5 SEQUENCE STRATIGRAPHIC FRAMEWORK

In order to understand facies relationships, facies dynamics, and the geotectonic setting of the Mader, the combined application of sequence stratigraphy, lithostratigraphy and biostratigraphy (integrative stratigraphy) turned out as a useful approach (Chap. 3.3).

Thickness and facies of the Devonian successions vary considerably in the Mader (Fig. 16): A thick Devonian succession (ca. 2100 m) in the northern study area (Boulchral-1, 3, Bou Dib) contrasts with thinner successions in the southern (ca. 400 m) and the northernmost (650 m) areas. Emsian and Eifelian deposits appear relatively similar with respect to thickness and facies in the entire Mader. The Givetian shows very pronounced lateral facies differences as reflected by a thick succession of shallow-water limestones in the north (Jebel Rheris), resedimented limestones farther to the south (Bou Dib), and a relatively thin succession of shallow-water limestones in the south (Madene El Mrakib). During the Late Devonian these contrasts increased: A thick succession in the northern Mader (pelagic deposits with turbidite intercalations at Bou Dib) contrasts with shallow-water limestones in the northernmost Mader (Jebel Rheris) and with a relatively thin succession of homogenous pelagic rocks in the southern area (Madene El Mrakib). The top of the Devonian succession is formed by a siliciclastic unit which is similar throughout the Mader and reflects deltaic conditions (Chap. 2.2). The sequence stratigraphic analysis of this study focuses on the upper Emsian to lower Givetian successions. According to the stratigraphic concepts of Cross & Lessenger (1998), Homewood (1996), Mitchum & Van Wagoner (1991), and Kendall & Schlager (1981), the studied interval was subdivided into 10 major depophases (1a-5e) which are separated at their bases and tops by maximum flooding zones or rise to fall turnaround zones (Chap. 3.3.1). According to the recorded bio- and lithofacies, the depositional system of each depophase was reconstructed under consideration of the carbonate ramp model of Burchette & Wright (1992).

App. 21-24 illustrate the stratigraphic framework for the Lower to Middle Devonian strata (depophases 1a-5e). Individual depophases were correlated with the conodont zonation (Fig. 18). For an better understanding of the geometry of correlative units, these were arranged along the depositional dip according to Fig. 17 and are displayed in Figs. 20, 21, 23 and 25. Facies relationships during maximum-fall conditions were reconstructed for most depophases and are shown in three-dimensional sketches (Figs. 22, 24, 26). Individual sections including field and thin section data are shown in Appendix 1-20.

5.1 Depophase 0, Emsian (*excavatus - serotinus* Zone)

Rocks deposited before depophase 1 include Emsian limestones and Emsian shales ("Emsien calcaire", "Emsien argilo-silteux" *sensu* Massa 1965). These strata were not studied in detail and are neither included in the figures nor in the appendix but will be briefly described below.

5.1.1 Depophase 0a, Emsian ("Emsien calcaire" *sensu* Massa 1965, Emsian limestones)

Even though thickness vary between 2 m at Jebel Kem and 40 m at Jebel Issoumour and Timerzit, this interval generally shows only minor thickness and facies differences throughout the Mader (Fig. 19a). The isopach map does not show indicative sedimetological trends and since the varying outcrop conditions limit the accuracy of detected thickness and lithology data, this pattern should be interpreted with caution.

Rocks attributed to depophase 0a show a very similar composition in the entire Mader; they mostly consist of dacryoconarid limestones (LF 9). Rocks are nodular to well bedded and lack significant geometries in outcrop. They are usually mud supported, show a wackestone to packstone texture, and sedimentary structures are almost absent. From lithostratigraphic evidence, this unit can be followed over large parts of the Mader (Pl. 6, Figs. 1, 5). It is considered as an isochronous unit because it yielded the same ammonoids in the upper part of the succession (*Erbenoceras* and *Mimagoniatites*).

Interpretation

The absence of significant sedimentary structures, the predominance of pelagic organisms, and the high clay content indicate that the palaeoenvironment was situated below the wave base, in the deep subtidal. Since a significant facies gradient was not observed in the Mader, the depositional dip during depophase 0a was very low and environmental conditions were rather similar throughout the Mader.

The high carbonate content, compared to the underlying strata, and the geometry of this unit may indicate highstand conditions. Because of the homogenous facies and thickness distribution, Emsian limestones are interpreted as the distal portion of a highstand systems tract (HST) whereas the proximal part is supposed to have been accumulated outside of the study area, probably further south.

5.1.2 Depophase 0b, Emsian ("Emsien argilo-silteux" *sensu* Massa 1965)

The thickness of this unit varies between 50 m at Jebel Kem and 160 in the northern Mader. The isopach map shows an ellipsoidal depocentre located in the northern Mader which is oriented NW-SE (Fig. 19b).

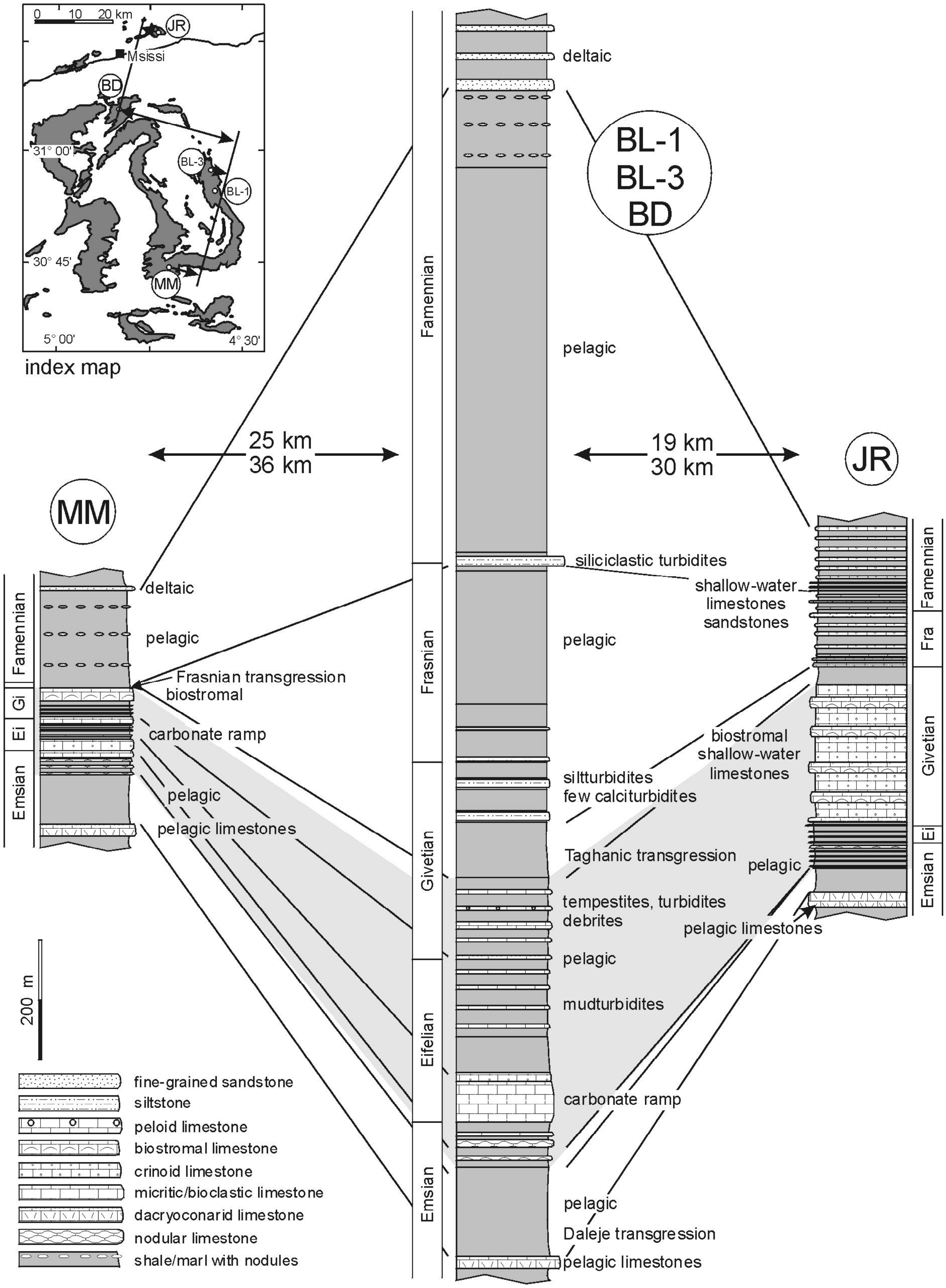

Fig. 16: Representative stratigraphic sections from the Mader with simplified lithology and environmental interpretation. The grey-shaded interval is the main subject of this study. Thickness of individual beds is not to scale within limestone-marl/shale alternations (JR: Jebel Rheris, BD: Bou Dib, BL: Boulchral).

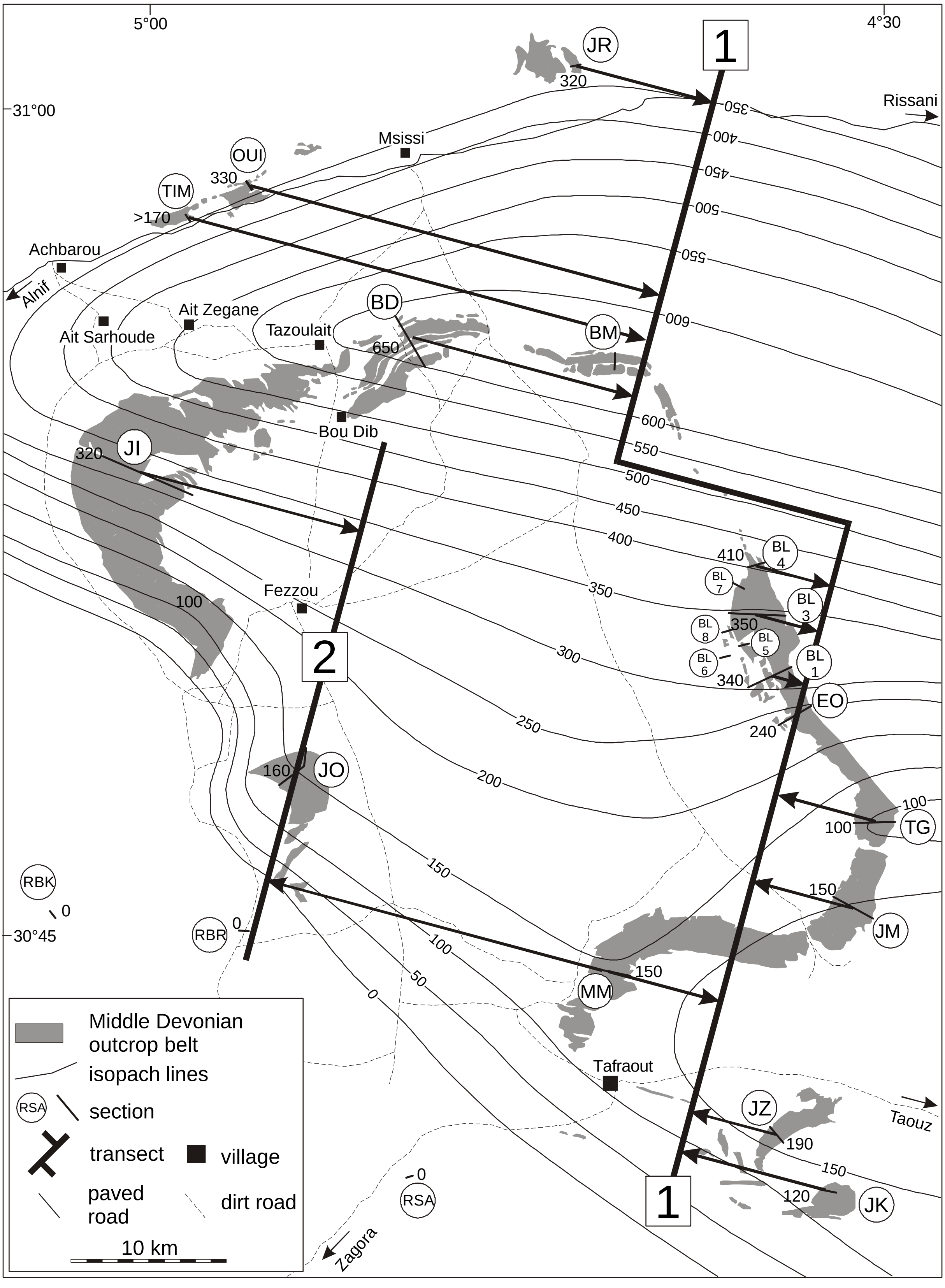

Fig. 17: Map of the Mader with the Middle Devonian outcrop belt, isopach lines of the Middle Devonian, location of sections, and transect lines 1 and 2. Sections RSA, RBK, RBR and BM are not included in the sequence stratigraphic framework, and sections Boulchral-5 - Boulchral-8 comprise only small stratigraphic intervals. (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).

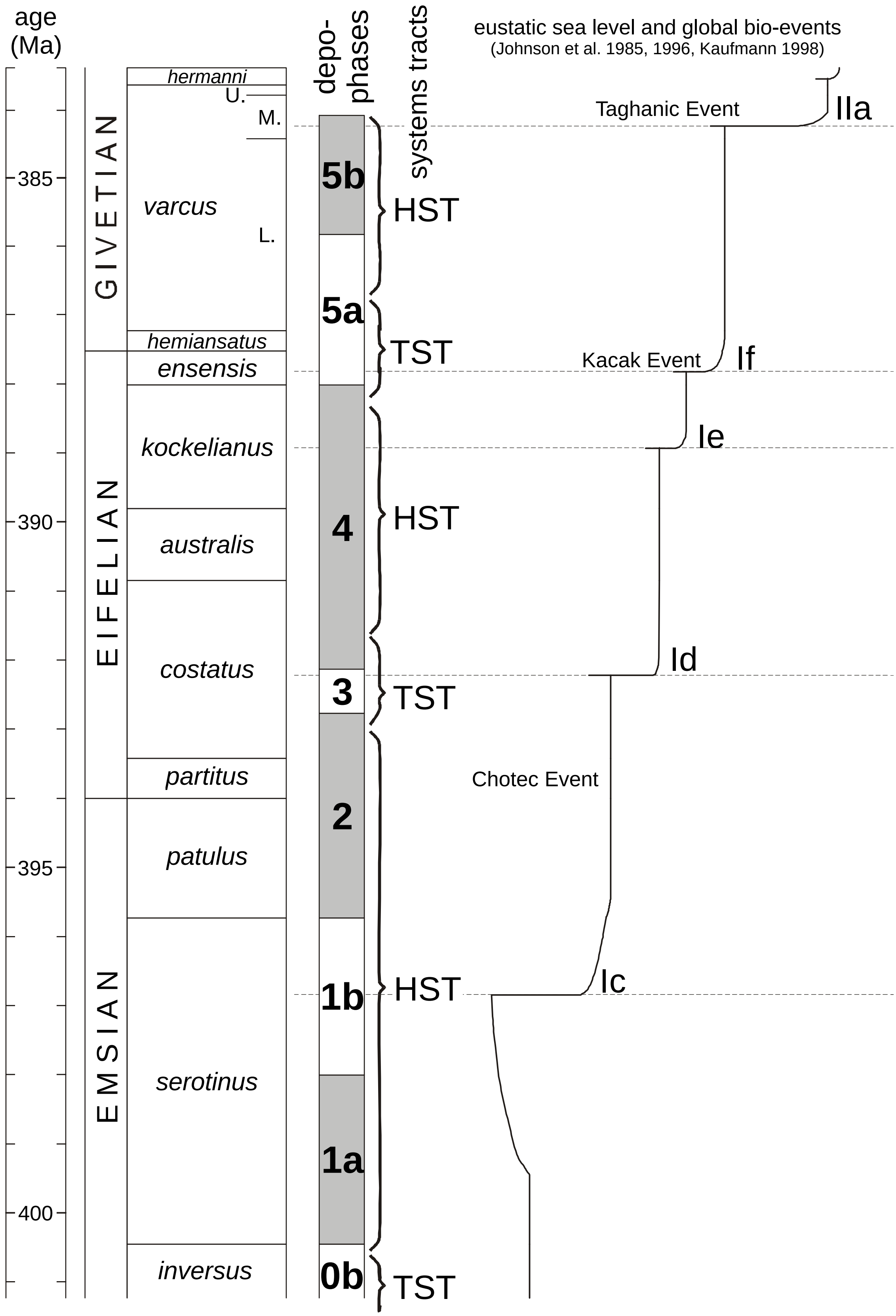

Fig. 18: Devonian conodont zonation for the studied stratigraphic interval and correlation with depophases, systems tracts, and the sea-level curve of Johnson et al. (1985). Conodont zonation after Weddige (1996), absolute ages from Tucker et al. (1998). Relative lengths of Emsian conodont zones after Weddige (1996), Eifelian ones after Belka et al. (1997) and Givetian ones after House (1995).

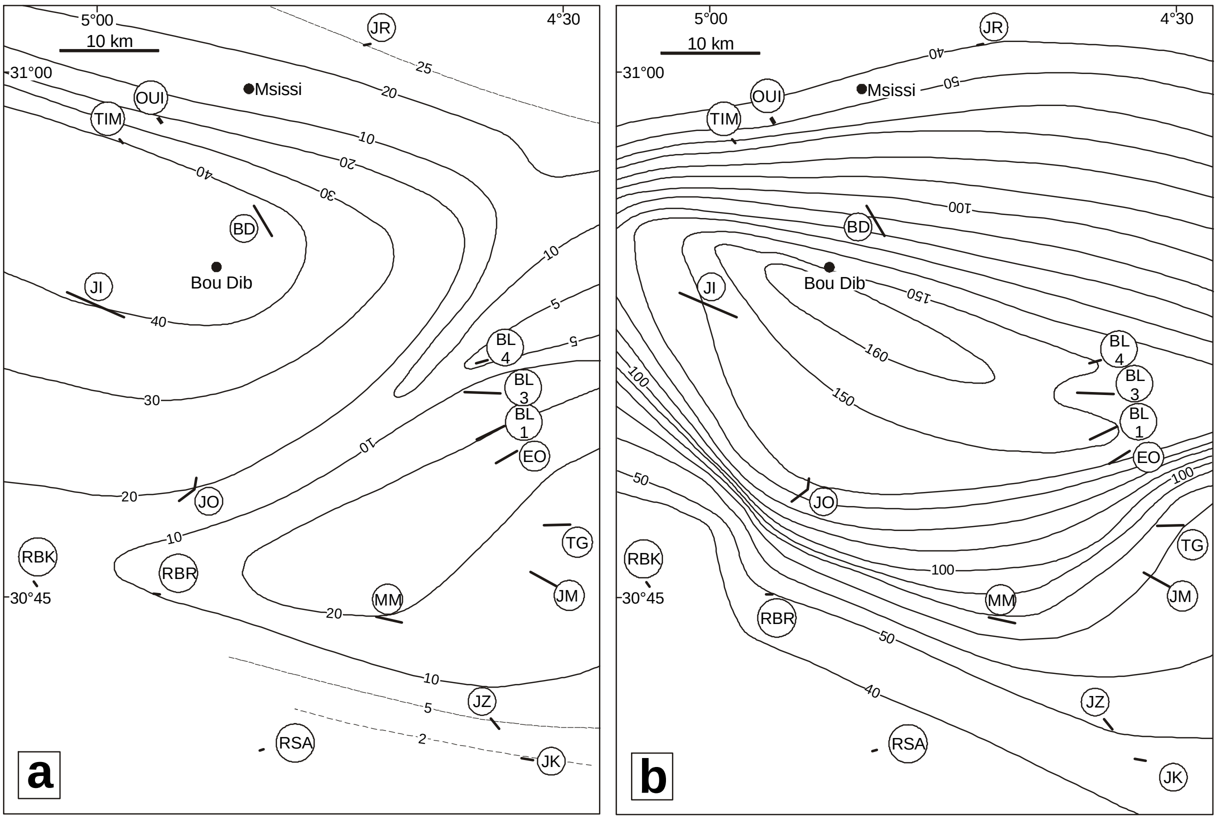

Fig. 19: Thickness variations of depophase 0a (lower Emsian limestones, a) and depophase 0b (Emsian shales/ marls, b) in the Mader. Abbreviations of sections correspond to Fig. 17.

