Formation.

Palaeoenvironmental evolution of a southern Tethys carbonate platform margin: response to global climate change (Late Aptian of north-central Tunisia)

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Abstract

During the Aptian, many subtropical carbonate platforms (e.g. on the northern Tethys margin and in the Gulf of Mexico) were repeatedly affected by severe perturbations in the carbonate production factory and drowning phases, often corresponding to anoxic events (OAE 1a, 1b) and other time intervals associated with global warming (such as the mid-Late Aptian warming event). In the last years, increasing evidence suggests that carbonate platforms on the southern Tethys margin were generally less or even not affected by environmental perturbations during these events. This raises the question on the responsible factors which promoted platform growth or decline in the different shelf areas. In the present study, Upper Aptian (Middle Gargasian–Upper Clansayesian) innertropical carbonate ramp deposits of the Serdj Formation at Djebel Serdj, north-central Tunisia were studied in detail with regard to microfacies, lithology, biostratigraphy, and chemostratigraphy. Our data allows us to reconstruct the palaeoenvironmental evolution of a southern Tethys carbonate platform margin and to investigate its response to global climate change. The unusually expanded, 600 metres thick deposits consist of limestones, marlstones, and siltstones, suggesting deposition within mid-ramp and inner ramp palaeoenvironments. The hermatypic platform biota within the deposits suggests a stable oligotrophic water regime throughout the entire Late Aptian. Biostratigraphy, $\delta^{13}C$-, and $\delta^{18}O$ stratigraphy allowed us to recognise a prominent mid-Late Aptian warming phase as well as two cooling phases prior to and after the warming event. Deposits of the warming event are siliciclastic-rich limestones and common siltstones, possibly resulting from intensified biogeochemical weathering rates in the hinterland and increased coastal runoff due to higher precipitation rates. A drowning episode during the warming phase as reported from some subtropical carbonate platforms did not occur. Sedimentary records of the cooling events show no signals of regional climate change.

A comparison to other Late Aptian carbonate platforms of low and mid-latitudes shows, that favourable growth conditions during the entire Late Aptian were more widespread than previously suggested. Drowning episodes were possibly restricted to the northern Tethys margin and the Gulf of Mexico.

Keywords: Late Aptian; microfacies; biostratigraphy; chemostratigraphy; global climate change

1. Introduction

Carbonate platforms are sensitive recorders of changes in the ocean/climate system and have attracted much attention as a means of evaluating the middle to Late Cretaceous (120–80 myrs ago) greenhouse earth. The carbonate platforms latitudinally expanded during this period, characterised by

globally averaged sea-surface temperatures possibly 6–14° warmer than at present (Barron, 1983; Pucéat *et al.*, 2003; Steuber *et al.*, 2005). Although the maximum expansion was reached in the Late Albian and Santonian (Johnson *et al.*, 1996; Skelton, 2003), the northern limit during the Late Aptian already reached 36° N (Takashima *et al.*, 2007), which is 3° further north than today. During the latter time interval, the carbonate platforms were extensively colonised by typical benthonic flora and fauna, e.g. dasycladacean algae, foraminifers (such as miliolids and orbitolinids), corals, rudists, bivalves, and nerineacean gastropods. Common abiogenic grains were ooids, being associated with the occurrence of high energy shoals (Masse, 1992; Kiessling *et al.*, 2003).

Whilst growth conditions were favourable for many carbonate platforms during the Late Aptian (e.g. Masse *et al.*, 1997; Castro *et al.*, 2001; Kiessling *et al.*, 2003; Takashima *et al.*, 2007), those on the northern Tethys margin were severely affected by perturbations in the carbonate production factory and drowning (Föllmi *et al.*, 1994; Weissert *et al.*, 1998; Föllmi *et al.*, 2006), especially during a prominent global warming phase (*H. trocoidea/T. bejaouensis* planktonic foraminifer zones) in the Gargasian/Clansayesian transition interval, termed “Aptian Greenhouse Earth 2” by Weissert and Lini (1991). Platform demise in this 3–4 myrs lasting interval has been also reported from the Gulf of Mexico (Lehmann *et al.*, 2000). The warming phase is reflected in the occurrence of a pronounced negative oxygen isotope excursion described by different authors (e.g. Clarke and Jenkyns, 1999; Weissert and Erba, 2004) and was possibly caused by elevated levels of volcanogenic CO_2 in the atmosphere (Weissert and Lini, 1991; Herrle and Mutterlose, 2003; Weissert and Erba, 2004). Increasing temperatures are thought to have caused intensified rainfall over the Tethyan subtropics, which led to accelerated biogeochemical weathering rates, enhanced coastal runoff, quartz sand shedding, and nutrification of coastal environments (Weissert and Lini, 1991; Weissert *et al.*, 1998, Wortmann *et al.*, 2004). The effects of excess nutrients on carbonate platforms have been discussed in several publications, they include reduced water transparency, destabilized oxygen levels and pH, leading to drastic changes in platform communities and reduced carbonate production (Hallock and Schlager, 1986; Wood, 1993; Weissert *et al.*, 1998).

Furthermore, two cooling episodes prior to and after the warming phase (Weissert and Lini, 1991; Price, 1999, 2003; Mutterlose and Bornemann, 2005) are reflected in positive oxygen isotope excursions (Price, 2003; Weissert and Erba, 2004). The first cooling phase in the Middle Gargasian (*G. algerianus* foraminifer zone) is associated with a cooling of surface waters and ecological changes within the Tethys and Pacific (Premoli Silva *et al.*, 1989; Weissert and Lini, 1991; Price, 2003). The second cooling phase during the Aptian/Albian transition interval probably led to a cooling of waters and ecological changes in polar regions only (Heimhofer *et al.*, 2007).

Until now, investigations on the aforementioned climatic changes and their effects on shallow marine carbonate platform sedimentation are generally rare and restricted to the platforms at mid-latitudes (e.g. Weissert *et al.*, 1998, Föllmi *et al.*, 2006; Takashima, 2007). Less attention has been paid to the more tropical carbonate platform belt of the southern Tethys continental margin. The aim of this paper is to reconstruct the palaeoenvironmental evolution of a southern Tethys carbonate platform margin in the Serdj area, north-central Tunisia, by using detailed lithology and microfacies analysis, bio- and chemostratigraphy, and geochemistry. Respect is paid to the prominent changes in palaeoclimate and

their effects on the area investigated. The results are compared to other investigations on Aptian carbonate platforms of low- and mid-latitudes.

2. Geological setting

2.1. Palaeogeography of the central Tunisian carbonate platform

The studied area was located on the northern platform margin of the Central Tunisian carbonate platform, about 25 km north of a large island (Kasserine island) (Fig. 1). The platform was part of the broad innertropical carbonate platform system that extended over large parts of the southern Tethys continental margin during the Late Aptian (Kiessling *et al.*, 2003). Shallow marine carbonate sedimentation in Tunisia during this time interval took place in a relatively stable realm delimited to the south by the clastic, estuarine sedimentation of the terrestrial Saharan platform and to the north by open, mainly deep marine sedimentation of the Tunisian Trough (e.g. Boltenhagen, 1985; M`Rabet, 1987, Lefranc and Guiraud, 1990) (Fig. 1). A mosaic of islands in the central part of the platform divided it into a more or less restricted southern-, and a Tethys-connected northern part with a ramp-type platform margin. (e.g. Tlatli, 1980; Marie *et al.*, 1982; M`Rabet, 1987). A north-south trending high zone ("North–South Axis") separated the platform from the eastern Tunsian shelf (e.g. Burollet, 1990; Ben Ferjani *et al.*, 1990).

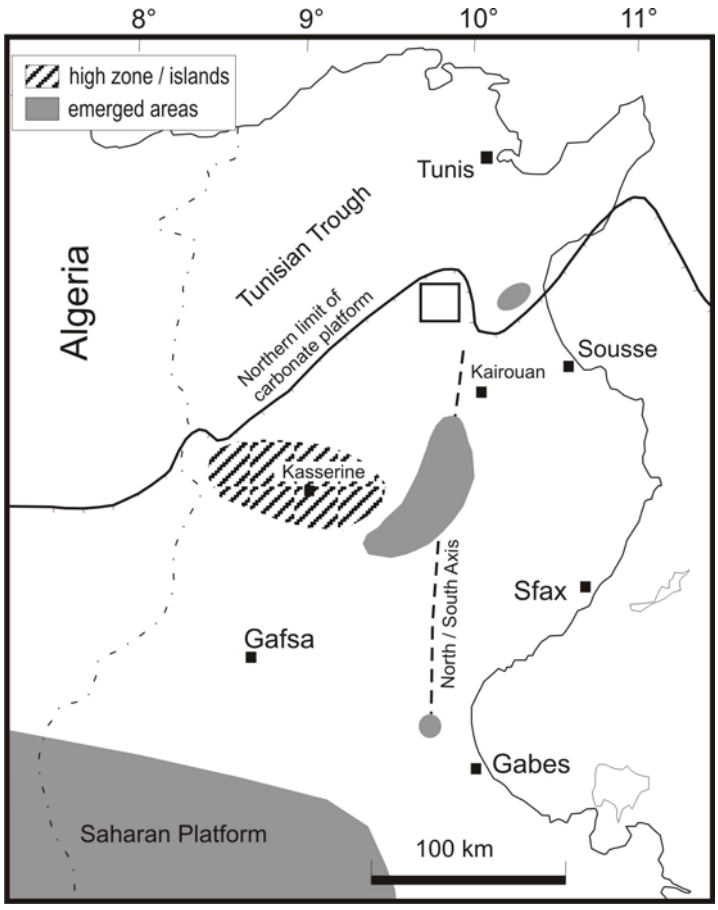

Figure 1: Palaeogeographic map of Tunisia for the Late Aptian. The black rectangle marks the investigated area (Fig. 2). After Tlatli (1980) and M`Rabet (1987).

2.2. Lithostratigraphy

Two main formations of Upper Aptian shallow marine carbonates are distinguished in central Tunisia: the Orbata Formation, which characterises the southern part of central Tunisia (Gafsa–Sidi Bouzid region) and the Serdj Formation, occuring in the more northern parts (Kasserine–Kairouan region) (Burollet, 1956; M`Rabet 1987; M`Rabet *et al.*, 1995). Both formations are 450–660 metres thick in average, but show considerably reduced thickness along the North–South Axis and in the island-zone around the city of Kasserine (Burollet, 1956, Ben Ferjani *et al.*, 1990). The Orbata Formation mainly consists of inner shelf carbonates with intercalations of evaporites and is ascribed to the southern, more protected part of the Tunisian carbonate platform. It passes northwards into the Serdj Formation, which is characterised by inner shelf carbonates and deposits of the ramp-type platform margin, e.g. reefal limestones (Tlatli, 1980; M`Rabet, 1987; Ben Ferjani *et al.*, 1990; Tandia, 2001; Chaabani and Razgallah, 2006). The upper boundary of both formations is commonly marked by an emergence surface, reflecting the exposure of the platform probably caused by tectonic movements in the Late Gargasian to Clansayesian (Marie *et al.*, 1982; Ben Ferjani *et al.*, 1990; Chaabani and Razgallah, 2006). It has been suggested that the central parts of the platform were affected first, hence Upper Aptian platform carbonates in this region comprise the shortest Upper Aptian chronology (M`Rabet *et al.*, 1995; Chaabani and Razgallah, 2006). However, the detailed ages of both formations are still a matter of debate, because biostratigraphic markers are generally scarce in Tunisian shallow marine successions and chemostratigraphic curves are not well established.

2.3. Geological setting of the studied area

The Serdj mountain is located in north-central Tunisia (Figs. 1 and 2). The evolution of the massif has been ascribed to different tectonic movements during the Cretaceous–Tertiary. It is characterised by a SW-NE striking anticlinorium affected by a variety of faults, e.g. faults with a SW–NE direction, a large normal fault of the NW-flanc of Djebel Serdj, and dextral and sinistal strike-slip faults of several directions (magnitude of displacement between one and several tens of metres) (Turki, 1977).

Barremian to possibly Albian sedimentary rocks (hemipelagic to shallow marine marlstone, limestone, siltstone) cropping out at Djebel Serdj have been studied by several authors over the years (e.g. Pervinquiére, 1903; Burollet, 1956; Turki, 1975; Tlatli, 1980; Heldt *et al.*, 2008). They belong to the Hamada Formation, Serdj Formation, and possibly Fahdene Formation (Tlatli, 1980; Heldt *et al.*, 2008). In the present paper we studied the Serdj Formation, which is characterised by 600 metres thick deposits of limestone (e.g. bioclastic and peloidal wacke-, pack-, and grainstones, oolitic grainstones, and coral framestones), marlstones, and siltstones. The upper boundary of the formation is characterised by two emergence surfaces, reflecting the exposure of the carbonate platform probably in the Late Clansayesian (Tlatli, 1980; M`Rabet, 1981). The emergence surfaces are overlain by limestone and marlstone, possibly of Lower and Middle Albian age (Fahdene Formation, Tlatli, 1980).

The facies of the Serdj Formation at Djebel Serdj has been investigated by Tlatli (1980) and dated as being Middle Gargasian–Late Clansayesian in age by using planktonic and benthic foraminifers for biostratigraphy. This author subdivided the deposits into 5 calcareous units (S1–S5) separated by silty and marly levels (T1–T4) (Fig. 4). He suggested that the deposits reflect inner and outer ramp

palaeoenvironments close to the open marine domain of the Tunisian Trough and described a trend to more shallow marine environments sections upwards.

3. Material and methods

The present study is based on three sections (SN, SH, BK; 575 m, 515 m, and 220 m thickness, respectively) along Djebel Serdj (Fig. 2 and 3), nearly comprising the entire Serdj Formation. The uppermost 50–70 metres of the formation only were not recorded for the present study. All sections show low syn- and postsedimentary tectonic overprint.

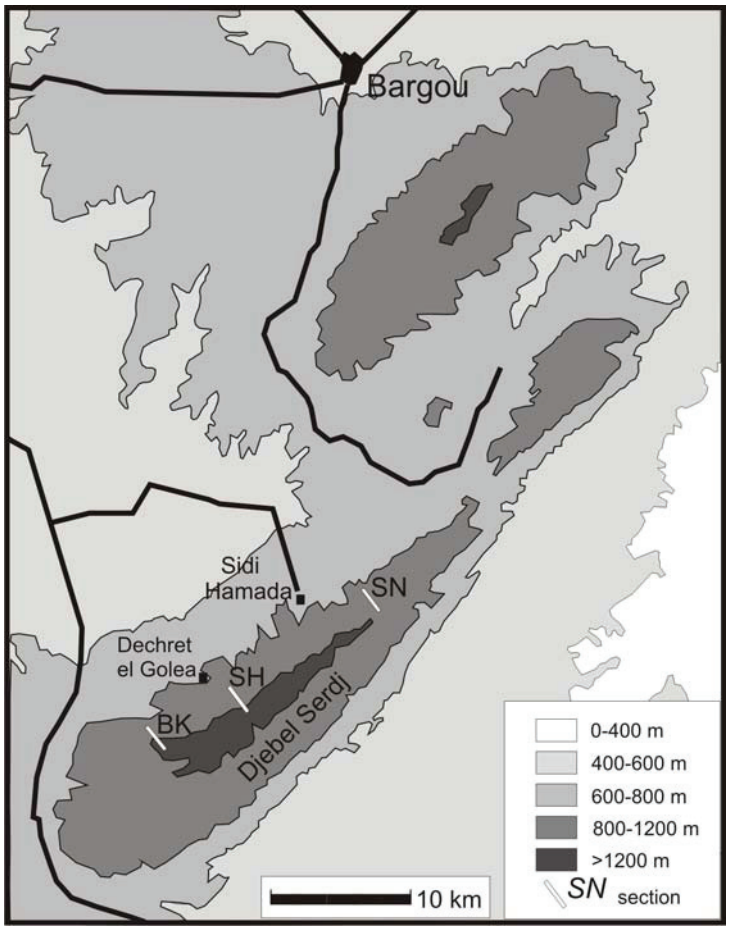

Figure 2: Map of the Serdj area with locations of the sections investigated.

Our detailed microfacies, biostratigraphical, and geochemical analyses presented in this paper were carried out on 319 samples (Fig. 5). In section SN and BK, the spacing of microfacies samples was mainly between 1 m and 5 m, whereas section SH was sampled at 5 to 10 m intervals. Two-hundred ninety-eight thin sections were prepared from indurate samples (limy marlstone, limestone and siltstone). Twenty-one marlstone samples were disaggregated in clay dispersion (Rewoquat) and subsequently washed through sieves of 630, 100, 63, and 20 micron-screen. Microfacies composition and rounding of components were determined in thin sections and washed samples. Depositional textures, relative abundances, and sorting of components were determined in thin sections only. Field observations and the results of the microscope analyses led to a division of the successions in 4

facies units (A–D), each being subdivided in 2–5 microfacies types. The palaeoenvironmental zonation of the Tunisian platform margin was established by adapting and modifying the division scheme for homoclinal carbonate ramps as suggested in Flügel (2004).

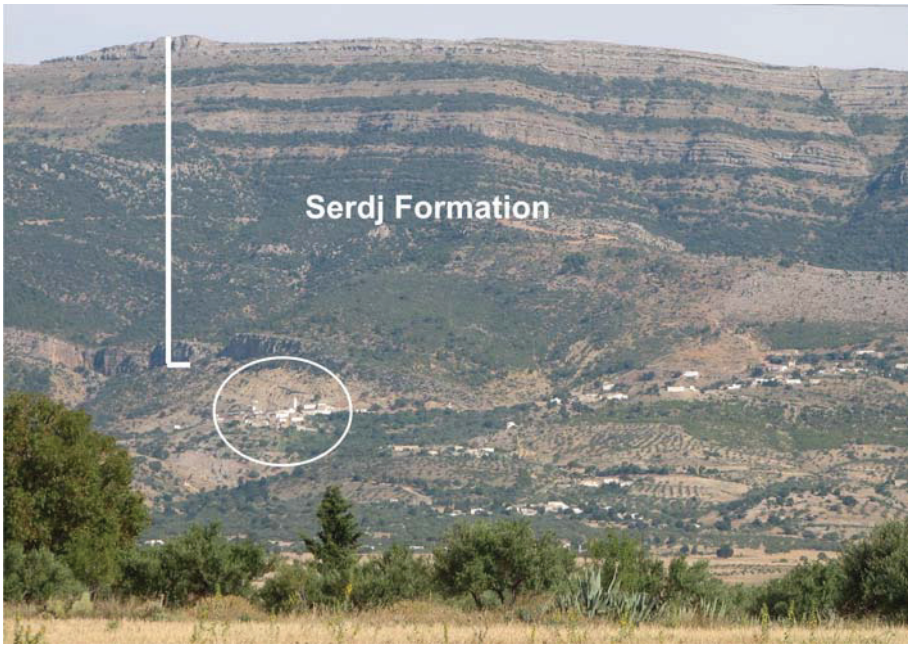

Figure 3: Sedimentary rocks of the Upper Aptian Serdj Formation cropping out in the central part of Djebel Serdj. View from the northwest. The village in the left (encircled) is Dechret el Golea (for location see Fig. 2). The thickness of the Serdj formation is up to 600 m in this area.

Stratigraphy is based on planktonic and benthic (orbitolines) foraminifers as well as $\delta^{13}C$ and $\delta^{18}O$ isotopes. Planktonic foraminifers were picked from residues of washed material (60–100 specimen per sample). Taxonomic classifications, based mainly on shell texture and morphology, refer to Premoli Silva and Sliter (2002). The age of the observed zone is deduced from the standard low-latitude zonal schemes of Premoli Silva and Sliter (1999). For taxonomic identifications of the orbitolines, internal structures, especially the embryonic apparatus were analysed in the thin sections sensu Schroeder (1975). The stratigraphical ranges of the species were deduced from the compilation of Tethyan ranges by Bachmann and Hirsch (2006). The taxonomy of the ammonite fauna collected during the fieldwork is extensively discussed in Lehmann *et al.* (submitted).

Carbon and oxygen isotope data, additionally used for stratigraphy, has been obtained from 52 bulk rock samples of section SN. They were measured in the RCOM, Bremen with a Finnigan MAT 251 mass spectrometer (accuracy +/- 0.07‰). Our $\delta^{13}C$ and $\delta^{18}O$ data were compared and correlated to data of time-equivalent Tethyan deposits (e.g. Weissert *et al.*, 1998; Herrle *et al.*, 2004; Weissert and Erba, 2004).

The $CaCO_3$ content of 130 samples (section SN) was derived from the measurement of C_{total} with a Leco CNS-200 elemental analyzer (accuracy +/- 0.05%). The TOC content of the same samples was measured with a Leco CS-125 analyzer (accuracy +/- 0.02%). The measurements were carried out in the Alfred Wegener Institute, Bremerhaven.

4. Geochemical data

4.1. $CaCO_3$ content

The carbonate content of section SN ranges from 0 to nearly 100% (Fig. 4).

Values fluctuate considerably between 0 to nearly 100% in the limestones and marlstones of the lowermost 200 m of the succession. Lowest values are noticed in siltstone beds. Values between 5 to 100% characterise the overlying limestone and siltstone dominated deposits between 200 and 400 m. Predominantly high values at around 80% characterise the the uppermost part of the section (400 to 575 m).

4.2. TOC content

The total organic carbon (TOC) content of section SN is generally low, values range from 0.1% to around 0.3% (Fig. 4). Samples in the lower 150 m of the succession are characterised by fluctuations in values between 0.1 and 0.3%. The deposits between 150 and 350 m predominantly contain around 0.1% TOC. The deposits from 350 to 575 m show values between 0.1 and 0.2%.

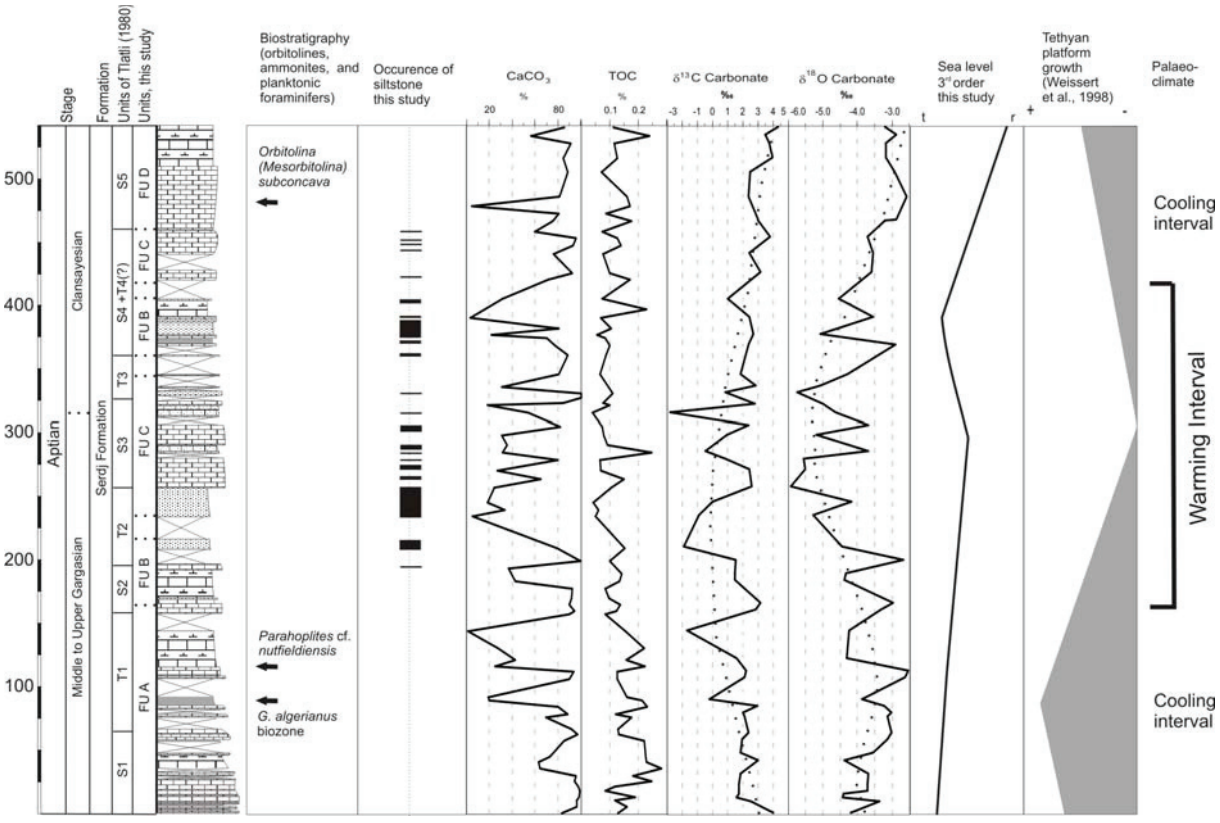

Figure 4: Section SN with facies units, bio- and chemostratigraphy, occurrence of siltstones, geochemistry, sea-level changes, and palaeoclimatic intervals. For the location see Fig. 2. For the description of the lithology see Fig. 5.

4.3. Carbon isotope ratio

$\delta^{13}C$ values of section SN range between -2.9‰ and 4,3‰. The lowermost part of the curve is characterised by a negative excursion (first 140 m), which finishes a long-lasting positive excursion characterising the late Early Aptian at Djebel Serdj (Heldt *et al.*, 2008) and other global localities (e.g.

Jenkyns, 1995; Weissert *et al.*, 1998). The succeeding deposits between 140–325 m show fluctuations in values between -2.9‰ and 3.1‰. A positive excursion characterises the deposits from 325 metres on. The last sample shows the highest $\delta^{13}C$ value of the whole succession (4.4‰).

4.4. Oxygen isotope ratio

$\delta^{18}O$ values of section SN range from -6‰ to -2.1‰. in the lowermost 210 m of the section values range mainly between -4‰ and -3‰. The overlying deposits (125–350 m) predominantly show more negative values, ranging between -6‰ and -3.5‰. A positive excursion to values of around -2‰ to -3‰ is then observed in the uppermost part of section SN (from 350 m to 575 m).

5. Stratigraphy

5.1. Biostratigraphy

Microfossils suitable for dating have been observed in the lowermost and uppermost parts of the sections only (Fig. 4). In one horizon of section SN, recrystallized moderately to well preserved planktonic foraminifers allowed the determination of the *Globigerinelloides algerianus* biozone. The deposits below and above contain no or scarce planktonic foraminifers, which prevents the identification of the zone borders. Following Premoli Silva and Sliter (1999), the *Globigerinelloides algerianus* zone indicates the Middle Gargasian.

In most parts of all sections, *Orbitolina* (*Mesorbitolina*) *texana* is observed, but does not provide additional stratigraphical information, due to its long stratigraphic range (Late Aptian to Late Albian; Bachmann and Hirsch, 2006). In the uppermost parts of sections SN and BK, the occurrence of *Orbitolina* (*Mesorbitolina*) *subconcava* suggests an age not older than Late Clansayesian. Following the range charts of Bachmann and Hirsch (2006), this species appears in the Late Clansayesian and disappears in the lowermost Cenomanian.

Tethyan range charts of *Ovalveolina reicheli*, occuring in the uppermost parts of sections SH and BK, have not yet been established. However, some authors working on platform carbonates of Italy (e.g. Chiocchini *et al.*, 1994) used this species as indicator for the Aptian/Albian boundary interval. A few ammonites have been collected in the investigated successions (Lehmann *et al.*, submitted), but typical zonal markers are scarce. *Cheloniceras* (*Cheloniceras*) sp. and *Parahoplites laticostatus* are dating the lowermost part of the Serdj Formation as Late Aptian. Furthermore, *Parahoplites* cf. *nutfieldiensis* probably indicates the *P. nutfieldiensis*-zone in the lower part of the successions.

5.2. Chemostratigraphy

The Middle Gargasian–Late Clansayesian age of the investigated deposits, proposed by Tlatli (1980), is confirmed by our integrated biostratigraphy, $\delta^{13}C$ stratigraphy, and $\delta^{18}O$ stratigraphy. The $\delta^{13}C$-curve of section SN (Fig. 4) exhibits excursions, which closely correlate with those described for Upper Aptian deposits worldwide (e.g. Jenkyns, 1995; Weissert *et al.*, 1998; Herrle *et al.*, 2004), characterised by a negative excursion in the Early–Middle Gargasian from around 3.5–4‰ to 2–3‰. These values then persist, until a positive shift appears in the Late Clansayesian (to around 3.5–4‰). The $\delta^{13}C$ curve of section SN exhibits comparable trends (Fig. 4), but values in the interval between the prominent excursions fluctuate considerably and minimal values are 2-3‰ lower.

Excursions of the $\delta^{18}O$ curve of the investigated sections can be correlated with data by Clarke and Jenkyns, 1999; Price, 2003; Weissert and Erba, 2004, and others. Curves of these authors exhibit values around 0.2‰ in the Middle Gargasian (in the *G. algerianus* biozone, see chapter on biostratigraphy), followed by more negative values (around -0.5‰) in the Gargasian/Clansayesian boundary interval. A positive shift to around 0.2‰ characterises the Late Clansayesian. Absolute values in the studied sections are considerably lower (around 3-6‰), but the trends are the same (Fig. 4). The similarities between our isotope curves and global curves as well as the absence of covariance between $\delta^{13}C$ and $\delta^{18}O$ values suggests a slight diagenetic overprint only.

6. Depositional environments

Four facies units (FU A–D), which are subdivided into 12 microfacies types (MFT 1–12), are distinguished on the base of main components, textures, macro-, and microfossil associations as well as lithological variations observed in the outcrops. The facies units represent different depositional environments and are clearly separated from each other. Figure 4 shows the distribution of the facies units and microfacies types in our sections. An overview of their characterisation and environmental interpretation is presented in Table 1. Typical thin sections are illustrated in Fig. 7. The facies units and microfacies types are:

6.1. Facies Unit A: limestone (MFT 1: bioclastic to peloidal wackestone and packstone) and marlstone (MFT 2) (Fig. 7 /A)

These 125-170 m thick deposits are composed of grey limestones (mostly bedded at dm–m scale) and grey to brownish marlstones. The base of facies unit A (FU A) is marked by a vertical limestone cliff of 25–30 m high, which is regarded as base of the Serdj Formation (Tlatli, 1980). Macrofossils are mainly rare, in few beds bivalves (e.g. oysters), rhynchonellid brachiopods, nautilids (*Cymatoceras neckerianum*), ammonites (*Cheloniceras* (*Cheloniceras*) sp., *Parahoplites laticostatus*, *Parahoplites* cf. *nutfieldiensis*) and toxasterid echinoids are observed. Two microfacies types can be distinguished:

MFT 1: bioclastic to peloidal wackestone and packstone. Bioclasts are mainly formed by fine-grained skeletal detritus (silt to sand-size) and subordinated smaller sized shell fragments (mainly <1 mm). Other common skeletal particles are planktonic foraminifers (mainly hedbergellids, rarely globigerinelloidids), small benthic foraminifers, ostracods, echinoderm remains (e.g. echinoid spines), and worm tube fragments. Orbitolines occur in the upper parts of the sections together with orbitolines, miliolids, fragmented shells with thin micritized rims (cortoids), small micritized skeletal grains (bahamite peloids), small gastropods, and calcispheres of unknown origin. Mud peloids often constitute a substantial part of the groundmass in all thin sections. Quartz grains are rare, slightly increasing in number in the upper parts of the successions. Components are poorly sorted in the lower parts and slightly better sorted in the upper parts. Skeletal fragments and quartz grains exhibit angular to subangular shapes.

MFT 2: marlstone. Biogenic particles in residues of washed material are characterised by fine-grained skeletal detritus and smaller sized fragmented shells (mainly <1 mm). Planktonic foraminifers (mainly hedbergellids, rarely globigerinelloidids) and small benthic foraminifers (e.g. *Praedorothia*

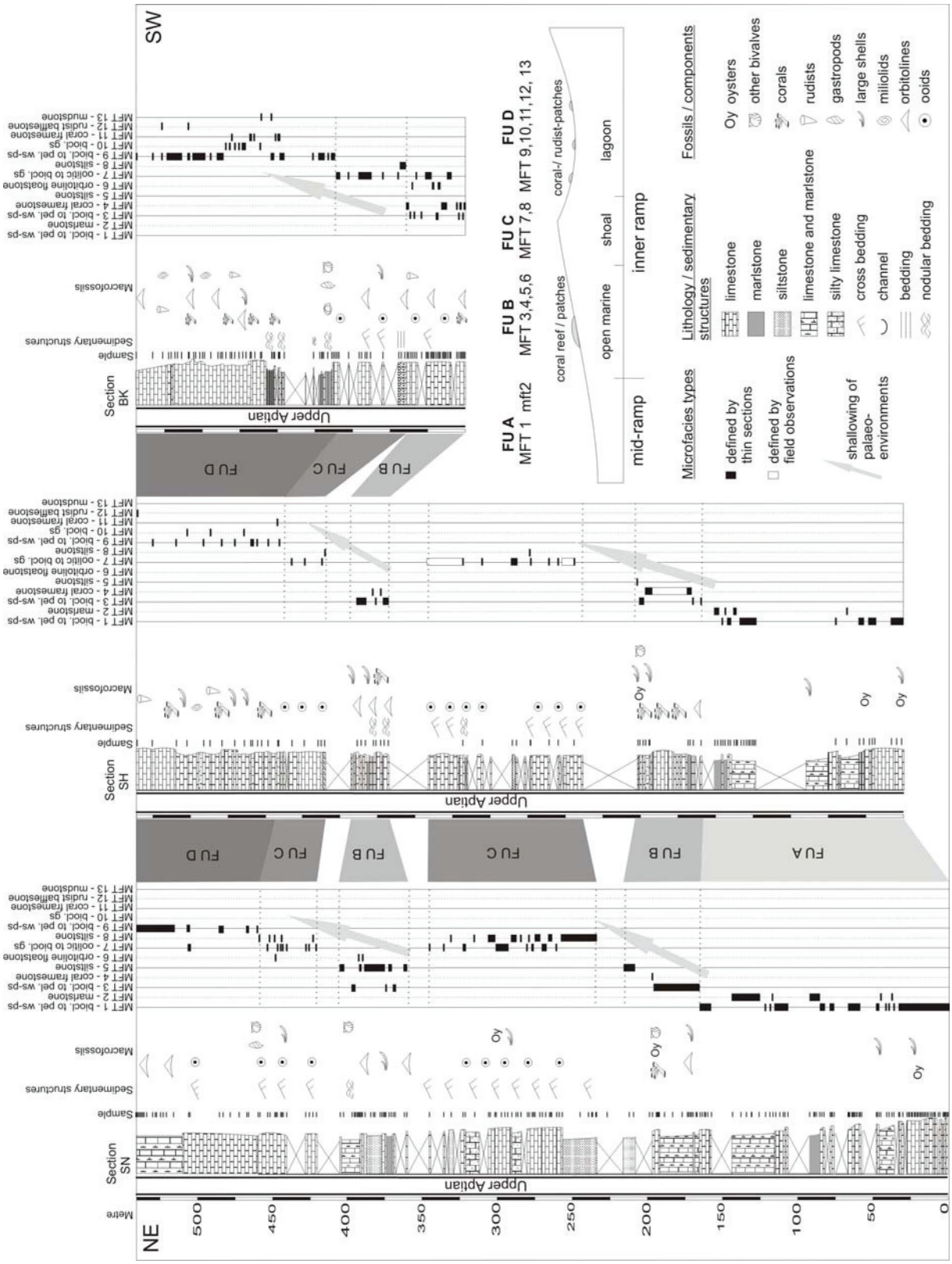

Figure 5: The occurrences of facies units and microfacies types in the sections investigated. For locations see Fig. 2.

