Evolution of a Devonian carbonate shelf at the northern margin of Gondwana (Jebel Rheris, eastern Anti-Atlas, Morocco)

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ABSTRACT

During the Devonian, a carbonate shelf was established at the northern rim of the West-African craton. In the eastern Anti-Atlas remnants of this shelf are preserved in the Mader area, where a basin started subsiding in the Eifelian. The Jebel Rheris is situated in a transitional zone between this basin (Mader Basin) in the south and the emerged Ougnate High in the north.

Emsian deposits consist of two pelagic nodular limestone successions, separated by 70 m thick shales. During this interval homogeneous thickness and facies pattern exist. Asymmetric shallowing-upward cycles can be correlated throughout the investigated area. The Eifelian succession, consisting of pelagic nodular limestones with slumping structures, is considerably condensed (8 – 20 m thick) with respect to successions farther south.

In the Givetian, stacked or amalgamated coral-stromatoporoid biostromes in the N evolved into an alternating biostrome – crinoidal grainstone succession, which passed over a low-angle slope setting towards the south to a pure crinoidal grainstone facies with abundant slumping structures. In the south, distal tempestites occur. This is first evidence of a carbonate ramp in the northern Mader. Considerable thickness changes within short lateral distances of the Givetian succession are attributed to differential subsidence. According to a sequence stratigraphic interpretation of an accommodation plot, the lower Givetian consists of a transgressive systems tract (TST), a highstand systems tract (HST), and again a TST. The mid-Givetian succession represents a thick HST, the uppermost Givetian deposits a TST.

In the Upper Devonian, nine different facies types can be distinguished. They were deposited on the inner ramp (e.g. stromatolite limestones, crinoid shoals) and on the mid-ramp (e.g. quartz-rich crinoidal-bryozoan packstones). Synsedimentary faulting, angular unconformities, and neptunian dikes are observed, which indicate an increasing tectonic activity from Middle into the Late Devonian. Stratigraphic gaps generally increase towards the NW. Lower Frasnian deposits represent a HST, separated from the uppermost Givetian rocks by a maximum flooding surface. A sequence boundary (SB) occurs in the mid-Frasnian, followed by a TST. Slightly above the Frasnian / Famennian – boundary, a maximum flooding zone can be noticed. The lower Famennian deposits consist of a HST. A SB occurs again in upper Famennian rocks. The uppermost Famennian succession is interpreted as a TST. This systems tract was probably caused by a eustatic sea-level rise, whereas the other Middle and Late Devonian sea-level oscillations are interpreted as tectonically induced.

At the eastern edge of the Jebel Rheris, Givetian deposits consist of a ca. 200 m thick biostrome – crinoidal grainstone succession. A detailed examination of the biostrome constructors showed that the biostromes developed due to the lack of a ‘binder guild’ in the fossil community, which hampered the establishment of mound-like structures, stable enough to resist high-energy storm events. Repeated interruption of the coral-stromatoporoid growth is attributed to drowning by sea-level rises. During favourable conditions, colonisation of the sea floor proceeded in three phases: a) *cluster settlement*; pioneer communities, mostly consisting of tabulate corals and domical to bulbous stromatoporoids, started growing in laterally delimited clusters; b) *lateral dispersion*; from these centres, settlement prograded laterally, until large areas of the sea floor were covered; c) *vertical accretion*; the organisms more and more grew on each other, causing a homogeneous vertical expansion. A significant difference of this biostrome–crinoidal grainstone succession compared to continuously growing reefs is the fact that communities repeatedly had to start with the colonisation stage, and therefore could not reach a mature or climax stage.

Diagenesis of the Givetian succession started in the marine environment, where fibrous calcite was precipitated in skeletal pores, and proceeded in the shallow burial realm. Here, non-luminescent scalenohedral calcite grew, succeeded by rapid precipitation of mostly bright-luminescent blocky spar I, which closed the whole pore space. After that, ferroan replacement dolomite grew. Dolomitisation obscured considerable areas of the Givetian rocks, crossing the original bedding and showing an irregular, patchy distribution. Smectite to illite conversion in Emsian shales possibly provided Mg^{2+} for the dolomitisation. During deeper burial, the dolomitised rock was fractured, and the fractures were subsequently cemented with dull-luminescent, ferroan blocky spar II. The filled fractures later were cut by stylolites. Biostrome constructing macro-organisms sometimes resisted dolomitisation and were later dissolved, leading to a considerable porosity in the rock. Rarely, some cavities were refilled by calcite cement.

In some horizons in the upper Famennian rocks of the Jebel Rheris, black pebbles and nodules occur, which can be traced over several kilometres. Two types of these components can be distinguished: (1) black pebbles with quartz grains and (2) less common black nodules, containing carbonate bioclasts. XRD studies reveal that type 1 black pebbles consist of quartz, calcite, and apatite (35.4 wt.% to 53.6 wt.%). The average content of total organic carbon is 0.12 wt.%. Phosphorous is an important constituent of type 2 black nodules, though it has not been found in the embedding rocks. Therefore the black colour must be the result of phosphatisation, which occurred during two different periods: (1) black pebbles consisting of sandstone must have been derived from Ordovician strata north of the Jebel Rheris and were phosphatised during that period. (2) Black nodules, in contrast, were formed during the Famennian, because they consist of the same facies as the surrounding rock; moreover a gradual transition from blackened to unstained areas has been observed. It is argued that the late Famennian transgression was responsible for the accumulation of phosphatic black pebbles. They were reworked by the progressing coastal erosion and shed onto the shelf. Thus, type 1 black pebbles are indicative of a transgressive systems tract and occur within retrogradational parasequences. Type 2 phosphatic nodules are probably not related to sea-level changes.

KURZFASSUNG

Während des Devons existierte am Nordrand des Westafrikanischen Kratons ein Karbonatschelf, dessen Überreste im östlichen Anti-Atlas erhalten sind. Dort entstand während des Eifels das Mader-Becken. In einer Übergangszone zwischen diesem Becken und einem nördlich gelegenen Landgebiet befand sich der Ablagerungsraum des Jebel Rheris.

Sedimentgesteine des Ems bestehen aus zwei pelagischen Knollenkalk-Abfolgen, die von ca. 70 m mächtigen Tonen getrennt werden. Sowohl das Fazies-Muster als auch die Mächtigkeiten sind homogen, asymmetrische Shallowing-upward Zyklen lassen sich über das gesamte Arbeitsgebiet korrelieren. Die Abfolge des Eifels ist am Jebel Rheris im Vergleich zu südlicher gelegenen Abfolgen stark kondensiert (8 – 20 m Mächtigkeit). Die Fazies besteht aus pelagischen Knollenkalken.

Im Givet entwickelte sich ein Fazies-Muster von gestapelten oder amalgamierten Korallen-Stromatoporen Biostromen im Norden des Jebel Rheris zu einer Biostrom – Crinoiden-Grainstone Wechsellagerung im Zentrum des Berges. Südlich davon wurde auf einem schwach geneigten Hang eine reine Crinoiden-Grainstone Fazies mit häufigen Slumping-Strukturen abgelagert, weiter südlich sind distale Tempestite mit Convolute-bedding Strukturen erhalten. Diese lateralen Fazies-Beziehungen in Ablagerungen des Givets sind der erste Nachweis einer Karbonatrampe im nördlichen Mader. Erhebliche Mächtigkeitsschwankungen innerhalb kurzer lateraler Entfernungen werden auf differentielle Subsidenz zurückgeführt. Die Auswertung eines Fischer Plots läßt folgende sequenzstratigraphische Interpretation zu: Das untere Drittel der Givet-Abfolge besteht aus einem Transgressive Systems Tract (TST), einem Highstand Systems Tract (HST) und erneut einem TST. Darauf folgt ein mächtiger HST, der oberste Teil der Givet-Abfolge ist ein TST.

Sedimente des Oberdevons bestehen aus neun verschiedenen Fazies-Typen. Diese wurden auf der inneren Rampe (z.B. Stromatolith-Kalke, Crinoiden-Shoals) und der mittleren Rampe (z.B. quarz-reiche Crinoiden-Bryozoen Packstones) abgelagert. Synsedimentäre Störungen, Winkeldiskordanzen und Neptunian Dikes lassen auf erhöhte tektonische Aktivität schließen. Ablagerungen des unteren Frasne bestehen aus einem HST, der durch eine Maximum Flooding Surface von Schichten des obersten Givets getrennt ist. Eine Sequenzgrenze (SG) existiert im mittleren Frasne, gefolgt von einem TST. Knapp oberhalb der Frasne / Famenne – Grenze liegt eine Maximum Flooding Zone, Schichten des unteren Famenne bestehen aus einem HST. Eine SG liegt in Ablagerungen des oberen Famenne, Schichten des obersten Famenne werden als TST interpretiert. Dieser Systems Tract wurde von einem eustatischen Meeresspiegelanstieg verursacht, die restlichen Meeresspiegelschwankungen des Mittel- und Oberdevons werden als tektonisch induziert angesehen.

Am Ostrand des Jebel Rheris ist eine ca. 200 m mächtige Biostrom – Crinoiden-Grainstone Abfolge des Givets erhalten. Aus einer detaillierten Untersuchung der Biostrom-Bildner wurde die Schlußfolgerung gezogen, daß sich Biostrome aufgrund der Abwesenheit einer ‚Binder Gilde‘ in der Fossilgemeinschaft bildeten. Hügelförmige Strukturen waren daher wahrscheinlich nicht stabil genug, um Sturm-Ereignissen widerstehen zu können. Für das zyklische Absterben der Biostrome werden Drowning-Ereignisse verantwortlich gemacht. Während geeignete Bedingungen herrschten, wurde der Meeresboden in drei Phasen besiedelt: a) *cluster settlement*; Pioneer Communities, die hauptsächlich aus tabulaten Korallen und domförmigen bis knolligen Stromatoporen bestehen, wuchsen in lateral begrenzten Clustern. b) *lateral dispersion*; von diesen Zentren ausgehend wurde der Meeresboden flächendeckend besiedelt. c) *vertical accretion*; die Organismen fingen an, übereinander zu siedeln, wodurch ein homogenes vertikales Wachstum stattfand. Ein wichtiger Unterschied von Biostrom-Abfolgen zu kontinuierlich gewachsenen Riffen ist, daß Fossilgemeinschaften wiederholt mit der Kolonisationsphase beginnen mußten und daher keine ‚reife‘ Gemeinschaft wurden.

Die Diagenese der Ablagerungen des Givets begann im marinen Milieu, wo fibröser Kalzit in einigen Skelett-Hohlräumen wuchs, und setzte sich während der flachen Versenkung fort. Hier wuchs nicht-lumineszierender skalenohedraler Kalzit, gefolgt von hellgelb-lumineszierendem blockigem Sparit I, womit der gesamte Porenraum gefüllt wurde. Danach bildete sich eisenreicher Verdrängungs-Dolomit. Die Dolomitisierung durchschneidet häufig die Schichtung und weist eine unregelmäßige, fleckige Verteilung auf. Während der tieferen Versenkung entstanden Klüfte im dolomitisierten Gestein, die mit orange-lumineszierendem blockigem Sparit II gefüllt und später von Styloliten gekreuzt wurden. Biostrom-Bildner widerstanden teilweise selektiv der Dolomitisierung und wurden später gelöst, was zu einer hohen Porosität im Gestein führte.

