6. FRASNIAN AND FAMENNIAN

During Emsian and Eifelian times, homogeneous deep slope and basinal deposits were accumulated; the Givetian was dominated by mid-ramp sediments. From Frasnian times on, five different inner ramp facies types occurred, but the majority of Upper Devonian rocks is represented by quartz-rich crinoidal bryozoan packstones (FT 7), which were deposited on the mid-ramp. The depositional environment during the Late Devonian was highly diverse compared to Early and Middle Devonian times and a complex facies pattern developed.

6.1 Facies and depositional interpretations

6.1.1 Quartz-rich crinoidal-bryozoan packstones (FT 7)

FT 7 is the most common facies in the Upper Devonian (Pl. 1/7, 8, Tab. 6). It is common in the syncline of the eastern Jebel Rheris, at the western edge of the mountain, and also crops out in some smaller hills WSW of the Jebel Rheris. Limestone layers are mostly thin-bedded (3-7 cm), but may be up to 30 cm thick. Intercalated shales are usually 4 cm thick, sometimes up to 40 cm. The composition of FT 7 carbonate layers ranges between two end-members: Bioclastic grainstones with a portion of silt- to sand-sized quartz grains of up to 10 % on the one hand and wacke- / packstones with 1 % quartz grains on the other hand.

In the upper Famennian (Middle *expansa* – Middle *praesulcata* Zone), black pebbles and nodules occur in several horizons within FT 7, which are mostly composed of apatite (see chapter 11).

Depositional environment

Grading, horizontal lamination, and wave ripples are typical sedimentary structures of tempestites. Because wave ripples (Pl. 2/1) and cross bedding are rare, a storm influenced mid-ramp depositional environment is inferred for most FT 7 occurrences. An exception is FT 7 on the inner ramp in section 10. Only fragmented benthic organisms occur within FT 7, which is a further argument for reworking. The higher the portion of micrite and the lower the amount of quartz grains in facies type 7, the more distal was the area of deposition. The occurrence of black pebbles indicates transgressions.

6.1.2 Debrites (FT 8)

Medium-bedded debrites (Pl. 2/6, 7) were formed at the eastern Jebel Rheris, intercalated in Famennian shales. Reworked 40 cm large FT 7 limestone layers occur together with subangular to angular dolostone and carbonate clasts (1-15 cm diameter). The matrix is quartz sand and crinoidal debris.

QUARTZ-RICH CRINOIDAL BRYOZOAN PACKSTONES (FT 7)

Lithology

Thin-bedded, quartz-rich, bioclastic pack-/grainstones, interbedded with shales.

Biota / Bioturbation

Crinoid ossicles and small fragments of bryozoans are common. Brachiopods, mollusc shells, vertebrate remains, and ostracodes occur, solitary rugose corals are rare.
Bioturbation is common, trace fossils (repichnia) sometimes occur.

Non-skeletal grains

Abundant quartz grains (~5%), some peloids.
Black pebbles are abundant in some horizons.

Stratigraphic occurrence

Upper Devonian.

Sedimentary structures

Common grading and horizontal lamination, very rare wave ripples.
Sometimes slumping.

Diagenetic features

Components often show sutured contacts, stylolites are common.

Depositional environment

Mid-ramp, rarely inner ramp.

Tab. 6: Characteristics of facies type 7.

CRINOID - BRACHIOPOD SHOALS (FT 9)		
Lithology	**Biota / Bioturbation**	**Non-skeletal grains**
Coarse crinoidal grainstones.	Abundant crinoid ossicles, whole brachiopods, fragmented bryozoans; some echinoid spines, fragmented mollusc shells and ostracodes. Rare solitary rugosa and fragmented thamnoporoids.	Some peloids.
		Stratigraphic occurrence
		Lower Frasnian (above Zone 3-4).
Sedimentary structures	**Diagenetic features**	**Depositional environment**
Layers mostly massive, some cross bedding.	Some pressure solution, syntaxial calcite cements.	Inner ramp.

Tab. 7: Characteristics of facies type 9.

Depositional environment

Debris flows originate at the mid-ramp, from where most limestones of FT 7, together with some sandstones and crinoidal debris, were shed into the middle Famennian shales. Because the shales are intercalated in mid-ramp deposits and the shoreline was probably not far to the north, the shales with debrites are interpreted as deposits of a small intra-ramp basin.

6.1.3 Crinoid – brachiopod shoals (FT 9)

Coarse crinoid – brachiopod grainstones (Pl. 1/3, Tab. 7) were deposited on top of lagoonal sediments (FT 10) at the eastern Jebel Rheris. Individual beds are mostly medium- to thick-bedded (10-100 cm), interbedded shales were not observed. The maximum thickness of the crinoid – brachiopod shoal can be observed at the easternmost part of the mountain (9 m); towards the west, it wedges out over a distance of about 1 km. One conodont date derived from the underlying facies type (Zone 3-4) shows that FT 9 was deposited during the early Frasnian. Due to its resistance to weathering, this lithology weathers out as a small morphologic ridge.

Depositional environment

The average grain size of 1.5 – 2 mm (up to 5 mm) in limestone layers and the lack of micrite or shales argues for a high-energy depositional environment on the inner ramp. The diverse fauna is fragmented, apart from abundant brachiopods (mostly rhynchonellids), and was probably winnowed by constant wave action, which also caused cross bedding. Only benthonic organisms occur in the shoals, which is a further argument for a shallow, near-shore environment.

6.1.4 Laminated skeletal wackestones / packstones (FT 10)

This facies type (Tab. 8) occurs on top of the Givetian biostromal limestones in the eastern part of the Jebel Rheris. Thin-bedded (3-10 cm) limestone layers are intercalated in 10-100 cm thick shales. Towards the west, the FT 10 succession (40 m thick at section 1) wedges out over a lateral distance of about 1 km. The stratigraphic occurrence ranges from the basal Frasnian to Zone 3-4. Limestone layers are mostly wackestones and packstones, but laminated mudstones and rarely grainstones can also be observed.

Depositional environment

The occurrence of echinoids (Pl. 1/2) and peloids, and the absence of a pelagic fauna indicates a shallow, coastal environment. Thick shales and a high portion of micrite in laminated limestone layers indicates a low-energy back-barrier depositional environment on the inner ramp. Coarser grained layers within FT 10 probably reflect storm events of different energy levels, which transported fragmented bioclasts from a shoal landward into protected lagoonal areas. Bioturbation indicates that the sea floor was oxygenated; but anoxic conditions occurred occasionally, as is shown by abundant pyrite crystals in some limestone layers.

6.1.5 Stromatolite limestone (FT 11)

Stromatolites (Tab. 9) can only be found at one

LAMINATED SKELETAL WACKESTONES / PACKSTONES (FT 10)

Lithology

Thin-bedded bioclastic wacke-/packstones, intercalated in medium- to thick-bedded shales.

Biota / Bioturbation

Crinoid ossicles, echinoid spines, fragments of bryozoans and brachiopods.
Bioturbation common.

Non-skeletal grains

Some peloids;
pyrite crystals are abundant in certain laminae.

Stratigraphic occurrence

Lower Frasnian.

Sedimentary structures

Horizontal lamination, grading, rarely bipolar sole marks.

Diagenetic features

Growth of microsparite in very fine-grained areas.

Depositional environment

Inner ramp, protected lagoon.

Tab. 8: Characteristics of facies type 10.

place at the western margin of the Jebel Rheris in a 1 m thick medium- to thick-bedded succession. They have mostly columnar branching growth forms (~ 5 x 1.5 cm) and can be classified after Logan et al. (1964) as SH – type (stacked hemispheroids; Pl. 1/1). These stromatolites are of late Famennian age, they overlie middle Frasnian limestones with a sharp contact.

Depositional environment

In general, stromatolites occur in coastal environments, from supratidal to shallow subtidal areas. Logan et al. (1964) found that their growth pattern is indicative of the water depth. SH – stromatolites of the Jebel Rheris occur in high-energy intertidal areas. After Burne & James (1986), SH – stromatolites grew in shallow subtidal environments. In contrast, Playford et al. (1976) reported Devonian stromatolites with diverse morphologies in the Canning Basin (Australia), that grew more than 100 m below sea level.

The coarse and massive limestone layers, which contain considerable amounts of quartz sand, peloids, and some black pebbles, were deposited in near-shore areas. Therefore the stromatolitic limestones at the Jebel Rheris are interpreted as shallow subtidal inner ramp deposits.

6.1.6 Iron oolite (FT 12)

Iron oolites (Tab. 10) at the Jebel Rheris can be observed in Upper Devonian rocks at the western edge and in the matrix of conglomerates of the eastern syncline. A synsedimentary fault developed at the former locality, where 11 m of iron-ooids were accumulated (see Fig. 27). 4 km west of the

STROMATOLITE LIMESTONES (FT 11)

Lithology

Thick-bedded stromatolitic boundstone.

Biota / Bioturbation

Abundant SH stromatolites, some orthocone nautiloids, crinoid stems, and brachiopods.
Bioturbation not observed.

Non-skeletal grains

Some peloids, quartz sand, rare black pebbles.

Stratigraphic occurrence

Upper Famennian (Middle *expansa* - Middle *praesulcata* Zone).

Sedimentary structures

Massive layers.

Diagenetic features

Selective dolomitization sometimes occurs.

Depositional environment

Inner ramp, shallow subtidal.

Tab. 9: Characteristics of facies type 11.

IRON OOLITES (FT 12)		
Lithology	**Biota / Bioturbation**	**Non-skeletal grains**
Massive or thin-bedded oolitic ironstone.	Some crinoid ossicles and brachiopods. No bioturbation.	Calcitic and iron ooids, some quartz grains.
		Stratigraphic occurrence
Sedimentary structures	**Diagenetic features**	Upper Frasnian to upper Famennian.
Massive appearance, also thin-bedded layers. Rare cross bedding.	Calcitization and ferruginization of ooids.	**Depositional environment**
		Inner ramp.

Tab. 10: Characteristics of facies type 12.

mountain at section 10, an about 40 m thick succession of yellowish weathering iron-ooids (0.3-2 mm diameter) occurs in upper Frasnian and Famennian rocks (Pl. 1/4). A thin-bedded to platy appearance can be noticed, which may be a result of diagenetic alteration.