Facies unit / microfacies type		Lithology / Macrofossils	Microfacies / Textures	Environmental interpretation
A	**MFT 1:** bioclastic to peloidal wackestone and packstone **MFT 2:** marlstone	**Bedding / sedimentary structures:** limestone bedded at dm-m scale **Macrofossils:** bivalves, brachiopods, echinoids, nautilids, ammonites	**Components:** fine-grained skeletal detritus, mud peloids, small fragmented shells, planktonic foraminifers, small benthic foraminifers, ostracods, echinoderm remains, worm tube fragments, quartz grains. In the upper part also orbitolines, miliolids, cortoids, bahamite peloids **Sorting/rounding:** poorly sorted, angular to subrounded shapes	Distal mid-ramp in the lower parts, proximal mid-ramp in the upper parts low-energy setting
B	**MFT 3:** bioclastic to peloidal wackestone and packstone **MFT 4:** coral framestone **MFT 5:** siltstone **MFT 6:** orbitoline floatstone	**Bedding / sedimentary structures:** limestone bedded at dm-m scale, nodular bedding is common. Siltstone rarely shows cross-bedding and occurs in channels **Macrofossils:** bivalves, solitary corals, colonial corals (coral reef, in-situ colonies or beds), gastropods, red algae, rudists (rarely in life-position)	**Components:** fragmented shells, mud peloids, quartz grains, cortoids, bahamite peloids. Skeletal fragments of: bivalves, gastropods, echinoderms, corals and others. Completely preserved: small benthic foraminifers (e.g. miliolids), orbitolines, large agglutinating foraminifers, ostracods **Sorting/rounding:** poorly to moderately sorted, angular to subrounded shapes	Inner ramp / open marine maximum water depth in more distal portions a few tens of metres. Water depth close to high energy shoals (MFU C) a few metres only moderate energy setting
C	**MFT 7:** bioclastic to oolitic grainstone **MFT 8:** siltstone	**Bedding / sedimentary structures:** all deposits show cross-bedding. Ripple marks and channels are observed at few horizons. Few silstones show nodular bedding **Macrofossils:** large bivalve shells only	**Components:** ooids, skeletal fragments (e.g. bivalves, gastropods, green algae, echinoderms, bryozoans and others),quartz grains **Sorting/rounding:** moderately to well sorted and rounded sometimes parallel orientation of bioclasts in the bedding plane	Inner ramp / high energy shoals water depths of a few metres influence of tidal currents high energy setting
D	**MFT 9:** bioclastic to peloidal wackestone and packstone **MFT 10:** bioclastic grainstone **MFT 11:** coral framestone **MFT 12:** rudist baffliestone **MFT 13:** mudstone	**Bedding / sedimentary structures:** limestone bedded at dm-m scale, nodular bedding is rare **Macrofossils:** bivalves, colonial corals (in situ colonies), rudist (in situ colonies), gastropods, echinoids, solitary corals. Rare ammonites	**Components:** fine-grained skeletal detritus, fragmented shells, mud peloids, cortoids, bahamite peloids. Skeletal fragments of: bivalves, gastropods, echinoderms, corals, worm tubes, and others. Completely preserved: small benthic foraminifers (especially miliolids), orbitolines, alveolinids, ostracods and others. **Sorting/rounding:** poorly to moderately sorted, angular to well rounded shapes	Inner ramp / lagoon water depth a few metres maximum influenced by the tides and wave action low to moderate energy setting

Table 1: Microfacies units, microfacies types, lithology, macrofossils, microfacies, and palaeoenvironmental interpretation of the sections. The ranges of the facies units and microfacies types are plotted in Figs. 4 and 5.

praeoxycona, *Lenticulina* spp.) are common. Further biogenic components are ostracods, echinoderm fragments, worm tube fragments, small gastropods, and unidentified skeletal remains. Quartz grains are rare. Bioclasts and quartz grains exhibit angular shapes.

Distribution

Both microfacies types are observed in in the lower parts of sections SN and SH, with MFT 1 being more common. The deposits in section SH are only partially exposed due to vegetation covering.

Palaeoenvironmental interpretation

The fully marine macro- and microfossil assemblage including common planktonic organisms and the muddy textures suggest open marine conditions. Sorting and rounding of components suggest low hydrodynamic energy. Shallow water components (miliolids, cortoids, bahamite peloids) and increasing detrital input in the upper part of FU A possibly suggest a shallowing. We assume a distal mid-ramp palaeoenvironment for the lower part and proximal mid-ramp environment for the upper part of FU A. A mid-ramp setting is supported by Heldt *et al.* (2008), describing the occurrence of tempestites close below the base of the Serdj Formation.

6.2. Facies Unit B: limestone (MFT 3: bioclastic to peloidal wackestone and packstone, MFT 4: coral framestone, MFT 6: orbitoline floatstone) and siltstone (MFT 5) (Fig. 7/B–C)

Facies unit B is characterised by 25–50 m thick grey limestones and grey to brownish siltstones (all bedded at dm to m-scale). Nodular bedding of limestones is common. Few siltstone beds show cross-bedding. Channels filled with siltstone are rare. Common macrofossils are oysters and other bivalves, solitary corals, and colonial corals (often dm-scale in-situ colonies or beds). Gastropods (e.g. *Natica sautieri*), encrusting red algae, and rudists (rarely in life-position) are scarce. The following four microfacies types are distinguished:

MFT 3: bioclastic to peloidal wackestone and packstone. The biogenic assemblage is dominanted by smaller sized fragmented shells (<2 mm), which commonly show thin micritic envelopes (cortoids). Other common skeletal fragments are remains of bivalves, gastropods, and echinoderms (e.g. echinoid spines). Common completely preserved skeletal grains are small benthic foraminifers (such as miliolids), orbitolines (*Orbitolina (Mesorbitolina) texana*), large agglutinating foraminifers (*Ataxophragmiides* sp.), and ostracods. Skeletal fragments of colonial corals, encrusting red algae, bryozoan colonies, worm tubes, rudists, and green algae are predominantly rare. Planktonic microfossils (foraminifers, calcispheres of unknown origin) occur only sporadically. Some small skeletal grains are nearly completely micritized (bahamite peloids). Mud peloids often constitute a substantial part of the components. Mud intraclasts are rare. Quartz grains are usually rare, but abundant in a few beds. Components are poorly to moderately sorted. Skeletal fragments and quartz grains exhibit angular to subrounded shapes, rounded to well rounded shapes are observed in few thin sections only. Quartz grains show angular to subrounded shapes.

MFT 4: coral framestone. This microfacies type is characterised by colonial corals with commonly few internal structures due to recrystallisation. Layers of red algae (*Rhodophycea* sp.), sometimes along

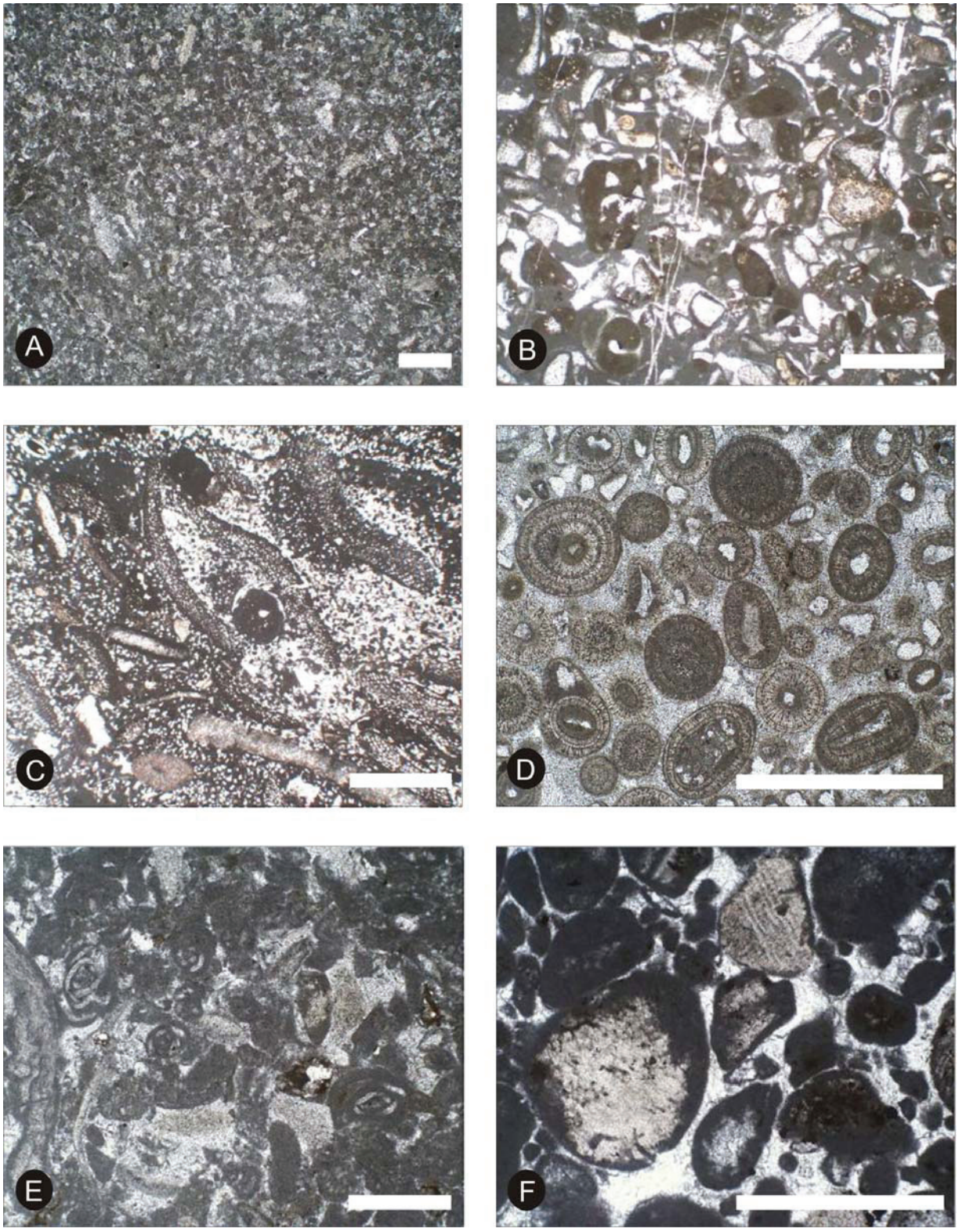

Figure 7: Microfacies of the Serdj Formation. The scale is 1 mm for all images. (A) Facies Unit A, Microfacies Type 1. Bioclastic to peloidal wackestone and packstone. (B) Facies Unit B, Microfacies Type 3. Bioclastic to peloidal wackestone and packstone. (C) Facies Unit B, Microfacies Type 6. Orbitoline floatstone. (D) Facies Unit C, Microfacies Type 7. Bioclastic to oolitic grainstone. (E) Facies Unit D, Microfacies Type 9. Bioclastic to peloidal wackestone and packstone. The thin section contains several miliolids. (F) Facies Unit D, Microfacies Type 10. Bioclastic grainstone. The thin section is dominated by fragmented shells which are almost completely micritized.

with layers of unknown micro-encrusting organisms are observed in few thin sections. If lime mud and other components are present, they are the same as described for MFT 3.

MFT 5: siltstone. The siltstone is characterised by high percentages of angular to subrounded quartz grains, which are often clustered with mud peloids and small skeletal grains as described for MFT 3. All components are predominantly moderately to well sorted.

MFT 6: orbitoline floatstone. This microfacies type exhibits high abundances of orbitolines (such as *Orbitolina (Mesorbitolina) texana*) as well as components corresponding to MFT 3. Moreover, high amounts of quartz grains occur in most thin sections.

Distribution

Microfacies types 3–5 are observed in all four studied sections and show variable abundances. MFT 4 was sampled from in-situ coral colonies or coral-beds in sections SN and BK, whereas in section SH this microfacies type forms a 25–30 m thick prominent cliff (Fig. 7). The occurrence of MFT 6 is restricted to section SN and BK, but few thin sections of section SH also contain high abundance of orbitolines. In section BK, cross-bedded oolitic to bioclastic grainstones (MFT 7) are intercalated.

Palaeoenvironmental interpretation

The presence of shallow water platform components (corals, cortoids, bahamite peloids, and miliolids) and the scarceness of planktonic microfossils indicate shallow marine environments. We assume an open marine/inner-ramp palaeoenvironment of FU B with a strong detrital influx at times. These deposits were generated during low to intermediate water energy. The complete preservation of benthic foraminiferal shells and ostracods may indicate in-situ deposition. A similar platform community with in-situ coral colonies, rudists, orbitolines, and miliolids has been described by Vilas *et al.* (1995) from a comparable outer platform setting of the upper Barremian–Lower Aptian in SE Spain. Intercalations with in-situ bioclastic to oolitic grainstones (MFT 7, FU C) indicate deposition close to a high energy depositional environment with a water depth of few metres only. The light-dependence of the corals allow a maximum water depth of a few tens of metres (Masse, 1992) for the more distal portions of the palaeoenvironment.

6.3. Facies Unit C: limestone (MFT 8: bioclastic to oolitic grainstone) and siltstone (MFT 9) (Fig.6/D)

This microfacies unit consists of 35–115 m thick commonly cross-bedded greyish limestone and grey to brownish siltstone-deposits (bedded at dm to m-scale). Ripple marks or channel (both microfacies types) are observed at few horizons. Few siltstones show nodular bedding. Macrofossils are represented by large bivalve shells (such as oysters) only. This facies unit consists of two microfacies types:

MFT 7: bioclastic to oolitic grainstone. The most common components observed in this microfacies type are moderately preserved ooids, skeletal fragments, and quartz grains. Common skeletal fragments are remains of bivalves and gastropods, echinoderms (e.g. echinoid spines), bryozoan colonies, and green algae (such as *Udoteacea* spp., *Arabicodium*, and *Cylindroporella* sp.). Fragments of encrusting red algae, abraded orbitolines, parts of large agglutinating foraminifers (e.g. *Ataxophragmiides* sp.), small benthic foraminifers (e.g. miliolids), and ostracods are rare. Fragmented

shells commonly exhibit thin micritized rims (cortoids). Few small skeletal particles are almost completely micritized (bahamite peloids). The ooids are characterised by alternating radial and concentric cortexes. Superficial ooids are rare. Nuclei of the ooids include skeletal grains, micrititic carbonate grains, and quartz grains. The latter occur with highly variable amounts (absent to abundant) without or with oolitic coating. Mud peloids and intraclasts are predominantly rare. All components are moderately to well sorted and rounded, including shell fragments with angular shapes in few thin sections. The shapes of the quartz grains are angular to subangular. Matrixes are mainly characterised by sparry calcite cement, only few thin sections show micritic admixtures. Some thin sections exhibit a parallel orientation of bioclasts in the bedding plane.

MFT 8: siltstone. The siltstone is characterised by high percentages of moderately to well sorted quartz grains, which often show oolitic coating. Additional components are the same as described for MFT 7, only mud peloids and small micritized skeletal grains (bahamite peloids) are more common. The quartz grains are angular to subangular shaped. Components are mainly well sorted. Bioclasts are occasionally oriented parallel in the bedding plane.

Distribution

Both microfacies types occur in all four sections with variable abundances. MFT 8 is most common in section SN, which might be related to the poorly exposure of the softer sedimentary rocks in the corresponding parts of section SH.

Palaeoenvironmental interpretation

The frequent ooids, textures and sedimentary structures suggest high energy deposition. Comparable deposits are usually associated with high energy shoals, characterised by a water depths of few metres only (e.g. Burchette and Wright 1992; Flügel, 2004). The parallel orientation of bioclasts in the bedding plane and the channel are most likely related to tidal currents. Green algae suggest transport from the platform interior.

6.4. Facies Unit D: limestone (MFT 9: bioclastic to peloidal wackestone and packstone, MFT 10: bioclastic grainstone, MFT 11: coral framestone, MFT 12: rudist bafflestone, and MFT 13: mudstone) (Fig. 6/E–F)

Facies Unit D is represented by 85-125 m thick, sometimes nodular bedded grey marly limestone and limestone (bedded at dm to m-scale) deposits. Macrofossils are oysters (e.g. *Rastellum (Arctostrea) macropterum*) and other bivalves (such as *Panopea zechi*), colonial corals (often in-situ colonies, maximum dm-scale), rudists (dm-scale in-situ colonies or single individuums), gastropods (e.g. Turrilitacea, *Natica sautieri*), echinoids, and solitary corals (often in growth position). Ammonites (*Parahoplites maximus*, *Neodeshayesites nicholsoni*) and belemnites (*Neohibolites* sp.) are rare. The base of FU D in section SN and BK is marked by nodular bedded marly limestone with common bivalves in life position, large gastropods, and echinoids.

MFT 9: bioclastic to peloidal wackestone and packstone. Thin sections are dominated by fine-grained skeletal detritus (silt to sand-size) in the lower parts of FU D in sections SN and BK and fragmented shells with varying sizes (mainly <3 mm) elsewhere. The latter often exhibits micritic envelopes

(cortoids and bahamite peloids). Other common skeletal fragments are remains of echinoderms (e.g. echinoid spines), bryozoan colonies, colonial and solitary corals, rudists, gastropods, and worm tubes. Common completely preserved microfossils are miliolids and other small benthic foraminifers (such as *Patellina subcretacea* and *Praedorothia praeoxycona*), orbitolines (*Orbitolina (Mesorbitolina) texana*, *Orbitolina (Mesorbitolina) subconcava*), ostracods, and alveolinids (*Ovalveolina reicheli*). Rare skeletal grains are fragments of red and green algae, large agglutinating foraminifers (*Ataxophragmiides* sp.*)*, planktonic foraminifers, calcispheres of unknown origin, and sponge spicules. Mud peloids and mud intraclasts are common, while quartz grains are predominantly rare. All components are poorly sorted and show angular to rounded shapes. The muddy matrix sometimes shows signs of reworking and exhibits sparite.

MFT 10: bioclastic grainstone. The grainstone mainly consists of fragmented, sometimes almost completely micritized shells of varying sizes (cortoids and bahamite peloids). Additional components are the same as described for MFT 9, but show stronger reworking and the abundance of mud intraclasts and mud peloids is consistently higher. In few thin sections, miliolids are abundant. Components are poorly to well sorted and exhibit subrounded to well rounded shapes. The matrix is characterised by sparry calcite cement or a mixture of carbonate mud and cement.

MFT 11: coral framestone. The coral framestone consists of skeletons of colonial corals. Incrustations of red algae (Rhodophycea) occur in few thin sections. If other components are present, they are the same as described for MFT 9.

MFT 12: rudist bafflestone. This microfacies type is characterised by rudist colonies in life position, miliolids, and other components as described for MFT 9.

MFT 13: mudstone. The biogenic assemblage consists of small fragmented shells (silt to sand-size, rarely larger), fragile sponge spiculae, small benthic foraminifers (mainly miliolids), and ostracods. All components are poorly sorted and exhibit angular shapes.

Distribution

The most common microfacies type in all sections is MFT 9. MFT 10, 11, and 12 occur in sections SH and BK only. MFT 13 is restricted to section BK.

Palaeoenvironmental interpretation:

High abundance of shallow water platform components (cortoids, bahamite peloids and miliolids), common in-situ rudist colonies, and the scarceness of planktonic organisms indicate shallow marine environments. We suggest lagoonal palaeoenvironments with maximum water depths of a few metres, influenced by tidal currents and/or wave action. The completely preserved microorganisms (benthic foraminifers and ostracods) probably indicate in-situ deposition. The bioclastic grainstone is interpreted as tidal related facies, because its components correspond to MFT 9 and the textures indicate common variations in hydrodynamic conditions. The mudstones observed in section BK might be related to times of restriction of the palaeoenvironment or to a deposition in areas with calmer water.

7. Discussion

7.1. Biostratigraphy and carbon isotope stratigraphy

The results of our integrated biostratigraphy and chemostratigraphy confirm a Middle Gargasian–Late Clansayesian age for investigated deposits of the Serdj Formation at Djebel Serdj, as proposed by Tlatli (1980) based on planktonic and benthic foraminifers. According to carbon isotope stratigraphy, the onset of the prominent positive δ^{13}C-excursion correlates with the Gargasian–Clansayesian boundary (e.g. Weissert *et al.*, 1998; Gradstein *et al.*, 2004).

The overall trends in δ^{13}C values of section SN are consistent with other records worldwide, but the absolute values in the interval between 125 and 320 m show some irregular minima which are up to 3‰ lower than the almost stable values of around 2–3‰ registered in other Tethyan sections (e.g. Grötsch *et al.*, 1998; Weissert *et al.*, 1998; Herrle *et al.*, 2004). This observation might be explained by deposition on a shallow shelf with a temporarily strong influence of δ^{12}C enriched ambient water (e.g. groundwater, riverine input of freshwater). Diagenesis could also be a cause for the anomalies, especially subaerial diagenesis can have an affect on the primary signature of carbon isotopes (e.g. Heydari *et al.*, 2001). Compared to carbon isotopes, oxygen isotopes are more sensitive to diagenetic processes (e.g. Brand and Veizer, 1981). The δ^{18}O curve of section SN correlates with time-equivalent global curves (e.g. Clarke and Jenkyns, 1999; Weissert and Erba, 2004), but absolute values are much lighter (around –3‰ lower). A lowering of δ^{18}O values has been often interpreted as being indicative for diagenesis, e.g. for increasing temperatures during deep burial (Hudson, 1977, Brand and Veizer, 1981; Schrag *et al.*, 1995).

Our integrated stratigraphic data suggests that the investigated time interval can be correlated with a prominent warming and two cooling phases, which have been discussed by several authors (e.g. Weissert and Lini, 1991; Herrle and Mutterlose, 2003; Weissert and Erba, 2004; Takashima *et al.*, 2007). They are particularly reflected by the occurrence of pronounced oxygen isotope excursions in the present study (Fig. 4).

7.2. Palaeoenvironmental evolution of the Late Aptian Tunisian shelf and sea level changes

Our microfacies analyses in combination with field observations provide information on the palaeoenvironmental evolution of the Tunisian carbonate platform margin during the Late Aptian as well as data on palaeoclimate, sea level changes, and nutrient levels. A block diagram which illustrates the characteristics and interfingering of the different palaeoenvironments is shown in Fig. 6. A 3rd-order sea-level curve for the eastern part of the Tunisian carbonate platform margin is shown in Fig. 4. We are going to focus the discussion on section SN (Fig. 4), which shows the most complete record and stands representatively for all sections.

In the first 300 m of section SN, the transition from a mid-ramp palaeoenvironment (Facies Unit A) to an inner ramp open marine and high energy shoal setting (FU B and C) indicates a continous shallowing of the sea level. The biotic assemblage of FU A (bivalves, echinoids, ammonites, planktonic and benthic foraminifers, and other biota) does not provide information on palaeoclimate and/or nutrient levels due to an absence of indicative fossils. Facies Unit B and C contain a more diverse biota, consisting of colonial and solitary corals, bivalves, gastropods, benthic foraminifers,

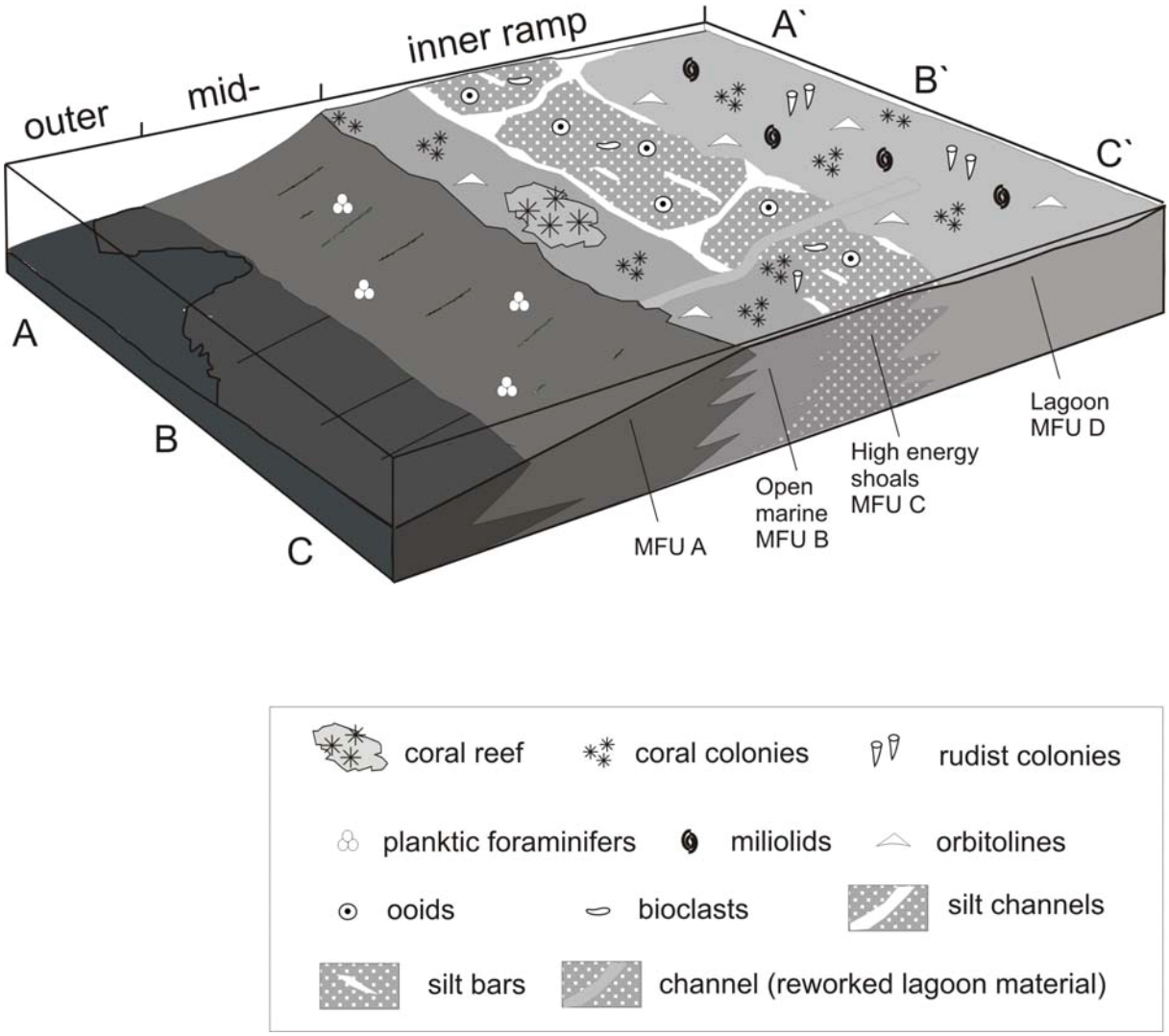

Figure 6: Block diagram illustrating the palaeoenvironments for each section (A–A`=section SN, B–B`=section SH, C–C`=section BK). For locations of the sections see Fig. 2.

echinoderms, bryozoans, red and green algae, and other organisms, suggesting oligotrophic platform growth conditions. Carbonate platforms extensively colonized by corals, rudists and with ooids are generally referred to warm, tropical settings with minimal turbidity and nutrient depletion (e.g. Hallock and Schlager, 1986; Wood, 1993; Kiessling *et al.*, 2003). Both facies units A and B reflect a high siliciclastic input (Fig. 4). Their reoccurrence between 325 and 405 m suggest a short-lived deepening and subsequent shallowing. A further shallowing of the the sea level is indicated by the lagoonal facies at 475 m (FU D), which prevails until the top of the successions (575 m). Platform communities within this facies consist of colonial and solitary corals, rudists, bivalves, gastropods, benthic foraminifers, echinoderms, red algae and other organisms, suggesting again nutrient depleted warm-water conditions as discussed for FU B and C.

Our facies analysis shows, that climatic and ecological conditions during deposition of FU B–C were stable on the Tunisian shelf and favourable platform growth conditions prevailed even during phases of strong siliciclastic input. Upper Aptian deposits of the platform interior (e.g. M`Rabet, 1987; Ben Ferjani *et al.*, 1990; Chaabani and Razgallah, 2006) reflect comparable platform communities to those

described in the present study, suggesting an oligotrophic regime on the whole Tunisian carbonate platform throughout the entire Late Aptian.

Our sea level curve does not correlate with the global curve of Haq *et al.* (1988) or the curve of Haq and Al-Qahtani (2005) for the Arabian platform, which confirms a strong tectonic activity during the Late Aptian in the investigated area as discussed in chapter 2.2. Late Aptian sea-level curves of Tandia (2001) for different successions in the western part of the Tunisian carbonate platform mainly show significant differences and do also not correlate with global curves, which indicates strong regional variations due to tectonic activity along the platform margin.

7.3. Response of carbonate platforms to Late Aptian palaeoclimate

Our facies analysis show, that growth conditions for the investigated carbonate platform were favourable on the Tunisian shelf, suggesting an oligotrophic water regime and rather stable climatic and ecological conditions throughout the entire Late Aptian. In contrast, contemporaneous carbonate platforms on the northern Tethys margin were severely affected by drowning and quartz sand shedding (e.g. Weissert *et al.*, 1998; Wortmann *et al.*, 2004; Föllmi *et al.*, 2006), culminating during the prominent warming phase in the Gargasian/Clansayesian boundary interval (Fig. 4) (Fries *et al.*, 1984; Weissert and Lini; 1991; Weissert *et al.*, 1998). Carbonate platforms in the Gulf of Mexico also experienced a complete demise during this time interval (Lehmann *et al.*, 2000). The observations on the northern Tethys margin have been explained by increased precipitation rates and accelerated chemical weathering in the hinterland, leading to increased terrigenous sedimentation and nutrification of coastal areas (e.g. Weissert *et al.*, 1998; Wortmann *et al.*, 2004). Before the platforms drowned, oligotrophic biotic communities were replaced by meso- or even eutrophic assemblages (Föllmi *et al.*, 1994; Weissert *et al.*, 1998; Föllmi *et al.*, 2006). The platforms were then not able to aggrade and kept pace with eustatic sea-level rise due to highly unfavourable conditions for primary carbonate producers (e.g. Hallock and Schlager, 1986; Weissert *et al.*, 1998). The observations on the northern Tethys margin led to the hypothesis of a widespread carbonate platform growth crisis in the Tethys along river influenced coasts (Weissert *et al.*, 1998), because rivers are the main source of siliciclastics and nutrients along coastlines. The argument was supported by the observation, that shallow water carbonate banks of the southern Tethys realm (such as the Apulia and Gavroro platform) without any major terrestrial input did not experience any growth crisis during the entire Aptian (e.g. Ferreri *et al.*, 1997, Grötsch *et al.*, 1998; Weissert *et al.*, 1998). However, the investigated Tunisian carbonate platform, which was located on the southern Tethys continental margin, was not affected by changes in trophic levels, even though it was located along large river delta systems (Lefranc and Guiraud, 1990; Barale *et al.*, 1998) and also affected by strong siliciclastic input during the warming phase (Fig. 4). Carbonate platforms on the southern Tethys continental margin seemed to be generally less affected by growth crises during the entire Aptian (e.g. also during the Lower Aptian Anoxic Event 1a) as reported by many authors in the last years (e.g. Masse *et al.*, 1997; Immenhauser *et al.*, 2005; Thielemann, 2006; Heldt *et al.*, 2008). This observation suggests, that the favourable growth conditions were most likely related to the warmer and more arid climatic conditions (Houérou, 1997; Ziegler *et al.*, 2003) and not to an absence of riverine input. The southern Tethys continental margin was located within the southern hot arid climatic belt of Chumakov *et al.* (1995),

which is confirmed for the central Tunisian carbonate platform by the occurrence of evaporites within deposits of the Late Aptian (M`Rabet, 1987; Ben Ferjani *et al.*, 1990; Chaabani and Razgallah, 2006). Studies on the hinterland of the Tunisian carbonate platform (Saharan platform) suggest open ground conditions and a certain level of plant productivity at times (Barale *et al.*, 1998, Benton *et al.*, 2000; Ziegler *et al.*, 2003). Arid regions are generally characterised by mineral poor soils. Even at low rainfall intensities surface runoff occurs due to the presence of surface crusts (Abu-Awwad and Shatanawi, 1997), which explains the expanded sandstone deposits in many parts of the southern Tethys realm during the Aptian (Weissert, 1990). The soils probably did not provide enough nutrients during times of intensified precipitation and runoff to change trophic levels in coastal environments noticeably. This explains the high siliciclastic input during the Late Aptian warming event in the sections investigated without nutrification as reported from the northern Tethys margin. Additionally, high evaporation rates in arid climates lead to increased salinity and density of shallow marine surface waters, resulting in an inflow of nutrient-depleted ocean surface water into the platform interior and an outflow at depth (antiestuarine circulation), promoting favourable oligotrophic conditions for primary carbonate producers (Hay, 1995). This mechanism must have also generally shortened residence times of river induced nutrients in euphotic communities.

On the other hand, carbonate platforms in the Gulf of Mexico were also located in an arid climatic zone but affected by drowning during the mid-Late Aptian warming phase (Lehmann *et al.*, 1998, 2000; Ziegler *et al.*, 2003). This region as well as the northern Tethys margin were located close to the northern reef line and thus near the water temperature limit for carbonate platforms. Smaller variations in nutrient levels or water temperatures, which would have not affected the southern Tethys realm to great extent, could have already destabilised these sensitive palaoenvironments. According to Föllmi *et al.* (2006), platform drowning on the northern Tethys margin was additionally triggered by upwelling of nutrient-enriched colder water. Upwelling in some subtropical areas could have added large amounts of nutrients and pushed the systems below the temperature limit for carbonate platforms.

Furthermore, it has been suggested that elevated CO_2 levels in the atmosphere during the Late Aptian warming phase globally weakened marine biocalcification by supporting ocean acidification (e.g. Herrle and Mutterlose, 2003, Weissert and Erba, 2004; Wortmann *et al.*, 2004). Burla *et al.* (2008) suggested that calcium carbonate supersaturation in marine environments of lower latitudes buffered acidification during times of increased CO_2, which would explain the favourable growth conditions on the southern Tethys margin and platform growth crises within mid-latitudes. A recent study on carbonate platforms during the Late Aptian warming phase weakens the hypothesis of changes in water chemistry, because it suggests favourable growth conditions and northward expansion of the reef line in the mid-latitudes of the Pacific (Takashima *et al.*, 2007). The good growth conditions for carbonate platforms in the southern Tethys realm and the Pacific during the warming event suggest, that platform growth crises were a regional phenomenon only, possibly restricted to the northern Tethys margin and the Gulf of Mexico, which can hardly be explained by global ocean acidification. We suggest that changes in water chemistry were less intense than previously discussed and could have been a final trigger for platform drowning in already destabilised ecosystems only.

In contrast to the occurrence of siliciclastica during the warming phase, there is no evidence for ecological changes during the cooling phases in the sections investigated. The first cooling phase in

the Middle Gargasian (*G. algerianus* foraminifer zone) is associated with a cooling of surface waters and ecological changes within the Tethys and Pacific (e.g. Weissert and Lini, 1991; Price, 2003). Ecological changes and a cooling of waters during the second cooling phase in the Aptian/Albian boundary interval was possibly restricted to polar regions (Price, 1999; Heimhofer *et al.*, 2007).

However, further investigations are required to enhance our knowledge on the intensity of the climatic changes during the Aptian, their driving forces, and their different effects on the tropical–polar regions. We suggest that climatic changes during the Aptian did not affect the arid regions within the lower latitudes to the same extent than palaeoenvironments within mid-latitudes, as indicated by relatively stable ecological conditions for platforms on the northafrican continental margin as well as on carbonate banks northwards off its shore.

8. Conclusions

The Upper Aptian (Middle Gargasian–Upper Clansayesian) deposits of the Serdj Formation at Djebel Serdj have provided excellent opportunity to study the palaeoenvironmental evolution of a southern Tethys tropical carbonate platform margin and to investigate its response to global climate change. The successions consist of limestones, marlstones, and siltstones, suggesting deposition within mid-ramp and inner ramp palaeoenvironments. The deposits contain a diverse platform biota, consisting of colonial corals, rudists, gastropods, bivalves, benthic foraminifers, green and red algae, and other organisms, suggesting a stable oligotrophic warm-water regime throughout the entire Late Aptian. Our integrated bio- and chemostratigraphy allowed us to identify a prominent warming phase in the Gargasian/Clansayesian boundary interval and two cooling phases prior to and after this event. Deposits of the warming phase are siliciclastic-rich limestones and siltstones, suggesting intensified precipitation rates, accelerated weathering, and increased coastal runoff in the hinterland. Sedimentary records of the cooling events show no signs of regional climate change. In contrast, Late Aptian subtropical carbonate platforms on the northern Tethys margin or in the Gulf of Mexico were repeatedly affected by eutrophication and drowning, especially during the prominent warming phase. We suggest that the more favourable growth conditions on the Tunisian shelf are related to the tropical arid climatic conditions, promoting nutrient-depleted water conditions due to antiestuarine circulation pattern and mineral poor soils. In comparison, the northern Tethys margin and the Gulf of Mexico were located close to the northern limit for carbonate platforms, which made them very sensitive for palaeoenvironmental disturbances.

A comparison to other investigations on Late Aptian carbonate platforms shows, that perturbations in carbonate production and platform drowning during the Late Aptian were possibly restricted to the northern Tethys margin and the Gulf of Mexico. This observation implies, that platform drowning during the Late Aptian was controlled by regional factors and can not be explained by CO_2 driven global ocean acidification hindering marine biocalcification as recently discussed.

Acknowledgements:

We are grateful to Hedi Negra and Saloua Bey (both University of Tunis) for joining and supporting the fieldwork. M. Segl measured the $\delta^{13}C$ content and R. Bätzel prepared the thin sections. David Fischer

and Patric Simundic helped in the laboratory (all University of Bremen). Christian Scheibner is thanked for helpful comments and suggestions during all stages of the scientific work.

This project was supported by the DFG (German Research Foundation, project no Ba-1571-11).

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CHAPTER 5

Aptian (Early Cretaceous) biostratigraphy and cephalopods from north-central Tunisia

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Accepted manuscript

Cretaceous Research

Collecting macrofossils within the marlstones of the Hamada Formation cropping out in the central part of Djebel Serdj, close to the village Dechret el Golea.

Aptian (Early Cretaceous) biostratigraphy and cephalopods from north-central Tunisia

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Abstract

Thick Aptian deposits in north-central Tunisia comprise hemipelagic Early Aptian, reflecting the sea-level rise of OAE 1a, and a shallow marine environment of the Late Aptian characterized by the establishment of a carbonate platform facies. Carbon isotope data permit the establishment of the OAE 1a event in the Djebel Serdj section. Cephalopods are rare throughout these successions, but occurrences are sufficient to date the facies changes and the position of the OAE1a event. Ammonite genera include Early Aptian *Deshayesites*, *Dufrenoyia*, *Pseudohaploceras*, *Toxoceratoides*, ? *Ancyloceras* and Late Aptian *Zuercherella, Riedelites*, *Parahoplites.* Correlation of carbon isotope data with other Tethyan sections is made together with the integration of planktonic foraminifera data.