In Ablagerungen des obersten Famennes kommen am Jebel Rheris ‚Black Pebbles‘ und ‚Black Nodules‘ in bestimmten Horizonten vor, die über mehrere Kilometer zu verfolgen sind. Es werden zwei Typen dieser Komponenten unterschieden: (1) ‚Black Pebbles‘, hauptsächlich bestehend aus Quarz –Körnern und (2) seltener vorkommend ‚Black Nodules‘, bestehend aus Karbonat-Bioklasten. XRD-Untersuchungen zeigen, daß Typ I ‚Black Pebbles‘ aus Quarz, Kalzit und Apatit (35,4 Gew.% bis 53,6 Gew.%) bestehen. Der Mittelwert des Gehalts an organischem Kohlenstoff beträgt 0,12 Gew.%. Phosphor ist ein wichtiger Bestandteil in Typ II ‚Black Nodules‘, kommt jedoch nicht im Nebengestein vor. Die Schwarzfärbung ist daher Resultat von Phosphatisierung, die während zwei unterschiedlichen Zeiten stattfand: ‚Black Pebbles‘ bestehen aus Sandstein, sie stammen aus Ordovizischen Schichten nördlich des Jebel Rheris und wurden zu dieser Zeit phosphatisiert. ‚Black Nodules‘ bildeten sich dagegen während des obersten Famennes, da sie aus der gleichen Fazies bestehen wie das sie umgebende Gestein; außerdem ist ein gradueller Übergang von geschwärzten zu ungeschwärzten Bereichen vorhanden. Eine Transgression im oberen Famenne wird für die Anhäufung von phosphatischen ‚Black Pebbles‘ verantwortlich gemacht. Sie wurden während der fortschreitenden Küstenerosion aufgearbeitet und auf das Schelf transportiert. Daher sind Typ I ‚Black Pebbles‘ Indikatoren für einen Transgressive Systems Tract, sie kommen in retrogradierenden Parasequenzen vor. Das Vorkommen von Typ II ‚Black Nodules‘ wird nicht mit Meeresspiegelschwankungen in Verbindung gebracht.

1. INTRODUCTION

Devonian deposits of the eastern Anti-Atlas have been studied for decades (e.g. Massa 1965, Hollard 1974, Wendt 1988). Due to weak tectonic deformation, individual horizons can often be correlated over several kilometres. During the Middle Devonian, a platform and basin topography was established in the Tafilalt and Mader. The subsidence history of the Mader Basin was studied by Döring (2002), who presented the first sequence stratigraphic interpretation for Emsian to lower Givetian deposits for this area. The Jebel Rheris is the only place, where Emsian to uppermost Famennian deposits of the transitional zone between the Mader Basin and the emergent Jebel Ougnate can be studied. Compared to contemporaneous deposits of the eastern Anti-Atlas, this area shows two remarkable differences: 1) In contrast to other Devonian bioconstructions of the eastern Anti-Atlas, which are represented by mud- and reef-mounds (Kaufmann 1998) or few thin biostromes, Givetian rocks consist of an up to 200 m thick coral-stromatoporoid biostromal succession. A major aim of the present study is a reconstruction of the Givetian facies pattern and the determination of the reason for biostromal growth at the Jebel Rheris (Fröhlich 2003). 2) Late Devonian tectonics and their influence on sedimentation were stronger in the study area than elsewhere in the eastern Anti-Atlas. These movements are expressed by considerable hiatuses, angular unconformities, synsedimentary faults, and neptunian dikes. Therefore it is another major topic of the present work to reconstruct the Late Devonian shelf evolution. Eustasy influenced sedimentation in the late Famennian, causing the deposition of reworked Ordovician phosphorites on the carbonate shelf. This topic is discussed in chapter 11, which is in print in the 'Journal of African Earth Sciences'.

A geological mapping and palaeogeographical interpretation of the Jebel Rheris was carried out by Erbacher (1991) and Spintzyk (1991). In the present study, new biostratigraphic and sedimentological data lead to modified facies models of the northernmost Mader. Furthermore, a sequence stratigraphic interpretation for Givetian to Famennian strata is presented.

2. GEOLOGICAL SETTING

The eastern Anti-Atlas of Morocco (Fig. 1) consists of a Precambrian crystalline basement and a thick pile of gently deformed upper Precambrian to Namurian strata, which are covered to the north, east, and south by undeformed Cretaceous and Tertiary sedimentary rocks. The Palaeozoic sediments were deposited on an epicontinental shelf at the northern rim of the West-African Craton. The Lower to Middle Cambrian succession of the eastern Anti-Atlas mostly consists of sandstones with intercalations of conglomerates, shales, and volcanic rocks (Destombes et al. 1985). Upper Cambrian deposits were not found so far. Ordovician strata are dominated by argillaceous rocks, which alternate with several hundred metre thick sandstones. The deglaciation at the beginning of the Silurian caused a transgression, which led to the sedimentation of graptolitic shales. Lower Silurian rocks contain a high amount of organic carbon and represent the major Palaeozoic petroleum source rock in North Africa (Lüning et al. 2000). In the upper Silurian two prominent marker horizons, the *Orthoceras* limestone and *Scyphocrinites* limestones, were deposited (Destombes et al. 1985), which mark the onset of carbonate sedimentation in the Palaeozoic succession of the eastern Anti-Atlas.

Deposits of Early Devonian age show a more or less homogeneous facies distribution in the eastern

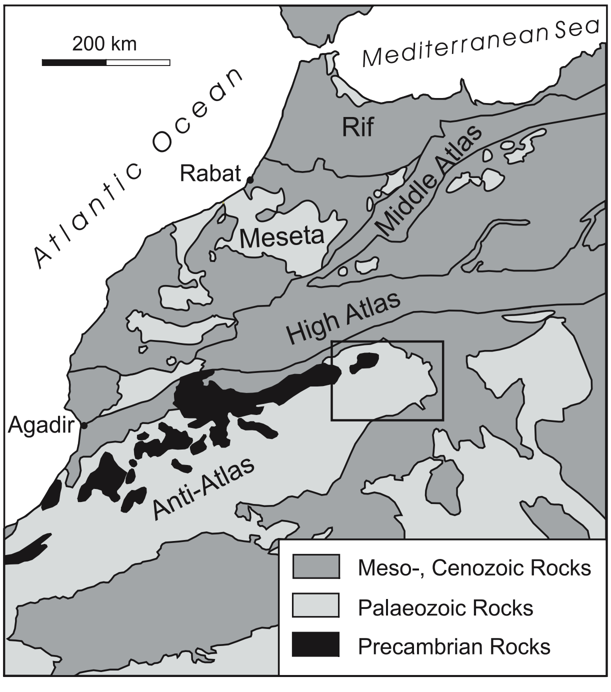


Fig. 1: Simplified geological map of NW-Africa (after Piqué & Michard 1989). Boxed area detailed in Fig. 2.

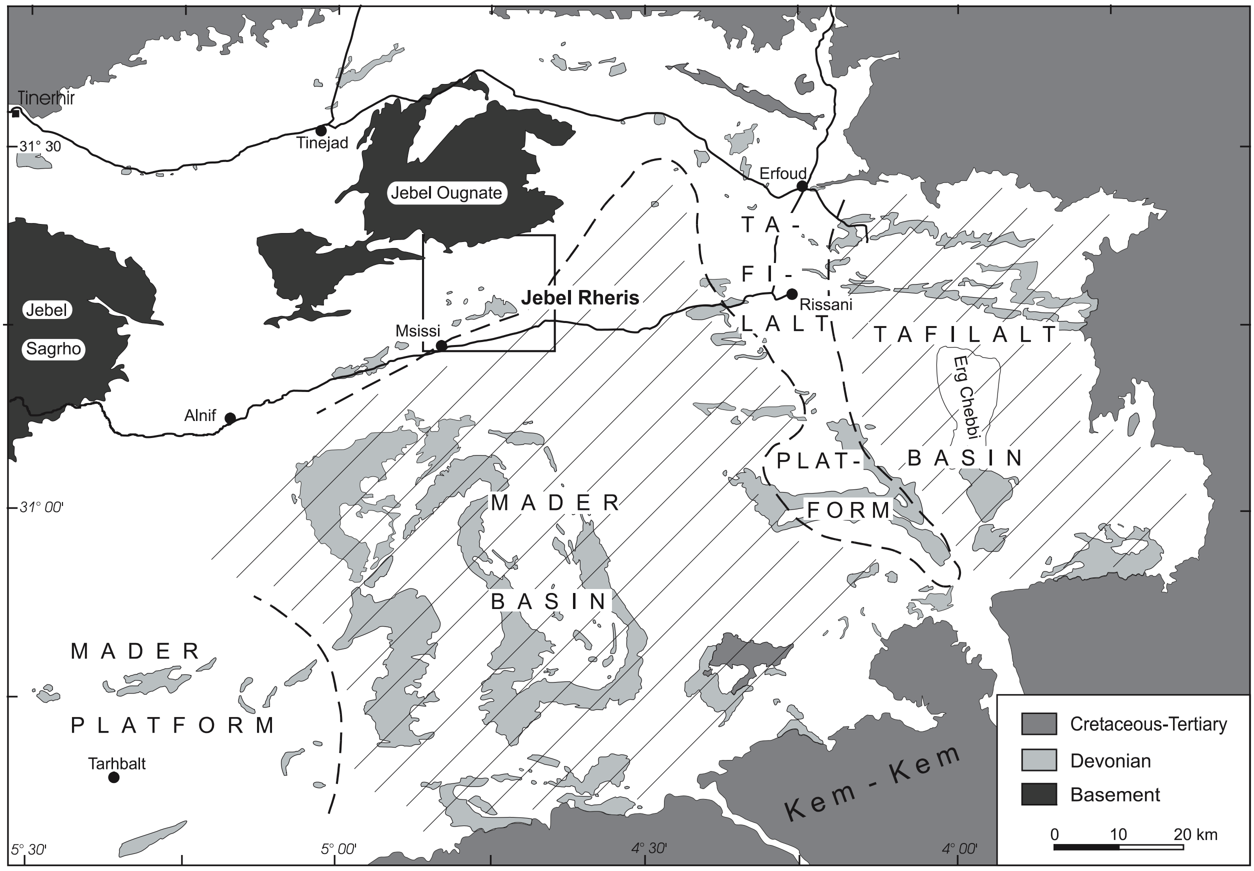


Fig. 2: Simplified geological map of the eastern Anti-Atlas (after Fetah 1986, Fetah et al. 1988). Middle Devonian palaeogeographic units modified after Wendt (1988). Boxed area shown in detail in Fig. 3.

Anti-Atlas. While shales are dominant in the Lochkovian, limestones and marls predominate in the Pragian and Emsian (Hollard 1981). Thicknesses of Emsian deposits range from 50 m to about 200 m (Kaufmann 1998) but still a uniform facies pattern exists: Lower Emsian limestones, for example, consist of massive to nodular carbonates with abundant nautiloids and tentaculitids, interrupted by a thick shale interval. This association can be found throughout the eastern Anti-Atlas and may therefore serve as a marker horizon (Hollard 1974). In the Middle and Late Devonian, carbonate deposition was predominant. Strong differential subsidence, probably a consequence of early Variscan block faulting, caused extreme lateral changes in thickness as well as in facies patterns (Wendt 1985). A platform and basin topography evolved, whereby four domaines established in the eastern Anti-Atlas (from W to E): the Mader Platform, Mader Basin, Tafilalt Platform, and Tafilalt Basin (Wendt 1988). Depending on the palaeogeographical position, Middle Devonian deposits are composed of biostromal shallow water float- and boundstones, shales and mudstones as basin