Rocks consist mainly of shales (LF 1) in which mm-thick laminated siltstones (LF 10) are intercalated locally (Jebel Issoumour, Jebel Oufatene). Organic remains are scarce, although towards the top of the unit, some intercalated limestone nodules may contain crinoids, brachiopods, and trilobites. Because of the unfossiliferous character of the lithology and the often poor outcrops, this interval was not investigated in further detail.

Emsian shales form a well-defined lithostratigraphic unit (Pl. 6, Figs. 1-3, 5) between the Emsian limestones and the upper Emsian nodular limestones. Strata of this unit are exposed in the entire Mader except for the westernmost parts (Rich Bou Kerzia). Biostratigraphic data are not available, but considering data from the underlying and overlying successions, it can be assumed that the Emsian shales were accumulated within the *excavatus* and *inversus* conodont Zones.

Interpretation

The low carbonate and fossil content and the homogenous appearance of the succession, indicate deposition in the deep subtidal, below the storm wave base. Depositional conditions were very similar throughout the Mader. Thickness contrasts are supposed to have originated from local subsidence differences. Towards the upper part of the successions, an initial baselevel fall is indicated by the increasing carbonate (limestone nodules) and organic content. This trend continues into the successions attributed to depophase 1a.

The abrupt facies change from the underlying dacryoconarid limestones (depophase 0a) to monotonous shales (depophase 0b), indicates rapid drowning during the early Emsian. Accordingly, the base of depophase 0b is interpreted as a flooding surface which correlates with the Daleje-Event (House 1985) or the younger of the two intra-Ib transgressions (Johnson et al. 1985, 1996). Consequently, most of depophase 0b represents a transgressive systems tract (TST). The uppermost part, is attributed to the early highstand systems tract which persisted during depophase 1.

It is assumed that shale and marl sedimentation during depophase 0b led to a more or less balanced topography. Upper Emsian nodular limestones (depophase 1a) overlying these shales and marls show only minor thickness changes and lack a clear facies gradient; they indicate the persistence of the balanced topography. Based on these considerations, younger strata (depophase 1b - depophase 5e) was subsequently stacked upon this level surface.

5.2 Depophase 1, late Emsian (*serotinus* Zone)

Depophase 1 corresponds to the early phase of carbonate-ramp development of the Mader. It can be subdivided into depophase 1a and 1b: Depophase 1a comprises the homogenous succession of upper Emsian nodular limestones, whereas depophase 1b consists of limestones and limestone-marl alternations including the *Sellanarcestes* marker bed (Pl. 6, Figs. 1-3).

5.2.1 Depophase 1a

Strata of this depophase are very similar with respect to lithology, faunal content, and thickness in the entire Mader. The successions are thinnest in the south and the north (several metres) and show a rather constant thickness in the central Mader (20-30 m). The lower part of the successions usually consists of limestone nodules intercalated in marls (LF 2a) which pass into more continuous beds of nodular limestones (LF 2a) upsection (App. 1, 3, 5, 7, 9, 11, 14-24). Higher up, usually massive, often amalgamated nodular limestone beds occur. Depophase 1a strata are laterally well traceable in outcrop over tens of kilometres (Pl. 6, Fig. 1).

Sedimentary cycles

The symmetry of the macro-scale cycles is proven to be very similar in all the sections (Fig. 20; App. 1, 3, 5, 7, 9, 11, 14-24). Most sections show strong asymmetrical cycles which are predominated by the fall hemicycle. At Ouihlane, obviously a small rise hemicycle is preserved.

Baselevel fall

Falling baselevel during depophase 1a is indicated by the frequent thickening-upward trend of nodular limestone beds and by the upsection increase of the maximum grain size. In addition, the increasing content of brachiopods and trilobites at Boulchral-3 and Tizi N'Guidou, the increasing content of detritic quartz at Tizi N'Guidou, and the decreasing content of dacryoconarids at Jebel Maharch corroborate the vertical fall trend. At Jebel Zireg, siltstone beds constitute the top of the fall trend, but the transition from underlying marls is not well documented due to poor outcrop conditions (App. 21-23). At Jebel Kem and Ouihlane, nodular limestones appear as amalgamated beds which lack indicative vertical trends. Due to dolomitisation, the primary composition of the rocks at Jebel Kem is obscured thus blurring sedimentological trends.

Biostratigraphy and lithostratigraphy

Apart from the very homogenous lithology, the occurrence of ammonoids of late Emsian age within the nodular limestones is a clue for the correlation of these strata (Tab. 23). According to ammonoid records within depophase 1a rocks and overlying deposits, it is concluded that depophase 1a was accumulated within the lower part of the *serotinus* Zone (Fig. 18). Locally (Madene El Mrakib, Jebel Oufatene, Jebel Issoumour), a conspicuous trilobite horizon occurs in the middle or upper part of the exposed succession; it can be used as a stratigraphic marker bed (App. 22; Fig. 20). The lithological definition of the lower boundary of this depophase is dependent on outcrop conditions (Pl. 6, Figs. 3, 5). Where outcrops are good (Jebel Maharch, Boulchral-1, Ouihlane, Jebel Rheris), the base is defined by the first occurrence of several cm thick layers of limestone nodules. Where successions are worse exposed, the lower boundary was interpolated from adjacent localities with better outcrops (Fig. 20).

Lithofacies distribution

During depophase 1a, lithofacies was very homogenous (LF 2a/b) throughout the Mader. Rocks consist predominantly of mudstones and wackestones with a slightly varying diversity of skeletal components. Fine-grained skeletal material is represented mainly by crinoids, bioclasts and dacryoconarids. Detritic quartz is generally rare or absent but may locally reach contents of 2-5% (Tizi N'Guidou, Madene El Mrakib). It is very abundant at Jebel Zireg where rocks consist of lithofacies 10 (20-50% quartz). Although bioturbation is usually recognised in thin sections, field observations reveal a varying degree of the macroscopic bioturbation: Moderate bioturbation was recorded in the southern sections, whereas intense bioturbation occurs at Boulchral-1; north of this locality, macroscopic bioturbation was not recorded. Locally, macrofauna was

Ammonoids (sections)	Range with respect to conodont zones (Klug in press)
Chlupacites (MM)	*serotinus* - uppermost part of *partitus*
Sellanarcestes (TIM)	*serotinus*
Latanarcestes (OUI)	*serotinus* and older
Anarcestes (OUI))	*serotinus* - uppermost part of *partitus*

Tab. 23: Biostratigraphic data of depophase 1a (abbreviations as in Fig. 5).

accumulated in small patches or clumps. The composition of these accumulations changes slightly in the Mader: In the south and parts of the central Mader, crinoid-brachiopod assemblages were found, whereas trilobite-rugose coral assemblages predominate in parts of the northern Mader.

Interpretation

Nodular limestones of depophase 1a show a gentle facies gradient thus indicating that the water depth was very uniform and the sediment surface was nearly horizontal. Lumpy accumulations of crinoids, rugose and tabulate corals, brachiopods and trilobites and frequent bioturbation suggest, that the sea floor was locally inhabited by organisms. Even though a deep subtidal setting, far below the wave base is inferred, slight differences with respect to facies and composition indicate a proximal-distal trend from south to north. This trend is reflected by: (1) the decreasing occurrence of macroscopic bioturbation towards the north and (2) the variation of macrofauna assemblages. The northernmost locations lack macrofauna accumulations thus indicating the deepest environment. Siliciclastic sedimentation occurred only locally and is represented by silty tempestites or turbidites (Jebel Zireg) which may originated from shallower areas further south.

Conclusions

Depophase 1a reflects basinal limestone deposition. The southern and central Mader may represent a slightly shallower part of the basin than the northern Mader. Assuming that the underlying depophase 0b reflects a transgressive systems tract and the initial highstand systems tract, depophase 1a is interpreted as an early highstand systems tract (early HST).

5.2.2 Depophase 1b

With respect to the preceding depophase, facies relationships indicate a more pronounced facies gradient from south to north. Similar to depophase 1a, thickness of strata is very uniform (20-30 m) except for Jebel Zireg where a thickness of 60 m was measured (App. 21-23).

Sedimentary cycles

Macro-scale cycles are well preserved in the entire Mader (Fig. 21; App. 1, 3, 5, 7, 9, 11, 14-23). In the northern Mader only the fall hemicycle is preserved whereas sections south of Boulchral-3 show complete sedimentary cycles of varying symmetry.

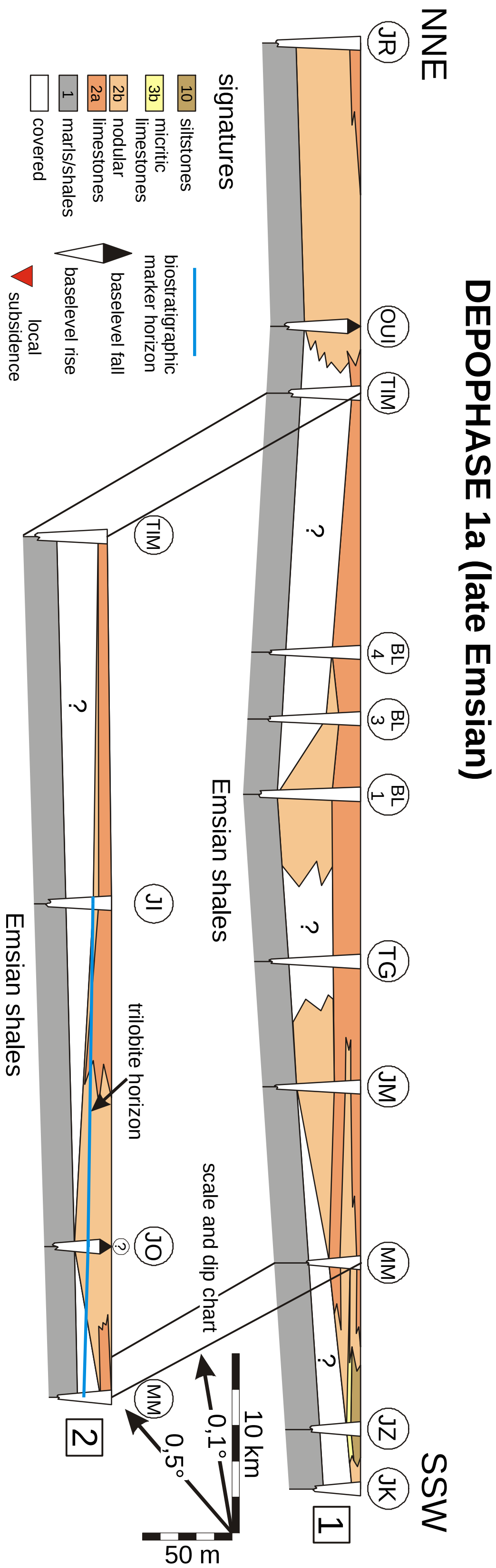

Fig. 20: Depositional geometry and facies relationships of depophase 1a (late Emsian) along transect line 1 and 2 of Fig. 17. The pale grey shading below depophase 1a strata represents underlying rocks of the preceeding depophase 0b. Lithofacies numbers as in Chap. 4, abbreviations of sections as in Fig. 17., vertical exaggeration is 100.

Baselevel fall

Strata assigned to depophase 1b show an overall vertical baselevel fall trend as indicated by the vertical succession from nodular limestones (LF 2) and marls with limestone nodules towards massive limestones (LF 4, LF 5). In almost every section, this trend is additionally reflected by the transition from mud-/wackestones to pack-/grainstones. Furthermore, an increasing grain size and an increasing quartz content upsection was observed at most of the sections. Successions in the southern and central Mader (Jebel Kem, Madene El Mrakib, Tizi N'Guidou, Jebel Issoumour), show sparite cementation within the upper part of the hemicycle, whereas rocks of the lower part always contain a micritic matrix. In some sections (Madene El Mrakib, Tizi N'Guidou, Jebel Oufatene, Jebel Issoumour, Boulchral-1, 4), an increasing abundance of macrofauna in combination with an increasing diversity of skeletal grains was recorded. Sections in the northern Mader (Boulchral-1, 3, 4, Timerzit, Ouihlane, Jebel Rheris), rarely show diagnostic vertical trends.

Baselevel rise

The subsequent rise is indicated by the overlying micritic limestones (LF 3) in parts of the northern Mader (Boulchral-1) and by the overlying bioclastic limestones (LF 4) in the southern Mader. It is most obviously reflected by the increasing number of marly interbeds in the southern Mader. Some sections show a fining-up trend (Jebel Kem, Madene El Mrakib, Boulchral-1), whereas in others the fossil content decreases towards the top (Jebel Kem, Madene El Mrakib, Jebel Issoumour). In some sections, macroscopic bioturbation was recorded above the fall-to-rise turnaround point (Jebel Kem, Jebel Oufatene, Boulchral-1). Outcrops in the northern Mader (Boulchral-3, 4, Timerzit, Ouihlane, Jebel Rheris), lack the rise hemicycle. Instead, rocks representing the maximum-fall are overlain by deep subtidal limestone-marl alternations (LF 3) which are attributed to the subsequent depophase. Poor outcrop conditions or pervasive dolomitisation make it difficult to recognise baselevel trends at Jebel Zireg, Jebel Maharch and Jebel Oufatene.

Biostratigraphy and lithostratigraphy

Besides the correlative baselevel trends, the massive limestones which were deposited during the maximum fall represent an excellent lithologic marker bed frequently containing *Sellanarcestes* (Tab. 24), which correlates with the upper part of the *serotinus* Zone (Fig. 18). In the eastern Mader, the *Sellanarcestes* bed can be followed easily in outcrop and on aerial photographs (Pl. 6, Figs. 1-3). Strata in the central and northern Mader, which lack fall and rise trends, were attributed to depophase 1b by litho- and biostratigraphy (Fig. 21; App. 1, 3, 5, 7, 9, 11, 14-23).

Lithofacies distribution

During maximum fall, facies zonation of depophase 1b was most pronounced (Fig. 21). Cross-bedded bioclastic limestones (LF 4c) represent the most proximal environment forming a SE-NW striking belt in the southern Mader (Fig. 22a). This belt was frequently situated above the storm wave base (Chap. 4.4.3). Palaeocurrent data from cross-bedding measurements, suggest that the sediment was transported predominantly from the south. At Jebel Kem, rocks of LF 4c contain abundant non-skeletal material such as detritic quartz with values up to 15% and dark, millimetre to centimetre-sized lithoclasts. South and southwest of this facies belt, a hiatus is documented which is probably caused by prolonged sediment by-pass on a swell (Mader Platform *sensu* Wendt 1988).

To the north, a NW-SE striking crinoid limestone belt was established (LF 5) which became narrow at Jebel Oufatene (Fig. 22a). Water depth was higher within this belt although temporarily bottom currents occurred as indicated by horizontal bedding and grading within the crinoid limestones (LF 5a) at Madene El Mrakib, Jebel Maharch, Jebel Oufatene and Jebel Issoumour. Sedimentary structures and faunal composition suggest that this facies belt was mostly situated below, but temporarily above the storm wave base (Chap. 4.5.1). Locally, crinoids and brachiopods were accumulated in centimetre- to decimetre-sized clumps or several decimetre-wide sheets (Pl. 2, Fig. 2; Fig. 12).

Ammonoids (sections)	**Range with respect to conodont zones (Klug in press)**
Anarcestes (MM, JO, BL-1)	*serotinus* - upper part of *partitus*
Sellanarcestes (JM, BL-3, BL-4, JR)	*serotinus*
Latanarcestes (OUI)	*serotinus* and older

Tab. 24: Biostratigraphic data from depophase 1b.

Sedimentary rocks of the central and northern Mader (Boulchral, Timerzit, Ouihlane, Jebel Rheris) lack features indicating bottom currents, and hence, indicate a deeper environment. Whereas at Boulchral-1, 3, 4 and Jebel Oufatene bioclast limestones (LF 4a) predominated during maximum fall conditions, north of these sections micritic limestones (LF 3a) and thin-bedded nodular limestones (LF 2a) were accumulated (Fig. 22a). Detritic quartz is absent in the northernmost sections (Timerzit, Ouihlane, Jebel Rheris) but is still present (1-3%) in lithofacies 4a rocks at Boulchral-1, 3, 4.

Conclusions

Depophase 1b reflects the initial establishment of a homoclinal carbonate ramp, which can be subdivided into an inner-, mid-, and outer-ramp segment (Fig. 22a). The inner ramp to mid-ramp was influenced by siliciclastic input from southern areas and parts of this area were inhabited by brachiopods and crinoids. Dark intraclasts (organic matter?) and the high quartz content, suggest the proximity of a land area to the south. Towards the north, the mid-ramp is documented by a crinoid limestone belt and a facies belt dominated by diverse bioclast limestones. Crinoid-brachiopod assemblages were accumulated as layers or clumps and are very frequent in the crinoid limestone belt. Grading demonstrates that the skeletal material of this area was repeatedly transported by off-shore currents of different origin (e.g. storms, backflow). The deeper mid-ramp areas were more quiescent as indicated by the high mud content of the bioclastic limestones (LF 4). Some of these rocks show a higher biodiversity than the crinoid limestones of the upper mid-ramp. Deeper depositional environments (outer ramp), are characterised by nodular or well-bedded micritic limestones. Indications for settling of organisms were not found in these rocks. Lacking sedimentary structures in combination with the nodular texture indicate a deep subtidal setting with little background sedimentation.

Carbonate sedimentation during depophase 1b reflects persisting highstand conditions (HST). The baselevel fall in combination with the deposition of crinoid limestones in the southern Mader is interpreted as a minor progradation phase during highstand conditions.

5.3 Depophase 2, late Emsian - early Eifelian (*patulus* - lower part of the *costatus* Zone)

Depophase 2 corresponds to the major interval of carbonate ramp development in the Mader (Fig. 21; App. 1, 3, 5, 7, 9, 11, 13-23). Strata form a prominent topographic crest in most of the area (Pl. 6, Figs. 1, 3, 5) and the thickness of the limestone succession is relatively high in the south and the centre compared to other depophases (20 m at Jebel Kem - 80 m at Boulchral-1). In the northern Mader (north of Boulchral-1), less thick limestone successions, ranging from 45 m (Boulchral-3) to 10 m (Jebel Rheris), occur.

