Sedimentological evolution of the late Emsian to early Givetian carbonate ramp in the Mader (eastern Anti-Atlas, SE-Morocco)

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With 33 Figures, 29 Tables, and 6 Plates

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ABSTRACT

During the Early to Middle Devonian, a small carbonate ramp was established on the northwestern margin of the Sahara Craton. Remnants of this ramp are perfectly exposed in the Mader (eastern Anti-Atlas) and allow a detailed investigation about the evolution of this Palaeozoic environment. The present study is based on the examination of several stratigraphic sections with lower Emsian to lower Givetian sedimentary successions. Since the successions are very homogenous with respect to composition and since they contain only scarce fossils of biostratigraphic value, correlation is based on an integrated approach including sequence-, litho- and biostratigraphy. According to this approach ten depophases can be distinguished.

From late Emsian to early Eifelian times, sediments of depophase 1a, 1b, and 2 were accumulated. These deposits reflect the geometry of a slightly inclined carbonate ramp which dipped to the northeast. Limestones consist mainly of bioclast and crinoid limestones on the mid-ramp and inner ramp (southern Mader) and predominantly of mud-dominated skeletal limestones and limestone-marl alternations on the outer ramp (northern Mader). In the basinal environment (northernmost Mader), shales and muddy limestones (altered to nodular limestones) were deposited. The stratal geometry and the facies relationships of depophase 1a, b, and 2 indicate a highstand systems tract (HST).

Subsequent deepening is suggested by the migration of facies belts during depophase 3 (early Eifelian), when outer-ramp and basinal facies retrograded above the crinod facies of the mid- to inner ramp (southern Mader) and mud mounds were established on the outer-ramp (central Mader). Thickness is significantly thinner in the northern Mader and indicates reduced sedimentation and basinal conditions. The landward facies shift and the stratigraphic geometry indicate a transgressive systems tract (TST).

Sediments of the following depophase 4 (early - late Eifelian) were recorded exclusively in the northern Mader. Whereas the southern Mader was probably subject to sediment bypass during this time, the mid- to outer ramp (northern Mader) was predominated by sedimentation of calcareous mud and peloids (overprinted to limestone-marl alternations). These sedimentary rocks are interpreted as muddy calciturbidites and basinal deposits. Farther north, thickness decreases thus indicating reduced sedimentation rates and a deeper basinal environment (northernmost Mader). The geometry of depophase 4 strata and the facies relationships suggest, that during this time the northern Mader was subject to higher subsidence rates than the southern Mader. Depophase 4 is interpreted as a highstand systems tract (HST).

The sea level increased during the latest Eifelian to the early Givetian (depophase 5a). In this time, carbonate accumulation on the inner and mid-ramp was reactivated. On the inner ramp (southern Mader), reef dwellers (corals, stromatoporoids) predominated, while shale sedimentation persisted in the basin (northern and northernmost Mader). Highstand conditions were established during subsequent depophase 5b, when inner-ramp facies (biostromal facies) slightly prograded from the south to the northeast. Contemporaneously, the northernmost Mader was uplifted as reflected by the establishment of an inner-ramp facies belt (biostromal limestones). The reefal buildups locally formed escarpments which were episodically destroyed by storms thus creating channelised debris-flows. Subsidence remained high in the basin (central Mader), where shales and intercalated resedimented limestones were accumulated.

Subsequently, sediments of depophase 5c, 5d, and 5e were deposited but were preserved exclusively in the northern Mader. The Givetian highstand (depophase 5b - 5e) was followed by a transgressive phase (TST) which partially originated from an eustatic sea-level rise (”Taghanic Event”). Correspondingly, reef growth was terminated and basinal conditions prevailed in most of the Mader.

Rock composition and facies relationships during late Emsian to early Eifelian times show close similarities to cool-water carbonates whereas lower Givetian limestones correspond more to tropical carbonates. The transition from non-tropical towards tropical conditions is in accordance with the view that the northwestern African Craton drifted from middle southern latitudes towards equatorial latitudes during the Devonian.

The geometry and facies relationships of the Devonian in the Mader suggest increasing tectonic activity during the Middle and Late Devonian. This culminated in the formation of a small basin centre in the northern Mader which was bordered to the north, west, and south by shallow areas. Basin formation during Middle and Late Devonian times was probably governed by transtensional forces and thus the Mader Basin represents a pull-apart structure.

KURZFASSUNG

Am Nordrand des Sahara-Kratons entwickelte sich während des Unter- und Mitteldevons eine kleine Karbonatrampe. Die Überreste dieser Rampe sind im Mader Gebiet (östlicher Anti-Atlas) in hervorragender Weise aufgeschlossen und ermöglichen eine detaillierte Untersuchung dieses paläozoischen Ablagerungsraums. Diese Arbeit beruht auf der Untersuchung von mehreren stratigraphischen Profilen, die aus Abfolgen vom Unterems bis in das untere Givet aufgebaut sind. Da die Abfolgen sehr einheitlich zusammengesetzt sind und nur wenige biostratigraphisch bedeutende Fossilien enthalten, basiert die Korrelation der Profile auf einem integriertem Ansatz, der die Sequenz-, Litho- und Biostratigraphie berücksichtigt. Folgt man diesem Ansatz, so lassen sich zehn Depophasen unterscheiden.

Vom späten Ems bis in das frühe Eifel lagerten sich Sedimente der Depophasen 1a, 1b und 2 ab. Diese Ablagerungen zeigen die Geometrie einer leicht nach Nordosten einfallenden Karbonatrampe an. Die Kalksteine bestehen vorwiegend aus Bioklasten- und Crinoidenkalken auf der mittleren und inneren Rampe (südliches Mader) und aus Schlamm-dominierten Skeletal Wackestones und Kalk-Mergel Wechselfolgen auf der äußeren Rampe (nördliches Mader). Im Becken-Environment (nördlichstes Mader) lagerten sich Tone und schlammige Kalksteine ab (überprägt zu Knollenkalken). Die stratale Geometrie und die Faziesbeziehungen der Ablagerungen der Depophasen 1a, 1b und 2 zeigen einen Hochstand-Systemtrakt an (HST).

Die Migration der Faziesgürtel während der Depophase 3 zeigt einen Anstieg des Meeresspiegels an. In dieser Zeit retrogradiert die Fazies der äußeren Rampe und des Beckens über die Crinoidenkalkfazies der mittleren und der inneren Rampe (südliches Mader) und Mud-Mounds entstehen auf der äußeren Rampe (nördliches Mader). Die Mächtigkeit ist im nördlichen Mader deutlich geringer und zeigt damit Beckenbedingungen an. Die landwärtige Faziesverschiebung und die stratigraphische Geometrie sprechen für einen transgressiven Systemtrakt (TST).

Sedimente der nachfolgenden Depophase 4 (frühes - spätes Eifel) sind nur im nördlichen Mader erhalten. Während es in dieser Zeit im südlichen Mader zu Sediment-Bypass kam, war die mittlere bis äußere Rampe (nördliches Mader) von Kalkschlamm- und Peloidablagerung dominiert (überprägt zu Kalk-Mergel Wechselfolgen). Diese Sedimentgesteine werden als schlammige Kalkturbidite und Beckenablager-

ungen interpretiert. Weiter im Norden nimmt die Mächtigkeit ab und zeigt damit reduzierte Sedimentation und ein tieferes Becken-Environment an (nördlichstes Mader). Die Geometrie und die Faziesbeziehungen zeigen, daß das nördliche Mader zu dieser Zeit erhöhter Subsidenz unterlag. Die Depophase 4 wird als ein Hochstand-Systemtrakt interpretiert (HST).

Der Meeresspiegel stieg während des spätesten Eifel und des frühen Givet an (Depophase 5a). In dieser Zeit wurde die Karbonat-Sedimentation auf der inneren und mittleren Rampe reaktiviert. Auf der inneren Rampe (südliches Mader) dominierten die Riffbildner (Korallen, Stromatoporen) während im Becken weiterhin Tone abgelagert wurden. Im Laufe der nachfolgenden Depophase 5b kam es erneut zu Hochstand-Bedingungen; während dieser Zeit progradierte die Fazies der inneren Rampe (biostromale Fazies) leicht von Süden nach Nordosten. Die Entstehung eines Inner-Ramp-Faziesgürtels (biostromale Kalke) zeigt die zeitgleiche Hebung des nördlichsten Mader an. Die Riff-Buildups bauten lokal Klippen auf, die episodisch durch Stürme zerstört wurden und kanalisierte Debris-Flows auslösten. Die Subsidenz blieb im Becken (nördliches Mader), in dem Tone mit eingeschalteten resedimentierten Kalken abgelagert wurden, weiterhin hoch.

Nachfolgend wurden Sedimente der Depophasen 5c, 5d und 5e abgelagert; diese sind jedoch nur im nördlichen Mader erhalten. Der Hochstand während des Givet (Depophasen 5b - 5e) wurde von einer transgressiven Phase gefolgt (TST), die teilweise auf einen eustatischen Meeresspiegelanstieg (”Taghanic Event”) zurückgeht. Daraufhin kam das Riffwachstum zum Erliegen und Beckenbedingungen herrschten im größten Teil des Mader Gebietes vor.

Die Gesteinszusammensetzung und die Faziesbeziehungen vom späten Ems bis in das frühe Eifel zeigen enge Beziehungen zu Kaltwasser-Karbonaten im Gegensatz zu den Kalksteinen des frühen Givet, die tropischen Karbonaten ähnlicher sind. Der Übergang von nicht-tropischen zu tropischen Bedingungen stimmt mit der Vorstellung überein, daß der nordwestliche afrikanische Kraton während des Devons von mittleren südlichen Breiten in äquatornahe Breiten driftete. Die Geometrie und die Faziesbeziehungen des Devons im Mader deuten eine steigende tektonische Aktivität während des Mittel- und Spätdevons an. Dieser Vorgang kulminierte in der Bildung eines kleinen Beckenzentrums im nördlichen Mader welches nördlich, westlich und südlich von flacheren Gebieten umgeben war. Die Beckenentwicklung während des Mittel- und Oberdevons wurde vermutlich von transtensionalen Kräften gesteuert, sodaß das Mader Becken als eine Pull-Apart Struktur angesehen werden kann.

1 INTRODUCTION

On the northwestern margin of the Sahara Craton, several prominent basins (e.g. Tindouf Basin, Reggane Basin, Ahnet Basin) existed during Devonian times (Boote et al. 1998). In the eastern Anti-Atlas, the remnants of a rather small basin, 60 - 80 km in diameter, are exposed in the Mader. Outcrops of Devonian sedimentary rocks provide an extraordinary insight into the sedimentary evolution of this time. Although outcrop conditions are favourable and many sections yielded numerous biostratigraphic data, only few attempts were made in order to reconstruct sedimentary environments and basin evolution for Emsian to Givetian times (Döring & Kazmierczak 2001, Wendt 1988, Kaufmann 1998).

Upper Emsian to lower Givetian sedimentary rocks in the Mader display features of a carbonate ramp system as already described by other authors (Wendt 1993, Kaufmann 1998). The remnants of the carbonate ramp can be recognised in continuous outcrop belts extending up to 50 km. The strata are only slightly folded, and faulted and hence there occur favourable conditions for the study of sedimentary geometries. The major aim of this work, is to extend the knowledge of regional stratigraphy and sedimentology in order to understand the facies dynamics and the basin evolution during the Devonian on the northwestern margin of the African Craton. Additionally, this study should provide further data for the understanding of Palaeozoic carbonate ramp systems.

2 GEOLOGICAL SETTING

The study area is located at the eastern termination of the 700 km long and up to 200 km wide SW-NE striking Anti-Atlas system (Fig. 1), which constituted a part of the northwestern margin of the Sahara Craton during the Palaeozoic (Piqué & Michard 1989). This mountain chain consists of a Precambrian crystalline basement and a thick section of gently deformed uppermost Precambrian to Namurian strata, which are covered to the north, east, and south by undeformed Cretaceous and Tertiary sedimentary rocks (Figs. 3, 4).

2.1 Basin evolution at the northwestern margin of the Sahara Craton

During Palaeozoic times, the eastern Anti-Atlas was situated on the northwestern margin of the Sahara Craton, which was a part of the Gondwana supercontinent. After its consolidation, the shelf of the northwestern African Craton was subject to a prolonged rifting phase from Late Precambrian to Early Cambrian, which was followed by a sag phase from Cambrian to Carboniferous (Lüning et al. 2000). During the late Ordovician (Ashgill), the northern Sahara Craton was situated at the southpole (Scotese & McKerrow 1990) as documented by glaciogenic deposits (Caradoc - Ashgill) in the Anti-Atlas (Hamoumi 1999). Global climatic differentiation was very pronounced by this time which was one of the coldest periods in earth history (Scotese 1997). In general, Cambrian and Ordovician successions consist mainly of siliciclastic rocks (sandstones and shales) apart from very rare limestones (Destombes et al. 1985).

During the Silurian, the Sahara Craton drifted northwards, in combination with an ongoing clockwise rotation (Scotese 1997). The palaeozoic sea level was highest during the Silurian (Lüning et al. 2000), with the consequence that shales with some limestone intercalations were deposited in the eastern Anti-Atlas. The first significant limestone deposition in the eastern Anti-Atlas occurred during the Ludlowian (*Orthoceras* limestones).

According to Scotese (1997), the northwestern edge of the African Craton reached latitudes between 50° south during the Early Devonian and 30° south during the Late Devonian. In Middle Devonian times (Fig. 2), the study area was located ca. at 40° S and was part of the shelf of the northwestern African Craton, bordered by the Rheic Ocean to the northwest (Scotese & McKerrow 1990, Scotese 1997). Climatic conditions are considered as "warm temperate" throughout the entire Devonian (Scotese 1997).

During the Early Devonian, mainly shales and marls with few intercalated pelagic limestones were deposited in the eastern Anti-Atlas. Beginning in the late Emsian, carbonate deposition prevailed and

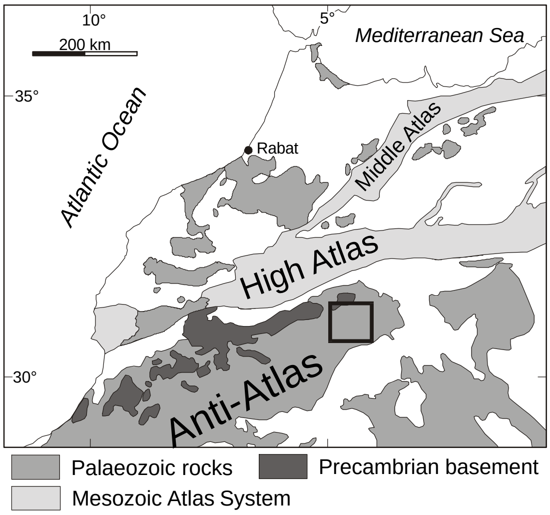

Fig. 1: Simplified geological map of Morocco with major structural units (modified from Piqué & Michard 1989). Box indicates location of the study area.

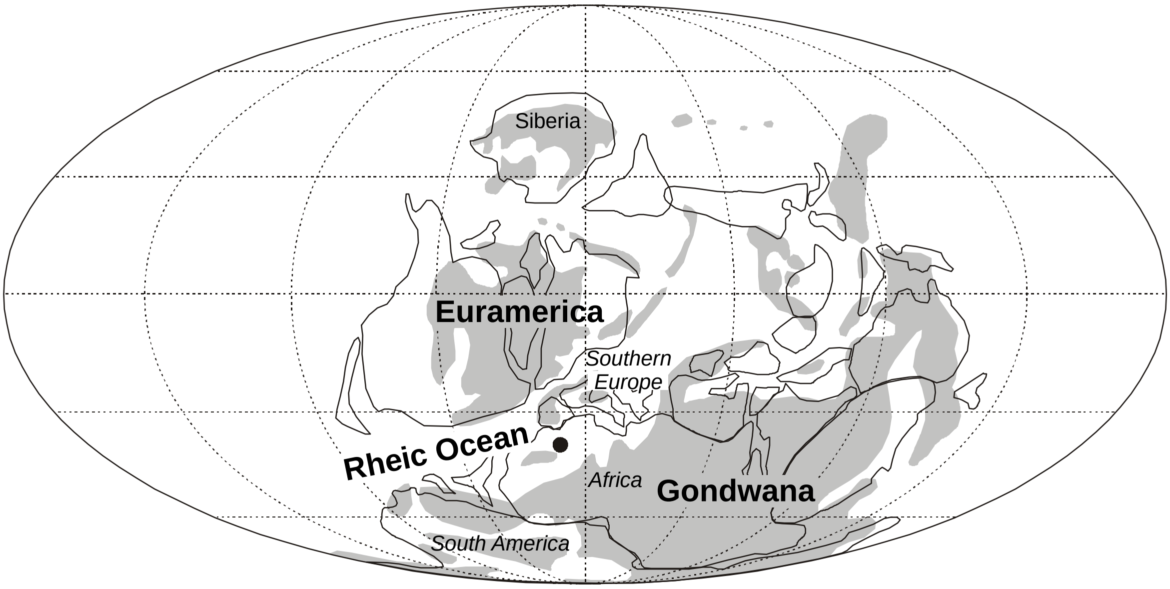

Fig. 2: Global palaeogeography during the Early Devonian (Emsian, 400 Ma) after Scotese (1997), black dot indicates the location of the eastern Anti-Atlas, light-grey shadings indicate land areas.

persisted until the late Famennian on the swell in the Tafilalt area (Tafilalt Platform *sensu* Wendt 1988) and until mid-Givetian in the shallower waters of the Mader (Mader Platform *sensu* Wendt 1988). Middle and Upper Devonian facies and thickness trends reveal a small-scale segmentation into basin and swells (Wendt et al. 1984, Wendt 1988). During the latest Famennian and early Tournaisian, the basin and swell topography was peneplaned by a thick succession of siliciclastic sediments (Wendt 1988).

Gondwana continued drifting northwards during the Carboniferous while continuously rotating clockwise (Scotese & McKerrow 1990, Neugebauer 1988). As a consequence of the Variscan convergence, the Rheic Ocean was closed during early Carboniferous to late Westphalian times (Scotese & McKerrow 1990). During the Variscan orogeny (Late Devonian - Late Carboniferous), the Anti-Atlas formed part of the cratonic domain of the Moroccan Variscides (Piqué et al. 1993) and thus was subject to minor folding and faulting.