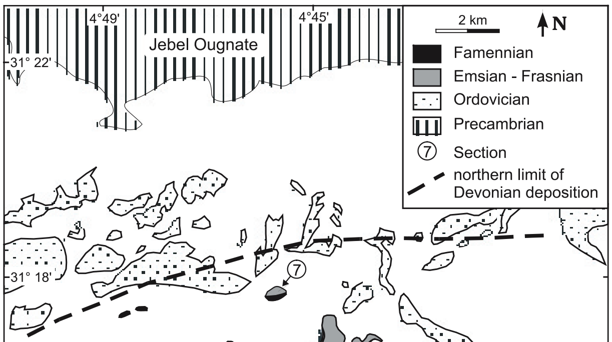
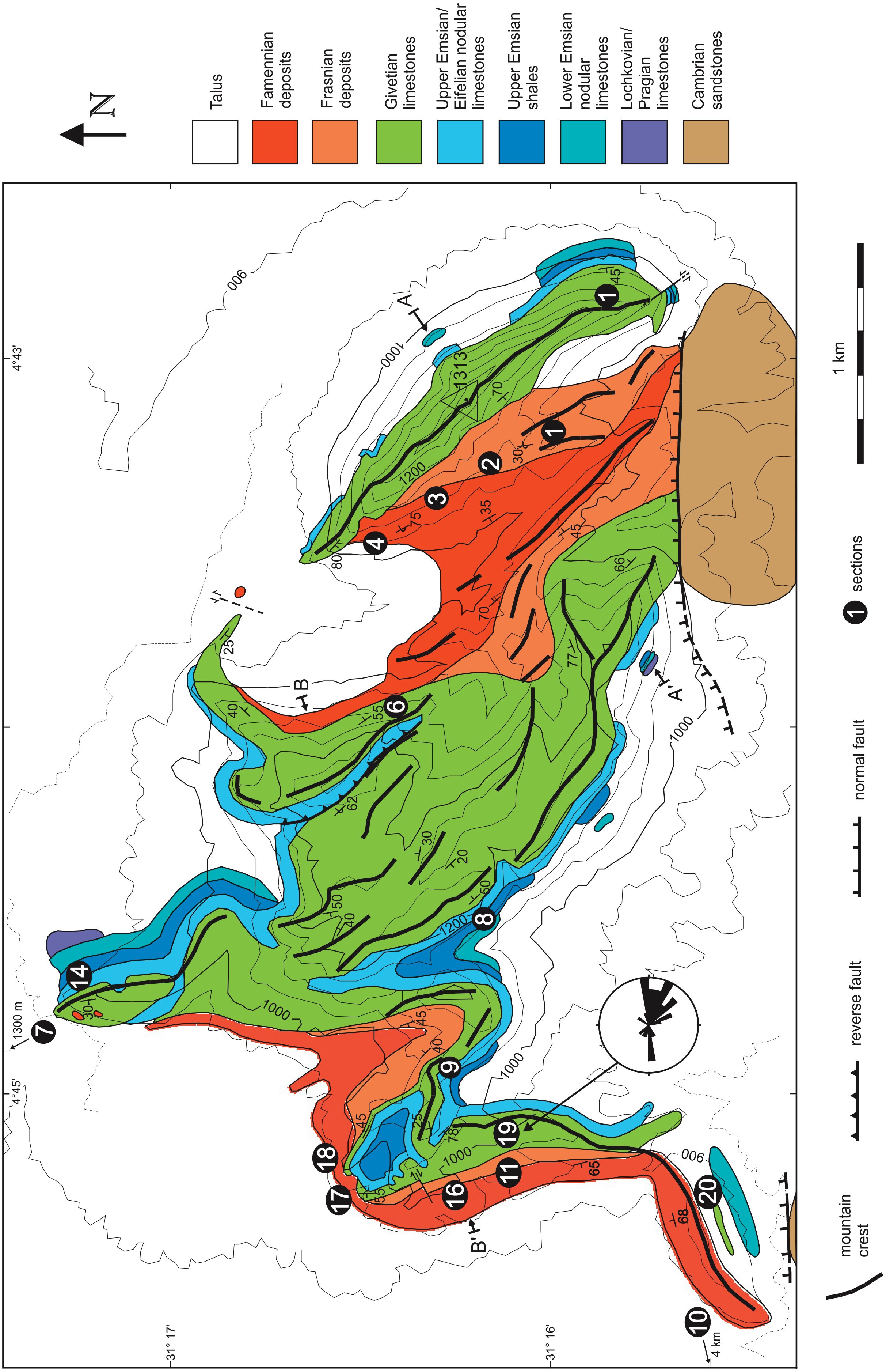


Fig. 3: Simplified geological map of the northern Mader (after Fetah et al. 1988 and own observations).

Fig. 4 (right page): Geological map of the Jebel Rheris (after Erbacher 1991, Spintzyk 1991, and own observations), including locations of sections. The rose diagram shows the orientation of 32 fold axes of Givetian crinoidal limestones, which differ from the Variscan NW-SE trending fold axes. Transects A - A' and B - B' are shown in Fig. 5.


N
Talus
Famennian deposits
Frasnian deposits
Givetian limestones
Upper Emsian/ Eifelian nodular limestones
Upper Emsian shales
Lower Emsian nodular limestones
Lochkovian/ Pragian limestones
Cambrian sandstones
1 sections
normal fault
reverse fault
mountain crest
1 km
4°43'
4°45'
-31° 17'
-31° 16'
1300 m
4 km
A
A'
B
B'
900
1000
1200
1313
1
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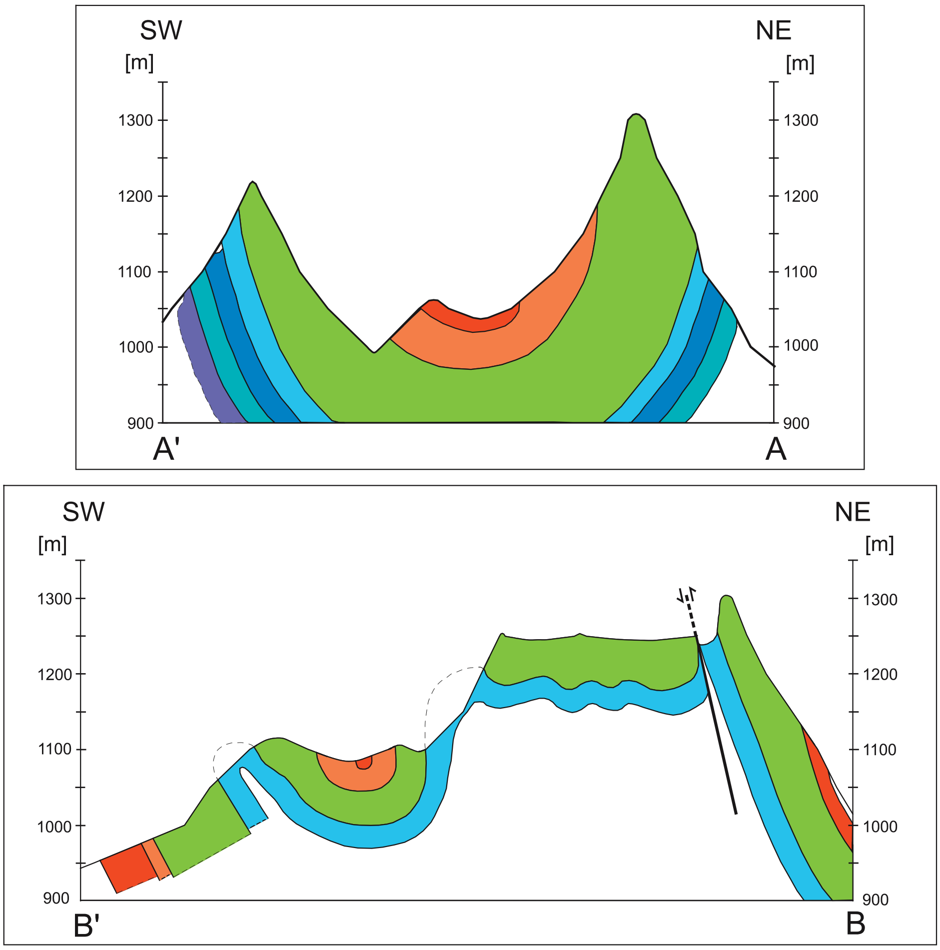

Fig. 5: NE - SW running sections through the Jebel Rheris, vertical scale exaggerated 2.5 times. For legend and location, see Fig. 4.

fills as well as condensed cephalopod-rich nodular limestones on pelagic ridges (Wendt 1988). During the Late Devonian, cephalopod limestone and shale sedimentation still was predominant, but increasingly affected by block faulting and tilting, which led to the development of angular unconformities and neptunian dikes (Wendt 1985). According to Scotese (1997), the palaeolatitude of northwest Africa shifted during the Devonian from 50° S to 30° S, but the drift history of Gondwana is still a matter of debate (e.g. McKerrow et al. 2000, Tait et al. 2000).

Carbonate production in the Anti-Atlas ceased in the upper Famennian: In the southern Tafilalt, the Lower Carboniferous consists of silt- and sandstones with cross bedding, deformation structures and current ripples that indicate transport direction from SW. The transition of this shallow-water sequence into slope and basinal settings is possibly situated in the northern Tafilalt region as is indicated by debris flow and turbidite deposits (Wendt et al. 1984).

Major Variscan deformation occurred during the Late Carboniferous in the eastern Anti-Atlas, but was rather mild because this region belongs to the stable cratonic domain, which represents the southern limit of the Variscan chains (Piqué et al. 1993). Palaeozoic strata are weakly folded, the fold axes run in more or less E – W and NW - SE direction (Choubert 1952). No metamorphosis occurred here. Flat lying Cretaceous and Tertiary sediments of the Hamada du Guir in the east and the Kem Kem in the south cap Palaeozoic sediments unconformably.

During the Devonian, the Jebel Rheris was situated between the Mader Basin in the south and the emergent crystalline Jebel Ougnate in the north (Figs. 2, 3). Crystalline components of the latter can be found in Devonian conglomerates of the Mader southwest of the Jebel Rheris (Kazmierzcak, pers. comm.), indicating that the Jebel Ougnate was emergent during that time. Lochkovian and Pragian lime- and siltstones rarely crop out at the Jebel Rheris and are therefore not considered in the present study. In contrast, a thick succession of Emsian and Eifelian nodular limestones and shales exists. Givetian coral-stromatoporoid biostromes and crinoidal grainstones build up the bulk of the Jebel Rheris (Figs. 4, 5), followed by Frasnian and Famennian quartz-rich crinoidal limestones and conglomerates.

The Palaeozoic deposits of the eastern Anti-Atlas reflect the palaeogeographic position of Gondwana. During the late Ordovician, the south pole was located in northwest Africa (Scotese & McKerrow 1990, Tait et al. 2000), resulting in the deposition of glaciogenic sediments in some areas (Deynoux 1985, Hamoumi 1999). The onset of carbonate sedimentation during the late Silurian and the growth of tabulate corals and stromatoporoids during the Givetian was probably made possible by the northward drift of Gondwana into lower latitudes.

3. THE CONCEPT OF SEQUENCE STRATIGRAPHY

Sequence stratigraphy can be defined as ”the subdivision of sedimentary basin fills into genetic packages bounded by unconformities and their correlative conformities” (Emery & Myers 1996). The principles mostly evolved in the 1970s, based on seismic studies of continental shelf strata (Vail et al. 1977a, b; Mitchum et al. 1977) and have subsequently been applied to numerous marine and also non-marine depositional systems (e.g. Wilgus et al. 1988). A depositional sequence is interpreted to form in response to the interaction between the rates of eustasy, subsidence, and sediment supply. It was the purpose of sequence stratigraphers to predict, with the aid of models derived from these three factors, stratal relationships and ages in areas where geological data are scarce or not available.

Basin-fills can be subdivided into a hierarchy of cycles (Duval et al. 1992): *First-order cycles* (>50 Ma) are related to changes in ocean basin volume due to plate tectonics; after Haq et al. (1987), only two first-order cycles exist in the Phanerozoic. *Second-order cycles* (3-50 Ma) are still related to long-term relative sea-level changes, mostly caused by tectonic subsidence in the basin or uplift of the hinterland. *Third-order cycles* (0.5-3 Ma) represent the basic units of sequence stratigraphy; they are also called sequence cycles. Glacio-eustasy is mostly considered to be the controlling factor (Vail et al. 1991). *Fourth-order cycles* (0.01-0.5 Ma) or parasequence cycles are caused by short-term relative sea-level changes, which are often related to autocyclic processes.