Keywords: Biostratigraphy; Early Cretaceous; Aptian; Ammonites; Nautiloids; Tunisia

1. Introduction

In the Early Aptian, superplume activity in the Pacific realm probably triggered greenhouse conditions and major global changes in the ocean/climate system (e.g. Larson and Erba, 1999). The most obvious reflection of these environmental changes is the Oceanic Anoxic Event 1a (OAE 1a), a time interval of deposition under low oxygen conditions mainly in the hemipelagic realm and the deep ocean, and as a consequence, research of the last decades focussed mainly on this event (e.g. Menegatti et al., 1998; Leckie et al., 2002). Recently the effect of major paleoceanographic and palaeobiological changes on shallow marine environments has attracted further research (Graziano 2000; Bernaus et al., 2003; Bachmann and Hirsch 2006; Luciani et al., 2006; Garcia-Mondejar et al., in press).

Ammonites are important in the precise dating of the OAE 1a and other Aptian environmental changes, but their occurrence is often scattered within the lithostratigraphic successions and are only satisfactory in a few areas within the Mediterranean Tethyan province (e.g. Ropolo et al., 2006; Aguada et al., 1999; Garcia-Mondejar et al., in press). As a rule Aptian ammonites are decreasing in occurrence from the hemipelagic realm to the shallow-marine environment. In the hemipelagic facies, they are usually present but uncommon in black shale-, limestone-, marlstone- or claystone facies (e.g. Bernaus et al., 2003), distal carbonate shelf settings often contain at least poor faunas (e.g. Aguado et al., 1999; de Gea et al., 2003), but proximal carbonate platform deposits are frequently undated by ammonites (e.g. Tasli et al., 2006; Memmi, 1999).

The first comprehensive documentation of ammonites and other cephalopods from Tunisia, is that of Pervinquière (1907). It included also descriptions of a few Aptian species. More recent papers focus on

less-expanded sections and aim to establish a biostratigraphy for this realm (e.g. Memmi, 1999). These data are mainly presented by species lists, and the colected ammonites are not documented. Here, we present a study of the thick and well-exposed lithological and facies successions in the study area dated by the rare occurrence of ammonites. This includes on the one hand material from the Lower Aptian OAE 1a interval represented within the hemipelagic facies by 45 m of sediments (Fig. 1A) and on the other by specimens obtained from the Late Aptian shallow-marine carbonate platform (Fig. 1B), a facies predominantly avoided by cephalopods. This permits dating of the Late Aptian re-establishment of a carbonate platform, after the Early Aptian crisis.

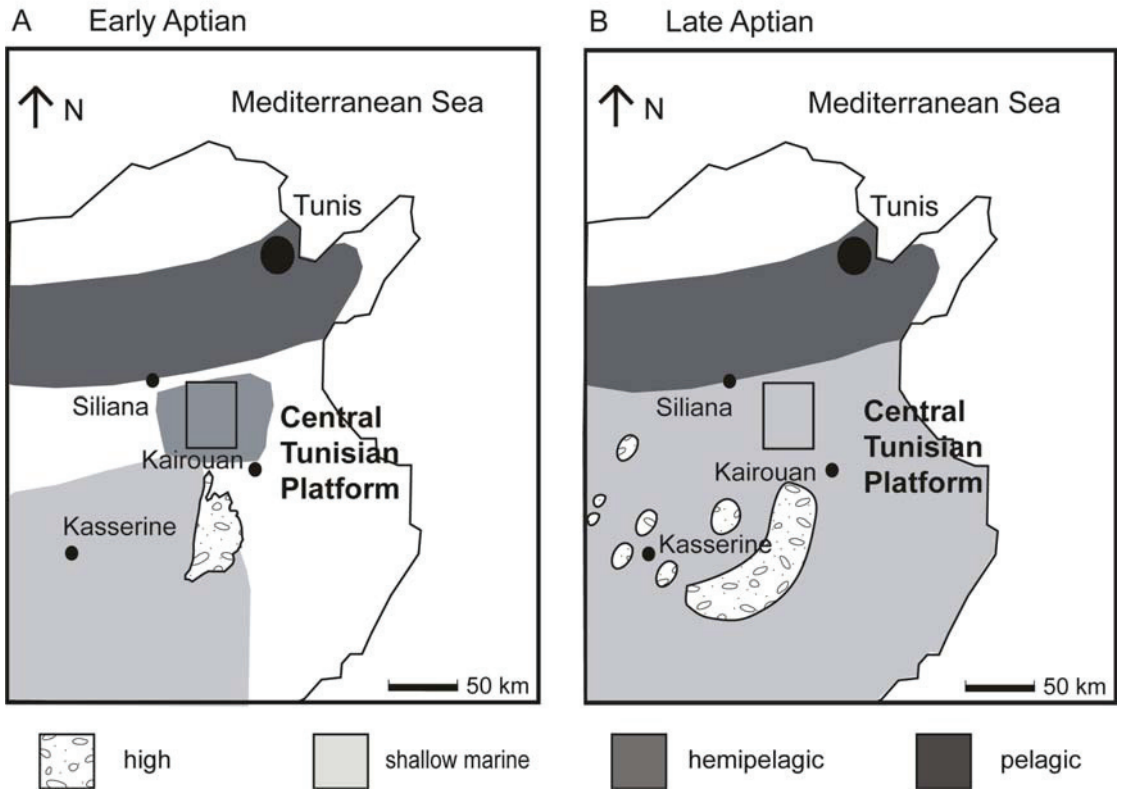

Figure 1: Palaeogeography for the Early Aptian (A) and Late Aptian (B) of central Tunisia with rectangle indicating the location of the working-area magnified in the topographic map in Fig. 2. Map simplified after Ben Ferjani et al., 1990.

The Early Aptian ammonite fauna in north-central Tunisia contains deshayesitids and *Pseudohaploceras* spp., and is, therefore, typical for the shelf environmental regions of the Tethys. This hemipelagic fauna shows affinities to the western and central Tethys as well as to the Boreal region. Ammonites with a supposed pelagic mode of life that are occur in more distal Tethyan environments, such as lytoceratids, phylloceratids and heteromorphs are a minor component if present at all. In the Late Aptian, large parahoplitid specimens are found in the inner ramp, lagoonal facies. A comparison with other regions suggests that this group of ammonites inhabited shallow-water areas rather than the shells having been transported to a proximal position by post-mortem drift. In the lagoonal Late Aptian the palaeobiogeographic affinities persist and additional records from the Americas hint on a more global distribution of taxa.

2. Locality details, profiles and conventions

The present account is based on two outcrops in north-central Tunisia. The main localities are located in the Siliana region, along Djebel Serdj (Fig. 2), where three major sections close to the villages of Beskra, Sodga and Sidi Hamada have been measured and sampled for microfacies, planktonic and benthic foraminifera and stable isotope geochemistry. The sections cover two formations, the Hamada Formation and the Serdj Formation, that were previously dated by planktonic and benthic foraminifera (Tlatli, 1980). The Hamada Formation is subdivided into three members, which cover the whole Early Aptian and the beginning of the Late Aptian (Fig. 3).

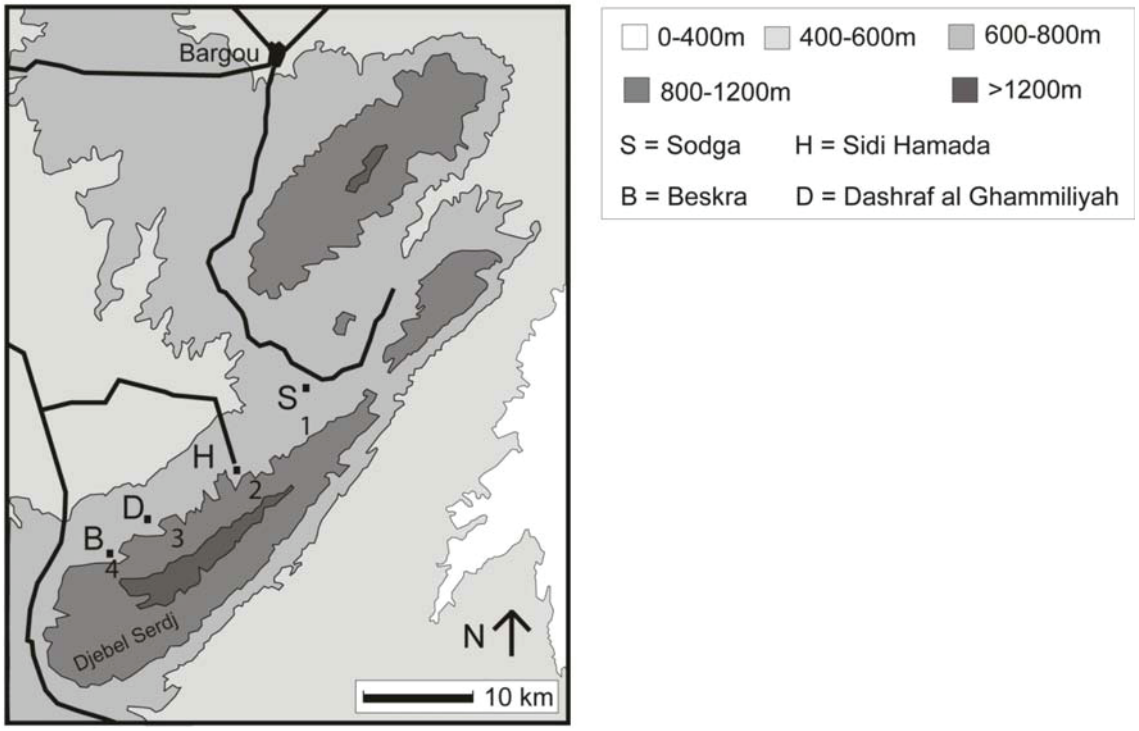

Figure 2: Main working-area at Djebel Serdj in north-central Tunisia, with villages and sampling localities (localities 1-4 in Table 1).

The lowermost part of the Hamada Formation belongs to carbon isotope segment C1, which is attributed to the latest Barremian (compare Menegatti et al., 1998; Heldt et al., 2008). Its top lies close to the upper part of segment C8 that indicates an early Late Aptian age that is confirmed by planktic foraminifera data (Heldt et al., 2008). Consequently, the base of the Serdj Formation lies in the Late Aptian, its upper limit is already Early Albian in age (Tlatli, 1980) and is not further considered here because of insufficient outcrops.

For a detailed data set focussing on the environmental reconstruction and in particular the development around OAE 1a, see Heldt et al., 2008. In Figure 3 we present a schematic profile based on the Djebel Serdj succession, which includes microfacies and carbon isotope data along with planktonic foraminifera data obtained from field-work of the present project. The position of OAE 1a is supported by our stable carbon isotope data, since the δ^{13} C-curve can be divided into segments representing characteristic isotopic excursions. Correlation is possible with time-equivalent sections for

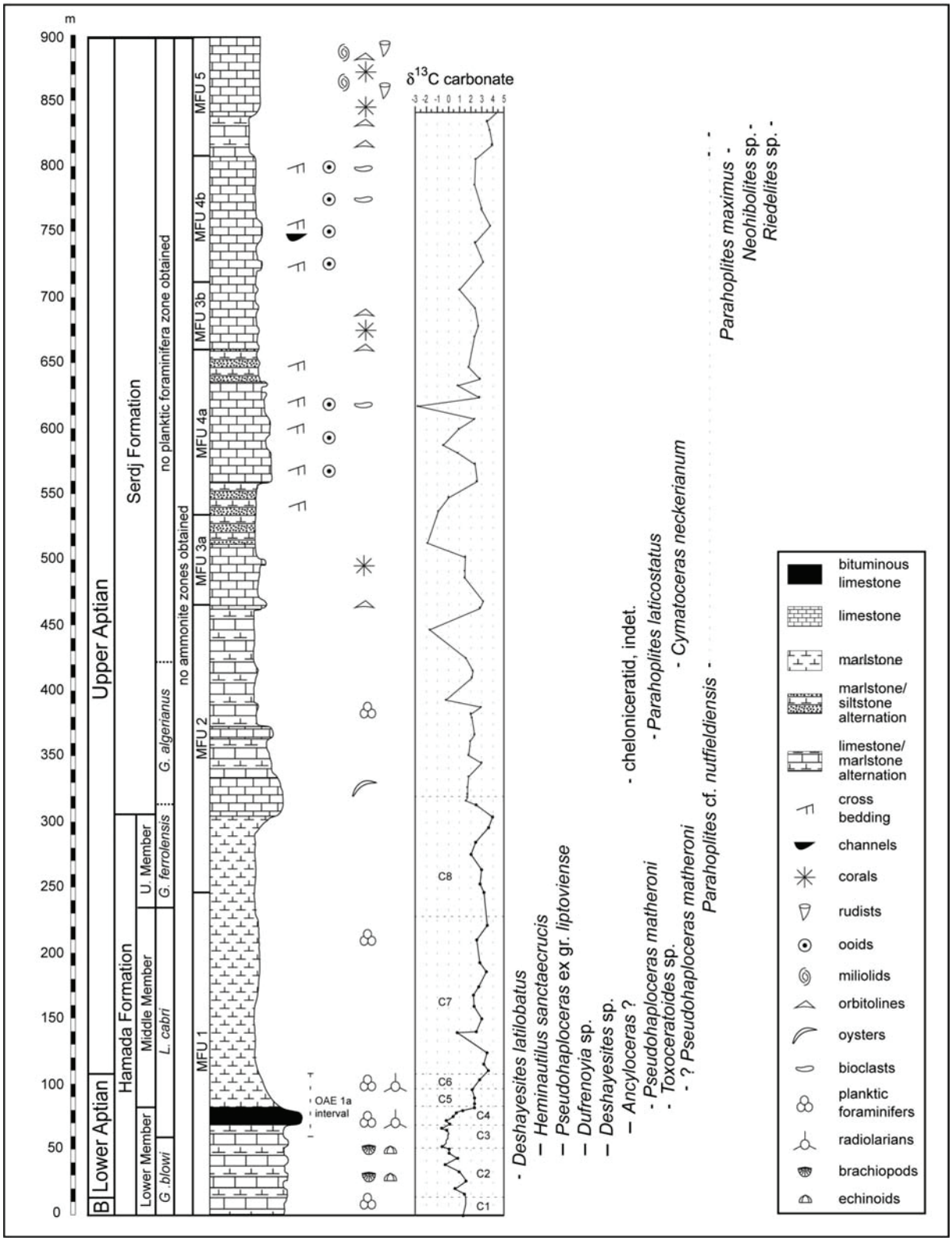

Figure 3: Simplified section for the uppermost Barremian and Aptian in north-central Tunisia. The subdivision of carbon isotope curve into segments C1-C8 follows Menegatti et al. 1998. “B” in the substage column refers to the uppermost Barremian.

example in the Swiss Préalps and southern Alps of northern Italy (Menegatti et al., 1998). Additionally, although a large part of the Djebel Serdj succession was deposited in a shallow-marine depositional environment an ammonite fauna was obtained. This data set was completed by ammonite specimens from similar shallow-water facies of the Late Aptian that have been collected from Djebel Slata also in northern Tunisia, about 100 km WSW of the Siliana area in the vicinity of Kalaat Senan, close to the Algerian border. The subdivision of the carbon isotope curve into segments C1-C8 used in the text and in Fig. 3 follows Menegatti et al., 1998.

The microfacies of the sections investigated was subdivided into five units, abbreviated MFU 1 to 5, with further subdivisions into a and b for MFU 3 and 4 (see Table 2). This classification has been established on the frequency of characteristic palaeoenvironmental components like ooids, cortoids, foraminifera as well as criteria like sorting and rounding of components. It uses common carbonate rock microfacies analysis (e.g. Flügel, 2004). A reinvestigation of the microfacies, chemostratigraphy, facies, palaeoenvironment and some palaeontological aspects on the Aptian of north-central Tunisia, as a whole, is currently under way with some results from the Lower Aptian succession having been completed (Heldt et al., 2008).

The abbreviation GSUB (Geosciences Collection of the University of Bremen, Germany) used in relation to the cephalopod occurrences recorded here, indicates the repository of specimens dealt with in the present paper. The material considered herein is sampled from five different areas, for each specimen represented by the inventory number the GPS positions are given in the following table.

Locality 1: South of Sodga village , Djebel Serdj

coordinates	inventory number	determination
N35.96949°, E009.58941°	GSUB C4053	*Parahoplites* cf. *nutfieldiensis*
	GSUB C4054, C4055	*Cymatoceras neckerianum*
N35.96735°, E009.59497°	GSUB C4050	*Parahoplites* sp.
	GSUB C4051	*Riedelites* sp.
	GSUB C4052	*Parahoplites* ?
N35.96667°, E009.59447°	GSUB C4048	*Parahoplites* cf. *nutfieldiensis*
N35.96674°, E009.59452°	GSUB C4049	*Neohibolites* sp.
N35.97048°, E009.58233°	GSUB C4031	*Dufrenoyia* sp.
	GSUB C4032	*Toxoceratoides* sp.
	GSUB C4033	*Deshayesites* sp.
	GSUB C4034	*Pseudohaploceras* ex gr. *liptoviense*
	GSUB C4035	*Heminautilus sanctaecrucis*
N35.97091°, E009.58276°	GSUB C4037	? *Toxoceratoides*
	GSUB C4044	*Pseudohaploceras matheroni*
N35.97070°, E009.58271°	GSUB C4036	*Ancyloceras* ?

Locality 2:Uphill (=southeast) of Sidi Hamada village, Djebel Serdj, see also Fig. 4C, D

coordinates	inventory number	determination
N35.95500°, E009.56435°	GSUB C4039	Deshayesitidae, gen. et sp. non det.
N35.95490°, E009.56371°	GSUB C4038	*Deshayesites latilobatus*
N35.95566°, E009.56524°	GSUB C4045, C4046	? *Pseudohaploceras matheroni*

Locality 3:Djebel Serdj mountainside, vicinity of Dashraf al Ghammiliyah

coordinates	inventory number	determination
N35.93897°, E009.54068°	GSUB C4047	*Parahoplites laticostatus*
N35.93230°, E009,53427°	GSUB C4083	cheloniceratid, indet.

Locality 4: Uphill (south) of Beskra village , Djebel Serdj, see also Fig. 4B

coordinates	inventory number	determination
N35.92228°, E009.48446°	GSUB C4042	*Parahoplites maximus*
N35.92276°, E009.48326°	GSUB C4043	*Parahoplites* cf. *nutfieldiensis*

Locality 5:Djebel Slata, about 80km NNW of Kasserine, see also Fig. 4A

coordinates	inventory number	determination
N35.86747°, E008.47315°	GSUB C4040	*Zuercherella* sp.
N35.86745°, E008.47361°	GSUB C4041, C4081	*Parahoplites* cf. *nutfieldiensis*
	GSUB C4082	*Parahoplites* sp. 1

Table 1: Locality details of material investigated.

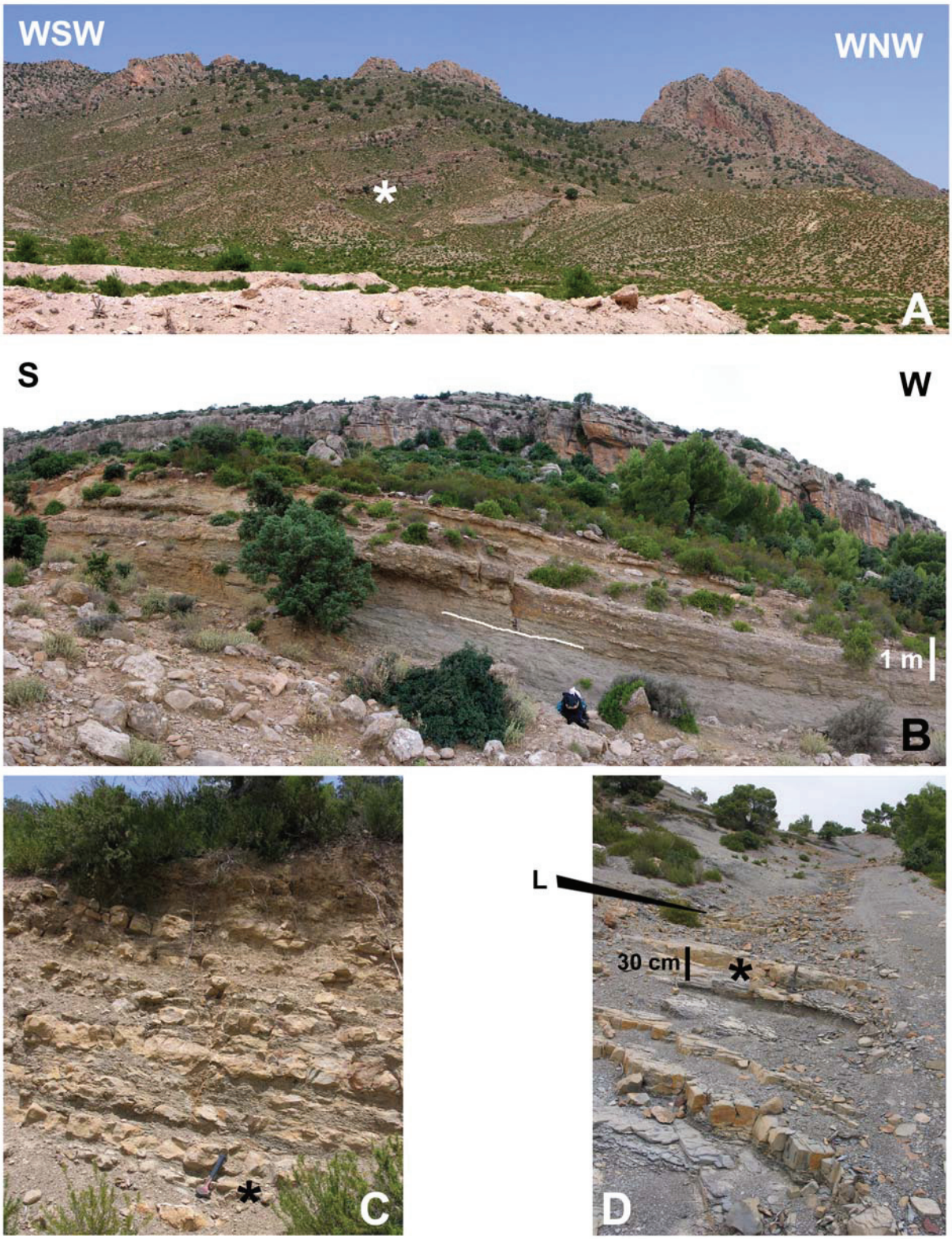
WSW
WNW
A
S
W
1 m
B
L
30 cm
C
D

Figure 4: (Previous page) Aptian ammonite localities in northern central Tunisia. A, Panoramic view of Aptian at Djebel Slata with an asterisk for locality 5 that yielded *Zuercherella* sp. and *Parahoplites* cf. *nutfieldiensis* (Table 1; GSUB C4040, C4041). GPS point: N35.86623°, E008.48003°, 669 m height. About 80 km NNW of Kasserine, west-central Tunisia. B-D, Djebel Serdj near Siliana, north-central Tunisia. B, Outcrop south of Beskra village, Panoramic view of silty peloidal marlstones (wacke- to packstone) of the Upper Aptian that are rich in macrofossils. A large specimen of *Parahoplites* cf. *nutfieldiensis* (GSUB C4043) from the level indicated by the white line. GPS point: N35.92276°, E009.48326°, 776 m height. C, Outcrop southeast of Sidi Hamada village of echinoid-brachiopod bearing silty marlstone-limestone couplets, bioclastic wacke- and packstones of the Lower Aptian with horizon (asterisk) yielding the large ammonite *Deshayesites latilobatus* (GSUB C4038). GPS point: N35.95490°, E009.56371°, 778 m height. D, Laminated bioclastic wacke- and packstones of the Lower Aptian OAE 1a interval southeast of Sidi Hamada village. Transition from the limestone-marlstone alternation to the pure marlstones above; the last indurated wacke-/packstone bed is indicated (L). The asterisk is indicating the bed with notably many ammonites (? *Pseudohaploceras matheroni*) in this area which is otherwise poor in fossil cephalopods. GPS point N35.95566°, E009.56524°, 831 m height.

3. Ammonite biostratigraphy

3.1. Previous work

Early authors in general have noted the scarcity of ammonites in the hemipelagic to pelagic facies of the Aptian deposits of Tunisia (Krenkel, 1911), but a biostratigraphical scheme for the region was developed by Stranik et al. (1970, 1974), Biely et al. (1973) and Memmi (1979, 1981 1999). Pervinquière (1903) first described the Djebel Serdj section in outline and mentioned the occurrence of a few Aptian macrofossils including the cephalopods '*Douvilleiceras' martini* d'Orbigny, '*Hoplites' fissicostatus* Phillips, a nautiloid he referred to the group of *Nautilus neocomiensis* and *N. neckerianus* (=*Nautilus* aff. *neocomiensis* in the species list of Pervinquière, 1903) as well as undetermined belemnites. To the north of Djebel Serdj, at Djebel Bargou, Pervinquière (1903) additionally mentioned *Belemnites* (*Hibolites*) *semicanaliculatus* Blainville and from the wider Bargou area, *Parahoplites uhligi* Anthula. On the basis of our own material we were able to identify the nautiloid species from Djebel Serdj mentioned by Pervinquière (1903, 1907) as *Cymatoceras neckerianus*. The belemnite is *Neohibolites semicanaliculatus* (Blainville, 1827) in current nomenclature, an Aptian species with a wide geographical range (Gauthier, 2006). However, Pervinquière (1903) obviously was unsure about this identification, since he mentions subsequently (Pervinquière, 1907) the Albian species *Belemnites* (*Hibolites*) *minimus* from Djebel Bargou, refering to the same material in his monograph.

Pervinquière's ammonite determinations, although in need of complete revision, indicate the presence of Early Aptian and Late Aptian sediments in this area of Tunisia. Whatever the taxonomic position of his *Hoplites fissicostatus*, the occurrence is sufficient to indicate the presence of Early Aptian sediments (Casey, 1964 shows that the records of *Hoplites* cf. *fissicostatus* (*Deshayesites*) by Pervinquière, 1903, 1907 are based on a misidentification). His records of '*Parahoplites*' *weissi* (Djebel Serdj) and '*Parahoplites*' *consobrinoides* (Bou Tis, North of Bargou) (Pervinquière, 1907), are both species of *Deshayesites* (e.g. Ropolo et al., 2006) and therefore Lower Aptian index ammonites, but Pervinquière's account are insufficient to be certain about the identity of his specimens from a modern taxonomic point of view.

Pervinquière's record of '*Douvilleiceras*' *martini,* whether or not it is correctly identified in modern nomenclature, is an *Epicheloniceras* indicating Late Aptian sediments. Equally, his record of '*Parahoplites*' *uhligi*, a species of *Hypacanthoplites*, indicates a late Late Aptian age (e.g. Immel et al., 1997).

From Djebel Slata Pervinquière (1903) mentioned no cephalopods except for undetermined belemnites, following Pervinquière's (1907) monograph the cephalopods obtained are Albian and Cenomanian in age only.

3.2. Present work

The compound uppermost Barremian to Aptian section shown here (Fig. 3) includes the Hamada Formation and a large part of the Serdj Formation. The ammonite zonation of the Mediterranean Tethyan region and the European province equivalents is shown in Fig. 5, together with the occurrence and ranges of the cephalopods collected from the study area listed separately in Table 1. The ammonite occurrences, although sparse, permit a correlation with similar ranges known from other areas in the European and Tethyan provinces and further correlation using chemostratigraphy and planktonic foraminifera data, in particular, permit a comparison with the standard ammonite zonation (Fig. 5).

In the lower Aptian part of the Hamada Formation, the lowermost level yielding ammonites contains *Deshayesites latilobatus* (Sinzov) (Fig. 7h). This horizon lies about 30 m below the OAE 1a interval, in the middle part of carbon isotope segment C2, and corresponds to one of the lowermost two ammonite zones of the Aptian of the European province (*Deshayesites forbesi* or *Prodeshayesites fissicostatus*), but probably within the *Deshayesites weissi* Zone of the current Tethyan province zonation (Reboulet et al., 2006). However, the only other records well-calibrated are those from the *Cheloniceras parinodum* Subzone of the *Deshayesites deshayesi* Zone s.l. in southern England (Casey, 1980).

An interval yielding mainly *Heminautilus sanctaecrucis* (Conte) (Fig. 7M), *Pseudohaploceras* ex gr. *liptoviense* (Zeuschner) (Fig. 7l), *Dufrenoyia* sp. (Fig. 7a) and *Deshayesites* sp. (Fig. 7j) can be attributed to the transition between carbon isotope segments C2 and C3, only a few meters below the OAE 1a interval (Fig. 3). Whereas *H. sanctaecrucis* and *P.* ex gr. *liptoviense* are of limited stratigraphic value, both are recorded from Barremian as well as Lower Aptian strata (Conte, 1980; González-Arreola et al., 1996). The record of *Dufrenoyia* sp. hints on a late Early Aptian age since *Dufrenoyia* evolved from *Deshayesites* and both genera have been previously recorded to overlap in the uppermost *D. deshayesi* Zone only (Bogdanova and Michailova, 2004). In most shallow marine sections, including the historical Aptian stratotype at La Bedoule (e.g. Ropolo et al., 2006), both genera do not occur in the same beds. However, in the Aralar section in northern Spain, a significant overlap can be observed just in the interval containing OAE 1a (Garcia-Mondejar et al., in press). This correlates with the Tunisian section, since the corresponding interval with the equivalent of OAE 1a contains *Dufrenoyia* sp. as well as *Deshayesites* sp. (Fig. 3).

There are a few ammonite records from the OAE 1a interval, including ? *Ancyloceras* (Fig. 7c) and *Pseudohaploceras matheroni* (d'Orbigny) (Fig. 7d). They do not allow a high-resolution biostratigraphy, since *P. matheroni* occurs from the Late Barremian to the Early Aptian (Vašícek and Summesberger, 2004) and the forms attributed to ? *Ancyloceras* probably suggest an Early Aptian age (Förster and Weier, 1983).

In summary, the lower part of the Hamada Formation at Djebel Serdj is Early Aptian in age on the base of the ammonites. From the geochemical evidence, the Hamada Formation also includes OAE 1a. We abdicate to establish ammonite zones, since the data is limited.

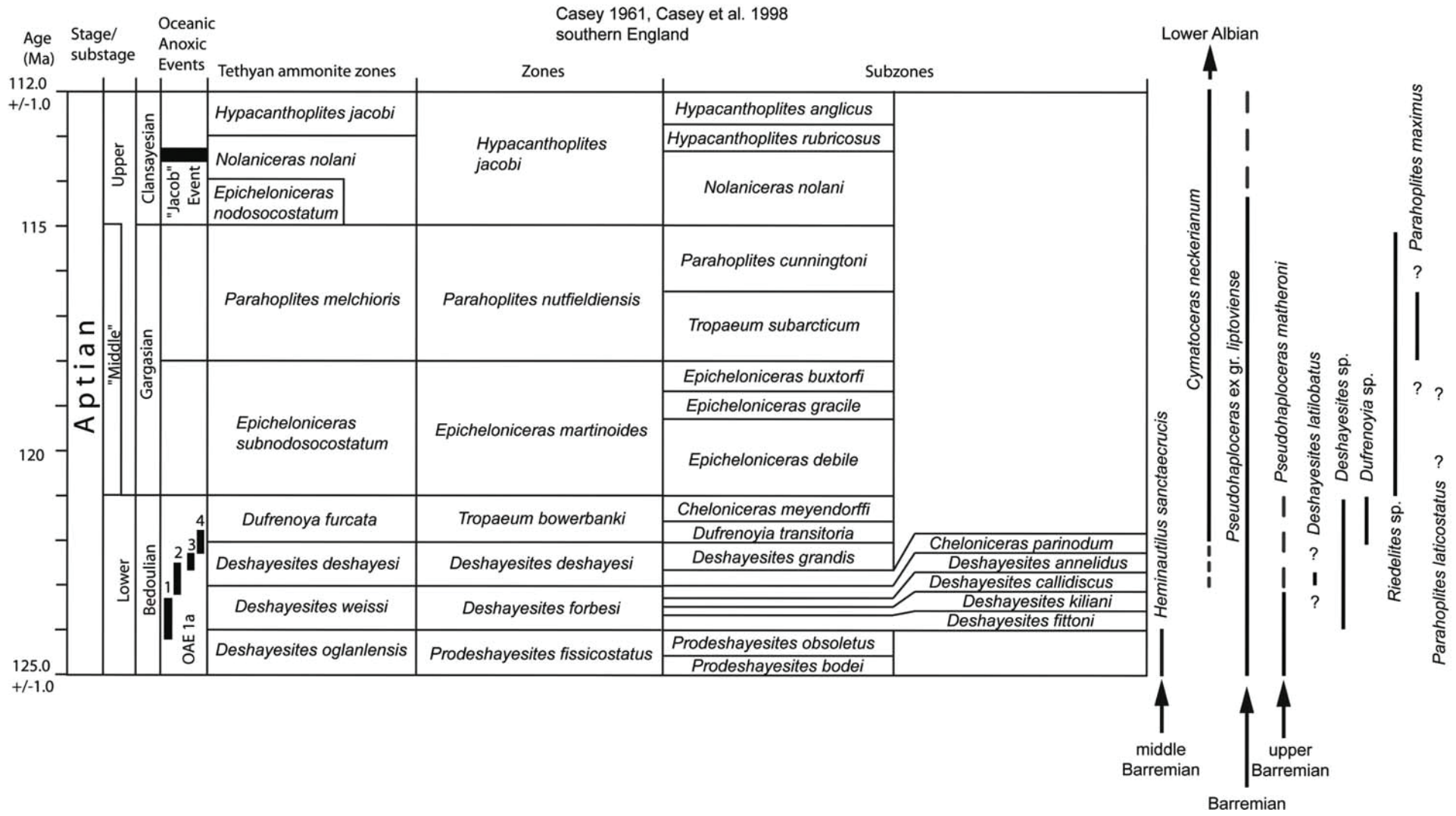
Casey 1961, Casey et al. 1998
southern England
Age (Ma)
Stage/ substage
Oceanic Anoxic Events
Tethyan ammonite zones
Zones
Subzones
112.0 +/-1.0
115
120
125.0 +/-1.0
Aptian
Upper
"Middle"
Lower
Clansayesian
Gargasian
Bedoulian
"Jacob" Event
OAE 1a
1
2
3
4
Hypacanthoplites jacobi
Nolaniceras nolani
Epicheloniceras nodosocostatum
Parahoplites melchioris
Epicheloniceras subnodosocostatum
Dufrenoya furcata
Deshayesites deshayesi
Deshayesites weissi
Deshayesites oglanlensis
Hypacanthoplites jacobi
Parahoplites nutfieldiensis
Epicheloniceras martinoides
Tropaeum bowerbanki
Deshayesites deshayesi
Deshayesites forbesi
Prodeshayesites fissicostatus
Hypacanthoplites anglicus
Hypacanthoplites rubricosus
Nolaniceras nolani
Parahoplites cunningtoni
Tropaeum subarcticum
Epicheloniceras buxtorfi
Epicheloniceras gracile
Epicheloniceras debile
Cheloniceras meyendorffi
Dufrenoyia transitoria
Deshayesites grandis
Prodeshayesites obsoletus
Prodeshayesites bodei
Cheloniceras parinodum
Deshayesites annelidus
Deshayesites callidiscus
Deshayesites kiliani
Deshayesites fittoni
Lower Albian
Heminautilus sanctaecrucis
Cymatoceras neckerianum
Pseudohaploceras ex gr. liptoviense
Pseudohaploceras matheroni
Deshayesites latilobatus
Deshayesites sp.
Dufrenoyia sp.
Riedelites sp.
Parahoplites maximus
Parahoplites laticostatus
middle Barremian
upper Barremian
Barremian

Figure 5: (Previous page) Ammonite biozonal scheme for the Aptian and range of the important taxa recorded herein. The range of OAE 1a referring to the ammonite biostratigraphy is applied different by various authors. 1: Ogg et al., 2004 for Boreal and Tethys, 2: Landra et al., 2000 respectively Erba et al., 1996 for the Tethys as well as Mutterlose, 1992; Keupp and Mutterlose, 1994 for the Boreal. 3: Renard et al., 2005 respectively Moullade et al., 1998 for the Bedoulian type section. 4: Garcia-Mondejar et al., in press. The "*Deshayesites weissi*" zone is inappropriate, but provisionally conserved until a new index is proven following Reboulet and Hoedemaeker et al., 2006. References for ammonite ranges see systematic part.

Above the OAE 1a horizon, there are no ammonite records for the following 230 m of section. Consequently, in our standard section (Fig. 3) the Early-Late Aptian boundary is based on the succession of planktonic foraminifera (Heldt et al., 2008). The earliest Late Aptian ammonite record is an indeterminable cheloniceratid (Fig. 3). Additionally, *Parahoplites laticostatus* has been recorded from this part of the Upper Aptian section at Djebel Serdj, dating the lowermost part of the Serdj Formation as Late Aptian (Fig. 3). The lowermost record of *Parahoplites* cf. *nutfieldiensis* in our compound section might suggest a *P. nutfieldiensis* Zone age already for the lower part of the Serdj Formation, nevertheless this is unlikely as discussed below. The record of *P*. cf. *nutfieldiensis* in the lowermost Serdj Formation is associated with an abundant occurrence of the nautiloid *Cymatoceras neckerianum,* a nautiloid ranging in age from the the late Early Aptian (Calzada and Viader, 1980). The overlying, almost 390 m in thickness, of the section did not yield cephalopods. An interval in the higher part of the Serdj Formation at a height between 500 and 525 m above the base, finally yielded the ammonites *P.* cf. *nutfieldiensis*, *Parahoplites maximus*, *Riedelites* sp. and the belemnite *Neohibolites* sp. Among these fossils the best species for dating is *P. maximus.* This species is restricted to the *Tropaeum subarcticum* Subzone in England, which corresponds to the lower half of the *P. nutfieldiensis* Zone of Casey (1965). If the record of *P*. cf. *nutfieldiensis* from the lower part of the Serdj Formation is correct, it would make the thickness of the *P. nutfieldiensis* Zone sediments at Djebel Serdj a total of 400 m of the total thickness of 650-700 m of this Formation. A trend to higher carbon isotope values above a height of 700 m in this section (Fig. 3) might be correlated with a general increase reported for the *P. nutfieldiensis* Zone or its correlatives e.g. by Weissert et al. (1998), Föllmi et al. (2006).