Sedimentary cycles

Depophase 2 strata can be recognised in the southern and parts of the northern Mader by the conspicuous macro-scale cycles (Fig. 21; App. 1, 3, 5, 7, 9, 11, 13-23). South of Boulchral-4, cycles show a varying symmetry from north to south (Fig. 21). Since sections in the northern Mader (Boulchral-3, 4, Timerzit, Ouihlane, Jebel Rheris) consist of rather unfossiliferous and very homogenous successions, correlation in this area relies on litho- and biostratigraphy.

Baselevel fall

In the southern and parts of the northern Mader (Jebel Kem, Jebel Zireg, Madene El Mrakib, Jebel Maharch, Tizi N'Guidou, Jebel Oufatene, Jebel Issoumour, El Otfal, Boulchral-1), the baselevel fall is indicated by the upward transition from mud-/wackestones into pack-/grainstones. Furthermore, fossil content and the diversity of non-skeletal material suggest a falling baselevel in the majority of the sections. This trend is also suggested by the increasing quartz content at Jebel Kem, Jebel Zireg and Tizi N'Guidou and by the deposition of laminated limestones during maximum fall at Jebel Oufatene and Jebel Issoumour. Due to the micritic composition of the limestones, the high proportion of marly interbeds, and the poor outcrop conditions, vertical sedimentary trends are hardly visible in the northern Mader (north of Boulchral-1).

Baselevel rise

Sections of the southern and parts of the northern Mader, except for Jebel Kem, reflect the subsequent baselevel rise most obviously (Madene El Mrakib, Jebel Maharch, Tizi N'Guidou, Jebel Oufatene, Jebel Issoumour, El Otfal, Boulchral-1). A transition from grain-/packstones to wacke-/mudstones and the increasing portion of marly interbeds is evident in most of these sections. The rise trend is locally indicated by increasing bioturbation (Jebel Zireg, Jebel Maharch, Jebel Issoumour), decreasing diversity of non-skeletal material (Jebel Oufatene, El Otfal, Boulchral-1), or decreasing quartz content (Tizi N'Guidou, Boulchral-1). Because the rise hemicycle is not well recognisable in the northern Mader, the top of depophase 2 strata is defined by bio- and lithostratigraphy.

Biostratigraphy and lithostratigraphy

Ammonoids (Tab. 25) indicate that sediments of depophase 2 were accumulated during an interval ranging from the *serotinus* to the *kockelianus* Zone. Additional biostratigraphic data is provided by

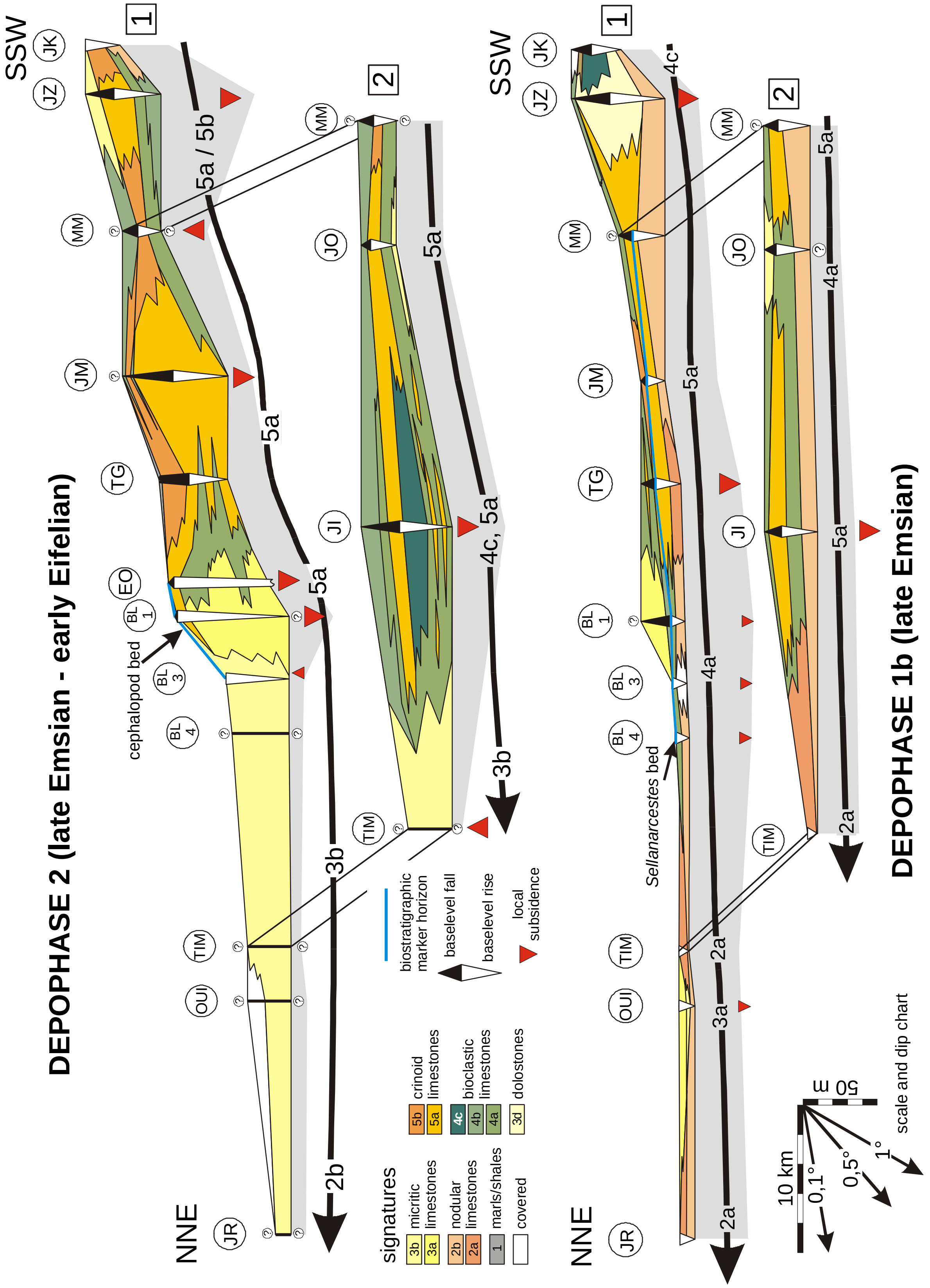

Fig. 21: Depositional geometry and facies relationships of depophase 1b and 2 (late Emsian - early Eifelian) along transect line 1 and 2 of Fig. 17. The pale grey shading below depophase 1b and 2 strata represents underlying rocks of the preceeding depophases; arrowheads indicate inferred vertical movements. Lithofacies numbers as in Chap. 4, abbreviations of sections as in Fig. 17., vertical exaggeration is 100.

Ammonoids (sections)	Range with respect to conodont zones (KLUG in press)
Agoniatites (JK)	lower part of *costatus*- Lower *varcus*
Subanarcestes (JO)	lower part of *costatus*- *kockelianus*
Fidelites (EO, BL-3?, JR?)	upper part of *partitus*- *kockelianus*
Anarcestes (BL-1)	*serotinus* - *partitus*
Exopinacites (BL-1)	middle part of *costatus*
Pinacites (BL-1)	uppermost part of *partitus*- middle part of *costatus*

Tab. 25: Biostratigraphic data from depophase 2 (abbreviations as in Fig. 5).

KAUFMANN (1998) who was able to attribute a cephalopod bed near the top of this depophase into a small interval within the lower part of the *costatus* Zone. The cephalopod bed which was found at El Otfal, Boulchral-1, 3, Timerzit, and Ouihlane can be utilised as marker bed for the correlation of depophase 2. From these data it appears reasonable that the shallowing hemicycle of depophase 2 ranges from the base of the *patulus* into the lower part of the *costatus* Zone (Fig. 18). Sections in the northern Mader, show a very similar lithologic successions overlying depophase 1 strata thus supporting the proposed correlations.

Lithofacies distribution and interpretation

Sections in the southwestern Mader show a large stratigraphic gap which documents the existence of a possible swell during Early to Late Devonian times (Mader Platform *sensu* WENDT 1988). North of the swell, a wide crinoid limestone belt was established during maximum fall of depophase 2 (Fig. 22b). In the southern part of this belt, crinoid limestones alternate with thin marl beds (LF 5b). North of this belt, accumulations of massive crinoid-limestones with minor marl intercalations (LF 5a) were recorded. At Jebel Issoumour, a subtidal channel system (Chap. 4.4.3, Fig. 11) was established as indicated by the sedimentary structures and the geometry of the limestone beds (Fig. 22b). Except for El Otfal and Boulchral, crinoid limestones and intercalated marls were deposited in a subtidal environment slightly below the storm wave base as is indicated by sedimentary structures and composition (Chap. 4.5.1). Crinoid limestones at El Otfal and Boulchral-1 (LF 5a) do not indicate bottom currents and hence reflect a deeper subtidal setting. Several carbonate mud mounds were established in this area above the crinoid-limestone beds during the subsequent depophase (KAUFMANN 1998). In general, the diversity of skeletal components was higher in the muddy environments of the deeper subtidal and lower in areas close to the storm wave base. The composition of the faunal assemblages preserved during event sedimentation changes from south to north: Crinoid-brachiopod assemblages were found in the southern sections; farther north, solitary corals occur within these assemblages and farther north, crinoid-bryozoan-trilobite and crinoid-rugose coral-trilobite assemblages predominate.

North of the crinoid limestone belt (Fig. 22b), calcareous mud and shales were accumulated during maximum fall of depophase 2. These fine-grained sediments were later transformed to limestone-marl alternations and nodular limestones (LF 3, LF 2). The rocks lack indicative sedimentary structures and contain only sparse skeletal grains thus suggesting a deep subtidal environment.

Conclusions

Strata of depophase 2 reflect the depositional geometry of a distally steepened carbonate ramp (Fig. 21). The major part of this ramp consisted of a slightly inclined mid-ramp area which was dominated by crinoid limestone and bioclastic limestone deposition. This zone was frequently influenced by offshore storm currents. Further distal, bioclastic limestones grade into micritic limestones of the outer ramp. The depositional geometry at El Otfal and Boulchral-1, 3, 4 indicates a steeper inclined sea floor in this area (Fig. 21). It passes to the north into an outer-ramp to basinal area which was dominated by the sedimentation of micritic limestones which contain scarce pelagic fauna.

Strata which were accumulated during baselevel fall of depophase 2, are interpreted as part of the highstand systems (HST) tract which persisted since the late Emsian. The uppermost part of the baselevel-fall succession reflects conditions of the late HST, as is suggested by the maximum progradation (Fig. 21) of the crinoid limestone facies towards the north (Boulchral-1). Deposits of the subsequent rise hemicycle, are interpreted as a part of the following transgressive systems tract (TST) which persisted during depophase 3.

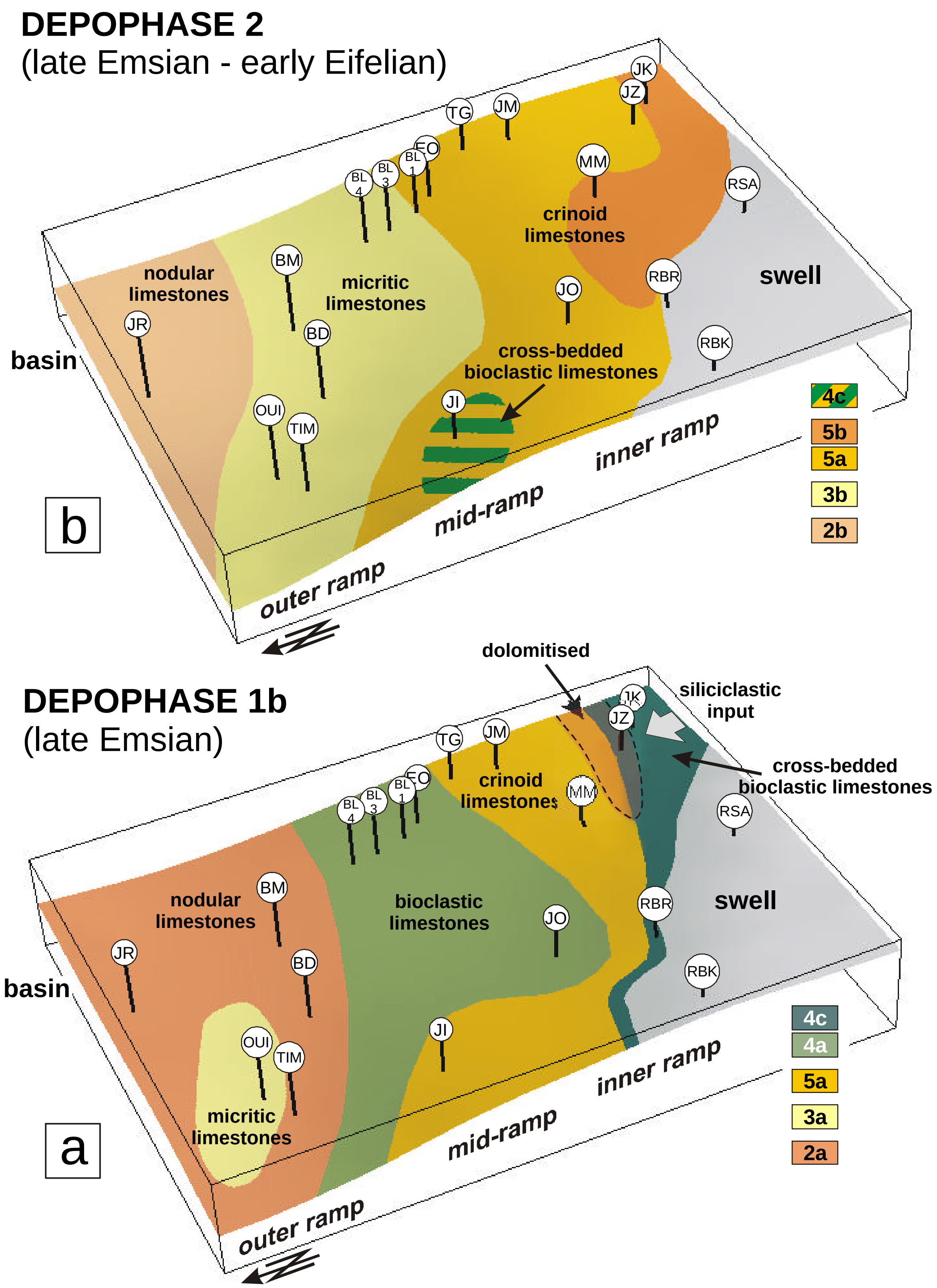

Fig. 22: Three-dimensional facies relationships during maximum fall of depophase 1b (a) and depophase 2 (b). Lithofacies numbers as in Chap. 4, abbreviations of sections as in Fig. 17, vertical exaggeration is ca. 90.

5.4 Depophase 3, early Eifelian (*costatus* Zone)

Depophase 3 is represented by a thin stratigraphic interval which consists mainly of crinoid-bioclast limestones (LF 4) alternating with marls in the southern Mader and a thin veneer of limestone-marl alternations (LF 3) in the central and northern Mader (Fig. 23; App. 1, 3, 5, 7, 9, 11, 13-17, 19-23). The thickness of depophase 3 strata is about 20 m in the southern and central Mader and is between 5 and 10 m in the northern Mader.

Sedimentary cycles

The correlation of the sections relies on macroscale cycles in the southern and western Mader and on lithostratigraphy in the northern Mader (Fig. 23; App. 1, 3, 5, 7, 9, 11, 13-17, 19-23). In certain sections of the southern and the northern area, apart from the overall fall hemicycle, a rise hemicycle can be recognised.

Baselevel fall

Strata attributed to depophase 3 show vertical trends indicating a fall in the southern and western Mader except for Jebel Kem where strata of depophase 3 are not preserved or amalgamated with those of depophase 2. An upward trend from limestone-marl alternations into massive limestones or an upward-increasing proportion of limestones beds in combination with a transition from mud-/wackestones to pack-/grainstones was recorded at Jebel Zireg, Madene El Mrakib, Jebel Maharch, Tizi N'Guidou, Jebel Oufatene and Jebel Issoumour. These sections also show an upward increase in grain size of skeletal grains. Furthermore, the content of macrofauna increases upward at Madene El Mrakib, Jebel Maharch, Jebel Oufatene and Jebel Issoumour. Except for Boulchral-1, where an upward-increasing bed thickness was recorded, sections of the central and northern Mader are very homogenous with respect to composition and sedimentary structures thus lacking indicative vertical trends.

Baselevel rise

The rise hemicycle of depophase 3 is only partially preserved in some sections (Madene El Mrakib, Jebel Maharch, Jebel Issoumour, Boulchral-1). At these localities a decreasing diversity of skeletal grains, decreasing quartz content or decreasing grain size upsection can be observed. At Jebel Maharch and Jebel Issoumour this trend is also indicated by an upward increase of marly interbeds. Sections in the northern Mader, neither show fall nor rise trends.

Lithostratigraphy

Although in the sections of the northern and central Mader (Boulchral-3, 4, Timerzit, Ouihlane, Jebel Rheris) diagnostic vertical trends are absent, the similar lithological succession allows a correlation with strata of depophase 3 of the southern Mader (Fig. 23; App. 1, 3, 5, 7, 9, 11, 13-17, 19-23). A cephalopod bed at Boulchral-3, Timerzit, and Ouihlane can be correlated towards Boulchral-1 where it is part of the rise hemicycle of depophase 2. Strata assigned to depophase 3, are overlain by a thick marl/shale unit in the northern Mader (Boulchral-3, 4, Timerzit, Ouihlane) and by a thinner marl/shale unit with limestone nodules in the northernmost Mader (Jebel Rheris). The latter unit wedges out south of Boulchral-3 but is probably still present at Jebel Maharch.

Biostratigraphy

Ammonoids below and above depophase 3 strata allow to estimate a time interval in terms of the conodont zonation (Tab. 26, Fig. 18). Accordingly, strata of depophase 3 were accumulated within the *costatus* Zone. Conodonts of the cephalopod bed underlying depophase 3 strata (El Otfal) assign an early *costatus* age to these deposits. Therefore, depophase 3 can be attributed to the lower and the middle part of the *costatus* Zone. At Jebel Maharch, the overlying cephalopod bed is attributed to the *kockelianus* Zone which supports the assumption that sediments of depophase 3 were accumulated during a short interval in the middle part of the *costatus* Zone (Fig. 18).

Lithofacies distribution and interpretation

In the southernmost Mader, the swell persisted during depophase 3 (Fig. 24a), but contrasting to depophase 2, the area around Jebel Kem was also part of the swell. During maximum fall, the southern Mader was dominated by the deposition of crinoid limestones (LF 5), bioclastic limestones (LF 4) and shales. Small scour and fill structures indicate frequent storm-related bottom currents at Jebel Maharch (Chap. 4.5.1). Non-skeletal material consists exclusively of detritic quartz with highest values (2-3%) at Jebel Maharch and Jebel Zireg. These data show that during depophase 3 the southeastern Mader was generally situated in the subtidal, below the storm wave base but temporarily above the storm wave base. The sea floor was predominantly inhabited by crinoids and bryozoans and temporarily by large colonial corals (Jebel Maharch).