A sequence (third-order cycle) is composed of systems tracts (Fig. 6), which are defined by their position within a sequence, their bounding surfaces and the stacking patterns of parasequence sets (Van Wagoner et al. 1988). Three types are distinguished: lowstand (LST), transgressive- (TST), and highstand (HST) systems tracts in a type 1 sequence and shelf-margin, transgressive-, and highstand systems tracts in a type 2 sequence. A type 1 sequence boundary is characterised by subaerial exposure due to a relative fall in sea level at the depositional-shoreline break (or offlap break). Fluvial incision takes place together with submarine fan deposition. A type 2 sequence boundary is created, when the relative sea level falls over the proximal area of the highstand topsets, but not down to the offlap break. Fluvial incision and

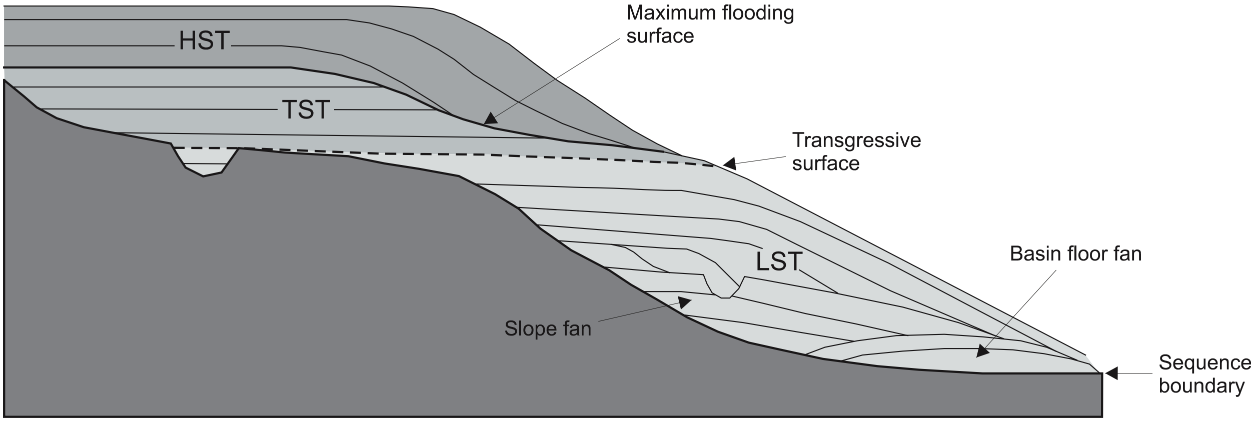

Fig. 6: Stratal geometries in a type 1 sequence on a shelf-break margin (after Emery & Myers 1996). LST: Lowstand systems tract; TST: Transgressive systems tract; HST: Highstand systems tract.

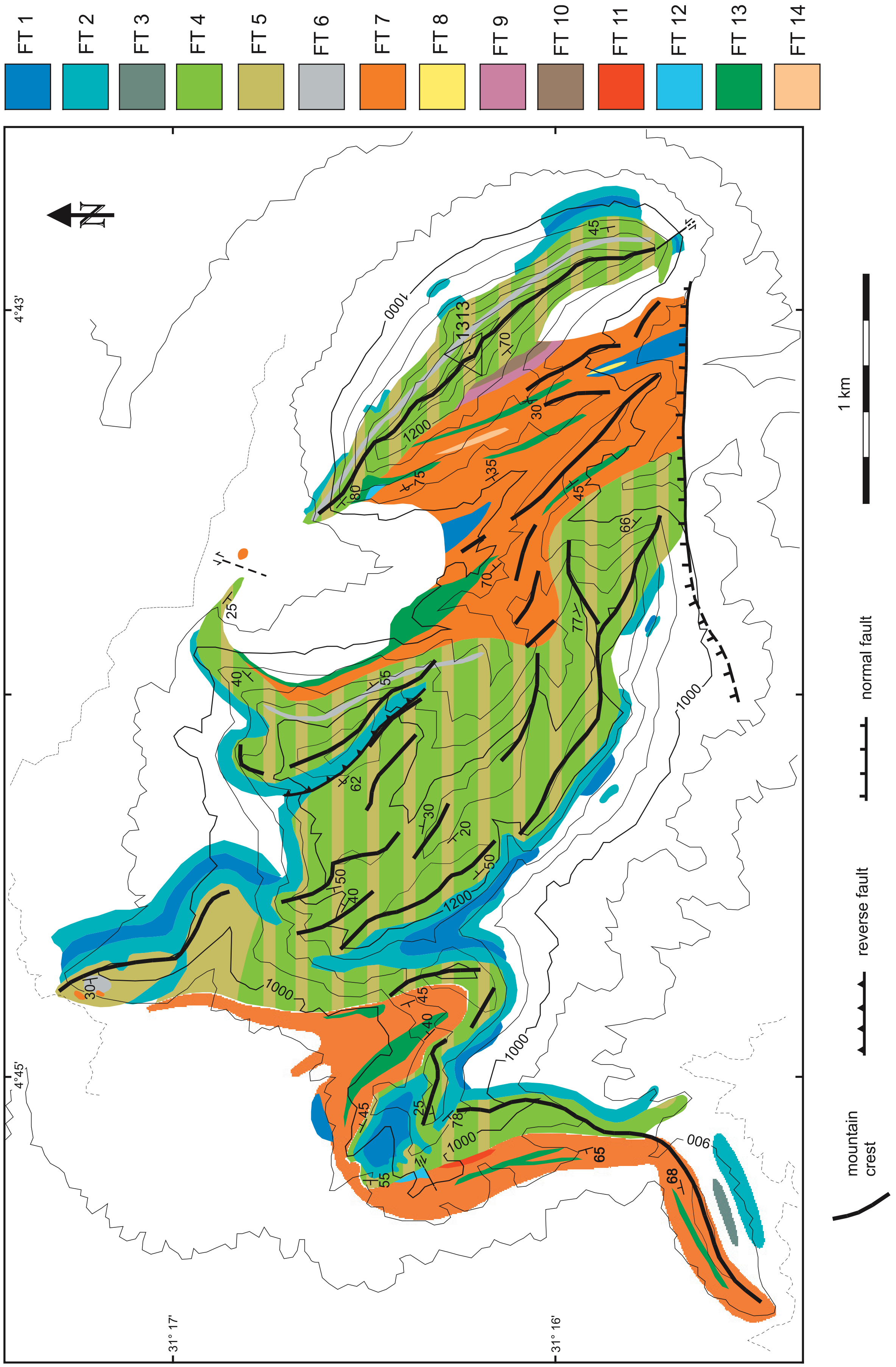

Fig. 7: Geographic occurrence of Emsian to Famennian facies types (FT) at the Jebel Rheris. Explanation of facies types in the text.

submarine fan deposition is lacking, but a downward shift in coastal onlap is characteristic.

In siliciclastic systems, the *lowstand systems tract* can be subdivided into a basin-floor fan, a slope fan, and a lowstand wedge (Van Wagoner et al. 1988) (Fig. 6). Sediment, eroded from the exposed shelf, bypasses the slope through valleys and forms fans on the basin floor (i.e. on top of a type 1 sequence boundary) during times of rapid eustatic fall. Slope fans on the middle or the base of the slope are characterised by turbidite and debris-flow deposition; they occur during the late eustatic fall or early rise. The progradational lowstand wedge, also deposited during the late eustatic fall or early rise, mostly onlaps onto the sequence boundary and downlaps onto the slope fan. While deposition during a LST occurs on the slope and in the basin, rivers adjust to the low sea level and incise into the highstand topsets of the previous sequence.

The *transgressive systems tract* is characterised by backstepping, retrogradational parasequences during rapid relative sea-level rise. The topset accomodation volume is increasing faster than the rate of sediment supply (Emery & Myers 1996). The boundary between the prograding lowstand wedge and the retrogradational TST is called *transgressive surface*.

The *highstand systems tract* starts, when the rate of relative sea-level rise is decreasing and progradation begins again. This boundary between TST and HST is called *maximum flooding surface*. The HST is deposited during the late part of a eustatic rise, stillstand, and the early part of a eustatic fall. Therefore, parasequence sets mostly are aggradational at first and succeeded by progradational sets (Van Wagoner et al. 1988).

Sequence stratigraphy in carbonate systems (e.g. Sarg 1988) differs from that of siliciclastic settings, because carbonate shelfs are 'living systems'. The terms, described above, are still valid, but differences need to be explained: During LST large parts of carbonate platforms or ramps are subaerially exposed and therefore 'killed' (Emery & Myers 1996). Chemical erosion (karst) may cause secondary porosity and permeability in humid climates, calcrete crusts develop in arid climates, but physical erosion rarely occurs. Therefore, only little carbonate is deposited during lowstand, which is possibly derived from fringing reefs (Eberli & Ginsburg 1987). During TST the 'start up' and 'catch up' phases of population growth (Neumann & Macintyre 1985) create aggradational rather than backstepping margins, if environmental conditions are favourable. If the sea level rises too fast, however, the carbonate system may drown (Schlager 1989). The most important difference between carbonate and siliciclastic systems is that in the latter, most sediment is shed into the basin during LST, whereas in the former, most carbonate is deposited in the basin during highstand ('highstand shedding'). The reason is that a carbonate platform actively overproduces sediment, when a large area of the shelf is flooded to a few tens of metres; this sediment then is redeposited onto the slope or in the basin (Emery & Myers 1996).

To recognise sequence boundaries and stratal geometries, most workers focussed on seismic lines. There are, however, several areas, where seismic data are lacking or useless for sequence stratigraphy because of deformed terranes. Both is true for the present study, which therefore is based on outcrop data, i.e. the analysis of facies changes and stratal stacking patterns. The concept of recognising a hierarchy of stratigraphic cyclicity in order to reveal accommodation changes and to establish a sequence stratigraphic framework was applied for example by Koerschner & Read (1989) and Goldhammer et al. (1990, 1993) to platform carbonates of various ages.

4. EMSIAN AND EIFELIAN

4.1 Facies and depositional interpretations

4.1.1 Shales (FT 1)

Green shales occur in almost all stratigraphic levels, mostly as thin interbeds between carbonate layers. However, there are three levels, where shales are preserved in a considerable thickness:

1) Upper Emsian shales ('Emsian argileux' after Massa 1965), which separate the two nodular limestone units (see above), are between 60 m and 70 m thick. They crop out at the base of the flanks of the Jebel Rheris and were deposited during the early Late Emsian (Fig. 8). Some trilobites have been found in the shales. Towards the top of this unit, 4 – 40 cm thick limestone layers are intercalated with increasing abundance (Pl. 2/8). These are mudstones and dacryoconarid wackestones with some bivalves and orthocone nautiloids.