Permian and most of Mesozoic times were characterised by terrestrial conditions in the Anti-Atlas. As a consequence of the Cenomanian transgression, shelf conditions established and the Anti-Atlas formed part of the southern Tethys. During the Tertiary, predominantly terrestrial sedimentation occurred on the northwestern African Craton. The collision between Africa and Iberia during the Alpine orogeny led to uplift of the Anti-Atlas from Pliocene to present which resulted in the exhumation of the Palaeozoic succession (Jacobshagen 1992).

2.2 Regional geological setting (Devonian - Carboniferous)

The oldest Devonian rocks (Lochkovian - Pragian) in the eastern Anti-Atlas consist mainly of shales and marls with thin limestone intercalations (e.g *Scyphocrinites* limestones). Emsian pelagic limestones ("Emsien calcaire" *sensu* Massa 1965, Emsian limestones) are the oldest Devonian carbonates with a continuous outcrop in the Mader. They are overlain by shales and marls with minor intercalations of limestones and siltstones ("Emsien argilo-silteux" *sensu* Massa 1965, Emsian shales). Apart from thickness variations, (Figs. 3a, 19) only minor differences with respect to facies are visible in the Emsian limestones. The thickness of these strata together with the overlying shales varies between total absence in the westernmost and 200 m in the northwestern Mader (Fig. 3a). The isopach map of the Emsian shales shows a NW-SE oriented depocentre (Fig. 19b) which corresponds well with the palaeogeographic pattern of younger strata (Figs. 3b, 4) thus suggesting a tectonic control of the stratal pattern. According to Massa (1965), the sedimentological evolution during the Emsian in the Mader reflects an intracratonic basin setting.

During the late Emsian and the Middle Devonian, most of the Mader was dominated by limestone deposition. This stratigraphic interval is the main subject of the study and is discussed in detail in the following chapters. Thickness varies considerably (Fig. 3b) between total absence in the southwestern (Mader Platform *sensu* Wendt 1988) and more than

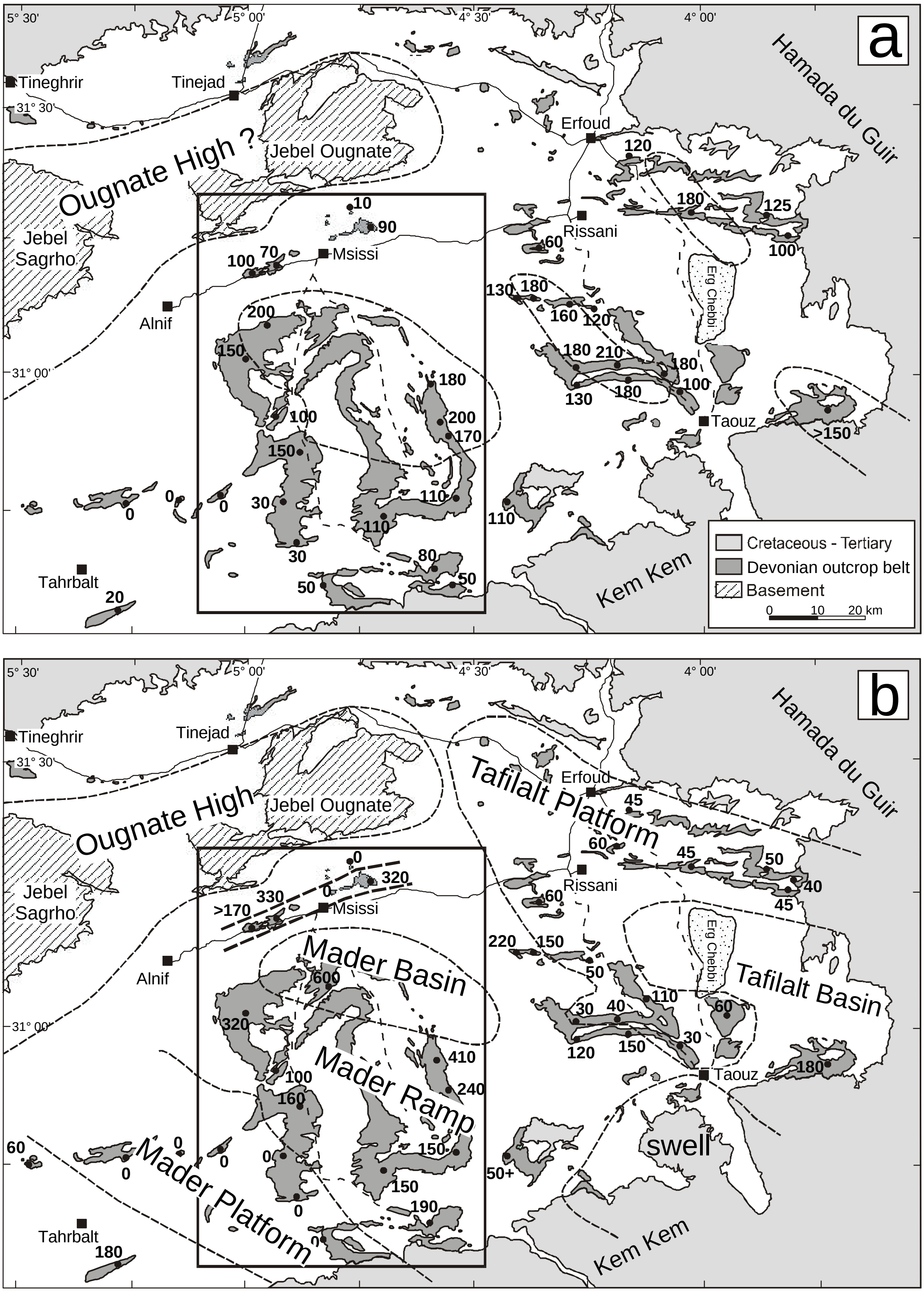

Fig. 3: Geological sketch maps of the eastern Anti-Atlas showing the Devonian outcrop belt, thickness of Emsian deposits (a) and thickness and palaeogeographic units of the Middle Devonian (b). Map compiled after Fetah et al. (1986, 1988), Kaufmann (1998), Wendt (1988) and own investigations. Dashed lines indicate palaeogeographic boundaries (b) and the extent of depocentres (a). Box indicates study area, for legend of (b) see (a).

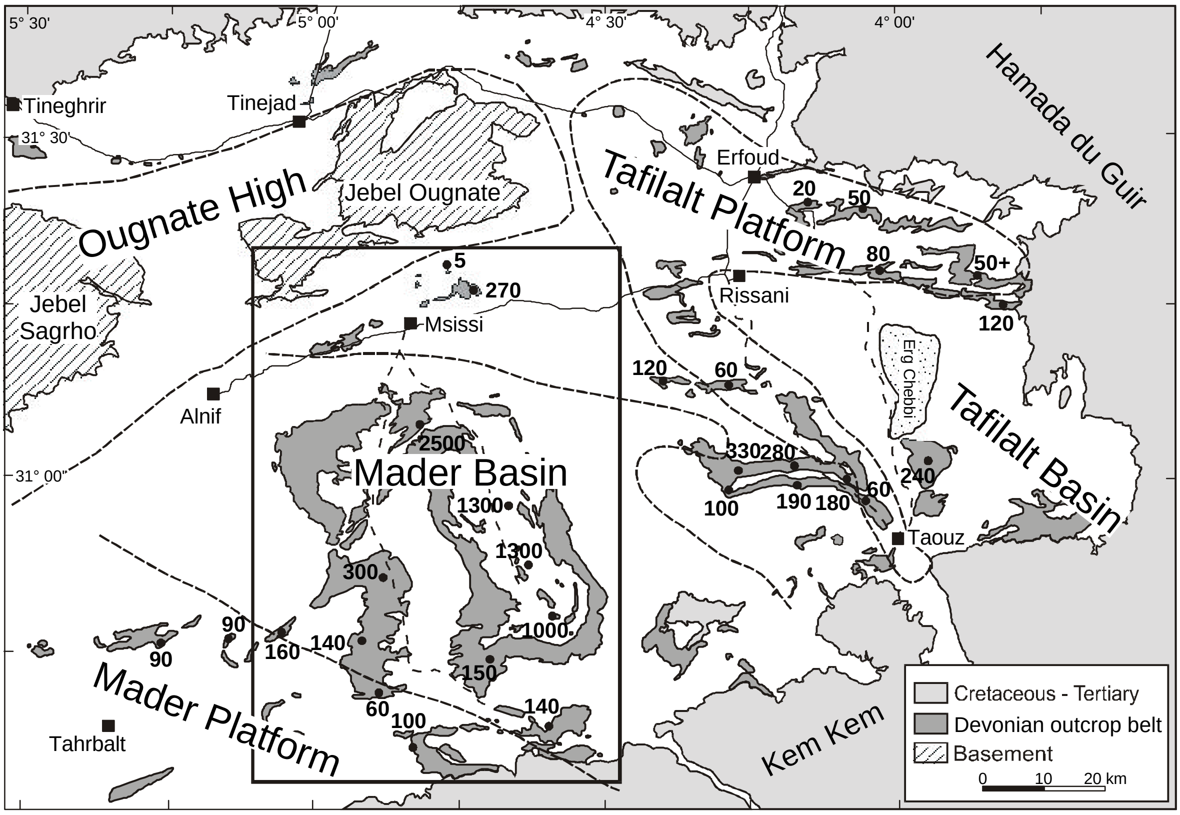

Fig. 4: Geological sketch map of the eastern Anti-Atlas showing the Devonian outcrop belt, thickness of upper Givetian to uppermost Famennian strata and palaeogeographic units. Map compiled after Fetah et al. (1986, 1988), Kaufmann (1998), Wendt (1988) and own investigations. Dashed lines indicate palaeogeographic boundaries, box indicates study area.

600 m in the northern Mader (Mader Basin *sensu* Wendt 1988). A great variety of rocks comprising shales, nodular limestones, reefal limestones, calcareous tempestites, and turbidites were accumulated during this time (Döring & Kazmierczak 2001). Simultaneously, various carbonate mud mounds were established (Kaufmann 1998). Own investigations and the work of Wendt (1993) and Kaufmann (1998) prove, that by the early Eifelian a carbonate ramp morphology was established. According to Massa (1965), thickness variations and facies distribution of Eifelian limestones indicate a relatively stable basin configuration. During the Givetian, reefal limestones, located at the margins of the Mader, contrast to thick outer-ramp and basinal deposits in the central and northern Mader (Wendt 1988). The Givetian facies pattern reflects a pronounced platform-basin topography which originated from local subsidence contrasts (Massa 1965). Upper Givetian rocks are exposed only in the northern Mader (Hollard 1974). Bultynck & Jacobs (1981) proved a late Givetian age for the lower part of the limestone marl alternations in the northern Mader (Bou Dib) where a complete Middle Devonian succession is represented.

According to Wendt (1988), the southwestern Mader was a palaeogeographic high during the Devonian (Figs. 3b, 4). Here, the Middle Devonian is completely absent and Frasnian shales and limestones directly overlie Emsian shales or older rocks. This hiatus was possibly caused by regional uplift and emersion of this area (Wendt 1988). A palaeosoil in the southwestern Mader (Rich Bel Ras) gives further evidence for a terrestrial phase during the Early and Middle Devonian (Massa 1965).

Upper Devonian deposits are only locally exposed in the Mader (Jebel Zireg, Madene El Mrakib, Bou Dib, Jebel Rheris) and consist predominantly of shales and marls with thin intercalations of resedimented limestones and siliciclastic turbidites. The thickness of the Upper Devonian succession varies between a few metres in the northernmost Mader (north of Jebel Rheris) to approximately 2500 m at Bou Dib, in the northern Mader (Fig. 4). These differences reflect the complex subsidence pattern which occurred during Late Devonian times as already mentioned by Wendt et al. (1984), Wendt (1988), and Wendt & Belka (1991).

In the southwestern Mader (Mader Platform *sensu* Wendt 1988), Frasnian sediments unconformably overlie strata of different age (late Emsian - early

Givetian). Farther to the west, an even larger hiatus is documented by Famennian rocks which unconformably overlie the Silurian (Massa 1965, Wendt 1988). At the Frasnian-Famennian transition, limestones and black shales of the "Kellwasser"-facies were deposited in almost the entire eastern Anti-Atlas (Wendt & Belka 1991). These deposits locally rest unconformably on older Devonian rocks. Regional uplift and tilting during the Late Devonian is best documented in the northernmost Mader (Jebel Rheris), where red-coloured conglomerates and sandstones (Massa 1965) erosively overlie limestone-marl alternations and reefal limestones. Locally, palaeokarst surfaces were developed which show neptunian dykes filled with red sediments (Fröhlich & Döring subm.).

In the adjacent Tafilalt area (Tafilalt Platform *sensu* Wendt 1988), the Late Devonian is represented by a condensed succession of cephalopod limestones (Wendt 1988). Differential subsidence produced a complex thickness and facies pattern during the deposition of the "Kellwasser" limestones (Wendt & Belka 1991). According to Wendt et al. (1984) and Wendt & Belka (1991), some of the Upper Devonian rocks can be interpreted as storm-influenced deposits which form distinct shallowing-upward cycles.

The uppermost Famennian - lower Carboniferous rocks of the eastern Anti-Atlas are poorly investigated. The predominantly siliciclastic successions, are interpreted as delta deposits (Wendt et al. 1984, Wendt 1988), similar to interpretations of coeval strata in the northern Tindouf Basin by Vos (1977). According to Wendt (1988), the deposition of these rocks peneplaned the pre-existing topography. Youngest Palaeozoic rocks consist of shales and limestones which crop out in the southeastern Tafilalt area. These successions contain ammonoids of Viséan to early Namurian age (Korn et al. 1999, Wendt et al. 2001).

3 DATABASE AND METHODS

3.1 Stratigraphic sections

Sedimentologic and stratigraphic data from 15 sections in the Mader are the base for this study (Fig. 5, Tab. 1). These are shown in appendix 1-20 including field and thin section data. Most sections contain strata ranging from lower Emsian to lower Givetian; seven sections comprise a stratigraphic range from lower Emsian to uppermost Famennian. Thickness of lower Emsian to Givetian strata extends from 120 m in the southern (Jebel Kem) to 350 m in the northern Mader (Boulchral-1). Lower Emsian and Upper Devonian strata are not included in the sequence stratigraphic framework of this study and are not illustrated in the appendix.

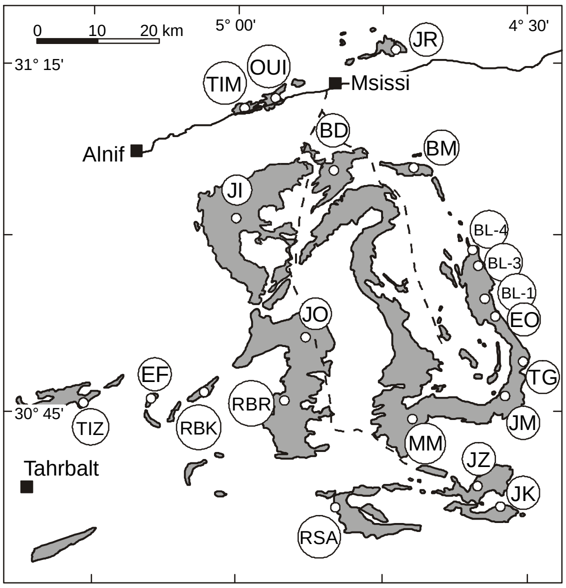

Fig. 5: Map of the Mader showing the Devonian outcrop belt (shaded) and the location of studied sections. Sections BM, RBR, RBK, EF, TIZ, and RSA are not part of the sequence stratigraphic study. (JR: Jebel Rheris, OUI: Ouihlane, TIM: Timerzit, BD: Bou Dib, JI: Jebel Issoumour, JO: Jebel Oufatène, BM: Bou Makhlouf, BL: Jebel Boulchral, EO: Jebel El Otfal, TG: Tizi N'Guidou, JM: Jebel Maharch, MM: Madène El Mrakib, JZ: Jebel Zireg, JK: Jebel Kem, RSA: Rich Sidi Ali, RBR: Rich Bel Ras, RBK: Rich Bou Kerzia, EF: El Fecht, TIZ: Tizoulla).

3.2 Thin section analysis and charting

300 samples were collected from upper Emsian to lower Givetian strata (Tab. 1) for a detailed microfacies study. Field observations and the results from thin section analysis led to the recognition of various lithofacies which were interpreted in terms of their palaeoenvironment (Chap. 4). Quantities of components, texture, average grain size, and maximum grain size were charted along the stratigraphic sections to elucidate vertical sedimentological and biological changes (Appendix 1-20). Relative component quantities were classified as low, medium, high and rock forming and are displayed by grey circles with varying diameters. Occurrences of components recorded during section logging are displayed by black bars with varying width. Components were subdivided into three groups: (1) non-skeletal components including detritic quartz, lithoclasts and peloids; (2) skeletal components with a wide environmental significance as crinoids and undifferentiated bioclasts; (3) skeletal components with a narrow environmental significance including stromatoporoids, tabulate and rugose corals, bryozoans, brachiopods, molluscs, trilobites, and dacryoconarids. Calcimicrobes and other microbial remains are restricted to the lower to middle Givetian and were

Section	Thickness of the studied stratigraphic interval (lower Emsian - lower Givetian)	Thickness of Upper Devonian strata	Number of rock samples
Jebel Kem (JK)	120 m	not preserved	35
Jebel Zireg (JZ)	200 m	min. 50 m (probably 100 m)	17
Madène El Mrakib (MM)	150 m	180 m	32
Jebel Oufatène (JO)	160 m	not studied	14
Jebel Issoumour (JI)	150 m (Givetian not included)	not studied	16
Jebel Maharch (JM)	150 m	not exposed	21
Tizi N`Guidou (TG)	100 m	not exposed	24
Jebel El Otfal (EO)	170 m (upper Emsian not included)	not exposed	14
Jebel Boulchral (BL-1)	350 m	not exposed	27
Jebel Boulchral (BL-3)	350 m	not exposed	16
Jebel Boulchral (BL-4)	350 m	not exposed	10
Bou Dib (BD)	360 m (Givetian - lower Frasnian)	ca. 1200 m	24
Timerzit (TIM)	170 m	not preserved	8
Ouihlane (OUI)	320 m	not preserved	16
Jebel Rheris (JR)	350 m	250 m	26

Tab. 1: Compilation of thickness data from the studied sections of the Mader.

not charted in the lithologs. Ammonoids are shown if they were determinable and of biostratigraphical value.