The western Mader (Jebel Oufatene, Jebel Issoumour), was dominated by the deposition of bioclastic and peloid limestones (Fig. 24a). Rocks are usually massive, except for some beds at Jebel Oufatene where horizontal lamination was recorded. In this area, the macrofauna consists of trilobites (Jebel Issoumour), tabulate, and rugose corals (Jebel Oufatene). Non-skeletal grains are represented by locally occurring peloids. Bioturbation is more frequent than in the southern Mader and especially abundant

Ammonoids, conodont samples (sections)	Range with respect to conodont zones (KLUG in press)
Pinacites above (JR, JM)	uppermost part of *partitus* - middle part of *costatus*
Fidelites below (JR, BL-3, EO)	base of *costatus* - upper part of *costatus*
Pinacites below (BL-1)	uppermost part of *partitus* - middle part of *costatus*
Cabrieroceras crispiforme at top (EO)	middle part of *costatus* - *ensensis*
Cabrieroceras above (JM)	middle part of *costatus* - *ensensis*
Cephalopod bed above (JM)	*kockelianus*
JZ-00-13	lower part *costatus* - Lower *varcus*

Tab. 26: Biostratigraphic data from depophase 3 (abbreviations as in Fig. 5)

in bioclastic limestones at Jebel Issoumour. The environment was slightly deeper than in the southern Mader, thus favouring the accumulation of peloids and restricting the accumulation of skeletal material, such as crinoids and bryozoans.

Northeast of the above described facies belts, predominantly micritic limestones with few skeletal material were accumulated (Fig. 24a). Bioturbation may occur in this area but is usually not very strong. Rocks are horizontally laminated at Boulchral-1 and may contain detritic quartz (1-2% at Boulchral, 5% at El Otfal). These features indicate resedimentation processes in a deep-subtidal setting, below the storm wave base (distal tempestites?). North of Boulchral-1, micritic limestones and shales were accumulated thus suggesting a deep marine setting (Fig. 24a).

Conclusions

In contrast to depophase 2, strata of depophase 3 show a rather uniform ramp geometry along the transect (Fig. 23). The carbonate ramp still shows a distinct zonation with a mid- to outer-ramp area in the south and an outer-ramp to basin environment in the north (Fig. 24a). The southern Mader was still part of the swell (Mader Platform *sensu* WENDT 1988), which extended as far as Jebel Kem where rocks of depophase 3 are absent. Facies relationships indicate a proximal-distal trend from south to north and from southwest to northeast. The mid- to outer-ramp environment extended from Jebel Zireg to Jebel Issoumour and Tizi N'Guidou and was dominated by the deposition of bioclast limestones, crinoid limestones with some large corals (Jebel Maharch), and massive peloid and bioclast limestones in the deeper environments (Jebel Oufatene, Jebel Issoumour). Farther north, the outer-ramp to basin environment persisted which was subject to limestone-shale sedimentation. The composition of faunal assemblages varies from north to south with crinoid-bryozoan-coral associations in the mid- to outer-ramp environments and bioclast-brachiopod-trilobite-dacryoconarid associations in the outer-ramp to basin environments.

Compared to depophase 2, distal environments shifted to the south indicating a transgression. Considering under- and overlying strata, it can be concluded that depophase 3 represents a transgressive systems tract (TST). During transgression, sedimentation rates were probably lower than in the previous phase and facies belts retrograded. The fall hemicycle reflects the continuous carbonate production which was probably coupled with a temporarily reduced rate of baselevel rise. Due to very low subsidence, the southern Mader Platform persisted during this depophase.

5.5 Depophase 4, early - late Eifelian (*costatus* - upper part of the *kockelianus* Zone)

Strata of depophase 4 are preserved exclusively in the northern and western Mader (Fig. 23; App. 1, 3, 5, 7-13, 15, 20-23). South of this area, the Quaternary cover (Tizi N'Guidou, Jebel Maharch) prevents detailed logging. In sections farther south and west (Jebel Kem, Jebel Zireg, Madene El Mrakib, Jebel Oufatene), strata of this depophase are obviously not preserved or represented by a thin stratigraphic interval.

Successions usually consist of limestone-marl alternations (LF 3c) or of bioclast-peloid limestones (LF 6a) as at Jebel Issoumour. The thickness of the limestone-marl alternations increases from 20 m in the north (Jebel Rheris) to 80 m at Timerzit and 120 m at Boulchral-1, 3, 4. South of Boulchral-1, thickness estimation is not possible due to the Quaternary cover.

Sedimentary cycles

Since vertical trends are hardly visible, except for the Jebel Issoumour section, correlation is mainly based on litho- and biostratigraphy. Nevertheless, the succession at Jebel Issoumour shows a vertical fall trend as is reflected by the increasing proportion of limestone beds (Fig. 23; App. 1, 3, 5, 7-13, 15, 20-23). The subsequent rise is indicated by an increasing proportion of marly interbeds.

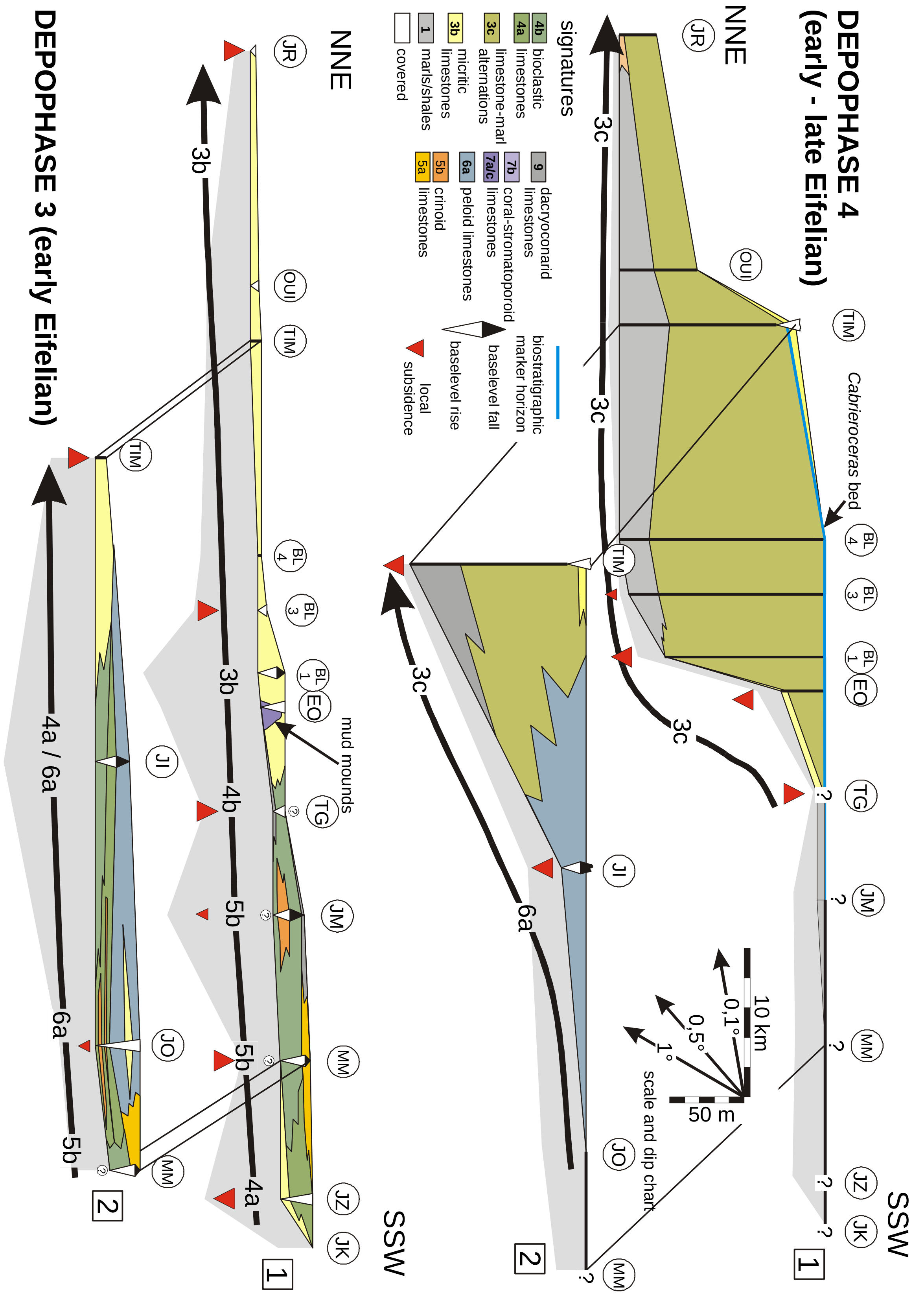

Fig. 23: Depositional geometry and facies relationships of depophase 3 (early Eifelian) and 4 (early - late Eifelian) along transect line 1 and 2 of Fig. 17. The pale-grey shading below depophase 3 and 4 strata represents underlying rocks of the preceeding depophases; arrowheads indicate inferred vertical movements. Lithofacies numbers as in Chap. 4, abbreviations of sections as in Fig. 17., vertical exaggeration is 100.

Litho- and biostratigraphy

Outcrop data and aerial photographs show that limestone-marl alternations of depophase 4 wedge out from north to south between Boulchral-1 and Tizi N'Guidou. At El Otfal and Boulchral, strata of depophase 4 are well exposed and can be correlated by lithostratigraphic features (Pl. 6, Fig. 2). The lower boundary is defined by the base of the underlying, mostly covered marl/shale unit, which was recorded at Boulchral-3, 4, Timerzit and Ouihlane. This unit obviously wedges out towards the south. The top of the succession is marked by a conspicuous cephalopod bed containing *Cabrieroceras* sp. and *crispiforme* at Boulchral-1, 3, 4 and El Otfal (Pl. 6, Fig. 2). Conodonts of this bed at Boulchral-1 indicate a stratigraphic range (Tab. 27) from the *kockelianus* to the upper part of the *eiflius* Zone. The lithological succession at Timerzit, Ouihlane, and Jebel Rheris is very similar to Boulchral-1, 3, 4 and also contains *Cabrieroceras* in the upper part (Tab. 27; App. 1, 3, 5, 8, 10, 12, 23, 24). The occurrence of *Pinacites* at Ouihlane and Jebel Rheris (Hollard 1974, Massa 1965) indicate that the lower part of the succession was deposited during the *costatus* Zone. Therefore, it can be assumed that strata of depophase 4 were accumulated during a time interval ranging from the middle part of the *costatus* to the uppermost part of the *kockelianus* Zone (Fig. 18).

Lithofacies distribution and interpretation

During depophase 4, only a slight facies gradient from the southwest towards the northeast existed in the Mader. In the western Mader, a peloid limestone belt (LF 6a) was established whereas the northern Mader (Fig. 24b) was dominated by the accumulation of muddy limestones (LF 3c) and shales in a mid- to outer-ramp setting. Laminated limestones are interpreted as muddy calciturbidites (Chap. 4.3.3) whereas the thick, shaly interbeds reflect autochthonous sedimentation and probably parts of the uppermost turbidite. Thickness of these deposits is highest around Boulchral and decreases towards the north thus indicating lower sedimentation rates and a basinal environment (Fig. 23). The southern Mader, was subject to low subsidence rates and sediment bypass during depophase 4 (Chap. 6.4). Muddy calciturbidites of the northern Mader reflect resedimentation of the peloid-mud material which was accumulated on the mid-ramp (western and southern Mader) but was only preserved in the western Mader.

Conclusions

Lithofacies of depophase 4 indicate deepening with respect to the preceding depophase. Marls and argillaceous limestones of the succeeding depophase indicate condensation and reduced limestone accumulation. Therefore, depophase 4 strata are interpreted as part of a highstand systems tract (HST).

The occurrence of *Cabrieroceras crispiforme* at the top of depophase 4 strata indicates an *australis* to *ensensis* Zone age. This interval and the overlying monotonous shales may correlate with the "If-Transgression" of Johnson et al. (1985, 1996) and the "Kacak-Event" of House (1985).

Although the geometry of depophase 4 strata is similar to a lowstand wedge (Fig. 23), the composition of the rocks and the generally low limestone content indicate a high sea level in combination with a low siliciclastic input from a possible hinterland. This view is supported by the facies relationships observed within under- and overlying strata: (1) Depophase 3 indicates a landward stepping of facies belts (TST) and (2) depophase 5a strata indicate transgressive to early highstand conditions (TST) with reduced sedimentation in the northern Mader.

5.6 Depophase 5, early Givetian (Lower *varcus* Zone)

Depophase 5 can be subdivided into depophases 5a - 5e (Fig. 25; App. 1-4, 6, 8, 10, 12, 13, 16-19, 21-24). During these, coral-stromatoporoid limestones were accumulated in the southern, western, and northernmost Mader whereas shales with intercalated resedi-

Ammonoids, conodont samples (sections)	Range with respect to conodont zones (Klug in press)
Cabrieroceras sp. and *crispiforme* (EO, BL-1, BL-3, BL-4, TIM, OUI)	lower part of *costatus* - *ensensis*
Pinacites sp. and *jugleri* (OUI, Hollard 1974, JR, Massa 1965)	upper part of *partitus* - upper part of *costatus*
Anarcestid (OUI)	*serotinus* - *ensensis*
conodont sample BL-1-35	*kockelianus*
cephalopod bed at the top of the JM section (sample M95 of Kaufmann 1998)	*kockelianus*

Tab. 27: Biostratigraphic data from depophase 4 (abbreviations as in Fig. 5)

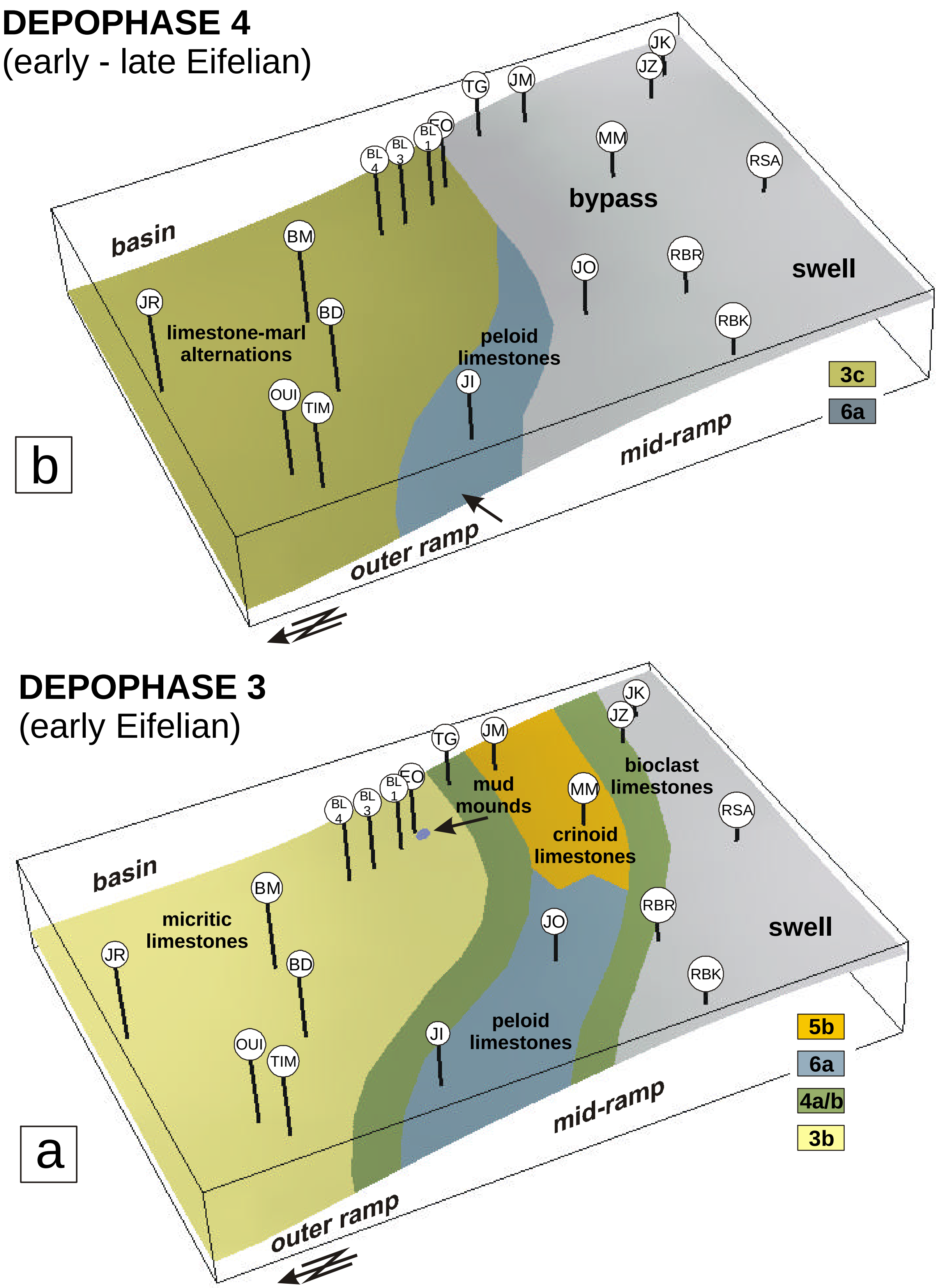

Fig. 24: Three-dimensional facies relationships during maximum fall of depophase 3 (a) and depophase 4 (b). Lithofacies numbers as in Chap. 4, abbreviations of sections as in Fig. 17, vertical exaggeration is ca. 90.

mented limestones and siltstones were deposited in the northern Mader. During depophase 5a, the northernmost Mader was still part of the basin, but subsequently experienced very low subsidence or even uplift (depophase 5b to 5e). Depophases 5c - 5e were not preserved in the southern Mader.

5.6.1 Depophase 5a

Thickness of depophase 5a strata changes slightly (20-30 m) along the studied transect and is highest (60 m) around Boulchral and lowest at Jebel Issoumour and Jebel Rheris (10 m). In contrast to the foregoing depophase, a clear facies gradient from south to north is observed (Fig. 25; App. 1-3, 6, 8, 10, 12, 13, 16-19, 21-24). At Jebel Maharch and Tizi N'Guidou, strata of depophase 5a is covered by Quaternary sediments.

Sedimentary cycles

Correlation of depophase 5a strata is based as well on macro-scale cycles as on litho- and biostratigraphy. Sections in the southern and western Mader clearly show fall and rise hemicycles (Pl. 6, Fig. 4) whereas those of the northern Mader are poorly-exposed and consist of unfossiliferous micritic limestones and shales. Therefore, the latter strata were correlated by litho- and biostratigraphy.

Baselevel fall

Sections in the southern and western Mader, show an upward-increasing proportion of limestone beds while marly interbeds decrease in thickness and frequency (Pl. 6, Fig. 4). Most successions show an upward increase in component content along with a transition from mud- to wackestones at Jebel Kem and wacke-/packstones to float-/rudstones at Jebel Zireg, Madene El Mrakib, Jebel Oufatene and Jebel Issoumour. Furthermore, the increasing grain size and the increasing diversity of skeletal components reflect the overall baselevel fall. Sections in the northern Mader, do not show indicative vertical trends and depophase 5a strata are often covered at these sections (El Otfal, Boulchral-1).

Baselevel rise

The subsequent rise is poorly visible in the southern Mader. It is best reflected by the increasing frequency and thickness of marly interbeds towards younger strata. However, poor outcrop conditions hamper the recognition of other trends. As an exception, the succession at Jebel Oufatene shows a decreasing grain size upwards and a decrease in component content.