Depositional environment

Crinoids and brachiopods occur in iron oolites of the Jebel Rheris area, which proves a marine depositional environment. Several modes of formation of iron-oolites were proposed (see Kimberley 1979 for references). In the present study, partly calcitic and ferruginised ooids can be observed, indicating a diagenetic ferruginisation of a formerly calcareous oolite. The occurrence of quartz grains (ca. 3 %) together with ooids argues for a shallow marine, near-shore environment on the inner ramp, in which iron was probably derived from fluvial input.

6.1.7 Conglomerates (FT 13)

Several 15 – 100 cm thick, red, iron stained conglomerate layers are intercalated in Frasnian and Famennian strata of the Jebel Rheris area (Pl. 1/5, Tab. 11). The components include well-rounded sandstones (probably Ordovician), micritic carbonate flat pebbles, angular limestone and dolostone clasts with stromatoporoids and corals of Givetian age, and well-rounded black pebbles. The size of the components ranges from a few millimetres to 30 cm. Some conglomerate layers wedge out towards SE. As an exception, a 10 m thick conglomerate occurs in sections 4 and 6. Here, the average diameter of the components is 15 cm. They are poorly sorted. Towards the S (section 1), the average diameter of the components decreases to 4 cm, the conglomerates are thin- to medium-bedded. The sorting is better than in sections 4 and 6. The rounding mostly depends on the

CONGLOMERATES (FT 13)		
Lithology	**Biota / Bioturbation**	**Non-skeletal grains**
Polymict components surrounded by crinoidal debris and iron-ooids.	Crinoid ossicles in the 'matrix', corals and stromatoporoids in Givetian limestone clasts.	Iron-ooids and quartz sand in the 'matrix'.
		Stratigraphic occurrence
Sedimentary structures	**Diagenetic features**	Upper Devonian.
Cross bedding and horizontal lamination in finer grained beds, coarse grained beds are massive.	Red iron precipitates are very common.	**Depositional environment**
		Inner ramp to mid-ramp.

Tab. 11: Characteristics of facies type 13.

type of component, i.e. sandstone pebbles and black pebbles are well rounded, limestone and dolostone components are subangular to rounded. Conglomerate layers sometimes can be traced laterally for 200 m, sometimes only for about 20 m. Generally, they occur from the middle Frasnian to the upper Famennian throughout the investigated area.

Depositional environment

Hollard (1974) proposed a fluvial origin of the conglomerates at the Jebel Rheris, but the occurrence of crinoidal debris in the 'matrix' of FT 13 indicates deposition in the marine environment. Conglomerates are interpreted as inner ramp near-shore deposits, which may extend into upper mid-ramp environments. They often wedge out within FT 7, which was deposited on the mid-ramp. Imbrication of flat pebbles shows a current direction towards SSE. Similarly, the decreasing average diameter of the components towards the S and the better sorting indicates a transportation direction from N to S. It is assumed that Ordovician sandstone pebbles were eroded from the emerged area N or NW of the Jebel Rheris. As they are better rounded than the carbonate components, the distance of transportation of sandstone pebbles was longer. Conglomerates often unconformably overlie older rocks and are thus related to transgressions (basal conglomerates).

6.1.8 Sandstones (FT 14)

Sandstones are very rare in Devonian rocks at the Jebel Rheris. In the Famennian succession of the eastern syncline, few thin-bedded (4-7 cm) layers occur, consisting of well-rounded and sorted quartz grains (~ 0.2 mm diameter), which are cemented by calcite. Sandstone layers have a massive appearance, they wedge out towards SE.

Depositional environment

Quartz grains were probably derived from the emerged area in the north and northwest and transported onto the shelf in southeastern direction, indicating a shallow coastal depositional environment. But sedimentary structures, which would argue for wave action, were not observed. As thin sandstone layers are intercalated in FT 7, they are interpreted as mid-ramp deposits.

6.2 Stratigraphy and facies development

6.2.1 Eastern Jebel Rheris (sections 1-4)

Apart from local exceptions, biostromal growth terminated at the Givetian / Frasnian boundary. In section 1 at the eastern part of the mountain, where the thickness of Upper Devonian strata is highest (280 m), 40 m thick laminated skeletal wackestones / packstones, alternating with medium- to thick-bedded shales (FT 10) were deposited above the mid-ramp biostromal limestones. FT 10 is interpreted as a back-barrier inner ramp deposit indicating shallowing at the beginning of the Frasnian. 200 m towards the NW in section 2 (Fig. 15), one coral-stromatoporoid biostrome is intercalated in the middle of the FT 10 succession, 400 m further in section 3, one biostrome occurs at the top of the FT 10 succession. The latter biostrome is of Frasnian age (Zone 3-4), so the Givetian / Frasnian boundary is situated at the base of the FT 10 succession.

On top of the laminated skeletal wackestones / packstones, coarse crinoid – brachiopod shoals (FT 9) were deposited. Their thickness varies between 15 m (section 2) and 5 m (section 3). These shoals probably acted as a barrier during the early Frasnian, which allowed the development of a protected lagoonal facies (FT 10). A sea-level rise caused the deposition of FT 9 onto FT 10, because the depositional environment of FT 9 presumably lay seaward of FT 10.

Still in the early Frasnian after the deposition of the crinoid – brachiopod shoals, quartz-rich crinoidal bryozoan packstones (FT 7) occur for the first time at the eastern Jebel Rheris (sections 1-3), which dominate the Upper Devonian succession from here on. At section 1, up to 40 cm thick conglomerate layers (FT 13) are intercalated in FT 7 about 10 m above the shoals for the first time. FT 7 is interpreted as a mid-ramp facies, which indicates a relative sea-level rise after the shoal deposition. The occurrence of quartz grains on carbonate ramps, however, usually is taken as an indicator of a sea-level fall (e.g. Goldhammer et al. 1993). In the Jebel Rheris area, input of siliciclastic material and conglomerates was probably caused by an uplift of the hinterland, creating a steeper relief.

20 m above the first conglomerate layers at section 1, the shale / limestone – ratio decreases within an interval of 15 m, which causes a morphologic ridge in the outcrop. The top was deposited within the Upper *gigas – crepida* Zone, so the Frasnian / Famennian

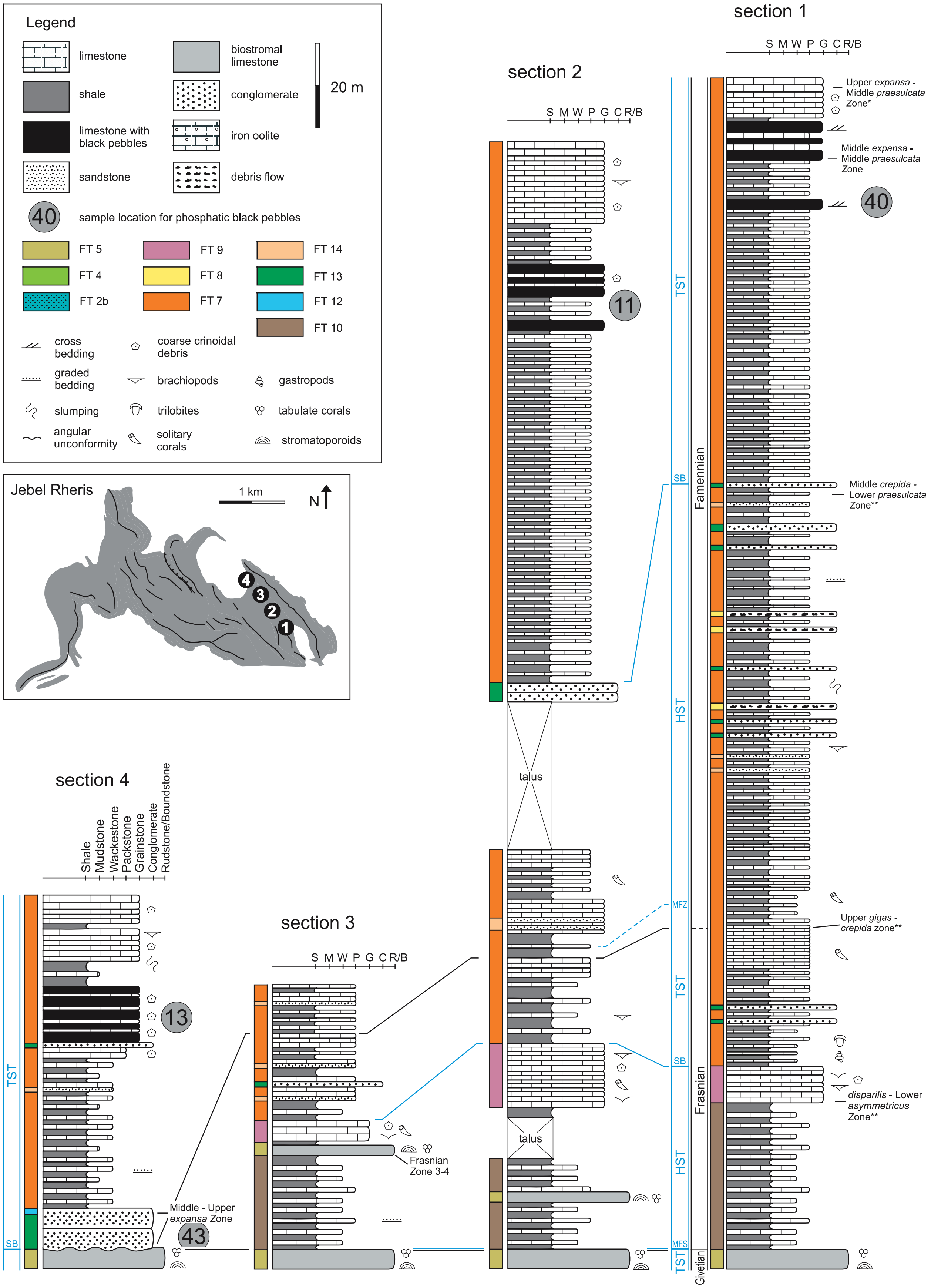


Fig. 15: Stratigraphic and sequence stratigraphic correlation of Upper Devonian sections at the eastern Jebel Rheris. Conodont data, marked with one asterisk after Wendt (unpubl. data), with two asterisks after Spintzyk (1991). TST: transgressive systems tract, HST: highstand systems tract, MFS: maximum flooding surface, MFZ: maximum flooding zone, SB: sequence boundary, FT: facies type.

boundary is situated here. This ridge also occurs in sections 2 and 3 with lower thickness. The thickness of the complete Frasnian succession decreases from 70 m in section 1 over a lateral distance of about 600 m to 50 m in section 3. Especially in upper Frasnian rocks of section 3, the portion of quartz sand is very high in some layers. Few thin-bedded layers are more or less pure sandstones.