3.3 Stratigraphy

The low content of biostratigraphically relevant fossils and the often homogenous composition of the Devonian successions in the Mader, require an integrated stratigraphic approach comprising physical (sequence stratigraphy, lithostratigraphy) and biological parameters (biostratigraphy). Accordingly, the regional stratigraphic framework of this study is based on the following elements: (1) sequence stratigraphy and baselevel approach (VAIL et al. 1977, CROSS & LESSENGER 1998), (2) lithostratigraphy, and (3) biostratigraphy. They are briefly described below with an emphasis on the baselevel approach which represents the main stratigraphic tool of the study. Correlation according to the baselevel approach and under consideration of litho- and biostratigraphy, enables the establishment of genetic sequences which are termed depophases within this study (Chap. 5). Geometry, facies relationships, and stacking of respective depophases were subsequently interpreted in terms of classical sequence stratigraphy (VAIL et al. 1977).

3.3.1 Sequence stratigraphy

3.3.1.1 Stratigraphic baselevel

The concept of stratigraphic baselevel as applied by CROSS and others (e.g. SONNENFELD & CROSS 1993, HOMEWOOD 1996, CROSS & Lessenger 1998) offers a method of stratigraphic correlation based on physical criteria similar to sequence stratigraphy *sensu* VAIL et al. (1977). But in contrast to the approach of VAIL et al. (1977), baselevel changes instead of sea-level changes are defined as the controlling factor for the formation of genetic sequences.

Stratigraphic baselevel (WHEELER 1964) refers to an imaginary surface which separates an area of potential erosion (above) from an area of potential sediment accumulation (below). The position of the baselevel is governed by the accomodation/sediment-supply ratio (A/S). Accomodation is mainly affected by the position of the eustatic sea level and the magnitude of regional subsidence whereas sediment supply includes factors as climate or the denudation rate of the hinterland. Spatial and temporal fluctuations of the baselevel surface reflect changing A/S conditions. Accordingly, a baselevel fall is related to a decrease in A/S ratio whereas a baselevel rise indicates an increasing A/S ratio. The transitions from decreasing to increasing A/S conditions and vice versa, are called turnaround points or turnaround zones. The rise-to-fall turnaround point corresponds to the maximum flooding surface which is the clue for regional correlations in this study.

Dependent on the stratigraphic baselevel, the major portion of the sediment transported during a certain interval accumulates in a distinct geographic position along the depositional profile. Contemporaneously, much less sediment accumulates or erosion predominates in other positions. These relationships are termed "sediment volume partitioning" (Cross & Lessenger 1998). Sedimentary successions show various cycle symmetries dependant on their geographical position. In a depositional profile ranging from the tidal environment to the outer shelf, symmetrical and asymmetrical sedimentary cycles can be found (Fig. 6). In the tidal environment, the A/S ratio is well balanced resulting in a symmetric shape. In the shallow-marine environment, asymmetrical cycles with an overlying ravinement surface may develop. The baselevel rise is then recorded within the ravinement surface. On the open marine shelf, symmetrical cycles will predominate because accomodation and sediment supply are well balanced and minor erosion takes place on the sea floor. Asymmetrical fall cycles will develop on the outer shelf and in deeper marine settings where sediment arrives only during a baselevel fall. Baselevel rise is documented by a condensation surface or zone.

Since Devonian rocks of the study area were accumulated predominantly in subtidal and deep-marine environments (Kaufmann 1998), it can be expected that cycle symmetry is mostly symmetric and asymmetric (only fall hemicycle preserved) and cycles may show condensation features but mostly lack erosional surfaces (Fig. 6).

Different magnitudes of sedimentary cycles can be distinguished and form a hierarchy. The cycle hierarchy can be established according to depositional cycles (parasequences, sequences) as defined by Mitchum & Van Wagoner (1991). A major point of the stratigraphic analysis is the recognition of an "ideal cycle" which includes several facies elements and occurs repeatedly within a succession. The degree of preservation of single facies elements is the clue for the generation of higher-order cycles which may be present in adjacent sections with other "ideal cycles" of different depositional environments (e.g. Ramon & Cross subm.).

In this study it was not attempted to achieve the highest possible resolution of sedimentary cycles. Instead, only cycles which are recognisable on a regional scale were utilised. Considering the absolute time included in the studied stratigraphic interval (Fig. 7), regional correlateable cycles correspond approximately to macro-scale (3rd order) cycles of Mitchum & Van Wagoner (1991).

Recognition of macro-scale cycles was derived from the interpretation of vertical sedimentological and biological changes recorded during section logging and by thin section analysis (App. 1-20). The following criteria were used in order to interpret macro-scale sedimentary cycles in the studied sections:

- Carbonate/shale ratio: An increasing proportion of limestone beds indicates a baselevel fall thus reflecting higher carbonate productivity in favourable waterdepths. By contrast, an increasing

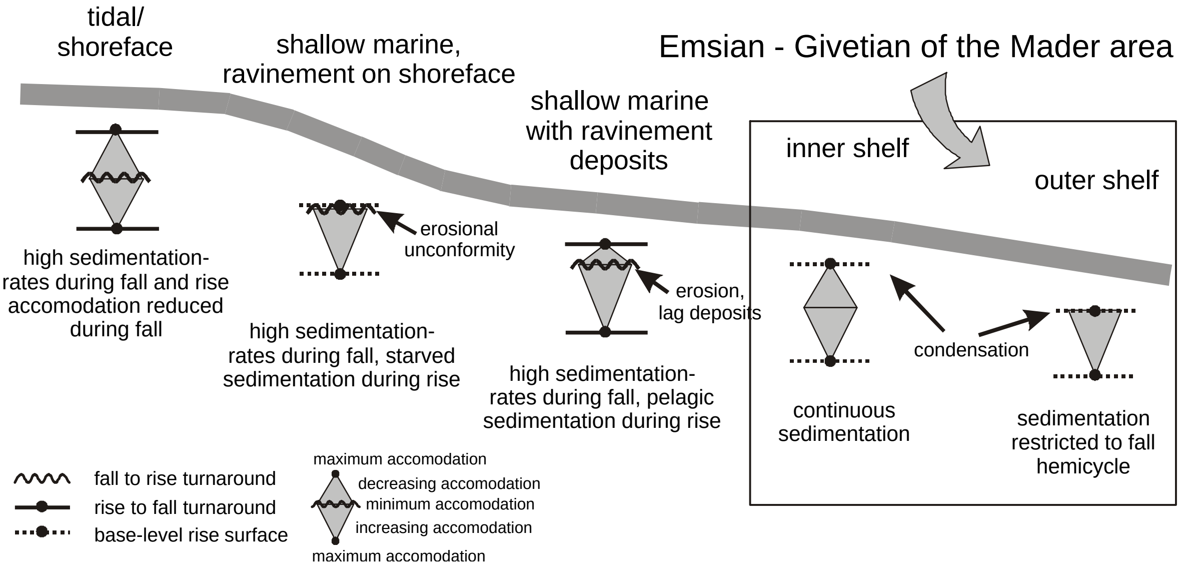

Fig. 6: Theoretical variations of baselevel cycle geometry and varying features of turnaround points along an idealised depositional profile (modified from Cross & Lessenger 1998).

proportion of shale beds is related to a baselevel rise which leads to landward shift of the carbonate factory and increasing pelagic sedimentation.

- Hydrodynamic energy: A change in texture according to the Dunham (1962) classification indicates increasing hydrodynamic energy and is related to a baselevel fall, whereas decreasing hydrodynamic energy indicates a baselevel rise.
- Facies changes: According to the interpretation of lithofacies types (Chap. 4) either falling or rising baselevel is reflected by vertical facies changes.
- Faunal assemblage: Increasing content of benthic elements (e.g., brachiopods, large corals, large stromatoporoids, accumulations of crinoids) indicates a baselevel fall, increasing abundance of planktonic and nektonic organisms (e.g. dacryoconarids, cephalopods) is related to a baselevel rise
- Diversity: Diversity of biogenic components may increase or decrease during a baselevel fall depending on the environment. Successions of crinoid limestones show decreasing diversity within a baselevel fall. In contrast, decreasing diversity within a succession of fine-grained, muddy limestones is interpreted to reflect a baselevel rise.
- Quartz content: Exceptionally high quartz contents (>10%) are interpreted to reflect a baselevel fall. Vertical variations of the quartz content within limestone successions containing less than 10% quartz, do not reflect reliable trends due to low sample density. Thus, these changes are not considered as diagnostic for the generation of sedimentary cycles but may support other indicators.

Usually only some of these criteria were available synchronously in the sections and only the combination with litho- and biostratigraphic data led to acceptable regional correlations. Some parts of the studied sections show very homogenous successions which do not show any of the above mentioned criteria (e.g. parts of the Boulchral, Timerzit, and Ouihlane sections) and were correlated only by litho- and biostratigraphy.

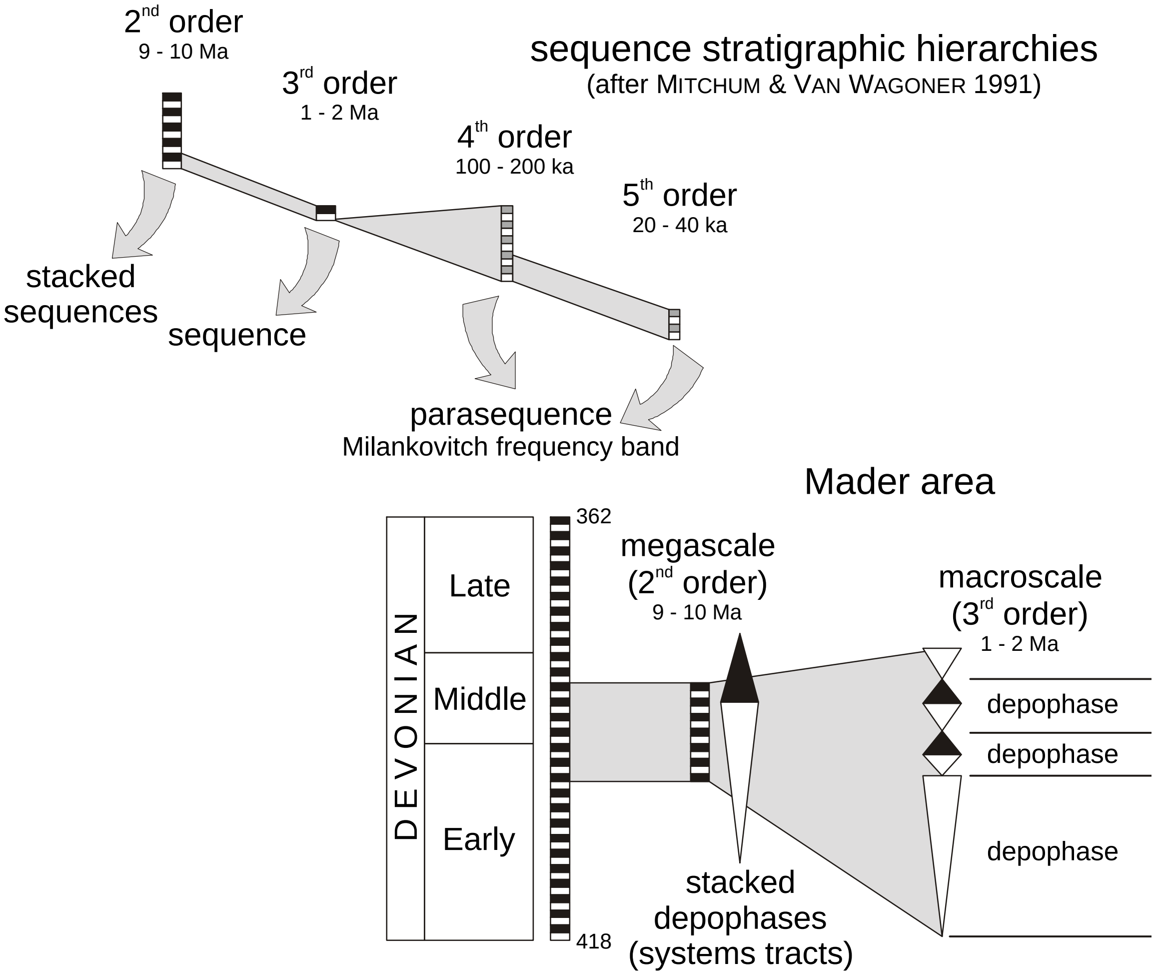

Fig. 7: Hierarchy of sedimentary cycles as defined by Mitchum & Van Wagoner (1991) and usage of terminology within this study. Absolute duration of the Devonian after Tucker et al. (1998).

3.3.1.2 Classical sequence stratigraphy

The concept of sequence stratigraphy was initially based on the recognition of correlateable surfaces which produce a significant response in seismic sections (Vail et al. 1977). Later, the concept was applied to outcrop studies (e.g. Elrick 1996) by mapping of erosional unconformities and condensation surfaces and by analysing outcrop geometries. The concept of classical sequence stratigraphy (Vail et al. 1977) was successfully applied to passive continental margins, especially to siliciclastic-dominated shelves where the above mentioned surfaces and geometries are well developed. It can be applied with some variations to carbonate systems as mentioned by Sarg (1988) and Schlager (1991). Features of respective systems tracts within carbonate depositional systems are briefly reviewed as follows:

Highstand systems tract (HST)

The stratal geometry of highstand deposits is regarded to be very similar in both the siliciclastic and the carbonate system. Carbonate production is very high under these conditions and consequently carbonate sediment may fills up the accomodation space created during the sea-level rise and show an aggradational stacking pattern (Schlager 1991). Subsequently, continuous carbonate accumulation will lead to progressive shallowing and may promote a prograding geometry. During a highstand, abundant platform material can be transported to the slope and the basin (highstand shedding *sensu* Schlager 1994).

Lowstand systems tract (LST)

During the lowstand systems tract, the carbonate factory is turned of or reduced to a very small area (James & Kendall 1992, Handford & Loucks 1993). Consequently, starved sedimentation will take place in the basinal areas. On emerged shelves, valleys may be incised during the LST. If siliciclastic material is available, it may be transported over the shelf and possibly spillover the shelf edge into the adjacent basin creating a lowstand wedge (Handford & Loucks 1993). In carbonate ramp settings, the carbonate factory may persist and only shifts basinwards (Handford & Loucks 1993, Burchette & Wright 1992). According to Betzler et al. (1999), calciturbidites with abraded non-skeletal platform material can also be deposited during lowstand conditions.

Transgressive systems tract (TST)

In the siliciclastic system, valleys which were incised during the foregoing LST are filled and the depocentre shifts landwards. The top of the TST is represented by a maximum flooding surface (mfs) or a maximum flooding zone (mfz). In the carbonate system, production starts during the TST after a certain lagtime. The carbonate factory is then able to produce thick sediment bodies showing a retrogradational stacking pattern (Handford & Loucks 1993). The lag time is due to adaptation of the organisms to the changed environmental conditions (start-up phase *sensu* Kendall & Schlager 1981). In a carbonate-ramp setting, the carbonate factory may only shifts landward during this phase (Burchette & Wright 1992). During transgression, shelf edges step back and tend to isolate slopes from sedimentation forming a sediment bypass zone (Handford & Loucks 1993).

3.3.2 Lithostratigraphy

Hollard (1974) and Massa (1965) established a stratigraphic framework for the Devonian of the eastern Anti-Atlas which formed the base for the subsequent geological maps (Fetah et al. 1986, 1988). Since lithology can vary significantly within several kilometres in the Mader, it is difficult to establish a reliable stratigraphic framework which is based on lithologic parameters only. Consequently, Hollard (1974) integrated biostratigraphic data in his stratigraphy. The result is a combined litho-/biostratigraphy which is often difficult to adapt in the field. Therefore, Hollard's(1974) stratigraphy (e.g. di, dm) was not integrated into this study. Nevertheless, biostratigraphic data from Hollard (1974) are a valuable contribution to the regional correlations and some units are excellent marker horizons (e.g. *Sellanarcestes* beds or di 4 of Hollard 1974). Lithostratigraphy is most helpful in the eastern, southern, and northwestern Mader where individual beds can be followed very well over long distances (Pl. 6, Figs. 1-3, 5). Especially in the Boulchral region certain beds or successions are easily recognisable in outcrop and on aerial photographs.

3.3.3 Biostratigraphy

In the majority of the sections, ammonoids are restricted to certain stratigraphic levels. Unfortunately, conodonts samples were almost barren within the whole study area, but some conodont data were adopted from other researchers (Massa 1965, Hollard 1974, Bultynck & Jacobs 1981, Bultynck 1985, and Kaufmann 1998). These data contribute to the stratigraphic framework but provide only a low resolution. Studies of Belka et al. (1997) and Klug (in press) carried out temporal lengths of conodont and ammonoid zones for the Devonian of the eastern Anti-Atlas. Their results allow to date genetic sequences with a higher precision. The investigations by Klug (in press) and Weddige (1996) help to combine ammonoid data with the Devonian conodont zonation.

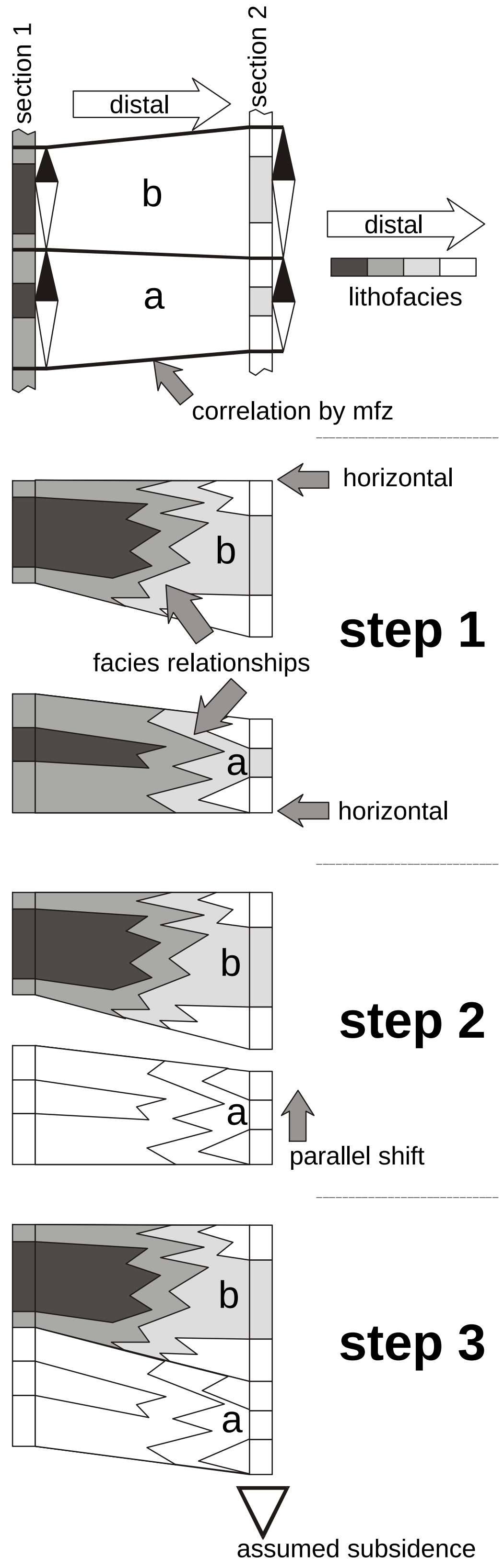

Fig. 8: Cartoon showing methodical steps for the reconstruction of stratigraphic geometry. For further explanation refer to text.