Lithostratigraphy and biostratigraphy

Strata were attributed to depophase 5a according to lithostratigraphic features (Fig. 25; App. 1-3, 6, 8, 10, 12, 13, 16-19, 21-24) if indicative sedimentologic trends were absent (El Otfal, Boulchral-1, 3, 4, Ouihlane, Jebel Rheris). In the Boulchral sections, the lower boundary of depophase 5a is defined by the top of the *Cabrieroceras* bed, whereas the upper boundary corresponds to the first occurrence of conspicuous debrites and resedimented limestones with peloids and calcimicrobes. In the northernmost Mader (Ouihlane), the lower boundary is hard to define, whereas the upper limit of depophase 5a strata corresponds to the first occurrence of debrite beds with abundant lithoclasts. At Jebel Rheris, depophase 5a strata includes a conspicuous stratigraphic level consisting almost entirely of dacryoconarid limestones. Rocks of depophase 5a were not recognised at Timerzit. Biostratigraphic data are based on conodonts from Jebel Rheris and Madene El Mrakib (Tab. 35). At the latter location, a conspicuous trilobite horizon was dated by conodonts into the Lower *varcus* Zone (Kaufmann 1998). This horizon is widespread in the southern and western Mader and was used for the correlation of Jebel Kem, Madene El Mrakib, Jebel Oufatene and Jebel Issoumour. In the northern and eastern Mader, this horizon was not found but conodonts of the dacryoconarid beds of Jebel Rheris also indicate the Lower *varcus* Zone.

Lithofacies distribution

In the southernmost Mader (Fig. 26a), a facies belt consisting of argillaceous bryozoan limestones and marls was established (LF 4) during depophase 5a. Towards the north, it graded into a coral-stromatoporoid facies belt (LF 7b/c), which was repeatedly subject to shale and peloid sedimentation (Jebel Zireg, Madene El Mrakib, Jebel Oufatene, Jebel Issoumour). The coral-stromatoporoid limestone belt may extended until Jebel Issoumour where detailed outcrop data of the Givetian are not available. Between Madene El Mrakib and Jebel Maharch, a reef mound (Aferdou El Mrakib) was established (Kaufmann 1998).

In the eastern Mader, between Jebel Maharch and Boulchral-1, a large outcrop gap makes it difficult to reconstruct early Givetian facies relationships. It can be speculated however, that thickness of depophase 5a deposits is not high and that rocks predominantly consist of marls and shales.

Successions in the northern Mader (Boulchral-1, 3, 4, Bou Dib, Ouihlane, Jebel Rheris), are very homogenous and consist of dacryoconarid marls, micritic limestones, and limestone-marl alternations.

Interpretation

In the southern and southwestern Mader, a rather calm subtidal environment which extended until Jebel Issoumour, existed during depophase 5a (Fig. 26a). The absence of indicative sedimentary struct-

Ammonoids, conodont samples (sections)	Range with respect to conodont zones (KLUG in press)
trilobite horizon below (MM), KAUFMANN (1998)	Lower *varcus*
styliolinid layer (MM) dated by KAUFMANN (1998)	early Frasnian (lower part of *asymmetricus*)
dating by BULTUYNCK & JACOBS (1981) (BD)	Lower *varcus*
dacryoconarid limestones below (JR)	Lower *varcus*

Tab. 28: Biostratigraphic data of depophase 5b strata (abbreviations as in Fig. 5).

ures, the high marl and peloid content, and the partially well-preserved bryozoans, indicate deposition under low-energy conditions. However, micritisation and the occurrence of calcimicrobes and reef-dwelling organisms (Chap. 4.7.4) indicate deposition within the photic zone.

Coeval successions of the northern Mader consist of limestone-marl alternations and dacryoconarid marls which suggest a deeper-marine setting, below the storm wave base. Micritic limestones within the alternations probably originated from deposition by turbidity currents or storm-waves.

Conclusions

During depophase 5a, sedimentation extended over most of the Mader except for the southernmost and parts of the southwestern Mader, where the swell (Mader Platform) persisted (Fig. 26a). The mid- to outer-ramp area was located in the southern Mader and was inhabited by bryozoans and reef dwellers. This environment was repeatedly subject to shale sedimentation and input of detritic quartz (Jebel Kem). In contrast, the northern Mader was part of the outer-ramp to basin environment which was subject to sedimentation of micritic limestones and shales with abundant dacryoconarids. These facies relationships reflect a transgressive to early-highstand systems tract (TST - HST).

5.6.2 Depophase 5b

Depophase 5b includes a great variety of rocks comprising coral-stromatoporoid limestones, crinoid limestones and various types of resedimented limestones (Fig. 25; App. 1, 3, 6, 8, 10, 12, 13, 16-19, 21-24). Highest thickness (45 m) was recorded in the northernmost Mader (Jebel Rheris); sections of the northern and southern Mader appear relatively homogenous with respect to thickness (20-30 m). In the eastern Mader, poor outcrop conditions prevent accurate thickness estimation and the reconstruction of facies relationships of depophase 5b.

Sedimentary cycles

Sections with crinoid limestones and coral-stromatoporoid limestones (Jebel Kem, Jebel Zireg, Madene El Mrakib, Jebel Oufatene, Jebel Rheris) show clear macro-scale cycles whereas they are less recognisable in sections consisting of marls/shales and resedimented limestones (El Otfal, Boulchral-1, 3, 4, Bou Dib, Ouihlane). Accordingly, correlation of the latter sections is mainly based on bio- and lithostratigraphy.

Baselevel fall

In the northern and northernmost Mader (Jebel Rheris, Ouihlane, Bou Dib, Boulchral-3, 4), a fall trend can be recognised in almost every section by the facies change from unfossiliferous lithologies (LF 1, LF 9) to limestones with a diverse spectrum of components (LF 5c, LF 6b, LF 8a/b, LF 11). This fall trend is additionally indicated by the upsection increase of the limestone content and a texture change from mud-/wackestones to packstones and locally rudstones; most sections show an upward increase of the grain size. At Jebel Rheris, a rapid vertical facies change from dacryoconarid limestones to crinoid pack-/grainstones including stromatoporoid-coral accumulations was recorded. Channel-shaped debrites at Ouihlane, indicate the fall hemicycle whereas at Bou Dib this trend is suggested by the occurrence of debrites, laminated peloid-bioclast limestones and brachiopod coquinas. Similar lithologies were found at Boulchral-3, 4, 5, 8, where laminated (partially hummocky-cross stratification) resedimented limestones (LF 6b) and debrites (LF 8a) indicate the fall trend. Resedimented limestones locally contain micritised material (Bou Dib) or calcimicrobes (Boulchral). In the southern and western Mader (Jebel Kem, Jebel Zireg, Madene El Mrakib, Jebel Oufatene), the fall hemicycle is most obviously recognised by the increasing proportion of limestone beds with abundant reef dwellers. Locally, the fall can be recognised by the texture change from packstones to grain-/rud-/ and boundstones (Jebel Kem, Jebel Oufatene), increasing maximum grain size, and the occurrence of sparite cement within the upper part of the hemicycle.

Baselevel rise

In the majority of the sections, a vertical transition from limestone-marl towards marl-dominated successions indicates the subsequent rise. This trend

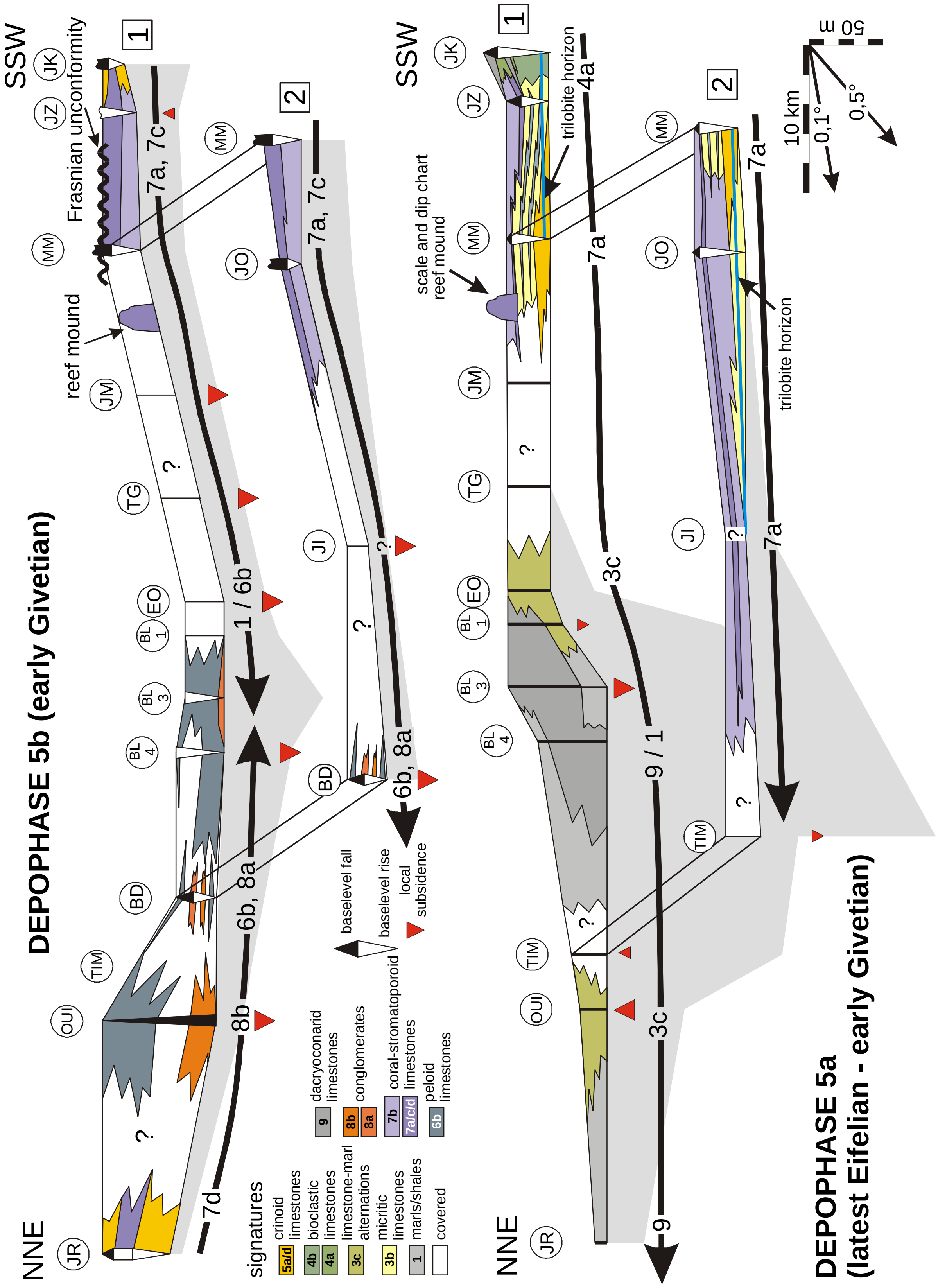

Fig. 25: Depositional geometry and facies relationships of depophase 5a and 5b (early Givetian) along transect line 1 and 2 of Fig. 17. The pale-grey shading below depophase 5a and 5b strata represents underlying rocks of the preceeding depophases; arrowheads indicate inferred vertical movements. Lithofacies numbers as in Chap. 4, abbreviations of sections as in Fig. 17, vertical exaggeration is 100.

is also reflected by the texture change from pack-/rudstones and locally boundstones to mud-/wackestones. Rocks of the rise hemicycle are usually poorly exposed, except for Jebel Issoumour and Jebel Rheris. However, the lower part of the rise hemicycle is documented at Jebel Kem, Madene El Mrakib, and Jebel Oufatene by the texture change from rud-/boundstones to float-/packstones and the decreasing abundance of reef-dwellers. At Jebel Rheris, a facies shift from stromatoporoid-coral limestones (LF 7d) towards crinoid limestones (LF 5d) indicates the rise hemicycle. At Jebel Issoumour this part of the section was not studied in detail, but field observations suggest that the rise hemicycle is well preserved as is documented by the increasing marl content upsection. In the southern Mader, depophase 5b strata are locally unconformably overlain by dacryoconarid packstones (Madene El Mrakib) which represent the Frasne-Event (*sensu* House 1985).

Lithostratigraphy

Very similar successions of depophase 5a and 5b strata were recorded in the southern and western Mader (Jebel Zireg, Jebel Kem, Madene El Mrakib, Jebel Oufatene). Depophase 5 b strata are recognised by the occurrence of coral-stromatoporoid limestones with minor marl intercalations and a conspicuous thickening-upward trend (Fig. 25; App. 1, 3, 6, 8, 10, 12, 13, 16-19, 21-24; Pl. 6, Fig. 4). Micritised components and calcimicrobes are common in these rocks and in resedimented limestones at Boulchral-3, 4, 5, 7, Bou Dib, and Ouihlane thus indicating a more or less contemporaneous accumulation. At the top of the Boulchral-3 and 4 sections, a conspicuously blue-grey-coloured, mostly massive limestone bed builds a prominent crest (Pl. 6, Fig. 2). This bed is interpreted to have been accumulated during maximum fall of depophase 5b. A very similar limestone bed (colour, thickness, composition) was found at Bou Dib where it overlies dacryoconarid marls as observed in the Boulchral-3 and 4 sections. This bed was termed "calcaire bleu marine" by Hollard (1974). In this study, it is used as a marker bed for the correlation of the Boulchral area with the Bou Dib section (App. 24). Debrite channels at Ouihlane contain abundant reef-dwellers and lithoclasts. Because large reef-dwellers are abundant in depophase 5b strata at the easterly located Jebel Rheris section, it is assumed that the debrites may be of the same age or younger. Remains of large stromatoporoids and other reef dwellers were also found at Bou Dib where they are associated with other resedimented limestones.

Biostratigraphy

Conodont data are available from underlying strata at Jebel Rheris and Madene El Mrakib (Tab. 28); they indicate the Lower *varcus* Zone. Strata at Bou Dib (App. 24) can be attributed to depophase 5b by conodonts (Bultynck & Jacobs 1981). Conodonts from the Ouihlane section (Bultynck 1985) contradict to the assumed correlations in this area. The latter author dated the debrite beds, which he interpreted as reefal limestones, into the Eifelian *kockelianus* Zone (Chap. 4.8.1). These beds contain only a small amount of matrix and are mainly composed of limestone lithoclasts and reef-dwellers. Therefore, it seems difficult to obtain a reliable conodont age of these rocks which may rather yield a mixture of reworked conodont elements. Locally, a styliolinite unconformably overlies the Givetian stromatoporoid-coral limestones at Madene El Mrakib (Pl. 6, Fig. 6); it was attributed to the lowermost Frasnian (Kaufmann 1998). Coeval and similar rocks are exposed 500 m north of the Guelb El Maharch mud mound (Kaufmann 1998), north of the Jebel Maharch section.

Lithofacies distribution

During maximum fall of depophase 5b (Fig. 26b), a vast coral-stromatoporoid facies belt (LF 7) extended from the southern to the northwestern Mader (Jebel Kem, Jebel Zireg, Jebel Oufatene, Jebel Issoumour) and in the northernmost Mader (Jebel Rheris). Southernmost (Jebel Kem, Jebel Zireg) and northernmost parts (Jebel Rheris) of this facies belt, were inhabited by abundant crinoids as demonstrated by the crinoid matrix and under- and overlying crinoid limestones. In other sections (Madene El Mrakib, Jebel Oufatene), a muddy matrix with a great variety of skeletal material, peloids, calcimicrobes, and micritised grains predominates. Most of the northern Mader (Boulchral, Bou Dib, Bou Makhlouf), was dominated by the deposition of shales, fine-grained resedimented limestones, conglomerates, and breccias (LF 5c, LF 6b, LF 8a/b, LF 10, LF 11). These rocks frequently contain reworked skeletal and non-skeletal grains from the adjacent coral-stromatoporoid limestone belts. In the northernmost Mader (Ouihlane), conspicuous debrite channels are cut into the marl/shale successions (Chap. 4.8.2). These contain abundant reef-dwellers and limestone clasts.

Interpretation

The coral-stromatoporoid limestone belt of the southern and western Mader reflects a proximal-distal trend from south to northwest (Chap. 4.7.4). Successions in the southernmost outcrops (Jebel Kem), indicate permanent reworking of skeletal grains thus reflecting an environment above the storm-wave base. Farther north, a more calm environment was established which was situated in the photic zone, but protected from storm-wave activity. Rocks of depophase 5b (LF 5d, LF 7d) in the northernmost Mader (Jebel Rheris), show clear evi-

Ammonoids, conodont samples (sections)	Range with respect to conodont zones (KLUG in press)
trilobite horizon below (MM), KAUFMANN (1998)	Lower *varcus*
styliolinid layer (MM) dated by KAUFMANN (1998)	early Frasnian (lower part of *asymmetricus*)
dating by BULTUYNCK & JACOBS (1981) (BD)	Lower *varcus*
dacryoconarid limestones below (JR)	Lower *varcus*

Tab. 28: Biostratigraphic data of depophase 5b strata (abbreviations as in Fig. 5).

dence for permanent bottom currents and thus indicate an environment in the photic zone and above the storm wave base (Chap. 4.5.3, 4.7.5).
Resedimented limestones in the northern Mader suggest bottom currents which may originated from storms or turbidity currents, in some cases. Coarse debrites were also accumulated in this environment. From these features, an environment which was temporarily above or slightly below the storm wave base can be inferred (Chap. 4.5.2, 4.6.2, 4.8).

Conclusions

Facies relationships suggest a carbonate-ramp depositional system with the inner-ramp located in the southernmost, western and northernmost Mader and the mid- to outer-ramp in the northern Mader (Fig. 26b). During depophase 5b, coral-stromatoporoid limestones prograded slightly. Contrasting to depophase 5a, the northernmost part of the Mader was situated in shallow waters thus suggesting very low subsidence or slight uplift in this area. Therefore, it can be concluded that a rather small basin was established during early Givetian times, which was surrounded to the south, west, and north by a shallow neritic facies belt.

Depophase 5b is part of the highstand systems tract (HST) which initiated during the late depophase 5a. The stratigraphic pattern and facies relationships are the result of a high sea level and regional subsidence contrasts.

5.6.3 Depophase 5c, d, e

Strata of depophase 5c, 5d and 5e are only preserved in the northern (Jebel Rheris, Ouihlane, Bou Dib) and probably in the northwestern Mader (Jebel Issoumour) which was not studied in further detail (App. 1, 2, 4, 6, 24). Facies relationships are similar to the foregoing depophase 5b; thickness is 175 m at Jebel Rheris), 140 m at Ouihlane, and 50 m at Bou Dib. Baselevel trends are not as well recognisable as for the preceding depophases and the isolated occurrence of the outcrops limits lithostratigraphic correlation.

Sedimentary cycles

At Jebel Rheris, macro-scale cycles were recorded by the vertical alternation of partially laminated crinoid limestones (LF 5d) with stromatoporoid-coral limestones (LF 7d). The latter, were accumulated predominantly during a baselevel fall whereas the crinoid limestones and the shales were deposited during the baselevel rise (App. 24). At Ouihlane and Bou Dib, conspicuous bundles of limestone-marl alternations are intercalated in unfossiliferous shales. The bundles include various lithofacies (LF 3c, LF 5c, LF 6b, LF 8a/b, LF 10, LF 11) and reflect a falling baselevel whereas the mar/shale successions represent times of a high or a rising baselevel.