A distinct facies change does not occur at the Frasnian / Famennian boundary, FT 7 prevails. About 40 m above the boundary at section 1, several conglomerate layers are intercalated into the quartz-rich packstones within a 60 m thick interval. The thickness of the shale layers is higher within this interval than in the rest of the Famennian succession. 100 m to 200 m east of section 1 at this level, about 20 m thick shales occur with some intercalated debris flows (FT 8), which indicates that a small intra-ramp basin existed during the middle Famennian at the easternmost Jebel Rheris. In section 2, a conglomerate also occurs, but no debris flows or thick shales. Above this interval, an around 70 m thick homogeneous FT 7 succession was deposited both in sections 1 and 2. Towards the NW in sections 3 and 4, large scale slumping structures occur in this level.

In the upper Famennian (Middle *expansa* to Middle *praesulcata* Zone), several horizons with black pebbles, which are reworked phosphorites (see chapter 11), can be recognised from section 1 to 4 within a 20 m thick interval, indicating a transgression. Above the black pebble horizons, 10 m to 30 m crinoidal packstones / grainstones with few admixed quartz grains represent the youngest Devonian limestones in the eastern Jebel Rheris syncline. Here, the Famennian deposits are about 200 m thick. Few patches of green shales crop out in the centre of the syncline, where Clariond (in Massa 1965) reports a *Merocanites* occurrence of Viséan age. However, later workers were not able to confirm the existence of Carboniferous strata here. At the western Jebel Rheris (section 18, see Fig. 19), 55 m thick green shales were deposited above crinoidal limestones of late Famennian age (Middle – Upper *expansa* Zone). Above these shales, a limestone layer was dated as uppermost Famennian, so the shale succession still was deposited in the Devonian. The green shales of the eastern Jebel Rheris syncline can probably be correlated with those of section 18, so the occurrence of Carboniferous rocks here is doubted.

In sections 1 and 2, no hiatus was found in Upper Devonian deposits. Only 400 m further NW in section 4, however, a considerable hiatus between upper Givetian biostromes and a 10 m thick upper Famennian conglomerate (Middle – Upper *expansa* Zone) occurs. The thickness of the conglomerate diminishes laterally within about 100 m to 30 cm, it totally wedges out 100 m further towards the SE. Imbrication of flat pebbles, which have diameters of up to 40 cm, shows a transportation direction towards SSE, crinoid ossicles in the 'matrix' indicate deposition in the marine environment. In the upper part of the conglomerate, iron-ooids are abundant. The facies of upper Famennian strata above the thick conglomerate in section 4 is similar to that of sections 1 and 2 (Fig. 15).

6.2.2 Central and southwestern Jebel Rheris (sections 4, 6, 11, 10)

The facies development from section 4 towards the west (Fig. 16) shows some differences compared to that of sections 1 - 4. In section 6, which is located at the western flank of the large syncline at the Jebel Rheris, a 10 m thick conglomerate occurs as in section 4, but it does not directly overlie Givetian biostromal limestones. About 25 m thin-bedded skeletal wackestones are intercalated, but largely covered with talus. These can probably be correlated with the lower Frasnian FT 10, which crops out in sections 1 – 3. Thus an unconformity between lower Frasnian and upper Famennian deposits exists at section 6. Around 30 m of the quartz-rich crinoidal packstones overlie the thick conglomerate. Towards the north of the large syncline, however, the thickness of the upper Famennian deposits is more and more reduced, until only some patches of the red-stained conglomerate remain on top of Givetian biostromes.

At the western edge of the Jebel Rheris in section 11, the change from coral-stromatoporoid biostromes (FT 5) to quartz-rich crinoidal-bryozoan packstones (FT 7) does not coincide with the Middle to Upper Devonian boundary. 40 m above the youngest biostrome, a conodont dating from FT 7 yielded an uppermost Givetian age (Lowermost *asymmetricus* Zone), whereas the youngest biostrome at the eastern Jebel Rheris occurs within lower Frasnian rocks (Frasnian Zone 3-4). No distinct facies change can be noticed at the Givetian / Frasnian boundary in section 11; only a small morphologic ridge occurs in the outcrop, indicating a decreased portion of shale interbeds. Frasnian deposits are only about 20

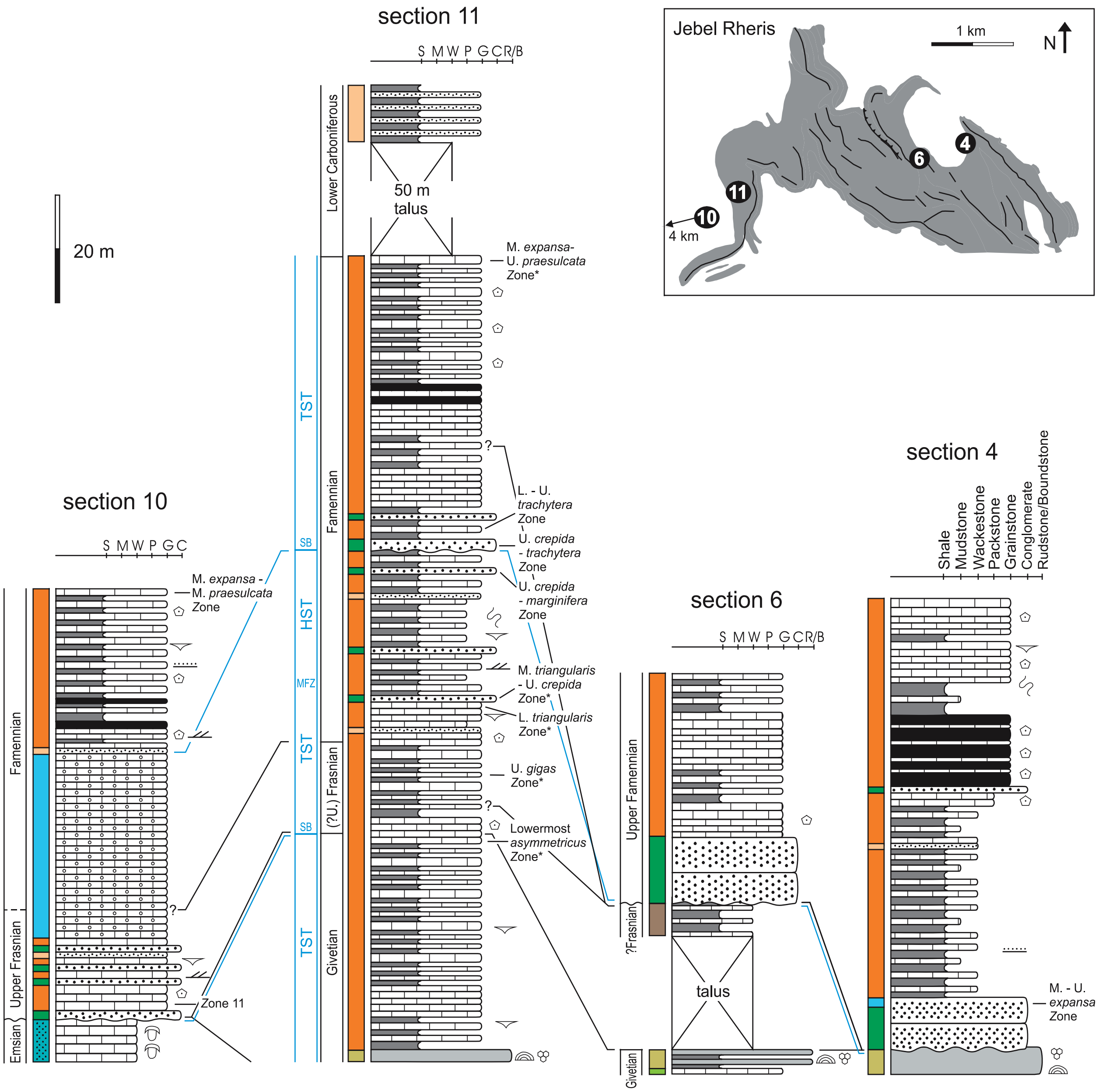


Fig. 16: Stratigraphic and sequence stratigraphic correlation of Upper Devonian sections at the Jebel Rheris. Conodont data, marked with asterisks, after Wendt (unpubl. data). Location of section 10 can be seen in Fig. 3; for legend, see Fig. 15.

m thick and consist, as upper Givetian deposits, of FT 7; conodonts from the lower Frasnian were not found, so a hiatus between the uppermost Givetian and the upper Frasnian can not be excluded.

Several conglomerate layers are intercalated into the lower half of the Famennian succession in section 11, which is characterised by laminated packstones, rarely cross-bedded crinoidal grainstones, and few sandstone layers. An angular unconformity of 30° occurs in middle Famennian rocks (Fig. 16, Pl. 3/3): A 2 m thick red-stained conglomerate (Upper *crepida* – *trachytera* Zone) cuts a 1 m thick conglomerate, which was deposited within the Upper *crepida* to *marginifera* Zone. Above this unconformity, 50 m more or less homogeneous crinoidal packstones were deposited until the uppermost Famennian. As at the eastern Jebel Rheris, black pebbles occur in upper Famennian strata in section 11, but only in small quantities.

The southernmost outcrop of Devonian rocks in the investigated area is located 4 km WSW of the Jebel Rheris (section 10, see Figs. 3, 16). About 8 m thick medium-bedded, trilobite-rich wackestones of Emsian age crop out above a slope, which is covered with talus. These wackestones are unconformably overlain by a 1 m thick conglomerate, containing elongated limestone clasts and black pebbles in coarse crinoidal debris. Directly above the conglomerate, conodonts of the Frasnian Zone 11 occur, indicating a hiatus between Emsian and upper Frasnian rocks in section 10. The latter are made up of 12 m thick coarse, often cross-bedded crinoidal grainstones, into which few sandstones and conglomerates are intercalated. A 35 m thick, homogeneous succession of yellow iron-ooids follows. Due to diagenetic alteration, the bedding and primary sedimentary structures are obscured within this interval. Coarse, sometimes cross-bedded quartz-rich crinoidal limestones lie above the oolite, containing black pebbles. These can probably be correlated with black pebble horizons of the other upper Famennian sections. 20 m above the black pebble horizons at the top of section 10, conodonts of the Middle *expansa* to Middle *praesulcata* Zone occur, indicating latest Famennian age. The total thickness of the Famennian strata is approximately 50 m in section 10, but the position of the Frasnian / Famennian boundary can not exactly be determined.