4. Regional facies and palaeoenvironment

In the Early Aptian a carbonate platform called the Central Tunisian Platform can be recognized (Ben Ferjani et al., 1990; Fig. 1A). A narrow hemipelagic zone can be traced between Siliana and Kairouan followed to the south by broad shallow marine area with only one large high south of Kairouan. The Early Aptian part of the fauna described herein was mainly obtained from an interval slightly below OAE 1a (Fig. 3). Together with the remaining cephalopods from the latest Barremian-Early Aptian part of the section this fauna can be attributed to the microfacies unit 1 (MFU in the following, see conventions; Table 2). MFU 1 hints on an outer ramp palaeoenvironment as indicated by mud- to packstones containing planktic foraminifera and radiolaria as well as cephalopods (Fig. 3). This is a Deshayesitid-*Pseudohaploceras* cephalopod occurrence (occurrence 1 in Fig. 6).

In the Late Aptian, carbonate production took place on an expanded Central Tunisian Platform under shallow marine conditions, with more numerous islands compared to the Early Aptian (Ben Ferjani et

al., 1990; Fig. 1). On this platform large-size and medium-size parahoplitids occur (*P. maximus*, *P*. cf. *nutfieldiensis*, *P. laticostatus*; occurrences 2 to 4 in Fig. 6).

MFU	rock classification	main and diagnostic components	component sorting / rounding	main macrofossils	cephalopod occurrences	palaeo-environment
MFU 1	bioclastic and peloidal mud- to packstones, marlstones	shells, mud-peloids, planktic- and small benthic foraminifers. During OAE1a additionally radiolarians and sponge spiculae	poorly to moderately sorted, angular to subrounded shapes	brachiopods, echinoids	1 - Deshayesitids-*Pseudohaploceras*	outer ramp
MFU 2	bioclastic to peloidal wacke- to packstones, marlstones	shells, mud-peloids, planktic- and small benthic foraminifers	moderately to well sorted, angular to rounded shapes	oysters, other bivalves	2 - *Cymatoceras*-*Parahoplites*	mid-ramp
MFU 3	peloidal to bioclastic wacke- to packstones, marlstones, coral framestones, siltstones	mud-peloids, shells, cortoids, quartz grains, small benthic foraminifers (e.g. miliolids), orbitolines, large agglutinating foraminifers, diverse bioclasts (e.g. of bryozoans, echinoderms)	poorly to well sorted, angular to well rounded shapes	oysters, other bivalves, colonial corals	——	inner ramp/ open marine
MFU 4	bioclastic to oolitic grainstones, silt-stones	ooids, quartz grains, shells, cortoids, bioclasts (e.g. of echinoderms, algae, bryozoans, orbitolines)	well sorted and rounded	large bivalve shells	——	inner ramp/ high energy shoal
MFU 5	bioclastic to pelo-idal/lithoclastic wacke- to grain-stones, coral framestones, rudist bafflestones, menial mudstones, marlstones	shells, mud-peloids, cortoids, diverse bioclasts (e.g. of echinoderms, algae and bryozoans), small benthic foraminifers (e.g. miliolids), orbitolines	poorly to moderately sorted, subangular-well rounded shapes	colonial corals, rudists, other bivalves, gastropods	3 - *Parahoplites* (3a=southwestern - 3b=northeastern Djebel Serdj)	inner ramp/ lagoon (restricted lagoon in parts of the SW section of the working area)

Table 2: Microfacies, interpretation of palaeoenvironment and associated cephalopod occurrences in the Aptian of north-central Tunisia. MFU = Microfacies unit, for details see conventions.

At the base of the Upper Aptian section, the nautiloid *Cymatoceras neckerianum* occurs with an undetermined cheloniceratid, *Parahoplites laticostatus* and *Parahoplites* cf. *nutfieldiensis* (Fig. 6). Specimens of *C. neckerianum* are accumulated in a prominent bioclastic to peloidal wacke- and packstone ledge in the lower part of the Serdj Formation. These limestones can be interpreted as mid ramp environment MFU2, as indicated by moderately to well sorted, angular to round components like occasionally oyster shells, mud-peloids, and planktonic and small benthic foraminifers (Table 2). The occurrence of *C. neckerianum* can be attributed to a general change from hemipelagic to inner ramp deposits (Fig. 6).

Cephalopod occurrence 3 is stratigraphically the highest (Fig. 3) and is characterized by parahoplitids in a very variable carbonate facies, mainly of wacke- to grainstones, coral frame- and rudist bafflestones (Fig. 6, Table 2). The southwestern part of the Djebel Serdj cephalopod occurrence (occurrence 3a in Fig. 6) contains *P. maximus* and *P*. cf. *nutfieldiensis*, whereas *P*. cf. *nutfieldiensis*, *Ridelites* sp. and *Neohibolites* sp. have been recorded in the northeastern part (Fig. 6, occurrence 3b). The interval with cephalopod occurrence 3 is the termination of the Aptian shallowing upwards sequence in this area. It can be attributed to the inner ramp, more precisely the lagoonal facies (Table 2 and Fig. 6).

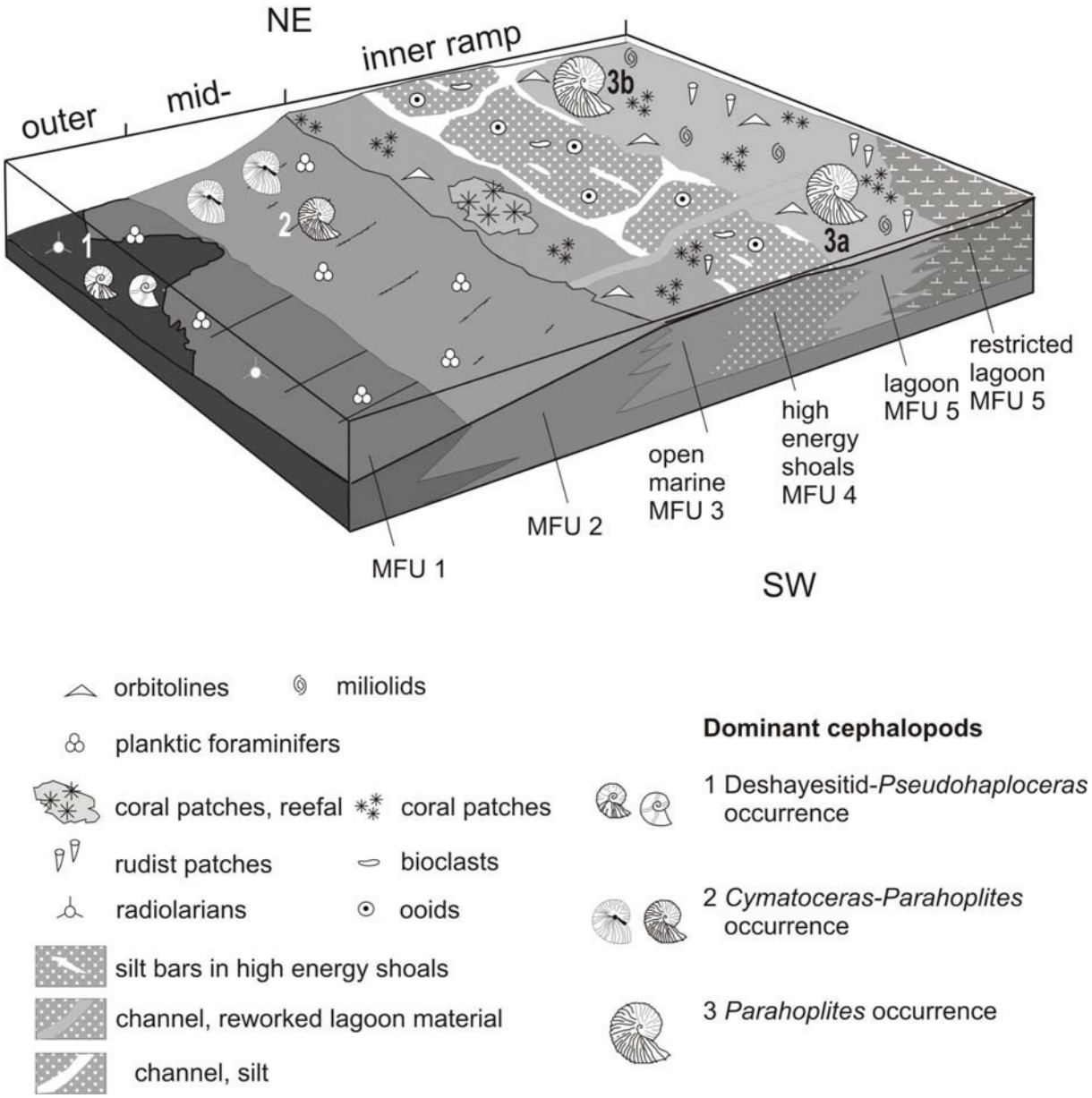

Figure 6: Facies diagram for the Aptian of north-central Tunisia with distribution of ammonite occurences.

5. Conclusions on facies and palaeobiogeography

Cretaceous cephalopod palaeobiogeography is largely affected by transgression-regression cyclicity, subsequent opening and closure of marine gateways and and perhaps to a lesser extent other factors such as temperature (Wiedmann, 1988; Rawson, 1993; Bengtson and Kakabadze, 1999). Generally, rising sea level eliminated geographical barriers and enabled wider distribution, whereas a high sea level might hinder migration by a decline of shallow-water connections and led to the development of specialized associations in isolated areas of shallow water (e.g. Wiedmann, 1988).

5.1. Early Aptian

Ammonites, and in particular biostratigraphic markers, are not only scarce in the Early Aptian in the OAE 1a interval in this area, but throughout much of the Mediterranean Tethyan region (Landra et al., 2000; Bernaus et al., 2003). Exceptions to this occur in the Aralar Mountain area of the Basque-Cantabrian basin (Garcia-Mondejar et al., in press), a rapidly subsiding region on the Biscay spreading margin. In the Lombardy basin in northern Italy Landra et al. (2000) assume an evolutionary stasis in the majority of the ammonite groups, especially Deshayesitidae which are rare in distal facies (upper and middle shelf). The dearth of ammonites at this interval in Italy agrees with our sections on the central Tunisian Platform (e.g. Chaabani and Razgallah, 2006; Fig. 1). In the sections in northern Italy deshayesitids are missing, but lytoceratids and heteromorphs occur (Landra et al., 2000). These are both groups merely with a supposed pelagic mode of life (Westermann, 1996). Our Tunisian fauna largely lacks these pelagic habitat forms except in the association of fairly common *Pseudohaploceras* with the otherwise sparse Early Aptian ammonite fauna. This further supports our microfacies interpretation of these sediments as outer ramp deposits (Fig. 6). Aguado et al. (1999) found a similar assemblage in some levels of the OAE interval on a distal carbonate ramp in southeastern Spain. This peculiar fauna is accompanied the nannoconid crisis in Spain and possibly reflects a lowered fertility as indicated by a lower number nannoconid phytoplankton that was inhabitating the deep photic zone (Erba, 2004).

Our material is statistically not significant, but the quantitatively poor ammonite fauna is probably not related to low oxygen conditions, although ammonites are generally nectic organisms that react sensitively to oxygenation (e.g. Batt, 1993). Coiled ammonites often occur in deposits which were clearly euxinic in nature with no bottom dwellers and the absence of heteromorphs in those successions might indicate a low-oxygen bottom or near bottom living environment (e.g. Bréheret, 1997). Although ammonites are rare throughout the Aptian in our area, there is a continuous record of benthic and planktic foraminifera in the sections, even throughout the OAE 1a, indicating rather well-oxygenated conditions for the bottom water as well as for the higher part of the water column (Heldt et al., 2008). Additonally benthic macrofossils occur, such as brachiopods and echinoids, indicate well-oxygenated conditions for many horizons.

The Early Aptian distribution pattern shows relations to the central and western Tethys as well as to the Atlantic province (*Riedelites* sp.). *Heminautilus sanctaecrusis* might indicate an affinity to the Boreal cephalopod fauna, a Tethys-Boreal faunal exchange would have been possible through the Anglo-Paris Basin and in the Proto-Atlantic northward (Rawson, 1992).

5.2. Late Aptian

A Late Aptian global warming episode is indicated by the migration of Tethyan faunas toward the Boreal realm, the positive excursion of ^{13}C and the negative excursion of ^{18}O in deep-sea carbonates, as well as an expanded northern limit of 'reef' growth in the Pacific realm (Takashima et al., 2007). This could explain why representatives of the ammonite family Parahoplitidae are characteristic elements of Late Aptian cephalopod faunas in the Mediterranean area as well as in Boreal high latitudes (e.g. Kemper, 1982, 1995; Martínez et al., 1994; Delamette, 1997; Raisossadat, 2006). In particular, the dominance of *Parahoplites* in the Late Aptian Tunisian Platform sections

represents a part of its conspicuously wide distribution in the Late Aptian and is probably temperature controlled. *Parahoplites* is well-known from Central and Western Europe (e.g. Casey, 1965; Kemper, 1971) and the wider area around the Caspian Sea (e.g. Sinzow, 1909; Rouchadzé, 1938; Raisossadat, 2006), where also the origin of this group is assumed (Kemper, 1982). Only a few accounts interpret their distribution in relation to palaeoenvironment and facies. Kemper and co-authors, especially, noted the characteristics of the genus *Parahoplites* in the Lower Saxony Basin in northern Germany (Gaida et al., 1978; Kemper, 1982, 1995). Large-size *Parahoplites* (particularly *P. nutfieldiensis*, *P. maximus*, *P. irregularis*) are strictly bound to a proximal position on the shelf, to marginal clay- and siltstone facies, as observed in northern Germany, southern England as well as in the Caucasus mountains and Mangyshlak (Kemper, 1982, 1995). For northern Germany, Kemper (1982) suggests that these large-size ammonites were not found autochthonous, but underwent a post-mortem transport from deep to shallow water deposits induced by upwelling. He assumed a provenence in a deep depression off the coastline or on the slope of the Rhenish Massif High. Today there is, however, no evidence for such a habitat in northern Germany during the Late Aptian and this is also missing for the English occurrences (Rawson, 1992). It is noteworthy that in the moderately deep shelf areas of northern Germany species of *Parahoplites* are small (*P. multicostatus*, *P. melchioris* and *P. schmidti*) and less frequent in occurrence compared to the marginal facies (Gaida et al., 1978; Kemper, 1982, 1995).

Our record of *Parahoplites* from a lagoonal environment in north-central Tunisia (Fig. 6) fits in with those from marginal facies recorded in other parts of the world, discussed above. The palaeoenvironmental position is close to coral and rudist patches, but distant from deep water, indicating that shallow water settings were at least a significant part of the habitat of the large-size *Parahoplites*. The idea of Kemper (1982, 1995) of an allochthonous origin of large *Parahoplites* in northern Germany disagrees with our data from Tunisia which suggests that this group of ammonites actually lived in shallow water habitats.

The interval with particularly large-size ammonites of the genus *Parahoplites* (Fig. 3) is also characterized by a belemnite migration event from the Tethys into the Boreal region observed for northern Germany (Mutterlose, 1998; note divergent stratigraphy in Takashima et al., 2007). The otherwise strictly Tethyan *Duvalia grasiana* invaded for a second time during the Aptian for the largest part of the *Parahoplites nutfieldiensis* Zone, a temperature-control of this invasion has been suggested (Mutterlose, 1988). This belemnite event could be linked to the event-like occurrence of large-size *Parahoplites* recognizable in many areas of the world during that time interval. A shallow water preference of large-size *Parahoplites,* as suggested in the present paper, fits well to a high temperature environment.

For the Late Aptian, there are palaeobiogeographic affinities of the Tunisian cephalopod fauna to the west and central Tethys in the Late Aptian. Affinities to South America are particularly indicated by *Ridelites* sp., resulting in a more cosmopolitan picture compared to that of the Early Aptian.

6. Systematic palaeontology

Specimens are preserved mainly as internal moulds, a few specimens are crushed impressions in the laminated carbonates around OAE 1a. Belemnites are the rarest cephalopods in the working-area.

Since only one longitudinal section of *Neohibolites* sp. (GSUB C4049) has been collected this group is not included in the systematic part.

Order: Nautilida Agassiz, 1847
Family: Cymatoceratidae Spath, 1927
Genus: *Heminautilus* Spath, 1927

Type species. *Nautilus saxbii* Morris, 1848, by original designation.

Heminautilus sanctaecrucis Conte, 1980
Fig. 7M
1980 *Heminautilus sanctaecrucis* Conte, p. 138, pl. 1, figs. 1, 2, 4a.
? 1985a *Heminautilus* cf. *sanctaecrucis* Conte, 1980; Conte, p. 30, pl. 1, fig. 6, text-fig. 4-1 to 4-5.

Material. 1 specimen, GSUB C4035, from the lower member of the Hamada Formation (Early Aptian), slightly bituminous bioclastic to peloidal packstones about 10 m below the base of the OAE 1a interval of locality 1 at Djebel Serdj (Tab. 1, Fig. 2).

Discussion. The tricarinate venter as well as the typical elongated lower branch of the lateral lobe with a flat angle assigns the specimen to *Heminautilus sanctaecrucis* and allows distinction from *Heminautilus lallierianus* (d'Orbigny, 1841), *Heminautilus saxbii* (Morris, 1848) and *Heminautilus tejeriensis* Martínez and Grauges, 2006 (see Martínez and Grauges, 2006). Conte (1980) gives the range of his species as middle Barremian to lowermost Aptian (base of Bedoulian). Conte (1985a) refers to *H.* cf. *sanctaecrucis* as lower Bedoulian, *Pseudocrioceras coquandi* Zone of the Lower Aptian. The specimens from Djebel Serdj in Tunisia are the first record out of France.

Genus: *Cymatoceras* Spath, 1927

Type species. *Nautilus pseudoelegans* d'Orbigny, 1840, by original designation.

Cymatoceras neckerianum (Pictet, 1847)
Fig. 7D

1847 *Nautilus neckerianum* Pictet, p. 16, pl. 1, fig. 9
1980 *Cymatoceras neckerianum* (Pictet, 1847); Calzada and Viader, p. 163; text-fig. 1 (and synonymy)
1983 *Cymatoceras neckerianum* (Pictet, 1847); Weidich, Schwerd and Immel, p. 564, pl. 2, fig. 5 (and synonymy)

Material. 8 specimens, GSUB C4054 and C4055, from a slightly more prominent bioclastic to peloidal wacke- and packstone ledge at locality 1 at Djebel Serdj (Tab. 1, Fig. 2). This corresponds to the lower part of the Serdj Formation of the Upper Aptian, almost 120 m above its base.

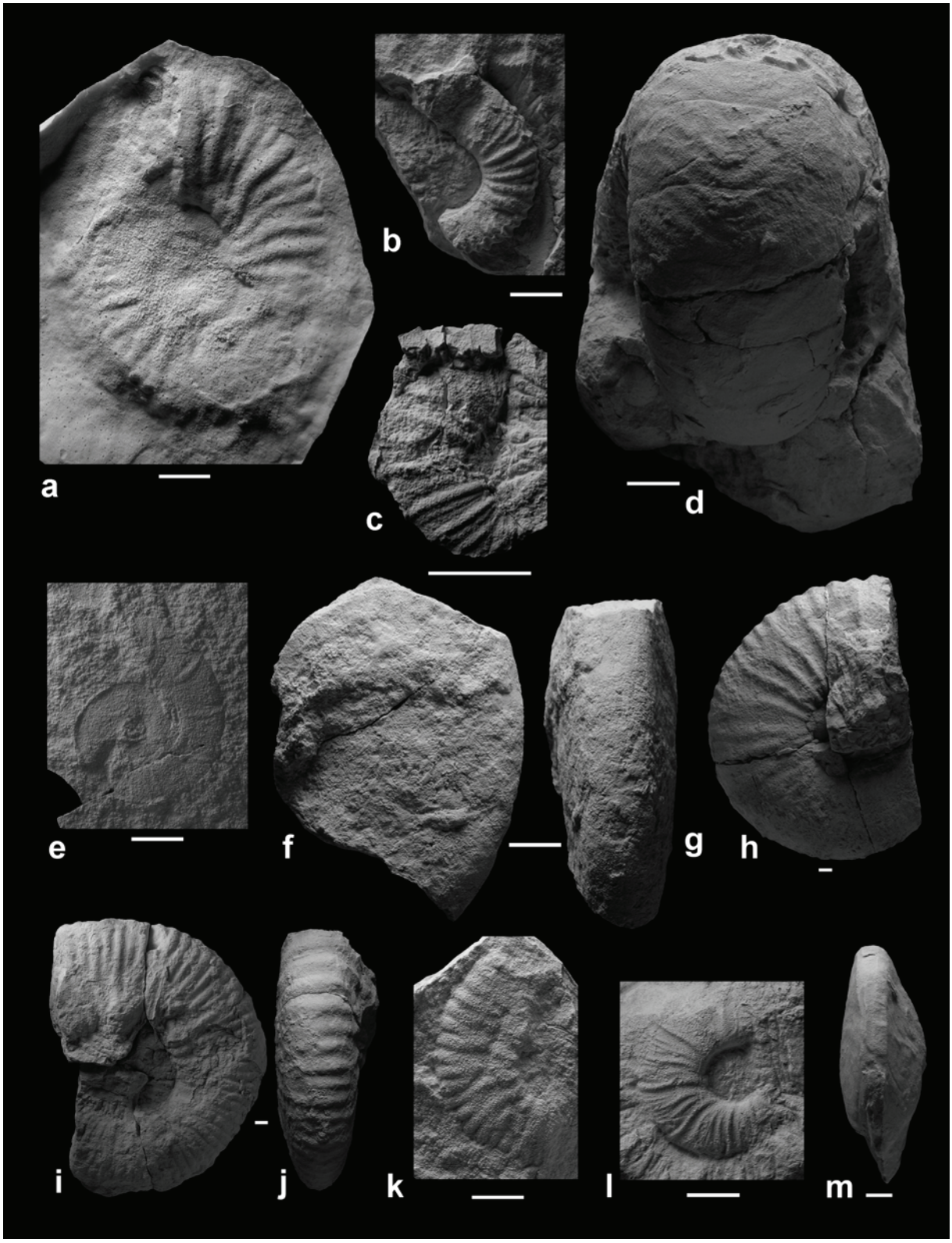

Figure 7: Cephalopods from the Aptian of northern Tunisia. A, *Dufrenoyia* sp., GSUB C4031. B, *Toxoceratoides* sp., GSUB C4032. C, ? *Ancyloceras*, GSUB C4036. D, *Cymatoceras neckerianum* (Pictet, 1847), GSUB C4055. E, *Pseudohaploceras matheroni* (d'Orbigny, 1841), GSUB C4044. F, G, *Zuercherella* sp., GSUB C4040. H, *Deshayesites latilobatus* (Sinzow, 1909), GSUB C4038. I, J, *Parahoplites* cf. *nutfieldiensis* (J. Sowerby, 1815), GSUB C4043. K, *Deshayesites* sp., GSUB C4033. L, *Pseudohaploceras* ex gr. *liptoviense* (Zeuschner, 1856), GSUB C4034. M, *Heminautilus sanctaecrucis* Conte, 1980, GSUB C4035. Scale bar each 10 mm.

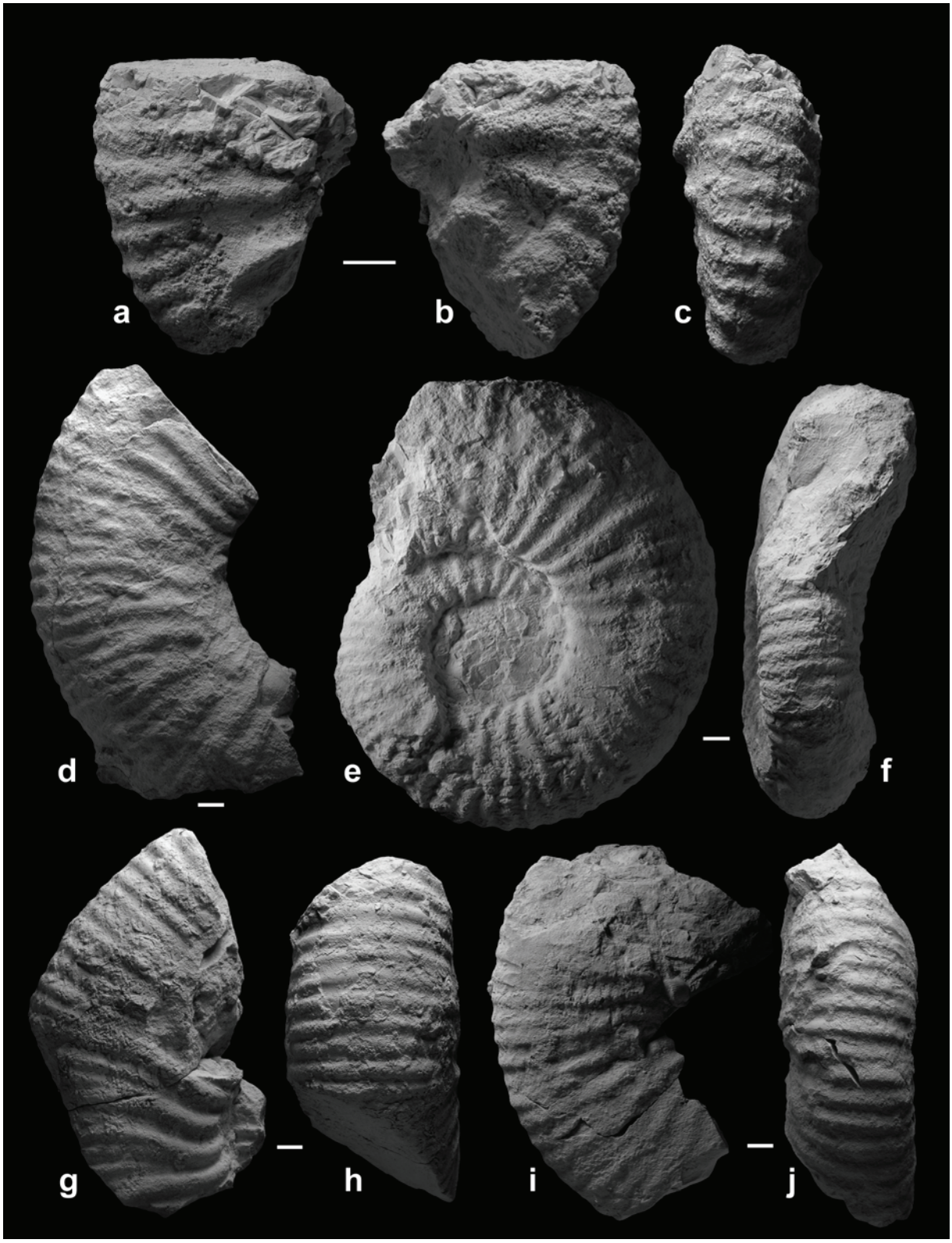

Figure 8: Ammonites from the Upper Aptian of northern Tunisia. A-C, *Riedelites* sp., GSUB C4051. D, *Parahoplites* cf. *nutfieldiensis* (J. Sowerby, 1815), GSUB C4048. E, F, *Parahoplites laticostatus* (Sinzow, 1908), GSUB C4047. G, H, *Parahoplites maximus* (Sinzow, 1908), GSUB C4042. I, J, *Parahoplites* cf. *nutfieldiensis* (J. Sowerby, 1815), GSUB C4053. Scale bar each 10 mm.

Discussion. Our material does not add to the debate of Weidich et al. (1983) on the distinction between *C. neckerianum* and *C. neocomiensis* (d'Orbigny, 1840). Perviquière (1903, 1907) mentioned nautiloids belonging to *Cymatoceras neocomiensis* or *C. neckerianum* (of modern nomenclature) already from Djebel Serdj, but the present specimens are the first documented records from Tunisia. The geographical distribution of *C. neckerianum* includes England, Mozambique, France, Rumania, Spain, Kazhakhstan (Calzada and Viader, 1980; Förster, 1975; Neagu, 1965; Sinzow, 1909; Weidich et al., 1983). The oldest record published yet is from the late Early Aptian of Spain (Calzada and Viader, 1980), who considered that it ranged from the upper "Bedoulian" to the lower "Gargasian". Unequivocal Late Aptian records are known from England, Mozambique and France, but the species has been recorded as occurring in the Lower Albian (Förster, 1975; Neagu, 1965; Weidich et al., 1983).

Subclass: Ammonoidea Zittel, 1884
Order: Ammonoitida Zittel, 1884
Suborder: Ammonitina Hyatt, 1889
Superfamily: Desmoceratacеae Zittel, 1895
Family: Desmoceratidae Zittel, 1895
Subfamily: Puzosiinae Spath, 1922
Genus: *Pseudohaploceras* Hyatt, 1900

Type species. *Ammonites liptoviensis* Zeuschner, 1856, by original designation.

Pseudohaploceras ex gr. *liptoviense* (Zeuschner, 1856)
Fig. 7L

A synonymy is given by González-Arreola et al. (1996), see also Delanoy (1997).

Material. 1 specimen, GSUB C4034, comes from the lower member of the Hamada Formation, from slightly bituminous bioclastic to peloidal packstones of the Lower Aptian limestones of the Lower Aptian; about 10 m below the base of the OAE 1a interval of locality 1 at Djebel Serdj (Tab. 1, Fig. 2).

Discussion. Since the venter is missing it remains unclear if the venter of our material is widely rounded as in *P. liptoviense*. Memmi (1981) mentioned *P. liptoviense* from a Djebel Nehal in Tunisia. This species also occurs in Barremian to the Aptian strata and is known from the Czech Republik, NW-Germany, Austria, Tunisia, Mexico (González-Arreola et al., 1996).

Pseudohaploceras matheroni (d'Orbigny, 1841)
Fig. 7E

Synonymy. A synonymy is given by Aly 2006, see also García et al., 2007.

Material. 1 specimen, GSUB C4044, from bioclastic wacke- and packstones in the upper OAE 1a interval in the lower part of the Hamada Formation of locality 1 at Djebel Serdj (Tab. 1, Fig. 2). 2 specimens possibly representing this species (GSUB C4045, C4046) in a laminated bioclastic wacke- and packstone from a slightly higher level in the upper OAE 1a interval at locality 2 at Djebel Serdj (Tab. 1 and Figs. 2 and 4D); there are further unregistered specimens from the same level.

Discussion. The straight constrictions, the wide umbilicus and the faint ribs of the same strength hint on *P. matheroni* and clearly separate it from *Pseudohaploceras douvillei* (Fallot, 1920) that has more falcoid constrictions and a narrower umbilicus and from *Pseudohaploceras liptoviense* with ribs of variable thickness and constrictions as well as ribbing that is usually more strongly curved (compare pl. 4 in González-Arreola et al., 1996). Memmi (1981) mentioned *P. matheroni* from Djebel Nehal, Tunisia. Out of Tunisia it is known from Late Barremian to Early Aptian strata of France, Spain, Bulgaria, Georgia (Vašícek and Summesberger 2004), Poland (Marek et al., 1989), Romania (Avram et al., 1990), Azerbaidjan (Ali-Zade et al., 1988) and Sinai (Hamama and Gabir, 2001; Aly, 2006).

Subfamily: Beudanticeratinae Breistroffer, 1953
Genus: *Zuercherella* Casey, 1954

Type species. *Desmoceras zuercheri* Jacob and Tobler, 1906, by original designation.

Zuercherella sp.
Fig. 7F, G and Fig. 9

Material. 1 specimen, GSUB C4040, from the Upper Aptian Serdj Formation of locality 5 at Djebel Slata (Tab. 1, Fig. 4A).

Discussion. Among the genus *Zuercherella* our specimen is most similar to *Z. etayosernai* Bogdanova and Hoedemaeker, 2004 from the Aptian of Colombia in lacking ribs as the same unique feature. The medium-size present shell (whorl height of around 40 mm) is smooth except for shallow constrictions on the outer half of the flank. The adult suture line of our specimen is moderately complex (Fig. 9), with an A/U saddle is about the same size and simplicity as the A lobe and the E/A of the same height as the A/U and similar to that of other species referred to this genus today (e.g. Rouchadzé, 1933, text-fig. 7; Renz, 1982, text-fig. 10d). However, the adult suture line of *Z. etayosernai* is unknown as also the differences to other species. Pervinquière (1907, p. 137, pl. 5, fig. 26a-c) referred to an ammonite from the Aptian-Albian boundary interval of Djebel Tella (Oust) in Tunisia as *Desmoceras* (*Uhligella*) cf. *Zürcheri* Jacob. This is a nucleus with a maximum diameter of 16 mm, no constrictions and a whorl section that is about as broad as high, with the greatest breadth around mid-flank. It is impossible to indicate possible relationships for ontogenetic and stratigraphic differences. The genus is known from Europe, northern and eastern Africa, central Asia, Mexico and Columbia and ranges from the Late Barremian to the Late Aptian (Wright, 1996; Bogdanova and Hoedemaeker, 2004).

Superfamily: Deshayesitaceae Stoyanow, 1949

Family: Deshayesitidae Stoyanow, 1949

Subfamily: Deshayesitinae Stoyanow, 1949

Genus *Deshayesites* Kasansky, 1914

Type species. *Deshayesites deshayesi* Leymerie in d'Orbigny, 1841, by original designation.

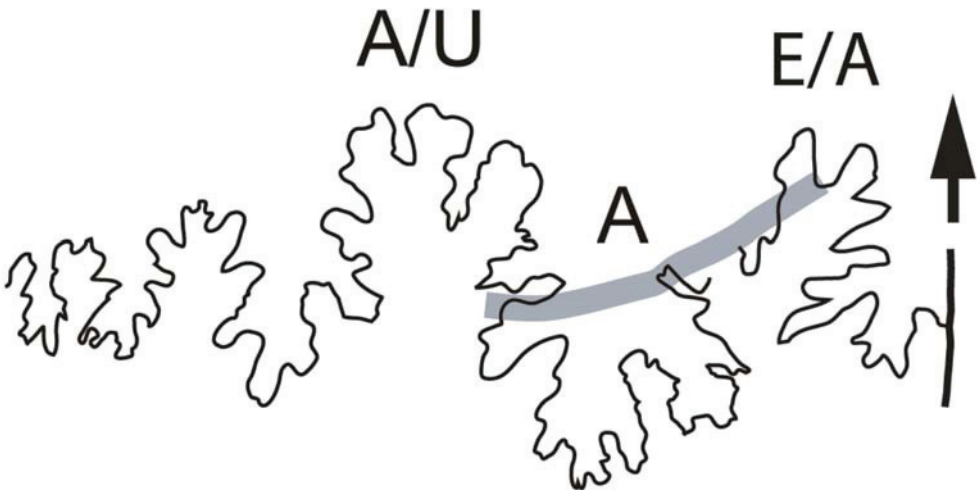

Figure 11: Suture of *Zuercherella* sp. at wh 48 mm. The grey shaded area indicates the position of constriction on the specimen. GSUB C4040, figured as Fig. 5G, H.

Deshayesites latilobatus (Sinzow, 1909)

Fig. 7H

1881 *Hoplites deshayesi* (Leymerie), Neumayr and Uhlig, pl. 45, figs. 1, 1a-b.

1997 *Deshayesites latilobatus* (Sinzow, 1909); Immel, Seyed-Emami and Afshar-Harb, p. 186; pl. 6, fig. 3 (and synonymy).

1999 *Deshayesites latilobatus* (Sinzow, 1909); Bogdanova and Prozorovsky, pl. 6, fig. a, b.

1999 *Deshayesites latilobatus* (Sinzow, 1909); Avram, p. 444, text-figs. 4d-f.

2007a *Deshayesites latilobatus* (Sinzow, 1909); Moreno, p. 60; pl. 1, figs. 1-3, 26; text-fig. 5.

2007b *Deshayesites latilobatus* (Sinzow, 1909); Moreno, text-fig. 4b.

Material. 1 specimen, GSUB C4038, from the lower member of the Hamada Formation at Djebel Serdj (locality 2, see Tab. 1, Figs. 2 and 4C), with brachiopod and echinoid rich marlstone-limestone couplets. These silty bioclastic wacke- and packstones are found about 30 m below the base of the OAE 1a interval.

Discussion. Although the present material is worn the ribbing is strong enough to be still discernible. This very large *Deshayesites* specimen (diameter more than 230 mm) fits well to the specimens of

similar size figured from Germany (Neumayr and Uhlig, 1881) and England (Casey, 1980). It shares the feature of fairly distant primary ribs compared to the secondary ribs with *D. fittoni* Casey, 1961, that is a much smaller species (see Casey, 1964). *D. latilobatus* is known from Russia, S-England, northern Germany and northeastern Iran yet, the present specimen is the first record from Tunisia; the stratigraphy of this Lower Aptian form is best-known for England (*Deshayesites deshayesi* Zone, *Cheloniceras parinodum* Subzone, see Casey, 1980).