3.4 Reconstruction of the depositional geometry and facies relationships

Most researchers who focused on Devonian stratigraphy and facies in the eastern Anti-Atlas, presented correlations which do not consider depositional trends or distal-proximal relationships. Hollard (1974) and Massa (1965) were the first to present regional correlations of the Devonian in the eastern Anti-Atlas. Massa (1965) used the base of "Carboniferous" strata as reference horizon. He did not present a depositional model for the Devonian of the eastern Anti-Atlas even though he gave explanations in the text. Hollard (1974) displayed his sections without using a reference horizon (e.g. Hollard 1974, Fig. 2). Wendt (1988) used the base of the "Strunian" as a reference horizon for the correlation of his sections.

The present study provides a reconstruction of the depositional geometries of genetic sequences. According to the depositional trend derived from thickness data, SW-NE striking transect lines were constructed (Chap. 5, Fig. 17). Sections were projected into these lines in order to attain more accurate distances in between. For the reconstruction of the geometry of genetic sequences three steps were made which are described in the following:

step 1: reconstruction of the depositional geometry

The geometry of the genetic sequences (depophases) was reconstructed under the assumption that the lower and the upper maximum flooding zone (mfz) or turnaround zone of each cycle must necessarily be at least horizontal or slightly inclined towards distal environments (Fig. 8). This supposition considers a minimum accomodation, and consequently downgradient-dips derived from this reconstruction must be regarded as minimum values of the original depositional dips. Estimation of the palaeobathymetry is difficult because most of the rocks show only poor indicative features for water-depth estimation and the facies gradient in Devonian rocks of the Mader is usually very low. Consequently, the palaeo-water-depth was not considered for the reconstruction of the depositional geometry.

step 2: successive stacking of sequences

Cycles were successively stacked by moving underlying depositional units below the next younger unit and then adjusting the dips so that the youngest depositional unit always keeps its supposed geometry.

step 3: localisation of local subsidence

Locations where movements of the underlying strata in an upward or downward sense were made, are marked by arrowheads. These should not be regarded as indicators for absolute movements, rather they display relative vertical displacements between neighbouring localities.

4 LITHOFACIES AND PALAEOENVIRONMENT OF EMSIAN TO GIVETIAN ROCKS OF THE MADER

Upper Emsian to lower Givetian rocks were attributed to 11 lithofacies with further subdivisions (Fig. 9). Based on this, each lithofacies was interpreted in terms of palaeoenvironment. Lithofacies or lithofacies subtypes may show transitions to others, especially in fine-grained lithologies with a low fossil content. In contrast to sediments which were deposited on the inner to mid-ramp, sedimentary rocks of the outer ramp and the basin frequently comprise a broad spectrum of lithofacies which may occur in a single bed or a thin stratigraphic interval. Consequently, the term "lithofacies succession" often comprises several metres of strata with one predominating lithofacies.

4.1 Shales and marls (LF 1)

Rocks of this lithofacies occur in almost all investigated sections and in various stratigraphic positions. Usually they are very poor in fossils and apart from horizontal lamination, sedimentary structures are absent. Consequently, these intervals were not studied in detail and the palaeoenvironmental interpretation is derived from that of intercalated limestone and siltstone beds. Shales and marls can be interpreted in two ways concerning the relative sea-level fluctuations (compare 6.2): (1) as an indicator for a rising sea level leading to pelagic background sedimentation or (2) as an indicator for a lowering sea level that promotes increased input of fine-grained siliciclastic material (e.g. Van Wagoner et al. 1988). In this study, however, shales and marls are usually interpreted to reflect increasing or a high sea level.

4.2 Nodular limestones (LF 2)

In the entire Mader, nodular limestones occur in the upper Emsian and locally in younger strata. A massive or amalgamated facies (LF 2a) can be distinguished from another one which is composed of alternations of nodular limestones with marls (LF 2b).

4.2.1 Palaeoenvironment of lithofacies 2a, b

The occurrence of a high mud content, nodular bedding, and intense bioturbation in combination with partially thick marl/shale intercalations (Tab. 2) suggest a palaeoenvironment in the deeper subtidal, below the storm wave base. This calm environment was temporarily inhabited by dendroid (e.g. *Thamnopora*) and small domal tabulate corals (e.g. *Favosites*) or small solitary rugose corals. The majority of the beds show bioturbation and hence suggest a well-oxygenated sea floor with low sedimentation rates. Faint grading and parallel alignment of bioclasts indicate local bottom currents. Corals and brachiopods are more common in the southern Mader whereas trilobites, dacryoconarids, and cephalopods dominate the central and the northern part of the Mader. Reduced thickness in the northern sections in combination with trilobite-dacryoconarid-cephalopod assemblages suggest a deeper environment in the central and northern Mader. In contrast to the massive lithofacies LF 2a, the alternations (LF 2b) indicate a deeper palaeoenvironment. Minor thickness changes and the gradual facies transitions prove deposition on a relatively stable platform or a gently inclined ramp.

4.3 Micritic limestones and dolostones (LF 3)

Micritic limestones of lithofacies 3 were found predominantly in sections of the central and northern Mader in various stratigraphic positions; they may occur in association with other lithofacies (LF 4, LF 5, LF 9). Four different subfacies can be distinguished: Lithofacies 3a and b are very similar in composition but differ with respect to the proportion of marls which is higher in LF 3b successions (Tabs. 3, 4) Lithofacies 3c (Tab. 5) consists of partially laminated limestone-marl alternations which occur only in the Boulchral area (El Otfal, Boulchral-1 - 4). Lithofacies 3d comprises dolomitised rocks with scarce skeletal grains (Tab. 6). They were assigned to lithofacies 3 based on descriptive criteria, even though the palaeoenvironment interpretation may differ significantly from other LF 3 rocks.

4.3.1 Palaeoenvironment of lithofacies 3a

The scarcity of sedimentary structures, the low fossil content, the absence of non-skeletal material, and bioturbation (Tab. 3) suggest deposition in a low-energy environment, below the storm wave base within the deep subtidal. Intense burrowing (Pl. 1, Fig. 1) indicates a well-oxygenated sea floor and relatively low sedimentation rates. Benthic fauna was dominated by rugose corals, trilobites, brachiopods and very rare dendroid tabulate corals. Sessile organisms inhabited the muddy sea floor as indicated by the clumpy accumulations of skeletal material. Locally, increased quartz content (El Otfal section) reflects siliciclastic input.

4.3.2 Palaeoenvironment of lithofacies 3b

The high micrite content, scarce biogenic remains, bioturbation, and intercalated marls (Tab. 4) indicate deposition below the storm wave base in a calm, deep subtidal environment which was well oxygenated. The scarce benthos was dominated by crinoids, small corals, and trilobites. Planktonic and nektonic organisms are represented by dacryoconarids and cephalopods. The environment of lithofacies 3b contrasts to the LF 3a environment by the

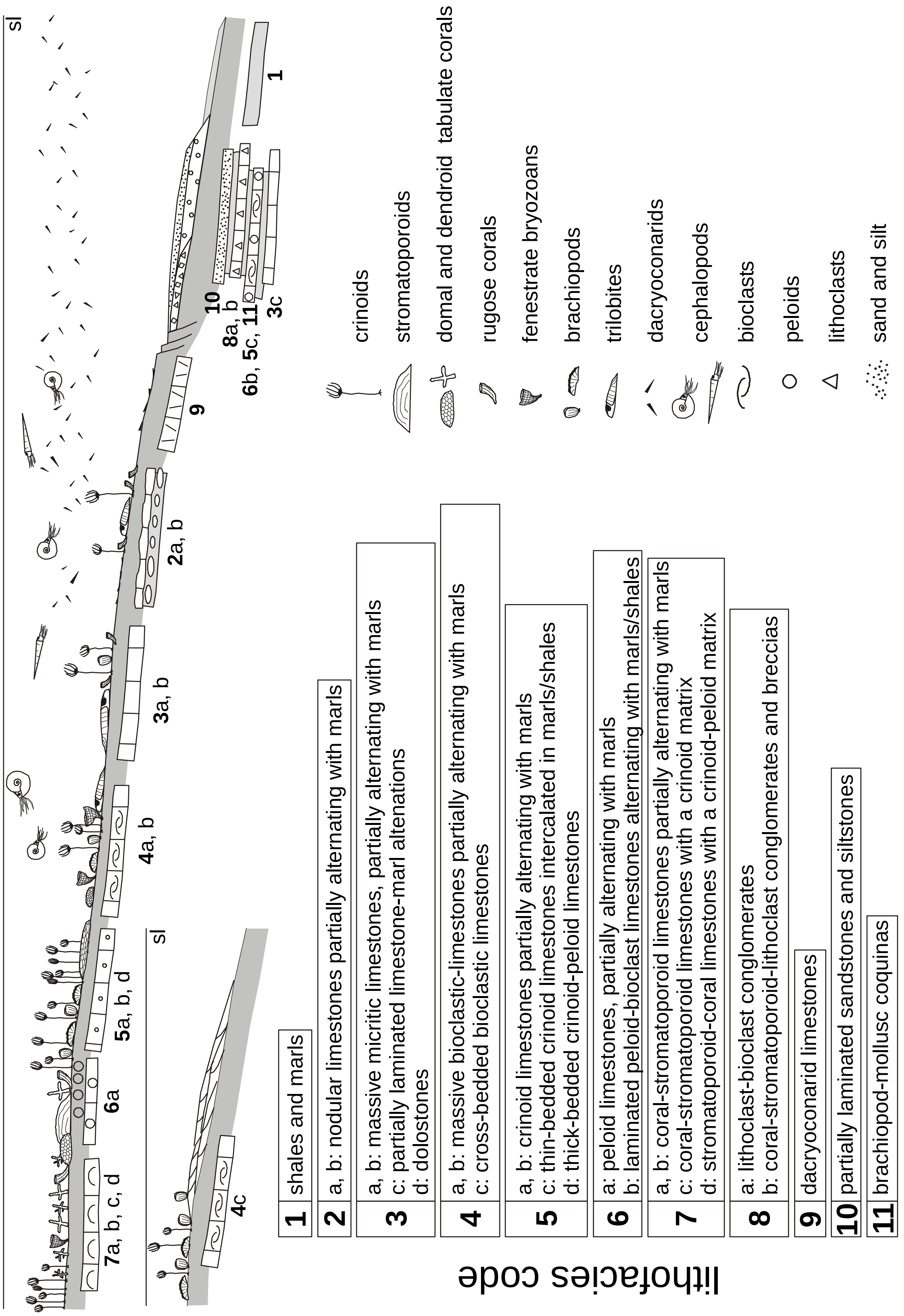

Fig. 9: Composite facies model for the lithofacies of the Emsian to Givetian rocks of the Mader (not to scale). The model also shows the faunal composition within individual facies belts and the lithology signatures used in the stratigraphic sections.

Nodular limestones (LF 2a, b)		
appearance in the outcrop	**texture (Pl. 1, Fig. 2)**	**sedimentary structures**
- nodular limestones - thickening-upward successions (JI, JM, TG, BL-1) - chert nodules	- wackestones and mudstones (locally packstones with abundant bioclasts and crinoids) - similar to LF 3a rocks	- poor to very poor sort - partially concordantly oriented bioclasts - faint grading (MM, TG, JO, BL-1)
skeletal components (Pl. 1, Fig. 2)	**bioturbation (Pl. 1, Fig. 2)**	**non-skeletal components**
- very fine-grained bioclasts - crinoids, rugose and tabulate corals, brachiopods, trilobites, and dacryoconarids - dendroid tabulate corals and large trilobites (TG) - corals and bryozoans (BL-1)	- bioturbation common - *Planolites* (Pl. 1, Fig. 1)	- very fine-grained bioclasts - crinoids, rugose and tabulate corals, brachiopods, trilobites, and dacryoconarids - dendroid tabulate corals and large trilobites (TG) - corals and bryozoans (BL-1)
thickness	**stratigraphic occurrence**	**geographic distribution**
- LF 2a: usually 10 - 15 m, few metres in northern Mader (TIM, OUI, JR) - LF 2b: around 30 m in the central Mader	- Emsian (*serotinus* - *patulus* Zone) - lower Eifelian at JK (*patulus* - lower part of *costatus* Zone)	- entire Mader

Tab. 2: Major characteristics of lithofacies 2a and 2b (abbreviations as in Fig. 5).

Massive micritic limestones (LF 3a)		
appearance in the outcrop	**texture**	**sedimentary structures**
- massive, bioturbated limestones - thickening-upward successions (BL-1, EO)	- mudstones (EO, BL-1), wackestones (OUI)	- massive, structureless - partially faint grading
skeletal components	**bioturbation (Pl. 1, Fig.1)**	**non-skeletal components**
- fine-grained bioclasts, small rugose corals, trilobites, and very rare cephalopods - cm- to dm-sized clumps with small rugose corals and trilobites	- common to absent - often *Planolites*	- usually absent - max. 5-10% detritic quartz at EO
thickness	**stratigraphic occurrence**	**geographic distribution**
- 70 m (BL-1) - 20 m (EO), LF 4a intercalated	- upper Emsian (*serotinus* Zone) - lower Eifelian (*costatus* Zone) at EO, BL-1 - upper Emsian (*serotinus* - *patulus* Zone) at OUI, JO	- northern and western Mader (EO, BL-1, OUI, JO)

Tab. 3: Major characteristics of lithofacies 3a (abbreviations as in Fig. 5).

Limestone-marl alternations (LF 3b)		
appearance in the outcrop	**texture**	**sedimentary structures**
- massive, bioturbated limestones alternating with marls - well bedded - limestones several cm to several dm thick - marls several dm to m thick - frequently associated with	- mudstones and wackestones	- well to very well sorted - structureless, homogenous - locally horizontal lamination (EO, BL-1)
skeletal components	**bioturbation**	**non-skeletal components**
- crinoids, bioclasts, small tabulate and rugose corals, trilobites, and dacryoconarids - cephalopod beds intercalated at BL sections	- very common - *Chondrites* (TIM), *Planolites* (BL-3) and *Zoophycos* (BL-1)	- absent - detritic quartz with higher values at EO and BL (2 - 10%) - locally peloids (EO)
thickness	**stratigraphic occurrence**	**geographic distribution**
- between 15 m (JZ) and 50 m (BL-4, BL-3)	- upper Emsian (*serotinus* Zone) at BL-1 - uppermost Emsian to lower Eifelian (*patulus* - *costatus* Zone) at EO, BL-1, 3, 4, OUI, and TIM - lower Eifelian (*costatus* Zone) at JZ	- northern Mader (EO, BL-1, BL-3, BL-4, TIM, OUI, JR) - southern Mader (JZ)

Tab. 4: Major characteristics of lithofacies 3b rocks (abbreviations as in Fig. 5).

Partially laminated limestone-marl alternations (LF 3c)		
appearance in the outcrop	**texture**	**sedimentary structures**
- limestone-marl alternations - limestone beds several cm to dm thick - marls several dm to several m thick - thickening-upward cycles at BL and EO sections	- mudstones, rare wackestones	- horizontal lamination present or absent - alternations of very fine shell debris with micrite in wackestones - very regular alternation of marls with limestones
skeletal components	**bioturbation**	**non-skeletal components**
- very scarce occurrences of crinoids, brachiopods, molluscs, trilobites, and dacryoconarids	- present to absent	- usually absent - up to 1% detritic quartz in some beds at the BL-1 section
thickness	**stratigraphic occurrence**	**geographic distribution**
- 20 (JR) to 120 m (BL-4)	- upper Eifelian (*kockelianus* Zone)	- northern Mader (EO, BL-1, 3, 4, TIM, OUI, JR)

Tab. 5: Major characteristics of lithofacies 3c rocks (abbreviations as in Fig. 5).

increased sedimentation of clay. Laminated rocks of this lithofacies may originate from turbidite sedimentation thus reflecting an increased off-shore transport whereas the massive limestones and the marls represent autochthonous sedimentation under calm conditions.

4.3.3 Palaeoenvironment of lithofacies 3c

The favourable outcrop conditions in the Boulchral area allow detailed logging of LF-3c successions. Any exposed bed was measured and thus vertical thickness variations and the fluctuations of the limestone-marl ratio can be plotted (Fig. 10). Highest limestone-marl ratios (0,7 - 0,8) were recognised in the lowermost limestone/marl couplets (numbers 1 - 30). Above these, the limestone-marl ratio decreases upward in every section. From the lateral variations of the limestone-marl ratio, it can be concluded that during the deposition of LF 3c successions the maximum limestone-marl ratio shifted from S to N (Fig. 10).

The very high content of marl/shale beds within these lithofacies successions and the micritic composition of the limestone beds (Tab. 5) suggest a deposition below storm wave base, in the deep subtidal. Horizontal lamination may indicate resedimentation processes although some limestone beds lack any sedimentary structures and are entirely composed of micrite and frequently show bioturbation. The micritic composition and the horizontal lamination may suggest a turbiditic origin of these limestone beds. Accordingly, the limestones can be classified as muddy calciturbidites (E1, E2, E3 units of Piper 1978 or Td, Te units of Bouma 1962) which were deposited in the outer-ramp or basin environment. Massive beds are assigned to the E2 and E3 units whereas laminated beds can be attributed to the E1 unit of Piper (1978). The thick marl/shale intervals represent both phases of pelagic background sedimentation and the late phase of mudturbidite accumulation (uppermost E3 unit or Te unit). Laterally and vertically varying bed thickness and limestone-marl ratio (Fig. 10) indicate fluctuating carbonate production in adjacent shallower environments or varying off-shore-transport energy which are both influenced by a fluctuating sea level. This led to progradation of the turbidite system during the deposition of the LF-3c succession.