6.2.3 Northwestern Jebel Rheris

Stromatolite limestones

In section 16 (about 500 m north of section 11), the Upper Devonian succession shows considerable differences compared to section 11 (Fig. 17). The lower Frasnian deposits are composed of well-bedded crinoidal grainstones, which include some phillipsastreids with up to 30 cm in diameter. The thickness of the Frasnian succession is unknown, because large parts are covered with talus. On top of the Frasnian Zone 8-10, a 1 m thick stromatolite limestone layer (FT 11) was deposited during the Middle *expansa* – Middle *praesulcata* Zone with a sharp contact, upper Frasnian to middle Famennian rocks are lacking. However, the stromatolite limestone wedges out towards the north. Above FT 11, a 2 – 3 m thick gypsum horizon is preserved, which is proven by a XRD-measurement of a powder sample from this horizon. Thereon, a red-stained conglomerate was deposited, followed by quartz-rich crinoidal packstones. The top of the Famennian succession in section 16 is covered with talus. The facies development of the upper Famennian deposits at this place indicates a change from a shallow subtidal to a supratidal environment (possibly a sabkha) during sea-level

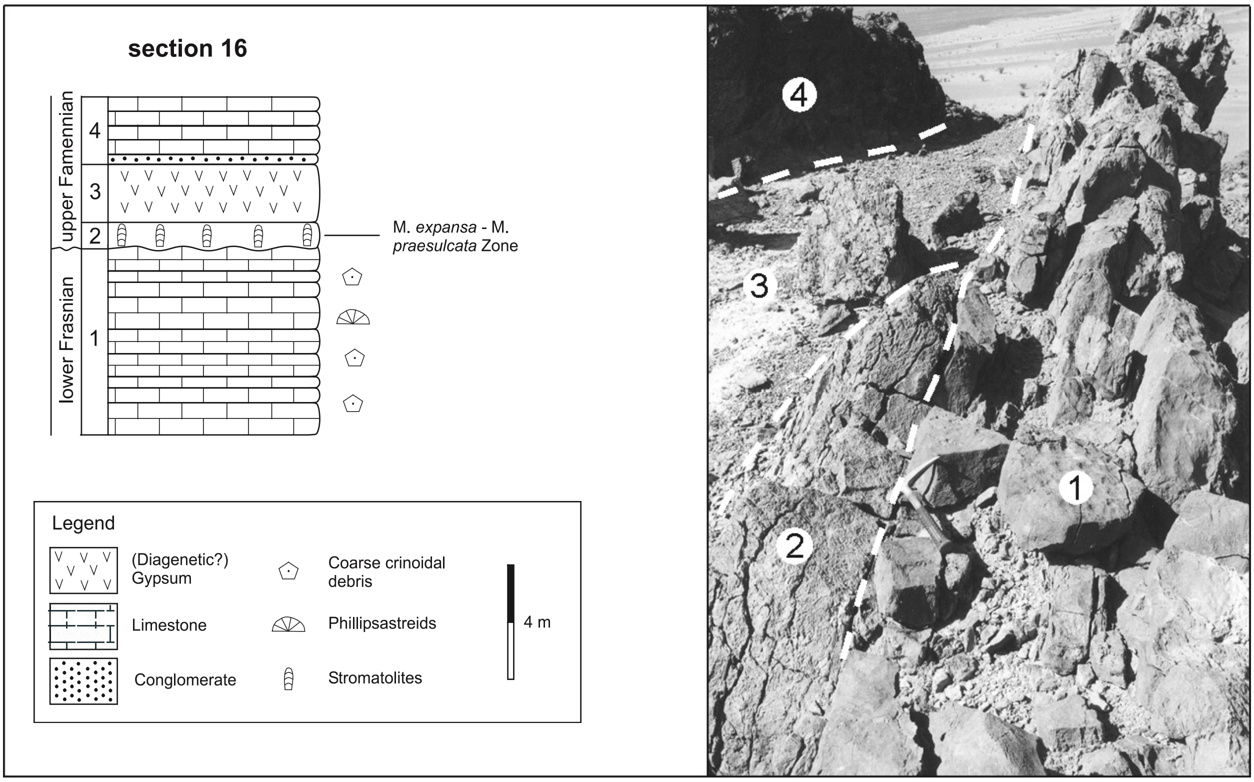
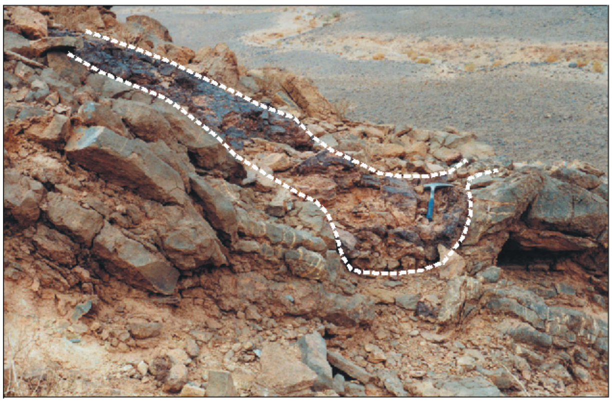


Fig. 17: Upper Devonian unconformity between lower Frasnian and upper Famennian rocks, western edge of the Jebel Rheris. 1: crinoidal grainstones with phillipsastreids; 2: stromatolite limestone; 3: diagenetic? gypsum; 4: conglomerate, overlain by quartz-rich crinoidal packstones.



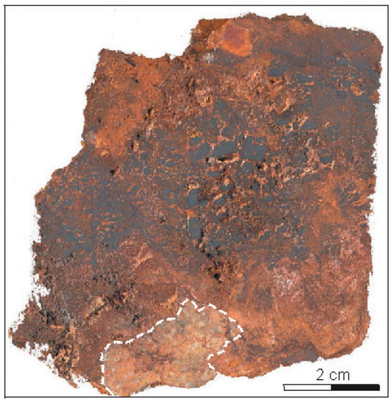


Fig. 18: Left: A red-brown palaeosol (within dashed lines) separates lower Frasnian crinoidal limestones (below) from middle Famennian limestones at the western edge of the Jebel Rheris (near section 17).
Right: A polished slab of the palaeosol shows a mottled structure; note brecciated limestone clast at the bottom of the sample (within dashed line).

fall, a subsequent transgression then deposited the basal conglomerate and subtidal limestones onto the supratidal facies. However it has to be mentioned that a diagenetic origin of the gypsum horizon can not be excluded.

Palaeosol

About 100 m NW of the stromatolite limestone, lower Frasnian crinoidal grainstones, which contain few phillipsastreids, are separated by a 40 cm thick, red-stained layer from middle Famennian limestones (Fig. 18). Several red, iron-rich conglomerates occur at the Jebel Rheris, but this layer at the western edge of the mountain is interpreted as a palaeosol for the following reasons: (1) Polished slabs show a mottled, brown-red to black stained structure. (2) Rarely, brecciated limestone clasts occur in lower parts of the horizon. (3) Apart from some subangular quartz grains, no components like brachiopods, crinoids and ooids were found, which do occur in other iron-rich horizons at the Jebel Rheris. A palaeosol in this stratigraphic interval can be found 100 m N of the stromatolite limestone to ca. 400 m S of section 14 (see Fig. 4).

Upper Famennian shales

At section 18 at the western Jebel Rheris, uppermost Famennian rocks crop out. A succession of medium-bedded coarse, quartz-rich crinoidal packstones is overlain by 55 m thick green shales, into which some thin sandstone layers are intercalated (Fig. 19). About 15 m thick sandstones with ripple marks and cross bedding lie on top of the shales, followed by two thick-bedded crinoidal limestone layers. Conodonts of the upper limestone layer still yielded a late Famennian age (Upper *marginifera* – Upper *praesulcata* Zone), conodonts of the limestones directly below the shale succession are derived from the Middle – Upper *expansa* Zone. This proofs that a shale succession was deposited in the uppermost Devonian at the Jebel Rheris. However, this is the only locality, where these shales completely crop out. Only some relics also occur in the centre of the eastern syncline of the mountain.

6.2.4 Lalla Mimouna

At the northern edge of the mountain Lalla Mimouna, 5 km west of the Jebel Rheris, the largest hiatus of the investigated area occurs. Here, a graben is cut in Ordovician sandstones, wherein a syncline made up of Silurian shales, late Famennian limestones, as well as Tournaisian shales and sandstones is preserved (Fig. 20). At the southern flank of the syncline, carbonate rocks consist of a 1.5 m thick succession of grey crinoidal packstone and nodular marly limestone (Upper *praesulcata* Zone), which yielded a hitherto unknown assemblage of clymeniids and goniatites of latest Famennian age (e.g. *Postclymenia evoluta* Schmidt, 1924; *Acutimitoceras hilarum* Korn, 2002) (Korn et al. subm.). A slightly different succession can be noticed at the northern flank of the syncline, where a 1,5 m thick crinoidal grainstone layer was deposited on Silurian shales and succeeded by 5 m thick green shales with a 5 cm thick sandstone intercalation, followed by a 50 cm thick crinoidal grainstone layer. The latter yielded

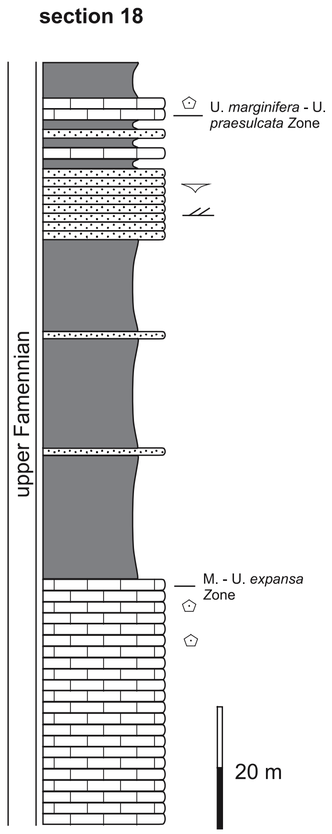


Fig. 19: Section 18 at the western Jebel Rheris is the only location, where thick upper Famennian shales crop out. Conodont data after Wendt (unpubl. data), legend as in Fig. 15. See Fig. 4 for the location.

conodonts from the Upper *expansa* to Middle *praesulcata* Zone, which shows that the limestone layers of both flanks of the syncline are of different ages and cannot be correlated. Sandstones and shales of probably Tournaisian age lie on top of the limestones. This is the westernmost outcrop of Devonian rocks in the investigated area.