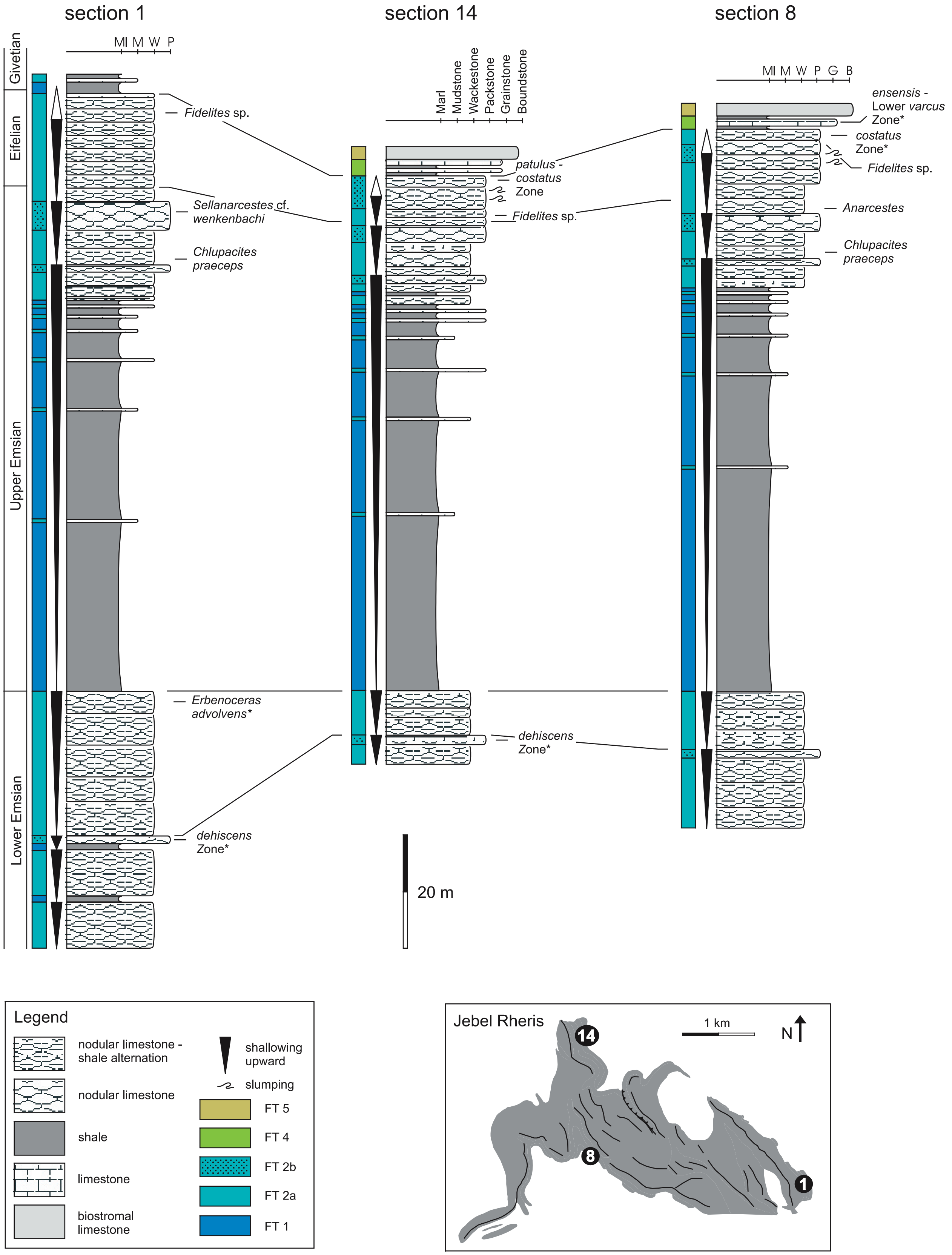

Fig. 8: Correlation of Emsian to basal Givetian sections of the Jebel Rheris. Conodont data and goniatites, marked with asterisks, after Erbacher (1991).

NODULAR LIMESTONES (FT 2a, b)

Lithology

Dacryoconarid wackestone/ packstone

Biota / Bioturbation

Abundant styliolinids, some orthoconic nautiloids, brachiopods, ostracods, trilobites, and gastropods; rare crinoids and goniatites.
Bioturbation common.

Non-skeletal grains

Not observed.

Stratigraphic occurrence

Lower Emsian - lower Eifelian (*dehiscens* Zone - *costatus* Zone).

Sedimentary structures

Nodular bedded; rare faint grading. Slumping structures are common in the Eifelian part.

Diagenetic features

Stylolites, microstylolite swarms.

Depositional environment

Pelagic / deep slope.

Tab. 1: Characteristics of facies type 2.

2) Middle Famennian shales: At the eastern edge of the Jebel Rheris, an up to 20 m thick shale unit occurs, which wedges out towards the west near section 1. According to conodont data of section 1, this unit was deposited in the middle Famennian. Thin-bedded sandy carbonates and sandstones are intercalated, as well as few up to 30 cm thick debris flows, where even 40 cm long reworked fragments of lithified thin-bedded limestone layers occur.

3) Upper Famennian shales crop out at the western edge of the Jebel Rheris with a thickness of 55 m. Conodonts of the Upper *expansa* – Middle *praesulcata* Zone occur in the underlying quartz-rich crinoidal limestones. At the top, sandstone layers and one limestone layer were deposited, the latter within the Middle *expansa* – Upper *praesulcata* Zone (Wendt, unpubl. data). Small patches of this shale unit occur in the centre of the syncline in the eastern part of the Jebel Rheris, but are mostly covered by Quaternary talus.

Depositional environment

The occurrence of shales generally can not directly be linked to a certain depositional environment. The lithofacies of intercalated layers has to be considered as well as the thickness of the shale succession. Upper Emsian shales were deposited in the basin, which is indicated by the considerable thickness of the shales and by the intercalation of pelagic limestones. In middle Famennian shales, however, sandstones, conglomerates, and debris flows are intercalated. Moreover, this shale succession occurs within quartz-rich crinoidal-bryozoan packstones of the mid-ramp, the shoreline was probably not far to the north. So the existence of a smaller intra-ramp basin is concluded here. Similarly, the upper Famennian shales were deposited onto mid-ramp limestones, crinoidal packstones / grainstones are intercalated in the upper part of the shales. Therefore, they are also interpreted as intra-ramp basin deposits.

4.1.2 Nodular limestones (FT 2a, b)

Light-grey nodular limestones mostly crop out at the base of the mountain, so the lower boundary is always covered by Quaternary talus. The Lower Emsian FT 2 succession is up to 44 m thick, the Upper Emsian and lower Eifelian FT 2 succession is between 23 m and 35 m thick; both successions are separated by Upper Emsian shales. Thickness patterns are more or less homogeneous throughout the Jebel Rheris.

Two subfacies can be distinguished: Thin-bedded (4-10 cm) nodular limestones, alternating with shales (1-40 cm) (FT 2a) and very thick-bedded (1-5 m) nodular limestones (FT 2b). While the amount of styliolinids in FT 2a is often rock-forming (Pl. 2/4), they are a less dominant component in FT 2b (Pl. 2/5), where the amount of ostracodes, trilobites, and brachiopods is higher. Both wackestones and packstones can be observed in facies type 2 (Tab. 1).

Depositional environment

High amounts of micrite and the dominance of styliolinids indicates deposition in the pelagic realm. Rare faint grading can probably be ascribed to distal tempestites; therefore a deep slope environment is inferred. A mottled structure due to bioturbation and the abundance of benthic organisms shows that the sea floor was well oxygenated. The nodular appearance of limestones is not an indicator for certain depositional environments, it is observed from neritic to pelagic facies in Phanerozoic limestones (see references in Wendt et al. 1984). At the Jebel Rheris, both bioturbation and diagenesis are probably responsible for the nodular appearance. Microstylolite swarms, which are common in FT 2, reflect diagenesis. They can develop in clayey limestones and produce a nodular structure; this process is called non-sutured seam solution by Wanless (1979).

FT 2a was deposited basinward of FT 2b because of the shale interbeds between the dacryoconarid limestones, lower bed thickness, and mostly higher amount of micrite. Abundant slumping structures in the lower Eifelian part of this succession might reflect a steepening of the sea-floor in that area.

4.2 Stratigraphy and facies development

Emsian and Eifelian strata consist only of nodular limestones (FT 2a, b) and shales (FT 1). A homogeneous facies pattern with only minor changes of thickness can be noticed (Fig. 8). The Lower Emsian part of the succession consists of mostly thin-bedded nodular limestone layers, alternating with thin shale layers (FT 2a). Two 1 m thick shales are intercalated in section 1 and in all three sections (1, 8, and 14), an about 1 m thick, easily recognisable FT 2b layer occurs, which was deposited in the *dehiscens* Zone. The Lower Emsian strata were called ‘Emsien calcaire’ by Massa (1965).

This succession is overlain with a sharp contact by 60 – 70 m thick green, almost unfossiliferous shales (‘Emsien argileux’ after Massa 1965). The onset of these shales can probably be related to the transgressive global Daleje Event (House 1985, Chlupac & Kukal 1988), it can be recognised throughout the eastern Anti-Atlas (e.g. Kaufmann 1998). Towards the top, nodular limestone layers are intercalated with increasing abundance.

Nodular limestones above the shale succession are similar to the Lower Emsian limestones. Two distinct FT 2b units occur in the entire Jebel Rheris area; a lower 1 m thick layer and an upper 3 – 5 m thick layer, separated by a 5 m thick FT 2a unit. *Sellanarcestes* cf. *wenkenbachi* was found in the upper layer, indicating an Upper Emsian age. 1 m above this layer, *Fidelites* sp. was found, indicating a lower Eifelian age.

The position and extent of Eifelian strata at the Jebel Rheris was controversially discussed by various authors (Massa 1965, Hollard 1974, Erbacher 1991). The occurrence of lower Eifelian strata is undoubted, but upper Eifelian rocks are extremely condensed or totally missing. Hollard (1974) described several goniatites, which occur within a 1 m thick horizon and concluded that the Eifelian succession is complete. According to Korn (pers. comm.), the described fauna is extremely heterogeneous and contains goniatites from Late Emsian to late Eifelian / early Givetian age. Erbacher (1991) found uppermost Eifelian / lower Givetian conodonts (*ensensis* – Lower *varcus* Zone) about 2 m above lower Eifelian conodonts (*costatus* Zone) in the central Jebel Rheris (section 8, this study) and concluded that upper Eifelian deposits are missing. However, arguments for extreme condensation of upper Eifelian deposits are that in sections 8 and 14, an about 1 m thick horizon with abundant bivalves (up to 10 cm large *Panenka* sp.), cephalopods (mostly orthocone nautiloids), trilobites (mostly *Phacops* sp.), and also solitary rugose corals and thamnoporoids occurs within the uppermost meters of the nodular limestone succession. In the same level at the western Jebel Rheris, *Agoniatites nodiferus* was found, which is restricted to the upper Eifelian Kacak-level (Klug pers. comm.). This indicates that there is no hiatus between lower Eifelian and Givetian deposits in the study area but upper Eifelian rocks are considerably condensed. In general, the Eifelian is represented by nodular limestones (FT 2a and b), thickness varies between 8 and 20 m. At sections 8 and 14, abundant slumping structures have been observed.

4.3 Cyclicity

With the onset of the Upper Emsian, an overall shallowing upward succession can be noticed until the middle Eifelian, which is composed of smaller scale asymmetric thickening and shallowing upward cycles. These can again be subdivided into basic units, made up of a shale layer and a FT 2a or b nodular limestone layer, both with varying thickness.

Two end-members of these basic cycles can be determined: A 40 cm thick shale layer, overlain by a 4 cm thick, dacryoconarid wackestone (type 1) and a 1 cm thick shale layer, overlain by a 5 m thick

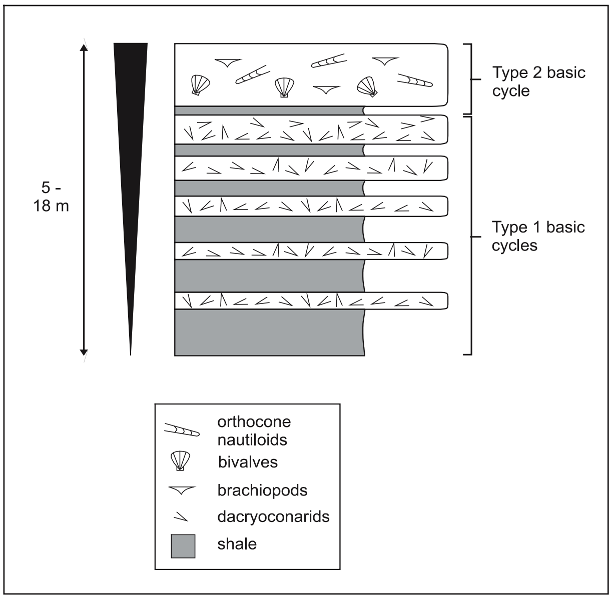

Fig. 9: Typical Emsian shallowing upward cycle, made up of type 1 and type 2 basic cycles.

nodular skeletal wacke-/packstone, mostly made up of orthocone nautiloids, brachiopods, gastropods and ostracods (type 2).

Fig. 9 shows an asymmetric thickening upward cycle, which is typical for Emsian and Eifelian strata at the Jebel Rheris. The cycles consist of type 1 units in the lower part, where the thickness of interbedded shales decreases upwards, the thickness of limestone layers slightly increases. A type 2 unit caps these asymmetric cycles.

Because of the deep slope and basinal setting of Emsian and Eifelian deposits, only large-scale sea-level changes are preserved in the rock record. As the base of Lower Emsian strata does not crop out at the Jebel Rheris, the amount of Lower Emsian cycles can not be determined. The Upper Emsian succession can be divided into two shallowing upward cycles, which together build one larger shallowing upward cycle. It is difficult to determine the absolute duration of one cycle, i.e. the time of relative sea-level fall and deposition of sediment plus the omitted relative sea-level rise.