According to Pittet et al. (2000), who examined Jurassic limestone-marl alternations, the formation of limestone-marl alternations can be explained by productivity cycles which are governed by the vari-

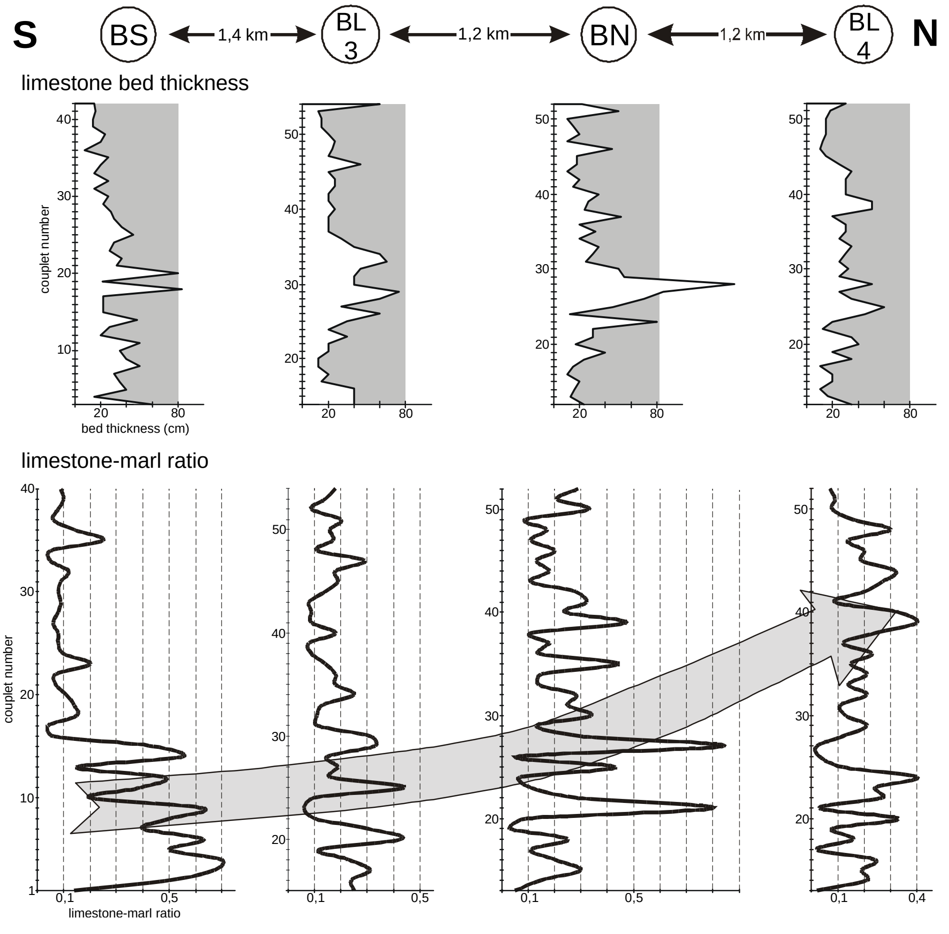

Fig. 10: Vertical and lateral variations of limestone bed thickness and limestone-marl ratio within the LF-3c succession in the Boulchral area (between Boulchral-1 and Boulchral-4). The grey-shaded arrow indicates the assumed progradation from S to N.

Dolostones (LF 3d)		
appearance in the outcrop	**texture / diagenetic features**	**sedimentary structures**
- yellowish to pale orange, massive dolostones	- obliterated by pervasive dolomitisation - chert nodules common	- massive
skeletal components	**bioturbation**	**non-skeletal components**
- rarely remains of larger (sand-sized) crinoid ossicles, brachiopods and tabulate corals	- burrows preserved in some beds at JZ	- max. 3-5 % detritic quartz
thickness	**stratigraphic occurrence**	**geographic distribution**
- 6 m (JK), 45 m (JZ)	- upper Emsian (*serotinus* Zone)	- southernmost Mader (JK, JZ)

Tab. 6: Major characteristics of lithofacies 3d (abbreviations as in Fig. 5).

Massive, bioclastic limestones (LF 4a)		
appearance in the outcrop	**texture / diagenetic features**	**sedimentary structures**
- well bedded, massive limestones - partially arranged in thickening upward successions - locally transitions from LF 4a to LF 5a (e.g. JI)	- wackestones and packstones - clumps with well-preserved macrofossils - occasionally cementation by syntaxial rim cements (JI) - chert nodules (EO, JO, JZ)	- inverse or normal grading common - rarely planar lamination (TG) - usually poor to very poor sorting - small-scale baselevel cycles: a) repeated reworking of bioclasts and mud during small-scale fall b) preservation of macrofossil assemblages during small-scale rise
skeletal components	**bioturbation**	**non-skeletal components**
- diverse bioclasts - dominated by crinoids, tabulate corals, bryozoans, brachiopods and trilobites	- common	- detritic quartz (0 - 2%) - exceptionally high quartz contents at MM (7%) - locally small peloids (JI)
thickness	**stratigraphic occurrence**	**geographic distribution**
3 m (BL-4) - 30 m (TG)	- uppermost Emsian (*serotinus* Zone) to lower Givetian (Lower *varcus* Zone) - large parts of *Sellanarcestes* marker bed (*serotinus* Zone)	- southern, western and parts of the northern Mader (BL-1, 3, 4, EO, JI, TG, JO, MM, JZ, JK)

Tab. 7: Major characteristics of lithofacies 4a (abbreviations as in Fig. 5).

ation of accomodation space and productivity of an adjacent platform or ramp area. Einsele & Ricken (1991) favour a carbonate dilution model. They state, that limestone-marl alternations originate from fluctuating siliciclastic input from an adjacent land area during stable carbonate accumulation.

The effects of diagenetic bedding which may have affected the lateral and vertical variations are not part of the present study. Accordingly, no further investigation of the composition of the limestones and marls (e.g. carbonate content and palynofacies) were attempted. Since the origin of the lime mud and the formation of the marl beds is not fully understood and the location of a land area is not known for the Mader, it appears difficult to assign the process that formed these limestone-marl alternations accurately.

4.3.4 Palaeoenvironment of lithofacies 3d

Strong diagenetic overprint caused poor preservation of components and texture (Tab. 6), and therefore an environmental interpretation is difficult. The quartz grains and the large crinoid remains suggest a close relation to rocks of lithofacies 5a. Stratigraphic considerations indicate a close relationship to coeval rocks of lithofacies 4c at the Jebel Kem section and lithofacies 5a at the Madene El Mrakib section (Chap. 5.2.2).

4.4 Bioclastic limestones (LF 4)

Rocks assigned to lithofacies 4 are characterised by their highly diverse skeletal components and a wackestone to packstone texture. Lithofacies 4 can be differentiated into a massive lithofacies (LF 4a, Tab. 7) which partially contains marly intercalations (LF 4b, Tab. 8) and a laminated (horizontal or cross-bedded) lithofacies (LF 4c, Tab. 9) which occurs exclusively in two sections (Jebel Kem, Jebel Issoumour) and is interpreted different with respect to palaeoenvironment.

4.4.1 Palaeoenvironment of lithofacies 4a

The high micrite content, the abundance of very fine-grained bioclastic material and bioturbation (Tab. 7) indicate a deposition in a calm, subtidal environ-

Bioclastic limestones alternating with marls (LF 4b)		
appearance in the outcrop	**texture / diagenetic features**	**sedimentary structures**
- limestone-marl alternations - grey to dark grey, well bedded, massive limestones - limestones 5 - 20 cm thick - marls several cm to 2 m thick - associated with crinoid limestones of LF 5b at JM and JO	- wackestones and packstones	- massive - poor to very poor sorted - occasionally inverse or normal grading (JK, MM, JO, JI, JM) - large components floating in a fine-grained matrix (BD, BL-1)
skeletal components	**bioturbation**	**non-skeletal components**
- diverse - predominantly unidentifiable bioclasts, crinoids and bryozoans - tabulate corals, brachiopods, and trilobites - abundant fenestrate bryozoans (JM, JO, MM, JZ, JK)	- usually present - *Planolites* at JZ - intense bioturbation at JK	- detritic quartz (usually 1 - 3%) - peloids in several beds at JI, JO, JM
thickness	**stratigraphic occurrence**	**geographic distribution**
- between several m at TG and BL-1 and 25 m (JK)	- upper Emsian (*serotinus* Zone) at BL-1, JZ - lower Eifelian (*costatus* Zone) at JI, JO, JM, MM - lower Givetian (Lower *varcus* Zone) at JK	- southern, western and parts of the northern Mader (JK, JZ, MM, JM, TG, JO, JI, BL-1)

Tab. 8: Major characteristics of lithofacies 4b (abbreviations as in Fig. 5)

ment below the storm wave base under well-oxygenated conditions. The diverse spectrum of bioclasts and the partially large remains of skeletal material indicate that the muddy sea-floor was temporarily inhabited by crinoids, small tabulate corals, and fenestrate bryozoans. Laminated and graded beds provide evidence for bottom currents which repeatedly reworked the patchy settlements. Probably, strong bioturbation fragmented the bioclastic material additionally. Transition towards lithofacies 5a suggests that lithofacies 4a is a distal equivalent of lithofacies 5a (Fig. 12).

4.4.2 Palaeoenvironment of lithofacies 4b

The high faunal diversity, inverse and normal grading, and the mud content (Tab. 8) indicate a deposition below the storm wave base in the subtidal. Although temporarily bottom currents occurred, as shown by the normal and inverse graded beds, evidence for winnowing was not observed in these rocks. Temporary deep-marine background sedimentation is reflected by the marly interbeds. Marls and argillaceous limestones of early Givetian age at the Jebel Kem section, are interpreted to have originated from locally-increased siliciclastic input. Large parts of the southern Mader (Jebel Oufatene, Jebel Maharch, Madene El Mrakib, Jebel Kem) were obviously temporarily inhabited by fenestrate bryozoans and corals. Transition of LF 4a, b to LF 5a, b indicates the close genetic relationship between these lithofacies. As shown in Fig. 12, the environment of LF 4a, b was situated slightly distally with respect to the crinoid-limestone facies (LF 5a, b). KELLER (1988) described rocks with similar compositions from the Lower Devonian of the Cantabrian Mountains and interpreted them to represent a transitional facies between pelagic limestones and shallow-water crinoid limestones, which corroborates own interpretations. Following his suggestions, bryozoans acted as sediment binders and stabilised the sediment thus favouring colonisation by crinoids.

4.4.3 Palaeoenvironment of lithofacies 4c

Sedimentary structures (low-angle cross bedding, trough cross bedding, hummocky-cross stratification) and the lenticular bed shape at Jebel Kem and Jebel Issoumour (Tab. 9) prove permanent bottom currents which may have originated from tempests (Fig. 11). The isolated occurrence of this lithofacies suggests that these rocks were deposited in a relatively narrow facies belt. The LF-4c environment at Jebel Issoumour may represent a distal equivalent of those at Jebel Kem as shown in Fig. 11. The low diverse faunal community in the shallower areas

Cross-bedded bioclastic limestones (LF 4c)		
appearance in the outcrop	**texture**	**sedimentary structures (Fig. 11)**
- yellowish to pale grey limestones - well-bedded, massive and laminated - conspicuous wedge-shaped beds - minor marl intercalations at JI	- wackestones and packstones	- lenticular and horizontal bedforms - horizontal lamination - trough cross bedding - low-angle cross bedding (HCS) - coarse lithoclast layers at JK
skeletal components (Pl. 1, Fig. 5)	**bioturbation**	**non-skeletal components (Pl. 1, Fig. 5)**
- fine-grained bioclastic material, brachiopod fragments (JK) - crinoids, bryozoans, brachiopods (JI)	- very rare	- highly abundant detritic quartz (1 - 15%) at JK - dark mm- to cm-sized flat, well-rounded lithoclasts (JK) - very low (0 - 1%) quartz content, lithoclasts absent at JI
thickness	**stratigraphic occurrence**	**geographic distribution**
- 15 m at JK and JI	- upper Emsian (*serotinus* Zone) at JK - upper Emsian - lower Eifelian (*patulus* - lower part of the *costatus* Zone) at JI	- exclusively at JI and JK

Tab. 9: Major characteristics of lithofacies 4c (abbreviations as in Fig. 5).

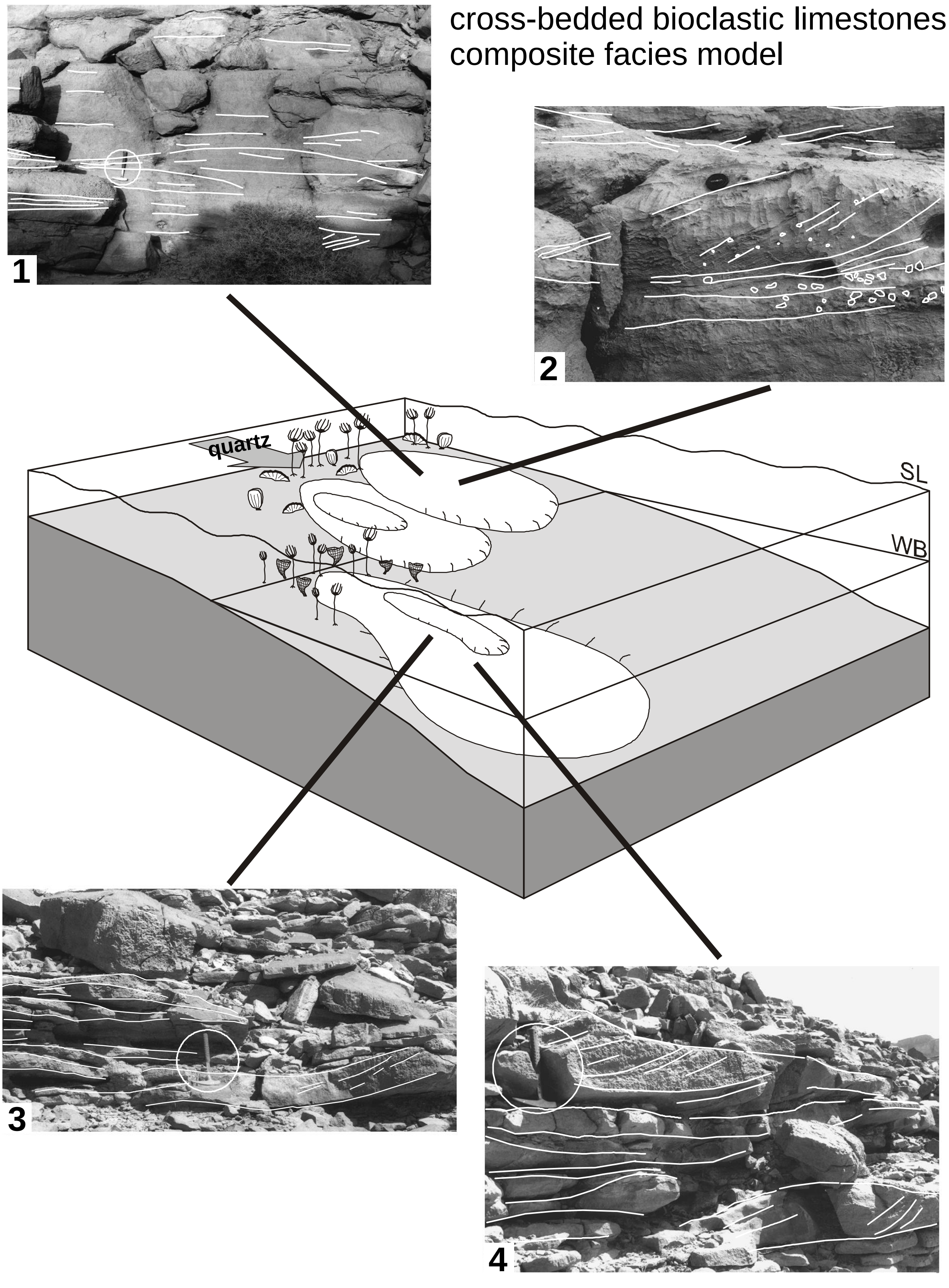

Fig. 11: Composite facies model for cross-bedded bioclastic limestones (LF 4c). The proximal environments are characterised by amalgamated limestone beds whereas in distal areas marl intercalations are common. Additionally, the composition changes from bioclast-quartz-dominated rocks with intraclasts (1, 2) to crinoid-bryozoan-dominated rocks without non-skeletal components (3, 4). The wave base was situated probably between these two environments and migrated temporarily up and down.

(Jebel Kem) which consists almost entirely of small brachiopods and crinoids is probably a result of the relatively high siliciclastic input. Parts of the sea floor in the deeper environments (At Jebel Issoumour) were inhabited predominantly by crinoids and fenestrate bryozoans. From the above described features it can be concluded, that the LF-4c succession at Jebel Kem represents one of the shallowest environments during the Early and the Middle Devonian of the Mader. At this locality, sediments were deposited mostly above the storm wave base whereas at Jebel Issoumour, the palaeoenvironment was only temporarily above the storm wave base. Nevertheless, the LF 4c succession at the Jebel Issoumour section represents one of the shallowest environments at this locality.

4.5 Crinoid limestones (LF 5)

Crinoid limestones of lithofacies 5 consist predominantly of packstones and grainstones with abundant bryozoans and several other skeletal components or microbial/peloidal material. While lithofacies 5a and 5b (Tab. 10) contain detritic quartz (1-5%), rocks attributed to LF 5c (Tab. 11) and 5d (Tab. 12) are lacking detritic quartz. The two latter lithofacies were found exclusively in Givetian rocks of the northernmost Mader (Ouihlane, Jebel Rheris) and contain abundant microbial remains and micritic envelopes.