6.3 Facies pattern and palaeogeography

While Lower and Middle Devonian palaeogeographic patterns are quite uniform in the Jebel Rheris area, those of the Upper Devonian show changes within short lateral distances and within relatively short time spans. Wendt (1988) and Spintzyk (1991) presented earlier attempts to interpret the palaeogeography of the Upper Devonian of the Jebel Rheris, but additional biostratigraphic and sedimentological data lead to a modified version in the present study.

6.3.1 Lower Frasnian

A biostratigraphic proof of lower Frasnian deposits only exists at the easternmost Jebel Rheris in sections 1 – 3. The relative sea level decreased at the base of the Frasnian, i.e. above the crinoidal grainstone / biostrome – succession, so that a lagoonal facies and crinoid – brachiopod shoals were deposited. This shows that for the first time in the early Frasnian, near-shore deposits occur. The shore-line and an emergent area were situated not far towards the N and NW, as the basin was situated in the S (Wendt 1988). Lower Frasnian deposits W of section 3 probably were eroded during a late Famennian transgression.

6.3.2 Upper Frasnian (Fig. 22)

Apart from sections 1 – 3, Upper Frasnian deposits occur also at the western Jebel Rheris (section 11) and 4 km WSW of the mountain in section 10. They are mostly characterised by quartz-rich crinoidal-bryozoan packstones of the mid-ramp. Therefore, a transgression occurred in the middle Frasnian. In the

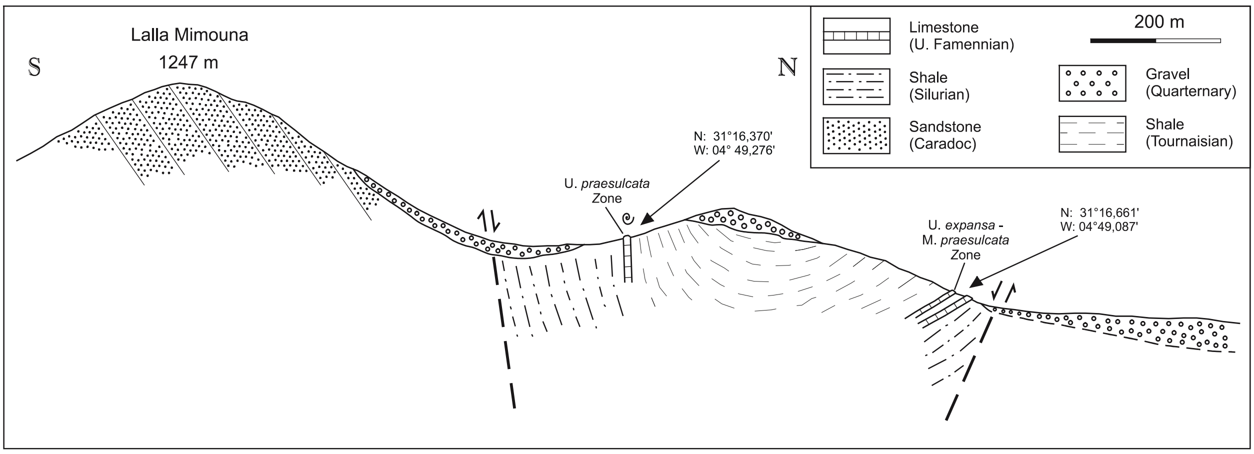


Fig. 20: N - S transect through the Lalla Mimouna (5 km west of the Jebel Rheris) showing a graben structure, where upper Famennian limestones occur between Silurian and Lower Carboniferous shales (Modified after Korn et al. (subm.).

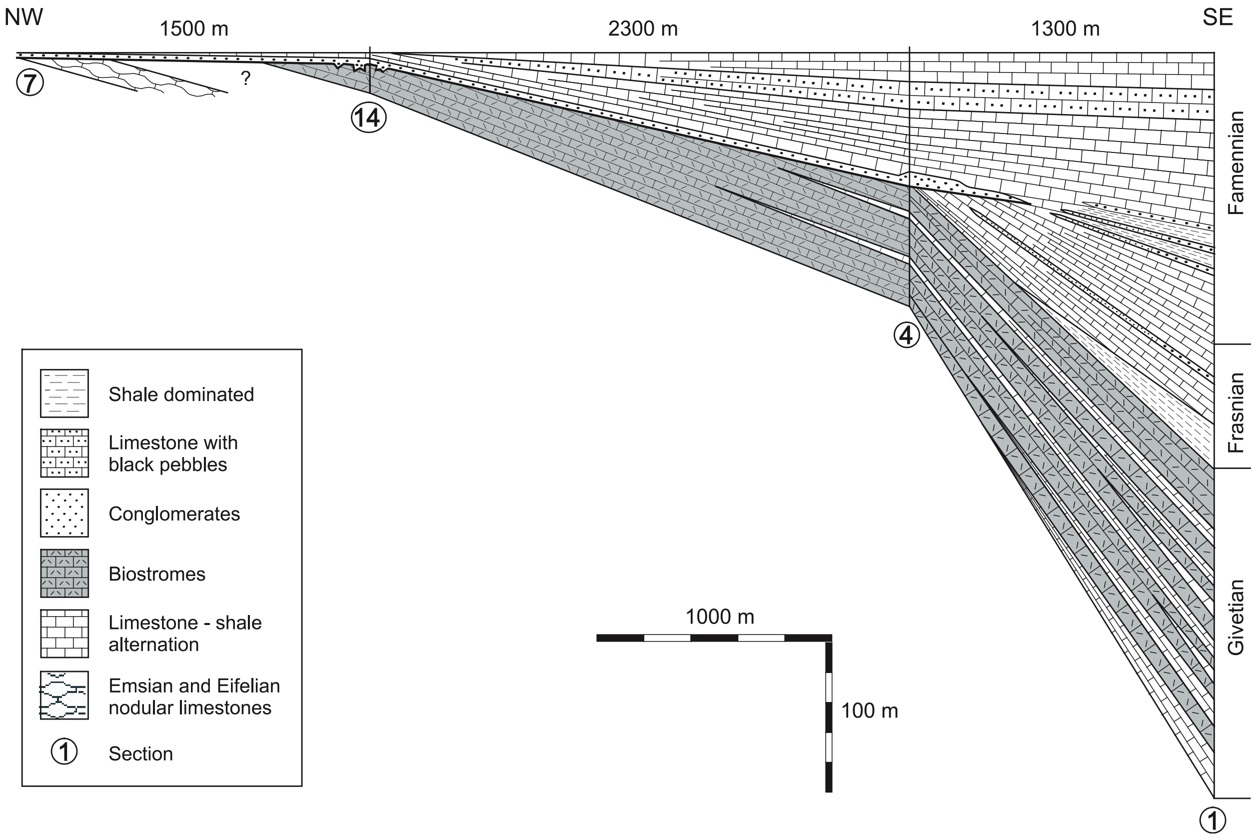


Fig. 21: Simplified transect, showing a considerable thickness reduction of Givetian to Famennian deposits from section 1 (eastern Jebel Rheris) towards NW to section 7.

SW of the investigated area (section 10), the middle Frasnian transgression led to the deposition of a basal conglomerate onto Emsian limestones. In contrast to the mid-ramp environment at the Jebel Rheris, the upper Frasnian cross-bedded, coarse crinoidal limestones and conglomerates SW of the mountain indicate a coastal environment. Upper Frasnian deposits of the northern Jebel Rheris were eroded before the late Famennian, an emergent area was situated in the northwestern part of the investigated area (N of section 10).

6.3.3 Lower Famennian (Fig. 23)

At the eastern (sections 1 and 2) and western edge (section 11) of the Jebel Rheris, the mid-ramp environment of late Frasnian times continued into the early Famennian, but the amount of intercalated sandstone layers and conglomerates in the crinoidal packstone succession increases. A different facies occurs 4 km WSW of the mountain at section 10. Here, the bulk of the lower Famennian consists of iron-ooids, which indicate a near-shore environment as during the late Frasnian. In contrast, at the southeastern margin of the Jebel Rheris east of section 1, a shale succession occurs, into which some debris-flow layers are intercalated. So it seems that during the early to middle Famennian, a facies pattern from near-shore sediments in the W through mid-ramp to basinal sediments in the E occurred. However, conglomerate layers within the lower Famennian in section 1 indicate that the coast was also near to the eastern Jebel Rheris. Furthermore the regional palaeogeographic pattern (Mader Basin in the S, Wendt 1988) did not significantly change since the Middle Devonian. So the shale succession possibly was deposited in a smaller intra-ramp basin. As in the upper Frasnian, lower Famennian deposits of the northern Jebel Rheris were eroded before the late Famennian. An emergent area still was situated NW of the mountain.