Deshayesites sp.
Fig. 7K

Material. 1 specimen, GSUB C4033, from the lower member of the Hamada Formation, the slightly bituminous bioclastic to peloidal packstones of the Lower Aptian, about 10 m below the base of the OAE 1a interval of locality 1 at Djebel Serdj in north-central Tunisia (Tab. 1, Fig. 2).

Discussion. Although the specimen is slightly worn the blunt and low ribs are an original feature. This ribbing in combination with the moderately evolute coiling and the origin of the secondary ribs comparatively high on the flank, does not fit to any species known from the late evolutionary history of this genus. Is reminiscent of species of the *deshayesi* Zone, such as *D. geniculatus* Casey. The evolute coiling and lack of ventrolateral tubercles, rules out *Paradeshayesites* and *Dufrenoyia*. *Deshayesites* is an Early Aptian genus, for a discussion on the stratigraphical significance see chapter 3.2.

Genus *Dufrenoyia* Kilian and Reboul, 1915

Type species. *Ammonites furcatus* J. de C. Sowerby, in Fitton, 1836, by subsequent designation of Kilian and Reboul, 1915.

Dufrenoyia sp.
Fig. 7A

Material. 1 specimen, a cast of a negative imprint, GSUB C4031, from the lower member of the Hamada Formation, more excactly the slightly bituminous bioclastic to peloidal packstones of the Lower Aptian, about 10 m below the base of the OAE 1a interval at locality 1 at Djebel Serdj (Tab. 1, Fig. 2).

Discussion. There are clear ventrolateral tubercles developed, in combination with its ribbing pattern and coiling this indicates *Dufrenoyia*. *Dufrenoyia* with ribs clearly broader than the interspaces that flatten and widen to the venter are found in *Dufrenoyia durangensis* Humphrey, 1949 and in particular the holotype seems also shows a similar fairly evolute coiling. This species is described from Mexico where it is limited to the *Dufrenoyia justinae* Zone that can be correlated with the European *Dufrenoyia furcata* Zone (Barrágan-Manzo et al., 2005). For a discussion on the stratigraphical meaning of

Dufrenoyia sp. in our section, a genus that is believed to characterize the late Early Aptian (e.g. Boganova and Michailova, 2004, Ropolo et al., 2006), see chapter 3.2.

Subfamily: Acanthohoplitinae Stoyanow, 1949
Genus *Riedelites* Etayo-Serna, 1979

Type species. *Riedelites esthersernae* Etayo-Serna, 1979, by original designation.

Riedelites sp.
Fig. 8A-C

Material. 1 specimen, GSUB C4051, from bioclastic peloidal wacke- and packstone in the upper Serdj Formation at its type locality (locality 1, Tab. 1 and Fig. 2).

Discussion. The distinct ornament of prominent and distant ribs crossing the venter and particularly the large smooth areas on the inner flank between primary ribs, recall the type of *Parahoplites inconstans* (Riedel, 1938, pl. 6, figs. 8-10), a member of the genus *Riedelites* (Sharikadze et al. 2004). Our specimen also agrees with its secondaries that mostly do not arise before the upper third of the flank, but it is too fragmentary for a specific assignment. We agree with Sharikadze et al. (2004) that the addition of umbilical tubercle-like thickenings to the original diagnosis by Etayo-Serna (1979) is necessary. These are present in GSUB C4051, but there can be more than just one intercalated rib between the primary ribs as can be seen in the type of *R. inconstans*. Previously, *Riedelites* has been described from Colombia only, suggesting an early Late Aptian age (Sharikadze et al., 2004).

Subfamily: Parahoplitinae Spath, 1922
Genus *Parahoplites* Anthula, 1899

Type species. *Parahoplites melchioris* Anthula, 1899, by original designation.

Parahoplites maximus (Sinzow, 1908)
Fig. 8G, H

A synonymy is given by Raisossadat (2006).

Material. 1 specimen, GSUB C4042, from a Late Aptian bioclastic to peloidal wacke- and packstone of the upper Serdj Formation of locality 4 at Djebel Serdj (Tab. 1, Fig. 2).

Discussion. The cross section in GSUB C4042 corresponds to that of the lectotype (Sinzow, 1908) in that it is oval, with slightly convex flanks, and the largest breadth on the lower third of the flank, close to the umbilical rim (WB/WH about 0.76), with a venter that is rounded and moderately broad. The lectotype as well as the specimen from England and northern Germany (Kemper, 1982) appear to

have slightly less flexuous ribs than the present specimen. The species is known from Caucasus (Daghestan), Mangyshlak (Kazakhstan), England, Germany, Iran (Raisossadat, 2006), Colombia (Sharikadze et al., 2004) and herewith from Tunisia. It is furthermore mentioned from Spain (Martínez et al., 1994). In southern England it occurs in the Upper Aptian *P. nutfieldiensis* Zone (*Tropaeum subarcticum* Subzone) following Casey (1965). According to Kemper (1982) it occurs in the Upper Gargasian, *P. nutfieldiensis* Zone of NW-Germany. In Colombia its stratigraphic occurrence is given as Middle Aptian.

Parahoplites laticostatus (Sinzow, 1908)
Fig. 8E, F

1908 *Acanthohoplites laticostatus* Sinzow, p. 482; pl. 5, figs. 9-13.
1938 *Parahoplitoides cerrosensis* Anderson, p. 168; pl. 33, fig. 1.
1953 *Acanthoplites laticostatus* Sinzow, 1908; Glazunova, p. 41; pl. 7, figs. 2a-c; text-fig. 16.

Material. 1 specimen, GSUB C4047, from nodular bioclastic to peloidal wacke and packstone bed in the lowermost Serdj Formation of the Late Aptian, above the prominent cliff which marks the base the Serdj Formation at Djebel Serdj (compare Fig. 3; locality 3, see Tab. 1 and Fig. 2).

Discussion. The Tunisian specimen corresponds with its sinuous, fairly distant and coarse ribs bending forward at about mid-flank well with the material figured by Sinzow (1908). *Parahoplites laticostatus* (Sinzow, 1908) from the Caucaus Mountains is most similar to *Parahoplitoides cerrosensis* of Anderson, 1938, from California as already noted by Anderson (1938). *Parahoplitoides* is regarded as a synonym of *Deshayesites* by Wright (1996), but *Parahoplitoides cerrosensis* clearly belongs to *Parahoplites*. The minor differences of *P. laticostatus* to *P. cerrosensis*, a more rounded section and slightly more sinuous ribs, are considered as intraspecific variation herein. In California *P. laticostatus* approximately occurs in the middle of the Horsetown Group, *Argonaut* Zone of Anderson (1938), corresponding to the Late Aptian ("Lower Gargasian", Anderson, 1938: table 2). It also occurs in the Caucasus, Mangyshlak (Kazakhstan), California (Sinzow, 1908; Glazunova 1953; Anderson 1938).

Parahoplites cf. *nutfieldiensis* (J. Sowerby, 1815)
Fig. 7I, J, 10D, I, J

A synonymy is given by Sharikadze et al. (2004).

Material. 5 specimens, GSUB C4041, C4043, C4048, C4053, C4081, from the lowermost from the lower part of the Serdj Formation, from bioclastic to peloidal wacke- and packstone about 120 section meters above the base, and ranges to a silty peloidal wacke- to packstone interval with common bivalves and gastropods at the top of our profile (Fig. 2). These records are from localities 1 and 2 (Tab. 1, Figs. 2 and 4B). Furthermore, it is recorded from locality 5 at Djebel Slata (Tab. 1 and Figs. 2 and 4A).

Discussion. Parahoplites nutfieldiensis is characterized by a dense and fairly strong ribbing, including the primary ribs, and a highoval cross section, as recognizable in most of the present specimens. Our specimens from Djebel Slata show an oval section (GSUB C4041 and C4081), recalling the only slightly compressed section of the otherwise very similar *Parahoplites melchioris* Anthula, 1899 (Anthula, 1899, pl. 8, fig. 5b). One of the specimens from Djebel Serdj (GSUB C4043) shows a tendency to smoothness after about 200 mm diameter (Casey, 1964) and indicates a fairly evolute coiling. Although the lectotype of *P. nutfieldiensis* is also rather evolute (Casey, 1965, pl. 67, fig. 5a), a more mature syntype of Sowerby (1815; Casey, 1965, pl. 68, fig. 2) tends to be more involute than GSUB C4043. The type material and other specimens of *P. melchioris* (Anthula, 1899, pl. 8, figs. 4a, 5a; Sinzow, 1908, pl. 2, fig. 1) are more evolute than *P. nutfieldiensis*, however, large-size adults of *P. melchioris* are unknown. *Parahoplites* is a Late Aptian genus (Wright, 1996), *P. nutfieldiensis* occurs in the eponymous zone of the Upper Aptian southern England (e.g. J. Sowerby, 1815), northern Germany (Kemper, 1971, 1976), France (Conte, 1985b), and possibly Chile (Perez et al., 1990) and Colombia (Sharikadze et al., 2004).

Parahoplites sp. 1
Fig. 10

cf. 1908 *Parahoplites campichei* Pictet and Renevier, 1908*;* Sinzow, p. 460; pl. 1, figs. 5, 6 only.
cf. 1967 *Parahoplites campichei* Pictet and Renevier, 1908; Wachendorf, Bettenstaedt and Ernst, p. 289; pl. 36, fig. 3.

Material. 1 specimen, GSUB C4082, from the Upper Aptian Serdj Formation of locality 5 at Djebel Slata (Tab. 1, Fig. 4A).

Discussion. The weak ribbing is an original feature of GSUB C4082 as indicated by the preservation of details of the suture, the venter even shows the frilling of sutural elements. The specimen from Tunisia shares a unique combination of features with specimens described from the Upper Aptian of Kazakhstan and Mozambique by Sinzow (1908, pl. 1, figs. 5, 6 only) and Wachendorf et al., 1967 (pl. 36, fig. 3), both referred to as *Parahoplites campichei*. Typical are dense, low ribs but strong umbilical bullae, an unusually strongly compressed whorl section with a small, arched venter. The Tunisian specimen differs from those from Kazakhstan and Mozambique in a somewhat denser ribbing. There are few further similar ammonites described, including *P. vectensis* Casey (Casey, 1964, p. 413), but these forms are only similar in having a compressed whorl section and low ribs as well.

Suborder: Ancyloceratina Wiedmann, 1966
Superfamily: Ancyloceratacеae Gill, 1871
Family: Ancyloceratidae Gill, 1871
Genus *Toxoceratoides* Spath, 1924

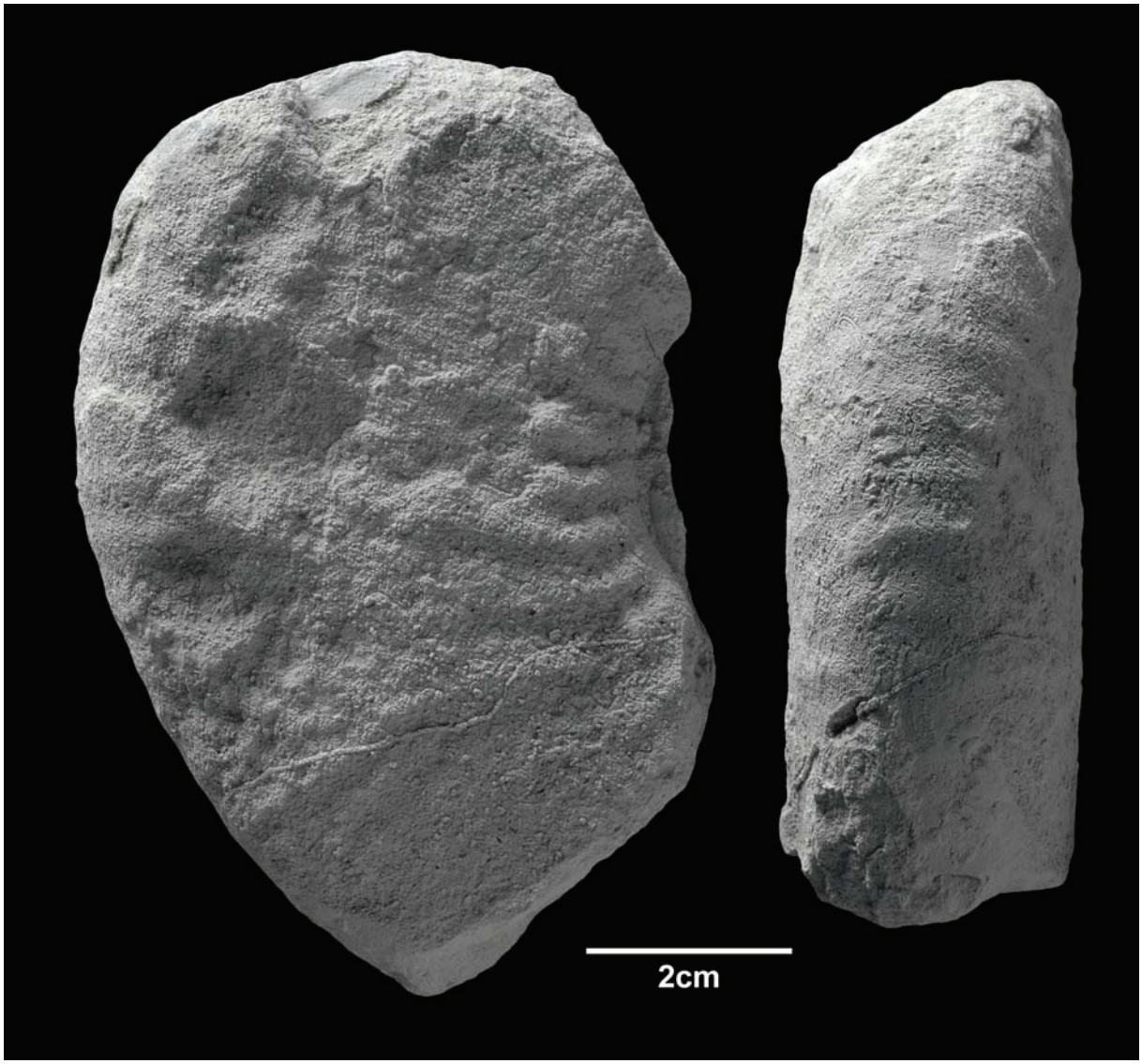

Figure 12: *Parahoplites* sp. 1, GSUB C4082, from the Late Aptian of Djebel Slata, northern Tunisia.

Type species. Toxoceratoides royerianum d'Orbigny, 1842, by original designation.

Toxoceratoides sp.
Fig. 7B

Material. 1 specimen, GSUB C4032, comes from bioclastic wacke- and packstones in the upper OAE 1a interval in the lower part of the Hamada Formation of locality 1 at Djebel Serdj, a specimen referred to as ? *Toxoceratoides* is from the same locality (Tab. 1, Fig. 2).

Discussion. The inital part of the left flank of fragment GSUB C4032 barely shows a damaged umbilical tubercle. That this is part of the typical double row of tubercles in *Toxoceratoides* is clear from the negative mould of the inner whorls that shows this feature. GSUB C4037 presumably belongs to the same taxon, but since it is a body chamber it is not showing the two tubercle rows for ontogenetic

reasons. This genus is of widespread geographical occurrence in the Upper Barremian-late Early Aptian of Europe, western Asia, eastern Africa, Zululand, California, Patagonia, Antarctica (Wright, 1996).

Family: Anisoceratidae Hyatt, 1900
Genus *Ancyloceras* d'Orbigny, 1842

Type species. Ancyloceras matheronianum d'Orbigny, 1842, p. 30, fig. 5, by subsequent designation of Haug, 1889, p. 212.

? *Ancyloceras*
Fig. 7C

Material. 1 specimen, GSUB C4036, from the lower member of the Hamada Formation, from slightly bituminous bioclastic wacke- and packstones of the Lower Aptian the lower OAE 1a interval of the Lower Aptian of locality 1 at Djebel Serdj (Tab. 1, Fig. 2).

Discussion. GSUB C4036 shows a very irregular patterns of straight ribs that vary between very strong and very weak, reminding on the initial spiral of Early Aptian *Ancyloceras* (e.g. Förster and Weier, 1983, pl. 1). *Ancyloceras* is widely distributed throughout Europe, Georgia, Azerbaijan, Russia, Turkmenistan, SE-Africa, Japan, California, Colombia (Kakabadze and Hoedemaeker, 2004; Wright, 1996), Turkey (Türkünal, 1962) and Venezuela (Renz, 1982) and occurs from the Lower Barremian to the Lower Aptian.

Acknowledgements
We appreciate technical support by M. Krogmann (Bremen) for producing the photos and part of the figures. M. Segl measured the $\delta^{13}C$ content and David Fischer and Patric Simundic helped in the laboratory with processing microfossil samples, R. Bätzel prepared the thin-sections (all Bremen). Thanks to our colleagues at Bremen, particularly J. Kuss, for valuable discussions and criticism. We particularly note the help of S. Bey (Tunis) during fieldwork. Peter Rawson (London) and C. J. Wood (Croydon) is thanked for reviews and valuable criticism. H. G. Owen (London) made comments on the identifications and biostratigraphy of the present fauna.
L. Cotton (Oxford), C. Wood and H. G. Owen kindly corrected the language in different versions of the manuscript. Last but not least the venture prizes financial support by the German Research Foundation (DFG), project number Ba-1571-11 and the “Zentrale Forschungsförderung” of the University of Bremen. Furthermore JL acknowledges library facilities made available by the “Synthesys” program during a stay at the Natural History Museum, London.

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CHAPTER 6

Conclusions and perspectives

The prominent, saddle-like shape of Djebel Serdj (Serdj=saddle) as seen from the southeast.

Conclusions and perspectives

The Upper Barremian–Upper Aptian deposits of the Hamada and Serdj formations in the Djebel Serdj area, north-central Tunisia, have provided excellent opportunity to study the palaeoenvironmental evolution of a southern Tethys carbonate platform margin in detail. Respect was paid to the sedimentary imprints of prominent palaeoceanographic and palaeoclimatic events, including the late Early Aptian OAE 1a and two time intervals associated with major carbonate platform drowning in the early- and mid-Late Aptian. Furthermore, the cephalopod fauna of the carbonate platform margin was investigated in detail. Accurate stratigraphy was crucial for the present study and therefore, much effort has been put on the establishment of detailed time frames, which allow global correlations and a precise dating of the prominent palaeoevents. Results of the combined bio- and isotope stratigraphy suggest a Latest Barremian–early Late Aptian age for the Hamada Formation at Djebel Serdj and an early Late Aptian–latest Aptian age for the Serdj Formation. Our combined stratigraphy modifies and extents local stratigraphic frameworks based on biostratigraphy only.

The sedimentologic analyses show, that the investigated area was characterised by hemipelagic sedimentation during the latest Barremian–early Late Aptian and shallow marine sedimentation during the mid-Late–latest Aptian. The hemipelagic, plankton-rich deposits are assigned to outer- and mid-ramp palaeoenvironments. The outer-ramp palaeoenvironments established due to an intense transgression during the Early/Late Aptian boundary interval. The establishment of shallow marine, inner-ramp palaeoenvironments at the onset of the mid-Late Aptian is reflected by the occurrence of shallow water platform components (e.g. ooids and cortoids) and typical light-dependant benthos, including colonial corals, rudists, green algae, and other organisms. An overall shallowing of the inner ramp palaeoenvironments during the mid-Late to latest Aptian corresponds to prominent tectonical uplift in north-central Tunisia during that time interval and does not reflect an eustatic signal.

The Tunsian carbonate platform margin was affected by severe ecological changes during the late Early Aptian due to the occurrence of the Oceanic Anoxic Event 1a, e.g. indicated by the mass-occurrence of radiolarians. By interpreting high abundance of radiolarians as high fertility indicator, this study confirms the high productivity model for the OAE 1a. The carbonate production rates during the event were high, which is a remarkable observation considering that the OAE 1a is usually associated with a biocalcification crisis. A comparison with global carbonate platform growth showed, that the carbonate production factories during the event were also intact on many other subtropical–tropical shelves. A global biocalcification or carbonate platform growth crisis during the event due to excess nutrients or ocean acidification can not be confirmed. Furthermore, the nutrient levels on the shelves were often lower than in pelagic palaeoenvironments, which is at odds with increased continental nutrient runoff as important trigger for pelagic eutrophication. Therefore, we support alternative hypotheses to explain highly elevated trophic levels in pelagic regimes during OAE 1a, e.g. a direct input of biolimiting metals by hydrothermal exchange related to increased submarine volcanism.

Deteriorated conditions for primary carbonate producers on the Tunisian shelf possibly occurred subsequent to the OAE 1a during the early Late Aptian, as indicated by thick deposits of fossil-poor marlstones. A comparison with other subtropical–tropical shelves shows, that many global carbonate platforms experienced a complete demise during this time interval.

The investigated shallow marine deposits of the mid-Late Aptian are rich in siliciclastics, possibly related to intensified precipitation rates and increased weathering in the hinterland. Bio- and chemostratigraphy shows, that this time interval corresponds to a prominent global warming pulse, in some publications associated with major carbonate platform drowning and elevated neritic trophic levels. In contrast, the biota in the investigated deposits suggest favourable growth conditions for the Tunisian carbonate platform and nutrient-depleted waters for this time interval. A comparison with global carbonate platform growth shows, that the extent of platform drowning during the warming interval was generally less widespread than previously suggested. In the subtropical Pacific, this time interval was even characterised by the northward expansion of the reef line.

The results of the present thesis contribute significantly to our knowledge of the ecological changes on the subtropical–tropical shelves during the onset of the Mid-Cretaceous greenhouse world. However, further studies on tropical carbonate platforms of this time interval, especially on those of the extended southern Tethys platform system, should be carried out for a comprehensive understanding of their response to the OAE 1a and subsequent platform drowning events.

The Tunisian carbonate platform still represents an ideal object for detailed studies, because all parts of the platform and of the adjacent deeper marine, Tethys-connected basin are well exposed and accessible. A transect covering sections from the palaeocoastline and inner parts of the platform seems to be a promising approach, because it could help to estimate the timing of ecological changes in the different parts of the platform during the palaeoevents and provide information on the relative roles of riverine/oceanic influences.

Acknowledgements

I warmly thank all present and past members of the Stratigraphy and Sedimentology Research Group at the University of Bremen who were involved in this thesis and supported it. Special thanks to Prof. Jochen Kuss, Dr. Christian Scheibner, and Dr. Martina Bachmann for reviews of the manuscripts and fruitful scientific discussions. Maria Petrogiannis helped with various problems within the department. Ralf Bätzel prepared the thin sections.

Dr. Jens Lehmann is thanked for his participitation in the fieldwork, reviews of the manuscripts, scientific discussions, and moral support.

Prof. Hedi Negra and Saloua Bey (El Manar University of Tunis) are thanked for supporting and joining the fieldwork in Tunisia. A cooperation with the El Manar University of Tunis made this thesis possible.

David Fischer and Patrick Simundic helped in the laboratory.

The reviewers of the first manuscript (Chapter 2), Dr. Jochen Erbacher and an anonymous reviewer are thanked for helpful comments and suggestions, which definitely improved the scientific content. Benjamin Slotnick (San Diego State University) corrected the English of this manuscript.
Both anonymous reviewers of the second manuscript (Chapter 4) are also thanked for helpful comments and suggestions.

Special thanks to Ulrike Rösler, Jan Lüthke, and Thomas Wölz.

Last but not least thanks to my mother and her husband, Renate and Winfried Tönsmeyer, for their moral and financial support.

This phD thesis is part of a project initiated by Dr. Martina Bachmann and funded by the DFG (German Research Foundation, project no Ba-1571-11).

Appendix

Measuring and sampling sections at Djebel Serdj.

Measured sections and samples at Djebel Serdj

Section / Formation	Thickness / samples	Stratigraphic range	Page
ST Hamada Formation	120 m thickness 107 samples	Latest Barremian-early Late Aptian OAE 1a: 45-118 m	IV
MF / SN Hamada Formation	272 m thickness 172 samples	early Early Aptian-early Late Aptian OAE 1a: 15-60 m	V, VI, VII
HG Hamada + Serdj Formations	461 m thickness 52 samples	early Late Aptian-mid-Late Aptian	VIII, IX, X, XI
SH Serdj Formation	385 m thickness 50 samples	mid-Late Aptian-late Late Aptian	XII, XIII, XIV, XV
BE Serdj Formation	164 m thickness 63 samples	mid-Late Aptian-late Late Aptian	XVI, XVII
HS Hamada + Serdj Formations	460 m thickness 120 samples	Early Aptian-Late Aptian tectonically disturbed section	XVIII, XIX, XX, XXI
SM Hamada Formation	120 m thickness 47 samples	Early Aptian	XXII
SN (II) Hamada Formation	460 m thickness 164 samples	early Late Aptian-late Late Aptian only first 120 m presented here	XXIII

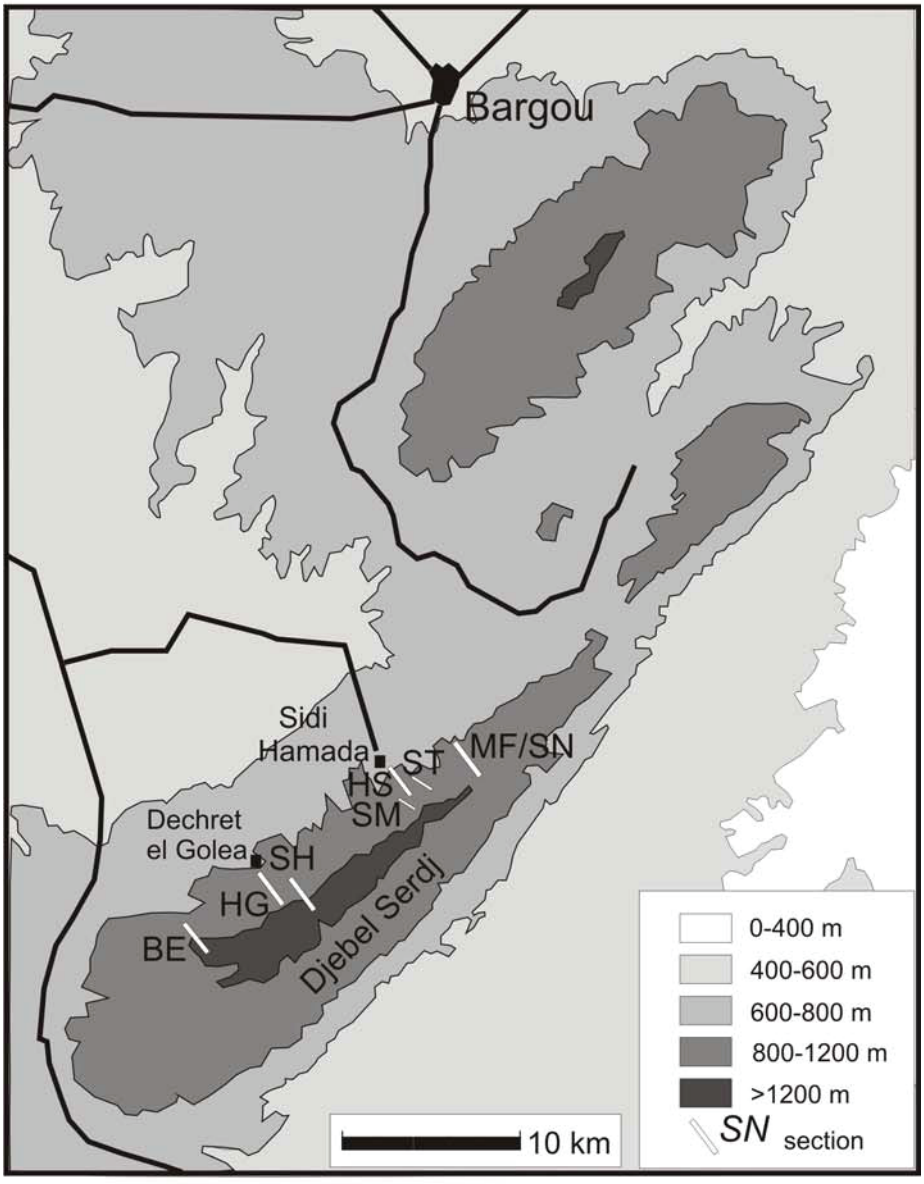
Measured sections and samples at Djebel Slata

SL Serdj Formation	280 m thickness 57 samples	Early Aptian-Late Aptian	XXIV, XXV, XXVI

Components and textures of section SH and BK

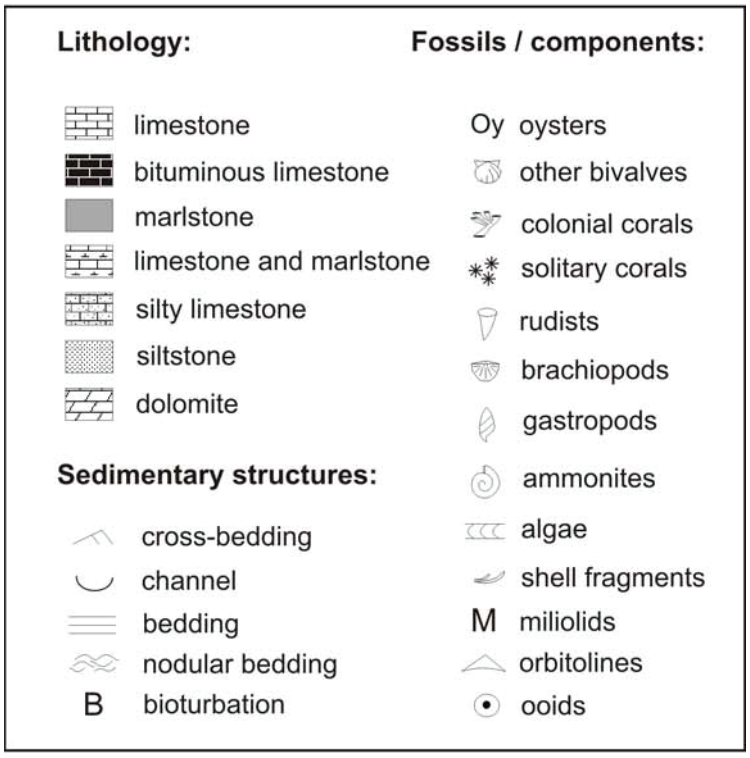
SH, components	(for more details see above)	XXVII, XXVIII
BE, components		XXIX
SH, textures		XXX, XXXI
BE, textures		XXXII