4.5.1 Palaeoenvironment of lithofacies 5a, b

The crinoid limestones (LF 5a, b) contribute the major volume to the upper Emsian to Eifelian carbonate ramp of the Mader (Tab. 10). Crinoids and brachiopods frequently inhabited the sea floor and were repeatedly reworked by bottom currents; larger remains were accumulated in conspicuous clumps or sheets (Fig. 12; Pl. 2, Fig.2). Regionally, bottom currents were relatively constant and strong enough to winnow the lime mud thus forming graded beds. Possibly these currents were induced by stormwaves although typical bedforms are rare. Evidence for wave-currents, however, is reflected by the edgewise shell accumulations at Jebel Kem (Fig. 12). Other current-deduced bedforms are found at Jebel Issoumour where small channels (Fig. 12) are interpreted to have originated from storm activity (gutter casts). Coated grains and stromatoporoids in the Madene El Mrakib section (Pl. 1, Fig. 6), indicate temporarily shallow water depths. At the Jebel El Otfal, rocks of this lithofacies formed the substrate for carbonate mud mounds (Kaufmann 1998).

Intercalated marls reflect increased pelagic background sedimentation and restricted conditions for limestone sedimentation. Large, domal colonial tabulate corals (Fig. 12) within these alternations may indicate prolonged exposure and surface corrosion (compare Speyer & Brett 1991). In contrast to the grainstones, limestones with higher micrite content are interpreted to have been deposited in slightly deeper environments below the storm wave base in the deeper subtidal zone (Fig. 12).

Rocks of LF 5a as well as rocks of LF 5b show small-scale sedimentary cycles in the order of several cm in individual limestone beds (Pl. 2, Figs. 1, 2). During baselevel fall, crinoids and other bioclasts were repeatedly reworked thus forming well-sorted, massive, and non-graded limestone beds. During baselevel rise, macrofauna accumulations experienced less fragmentation and were preserved as clumps, patches or layers (Pl. 2, Fig. 2). These were subsequently overlain by shales. Therefore it can be concluded, that the major proportion of the limestone beds reflects baselevel-fall conditions, whereas the macrofossil accumulations and the marl/shale intervals indicate the subsequent baselevel rise.

4.5.2 Palaeoenvironment of lithofacies 5c

In contrast to other crinoid limestones, these were deposited in a deep subtidal environment as indicated by the thick marly interbeds with limestone nodules (Tab. 11). Grading, lamination, and the scarce bioturbation provide evidence for rapid deposition while the thick marly interbeds with limestone nodules suggest a distal marine environment. Two interpretations are possible: (1) calciturbidites (Ta unit of Eberli 1991, 1a unit of Meischner 1964) or (2) distal tempestites. The high abundance of calcimicrobes and algal lumps give evidence for shedding during a sea-level highstand *sensu* Schlager (1994). The material was shed from a northerly located platform area as indicated by the very similar composition of coeval rocks (LF 5d) ca. 15 km WNW at Jebel Rheris (Fig. 15).

4.5.3 Palaeoenvironment of lithofacies 5d

Beds of lithofacies 5d (Tab. 12) at the Jebel Rheris section alternate with reefal limestones of lithofacies LF 7d (Fig. 14). Towards the NW, the thickness of this stratigraphic interval decreases and reefal facies predominates coeval successions (Fröhlich & Döring subm.). These facies relationships in combination with the occurrence of slumping structures, indicate a shallow slope environment with stromatoporoid-coral patch reefs and crinoid thickets (Fig. 14). Patch reefs as well as crinoid thickets were repeatedly subject to reworking by storms. Micritisation and the abundance of microbial remains suggest that the environment was situated within the photic zone. The dominance of crinoids may reflect deposition in a slightly deeper setting than the coeval stromatoporoid-coral limestones (LF 7d). Horizontal lamination, grading and local gutter casts provide evidence for an interpretation as tempestites.

Crinoid limestones, partially alternating with marls (LF 5a, b)

appearance in the outcrop (Fig. 12)	**texture / diagenetic features**	**sedimentary structures (Pl. 2, Figs. 1, 2; Fig. 12)**
- well bedded limestones - frequently thickening-upward cycles - marly interbeds usually as thick as limestone beds - coquinas and cm- to dm-sized clumps with macrofossils - transitions towards lithofacies 4a and 4b	- packstones and grainstones - occasionally wackestones - micrite usually absent (LF 5a) - frequently cementation by syntaxial rim cements (LF 5a) - LF 5b limestones show mud-supported texture - dolostones usually contain chert nodules	- usually poor - to medium sorting - inverse and normal grading - occasionally horizontal lamination (TG, JO) - occasionally shell fragments oriented concordantly (JZ, MM, JI) - locally dm-sized channels (JM) - often coquinas or clumps with crinoids, brachiopods (e.g. *Atrypa* sp., *Rafinesquina* sp., Spiriferida) or corals - edgewise shell accumulations
skeletal components (Pl. 1, Figs. 6-8; Pl. 2, Fig. 1)	**bioturbation**	**non-skeletal components**
- rock-forming quantities of crinoids - frequently bryozoans - tabulate and rugose corals, brachiopods, and trilobites - dendroid tabulate corals in certain levels (TG) - dm to m-sized flat colonial tabulate corals *in situ* within limestones or marls (JM) - frequent auloporids at EO	- very rare - *Planolites* at JM	- detritic quartz (1 - 3%) - maximum quartz contents of 10%
thickness	**stratigraphic occurrence**	**geographic distribution**
- several metres (MM) - 60 m (JM)	- upper Emsian (*serotinus* Zone) - lower Eifelian (*costatus* Zone) at JK, JZ, MM, JM, TG, JI, JO - lower Eifelian (lower *costatus* Zone) at BL-1, EO	- southern, western and parts of the northern Mader (BL-1, EO, JI, JO, JM, TG, MM, JZ)

Tab. 10: Major characteristics of lithofacies 5a, b (abbreviations as in Fig. 5)

4.6 Peloid limestones (LF 6)

Two different types of peloid limestones (Tabs. 13, 14) can be distinguished in the Mader: (1) massive and laminated peloid limestones with minor marl intercalations (Jebel Zireg, Madene El Mrakib, Jebel Oufatene, Jebel Issoumour) and (2) thin bedded, laminated or massive peloid-bioclast limestones which are intercalated in thick shale/marl successions (Jebel El Otfal, Boulchral-1, 3, 4, Bou Dib, Ouihlane).

4.6.1 Palaeoenvironment of lithofacies 6a

The environment of lithofacies 6a was situated temporarily above the storm wave base, in the deeper subtidal as indicated by horizontal lamination, fine grain size, high mud content, and the fossil content (Tab. 13). Peloids are interpreted as very fine-grained mudstone clasts. Temporarily low sedimentation rates in a well-oxygenated environment are documented by strong bioturbation and the settling of small rugose corals on soft substrates in the southern Mader (Madene El Mrakib, Jebel Zireg). The limestone-marl alternations at Jebel Issoumour were accumulated in a slightly deeper setting as indicated by the higher proportion of shales.

4.6.2 Palaeoenvironment of lithofacies 6b

Sedimentary structures (hummocky-cross stratification, horizontal lamination), the lack of bioturbation, and the frequently erosional base in addition with

Thin-bedded crinoid limestones intercalated in marls/shales (LF 5c)		
appearance in the outcrop	**texture**	**sedimentary structures**
- limestone-marl alternations - limestone beds 10 - 30 cm thick - intercalated marls with limestone nodules several decimetres - 1 m thick	- packstones and grainstones - low micrite content	- well to poor sorting - partially graded - frequent horizontal lamination and mm-thick alternations of fine grained- with coarse-grained layers
skeletal components (Pl. 2, Fig. 5)	**bioturbation**	**non-skeletal components (Pl. 2, Fig. 5)**
- predominantly crinoids - fine-grained bioclasts - similar to LF 5d	- usually absent - rarely at the top of limestone beds	- peloids, calcimicrobes - lithoclasts - similar to LF 5d
thickness	**stratigraphic occurrence**	**geographic distribution**
- around 10 m	- lower Givetian	- exclusively at OUI

Tab. 11: Major characteristics of lithofacies 5c rocks (abbreviations as in Fig. 5)

Thick-bedded crinoid-peloid limestones (LF 5d)		
appearance in the outcrop (Fig. 14)	**texture / diagenetic features**	**sedimentary structures (Pl. 2, Figs. 3, 4; Fig. 14)**
- beds partially arranged in thickening- or thinning-upward cycles - minor marl intercalations	- predominantly grainstones, some packstones - matrix with fine-grained bioclasts, peloids and very little microspar or micrite - skeletal material frequently micritised - pore space cemented by syntaxial rim cements or blocky cements - partially dolomitised	-horizontal lamination, frequently mm-thick alternations of coarse and fine layers - well to very-poor sorted - often inverse or normal graded - small channel structures (gutters) - slumping
skeletal components (Pl. 2, Fig. 4)	**bioturbation**	**non-skeletal components (Pl. 2, Fig. 4)**
- crinoids, bioclasts, highly-fragmented tabulate corals, and brachiopods	- rare - scarce *Zoophycos*	- abundant - calcimicrobes, microbial lumps, peloids
thickness	**stratigraphic occurrence**	**geographic distribution**
- 230 m thick massive limestone unit with intercalated stromatoporoid-coral limestones (LF 7d)	- lower - middle? Givetian (Lower *varcus* Zone - ?)	- northernmost Mader (JR)

Tab. 12: Major characteristics of lithofacies 5d (abbreviations as in Fig. 5)

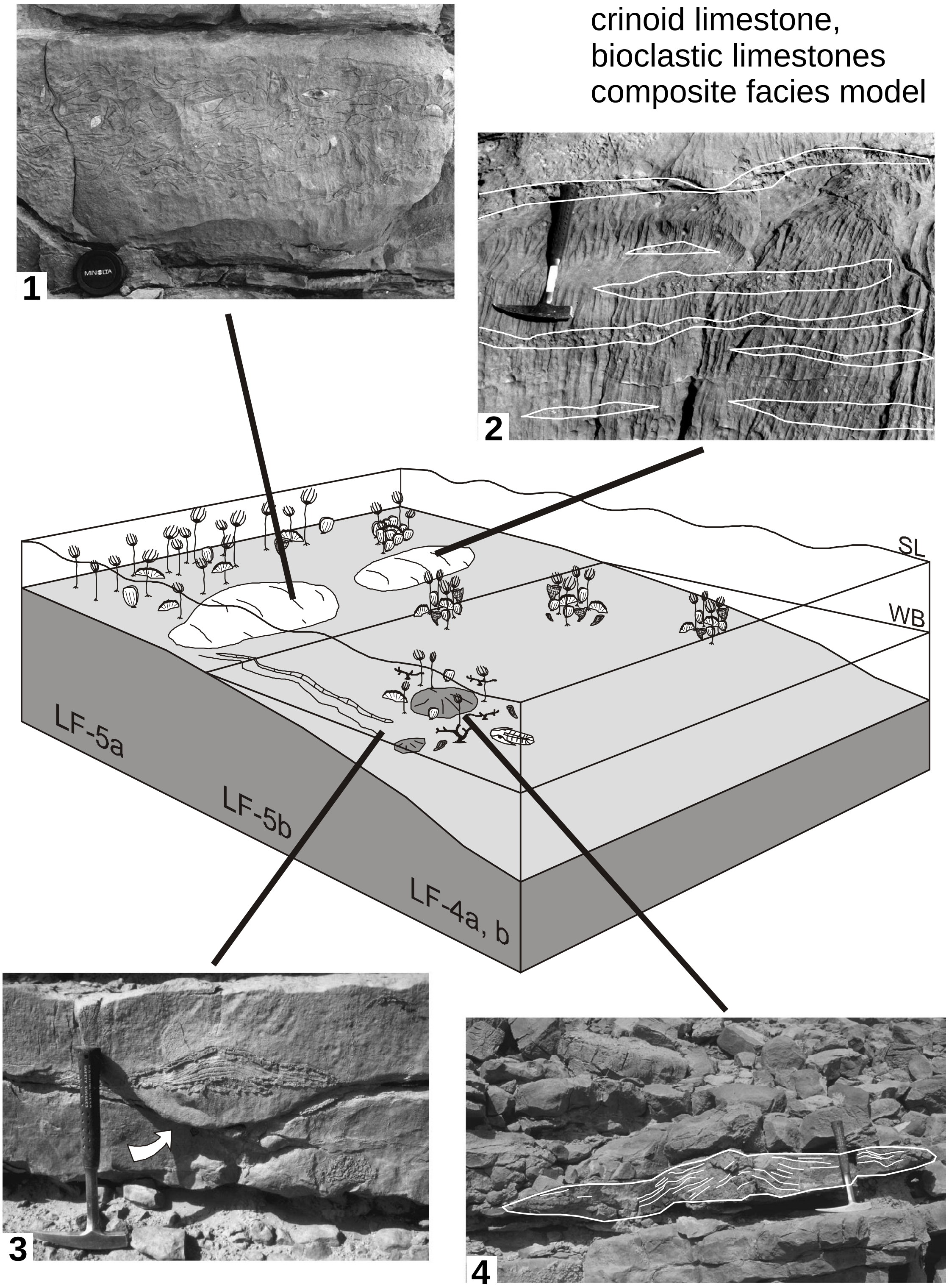

Fig. 12: Composite facies model for crinoid limestones (LF 5a, b) and bioclastic limestones (LF 4a, b). Photographs 1 and 2 show sedimentary structures which represent the proximal environment (Jebel Kem, MM), whereas photographs 3 and 4 display sedimentary structures and outcrop geometries attributed to more distal environments (Jebel Maharch). Proximal environments are characterised by the occurence of coarse layers with brachiopods (1) or crinoids (white outline in 2). Distal environments are characterised by marl intercalations (4), scour and fill structures (3) and clumpy accumulations of macrofauna. Lithofacies 4a, b represent further distal environments as reflected by less abundant crinoids, a higher mud content and a diverse spectrum of bioclasts. The wave base was temporary situated between LF-5a and LF-5b environments but migrated down- and upwards. The environment of Lithofacies 4a, b was permanently situated below the wave base.

<table>
<tr><th colspan="3">Peloid limestones, partially alternating with marls (LF 6a)</th></tr>
<tr><th>appearance in the outcrop</th><th>texture / diagenetic features</th><th>sedimentary structures</th></tr>
<tr><td>- massive limestone beds and limestone-marl alternations
- associated with coral-stromatoporoid limestones of lithofacies 7 at JZ, MM
- well or nodular bedded (JO)
- occasionally thickening-upward cycles</td><td>- packstones
- microspar or pseudospar</td><td>- very well - very poor sorting
- locally horizontal lamination (JO, MM)</td></tr>
<tr><th>skeletal components</th><th>bioturbation</th><th>non-skeletal components</th></tr>
<tr><td>- rare
- mainly fine-grained bioclasts
- some tabulate and rugose corals, brachiopods, and trilobites</td><td>- rare
- scarce Z<i>oophycos</i></td><td>- abundant
- calcimicrobes, microbial lumps, peloids</td></tr>
<tr><th>thickness</th><th>stratigraphic occurrence</th><th>geographic distribution</th></tr>
<tr><td>- 10 m (JI) - 15 m (JZ)</td><td>- lower Eifelian (<i>costatus</i> Zone) at JO
- lower Eifelian - upper Eifelian (<i>costatus</i> -<i>kockelianus</i> Zone) at JI
- lower Givetian (Lower <i>varcus</i> Zone) at MM and JZ</td><td>- western Mader (JI, JO)
- southern Mader (JZ, MM)</td></tr>
</table>

Tab. 13: Major characteristics of lithofacies 6a (abbreviations as in Fig. 5).

<table>
<tr><th colspan="3">Laminated peloid-bioclast limestones alternating with marls/shales (LF 6b)</th></tr>
<tr><th>appearance in the outcrop</th><th>texture</th><th>sedimentary structures (Pl. 3, Figs. 1-3; Fig. 15)</th></tr>
<tr><td>- limestones and pale yellow marls
- limestones intercalated in thick marl / shale successions.
- limestone bed thickness 10 - 40 cm
- intercalated marls several m thick.
- associated with LF 5c, LF 8a / b, LF 9, LF 10, LF 11
- debrite layers (LF 8a / b) frequently form the base of LF 6b beds</td><td>- wackestones, packstones
- few grainstones</td><td>- very well to well sorting
- grading
- horizontally laminated or low-angle cross bedding (HCS)
- soft-sediment deformation (load casts, convolute bedding and slumping) frequent at BD
- frequently erosive base
- locally overlying burrowed hardgrounds (BM)</td></tr>
<tr><th>skeletal components (Pl. 2, Figs. 6-8)</th><th>bioturbation</th><th>non-skeletal components (Pl. 2, Figs. 6-8)</th></tr>
<tr><td>- bioclasts, brachiopods and dacryoconarids</td><td>- not recorded</td><td>- mainly peloids
- detritic quartz (0 - 10%)</td></tr>
<tr><th>thickness</th><th>stratigraphic occurrence</th><th>geographic distribution</th></tr>
<tr><td>- 4 m (BL-3) - 30 m (OUI)</td><td>- uppermost Eifelian to lower Givetian times (<i>ensensis</i> Zone - Lower <i>varcus</i> Zone)</td><td>- northern Mader (BL sections, BD, OUI)</td></tr>
</table>

Tab. 14: Major characteristics of LF 6b (abbreviations as in Fig. 5).

synsedimentary deformation structures (Tab. 14) indicate rapid deposition as tempestites. The high amount of peloidal material and the locally recorded calcimicrobes suggest highstand conditions. Contemporaneously, laminated siltstones (LF 10), crinoid-bioclast limestones (LF 5c), shell coquinas (LF 11) and conglomerates/breccias (LF 8a/b) were deposited (Fig. 15). This lithofacies association is interpreted to have originated from tempestite sedimentation and debris flows. Two-layer beds with a lower unit consisting of lithoclast debrites and an upper one consisting of peloid limestones indicate, that tempestites locally assimilated limestone clasts. These features indicate the mid- to outer ramp, where, apart from the autochthonous shale sedimentation, repeatedly tempestites of varying composition were accumulated (Fig. 15).

Some horizontally laminated peloid-bioclast beds may have originated from turbidity currents which were initiated by debris flows as inferred for Lower Cambrian rocks of northern Canada by Krause & Oldershaw (1979). This interpretation is supported by the combined occurrence of shallow-water and deep-water biogenic particles (compare Einsele & Seilacher 1991). Consequently, beds of lithofacies 6b and the associated lithofacies (LF 6c, LF 8a) reflect features of turbidites as well as tempestites and thus suggest an environment where storm and gravity-flow deposits occur.