6.3.4 Upper Famennian (Fig. 24)

In Devonian sections of the northern and western Jebel Rheris, stratigraphic gaps between middle Givetian and middle Famennian rocks are very common. In the upper Famennian, a major transgression can be noticed in sections throughout the eastern Anti-Atlas (Hollard 1960, Wendt 1988, Wendt & Belka 1991) and also at the Jebel Rheris. Here, the former emergent areas in the N and NW were flooded. So a few

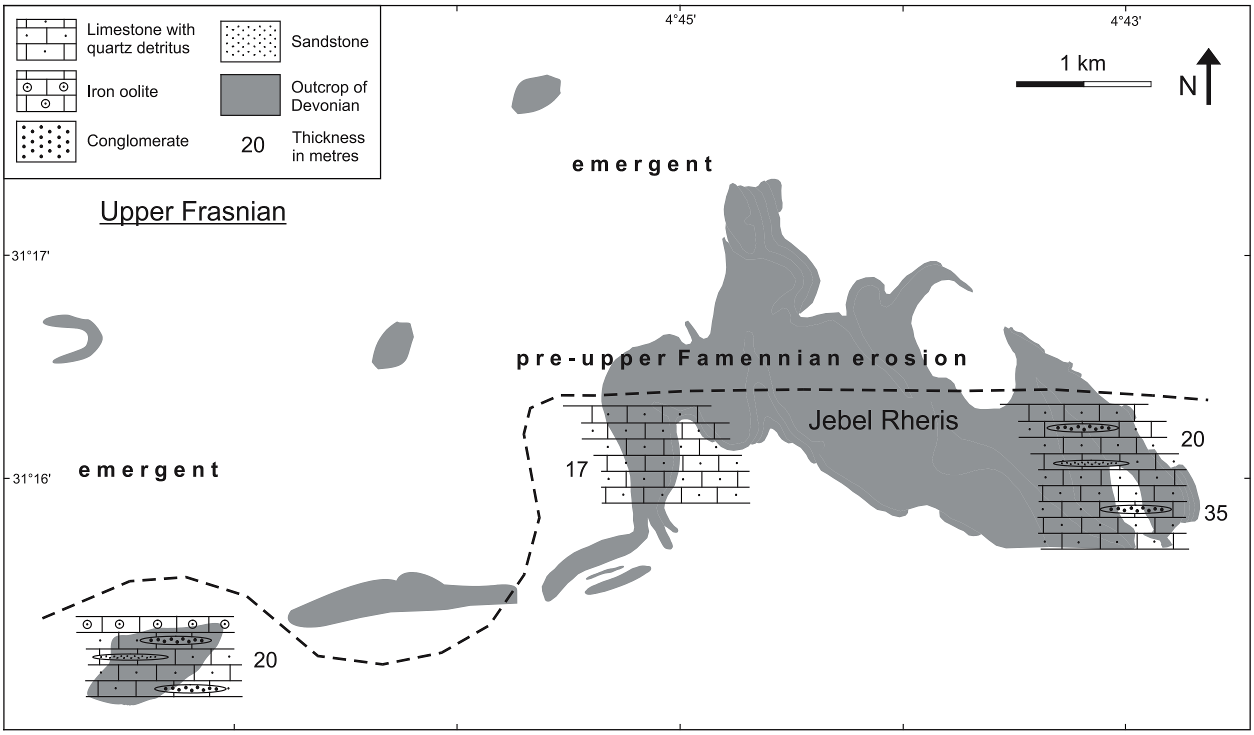


Fig. 22: Upper Frasnian facies pattern.

metres thick mid-ramp crinoidal limestones can be found north of the Jebel Rheris. At the western edge of the mountain, emergence during parts of the upper Famennian is inferred from a palaeosol (section 17), which shows the inhomogeneous topography during this time. In contrast to the northern and northwestern areas of the Jebel Rheris, deposition in the southern areas (sections 1, 2, 11, and 10) during the late Famennian was more or less homogeneous. Crinoidal limestones of mostly mid-ramp environments occur, sometimes with abundant quartz grains. The upper Famennian transgression caused the deposition of phosphatic black pebbles, which were reworked from Ordovician deposits (see chapter 11).

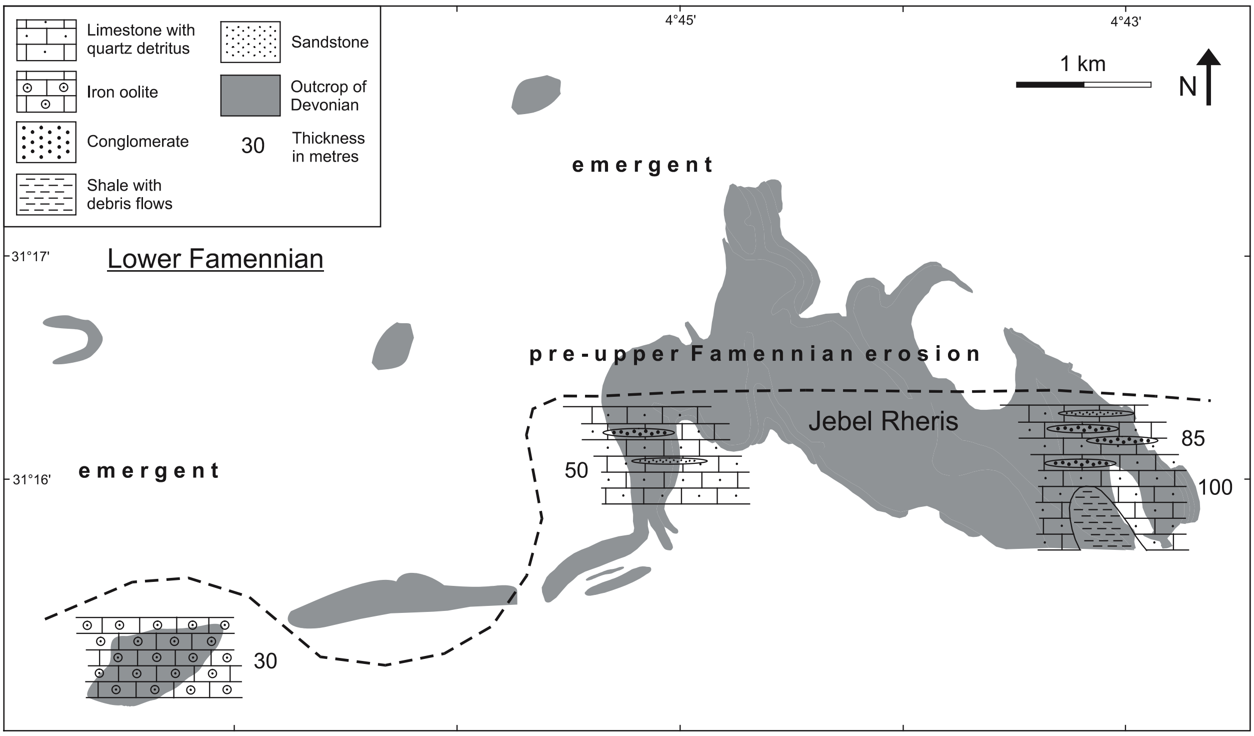


Fig. 23: Lower Famennian facies pattern.

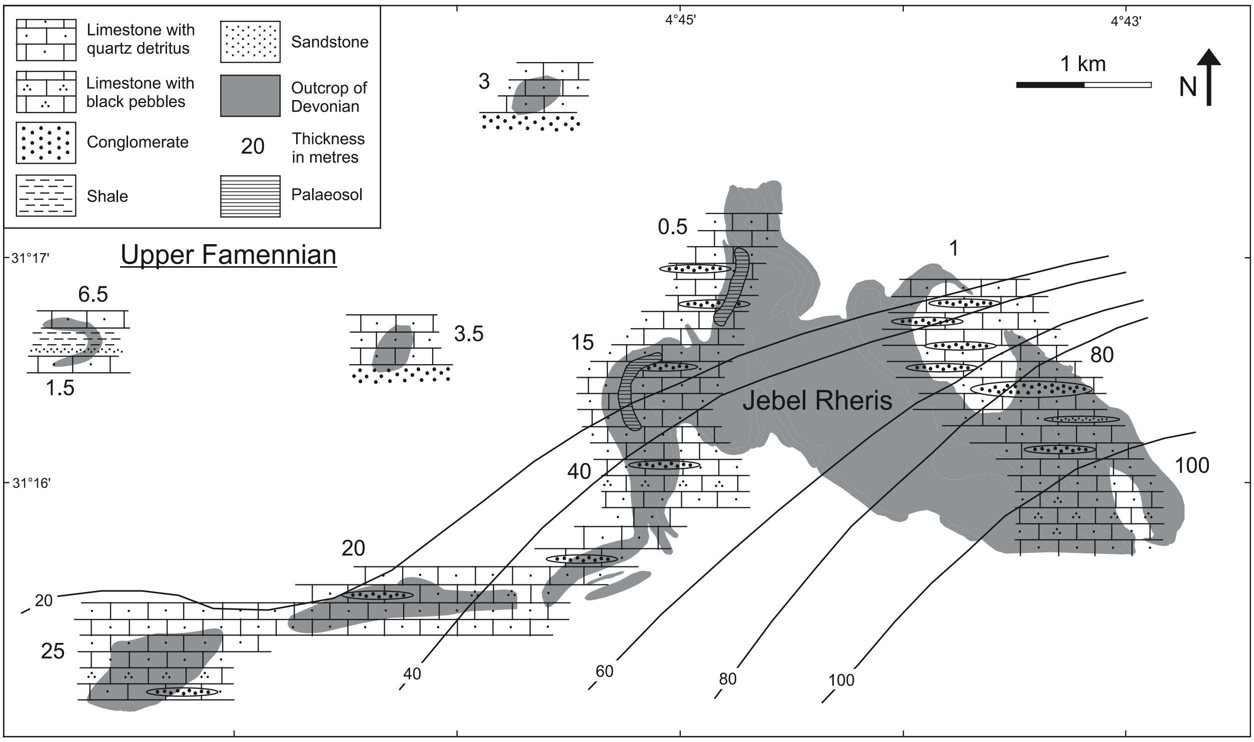


Fig. 24: Upper Famennian facies pattern.

6.4 Cyclicity

The smallest scale cycle (microcycle) in Upper Devonian strata of the Jebel Rheris consists of an about 2 cm thick shale layer and a ca. 6 cm thick quartz-rich crinoidal-bryozoan limestone layer (FT 7). At the eastern part of the mountain, a shallowing-upward hemicycle, consisting of these microcycles, can be recognised by an increasing amount of bioclasts and quartz detritus and a decreasing amount of micrite towards the top within successive limestone layers. The thickness of the layers usually does not change. The turnaround point mostly is marked by a sandstone or conglomerate layer (Fig. 25). Deepening-upward hemicycles with increasing amount of micrite and decreasing amount of bioclasts and quartz detritus towards the top are less thick than shallowing-upward hemicycles. Such transgressive / regressive cycles are called basic cycles here. Their thickness ranges between 2 and 10 m. However, it must be mentioned that indicators of shallowing and deepening are not very obvious in the field and sometimes can only be recognised in thin sections. Moreover, sandstone layers and conglomerates often are discontinuous, thus cycles can not well be traced laterally. In sections 1 and 2, about 70 m thick Famennian deposits are very homogeneous without

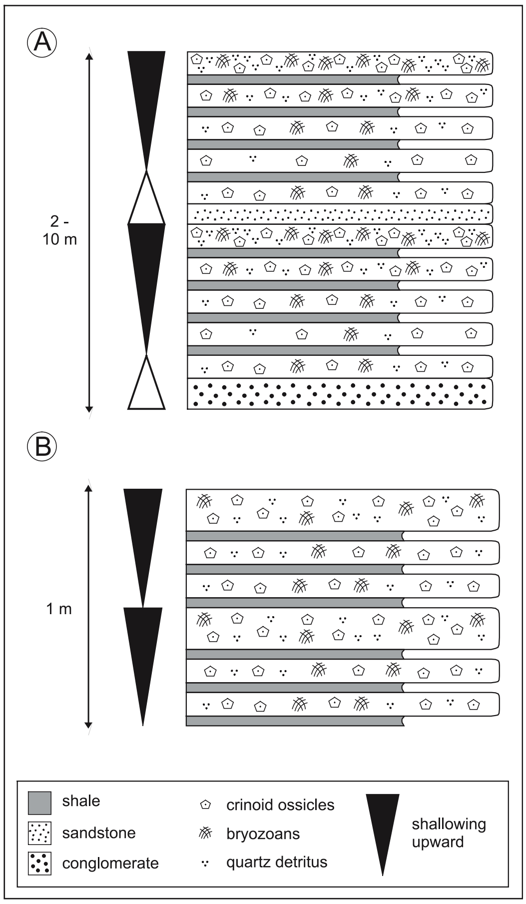


Fig. 25: Typical Upper Devonian cycles. (A) Asymmetric cycles, which mostly occur at the eastern Jebel Rheris. (B) Asymmetric thickening and shallowing upward cycles, which occur at the western Jebel Rheris.

thickness changes of microcycles or distinct facies changes; basic cycles can not be recognised in the field within these intervals.