Section Locations, Djebel Serdj

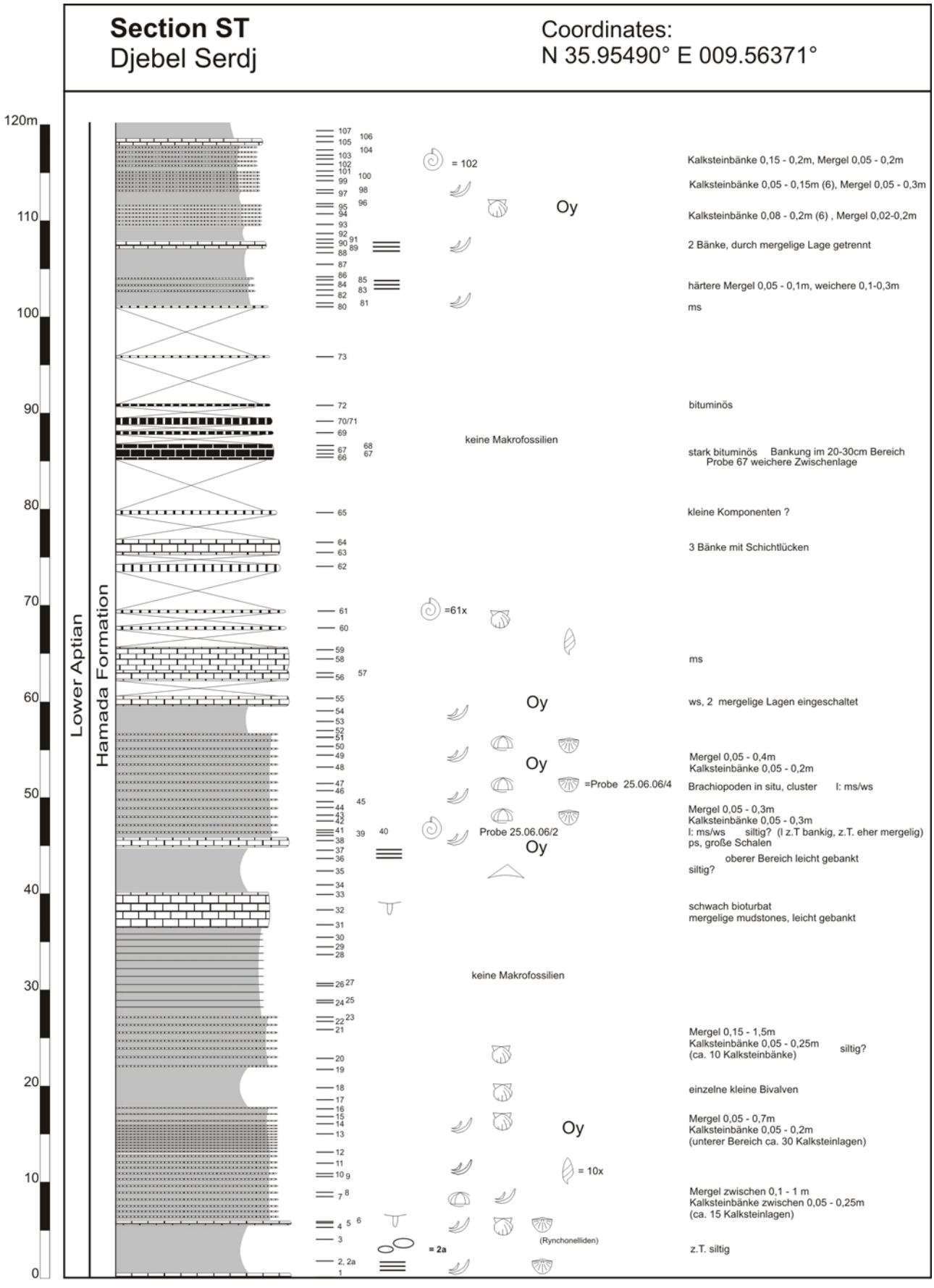


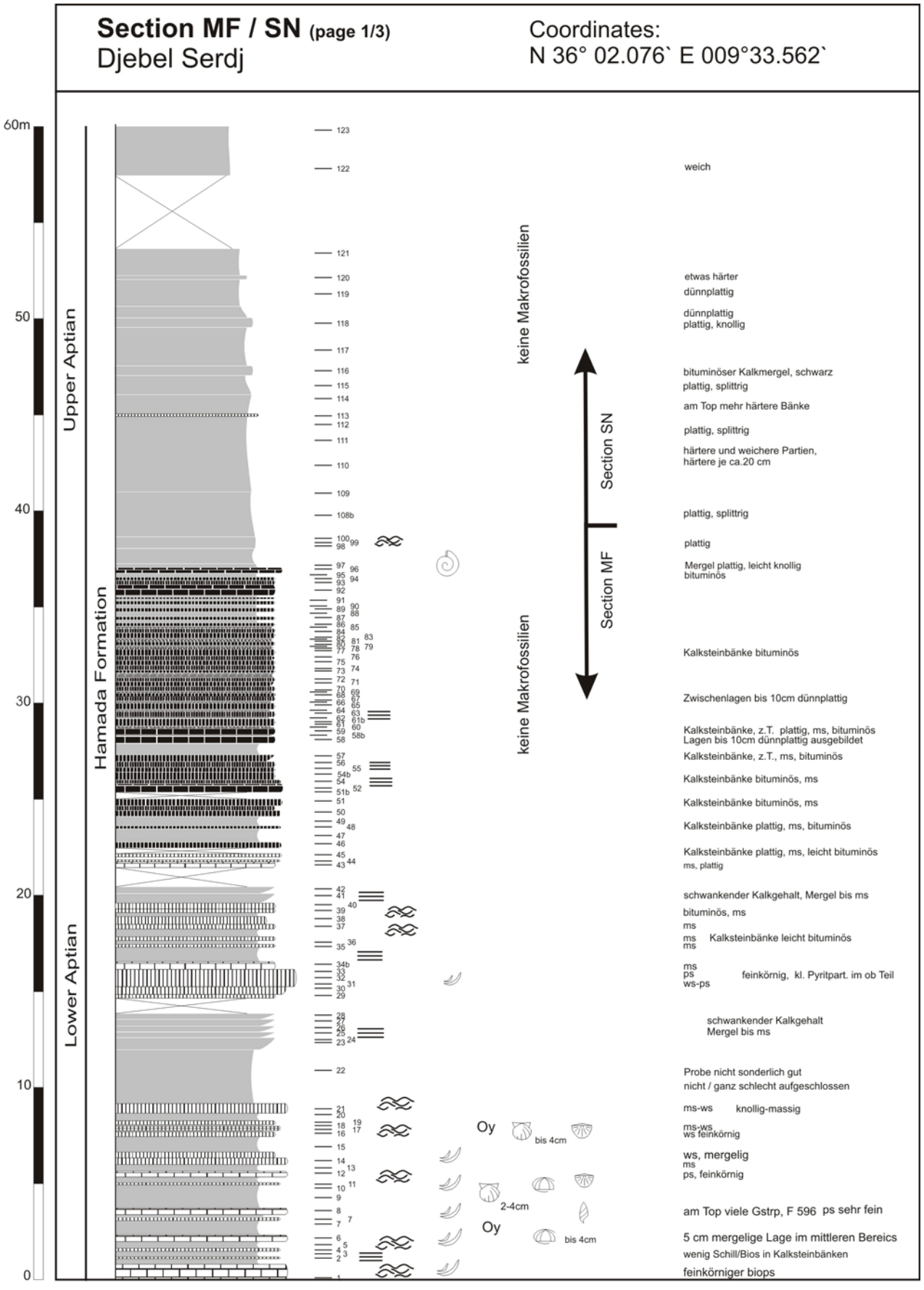
II

Legend for sections

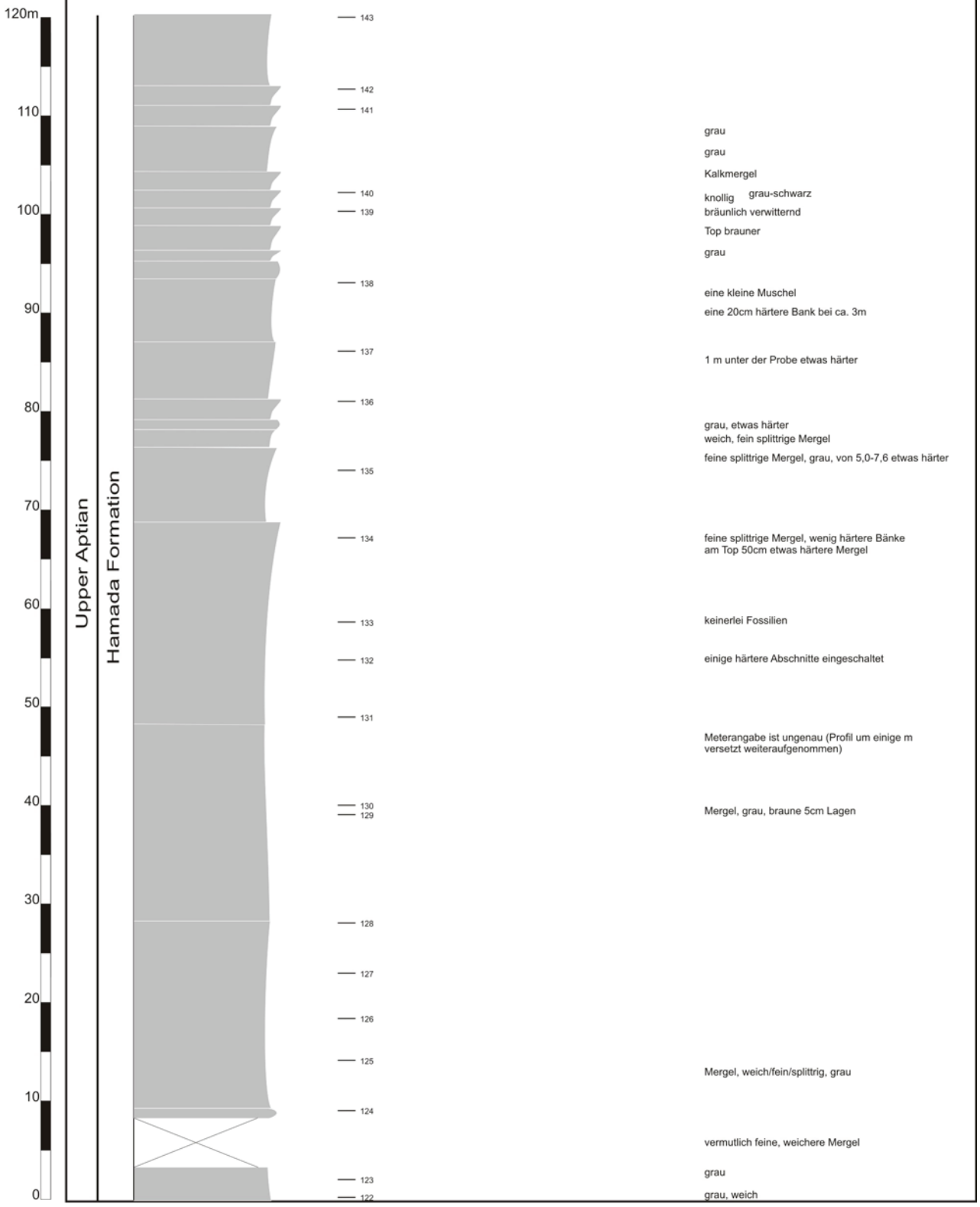


III

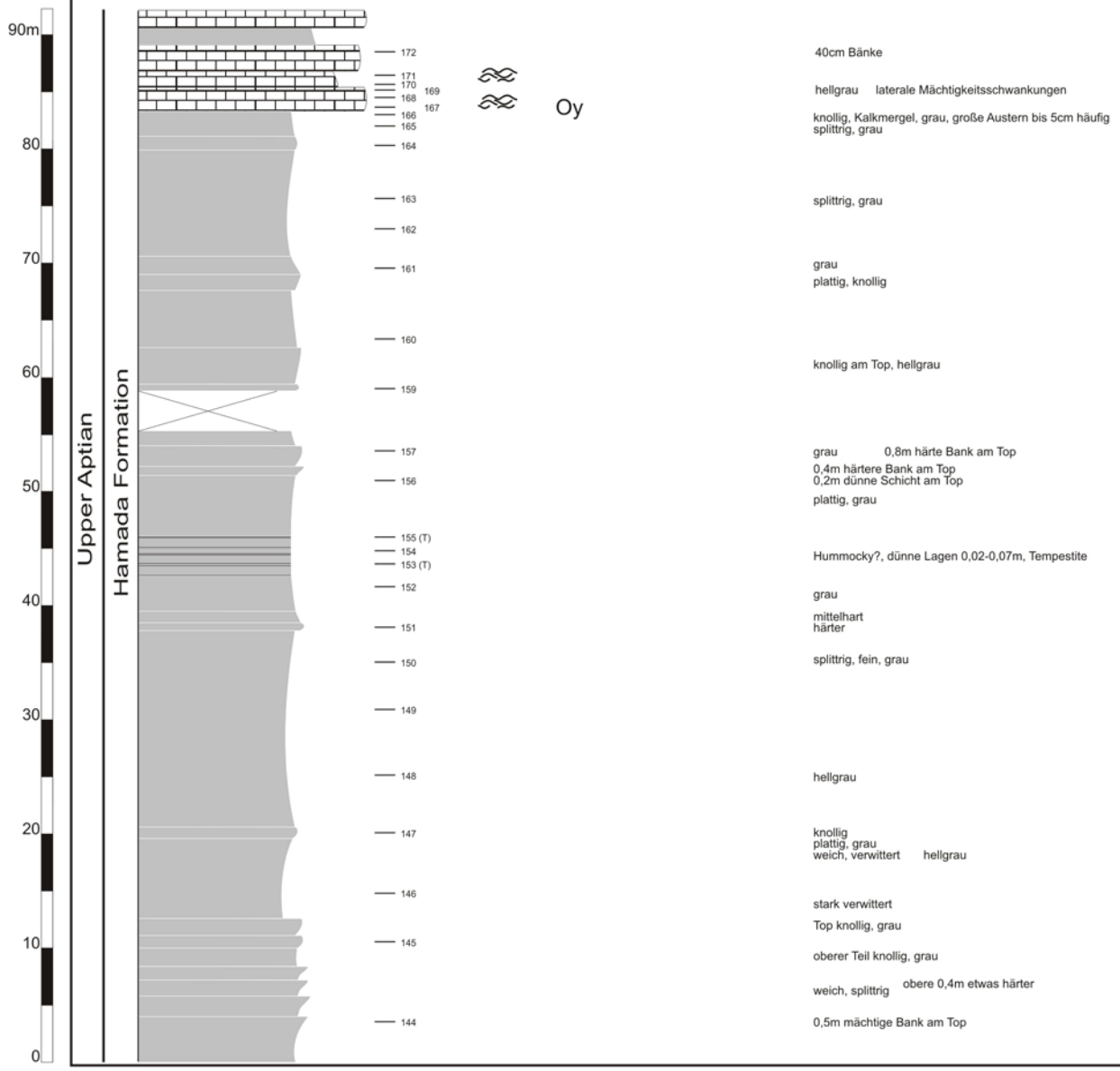

Section ST
Djebel Serdj
Coordinates:
N 35.95490° E 009.56371°
120m
110
100
90
80
70
60
50
40
30
20
10
0
Lower Aptian
Hamada Formation
= 102
Oy
Kalksteinbänke 0,15 - 0,2m, Mergel 0,05 - 0,2m
Kalksteinbänke 0,05 - 0,15m (6), Mergel 0,05 - 0,3m
Kalksteinbänke 0,08 - 0,2m (6) , Mergel 0,02-0,2m
2 Bänke, durch mergelige Lage getrennt
härtere Mergel 0,05 - 0,1m, weichere 0,1-0,3m
ms
bituminös
keine Makrofossilien
stark bituminös Bankung im 20-30cm Bereich
Probe 67 weichere Zwischenlage
kleine Komponenten ?
3 Bänke mit Schichtlücken
=61x
ms
Oy
ws, 2 mergelige Lagen eingeschaltet
Oy
Mergel 0,05 - 0,4m
Kalksteinbänke 0,05 - 0,2m
=Probe 25.06.06/4
Brachiopoden in situ, cluster l: ms/ws
Mergel 0,05 - 0,3m
Kalksteinbänke 0,05 - 0,3m
l: ms/ws siltig? (l z.T bankig, z.T. eher mergelig)
ps, große Schalen
Probe 25.06.06/2
Oy
oberer Bereich leicht gebankt
siltig?
schwach bioturbat
mergelige mudstones, leicht gebankt
keine Makrofossilien
Mergel 0,15 - 1,5m
Kalksteinbänke 0,05 - 0,25m siltig?
(ca. 10 Kalksteinbänke)
einzelne kleine Bivalven
Mergel 0,05 - 0,7m
Kalksteinbänke 0,05 - 0,2m
(unterer Bereich ca. 30 Kalksteinlagen)
Oy
= 10x
Mergel zwischen 0,1 - 1 m
Kalksteinbänke zwischen 0,05 - 0,25m
(ca. 15 Kalksteinlagen)
(Rynchonelliden)
= 2a
z.T. siltig


Section MF / SN (page 1/3)
Djebel Serdj
Coordinates:
N 36° 02.076` E 009°33.562`
60m
50
40
30
20
10
0
Upper Aptian
Lower Aptian
Hamada Formation
keine Makrofossilien
keine Makrofossilien
Section SN
Section MF
Oy
bis 4cm
2-4cm
Oy
bis 4cm
weich
etwas härter
dünnplattig
dünnplattig
plattig, knollig
bituminöser Kalkmergel, schwarz
plattig, splittrig
am Top mehr härtere Bänke
plattig, splittrig
härtere und weichere Partien,
härtere je ca.20 cm
plattig, splittrig
plattig
Mergel plattig, leicht knollig
bituminös
Kalksteinbänke bituminös
Zwischenlagen bis 10cm dünnplattig
Kalksteinbänke, z.T. plattig, ms, bituminös
Lagen bis 10cm dünnplattig ausgebildet
Kalksteinbänke, z.T., ms, bituminös
Kalksteinbänke bituminös, ms
Kalksteinbänke bituminös, ms
Kalksteinbänke plattig, ms, bituminös
Kalksteinbänke plattig, ms, leicht bituminös
ms, plattig
schwankender Kalkgehalt, Mergel bis ms
bituminös, ms
ms
ms Kalksteinbänke leicht bituminös
ms
ms
ps feinkörnig, kl. Pyritpart. im ob Teil
ws-ps
schwankender Kalkgehalt
Mergel bis ms
Probe nicht sonderlich gut
nicht / ganz schlecht aufgeschlossen
ms-ws knollig-massig
ms-ws
ws feinkörnig
ws, mergelig
ms
ps, feinkörnig
am Top viele Gstrp, F 596 ps sehr fein
5 cm mergelige Lage im mittleren Bereics
wenig Schill/Bios in Kalksteinbänken
feinkörniger biops

Section SN (page 2/3)
Djebel Serdj

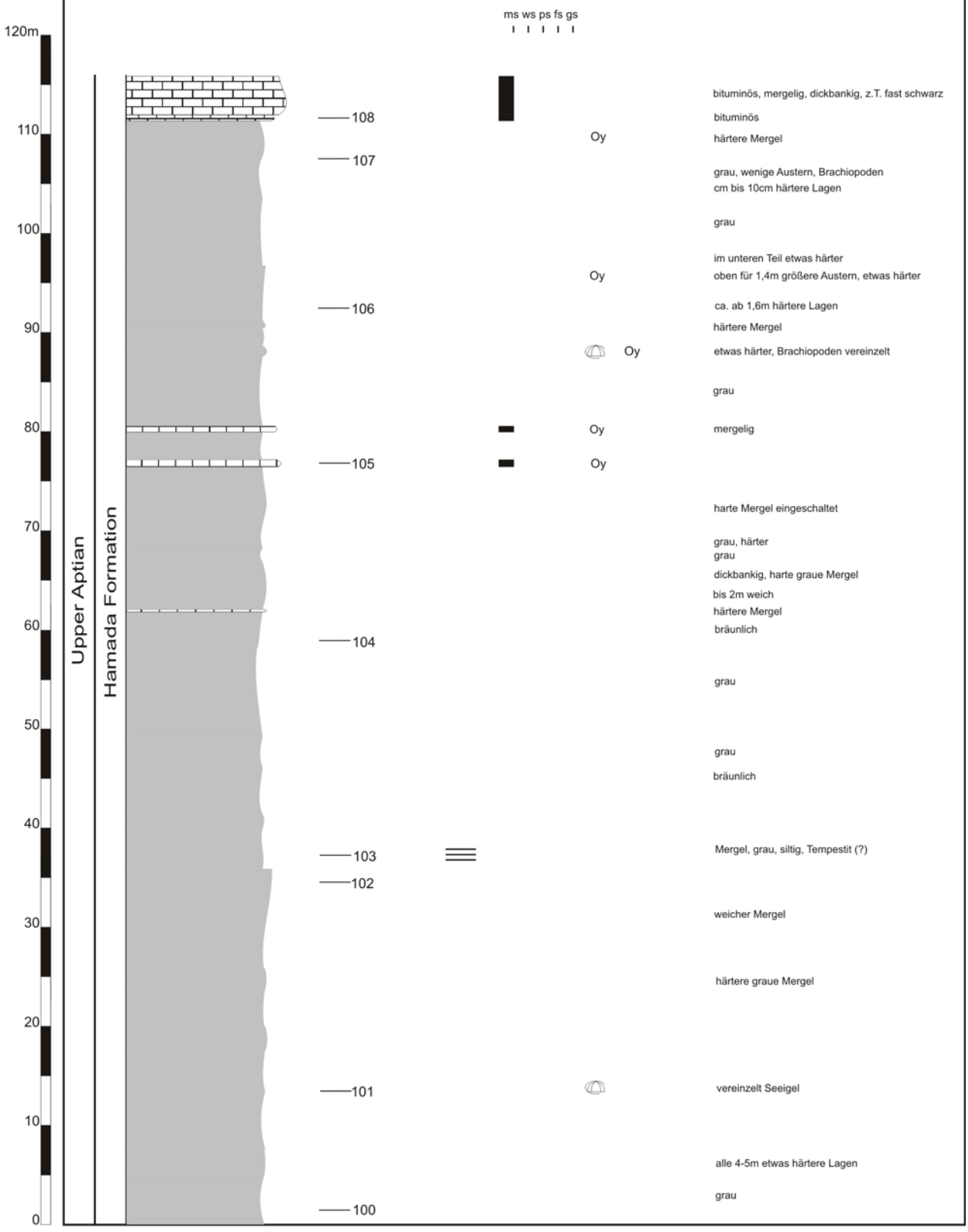


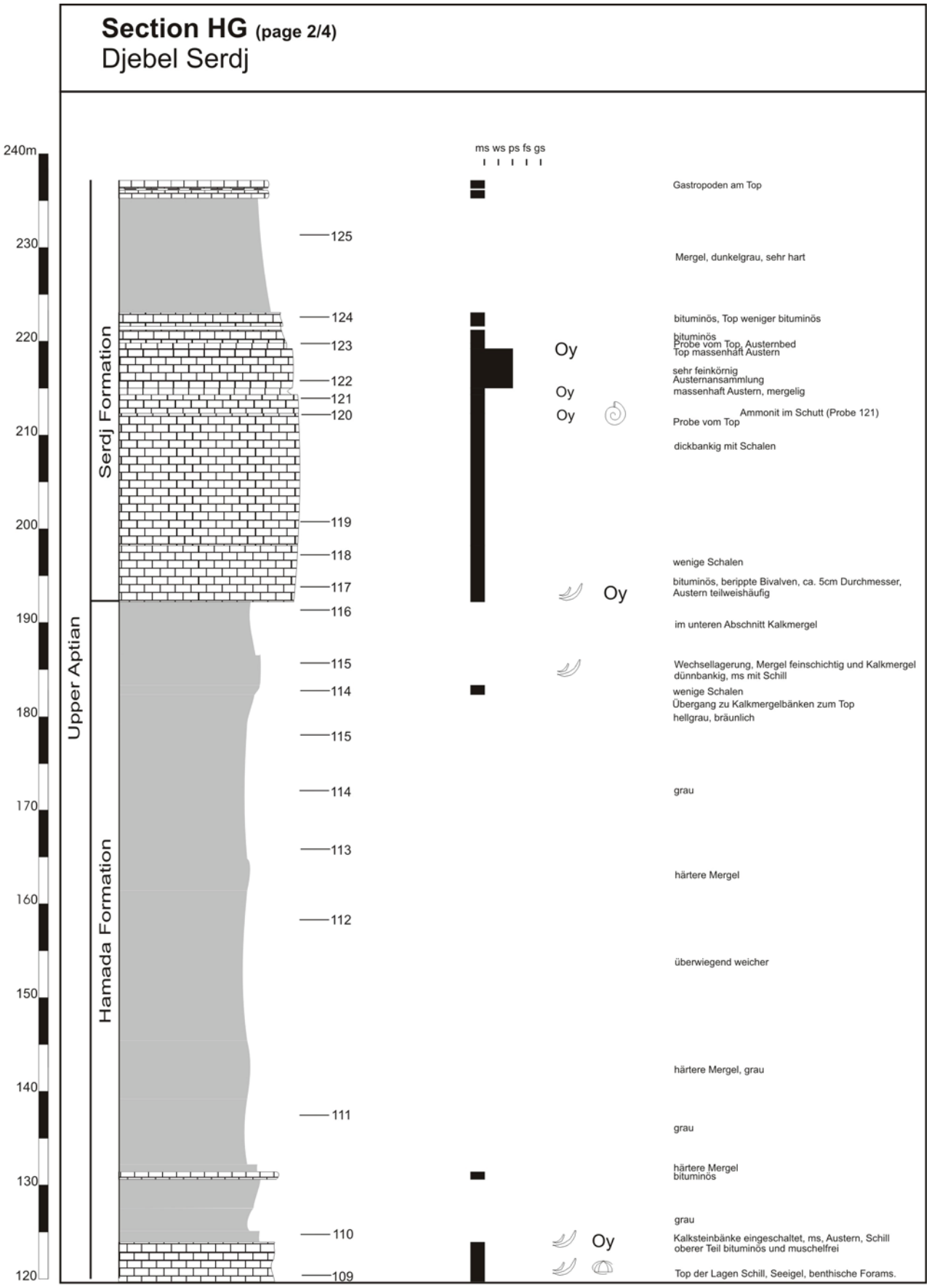
Section SN (page 3/3)
Djebel Serdj



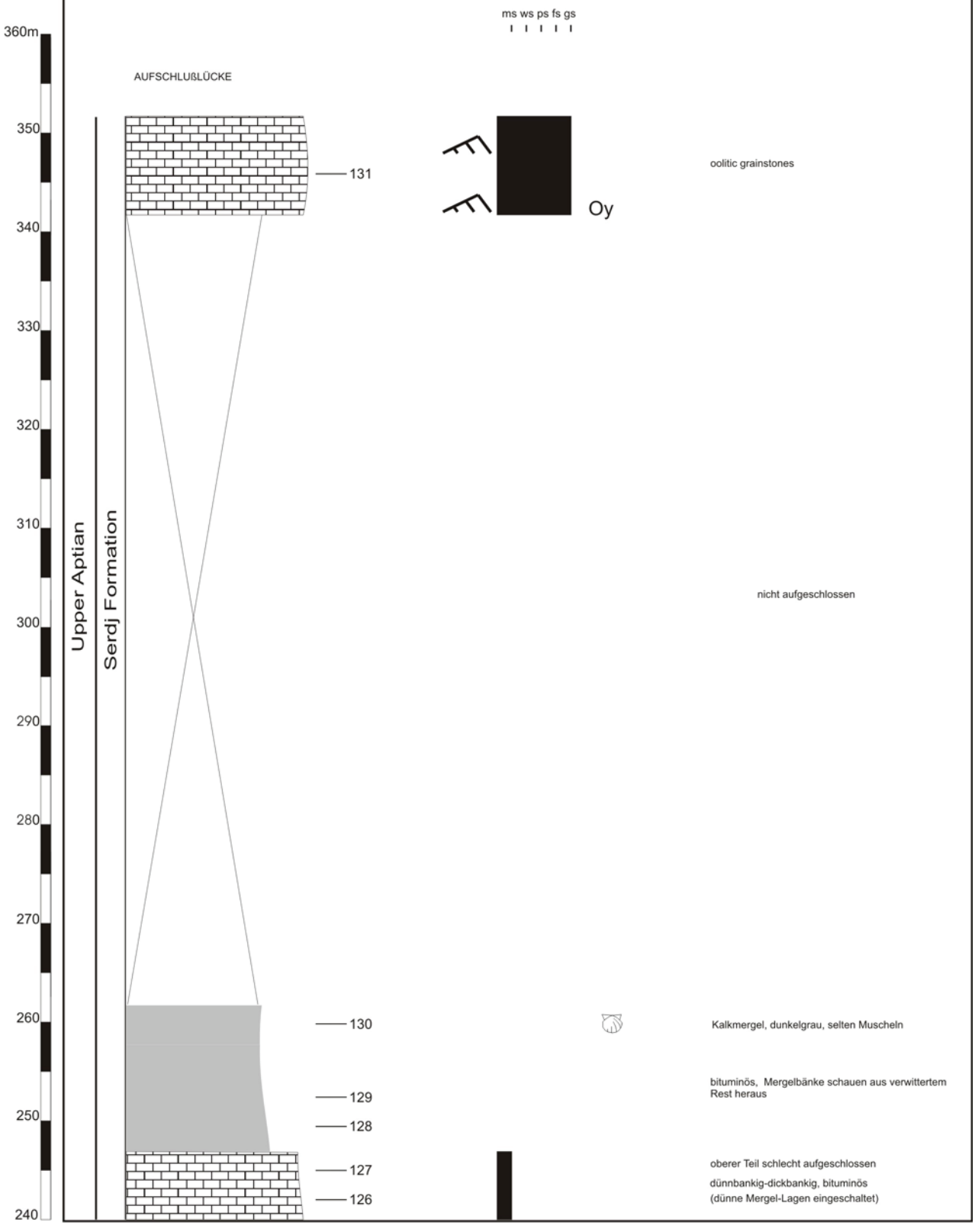
Section HG (page 1/4)
Djebel Serdj

Coordinates:
N 35° 56.065` E 009°31.050`

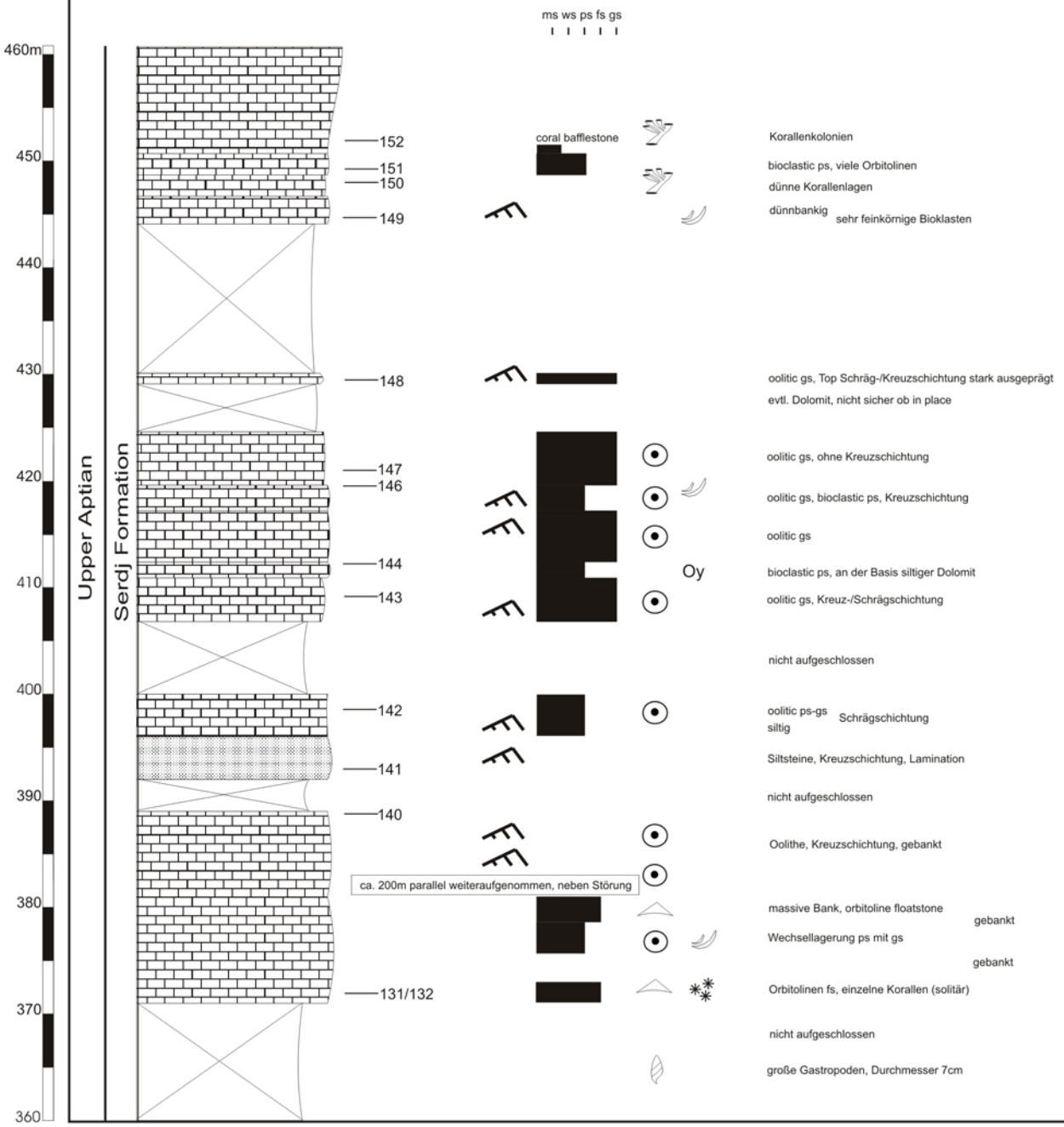


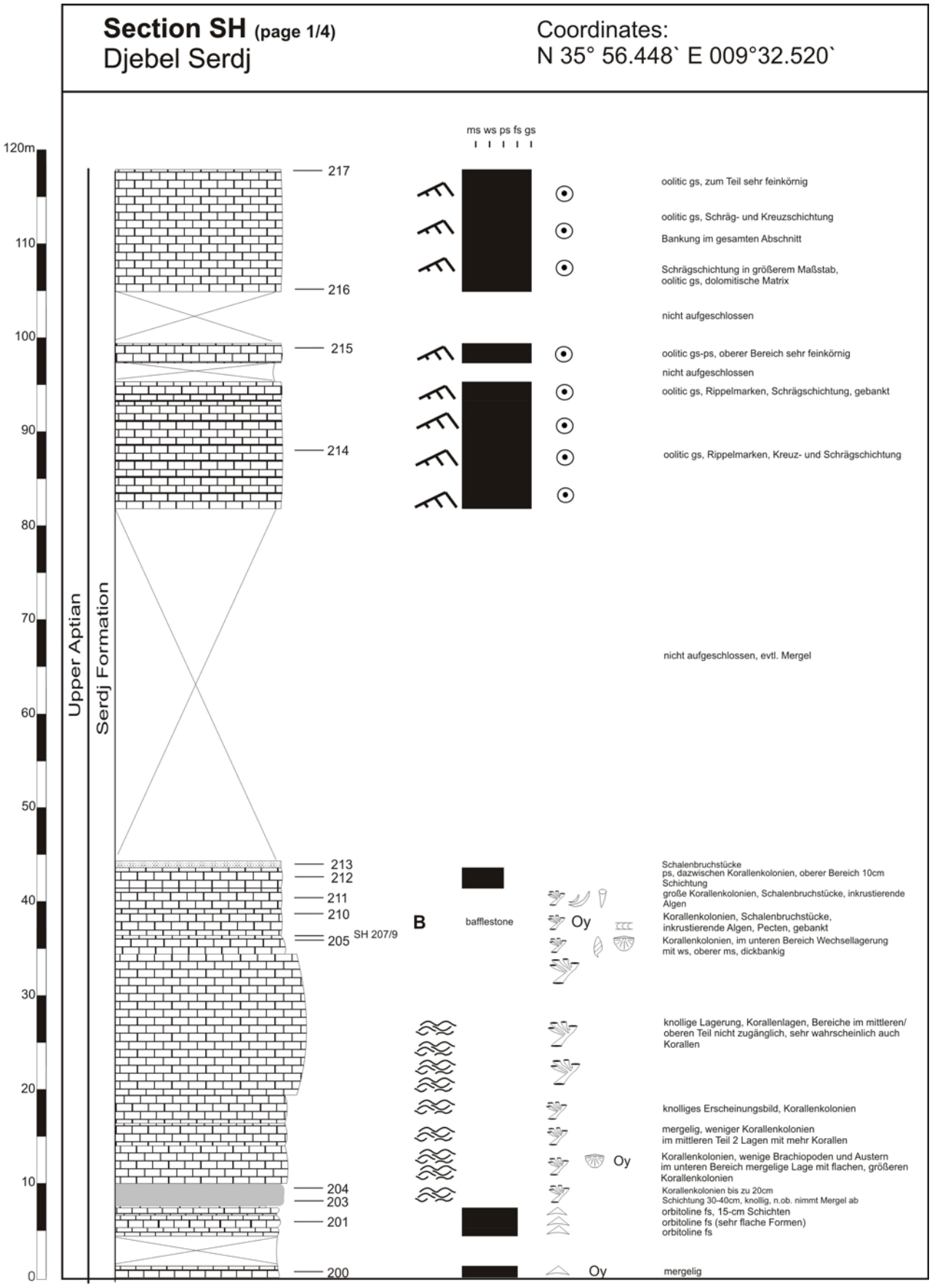

Section HG (page 2/4)
Djebel Serdj
240m
230
220
210
200
190
180
170
160
150
140
130
120
Upper Aptian
Serdj Formation
Hamada Formation
125
124
123
122
121
120
119
118
117
116
115
114
115
114
113
112
111
110
109
ms ws ps fs gs
Oy
Oy
Oy
Oy
Oy
Gastropoden am Top
Mergel, dunkelgrau, sehr hart
bituminös, Top weniger bituminös
bituminös
Probe vom Top, Austernbed
Top massenhaft Austern
sehr feinkörnig
Austernansammlung
massenhaft Austern, mergelig
Ammonit im Schutt (Probe 121)
Probe vom Top
dickbankig mit Schalen
wenige Schalen
bituminös, berippte Bivalven, ca. 5cm Durchmesser,
Austern teilweishäufig
im unteren Abschnitt Kalkmergel
Wechsellagerung, Mergel feinschichtig und Kalkmergel
dünnbankig, ms mit Schill
wenige Schalen
Übergang zu Kalkmergelbänken zum Top
hellgrau, bräunlich
grau
härtere Mergel
überwiegend weicher
härtere Mergel, grau
grau
härtere Mergel
bituminös
grau
Kalksteinbänke eingeschaltet, ms, Austern, Schill
oberer Teil bituminös und muschelfrei
Top der Lagen Schill, Seeigel, benthische Forams.