Eifelian strata show one shallowing upward hemicycle and also a deepening upward hemicycle; the latter is mostly characterised by a slight increase in shale thickness between FT2 layers and a higher concentration of cephalopods and bivalves, indicating condensation.

A sequence stratigraphic interpretation for the Emsian and Eifelian succession remains speculative, because deep slope and basinal deposits were not subaerially exposed, long term hiatuses can not be proven and onlapping or offlapping structures can not be noticed in outcrop. Transgressive systems tracts are probably not represented in Emsian and Eifelian deposits. During times of relative sea-level rise, deposition occurred in shelf environments, which are not exposed at the Jebel Rheris. The shallowing upward cycles possibly belong to highstand systems tracts (highstand shedding), but sequence boundaries can not be determined in this environment, especially when coeval shelf-environments are missing.

5. GIVETIAN

5.1 Facies and depositional interpretations

In chapter 5.2 it is shown that a distally steepened carbonate ramp developed during the Givetian in the Jebel Rheris area (Figs. 12, 35). Therefore, in the following description and interpretation of Givetian facies types, the terminology of carbonate ramp environmental subdivisions of Burchette & Wright (1992) is used, which is briefly defined: *Inner ramp* – Zone above fair weather wave base (FWWB), including peritidal areas. *Mid-ramp* – Zone between FWWB and storm wave base (SWB). *Outer ramp* – Zone, extending from SWB to the basin floor. Distal tempestites may still occur. *Basin* – Depositional environment below the pycnocline, where tempestites are mostly absent.

5.1.1 Styliolinid-peloid packstones / grainstones (FT 3)

Facies type 3 (Tab. 2) crops out only at the southwestern edge of the Jebel Rheris. Thin- to medium-bedded (5-25 cm) limestones alternate with very thin-bedded shales. Major parts of this succession are covered by talus, the exact thickness can not be estimated. One conodont sample yielded a middle Givetian age (*rhenanus* – *latifossatus* Zone). Grading can be noticed in thin sections, where styliolinids, brachiopod shells, and some large crinoid ossicles dominate in the lower part, and peloids in the upper part (Pl. 2/2, 3).

Depositional environment

The occurrence of parallel oriented pelagic

STYLIOLINID-PELOID PACKSTONES/GRAINSTONES (FT 3)

Lithology

Graded styliolinid-peloid pack-/grainstone, interbedded with thin shales.

Biota / Bioturbation

Abundant styliolinids, often cone-in-cone; some brachiopod shells and crinoid ossicles. Bioturbation not observed.

Non-skeletal grains

Abundant peloids.

Stratigraphic occurrence

Givetian.

Sedimentary structures

Common grading and convolute bedding.

Diagenetic features

Fractures.

Depositional environment

Outer ramp.

Tab. 2: Characteristics of facies type 3.

styliolinids with cone-in-cone structures indicates transportation. Grading and convolute bedding argues for turbidites or distal tempestites. The latter is more probable, as storm deposits can be recognised in the same interval in mid-ramp environments. An outer ramp depositional environment is inferred for FT 3, peloids were presumably transported from shallower regions. The ramp was probably steepened at this place during the Givetian.

5.1.2 Crinoidal grainstones (FT 4)

This facies type (Pl. 4/1, Tab. 3) can be found in Givetian rocks throughout the Jebel Rheris, apart from its southwestern edge. The dark grey limestone layers are thin- to thick-bedded (5-40 cm) and usually separated by centimetre-thick shales. FT 4 occurs within a 220 m thick succession at the eastern Jebel Rheris, but the thickness diminishes considerably towards the west.

This facies type is not always dominated by crinoid ossicles, although they were observed in all FT 4 – thin section. Peloids are sometimes the dominant components and locally fragments of corals and stromatoporoids dominate. Micrite hardly occurs; poorly washed grainstones and rarely packstones formed.

Depositional environment

Grading in the limestone layers is caused by storm events. Because cross bedding and gutter cast occur only rarely, a large portion of the crinoidal grainstones are probably distal tempestites. It is concluded that FT 4 was deposited on the mid-ramp. Two end-members of this facies can be defined: A high amount of fragments of corals and stromatoporoids, which

CRINOIDAL GRAINSTONES (FT 4)

Lithology

Well bedded crinoidal / peloidal grainstone.

Biota / Bioturbation

Abundant crinoids, some brachiopods, gastropods, and ostracods; rare bryozoans, tabulate corals and stromatoporoids. Bioturbation common; mostly *Zoophycos*, rarely *Thalassinoides*.

Non-skeletal grains

Abundant peloids, some intraclasts.

Stratigraphic occurrence

Givetian.

Sedimentary structures

Graded layers are common, cross bedding and gutter cast is very rare. Some slumping structures.

Diagenetic features

Dolomitization, cutting through the original bedding, is common. Rare stylolites occur.

Depositional environment

Mid-ramp.

Tab. 3: Characteristics of facies type 4.

are relics of storm-reworked biostromes, is indicative of a proximal FT 4, whereas layers without coral and stromatoporoid fragments but with a considerable portion of micrite represent a distal FT 4.

Zoophycos, which is common in shale-rich interbeds of the crinoidal-grainstone facies, according to Seilacher (1967) generally occurs below wave-dominated environments but above the shelf break. In contrast, Byers (1982) describes the *Zoophycos*-facies above the wave base and down to abyssal environments. So this trace fossil can not be used to define a certain depositional environment. The origin of peloids can not unambiguously be determined. Some of these internally structureless grains (0.2-0.4 mm diameter) show irregular outlines and may represent micritic intraclasts. Peloids with ovoid ellipsoidal outlines, usually interpreted as faecal pellets (Folk & Robles 1964), were hardly observed. Dolomitisation, which obscured some of the primary structures of FT 4, probably occurred under shallow burial conditions (see chapter 10) and thus is not indicative of a certain depositional environment.

5.1.3 Coral-stromatoporoid biostromes (FT 5)

Biostromal limestones (Tab. 4) occur throughout the Givetian at the Jebel Rheris. Like crinoidal grainstones (FT 4), they are missing at the southwestern edge of the mountain. The thickness of individual biostromes ranges from 0.2 m to 3.7 m, however it can change within a lateral distance of a few meters for example from 2 m to 0.5 m. Biostromes may have irregular boundaries, but from a distance, they should have flat and parallel upper and lower surfaces (Kershaw 1994). This can be recognised at the Jebel Rheris. A classification, mainly based on the percentage of in-place versus allochthonous components shows that all stages from the completely transported allobiostrome to the *in-situ* preserved autobiostrome occur at the Jebel Rheris (see chapter 9). At the eastern edge of the mountain, FT 5 occurs within a 190 m thick succession. Towards the west, the thickness of Givetian strata is reduced to 40 m.

Depositional environment

Large amounts of colonial corals and stromatoporoids indicate shallow water conditions, but sedimentary structures, typical for constant wave action, are missing. So a mid-ramp depositional environment below FWWB is inferred for FT 5. Autobiostromes represent the proximal FT 5, whereas allobiostromes, which are frequently graded, represent the storm reworked and transported distal FT 5. Biostromal limestones alternate in large parts of the Jebel Rheris with FT 4, except for the northernmost part. Here, amalgamated or stacked biostromes occur. Because near the southern edge of the mountain towards the Mader basin, FT 4 can be noticed without interbedded biostromal limestones, FT 5 was deposited landward of FT 4 in a shallower environment (see chapter 5.2 for details).

5.1.4 Brachiopod coquina (FT 6)

A prominent shell coquina occurs in the lower middle Givetian at the Jebel Rheris (Pl. 1/6, Tab. 5). It can be observed over a lateral distance of more than 5 km. Shells are impunctate brachiopods and are concentrated in 20-100 cm thick layers. Under-

CORAL-STROMATOPOROID BIOSTROMES (FT 5)		
Lithology	**Biota / Bioturbation**	**Non-skeletal grains**
Coral-stromatoporoid boundstones / rudstones; crinoidal / peloidal grainstone matrix.	Abundant stromatoporoids, tabulate corals, some colonial and solitary rugose corals. Crinoids commonly, brachiopods rarely occur.	Some peloids and intraclasts.
		Stratigraphic occurrence
		Givetian.
Sedimentary structures	**Diagenetic features**	**Depositional environment**
Biostromes are mostly massive, sometimes grading occurs.	Dolomitization is common.	Mid-ramp, below FWWB.

Tab. 4: Characteristics of facies type 5.

and overlying rocks are crinoidal grainstones (FT 4) or biostromal limestones (FT 5). Döring (2002) reports similar coquinas in the northern Mader, but they seem to occur only in upper Eifelian to lower Givetian rocks.

Depositional environment

The concentration of shells within an up to 1 m thick layer and the lateral continuity of this horizon over several kilometres argues for a high-energy event, probably a major storm or a tsunami. The occurrence of FT 6 within FT 4 and FT 5 indicates that the brachiopod shells were transported from nearshore regions onto the mid-ramp.

5.2 Facies pattern and palaeogeography

With the onset of the Givetian, an abrupt facies change occurred, mostly caused by a fall of relative sea level. Eifelian deep slope nodular limestones are overlain by Givetian crinoidal grainstones (FT 4) and coral-stromatoporoid biostromes (FT 5) of a mid-ramp depositional environment in most areas of the Jebel Rheris. The homogeneity of thickness and facies pattern, typical for Lower Devonian and Eifelian deposits, also changed: Thickness of the Givetian strata varies considerably over short lateral distances, which is partly due to condensation, partly due to erosion. Lateral facies changes can be noticed from N to S.

The maximum thickness of Givetian deposits with about 250 m is found in section 1 at the eastern edge of the Jebel Rheris (Fig. 10). The base of the Givetian still consists of pelagic dacryoconarid wacke-/packstones, which yielded conodonts of the Lower – Middle *varcus* Zone. 25 m above the base, crinoidal grainstones occur and then alternate with biostromal limestones until the base of the Frasnian. A brachiopod coquina (FT 6) was deposited in the lower half of the succession, which can also be found in most other Givetian sections at the mountain and therefore serves as a marker bed. Parts of Givetian rocks (FT 4 and FT 5) were dolomitised during burial diagenesis (see chapter 10). The facies pattern changes in certain ways at the Jebel Rheris. About 50 biostromes alternate with crinoidal grainstones at section 1, whereas 1700 m to the NW at section 4, about 70 % of the Givetian strata consist of biostromes and the few intercalated crinoidal grainstones contain significant amounts of fragments of corals and stromatoporoids. Thickness is reduced to 80 m. 2400 m further to the NW at the northern edge of the mountain (section 14), Givetian rocks are only 20 m thick and have a massive appearance (Fig. 12/A). Apart from one marker bed, a shell coquina, no grainstone interbeds can be observed. But the upper and lower boundaries still are flat and parallel, so the term bioherm can not be applied. This succession seems to consist of amalgamated or stacked biostromes. The reduced thickness is partly a result of erosion, which can be recognised by comparing the position of the coquina in Givetian strata (Fig. 10). Nearly two thirds of the succession probably have been eroded during Frasnian and early Famennian times.

From section 4 towards SW it can be noticed that the portion of crinoidal grainstones increases (Fig. 11), whereas the thickness of the Givetian strata decreases. Biostromes still make up more than 50 %

BRACHIOPOD COQUINA (FT 6)		
Lithology	**Biota / Bioturbation**	**Non-skeletal grains**
Coarse brachiopod-peloid grainstone.	Abundant large fragments of brachiopods, often crinoid ossicles. Bioturbation not observed.	Abundant peloids, some intraclasts.
		Stratigraphic occurrence
		Middle Givetian.
Sedimentary structures	**Diagenetic features**	**Depositional environment**
Layers often graded, sometimes massive.	Rarely pressure solution.	Mid-ramp.

Tab. 5: Characteristics of facies type 6.