At the western Jebel Rheris, rhythmic thickness changes often occur in Upper Devonian FT 7 successions: One medium-bedded (10 – 20 cm) limestone layer is intercalated every 0.5 m in thin-bedded (3 – 5 cm) limestones (Fig. 25). Thickness of the thin-bedded limestone layers slightly increases towards the top, so these cycles are asymmetric thickening-upward cycles.

Upper Devonian strata without detectable stratigraphic gaps only exist in sections 1 and 2, so the total amount of transgressive / regressive cycles during the Frasnian and Famennian should be counted here. But due to the problems in defining boundaries of basic cycles in some intervals for the reasons mentioned above, no precise number can be presented here.

6.5 Sequence stratigraphy

The transition from upper Givetian to lower Frasnian rocks is only visible at the eastern Jebel Rheris (sections 1 – 3, Fig. 15). Here, a distinct facies change from mid-ramp biostromal limestones to inner ramp deposits occurs, indicating progradation during a regression. Therefore, the lower Frasnian inner ramp deposits are interpreted as highstand systems tract (HST), separated by the maximum flooding surface (MFS) from the transgressive systems tract (TST) of the upper biostromal facies.

During the late Frasnian, a mid-ramp environment was established at the Jebel Rheris due to a transgression. At section 10, 4 km WSW of the mountain, this transgression can be recognised by a basal conglomerate, which unconformably overlies Emsian limestones. So a sequence boundary (SB) is situated at the base of the conglomerate, followed by a TST. The SB in sections of the eastern Jebel Rheris is placed between the inner ramp crinoid-brachiopod shoals and the mid-ramp quartz-rich crinoidal-bryozoan packstones. Quartz detritus occurs in varying amounts in the whole upper Frasnian and Famennian succession, so it is not considered as an indicator of sea-level lowstand here. Instead, its occurrence is interpreted as a result of a steeper relief of the hinterland. Lowstand systems tracts (LST) were probably deposited south of the working area during the Late Devonian in positions nearer to the basin, only TSTs and HSTs alternate in the Jebel Rheris area. The MFS between the upper Frasnian TST and the succeeding HST can not easily be determined, because no distinct retrograding and prograding patterns occur. So the term maximum flooding zone (MFZ), formerly applied by Elrick (1996), is used here for an about 7 m thick succession in basal Famennian rocks at the eastern Jebel Rheris, where wackestones instead of packstones predominate and shale layers are thicker than average. From the MFZ until the middle Famennian, conglomerate layers are intercalated with increasing abundance, which indicates shallowing and therefore is interpreted as a HST. In section 11 at the western Jebel Rheris, the angular unconformity within the middle Famennian (Upper *crepida – trachytera* Zone) represents a SB, because of a stratigraphic break, overlain by a basal conglomerate. This horizon is correlated with the youngest conglomerate in the middle Famennian at the eastern Jebel Rheris, as the lack of conglomerates from here on indicates deepening. Upper Famennian strata of the Jebel Rheris area represent a TST. In the northern and western parts of the working area, the rising sea level caused deposition onto previously eroded and / or emergent regions, black phosphatic pebbles were reworked and shed onto the shelf (see chapter 11). Upper Famennian unconformities with overlying beds of four different ages (see Tab. 12) are interpreted as the same SB, the overlying beds are part of different backstepping retrogradational parasequences.

7. EUSTATIC SEA-LEVEL CHANGES (FIG. 26)

The occurrence of basinal to shallow subtidal deposits within the about 660 m thick Lower Emsian to upper Famennian succession at section 1 can be used to document relative sea-level changes in the northern Mader, especially because of the high temporal resolution and the lack of larger stratigraphic gaps. Additionally, obvious indicators of sea-level fluctuations within the same time span in other sections can be included. The results are compared with other studies of Devonian sea-level changes (Johnson et al. 1985, 1996 for Euramerica, Wendt & Belka 1991 for the Upper Devonian of the eastern Anti-Atlas, Kaufmann 1998 for the Lower and Middle Devonian of the eastern Anti-Atlas, see Fig. 26) to distinguish between local tectonically induced and eustatic fluctuations.

Emsian and Eifelian sediments were deposited on a deep slope and in the basin, so small scale sea-level changes are not preserved. The up to 70 m thick shale succession at the base of the Upper Emsian, however, can be recognised in the whole Jebel Rheris area. It overlies nodular limestones with a sharp contact. The same facies change occurs at this stratigraphic level throughout the eastern Anti-Atlas (Massa 1965, Hollard 1974, Kaufmann 1998), and also in the Barrandian (Chlupac & Kukal 1988). House (1985) called a shift to deep-water facies and global ammonoid extinction event at this stratigraphic level the Daleje Event; so the Upper Emsian shale deposition of the Jebel Rheris was caused by a eustatic sea-level rise.

No indicators of sea-level changes could be found within the condensed Eifelian nodular limestones at the Jebel Rheris. In the Tafilalt area of the eastern Anti-Atlas, in contrast, both the transgressive lower Eifelian Chotec Event and the upper Eifelian Kacak Event were recognised by Alberti (1980) and Becker & House (1994).

A considerable relative sea-level fall during the early Givetian caused the deposition of mid-ramp crinoidal grainstones and coral-stromatoporoid biostromes onto the deep-slope facies at the Jebel Rheris, followed by three smaller scale transgressions and two regressions until the late Givetian, which are interpreted from changes within the accommodation plot (Fig. 14). The sea-level curve of Johnson et al. (1985) shows an opposite trend in Euramerica. Becker & House (1994), Kaufmann (1998), and Aboussalam & Becker (2001) recognised a transgression in the upper part of the Givetian in the eastern Anti-Atlas (e.g. Jebel Amelane, Bou Tchrafine), which probably correlates with the global Taghanic Event. This could not be detected in successions of the Jebel Rheris. Furthermore, Döring (2002) recognised a transgression at the base of the Givetian in the central Mader, which is directly opposed to the development at the Jebel Rheris. Therefore it is interpreted that the Givetian sea-level changes were induced by local tectonic movements here.

The change from mid-ramp biostromal limestones to inner ramp lagoonal deposits at the base of the Frasnian at the Jebel Rheris indicates a sudden sea-level fall. The termination of coral-stromatoporoid growth is not interpreted as a cause of sea-level fluctuations, but as a result of siliciclastic input. Above the lagoonal facies, a deepening can be recognised by the successive deposition of shoals and mid-ramp limestones. Wendt & Belka (1991) reported a major transgression in the lowermost Frasnian, when black shales were deposited in the Tafilalt, and another one in the middle Frasnian, which were correlated to the lower and upper Kellwasser members. However, Dopieralska (2003) interpreted the Kellwasser members as regressive on the basis of Nd isotopic data. House (1985) found a global extinction event (Frasnes Event) at the base of the Lower *asymmetricus* Zone and also indicators of deepening in Europe. Kellwasser members, whether transgressive or regressive, and the transgressive Frasnes Event can not be recognised at the Jebel Rheris. The overall deepening trend, which is very pronounced during the Frasnian in the Johnson et al. (1985) sea-level curve, with the peak transgression in the upper Frasnian and a subsequent pronounced regression slightly resembles the Jebel Rheris sea-level curve. So a eustatic influence on the sedimentation during the Frasnian in the northern Mader can not be precluded, but local tectonic movements are considered to be the main reason for the sea-level fluctuations.

Lower Famennian sediments of the Jebel Rheris were deposited during a moderate regression, indicated by the accumulation of conglomerate layers around the middle Famennian. During the upper Famennian, a prominent transgression occurred, whereby previously emergent areas were flooded. This is in agreement with the Wendt & Belka (1991) sea-level curve, which shows a regression in the middle Famennian, responsible for several stratigraphic gaps in the eastern Anti-Atlas, and a transgression in the upper Famennian. The Johnson et al. (1985) sea-level curve also shows a similar pattern, especially the upper Famennian transgression is very prominent. Therefore it is concluded that eustatic sea-level changes influenced the sedimentation at the Jebel Rheris during the Famennian. As an exception, the regression in the uppermost Famennian in both the Johnson et al. (1985) and Wendt & Belka (1991) sea-level curve can not be noticed in sediments of the northernmost Mader. The youngest dated Devonian sediments north of the mountain Lalla Mimouna transgressed over Silurian rocks during the Upper *praesulcata* Zone (Fig. 20). Several other beds above unconformities were deposited during the *praesulcata* Zone in the Jebel Rheris area (Tab. 12), but indicators of a regression in the uppermost