Section HG (page 3/4)
Djebel Serdj

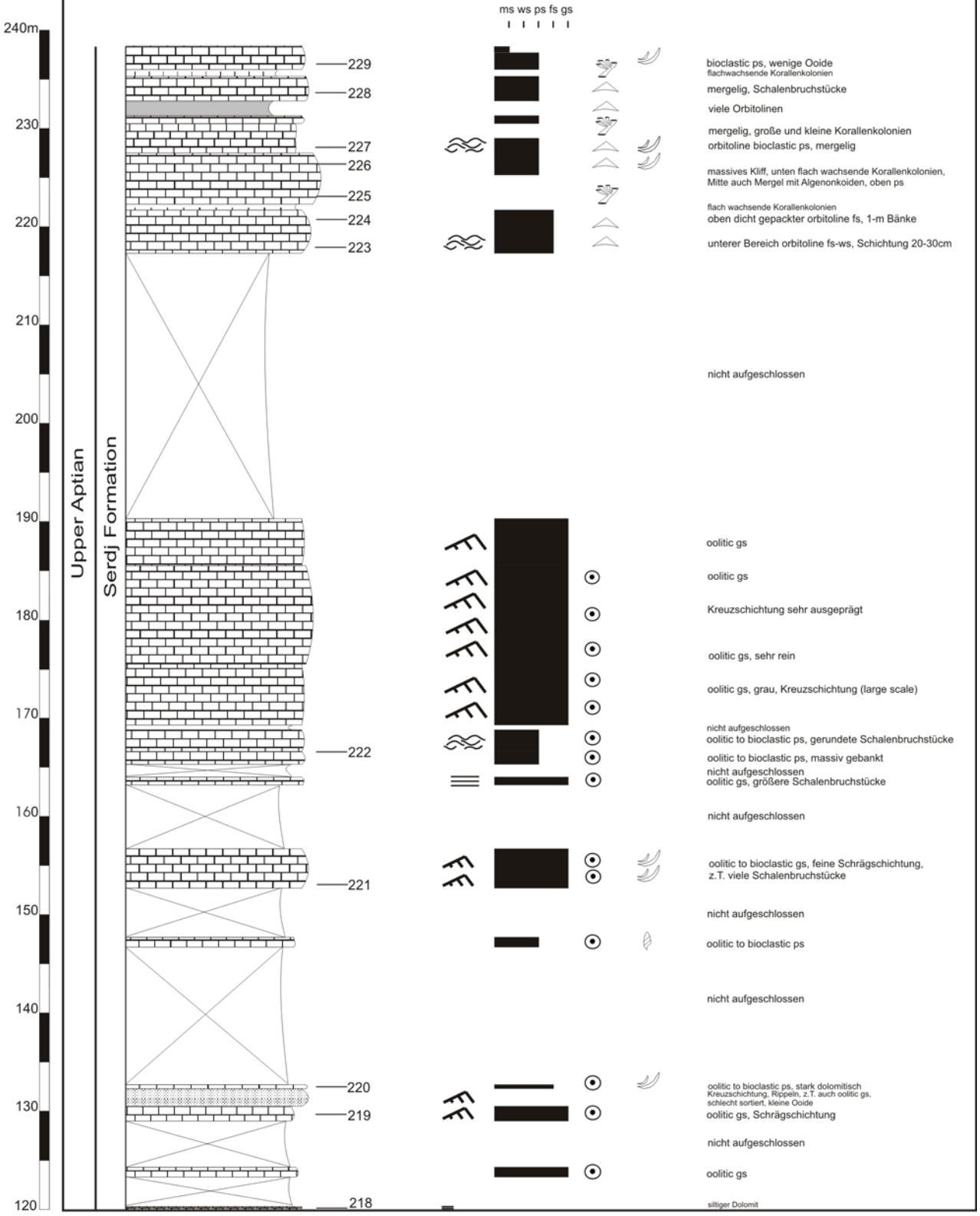


Section HG (page 4/4)
Djebel Serdj

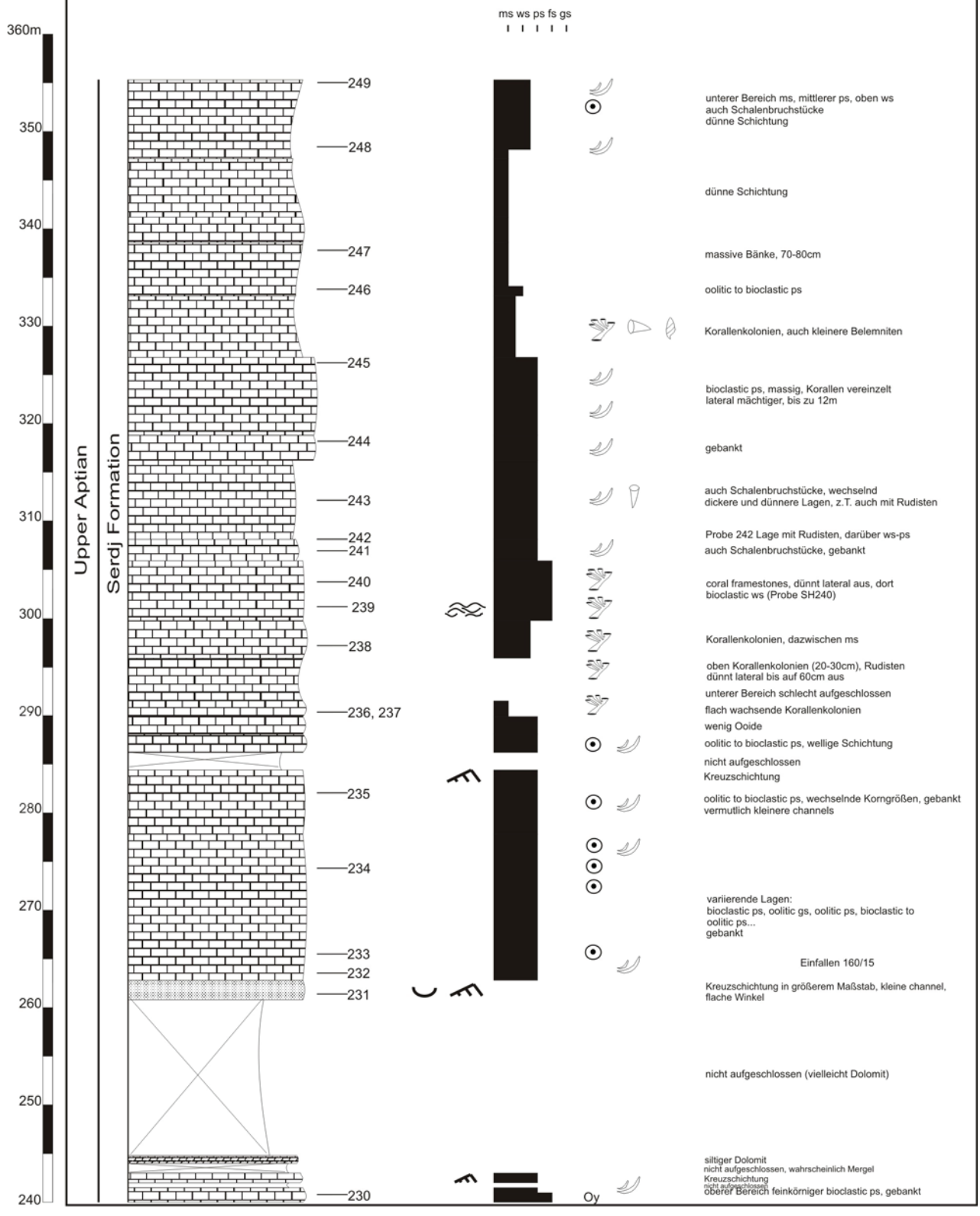



Section SH (page 1/4)
Djebel Serdj
Coordinates:
N 35° 56.448` E 009°32.520`
120m
110
100
90
80
70
60
50
40
30
20
10
0
Upper Aptian
Serdj Formation
ms ws ps fs gs
217
216
215
214
213
212
211
210
205
SH 207/9
204
203
201
200
B
bafflestone
Oy
oolitic gs, zum Teil sehr feinkörnig
oolitic gs, Schräg- und Kreuzschichtung
Bankung im gesamten Abschnitt
Schrägschichtung in größerem Maßstab,
oolitic gs, dolomitische Matrix
nicht aufgeschlossen
oolitic gs-ps, oberer Bereich sehr feinkörnig
nicht aufgeschlossen
oolitic gs, Rippelmarken, Schrägschichtung, gebankt
oolitic gs, Rippelmarken, Kreuz- und Schrägschichtung
nicht aufgeschlossen, evtl. Mergel
Schalenbruchstücke
ps, dazwischen Korallenkolonien, oberer Bereich 10cm Schichtung
große Korallenkolonien, Schalenbruchstücke, inkrustierende Algen
Korallenkolonien, Schalenbruchstücke, inkrustierende Algen, Pecten, gebankt
Korallenkolonien, im unteren Bereich Wechsellagerung mit ws, oberer ms, dickbankig
knollige Lagerung, Korallenlagen, Bereiche im mittleren/ oberen Teil nicht zugänglich, sehr wahrscheinlich auch Korallen
knolliges Erscheinungsbild, Korallenkolonien
mergelig, weniger Korallenkolonien
im mittleren Teil 2 Lagen mit mehr Korallen
Korallenkolonien, wenige Brachiopoden und Austern
im unteren Bereich mergelige Lage mit flachen, größeren Korallenkolonien
Korallenkolonien bis zu 20cm
Schichtung 30-40cm, knollig, n.ob. nimmt Mergel ab
orbitoline fs, 15-cm Schichten
orbitoline fs (sehr flache Formen)
orbitoline fs
mergelig

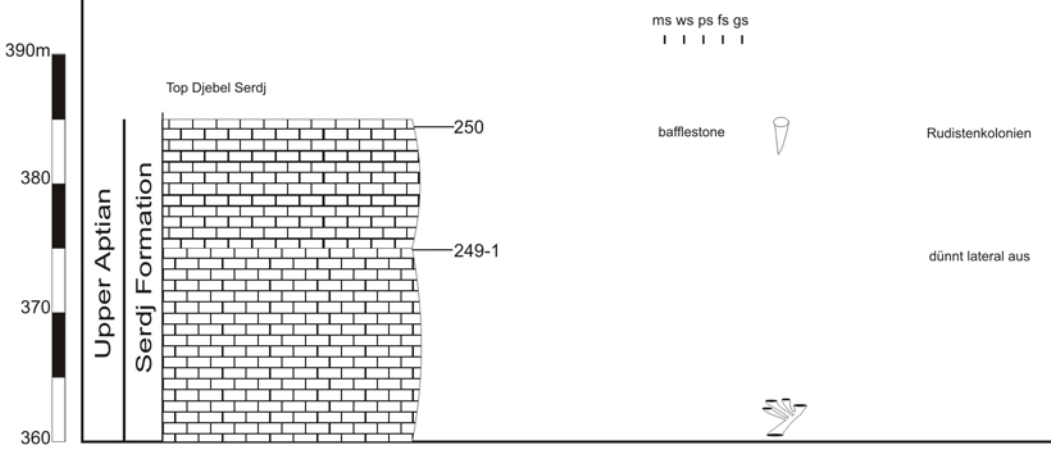
Section SH (page 2/4)
Djebel Serdj



Section SH (page 3/4)
Djebel Serdj

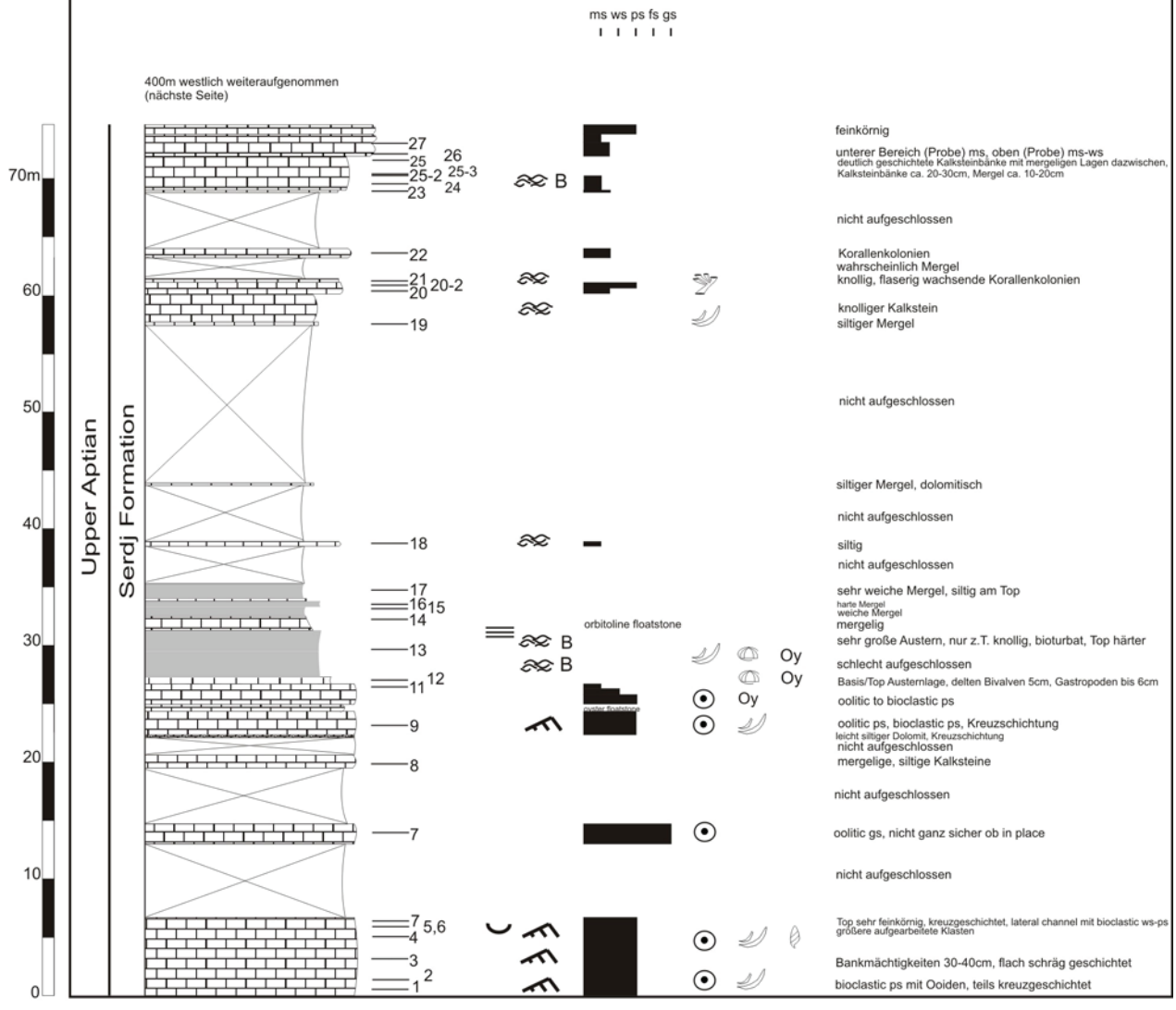


Section SH (page 4/4)
Djebel Serdj

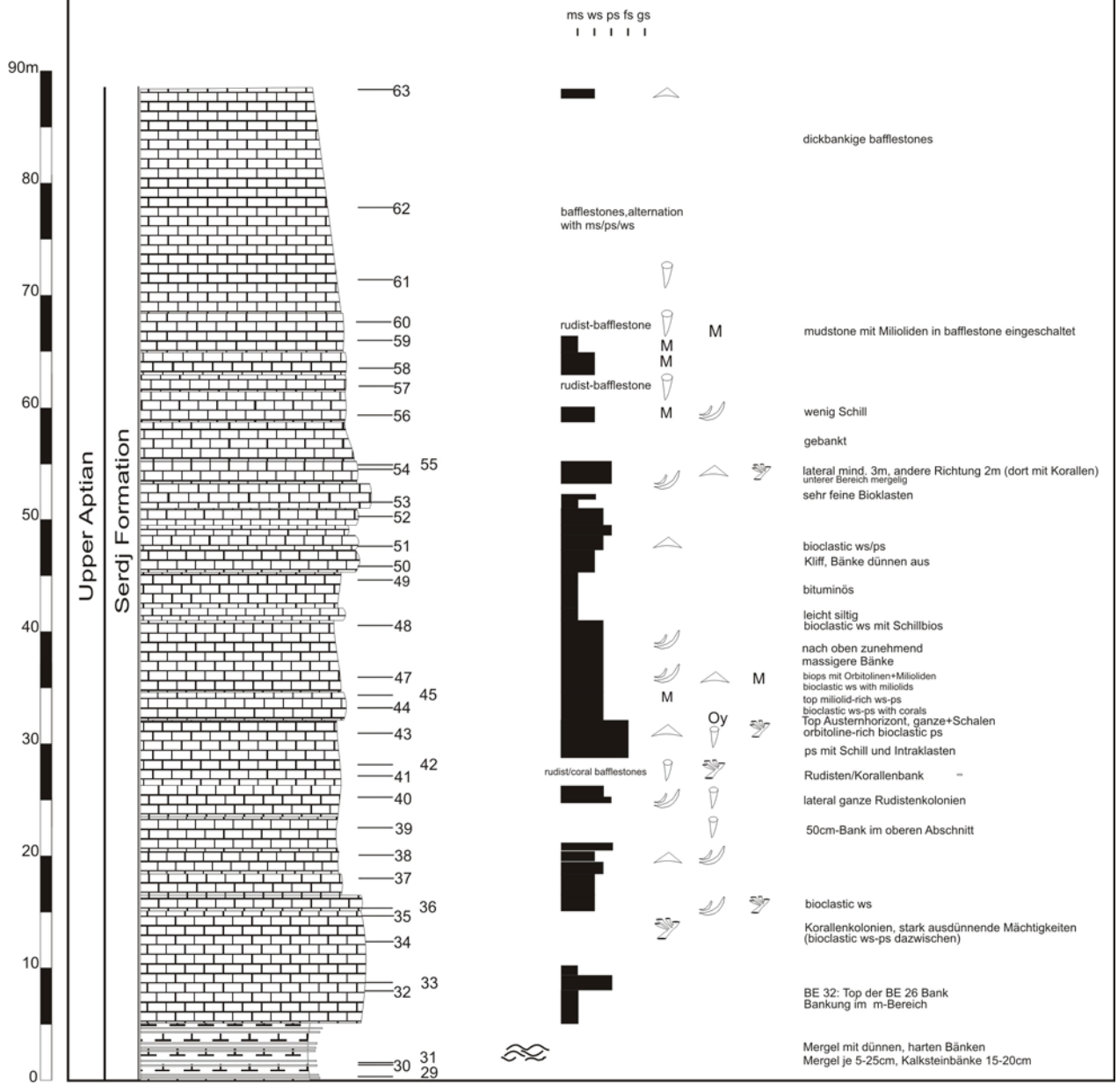


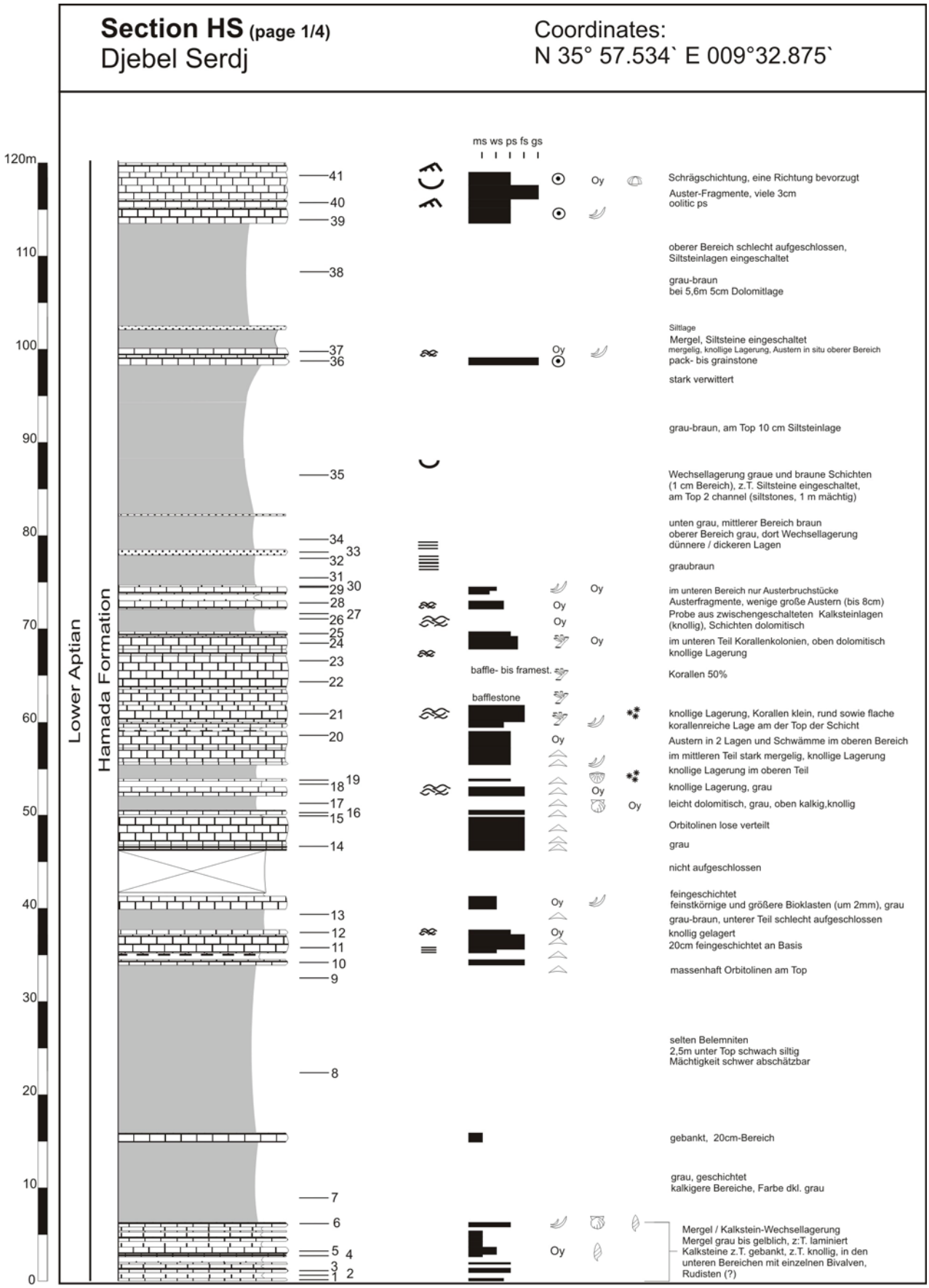
Section BE (page 1/2)
Djebel Serdj

Coordinates:
East of Beskra village

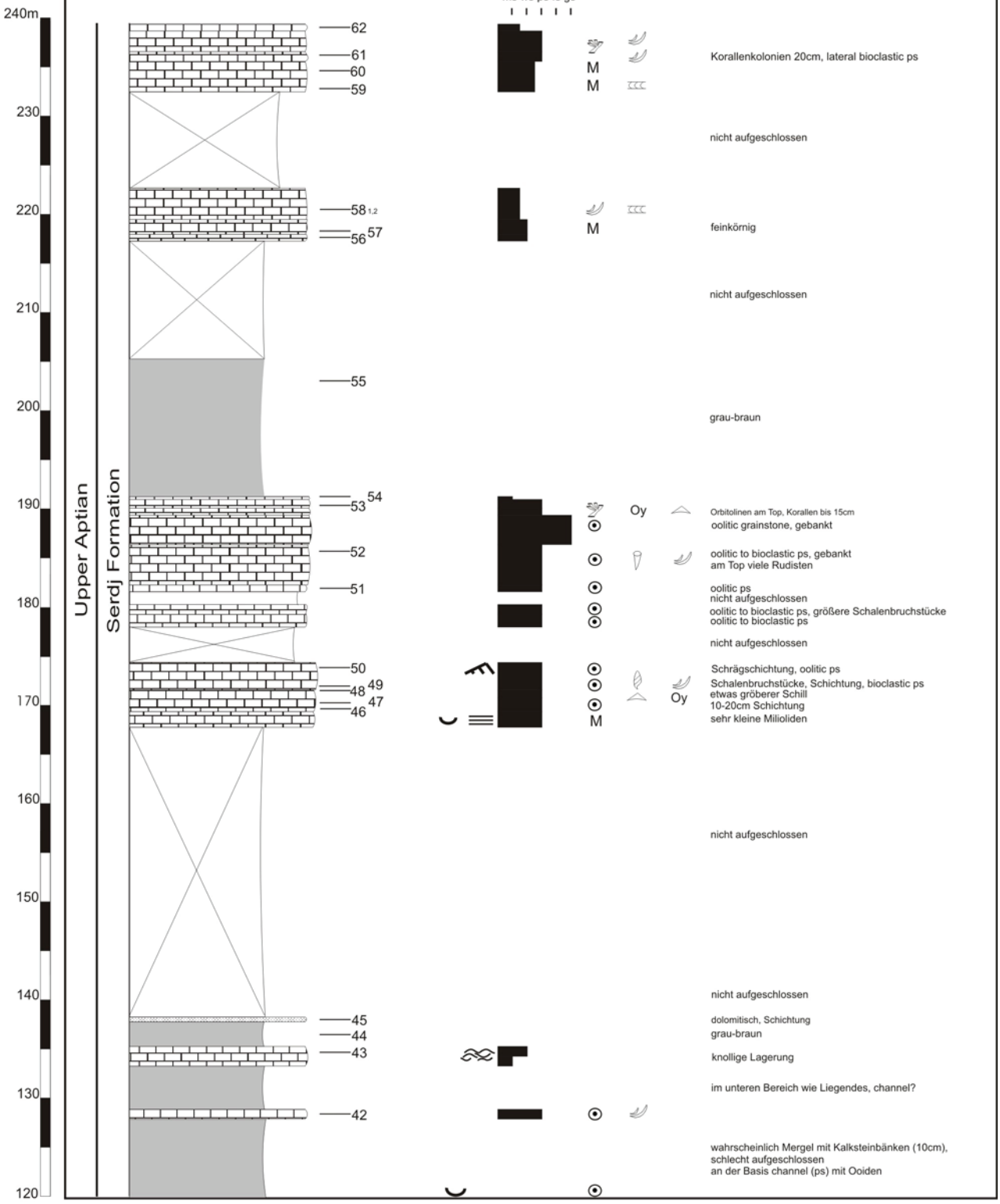


Section BE (page 2/2)
Djebel Serdj

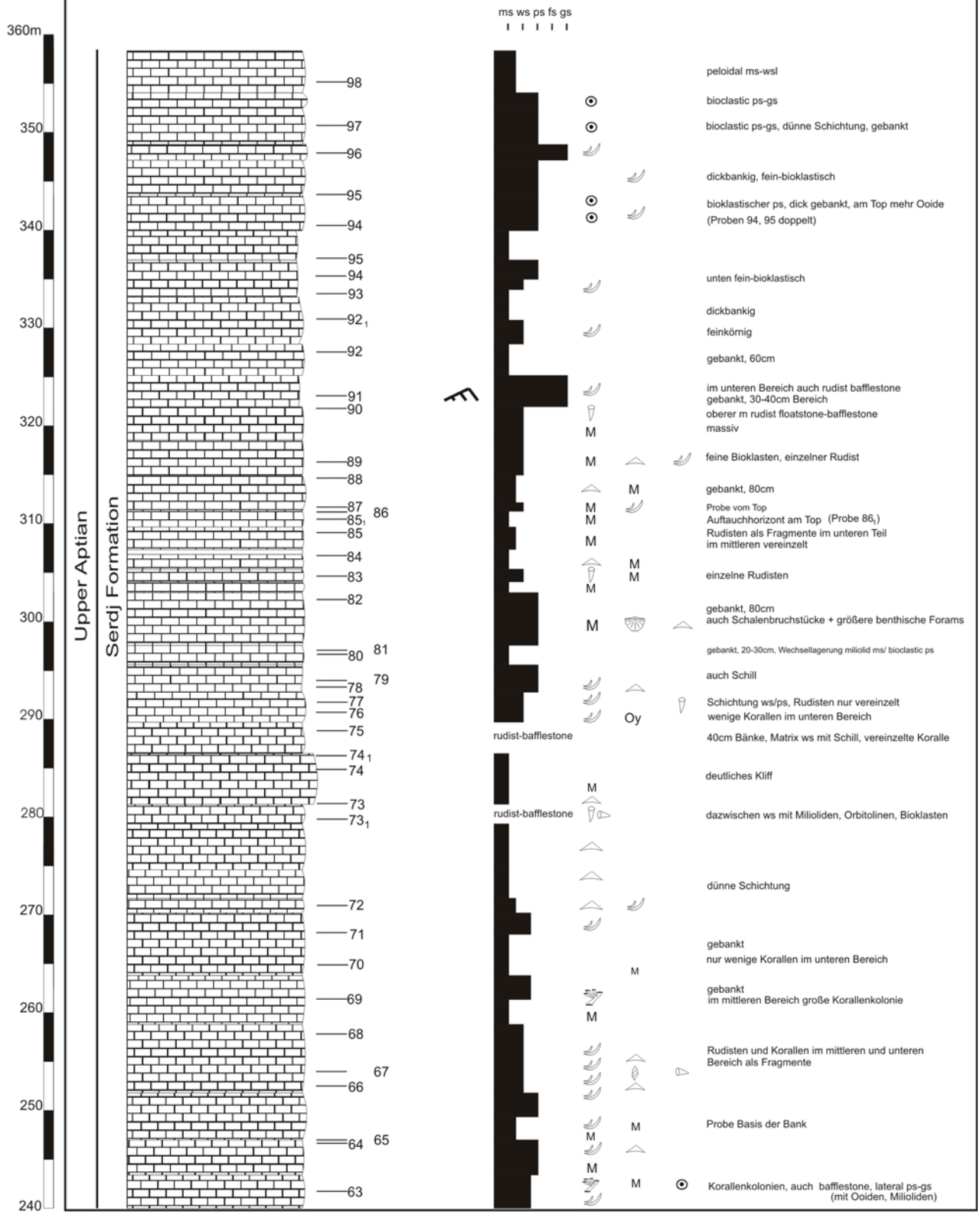



Section HS (page 1/4)
Djebel Serdj
Coordinates:
N 35° 57.534` E 009°32.875`
ms ws ps fs gs
120m
110
100
90
80
70
60
50
40
30
20
10
0
Lower Aptian
Hamada Formation
41
40
39
38
37
36
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Oy
Schrägschichtung, eine Richtung bevorzugt
Auster-Fragmente, viele 3cm
oolitic ps
oberer Bereich schlecht aufgeschlossen,
Siltsteinlagen eingeschaltet
grau-braun
bei 5,6m 5cm Dolomitlage
Siltlage
Mergel, Siltsteine eingeschaltet
mergelig, knollige Lagerung, Austern in situ oberer Bereich
pack- bis grainstone
stark verwittert
grau-braun, am Top 10 cm Siltsteinlage
Wechsellagerung graue und braune Schichten
(1 cm Bereich), z.T. Siltsteine eingeschaltet,
am Top 2 channel (siltstones, 1 m mächtig)
unten grau, mittlerer Bereich braun
oberer Bereich grau, dort Wechsellagerung
dünnere / dickeren Lagen
graubraun
im unteren Bereich nur Austerbruchstücke
Austerfragmente, wenige große Austern (bis 8cm)
Probe aus zwischengeschalteten Kalksteinlagen
(knollig), Schichten dolomitisch
im unteren Teil Korallenkolonien, oben dolomitisch
knollige Lagerung
baffle- bis framest.
Korallen 50%
bafflestone
knollige Lagerung, Korallen klein, rund sowie flache
korallenreiche Lage am der Top der Schicht
Austern in 2 Lagen und Schwämme im oberen Bereich
im mittleren Teil stark mergelig, knollige Lagerung
knollige Lagerung im oberen Teil
knollige Lagerung, grau
leicht dolomitisch, grau, oben kalkig,knollig
Orbitolinen lose verteilt
grau
nicht aufgeschlossen
feingeschichtet
feinstkörnige und größere Bioklasten (um 2mm), grau
grau-braun, unterer Teil schlecht aufgeschlossen
knollig gelagert
20cm feingeschichtet an Basis
massenhaft Orbitolinen am Top
selten Belemniten
2,5m unter Top schwach siltig
Mächtigkeit schwer abschätzbar
gebankt, 20cm-Bereich
grau, geschichtet
kalkigere Bereiche, Farbe dkl. grau
Mergel / Kalkstein-Wechsellagerung
Mergel grau bis gelblich, z:T. laminiert
Kalksteine z.T. gebankt, z.T. knollig, in den
unteren Bereichen mit einzelnen Bivalven,
Rudisten (?)