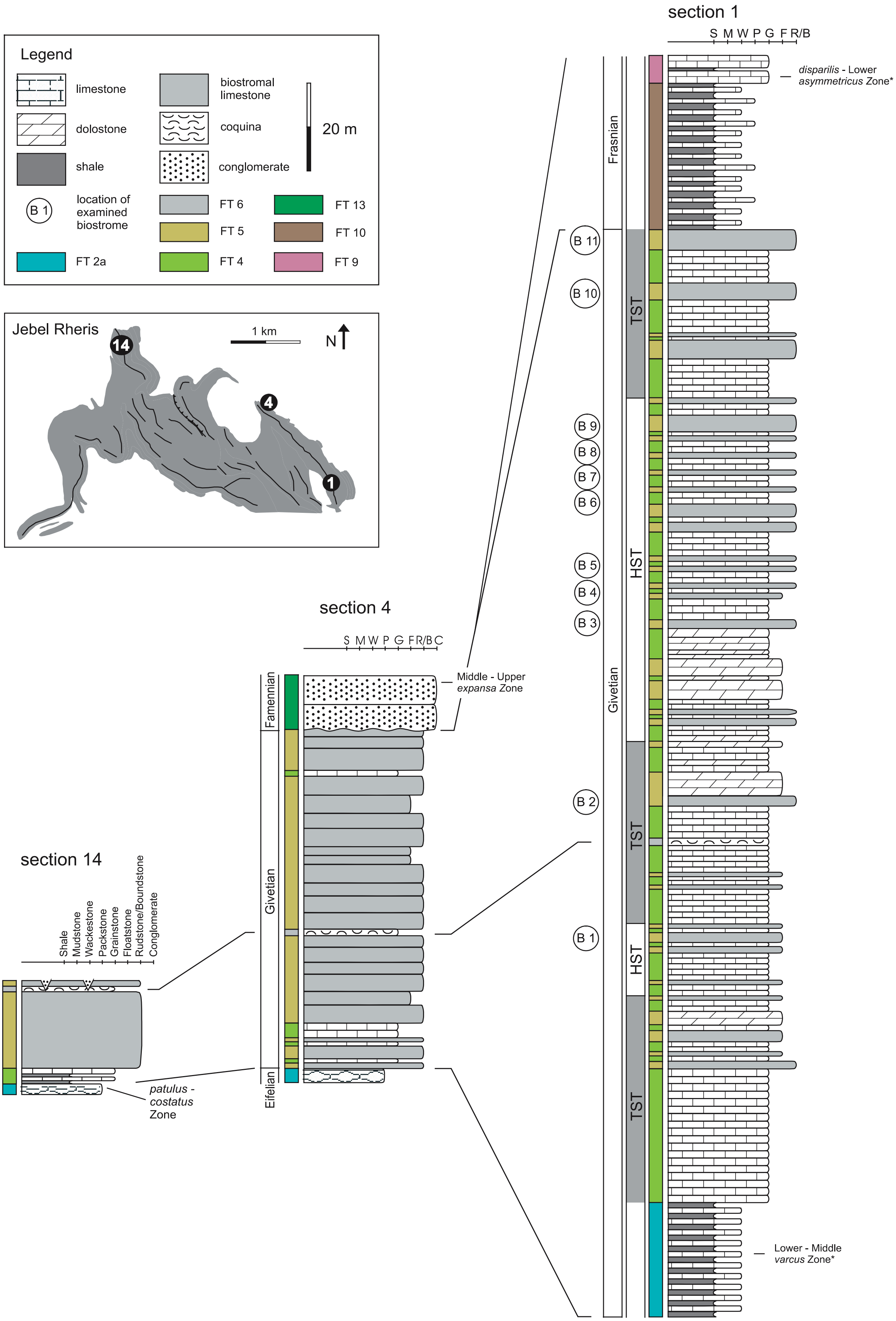

Fig. 10: Correlation of Givetian sections in NW-SE direction at the Jebel Rheris (conodont data marked with asterisks after Erbacher 1991). TST: Transgressive systems tract; HST: Highstand systems tract.

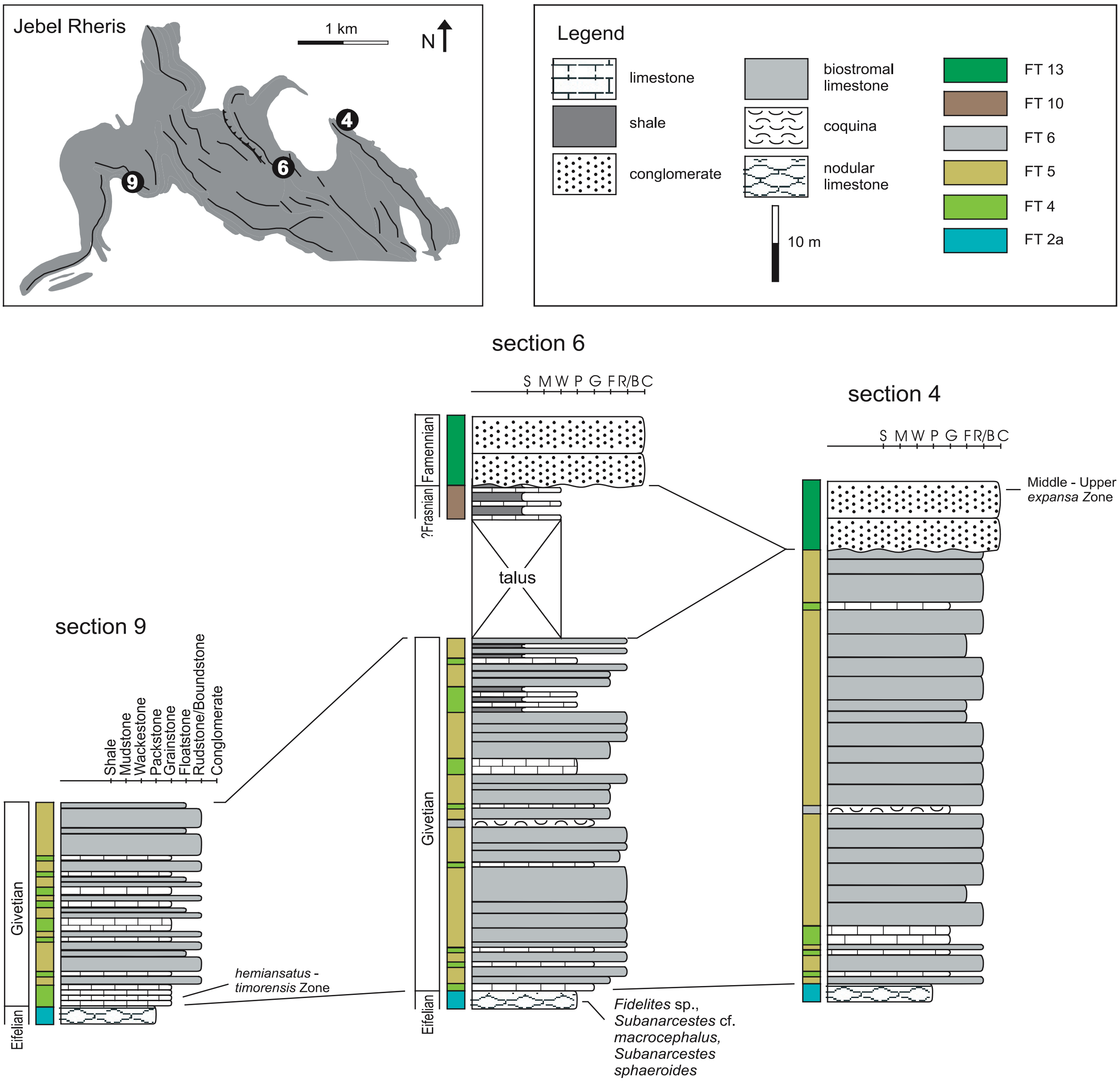

Fig. 11: Correlation of Givetian sections at the Jebel Rheris.

of section 9, but towards the south they disappear. At location 19, only crinoidal grainstones were deposited, which show conspicuous slumping structures with E – W oriented slumpfold axes (Fig. 4). As the axes of Variscan tectonic folds at the Jebel Rheris are oriented NW – SE and over- and underlying strata are not folded, these Givetian folds must be synsedimentary. Therefore, a slope towards the south is inferred, which is also confirmed by the occurrence of distal tempestites with convolute bedding structures at location 20. This is the southernmost area, where Givetian rocks crop out at the Jebel Rheris. Quaternary talus covers much of location 20, but outer ramp styliolinid-peloid packstones / grainstones (FT 3) can be observed, which were deposited during the middle Givetian (*rhenanus* – *latifossatus* Zone).

Generally it can be noticed that the thickness of Givetian strata diminishes from E to W. This is attributed to differential subsidence, creating different amounts of accommodation space. From N to S, the portion of biostromal limestones decreases, so it is concluded that crinoidal grainstones were deposited in deeper water than biostromal limestones. The lateral facies changes (from FT 5 to FT 4 and finally to FT 3 in the S) indicate that a distally steepened carbonate ramp developed during the Givetian (Fig. 12); but only the mid-ramp and – in the south – outer ramp portion is preserved at the Jebel Rheris. Givetian rocks are eroded N and NE of the Jebel Rheris but it is probable that this carbonate ramp extended

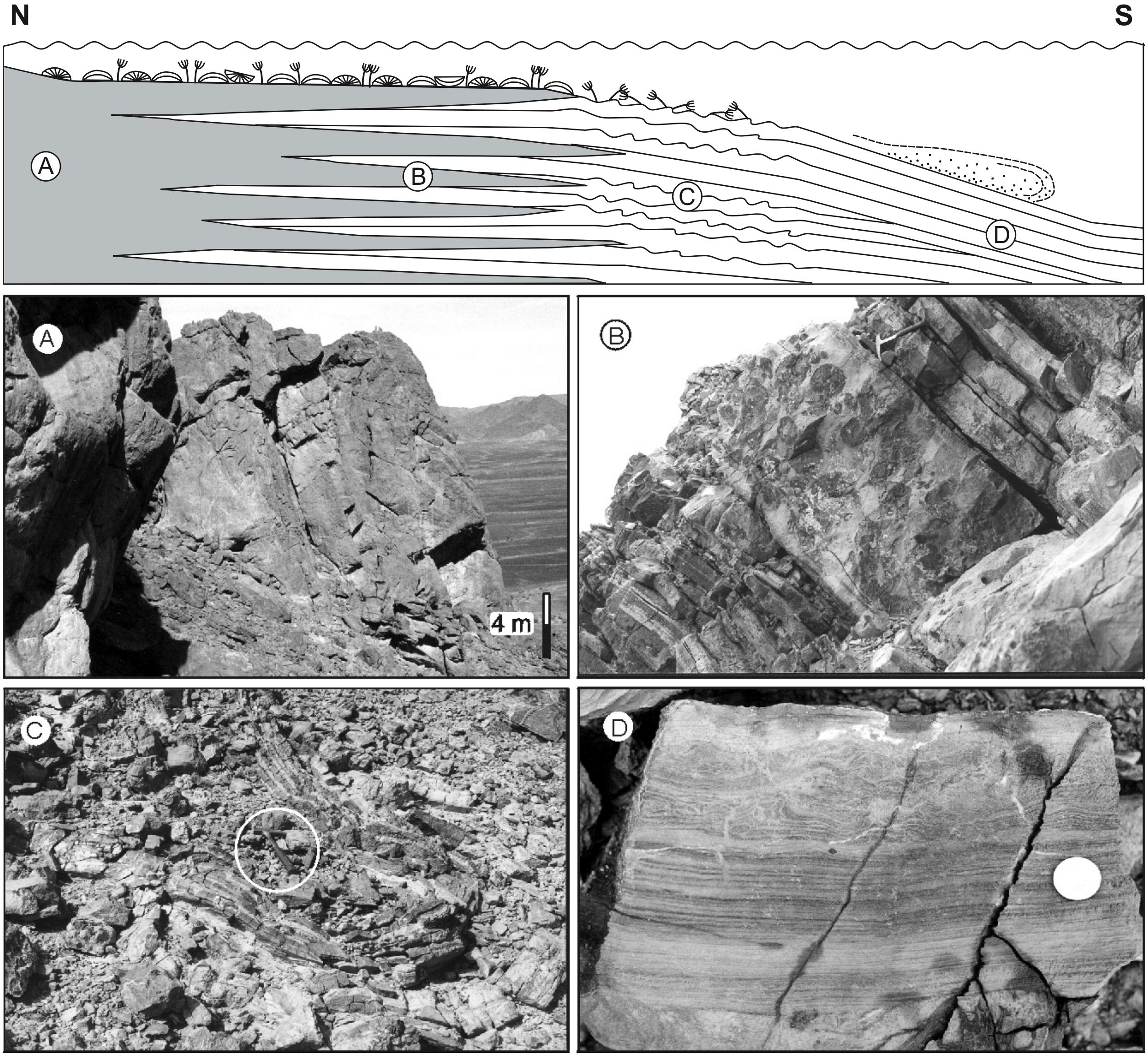

Fig. 12: *Model of a distally steepened carbonate ramp, which developed at the Jebel Rheris during the Givetian. (A) Amalgamated or stacked biostromes occur in the northern part at section 14. (B) Towards the south, crinoidal grainstones are more and more intercalated, observable for example in sections 1 and 9, and (C) finally replace the biostromal facies at location 19, where slump folds developed. (D) Givetian rocks at the southernmost part of the mountain at location 20 show horizontally laminated layers with convolute bedding at the top, indicative of a deeper environment (distal tempestites).*

several kilometres or tens of kilometres towards the NE during the Givetian.