4.7 Coral-stromatoporoid limestones (LF 7)

Lithofacies 7 is subdivided into four subtypes: lithofacies 7a and 7b (Tab. 15) are characterised by a muddy matrix containing a great variety of bioclasts. LF 7a comprises massive limestones with minor marl intercalations whereas LF 7b is composed of limestone-marl alternations. Rocks of lithofacies 7c (Tab. 16) contain abundant crinoids and less micrite within the matrix and may form limestone-marl alternations or pure limestone successions. Lithofacies 7d occurs exclusively in the northernmost Mader (Jebel Rheris) and shows a crinoid-peloid-calcimicrobe matrix (Tab. 17). Successions of LF 7d alternate with laminated crinoid limestones of LF 5d.

4.7.1 Palaeoenvironment of lithofacies 7a

The diverse macrofauna, microbial remains and a high mud content (Tab. 15) indicate accumulation within the photic zone. Within this environment, small bioherms were constructed mainly by domal corals and stromatoporoids in wide muddy zones. The latter areas were inhabited by isolated dendroid tabulate corals and cup-shaped rugose corals (Fig. 13). Bottom currents were rare, thus suggesting a protected environment within shallow waters. Rugose corals and dendroid tabulate corals were encrusted by laminar stromatoporoids or micritised during times of lowered sedimentation rates (Pl. 4, Fig. 5). The dark colour may be due to a high content of organic matter. The vagile benthic community was predominated by large gastropods and brachiopods.

4.7.2 Palaeoenvironment of lithofacies LF 7b

During the deposition of lithofacies 7b, the palaeoenvironment was similar to lithofacies 7a. but by contrast it was repeatedly subject to clay sedimentation. The minor content of microbial remains suggests partially restricted photic conditions and a slightly higher waterdepth than during deposition of LF 7a. Nevertheless, reef-dwellers existed during these intervals. They comprise more isolated and larger growth forms such as domal stromatoporoids, domal and dendroid tabulate corals, and large cup-shaped rugose corals (Tab. 15). Limestone deposition may have occurred during relatively short intervals allowing only minor growth of reef dwellers whereas during periods of prolonged shale deposition, large individual stromatoporoids and rugose corals inhabited the sea floor.

4.7.3 Palaeoenvironment of lithofacies LF 7c

Rocks of lithofacies 7c indicate a shallow-water environment which was inhabited by abundant crinoids, dendroid tabulate corals and bryozoans (Fig. 13). Strong reworking prevented prolonged growth of reef dwellers. Dendroid corals were common inhabitants of this setting but were repeatedly subject to reworking as shown by their frequent orientation parallel to the bedding plane (Tab. 16). In the Jebel Kem section, dendroid tabulate corals and tabulate stromatoporoids settled on a hard substrate consisting of crinoidal debris (Pl. 4, Fig. 3; Fig. 13). Bryozoans are more common than in lithofacies 7a and 7b (Fig. 13). Although microbial remains are less abundant than in lithofacies 7a and 7b, the environment may have been situated in the photic zone.

4.7.4 Conclusions on the palaeoenvironment of lithofacies 7a, b, c

Sections in the southwestern Mader (Jebel Kem, Jebel Zireg, Madene El Mrakib, Jebel Oufatene) provide an insight in the proximal-distal relationships of lower Givetian coral-stromatoporoid limestones (Tabs. 15, 16) and allow the construction of a composite depositional model (Fig. 13).

The matrix of the different locations varies considerably from a crinoid-bioclast dominated one in the southernmost sections (Jebel Kem, Jebel Zireg) towards a bioclast-peloid-microbial one at Madene El Mrakib and Jebel Oufatene. In the same direction, an increasing size of stromatoporoids within the marls and an increasing content of bulbous, ragged and domal reef dwellers within the limestones was recorded. Large gastropods and brachiopods are

Coral-stromatoporoid limestones, partially alternating with marls (LF 7a, b)		
appearance in the outcrop	**texture / diagenetic features**	**sedimentary structures (Pl.4, Fig. 1, 2, 5-7; Fig. 13)**
- marl intercalations within LF 7b - biostromal geometry - large reef-dwelling organisms with varying growth forms - large gastropods and brachiopods - very large isolated stromatoporoids and rugose corals in marly interbeds of LF 7b - small reef-dwellers in limestone beds of LF 7b	- floatstones, rudstones, boundstones - fine sand to coarse sand matrix composed of diverse bioclasts, peloids and calcimicrobes - occasionally micritisation - mud supported fabric	- usually slightly reworked reef-dwellers - corals and stromatoporoids locally in life position
skeletal components (Pl. 4, Figs. 1, 2, 5; Fig. 13)	**bioturbation (Pl. 4, Fig. 4)**	**non-skeletal components**
- reef dwellers (e.g. stromatoporoids, *Thamnopora*, *Platyaxum*, *Favosites*, *Heliolites*) - large brachiopods (e.g. *Stringocephalus*) and gastropods - mm-thin stromatoporoids attached to dendroid tabulate corals and rugose corals - crinoids, trilobites	- rare - occasionally visible in thin sections	- microbial lumps - calcimicrobes (e.g. *Rothpletzella*) - peloids
thickness	**stratigraphic occurrence**	**geographic distribution**
- 30 m (MM), 40 m (JO)	- lower Givetian (Lower *varcus* Zone)	- southern and western Mader (MM, JO and JI?)

Tab. 15: Major characteristics of lithofacies 7a, 7b (abbreviations as in Fig. 5).

common in the uppermost part of the succession at Madene El Mrakib and Jebel Oufatene whereas they are absent in the southernmost Mader (Jebel Kem, Jebel Zireg). The thickest limestone beds and the highest degree of amalgamation were recorded at Jebel Zireg and Madene El Mrakib.

High-energy reefal environments were characterised by turbulence (Fig. 13) and were predominantly inhabited by crinoids and bryozoans apart from reef dwellers such as small corals and tabular stromatoporoids. Towards the protected environments, the mud-content increased and larger reef-dwelling organisms existed; largest organisms grew in the muddy areas. As indicated by the abundance of microbial remains, the distal parts were situated within the photic zone but features which indicate bottom currents are absent. In this calm environments, domal- and ragged-shaped reef dwellers as well as various microbial organisms were much more common than in the high-energy zones. Large brachiopods and gastropods obviously preferred these areas too.

4.7.5 Palaeoenvironment of lithofacies LF 7d

Microbial components, abundant reef dwellers, the absence of mud, alternation with crinoid limestones (LF 5d), and the occurrence of slumping structures within the well-bedded crinoid limestones (Tab. 17) indicate a slope environment within the photic zone, above the storm wave base (Fig. 14). The environment was predominantly inhabited by crinoids, stromatoporoids and some corals. Crinoids were subject to reworking by bottom currents (lamination) which were probably induced by storms as indicated by scour and fill structures and grading (compare LF 5d). The crinoid accumulations frequently constituted the substrate for patch-reef communities. Thick beds may contain a several dm-wide patch-reef core which laterally passes over into a reef-debris zone and then into crinoid-peloid grainstones (Fig. 14). Locally, stromatoporoids were repeatedly overturned and overgrown by subsequent generations of stromatoporoids thus forming framestone beds (Fig. 14).

Coral-stromatoporoid limestones with a crinoid matrix (LF 7c)		
appearance in the outcrop	**texture / diagenetic features**	**sedimentary structures (Fig. 13)**
- limestones and dolostones - massive, partially alternating with marls - occasionally biostromal geometry	- floatstones, rudstones, boundstones - crinoid matrix - remains of micrite or microspar - pervasive dolomitisation at JZ	- dendroid tabulate corals usually oriented parallel to bedding plane - lenticular coral biostrome with abundant tabulate and rugose corals with coarse crinoid matrix at JK - small-scale baselevel cycles - crinoid grainstones during fall and rise - corals mainly preserved during rise
skeletal components (Pl. 4, Fig. 3; Fig. 13)	**bioturbation**	**non-skeletal components (Pl. 4, Fig. 3)**
- dendroid tabulate corals (*Thamnopora* sp.,*Platyaxum* sp.), small tabulate corals with domal shapes (*Favosites* sp.), cup-shaped rugose corals (*Acantophyllum* sp., *Plasmophyllum* sp.), - domal and tabulate stromatoporoids less abundant - abundant crinoids - fine coral, bryozoan, brachiopod and mollusc debris	- absent	- peloids
thickness	**stratigraphic occurrence**	**geographic distribution**
- 40 m (JZ), 5 m (JK)	- lower Givetian (Lower *varcus* Zone)	- southernmost Mader (JK and JZ)

Tab. 16: Major characteristics of lithofacies 7c (abbreviations as in Fig. 5).

Stromatoporoid-coral limestones with a crinoid-peloid matrix (LF 7d)		
appearance in the outcrop (Fig. 14)	**texture / diagenetic features**	**sedimentary structures (Pl. 4, Fig. 7; Fig. 14)**
- massive limestones and dolostones with prominent patch reefs - intercalated in or overlain by limestones of LF 5d - scarce marly interbeds (less than several dm thick)	- floatstones, rudstones and boundstones - crinoid-peloid-calcimicrobe matrix - micrite generally absent - frequent cementation by syntaxial rim cements - partially pervasive dolomitisation	- elongated outline of patch reefs in plan view - vertical and lateral transition into laminated rocks of LF 5d - occasionally graded beds (transition to LF 5d)
skeletal components (Pl. 4, Fig. 8; Fig. 14)	**bioturbation**	**non-skeletal components (Pl. 4, Fig. 8)**
- abundant stromatoporoids - some tabulate and rugose corals - dendroid tabulate corals and colonial rugose corals (e.g. *Phillipsastrea*) - matrix dominated by crinoids, and bioclasts - some fragments of bryozoans and brachiopods	- absent	- peloids, calcimicrobes, microbial lumps - detritic quartz absent
thickness	**stratigraphic occurrence**	**geographic distribution**
- several metres - 15 m thick - large part of a 230 m thick succession at JR	- lower Givetian (Lower *varcus* Zone)	- northernmost Mader (JR)

Tab. 17: Major characteristics of lithofacies 7d (abbreviations as in Fig. 5)

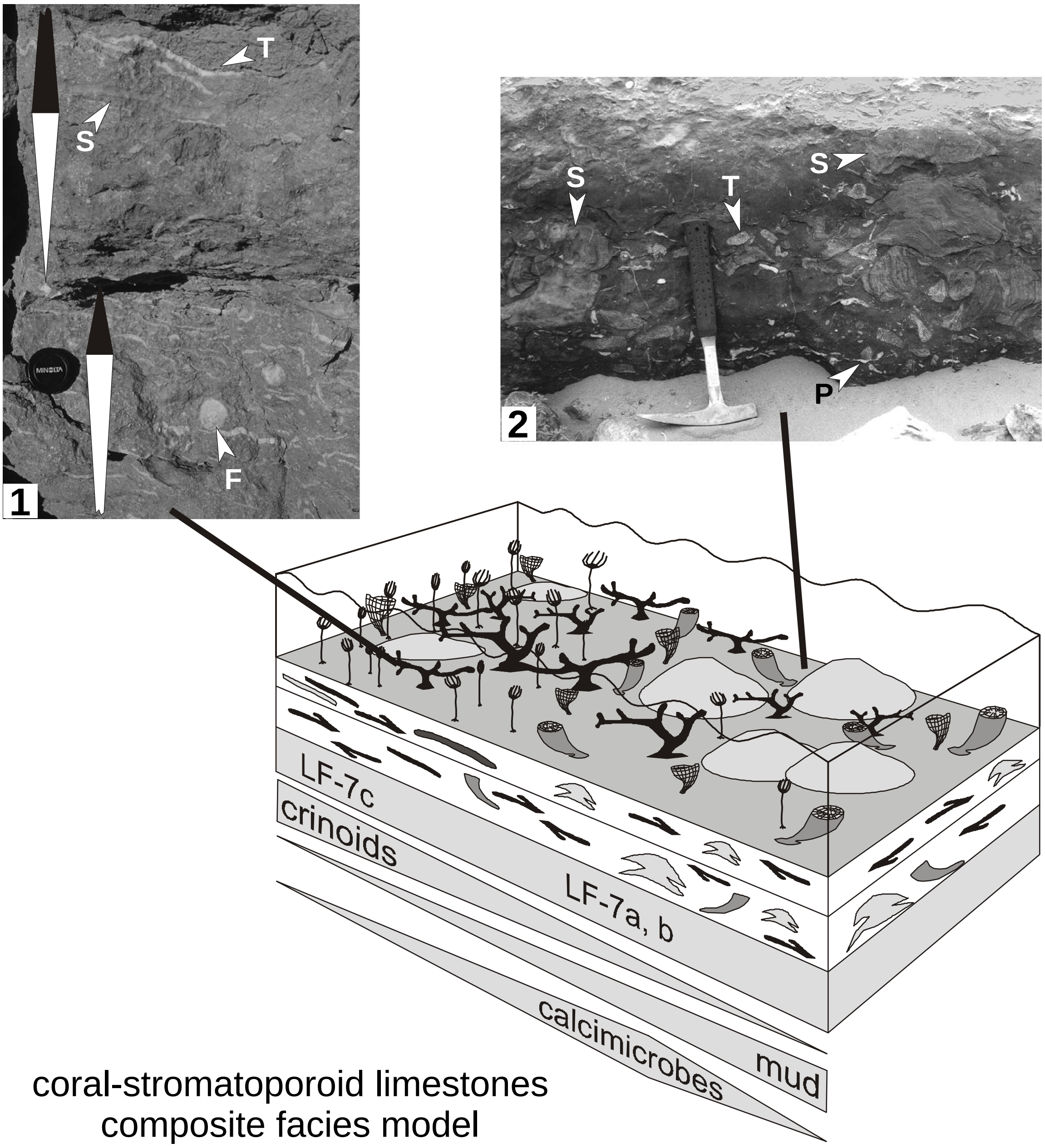

Fig. 13: Composite facies model for coral-stromatoporoid limestones of LF 7a, b, c of the southern and western Mader. Dendroid tabulate corals were the predominating reef dwellers in the high-energy environments (1) where minor mud was accumulated and abundant crinoids were deposited. In the low-energy environment , domal stromatoporoids were increasingly abundant which may grew upon each other (2). Dendroid tabulate corals and rugose corals were also common in the low-energy environment (2). The LF-7c environment was temporarily situated above the storm-wave base whereas the LF- 7a, b environment was subject to very low hydrodynamic energy.

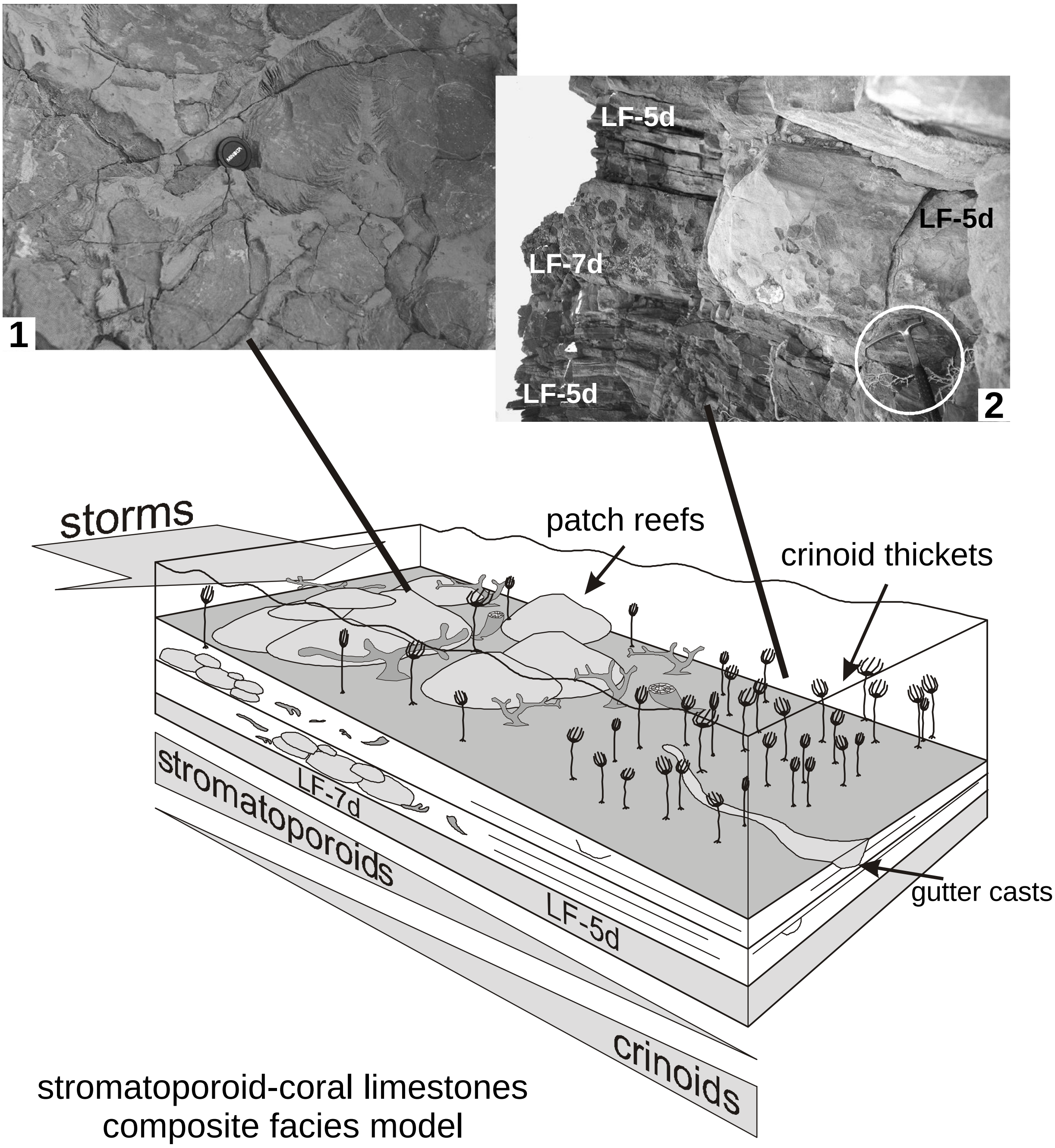

Fig. 14: Composite facies model for stromatoporoid-coral limestones (LF 7d) and well-bedded crinoid-peloid limestones (LF 5d). The latter represent the distal facies whereas stromatoporoid-coral limestones (LF 7d) formed in shallower waters. Photograph 1 shows a limestone bed which consists almost entirely of large stromatoporoids. Such beds represent patch-reef cores, where stromatoporoids were repeatedly overturned and subsequently overgrew each other. The facies model shows discrete patch reefs with accumulations of stromatoporoids and an adjacent environment characterised by crinoid thickets which were repeatedly subject to reworking (lamination, gutter casts).