Lithostratigraphy and biostratigraphy

The composition of resedimented limestones (calcimicrobes, micritic envelopes, reef dwellers) at Ouihlane and Bou Dib (Chap. 4.5.2, 4.6.2) indicates a genetic relationship with coeval shallower environments at Jebel Rheris (Chap. 4.5.3, 4.7.5). The recognition of the depophases is based on these relationships in combination with vertical sedimentological trends. Biostratigraphic data are rare and provide a rather low resolution (Lower *varcus* Zone); conodont data from Ouihlane (BULTYNCK 1985) are questionable (compare Chap. 5.6.2).

Lithofacies distribution and interpretation

The northernmost Mader (Jebel Rheris) was dominated by the deposition of crinoid limestones (LF 5d) and stromatoporoid-coral limestones (LF 7d) in a slope environment (slumping). High abundance of micritic envelopes and microbial components suggest deposition within the photic zone. Lamination and scour-and-fill structures in crinoid limestones indicate sedimentation above the storm wave base. The high shale content in the sections farther west and south (Ouihlane, Bou Dib), indicates a deeper environment. Here, the intercalated limestones (LF 6b) show lamination (partially hummocky-cross stratification) and at Bou Dib brachiopod

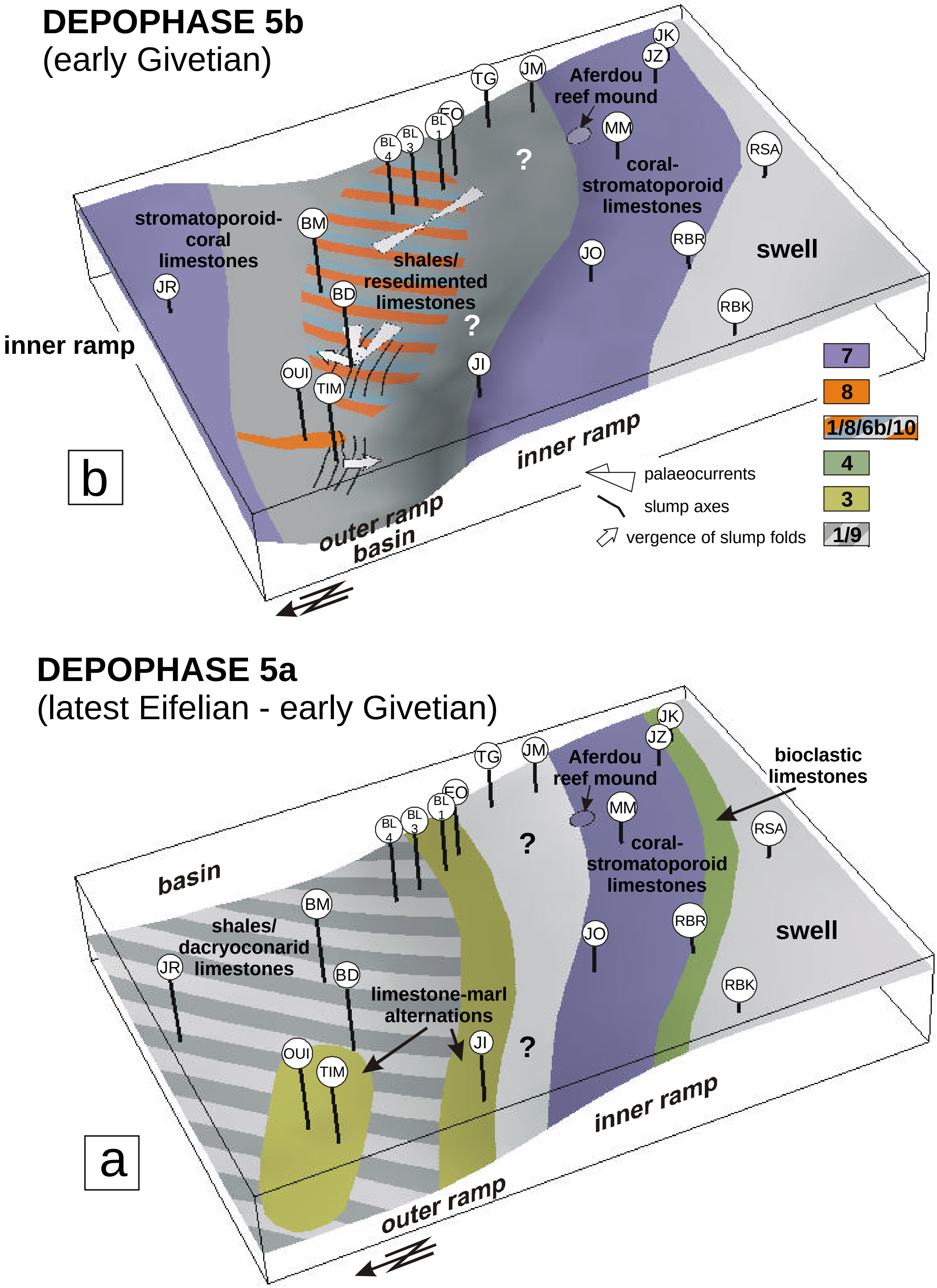

Fig. 26: Three-dimensional facies relationships during maximum fall of depophase 5a (a) and depophase 5b (b). Lithofacies numbers as in Chap. 4, abbreviations of sections as in Fig. 17, vertical exaggeration is ca. 90. Detailed structural data of slumps is displayed in Fig. 33.

coquinas (LF 11) are intercalated frequently. These features suggest an environment which was temporarily situated above the storm wave base but which was repeatedly subject to autochthonous shale sedimentation in a calm environment. The central and southern Mader was probably subject to sediment bypass whereas in the western Mader (Jebel Issoumour) sedimentation was more or less continuous until the Frasnian.

Conclusions

The northernmost Mader (Jebel Rheris) represents the inner-ramp environment, whereas the mid-ramp to outer-ramp extended from Ouihlane to Bou Dib and Boulchral. In the latter area, the poor outcrop conditions prevent the accurate reconstruction of the environment. The southern Mader was probably part of a swell (Mader Platform) during depophase 5c to 5e but poor outcrop conditions and stratigraphic gaps (Madene El Mrakib) restrict the reconstruction of the sedimentological evolution. Facies relationships reflect persisting highstand (HST) conditions for depophase 5c to 5e although the large-scale stratal pattern may suggests lowstand conditions (App. 24).

5.7 Synsedimentary deformation during depophase 4 and 5

In the eastern Anti-Atlas, locally small-scale folds occur in Middle and Upper Devonian strata. Most of these structures were interpreted to originate from slumping and hence as evidence for Devonian palaeoslopes and platform-margin environments (Wendt 1988). Wendt (1985) claimed that weak block faulting occurred during the Middle Devonian and became more pronounced during the Late Devonian.

Investigations by Walker (1997) carried out that small-scale folds in the southern Tafilalt area originated exclusively from tectonic processes. Unfortunately structural data was analysed without considering the differing fold and bed shapes which appears very different in outcrop thus pointing to a diverse origin of small-scale folds.

Own observations reveal, that small-scale deformation structures occur in the northern Mader within limestone successions (LF 3, LF 4) of depophase 2 at Boulchral-1 and 3, within limestone-marl alternations (LF 3b, 3c, 5c, 6b, 8a/b, 11) of depophase 4 and 5 at Timerzit and Bou Dib, within laminated crinoid limestones (LF 5d) of depophase 5 at Jebel Rheris, and within siltstone-shale (LF 10) alternations of Givetian and Late Devonian age at Bou Dib and Boulchral-6.

A distinction between slump folds and tectonic folds can be made by analysing the geometry of folds and the associated bedforms. According to Maas (1974) there is a continuum of geometries from synsedimentary folds to tectonic folds. The favourable outcrop conditions in the Mader (Figs. 27, 28) challenge the study on the origin of the small-scale folds.

5.7.1 Boulchral area

Structural data from depophase 2 strata at Boulchral reveal, that small-scale folds are oriented more or less parallel to the regional tectonic strike which is SSE-NNW (Fig. 29a-c). Small-scale folds in this area are frequently isoclinal, show an amplitude of several metres, and a uniform geometry along tectonic strike, and the thickness of individual beds appears constant within the fold structures. Occasionally fold hinges can be followed in the outcrop over several 100's of metres. The lateral distance between individual folds can be very large, extending to several 10's of metres. The strata between the folds is rather undeformed and dip according to the regional dip pattern. From these field observations and the analysis of structural data it is concluded that the small-scale folds at Boulchral originated from tectonic deformation.

5.7.2 Bou Dib section

At Bou Dib, structural data show that small-scale folds of depophase 5b strata are oriented perpendicular to the regional tectonic strike which is SW-NE (Fig. 29d-f). Fold axes are well visible on aerial photographs and strike in a NW-SE direction. Bedding planes of the small-scale folds locally show a random orientation (Fig. 29e) but are mostly oriented perpendicular to the regional strike. Small-scale, centimetre-sized slumpings (Fig. 15/5) show axial planes with a preferred vergence towards NW (Fig. 29f). Field observations reveal that folded horizons are under- and overlain by rather undeformed strata (Fig. 27/1, 2). Compared to the above described folds of Boulchral, fold shapes at Bou Dib appear chaotic (Fig. 27). Locally, eroded folds can be found (Fig. 27/5, 6) and some beds show internal deformation structures (Pl. 3, Fig. 1). According to these observations, the small-scale folds within strata of depophase 5b - 5e at Bou Dib are interpreted to originate from slumping.

5.7.3 Nortwestern Mader (Timerzit, Ouihlane)

In the northernmost Mader (Ouihlane, Timerzit), the regional tectonic strike is WSW-ENE (Fetah et al. 1988). The small-scale folds of depophase 4 strata at Timerzit are oriented nearly perpendicular (Fig. 29h) or at 45° (Fig. 29i) with respect to the regional tectonic strike. Axial planes of the small-scale folds show a vergence towards SSW (Fig. 29j). Bed geometries are very variable and bed thickness changes considerably within short lateral distances; some beds even wedge out (Fig. 28/5 - 8). The small-scale folds occur within a distinct stratigraphic interval

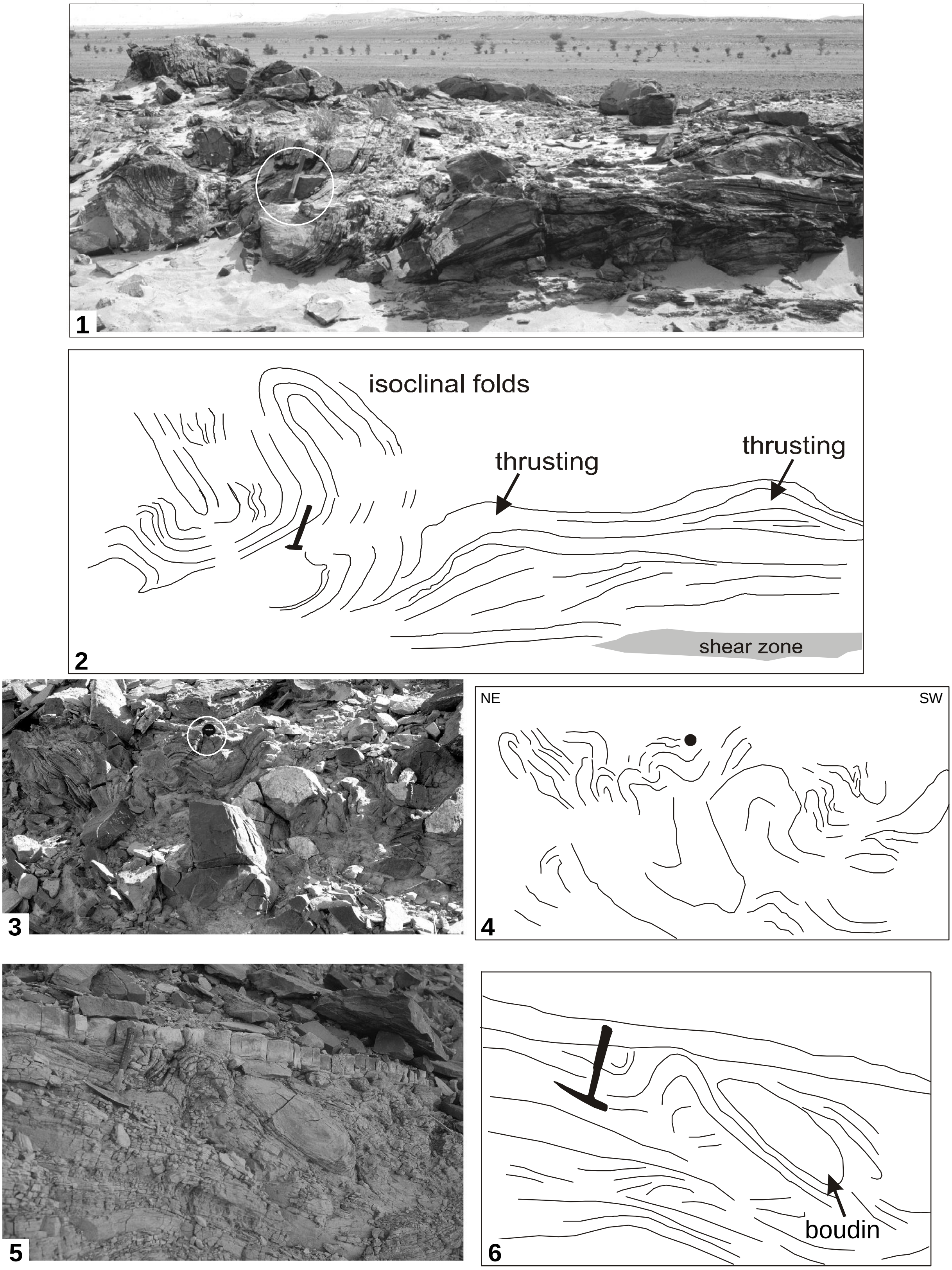

Fig. 27: 1/2: Chaotic slumping structures in medium-bedded limestones (LF 6b) at Bou Dib with a distinct shear zone at the base and different features of soft-sediment deformation as thrusting and folding. 3/4: Chaotic slump folds in medium-bedded limestones (LF 6b) at Bou Dib. Slump folds show vergence to the NE. Note the lateral rapidly changing bed thickness and extreme thickening at hinge points. 5/6: Slumping structure in medium-bedded, monotonous argillaceous limestones (LF 9) with a discordantly overlying limestone bed (Bou Dib). Note the large ellipsoidal block (boudin) within the slump fold which may formed by extensional strain and was then involved in the slump fold.

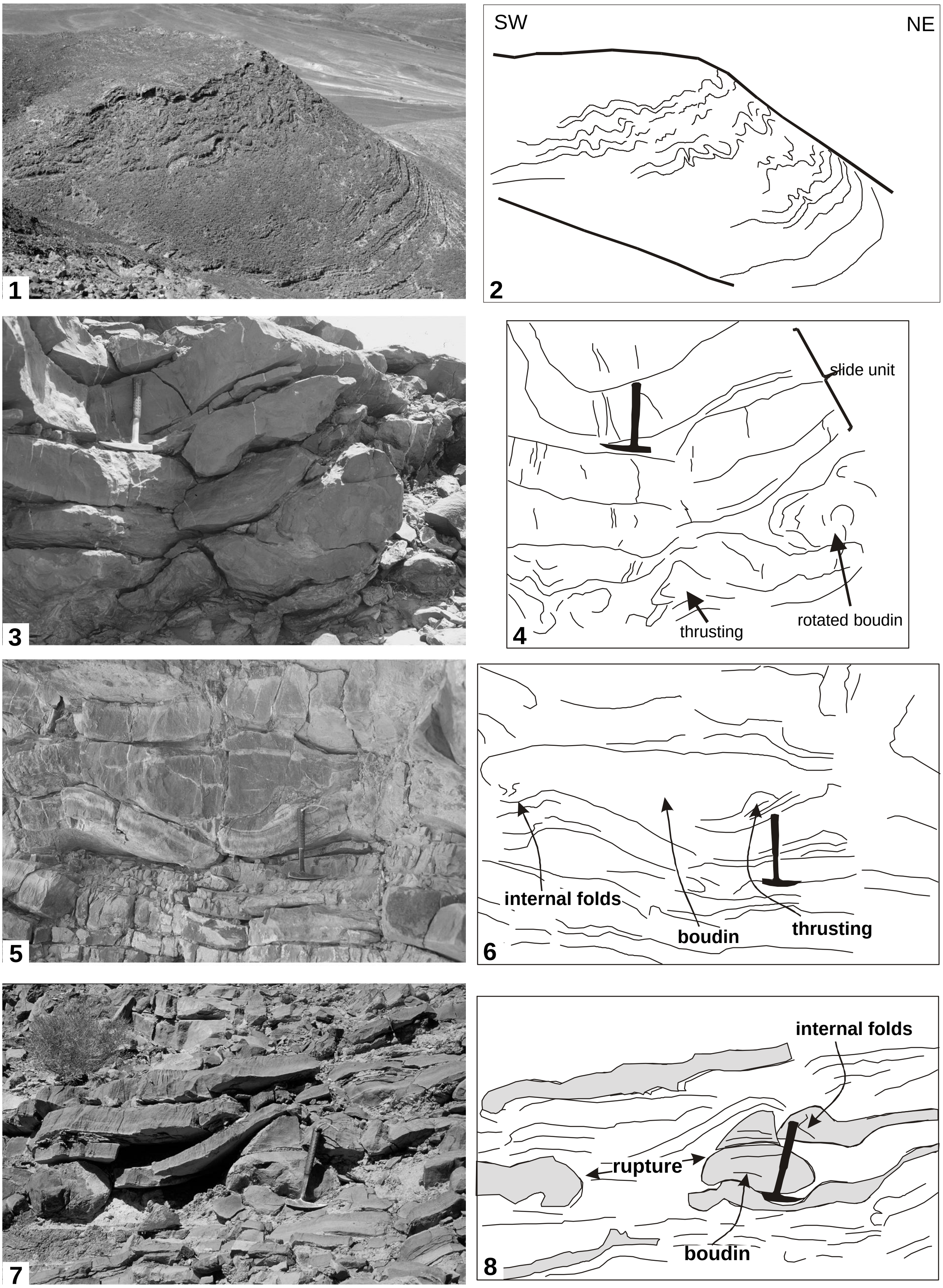

Fig. 28: 1/2: Middle- upper Eifelian succession at Timerzit consisting of limestone-marl alternations (LF 3c) with rather undeformed beds in the lower part and small-scale folding in the upper part of the succession. The entire succession is ca. 80 m thick. 3 - 8: Small-scale fold structures at Timerzit showing lateral variability of bed thickness, boudinage, thrusting and synsedimentary rupture within monotonous limestone-marl alternations (LF 3c). Note that some beds show internal folds.