5.3 Cyclicity

Most of the Givetian deposits at the Jebel Rheris consist of an alternation of crinoidal grainstones and coral-stromatoporoid biostromes. Towards the north of the mountain, this cyclicity is more and more obscured, because the biostromes are amalgamated; at section 14, no cycles can be observed any more. The best place to document Givetian cycles is section 1, as the highest thickness guaranties the highest resolution, furthermore FT 4 and FT 5 are present in similar quantities here.

Asymmetric cycles with a dominant shallowing upward hemicycle and a thin deepening upward hemicycle are most common, but the deepening upward hemicycle sometimes is completely missing. A typical cycle begins with an about 5 cm thick crinoidal grainstone layer; overlying layers are increasing in thickness to up to 40 cm, also the amount of fragmented corals and stromatoporoids increases upward. Very thin shale interbeds do not vary in thickness. An up to 3.7 m thick biostrome lies on top. Crinoidal grainstone layers above the biostrome are decreasing

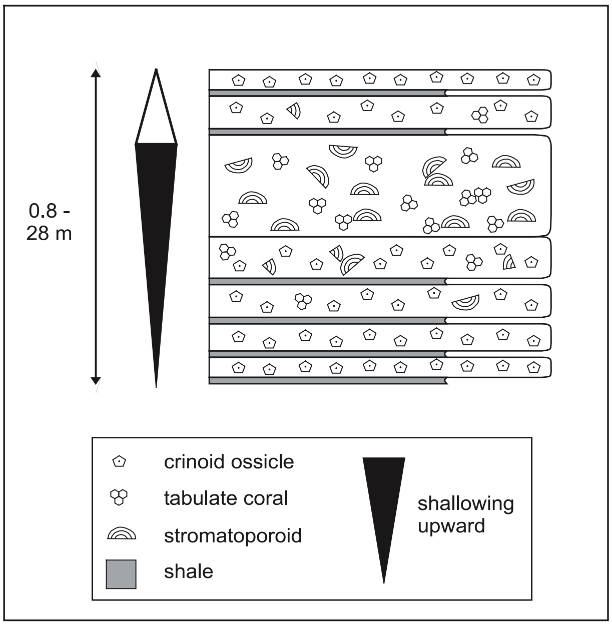

Fig. 13: Typical Givetian asymmetric cycle.

in thickness and show a decreasing amount of coral- and stromatoporoid-fragments (Fig. 13).

The Givetian deposits of section 1 consist of 49 cycles. The thickness of each cycle varies between 28 m and 0.8 m, the average cycle thickness is 4.48 m. In order to visualise variations of the accommodation space during the Givetian, a Fischer plot was drawn for the succession of section 1 (Fig. 14). Fischer (1964) used this type of diagram for the first time to explain variations in the thickness of the Triassic peritidal ”Lofer cyclothems”. Sadler et al. (1993) discussed the correct labeling of the axes and the database of Fischer plots in order to make sure that the plots are objective descriptions of the stacking pattern of stratigraphic sections. To create a Fischer plot, the thickness of the first cycle of a succession is drawn as a vertical column. The thickness of the second cycle is again drawn as a vertical column, and the base is shifted to the right and down from the top of the one below. The distance to the right and down is equal for every cycle of the diagram whereby the downward shift is the mean cycle thickness. A line, which connects all cycle tops, therefore has a negative slope where the cycle has a lower thickness than average and a positive slope where the cycle has a higher thickness than average.

Fischer plots were mostly used in studies concerning peritidal carbonates, but they are also useful in the present study where Givetian cycles were formed in a mid-ramp setting. The changes of the accommodation space and a cycle hierarchy could otherwise hardly be detected. The base of the first Givetian cycle in section 1, which is by far the thickest, marks the facies change from pelagic dacryoconarid packstones to the mid-ramp crinoidal grainstones. From here up to the youngest biostrome, 49 cycles are preserved. By analysing the cycle thickness pattern, 9 cycles of higher order can be distinguished, which start with a negative slope (i.e. time of slow creation of accommodation space) and end with a positive slope (fast creation of accommodation space). Individual ‘megacycles’ usually are asymmetric, they show a gentle fall and a steep rise. According to Sadler et al. (1993), this asymmetry can be observed in most Fischer plots and should not be attributed to tectonic or eustatic processes. The Givetian epoch lasted for 5 Ma (McKerrow & Van Staal 2000), so the 9 ‘megacycles’ are interpreted to represent fourth-order relative sea-level changes, the 49 basic cycles fifth-order relative sea-level changes.

5.4 Sequence stratigraphy

To establish a sequence stratigraphic framework for the Givetian strata at the Jebel Rheris, the Fischer plot of section 1 cycles appears useful (Fig. 14). Systems tracts and boundaries of third-order sequences can be recognised by the cycle stacking patterns, because systematic shifts in cycle thicknesses record long-term changes in third-order accommodation. This method was applied by Goldhammer et al. (1993) for Ordovician platform carbonates, but these authors noticed also changes of the depositional subfacies, for instance siliciclastic input during LST, to strengthen the sequence stratigraphic interpretation. In the present study, the facies development is rather monotonous, mostly two facies types (crinoidal grainstones and coral-stromatoporoid biostromes) occur. Moreover, onlapping or downlapping of strata can not be identified in the field, so the subdivision into third-order sequences is merely based on the stacking pattern.

Changes of accommodation space are interpreted as relative sea-level changes, so periods with increasing cycle thickness, expressed as a rising line on the Fischer plot, represent transgressive systems tracts (TST). This can be recognised two times within the lower third of the Givetian section and one time at the top. The inflection points mark the top of the TSTs, which are by definition the maximum flooding surfaces (MFS). The following thinning upward cycle

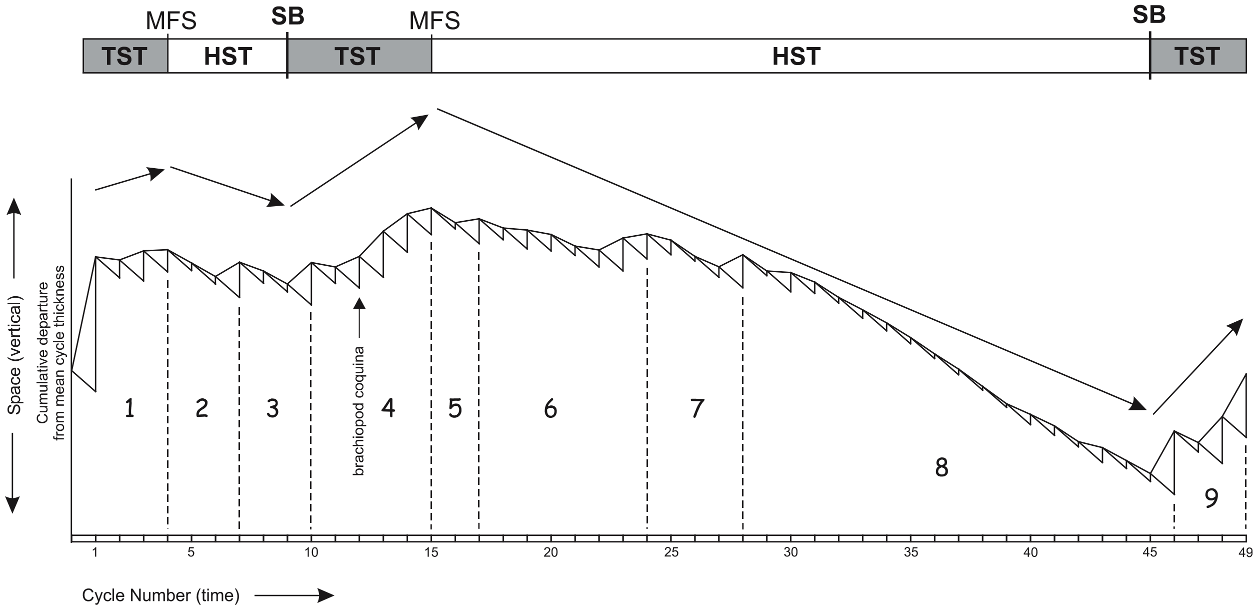

Fig. 14: Fischer plot of Givetian deposits in section 1, which is composed of 49 fifth-order cycles. These are grouped into 9 fourth-order cycles, each showing a falling and a subsequent rising limb, indicating decreasing and increasing accommodation. Longer-term trends in accommodation changes, interpreted as relative sea-level changes, are used to define third-order sequences and systems tracts. TST: transgressive systems tract, HST: highstand systems tract, MFS: maximum flooding surface, SB: sequence boundary.

stacking pattern indicates a decline in third-order accommodation, which developed during a decreasing sea-level rise and the subsequent sea-level fall and thus is interpreted as highstand systems tract (HST). A lowstand systems tract (LST) can not be noticed in section 1, probably because of the mid-ramp position. Therefore, the sequence boundaries (SB) occur between the HST and the TST. Type 1 versus type 2 sequence boundaries generally are difficult to define in carbonate ramp depositional systems (Goldhammer et al. 1993, Montañez & Osleger 1993). Also in the present study a separation is impossible. Sequence boundaries in Givetian deposits of the Jebel Rheris do not show evidence of subaerial exposure; they are located within conformable stratigraphic intervals, their positions are determined by analysis of the Fischer plot.

Compared to section 1, Givetian successions towards the west of the Jebel Rheris are considerably condensed and were partly eroded before the late Famennian. Because the number of cycles is too low, Fischer plots were not created for these sections. According to Sadler et al. (1993), interpretations may be misguiding if the cycle number is much below 50. Nevertheless, if the cyclicity was caused by eustatic sea-level changes, it should be possible to recognise a similar cycle pattern at least in sections 6 and 9, where crinoidal grainstones and biostromes alternate more or less regularly. Because this was not possible, it is concluded that tectonic processes are responsible for the third-order cycles. Subsidence rates had different intensities during the Givetian within the Jebel Rheris area, which probably resulted in different stacking patterns.

Döring (2002) presented a different sequence stratigraphic interpretation for deposits of the Mader area. On the basis of slightly prograding facies pattern, he suggested a HST for the whole Givetian succession except for the lowermost part, which is represented by dacryoconarid limestones at the Jebel Rheris. Lubeseder (2000) interpreted Givetian deposits of the western Tafilalt as a HST lasting until the upper Givetian (*Pharciceras amplexum* Zone), where he found a SB. This SB might correlate with that of the Jebel Rheris deposits, but the lower Givetian sequence stratigraphy of both studies can not be correlated.