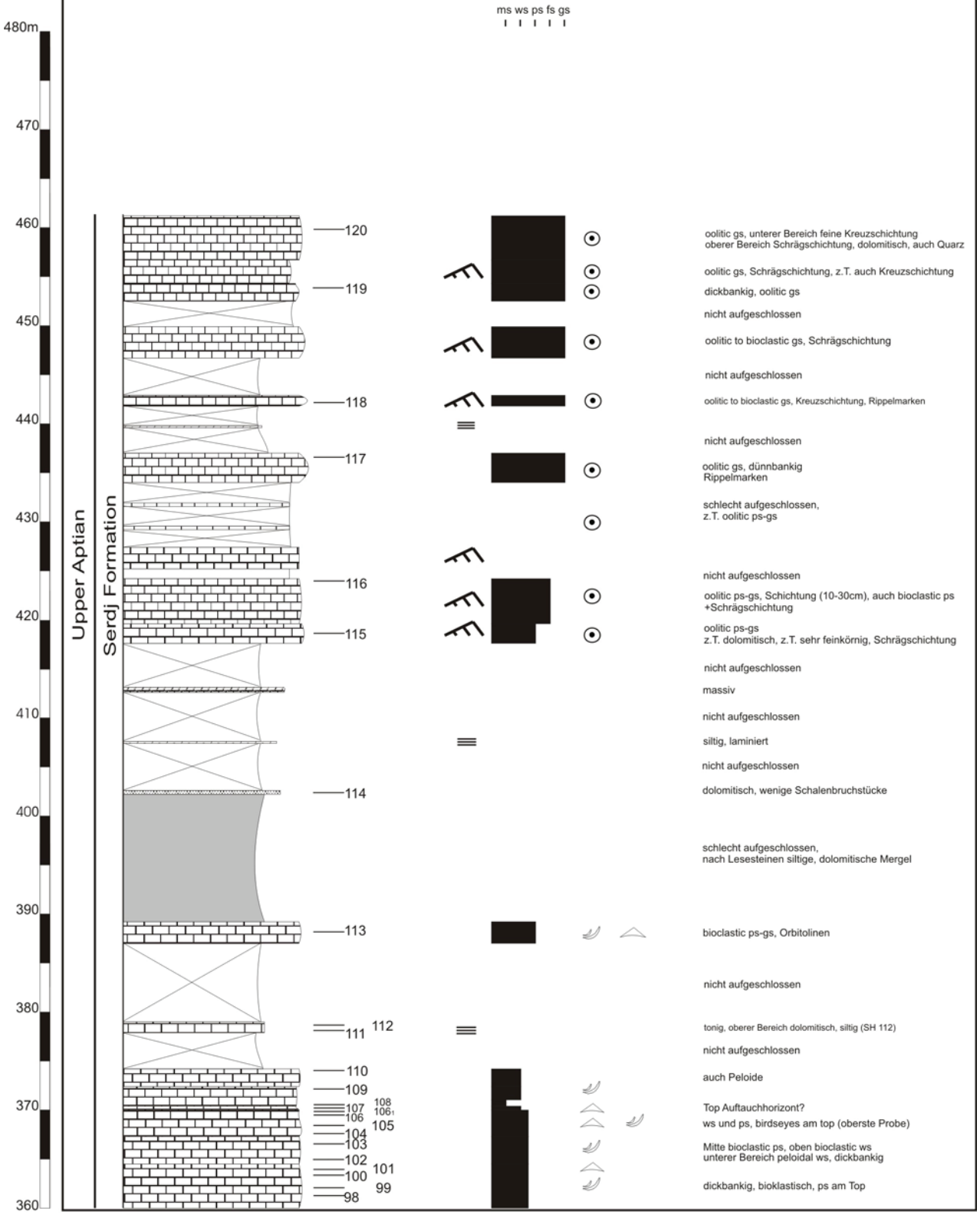
Section HS (page 2/4)
Djebel Serdj



Section HS (page 3/4)
Djebel Serdj

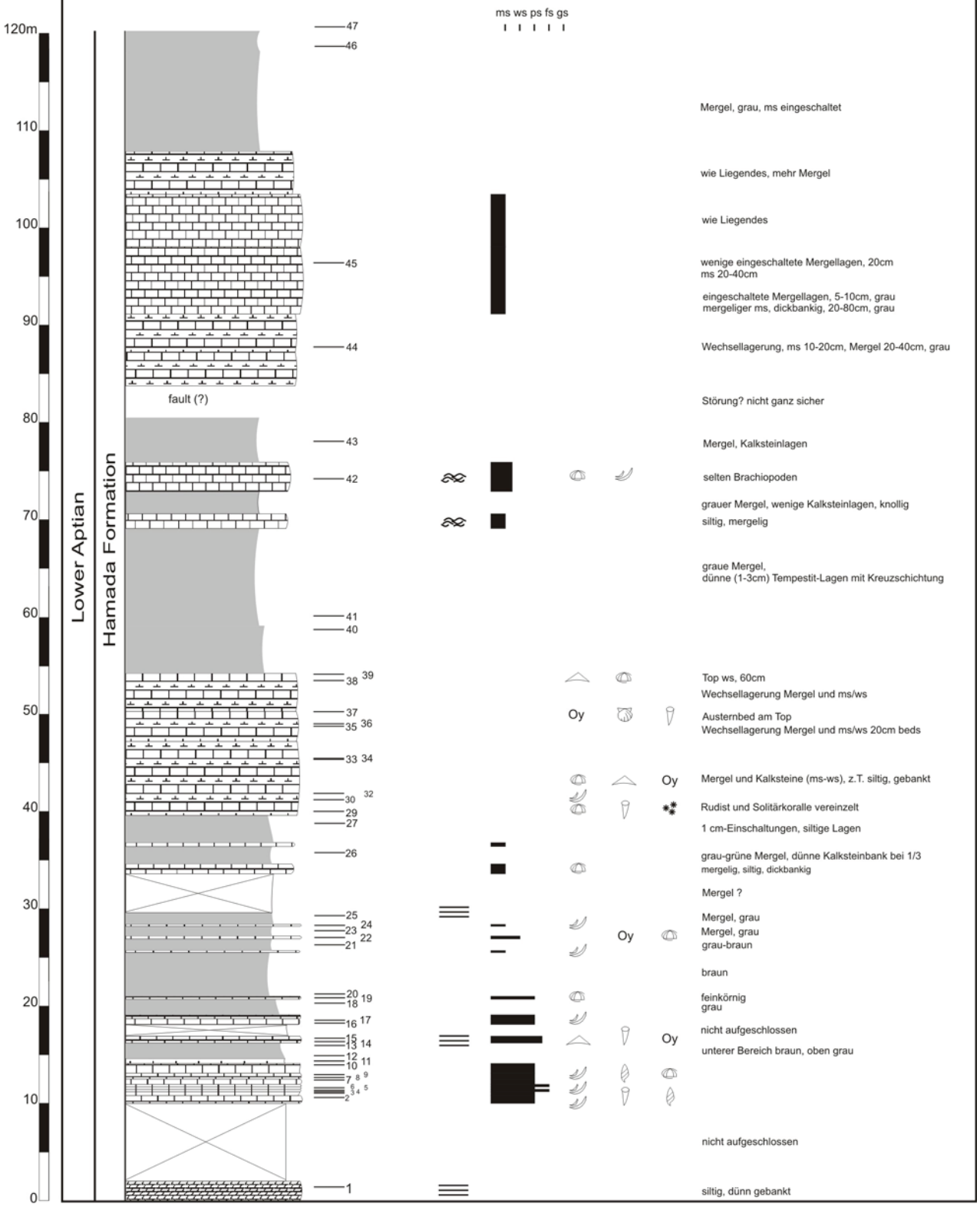


Section HS (page 4/4)
Djebel Serdj



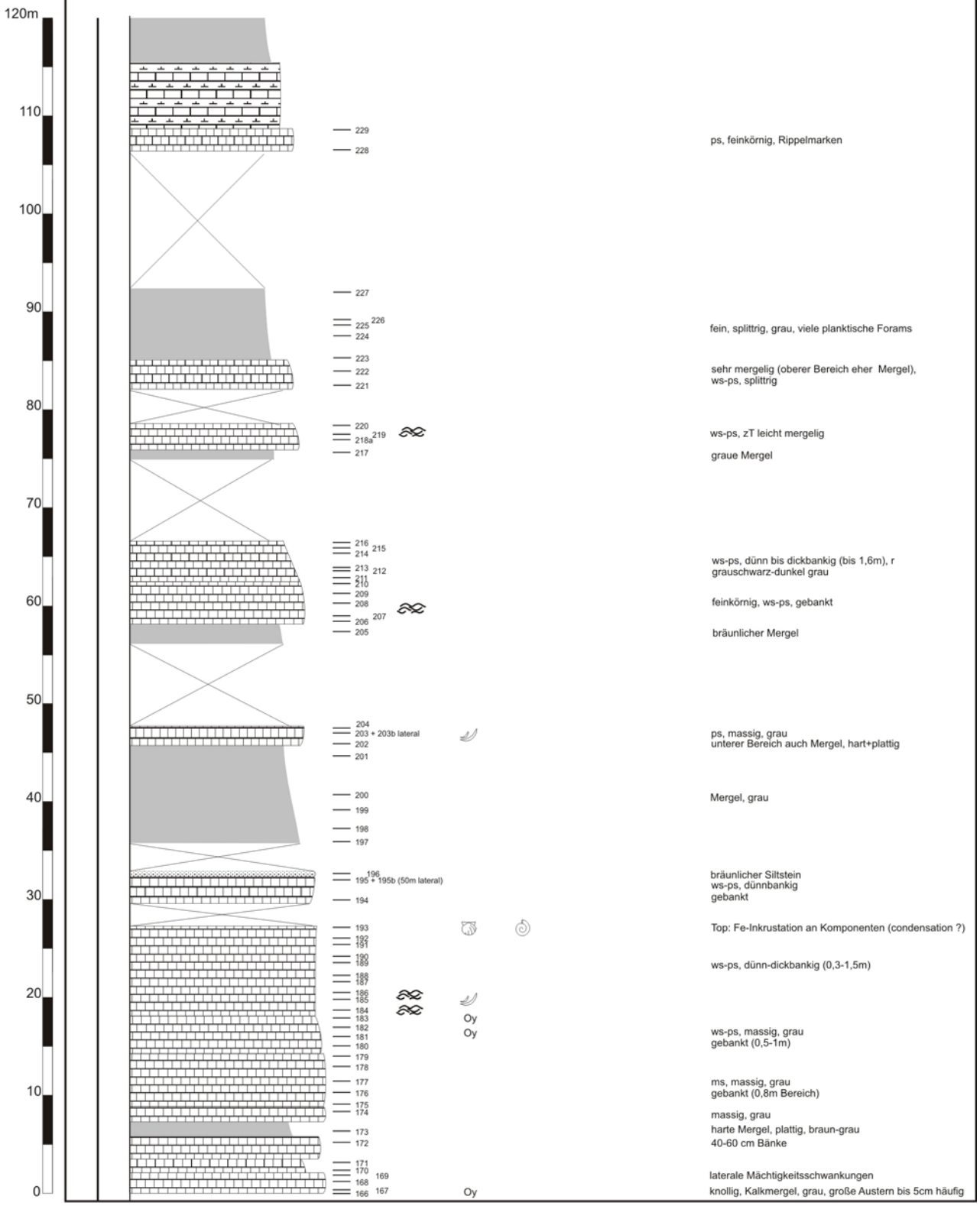
Section SM
Djebel Serdj

Coordinates:
N 35° 56.450` E 009°32.521`



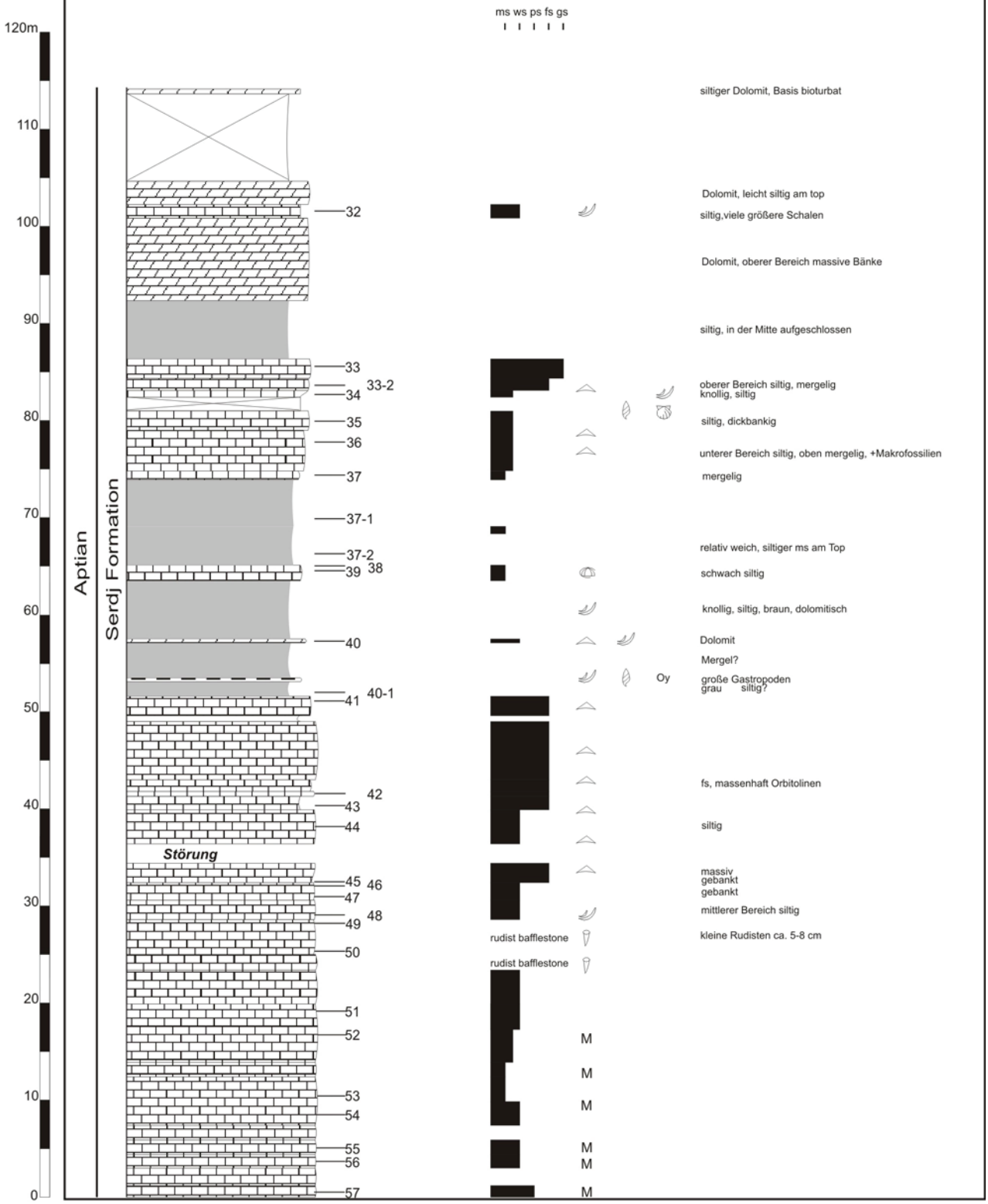
Section SN
Djebel Serdj

Coordinates:
N 35.96667° E 009.59447°

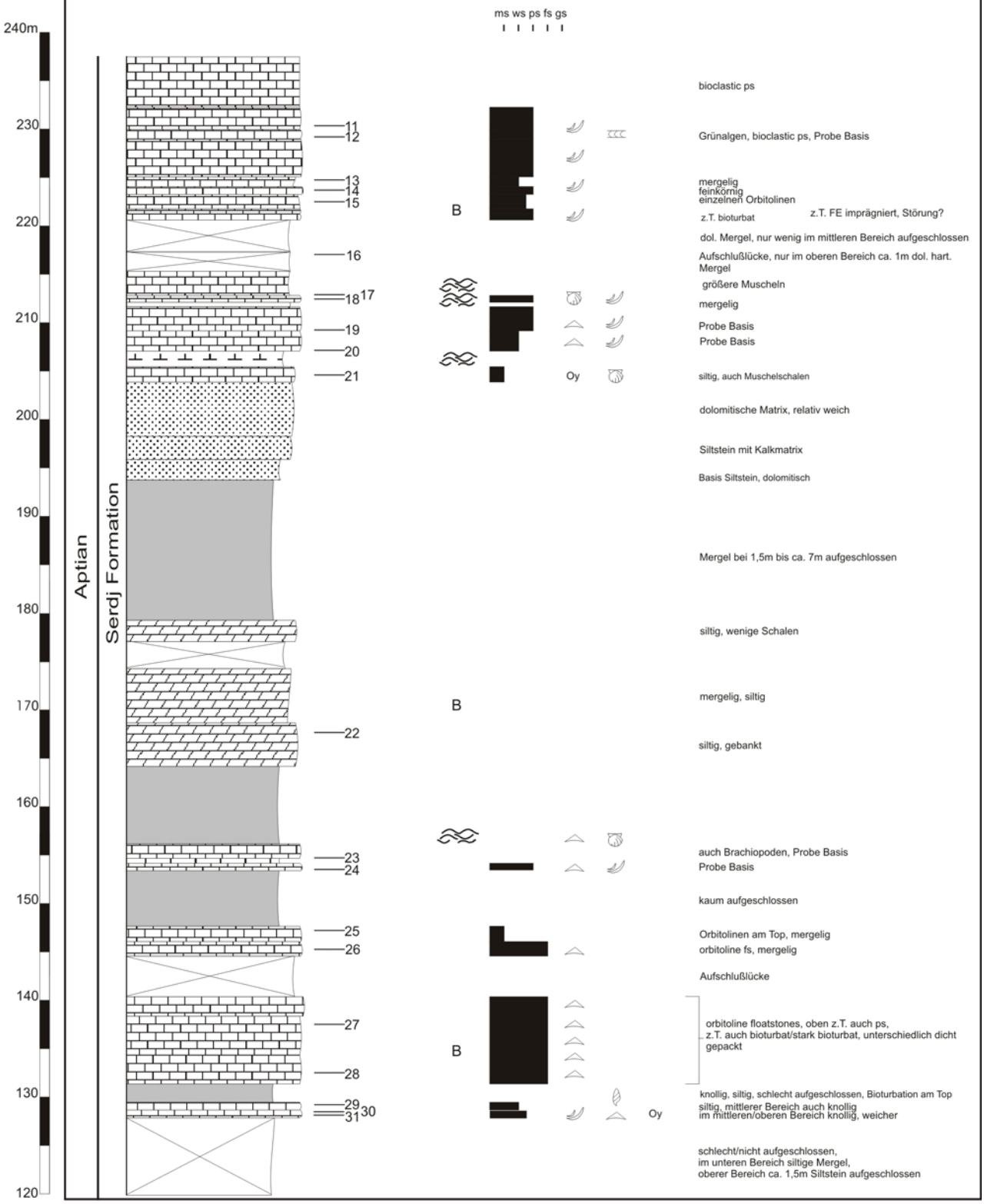


Section SL (page 1/3)
Djebel Slata

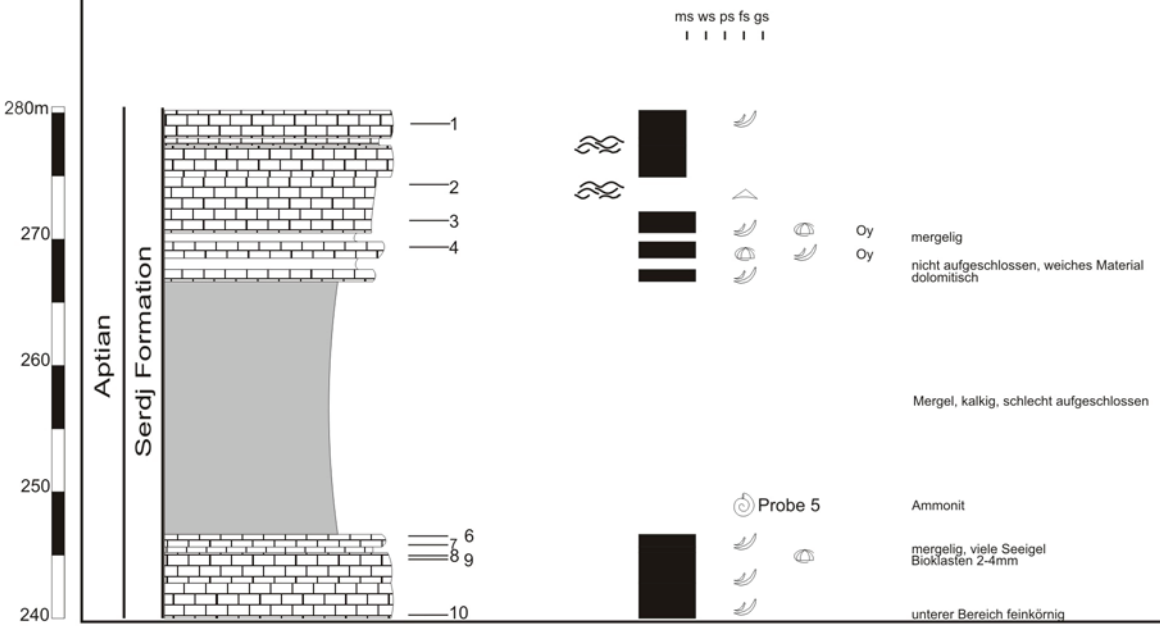
Coordinates:
N 35.86747° E 008.47315°

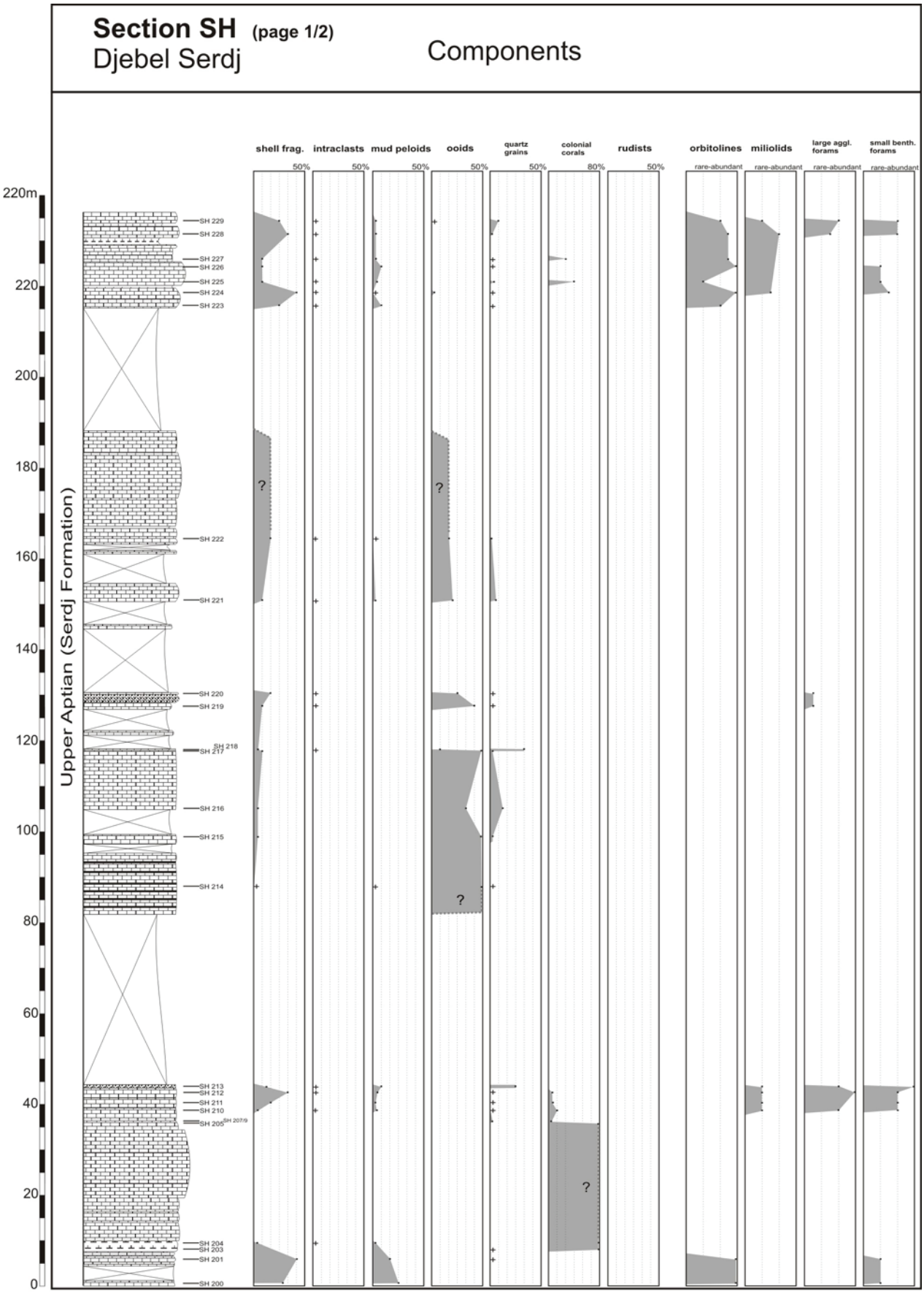


Section SL (page 2/3)
Djebel Slata



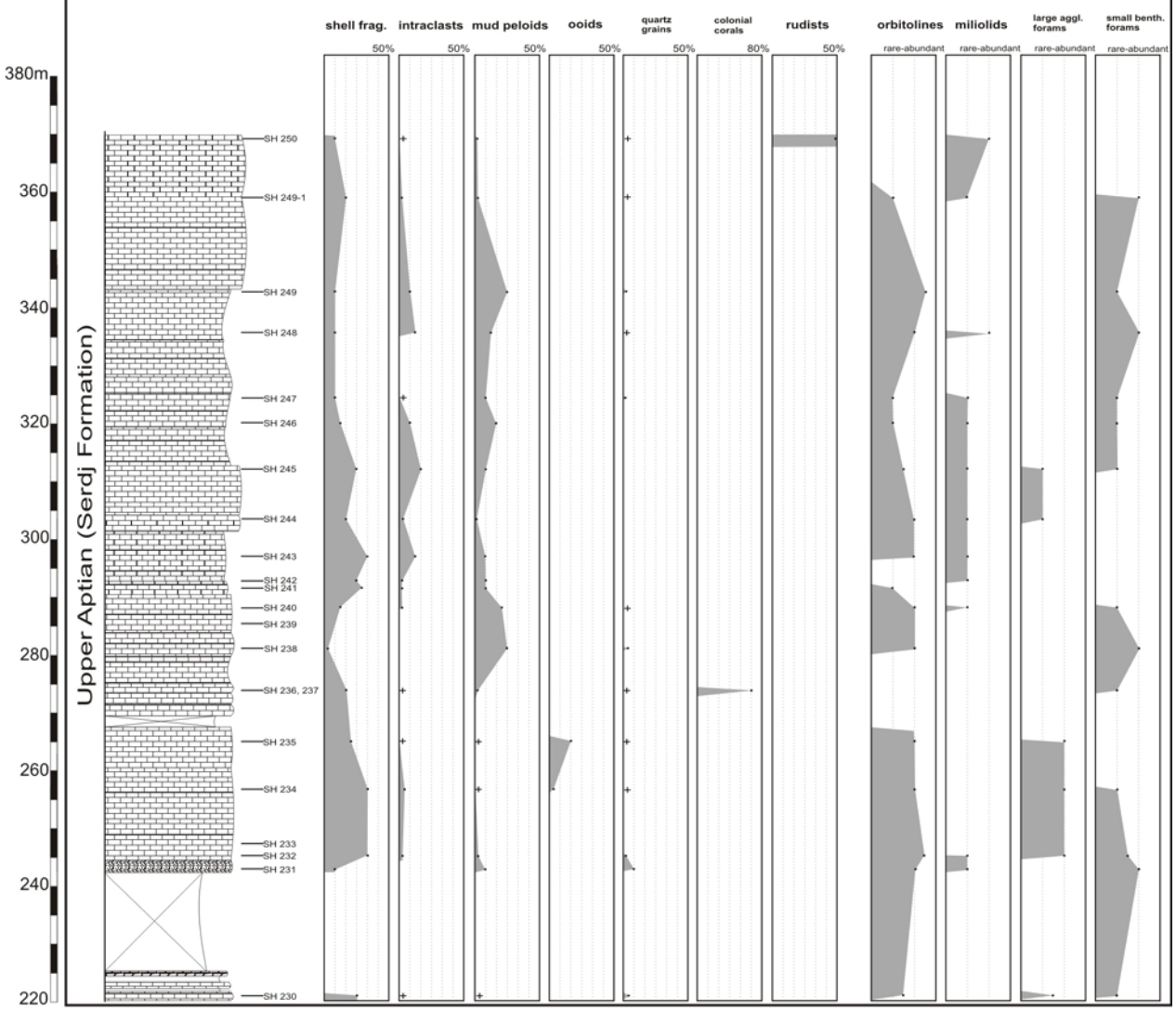
Section SL (page 3/3)
Djebel Slata

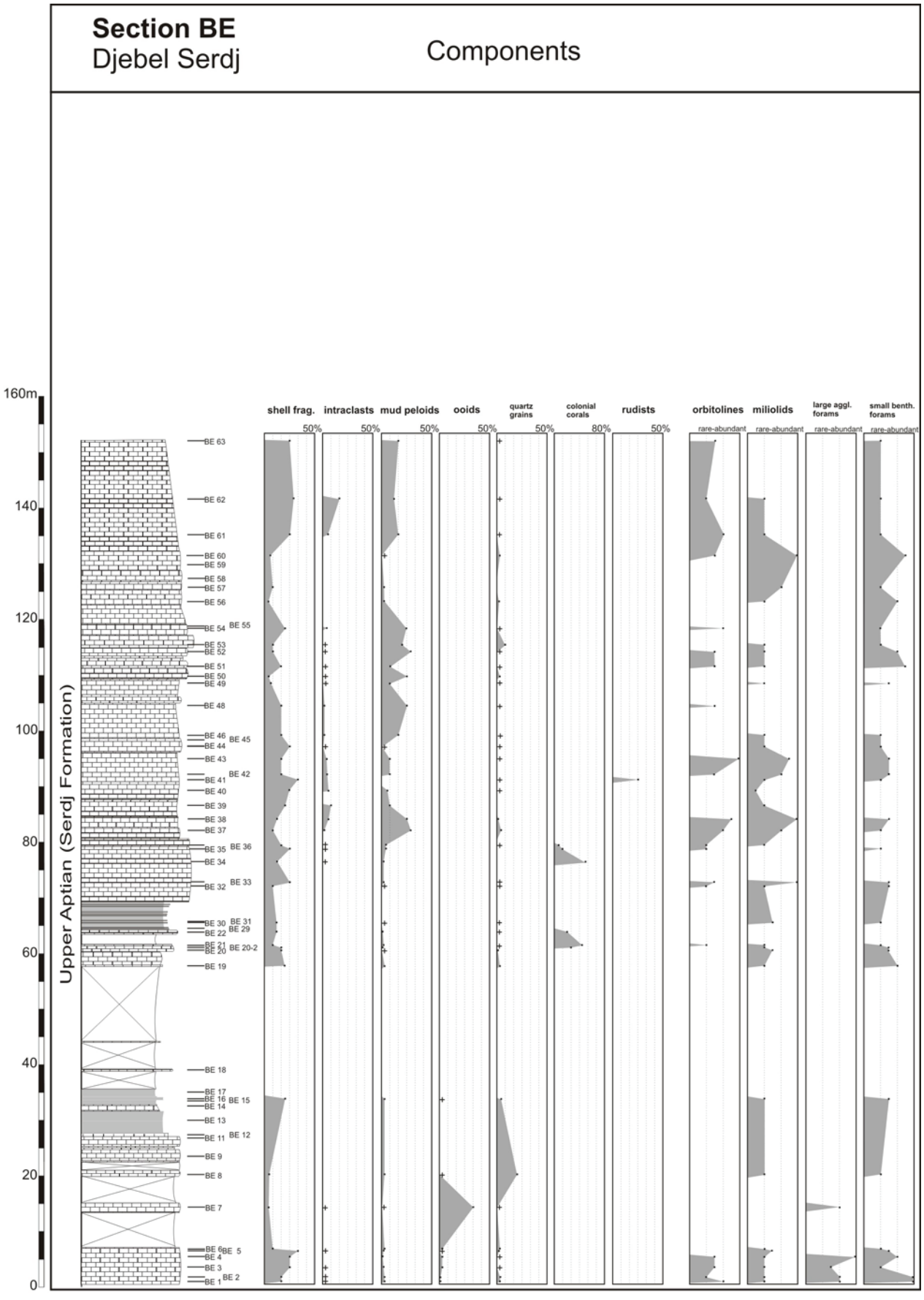



Section SH (page 1/2)
Djebel Serdj
Components
shell frag.
intraclasts
mud peloids
ooids
quartz grains
colonial corals
rudists
orbitolines
miliolids
large aggl. forams
small benth. forams
50%
80%
rare-abundant
220m
200
180
160
140
120
100
80
60
40
20
0
Upper Aptian (Serdj Formation)
SH 229
SH 228
SH 227
SH 226
SH 225
SH 224
SH 223
SH 222
SH 221
SH 220
SH 219
SH 218
SH 217
SH 216
SH 215
SH 214
SH 213
SH 212
SH 211
SH 210
SH 207/9
SH 205
SH 204
SH 203
SH 201
SH 200

Section SH (page 2/2)
Djebel Serdj

Components




Section BE
Djebel Serdj
Components
160m
140
120
100
80
60
40
20
0
Upper Aptian (Serdj Formation)
BE 63
BE 62
BE 61
BE 60
BE 59
BE 58
BE 57
BE 56
BE 54
BE 55
BE 53
BE 52
BE 51
BE 50
BE 49
BE 48
BE 46
BE 44
BE 45
BE 43
BE 41
BE 42
BE 40
BE 39
BE 38
BE 37
BE 35
BE 36
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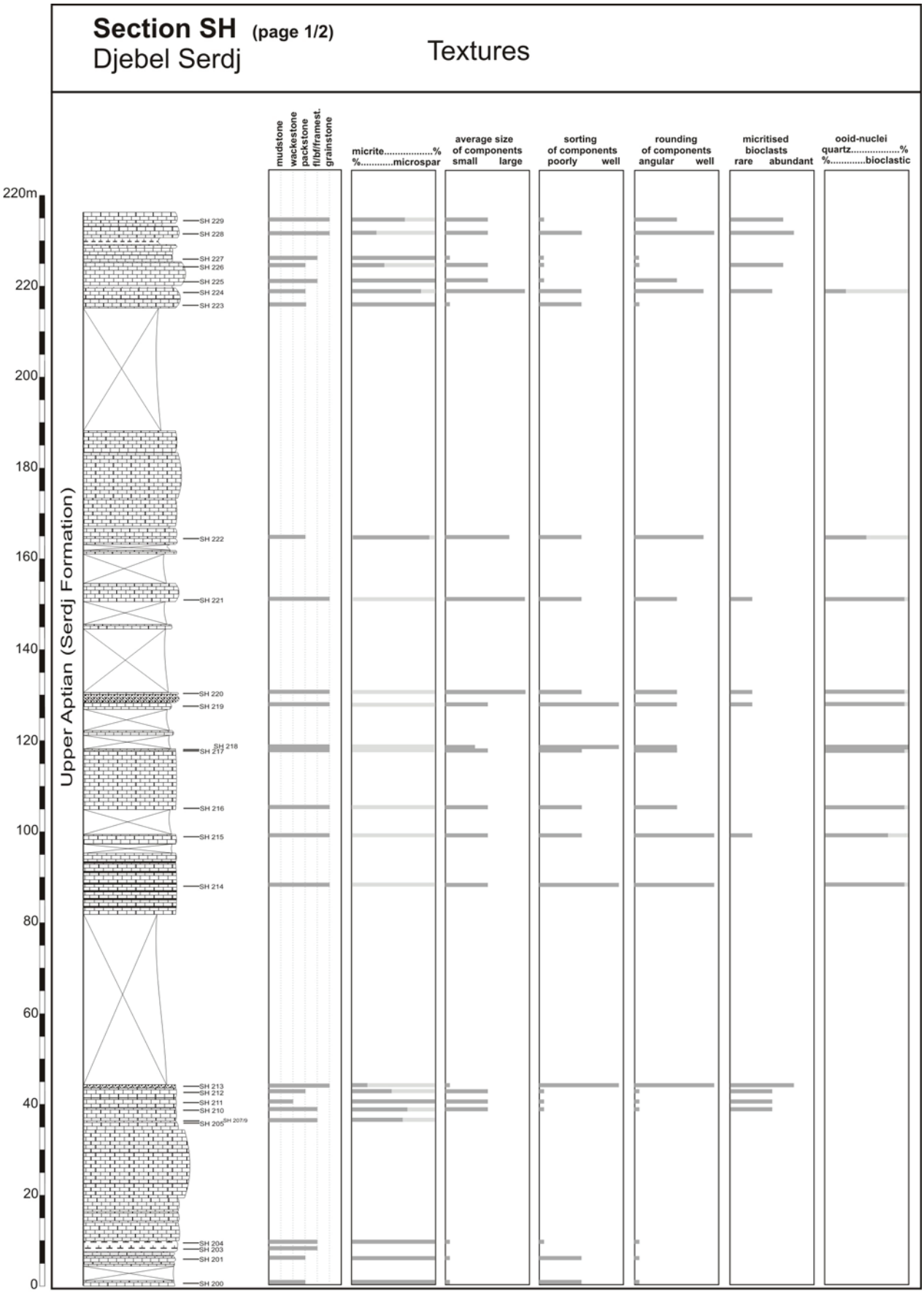
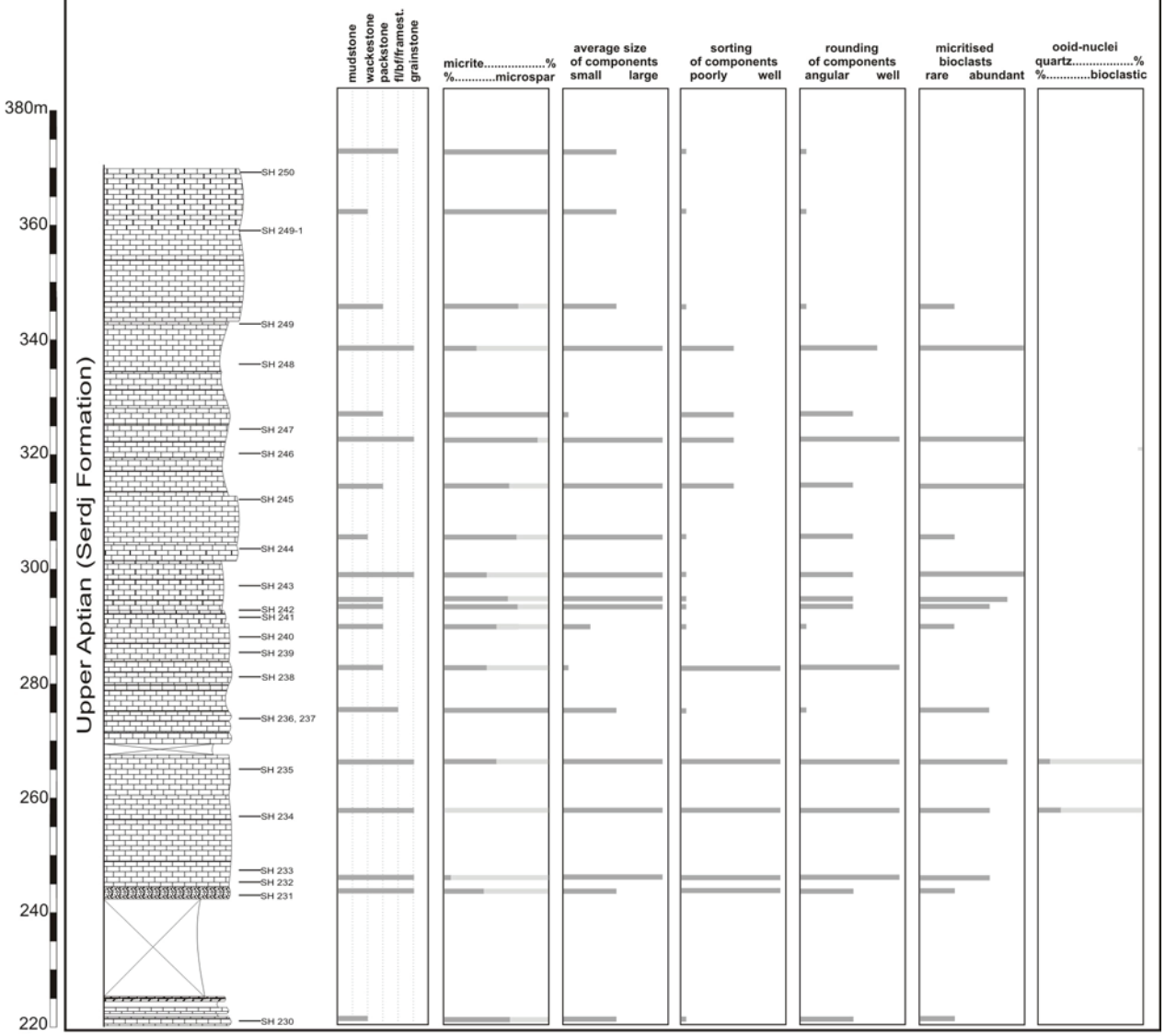
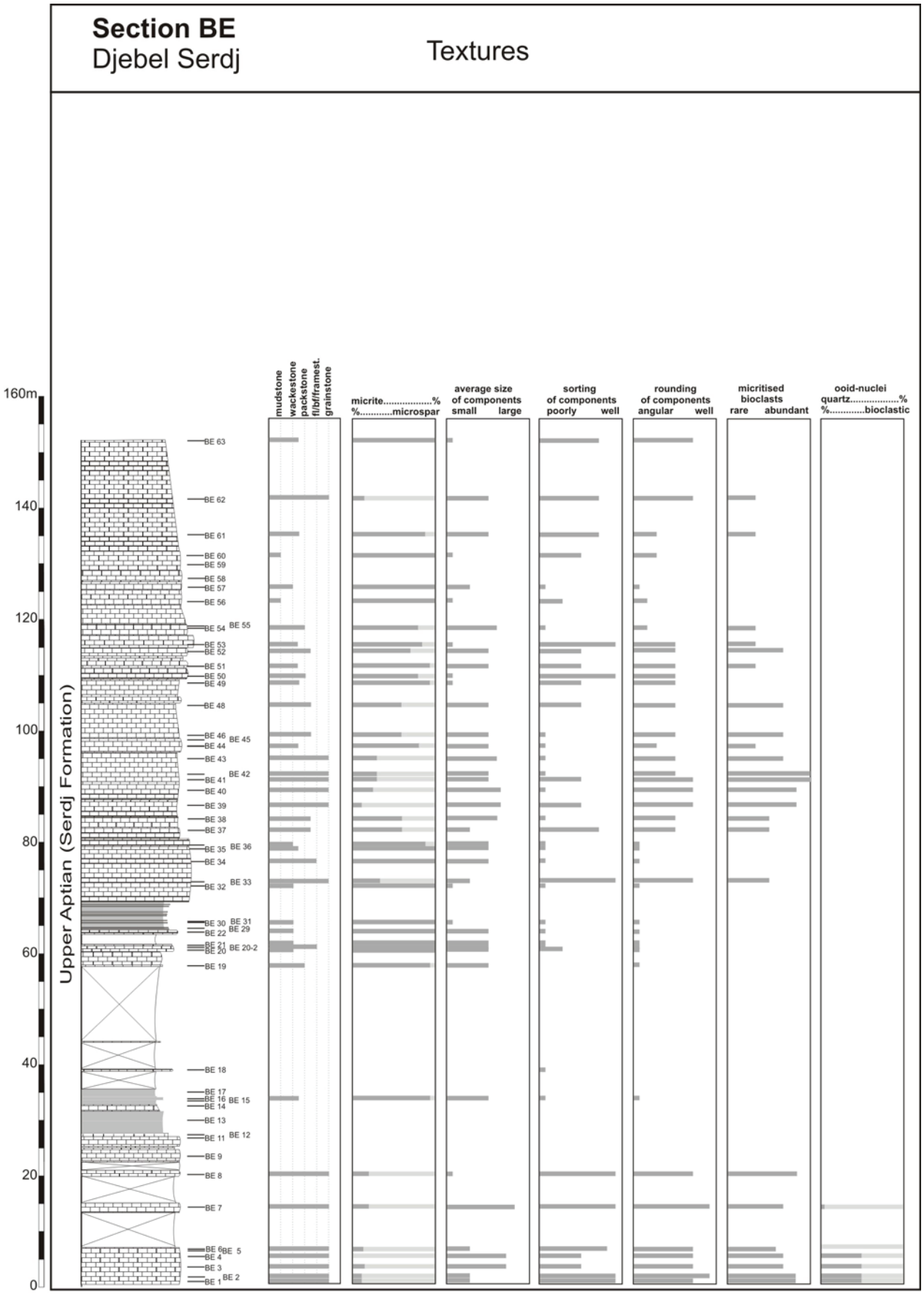
BE 32
BE 33
BE 30
BE 31
BE 22
BE 29
BE 21
BE 20
BE 20-2
BE 19
BE 18
BE 17
BE 16
BE 15
BE 14
BE 13
BE 11
BE 12
BE 9
BE 8
BE 7
BE 6
BE 5
BE 4
BE 3
BE 2
BE 1
shell frag.
intraclasts
mud peloids
ooids
quartz grains
colonial corals
rudists
orbitolines
miliolids
large aggl. forams
small benth. forams
50%
80%
rare-abundant


Section SH (page 1/2)
Djebel Serdj
Textures
mudstone
wackestone
packstone
fl/bf/framest.
grainstone
micrite.....%
%.....microspar
average size
of components
small large
sorting
of components
poorly well
rounding
of components
angular well
micritised
bioclasts
rare abundant
ooid-nuclei
quartz.....%
%.....bioclastic
220m
200
180
160
140
120
100
80
60
40
20
0
Upper Aptian (Serdj Formation)
SH 229
SH 228
SH 227
SH 226
SH 225
SH 224
SH 223
SH 222
SH 221
SH 220
SH 219
SH 218
SH 217
SH 216
SH 215
SH 214
SH 213
SH 212
SH 211
SH 210
SH 207/9
SH 205
SH 204
SH 203
SH 201
SH 200

Section SH (page 2/2)
Djebel Serdj

Textures




Section BE
Djebel Serdj
Textures
Upper Aptian (Serdj Formation)
160m
140
120
100
80
60
40
20
0
BE 63
BE 62
BE 61
BE 60
BE 59
BE 58
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BE 32
BE 31
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BE 29
BE 22
BE 21
BE 20-2
BE 20
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BE 15
BE 14
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BE 11
BE 9
BE 8
BE 7
BE 6
BE 5
BE 4
BE 3
BE 2
BE 1
mudstone
wackestone
packstone
fl/bf/framest.
grainstone
micrite.....%
%.....microspar
average size
of components
small large
sorting
of components
poorly well
rounding
of components
angular well
micritised
bioclasts
rare abundant
ooid-nuclei
quartz.....%
%.....bioclastic

Erklärung

Matthias Heldt
Hollerallee 43

28209 Bremen

Hiermit erkläre ich, daß ich

- die vorliegende Arbeit ohne fremde Hilfe angefertigt habe.

- keine anderen, als die von mir angegeben Quellen und Hilfsmittel verwendet habe.

- die den benutzten Quellen wörtlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.

Bremen, den 26.08.2008