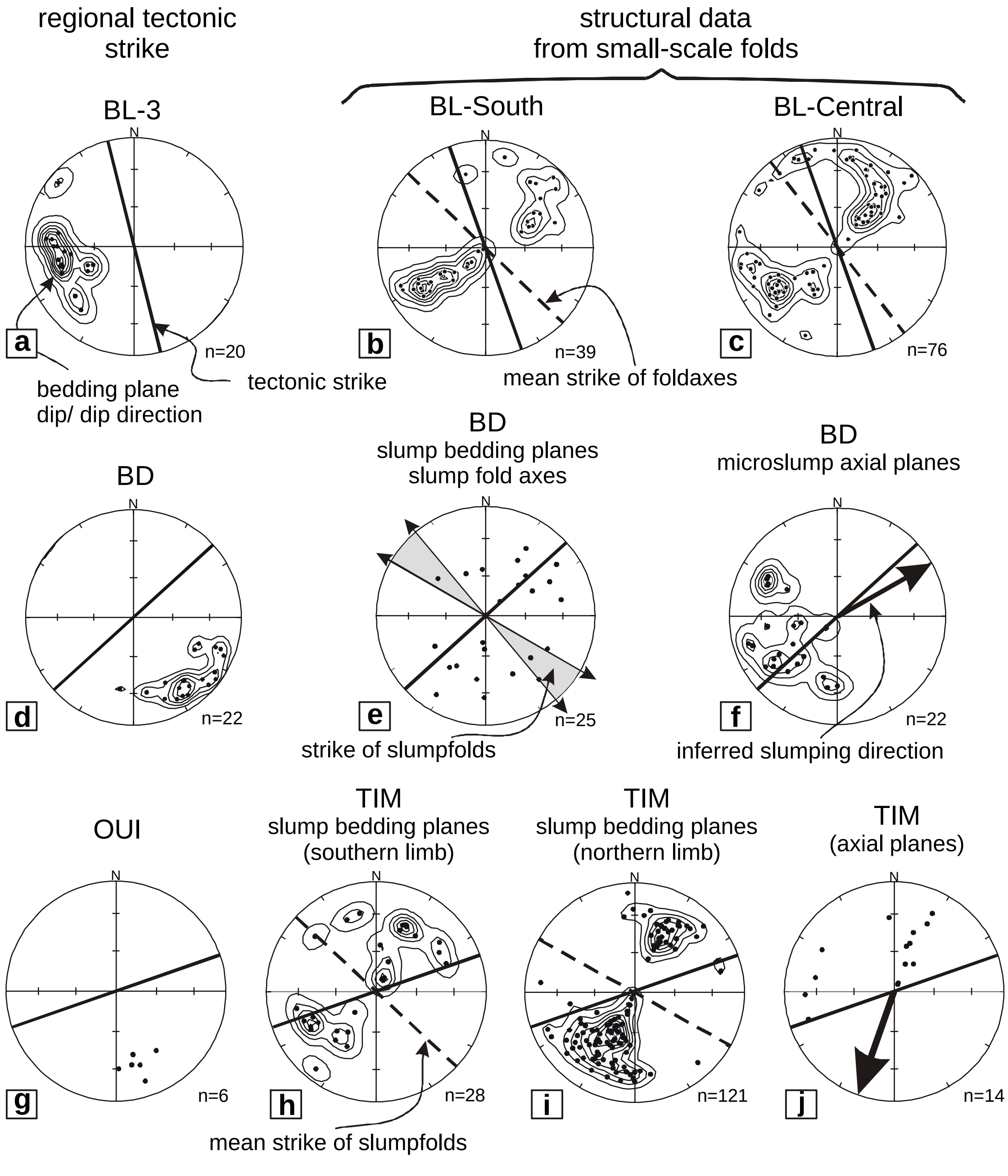

Fig. 29: Structural data of small-scale folds of the northern Mader displayed as stereographic projection onto the lower hemisphere (BL: Boulchral, BD: Bou Dib, TIM: Timerzit, Ouihlane: OUI). Bedding planes are illustrated by their dip / dip direction, regional tectonic strike is displayed as lines and fold axes are displayed as arrows or dashed lines crossing the stereographic projection. The vergence of fold axes is displayed by the dip / dip direction of the axial plane and an arrow pointing towards the inferred slumping direction.

(around 30 m thick) which is underlain by rather undeformed beds (Fig. 28/1, 2). The combined occurrence of the above described features indicates that small-scale folds at Timerzit originated from slumping.

5.7.4 Conclusions

Small-scale folds of depophase 4 and 5 strata in the northern Mader (Jebel Rheris, Timerzit, Bou Dib) are the result of slumping. The folds and facies relationships can be integrated into the slump model (Fig. 30) of Dingle (1977) in which the folds of the Mader occupy a position on the lower slope. According to structural (Fig. 29d-j) and field data, a palaeoslope extended from Jebel Rheris to Timerzit during late Eifelian to early Givetian times (Fig. 26b). This slope was inclined towards SW as indicated by the orientation of the foldaxes and the vergence of small-scale folds (Fig. 29g-j). To the south, another slope (Bou Dib) existed contemporaneously (Fig. 26b); it was

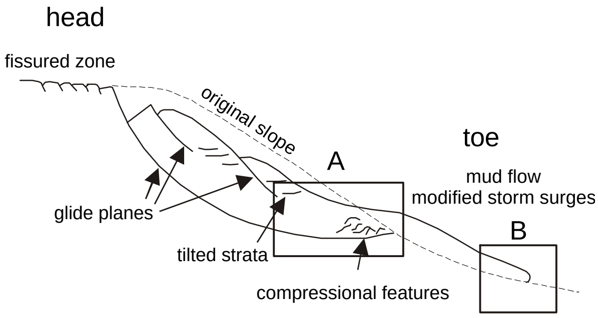

Fig. 30: Schematic model showing the main morphological and structural features of submarine slumps (modified after Dingle 1977). Boxed areas indicate the possible position of the studied slumping and sliding structures (a) and surrounding lithofacies (b) within the model (not to scale).

inclined towards NW as suggested by the orientation of foldaxes and the vergence of small-scale folds (Fig. 29d-f). These data support the view, that the northern Mader was a small basinal area which was surrounded by slope environments (Timerzit, Bou Dib) and shallow-water areas to the north (Jebel Rheris), west?, and south (Jebel Issoumour, Jebel Oufatene, Madene El Mrakib) during Middle Devonian times (Fig. 26b). This interpretation corresponds to the observed facies relationships and the reconstructed depositional geometries. The absence of slumping in the southern and western Mader and the combined occurrence of debrite channels (Ouihlane) and slumping (Jebel Rheris, Timerzit, Bou Dib) in the northernmost Mader reflect the existence of a half-graben-shaped basin with a steeper inclining slope on the northern margin and a slightly, northwards dipping inclined ramp south of the basin.

With respect to sea level fluctuations, slumps, slides and debris flows preferably occur during lowstand conditions (Handford & Loucks 1993). But in the study area Givetian slumping and debris flows occurred during highstand conditions (Fig. 18). However, Handford & Loucks (1993) mention that sediment loading during a highstand may also favours the formation of slides and debris flows which is obviously the case for the Givetian of the Mader.

6 CONCLUSIONS AND OUTLOOK

6.1 Carbonate ramp sedimentation

The major components of the upper Emsian to lower Eifelian carbonates (depophase 1a, 1b, 2) are crinoids, bryozoans, brachiopods, and mud. Typical shallow-water components as reef dwellers, ooids, oncoids, micritic envelopes, or calcimicrobes are almost absent. The majority of published carbonate facies models is based on studies of modern tropical environments and thus do not consider facies zones with the predominance of the Emsian to Eifelian components (e.g. Wilson 1975, James & Kendall 1992). Comparing the upper Emsian to lower Eifelian carbonate ramp of the Mader with modern cool-water carbonate shelves, some striking similarities with respect to composition, sedimentation rates, and depositional gradient can be observed (Tab. 29). Rocks of the inner to mid-ramp of the Mader, show the closest similarities to modern cool-water-shelf deposits as described by Ferland & Roy 1997 for the southeastern Australian shelf. The most obvious difference of the Mader ramp with modern cool-water settings is the high mud content in most of the studied rocks. Since the majority of the investigations dealing with cool-water carbonates refer to environments which do not exceed water depths of 100 m, it is likely that within the distal parts of a carbonate environments, a higher proportion of mud may be present as in the case of the Mader carbonate ramp.

Other evidence for cool-water conditions is provided from delta^{18}O isotope values of brachiopod shells and marine cements. They suggest seawater temperatures which were about 5°C lower than in coeval low-latitude environments of North America (Kaufmann 1998). Palaeogeographic reconstructions of Scotese (1997), show that the northern margin of the Sahara Craton was situated on the southern hemisphere between 30 and 50° with a temperate climate throughout the Devonian. This area did not reach very low latitudes until the Carboniferous and thus obviously was not subject to tropical conditions during the Devonian.

Facies models for cool-water carbonates (James 1997), reflect the here postulated facies relationships of the upper Emsian to lower Eifelian carbonate ramp of the Mader very well (Fig. 31a). Beach and intertidal environments are not preserved in the study area which is probably an effect pre-late-Famennian erosion. Deeper environments, above and below the storm wave base, however, are present in the Mader. Faunal communities almost exclusively comprise heterozoans (*sensu* James 1997). The shallowest environments were characterised by the sedimentation of crinoid sand and silt (LF 5). Further distally, crinoid-bryozoan-skeletal mud was accumulated and in deeper environments skeletal argillaceous mud predominated. In the latter facies belt, mud mounds were locally established. The deepest environments were subject to the deposition of argillaceous mud and planktonic organisms (e.g. dacryoconarids).

During the early Givetian, photozoan communities predominated the shallow waters of the Mader. They comprise stromatoporoids, rugose, tabulate corals, and calcimicrobes. Local patch reefs and bioherms, which were several decimetres high and several metres wide, were established. Based on these observations, the facies scheme of JAMES (1997) was modified for the lower Givetian of the Mader (Fig. 31b). Lagoonal and intertidal environments were not preserved in the study area, similar to Emsian and Eifelian times. The shallowest areas were dominated by coral-stromatoporoid patch reefs and crinoid sands; further distally these deposits interfingered with muddy sediments. In the latter environment, a large reef mound (Aferdou El Mrakib) was established. Further offshore, a facies belt consisting of mud, tempestites with peloids and skeletal debris, and local mud mounds was established. Most distal environments were characterised by the deposition of shales and resedimented limestones including debrites, tempestites, and turbidites.

The facies evolution from the late Emsian to the early Givetian of the Mader suggests a climatic change. Whereas the exclusive occurrence of heterozoan associations during late Emsian to Eifelian times reflects a non-tropical carbonate ramp, photo-

	New Zealand modern shelf carbonates	eastern Anti-Atlas Emsian - Eifelian carbonate ramp
setting	- latitude higher than 30° - open shelves or ramps - stable to unstable tectonic - low - high terrigenous supply	- latitude higher than 30° S - ramp - stable to unstable tectonic - low - medium terrigenous supply
shelf gradient	0,25 - 2 m / km 0,01 - 0,1°	probably 0,1 - 0,3°
reef structures	none (some oyster banks)	carbonate mud-mounds
sedimentation rate	1 - 15 cm / ka	90 m - 160 m in 7 Ma 1 - 2 cm / ka (compacted)
$CaCO_3$ content	50 - 100%	+ / - 50 - 95% (MASSA1965)
siliciclastic grains	rare-abundant	rare - medium abundant
glauconite	common, especially in skeletal voids	not recorded
dolomite and evaporite minerals	absent	absent
non-skeletal carbonate grains	absent	absent - very rare (lithoclasts, pseudopeloids)
major skeletal grain types	bryozoans, molluscs, foraminifers, echinoderms, barnacles, coralline algae, serpulids, brachiopods, corals, sponge spicules	crinoids, bryozoans, brachiopods, small solitary corals, trilobites, molluscs, dacryoconarids
main skeletal assemblages	bryomol, bimol, nannofor	crinoid-bioclast, crinoid-bryozoan, crinoid-brachiopod, dacryoconarid-bioclast
algal mats / stromatolites	absent	absent
carbonate petrography	grain- and rudstones	mud-, wacke-, pack-, grainstones
carbonate mud	absent - rare, flushed and by-passed offshore	common, possibly supplied by offshore currents which bypass shallower environments
main origin of carbonate mud	physical abrasion, bioerosion and maceration of skeletons	unknown

Tab. 29: Comparison of the early Emsian - early Eifelian carbonate ramp of the Mader with a modern cool-water shelf setting (First and second column after Nelson 1988 and Nelson 2001 written comm.).

zoan associations in the Givetian rocks indicate increased water temperatures by this time. This is also suggested by the changing composition of the coeval buildup structures which are mud mounds (El Otfal) during the early Eifelian and a reef and a mud mound (Aferdou El Mrakib, Guelb El Maharch during the early Givetian (KAUFMANN 1998).

6.2 The concept of stratigraphic baselevel and sequence stratigraphy - application and limits

Studies utilising the concept of stratigraphic baselevel (e.g. HOMEWOOD 1996, PAWELLEK 2001, SCHAUER 1998) rely on the detection of small-scale sedimentary cycles and the understanding of the processes which generate the cycles. For example, crinoid limestones (LF 5a, b) locally show small-scale cycles (Pl. 2, Figs. 1, 2): The proportion of preserved macrofauna patches or layers can provide information about a rising or falling baselevel. As mentioned in Chap. 4.5.1, the well-sorted crinoid limestones possibly indicate a falling baselevel or a low baselevel, whereas the patches and the layers with macrofauna and intercalated marls represent the time of rising baselevel. A similar scheme can be recognised in fine-grained lithologies (LF 4, LF 3). However, it is also possible that the proposed small-scale cycles are autocyclic in origin: larger crinoids and brachiopods locally settled not until a suitable substrate in the form of a well-sorted crinoid-debris sediment was deposited.

Due to the aim of this study, these vertical changes were not recorded in such detail in the entire Mader. Instead, mainly the carbonate/shale content, texture, grain size, and sedimentary structures were considered which were interpreted in terms of rising or falling macro-scale baselevel (compare Chap. 3.3.1.1). Consequently, a process-oriented interpretation was only partially achieved. Further investigations on the studied strata should include the detection of small-scale cycles and successive stacking in order to generate macro-scale cycles.

The interpretation of marly interbeds or thick shaly successions with respect to baselevel is still a matter of debate: PAWELLEK (2001) or BACHMANN & KUSS (1998) interpreted such lithologies as evidence for a rising or high sealevel and a landward stepping of the carbonate factory. By contrast, VAN WAGONER

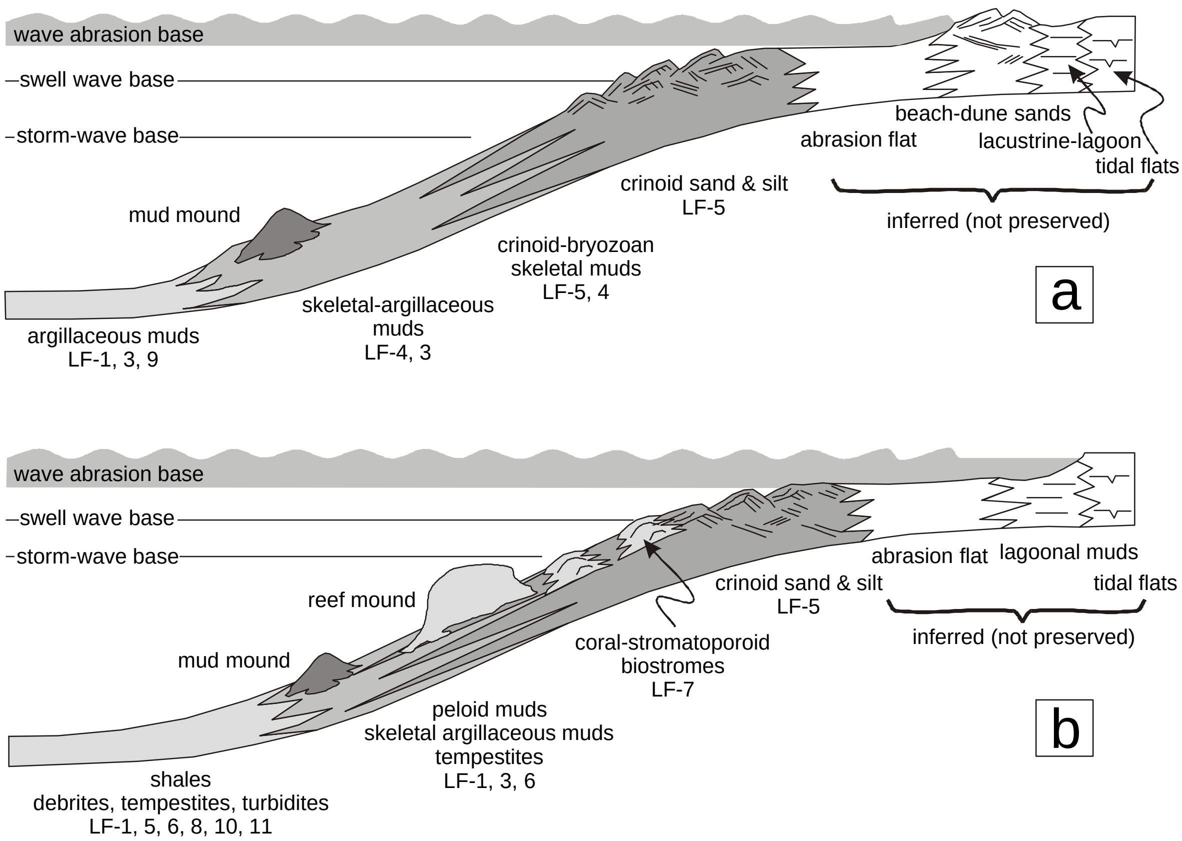

Fig. 31: Generalised facies models for the upper Emsian to lower Eifelian (a) and the lower Givetian carbonate ramp (b) of the Mader (not to scale). Models are based on cool-water-carbonate facies models of James (1997). Lithofacies codes as in Chap. 4 (1: marls/shales, 3: monotonous limestones, 4: bioclastic limestones, 5: crinoid limestones, 6: peloid limestones, 7: coral-stromatoporoid limestones, 8: conglomerates, 9, dacryoconarid limestones, 10: siltstones, 11: coquinas).

et al. (1988) assumed that such successions are evidence for increased siliciclastic input related to a sea-level fall and for a seaward-stepping supply area. Obviously, shale sedimentation can be related to regional effects and a simple scheme whether they must be interpreted as a rise or a fall in sea level cannot be developed. Only investigations of the included organic remains of terrestrial or marine organisms (palynofacies) can provide a clue to the origin of these lithologies. Most of the thicker marl/shale intervals in this study, however, were interpreted in terms of a rising baselevel (Chap. 3.3.1.1).

The varying outcrop conditions, the low fossil content of some successions, and scarce sedimentary structures limit the accuracy of regional correlations by the baselevel concept. Particularly the sections of the northern and northernmost Mader mostly lack indicative sedimentological or biological trends (Boulchral, Timerzit, Ouihlane, Jebel Rheris). These rather homogenous successions were integrated into the sequence stratigraphic framework by litho- and biostratigraphy. Consequently, sections representing mid- to inner-ramp environments can be correlated more accurately by the baselevel concept than sections of more distal environments.

6.3 Sequence stratigraphy and subsidence pattern

6.3.1 Late Emsian - early Givetian

Sequence stratigraphic analysis of the upper Emsian to lower Eifelian successions resulted in a subdivision (Fig. 32) into a highstand systems tract (depophase 1a, 1b, 2), a transgressive systems tract (depophase 3), a highstand systems tract (depophase 4), a subsequent transgressive systems tract (depophase 5a), and a highstand systems tract (depophase 5b-e).