4.8 Conglomerates and breccias (LF 8)

Lithofacies 8 can be subdivided into two subfacies: Lithofacies 8a comprises lithoclast-bioclast conglomerates that contain abundant well-rounded lithoclasts from a few millimetres to 2 cm in diameter (Tab. 18). These rocks frequently form the base of two layer beds (compare LF 6b and LF 5c). Lithofacies 8b contains well-rounded to angular lithoclasts and abundant reef dwellers and may also form the base of two-layer beds (Tab. 19). In contrast to LF 8a, lithoclasts frequently attain large sizes of several centimetres to decimetres.

4.8.1 Palaeoenvironment of lithofacies LF 8a

Rocks of lithofacies 8a are frequently associated with thin-bedded, often laminated limestones of lithofacies 3c, 5c, 6b, 9, 10, or 11 (Fig. 15) and are intercalated in thick marl/shale successions (Tab. 18). They frequently constitute the coarse part of two-layer beds which can be interpreted following the investigations of Krause & Oldershaw (1979) who found out that two-layer beds of the Canadian Mackenzie Mountains originate from debris flows in which fine-grained material was internally moved upwards thus constituting a cloud in the turbulent zone above the debris flow. This process was also described by Einsele (1991) as "uptake of water suspension". Minor fragmentation of the bioclasts (Pl. 3, Fig. 7) suggests debris-flow sedimentation whereas sedimentary structures (hummocky-cross stratification and horizontal lamination) of the overlying laminated limestones indicate tempestite sedimentation (Pl. 3, Fig. 6). Therefore, it is proposed, that the lower part of the two-layer beds in the northern Mader originated from debris-flows whereas the upper part formed as a fine-suspension cloud during debris-flow movement. Subsequently, the fine-grained material above the coarse layer was reworked by storm surges as documented by the sedimentary structures. Towards the outer ramp, the proportion of the fine-grained bed increases and a great number of coarse components of the lower layer are concordantly oriented. Debris-flow deposits occur within relatively narrow zones (hundreds of metres) in the northern Mader thus probably indicating a fault-induced origin of the intraclasts. Therefore, it is assumed, that minor synsedimentary faults due to slope instability may have fractured the semi-consolidated sediment thus providing coarse, subrounded to rounded lithoclasts (Pl. 3, Figs. 5, 8, Fig. 15). Initiation of the debris flows was related to steepening of the depositional slope rather than to sea-level fluctuations.

4.8.2 Palaeoenvironment of lithofacies LF 8b

The base of the breccia beds at Ouihlane is convex shaped whereas the top is almost planar; flat lithoclasts and corals are oriented parallel to the channel base (Tab. 19, Fig. 15). The breccias are intercalated in thick unfossiliferous shales/marls thus indicating a deep-marine environment. Playford (1980) described very similar beds of Devonian age from the Canning Basin of Australia. According to his interpretation, the channel-shaped breccia beds of the Ouihlane section can be interpreted as channelised

Lithoclast-bioclast conglomerates (LF 8a)		
appearance in the outcrop	**texture**	**sedimentary structures (Pl. 3, Figs. 5, 6; Fig. 15)**
- thin beds (cm - dm) intercalated in thick marl/shale successions - frequently associated with LF 3c, LF 5c, LF 6b, LF 9, LF 10, LF 11	- packstones, rudstones	- faint grading - lower part of two-layer beds - upper unit frequently consists of lithofacies 6b or 5c - fossil remains only weakly fragmented
skeletal components (Pl. 3, Figs. 6, 7)	**bioturbation**	**non-skeletal components Pl. 3, Figs. 5, 6, 8; Fig. 15)**
- crinoids, bryozoans, brachiopods, molluscs, trilobites, dacryoconarids	- absent	- peloids, calcimicrobes, microbial lumps - detritic quartz absent
thickness	**stratigraphic occurrence**	**geographic distribution**
- individual beds several centimetres thick	- lower Givetian (Lower *varcus* Zone)	- northern Mader (BL, BD)

Tab. 18: Major characteristics of lithofacies 8a (abbreviations as in Fig. 5).

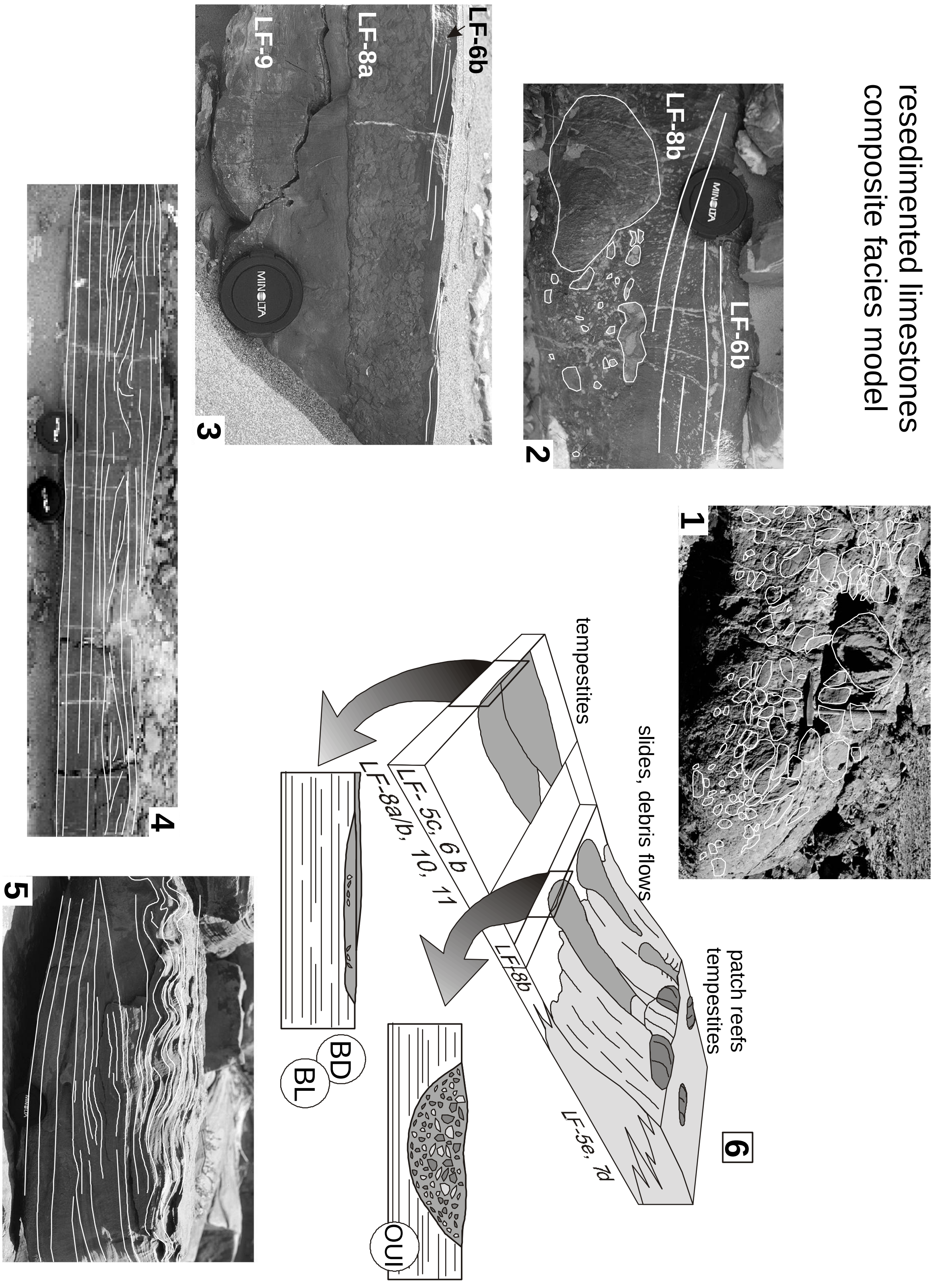

Fig. 15: Composite facies model (6) for resedimented limestones of the Mader. Coarsest lithologies are represented by LF 8b at OUI and Bou Dib (1, 2) and LF 8a at Boulchral (3). Whereas at OUI channel structures (6) were preserved, at Bou Dib and Boulchral rather horizontal beds occur (6, 2). Finer-grained lithologies represent the more distal environments at Bou Dib and Boulchral where dominantly laminated limestones of LF 6 b were deposited. They show planar lamination (4), hummocky-cross stratification (2 - 5) and synsedimentary deformation as convolute bedding (4) and microscale slumping (5). Resedimented limestones of LF 5c, 10 and 11 are integrated into this facies model because they are interpreted similar to LF-6b rocks.

Coral-stromatoporoid-lithoclast conglomerates and breccias (LF 8b)		
appearance in the outcrop - isolated outcrops (OUI) - locally two layer beds (BD) - intercalated in thick marl/shale successions	**texture** - breccias, conglomerates, packstones, rudstones - low matrix content in proximal deposits - micrite and microspar - bioclastic matrix	**sedimentary structures (Fig. 15)** - prominent channel structures at OUI (20 - 50 m wide and max. 3 - 4 m thick) - flat clasts oriented parallel to channel bottom (OUI) - poor sorting - locally lower part of two layer beds (BD)
skeletal components (Fig. 15) - stromatoporoids (10 - 30 cm) - corals (e.g. *Heliolithes* sp.) - fine-grained bioclasts, fragmented corals, stromatoporoids, crinoids, brachiopods, molluscs, dacryoconarids	**bioturbation** - absent	**non-skeletal components (Fig. 15)** - large (5 cm - 30 cm) flat, angular to subrounded lithoclasts - peloids
thickness - bed thickness several centimetres to several decimetres	**stratigraphic occurrence** - lower Givetian (Lower *varcus* Zone)	**geographic distribution** - northern Mader (OUI, BD)

Tab. 19: Major characteristics of lithofacies 8b (abbreviations as in Fig. 5)

debris-flow deposits which originated from the failure of massive stromatoporoid-coral buildups due to storm activity. The latter were probably situated at a platform margin farther to the N (Fig. 15). This contrasts with Schröder & Kazmierczak (1999) and Le Maître (1947) who interpreted these rocks as parautochthonous coral reefs. Biostratigraphic data from Bultynck (1985), prove a late Eifelian age (*kockelianus* Zone) to these rocks. This age remains questionable because the rocks consist of abundant resedimented lithoclasts, reef dwellers and minor fine-grained matrix. Additionally, these rocks are genetically related to small reefal buildups which are generally of early Givetian age in the eastern Anti-Atlas (Wendt 1988, Kaufmann 1998). These features favour an early to middle Givetian age for these rocks, whereas the biostratigraphic data may display the age of resedimented intraclasts. Similar limestone beds in the Bou Dib section represent the distal equivalents of LF 8b which are intercalated in tempestite successions (Fig. 15).

4.9 Dacryoconarid limestones (LF 9)

Rocks of lithofacies 9 are very abundant in lower Emsian strata ("Emsien calcaire" *sensu* Massa 1965) but also occur in upper Emsian to lower Givetian successions in the northern and northernmost Mader. They occur as (1) thick-bedded, often amalgamated dacryoconarid limestones with minor marl intercalations, (2) limestone-marl alternations and (3) argillaceous dacryoconarid limestones (Tab. 20).

4.9.1 Palaeoenvironment of lithofacies LF 9

The high content of micrite, strong bioturbation and the great abundance of pelagic organisms in combination with the sedimentary structures, indicate a deep-subtidal environment below the storm wave base. Parallel orientation and telescoping of dacryoconarid shells originate from minor currents without environmental significance (Wendt 1995). Benthic organisms include trilobites, large bivalves (*Panenka* sp.), some small rugose corals, and tabulate corals. The predominance of planktonic and nektonic organisms suggests a sea-level highstand and low sedimentation rates. Detritic quartz exclusively occurs in the southern and western Mader indicating local siliciclastic input.

4.10 Partially laminated sandstones and siltstones (LF 10)

Lithofacies 10 comprises siliciclastic rocks with abundant detritic quartz of silt- or fine-sand grain size which are frequently intercalated in shale/marl successions. At Bou Dib, beds of this lithofacies form discrete bundles within the mostly covered shaly succession (Tab. 21). Most rocks appear as laminated siltstones and sandstones with minor bioclastic ma-

Dacryoconarid limestones (LF 9)		
appearance in the outcrop	**texture**	**sedimentary structures (Pl. 1, Fig. 4)**
- well-bedded and nodular limestones - marls with limestone nodules (JO, JI , JM) - partially alternations with marl - partially argillaceous	- mudstones, wackestones and packstones	- very well to very poor sorting - best sorting at MM - telescoping of dacryoconarid shells - occasionally horizontal lamination
skeletal components (Pl. 1, Figs. 3, 4)	**bioturbation (Pl. 1, Fig. 4)**	**non-skeletal components**
- predominantly dacryoconarids - some crinoids - rare tabulate and rugose corals, brachiopods, molluscs, and trilobites - locally sponge spicules (BL-1, TIM)	- common - *Zoophycos*, *Fucoides*, *Planolites*, or *Thalassinoides*	- variable contents of detritic quartz (0-10%) - 2-10% quartz content at MM
thickness	**stratigraphic occurrence**	**geographic distribution**
- 15 m (JM) - 40 m (JI, TIM), 70 m (BL-3)	- lower Emsian (*nothoperbonus* - *inversus* Zone) - uppermost Eifelian - lower Givetian (*ensensis* - Lower *varcus* Zone)	- entire Mader - lower Emsian rocks at JK and JZ predominated by crinoids

Tab. 20: Major characteristics of lithofacies 9 (abbreviations as in Fig. 5).

terial and varying clay content. Some are massive, may contain some bioclasts, and are frequently bioturbated.

4.10.1 Palaeoenvironment of lithofacies LF 10

Abundant sole marks, grading, horizontal lamination, low-angle cross bedding, hummocky-cross stratification, synsedimentary deformation structures, and intercalated marls (Tab. 21) indicate tempestite sedimentation in the deep subtidal. Sandstones and siltstones of Givetian age mostly occur as discrete bundles, and beds are laterally uniform with respect to composition, thickness, and sedimentary structures demonstrating the geometry of a distal tempestite sheet. Channel structures were not observed in Middle and Upper Devonian deposits of the northern Mader (Bou Dib, Boulchral-6, Fig. 15). At Bou Dib, convolute bedding, such as small-scale folds with a uniform vergence, and slumping structures indicate an inclined depositional floor. Palaeocurrents at this locality suggest, that during Middle and Late Devonian times, siliciclastic material was transported from NW and W to the SE and E. By contrast, the tempestite material at Boulchral-6 was transported from S or SW towards the N and NE as indicated by palaeocurrent data. Tempestite bundles with fining-up trends may reflect an increased detritic input triggered by variation of the denudation rate in the hinterland or steepening of the depositional slope.

4.11 Brachiopod-mollusc coquinas (LF 11)

Rocks attributed to lithofacies 11 were found exclusively in upper Eifelian to lower Givetian rocks of the northern Mader. They show different colours and slightly differing compositions but were not further subdivided (Tab. 22). Beds of LF 11 are always intercalated in thick marl/shale successions and are associated with various limestones of other lithofacies.

4.11.1 Palaeoenvironment of lithofacies LF 11

The under- and overlying rocks of LF 11 are interpreted as tempestites and pelagites which were deposited on the mid- to outer ramp (see above). Therefore, shell beds of LF 11 may have been accumulated by similar mechanisms (storms) like the associated rocks. The laminated red brachiopod coquinas contain a monospecific brachiopod fauna which points towards event sedimentation as well.

Partially laminated sandstones and siltstones (LF 10)

appearance in the outcrop	**texture**	**sedimentary structures (Pl. 5, Figs. 1-5)**
- frequently intercalated in marl / shale successions - bed thickness between several centimetres and few decimetres - partially associated with LF 3c, 5c, LF 6b, LF 8a / b, LF 11	- silty mudstones, siltstones, fine sandstones - mud-supported or grain supported - calcareous or clayey matrix	- well to very-well sorting - frequent grading - horizontal lamination - low-angle cross bedding (HCS) - ripple bedding - flute casts, bounce marks, groove casts - load casts, convolute bedding - slumping
skeletal components	**bioturbation**	**non-skeletal components**
- rare crinoids, corals, brachiopods, bivalves, trilobites, dacryoconarids	- absent - frequent in massive siltstones at JZ	- silt- to sand-sized angular to subangular quartz grains (15 - 55%) - peloids
thickness	**stratigraphic occurrence**	**geographic distribution**
- beds several centimetres to few decimetres thick	- lower Givetian (Lower *varcus* Zone - Late Devonian - upper Emsian (*serotinus* - *patulus* Zone) at JZ and JK	- exclusively at BL-6, BD, JK, JZ

Tab. 21: Major characteristics of lithofacies 10 (abbreviations as in Fig. 5)

Brachiopod-mollusc coquinas (LF 11)

appearance in the outcrop	**texture**	**sedimentary structures (Pl. 5, Figs. 6, 7)**
- thin limestone beds intercalated in marl / shale successions - associated with LF 3c, 5c, LF 6b, LF 8a / b, LF 10, LF 9	- packstones	- parallel alignment of shells or random orientation of shells - poor - well sorting - occasionally faint grading - conspicuous red-coloured beds with thin-shelled brachiopods and horizontal lamination (Pl. 5, Fig. 7)
skeletal components (Pl. 5, Figs. 6, 7)	**bioturbation**	**non-skeletal components (Pl. 5, Fig. 6)**
- brachiopods, molluscs - abundant gastropods at TIM - some crinoids, tabulate corals, trilobites, and dacryoconarids	- absent	- lithoclasts
thickness	**stratigraphic occurrence**	**geographic distribution**
- several centimetres thick beds intercalated in marls and shales	- upper Eifelian (*kockelianus* - *ensensis* Zone) at TIM, BL-5 - lower Givetian (Lower *varcus* Zone) at BL-5, BD, OUI	- northern Mader (BL, BD, TIM, OUI)

Tab. 22: Major characteristics of lithofacies 11 (abbreviations as in Fig. 5).