Lower Emsian to lower Eifelian strata (depophase 1a, b, 2, 3) are characterised by minor thickness variations. Sediments were deposited on a slightly inclined ramp during this time. A gentle facies gradient from SSW to NNE existed during depophase 1a and 1b, whereas depophase 2 deposits show a more pronounced facies gradient and a progradational pattern towards NNE, thus indicating late highstand conditions. Depophase 3 is characterised by retrograding facies belts and thus represents a transgressive systems tract. Only minor subsidence differences occurred during depophase 1a, 1b, 2, and 3 but became more pronounced during depophase 4. The latter is exclusively preserved in the northern Mader and is characterised by a minor facies gradient and a slightly prograding facies pattern. A transgression during depophase 5a is reflected by a homogenous thickness pattern and the trapping of siliciclastic material on the proximal shelf; this promoted the growth of reef dwellers in the southeastern Mader. Increasing subsidence contrasts during depophase 5b, resulted in a more complex thickness and facies pattern. Siliciclastics were still trapped on the proximal shelf and reef-dwellers persisted in the southwest and initiated settling in the northernmost Mader where regional uplift caused shallowing. This is well documented by the upper Eifelian to lower Givetian succession at Jebel Rheris which shows evidence for rapid shallowing. This can hardly be explained by the eustatic sea-level which was obviously rising during Givetian times (Fig. 18). Therefore it can be concluded, that regional uplift and high sedimentation rates led to progressive shallowing during the Givetian in this area. Fault-controlled subsidence in the north is suggested by the occurrence of local conglomerates, slumping and rapid thickness changes (Fig. 32).

Recorded macro-scale cycles of the early Emsian to the early Eifelian correspond roughly to the eustatic sea-level curve (Fig. 18) of JOHNSON et al. (1985) and to global bio-events (CHLUPAC & KUKAL 1986, HOUSE 1985). The Ic transgression may correlate with the rise during depophase 1b whereas the "Chotec Event" (CHLUPAC & KUKAL 1986) does not appear as a major transgressive event as postulated by JOHNSON et al. (1985). The Id transgression correlates with the basal transgressive systems tract (depophase 3) which was dated into the middle part of the *costatus* Zone. The base of a transgressive systems tract (depophase 5a) clearly corresponds to the If transgression of JOHNSON et al. (1985) which is equivalent to the "Kacak Event" (HOUSE 1985). In certain sections (Bou Dib, Jebel Rheris), the IIa transgression (JOHNSON et al. 1985) can be recognised which coincides with the "Taghanic Event" (HOUSE 1985).

6.3.2 Late Devonian

Facies contrasts were more pronounced than during preceding times: Upper Devonian shallow-water limestones (cross-bedded crinoid limestones at Jebel Rheris) contrast with homogenous basinal shales and marls with turbidite intercalations approx. 20 km to the southwest (Figs. 16, 33a). Additionally, prominent angular unconformities occur within the Upper Devonian strata. Upper Devonian successions in the northernmost Mader (Jebel Rheris), reflect permanent shallow-water conditions, increased input of coarse-grained siliciclastic material, and temporarily subaerial exposure with karst phenomena. Local sea-level fluctuations recorded in the Jebel Rheris section, do not correlate with those of JOHNSON et al. (1985) whereas farther south (Bou Dib, Madene El Mrakib, Rich Bel Ras), sea-level fluctuations correlate very well with JOHNSON et al. (1985). At these localities, the high sea level is reflected by the thick, homogenous marl/shale successions (Figs. 4, 16, 33a). Outside the Jebel Rheris area, unconformities are barely

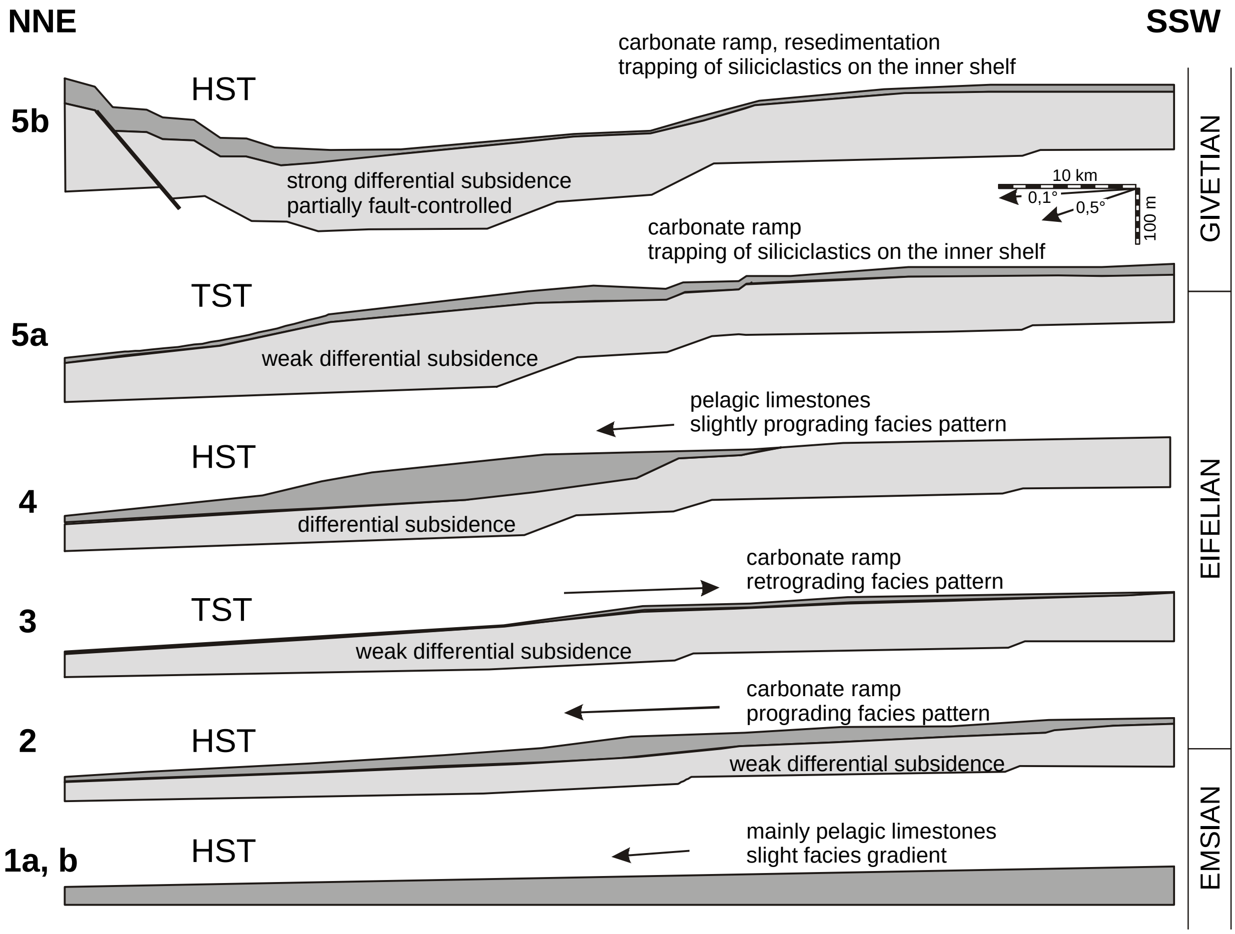

Fig. 32: Sequence stratigraphic evolution of the Mader from late Emsian to early Givetian times along transect line 1. Numbers refer to depophases as Chap. 5, vertical exaggeration is 20.

visible. However, some localities in the western and southwestern Mader show successions which are interrupted by rather horizontal unconformities. This is the case in the westernmost Mader, where Upper Frasnian strata (e.g. the "Upper Kellwasser Member" *sensu* WENDT & BELKA 1991) overlies Ordovician to Lower Devonian strata (Rich Bou Kerzia, El Fecht, Tizoula; compare Fig. 5). Another unconformity is documented in the southwestern Mader (Madene El Mrakib), where limestones of the Frasne Event (HOUSE 1985) overly lower Givetian coral-stromatoporoid limestones (Figs. 16, 37a).

From these observations, it is concluded that the Upper Devonian stratigraphic pattern and facies relationships are the result of differential subsidence, which increased since the middle Eifelian and were most pronounced during the Late Devonian. The northern Mader was subject to local uplift as indicated by the individual facies evolution which contrasts with the eustatic sea-level curve (Figs. 18, 33a).

6.4 Origin of stratigraphic gaps (depophase 4, early Emsian - Frasnian/Famennian)

Several sections in the southwestern, southern Mader, and northernmost Mader are characterised by remarkable stratigraphic gaps: lower Emsian to Frasnian/Famennian at Rich Bel Ras and Rich Sidi Ali, lower Eifelian to upper Eifelian (depophase 4) at Jebel Kem, Jebel Zireg, and Madene El Mrakib, and lower Emsian to uppermost Famennian north of Jebel Rheris. Although these gaps are biostratigraphically well-documented, features indicating emersion and erosion were only recorded in the northernmost Mader (Jebel Rheris). Possibly weak but permanent bottom currents, which resulted in prolonged sediment by-passing, occurred in these areas. Contour currents may explain this process to some extent: From observations on modern shelves, it is likely that contour drifts remarkably influence the facies zonation and the preservation of certain bathymetric environments (LIGHT & WILSON 1998). These authors found, that in water depths between 130 and 500 m on the recent West-Shetland Shelf mud is absent due to a contour current. Transferring these observations to the study area, the stratigraphic gap of depophase 4 (Figs. 23, 24b, 32) can be explained as the result of continuous sediment by-passing in the southern Mader. During this time, calcareous mud was only deposited in the northern Mader, where it formed a sedimentary wedge with the geometry of a lowstand systems tract. Another process which may exist in deeper waters and which produces sediment transport, are internal waves. These can form between subsurface water layers of varying density, most notably the thermocline (Reading 1986, Lafond 1962). Although their speed is low, these waves may exceed surface waves in amplitude. Consequently, it is proposed that differential subsidence in combination with contour currents and/or internal waves produced large stratigraphic gaps in the southwestern and southern Mader. In the northernmost Mader (Jebel Rheris), stratigraphic gaps partially originate from emergence (karst) and sediment bypass in a shallow-marine environment (red beds).

6.5 Basin-forming processes

The basin-forming processes and the reconstruction of the basin type during the Devonian of the eastern Anti-Atlas are only scarcely known up to date. Wendt (1988) claimed that the Devonian facies and thickness pattern is largely a consequence of differential subsidence on a passive continental margin. According to (Kazmierczak & Schröder 1999) the facies pattern of the Givetian in the Mader indicates the establishment of a halfgraben-shaped (intra-shelf) basin.

Own results (Chap 6.3) prove the evolution from a homclinal ramp with low subsidence differences towards a distally steepened ramp from Emsian to Eifelian times. In the Givetian, a small furrow-shaped basin, which was bordered to the north and south by shallow-water environments, evolved. This is explained by active uplift in the northernmost Mader. During the Late Devonian, the basin configuration persisted while subsidence contrasts increased leading to temporary emersion in the northernmost Mader. The result of the entire Devonian basin evolution is an asymmetric basin fill (Fig. 33a).

Comparable geometries and facies patterns were observed in the much younger off-shore basins of the Californian borderlands (Howell et al. 1980). These basins are well-studied with respect to geometry and facies ditribution and the strike-slip origin of these basins is well established (Blake et al. 1978). Here, slumps and conglomerates are concentrated on the steeper basin margins, and the basin shape is clearly asymmetric. Basins are several tens of kilometres wide and filled with up to 2000 metres of siliciclastic material. It is assumed, that the formation of the basins in this area was linked to plate interactions from Cretaceous to Holocene time (Howell et al. 1980). Very similar features can be observed in the Mader as shown in Fig. 33.

In addition to these similarities, the Devonian of the Mader shows other features of typical pull-apart settings as enlisted by Reading (1980): (1) thick, but laterally not extensive sediment piles were deposited rapidly (Upper Devonian shales in the northern Mader), (2) local uplift and erosion caused unconformities which are absent in thick sedimentary successions nearby (unconformities localised at the Jebel Rheris area and at Madene El Mrakib), (3) extreme lateral facies variations (shallow-water limestones at Jebel Rheris contrast with pelagic sediments at Bou Dib during the Late Devonian), (4) simultaneous development of both extensional and compressional tectonics in the same area (contemporaneous subsidence and uplift in the eastern Anti-Atlas during the Givetian and the Late Devonian), (5) little or no metamorphism and little igneous activity (volcanic rocks of Early Devonian age at Hamar Laghdad, in the northern Tafilalt).

From the similarities of the Mader with the Californian borderland basins and with the features mentioned by Reading (1980), it is inferred that the Mader was subject to strike-slip movements and related subsidence and uplift (pull-apart basin). These processes initiated during the middle to late Eifelian and were obviously strongest during the Givetian and the Late Devonian.

It can not be determined exactly by this study whether the recorded subsidence pattern was fault-controlled or related to varying flexural crustal movements. Regarding cross sections without vertical exaggeration, it appears reasonable that flexural subsidence occurred during the Early and Middle Devonian and some fault-controlled subsidence during the Late Devonian. The latter is indicated by the occurrence of angular unconformities in the northernmost Mader.

In order to elucidate the origin of the basin-forming mechanisms during the Middle to Late Devonian, the stress regime of the North African Craton must be regarded. The beginning of the Variscan convergence on the north-western African Craton dates into the Late Devonian. Piqué et al. (1993) found evidence for a Late Devonian to Early Carboniferous orogeny (Eovariscan orogeny) in the High and Middle Atlas and Wendt (1985) claimed that block faulting, angular unconformities, and neptunian dykes of Late Devonian age in the Tafilalt and Mader area indicate the Variscan convergence and the breakup of Gondwana. Radiometric dating of tectono-metamorphous events revealed ages around 370 Ma in eastern Morocco (Huon et al. 1988) and in the Middle Atlas (Clauer et al. 1980). According to the time scale of Tucker et al. (1998) this reveals a

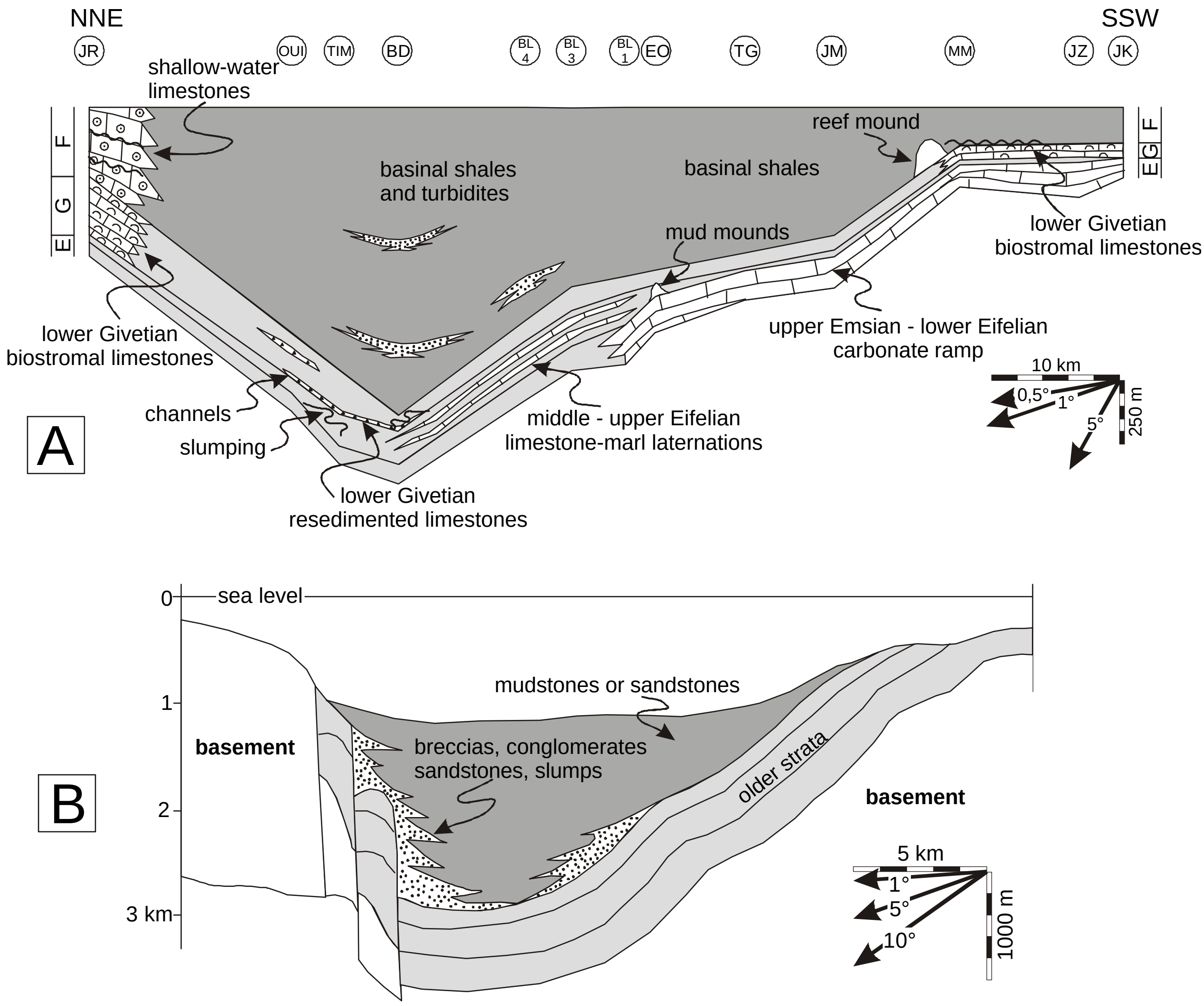

Fig. 33: SSW-NNE transect (line 1) showing the generalised facies and thickness distribution of upper Emsian to upper Famennian strata in the Mader (a) and a comparable transect (b) from the Californian borderland basins (Howell et al. 1980). Vertical exaggeration is 20 in a and 4 in b.

middle Famennian age for the tectono-metamorphic peak and thus suggests the possibility of compression during earlier times.

According to the palaeo-tectonic map of the late Variscan (Arthaud & Matte 1977), a large fault system affected the northwestern African Craton. It obviously coincides with the later evolving South Atlas Fault Zone which was active during the Alpine orogeny (Jacobshagen 1992). It is well known that during the Variscan orogeny strike-slip movements occurred on the northwestern edge of the Sahara Craton (Neugebauer 1988). The majority of the inferred fault systems were obviously active during the late Carboniferous and Early Permian and most authors agree that lateral movements played a key role during the Carboniferous (e.g. Heward & Reading 1980, Neugebauer 1988, Arthaud & Matte 1977). However, Piqué et al. (1993) remarked that already during the Early and Middle Devonian a series of pull-apart basins existed in the internal Variscan belt north of the Anti-Atlas.

Basin evolution was obviously related to Variscan convergence, which strengthened the magnitude of lateral movements on the northwestern African Craton. Beginning with the late Eifelian, the regional subsidence in the eastern Anti-Atlas was controlled by SE-NW striking fault systems which led to differential subsidence and local uplift. The importance of fault-controlled subsidence and associated uplift increased during the Late Devonian. These features display the progressive convergence between the northwestern margin of the Sahara Craton with northerly located terranes and plates.

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