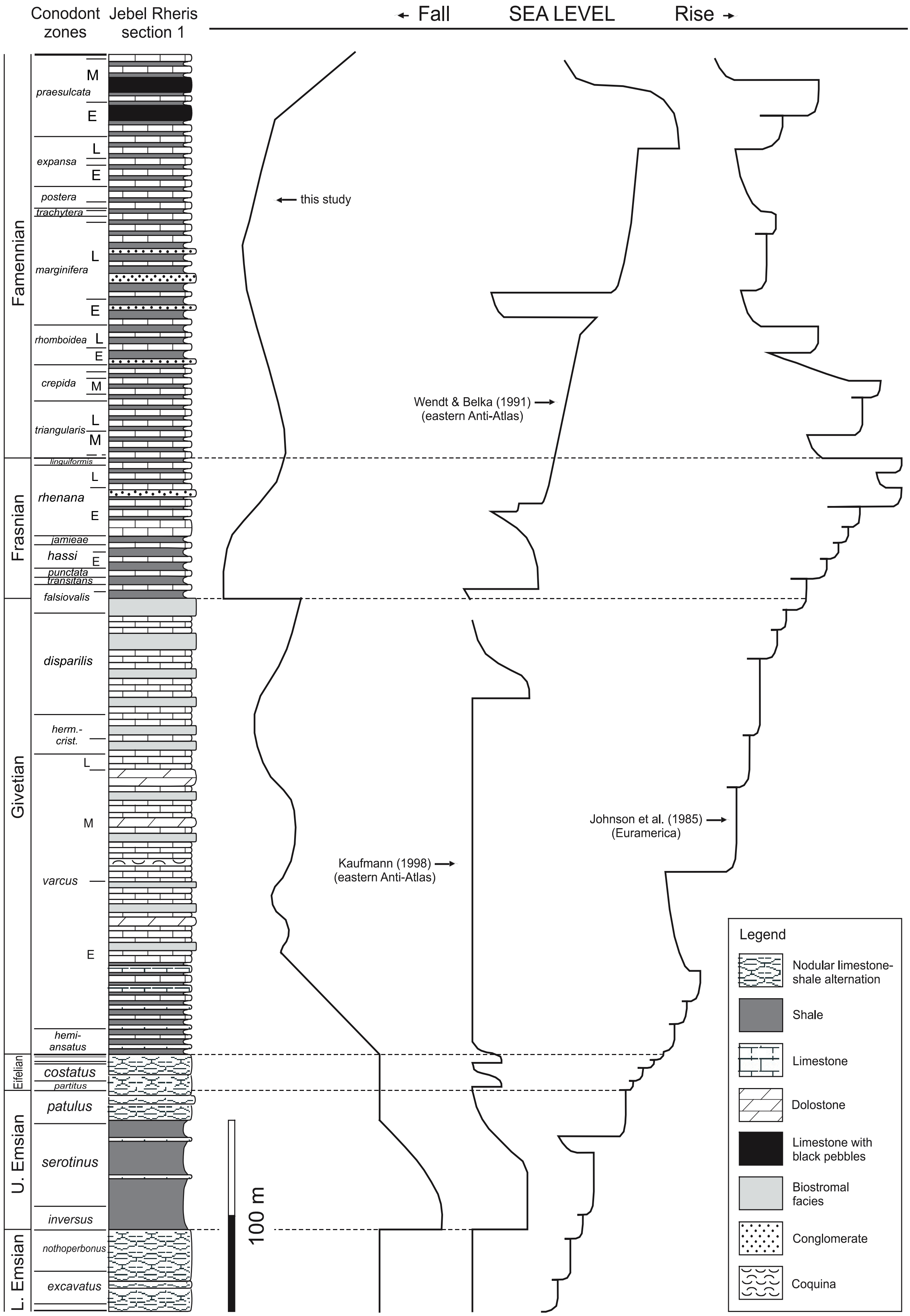


Fig. 26: Comparison of eustatic sea-level changes in Euramerica, the eastern Anti-Atlas, and the Jebel Rheris.

Famennian do not occur.

To summarise, two eustatic sea-level changes can clearly be recognised in the Devonian succession of the Jebel Rheris: The transgressive Daleje Event at the base of the Upper Emsian, and the upper Famennian transgression. Eifelian to Frasnian sea-level fluctuations were probably caused by local tectonic movements.

8. TECTONICS

8.1 Devonian

Homogeneous facies and thickness of Emsian and Eifelian deposits throughout the investigated area indicate that a stable environment predominated during this time.

The considerable thickness changes of Givetian deposits are probably a result of differential subsidence, which created more accommodation space at the eastern part of the Jebel Rheris compared to the western part. Progradation can not be the reason for the thickness changes, because the facies pattern indicates that the basin was situated SW of the mountain (see chapter 5.2); but towards this direction the thickness of the Givetian succession is not increasing.

Deposition during the Late Devonian is considerably influenced by synsedimentary tectonics at the Jebel Rheris. Hollard (1960, 1974) was the first who recognised an Upper Devonian tectonic phase in the Tafilalt and Mader ("phase tectonique intra-famennienne"), he noticed block faulting. Wendt (1985) and Wendt & Belka (1991) specified the tectonic events and reported in addition to block faulting also tilting, angular unconformities, and neptunian dikes. Wendt (1985) found that the majority of these tectonics occurred during the late Frasnian and early Famennian. The effects of Upper Devonian tectonic movements can well be observed at the Jebel Rheris.

8.1.1 Faulting

50 m NW of section 16 at the western Jebel Rheris, a synsedimentary fault created a palaeorelief during the late Frasnian or early Famennian (Fig. 27). The normal fault has a vertical dislocation of about 10 m. Slickensides (60°/15° = dip direction/dip) on the fault plane (350°/40°) indicate transtensional displacement. Directly above the foot wall, 11 m of iron-oolite accumulated. Thickness of the oolite diminishes rapidly, only 2 m thickness are left 50 m towards the NW. Underlying well-bedded crinoidal grainstones were deposited during the early Frasnian (Zone 8-10), quartz-rich crinoidal packstones above the oolite are of middle Famennian age (*marginifera*? – *expansa* Zone).

8.1.2 Neptunian dikes

On top of section 14, ESE – WNW oriented neptunian dikes, between a few millimetres and 15 cm wide, cut into the biostromes. Their filling consists of marine conglomerates and upper Famennian quartz-rich crinoidal limestones (Upper *postera* – Lower *expansa* Zone; after Wendt, unpubl. data). The voids mostly have parallel boundaries and in one case, a second filling of dark sandstones can be noticed (Pl. 3/6). For these reasons, the former interpretation as palaeokarst (Hollard 1974) is rejected. They also cut a shell coquina (Pl. 3/5), which is a marker horizon in most Givetian sections. A comparison of the position of this horizon with complete sections (Fig. 10) indicates that the upper two thirds of the Givetian succession are missing in section 14.

8.1.3 Unconformities

Eifelian-Famennian contact

In section 17, which is located at the western Jebel Rheris, Eifelian nodular limestones are overlain by 10 m thick Givetian biostromal limestones. An iron-rich palaeosol and a 10 m thick succession of coarse, quartz-rich crinoidal limestones of late Famennian age (Upper *expansa* – Middle *praesulcata* Zone) unconformably overlie the Givetian rocks. So Frasnian to upper Famennian strata are missing here. Within a lateral distance of about 30 m next to section 17, the Givetian rocks are also missing (Fig. 28), therefore a hiatus exists between Eifelian and upper Famennian rocks. Especially at this place, the succession is conspicuously folded, probably because the rigid biostromal limestones are missing.

Emsian-Famennian contact

1300 m NW of the northern edge of the Jebel Rheris, an isolated outcrop of Devonian rocks occurs (Fig. 29). Blue-coloured nodular limestones with abundant styliolinids, orthocone nautiloids, crinoids, and rarely fragments of tabulate corals are documented, which were deposited during the Early Emsian (*dehiscens* Zone). An upper Famennian 1.8 m thick conglomerate overlies these limestones (Up-

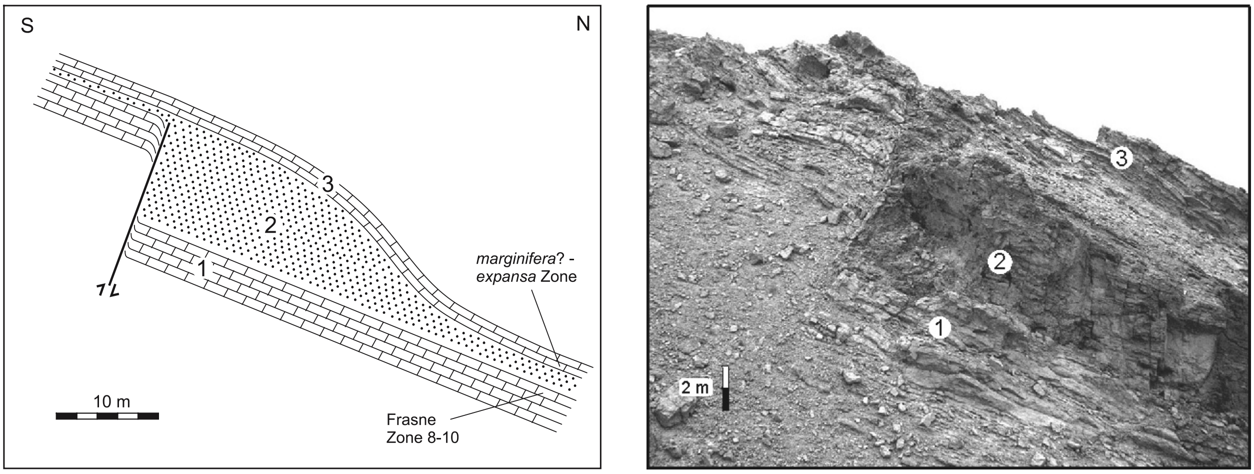


Fig. 27: Sketch and photograph of a synsedimentary fault, which developed during the late Frasnian or early Famennian. 1: Lower Frasnian crinoidal grainstones, containing some large phillipsastreids; 2: iron-oolite with some brachiopods and crinoid ossicles; 3: Upper Famennian quartz-rich crinoidal packstones. Western edge of the Jebel Rheris.

per *postera* – Middle *expansa* Zone) with an angular unconformity of 15°. The iron-rich conglomerate contains mostly well-rounded phosphatic black pebbles, some sandstone pebbles, crinoidal debris, and iron-ooids. A medium-bedded quartz-rich crinoidal limestone layer on top of the conglomerate was deposited within the Middle *expansa* – Middle *praesulcata* Zone. Dark, cross-bedded sandstones with brachiopod-rich horizons are the youngest deposits in this succession. They are probably of Early Carboniferous age.

Unconformities also occur in several other localities at the Jebel Rheris. As described in chapter 6.2, the layers above the unconformities are of late Famennian age except for one in section 10, which is of Frasnian age.

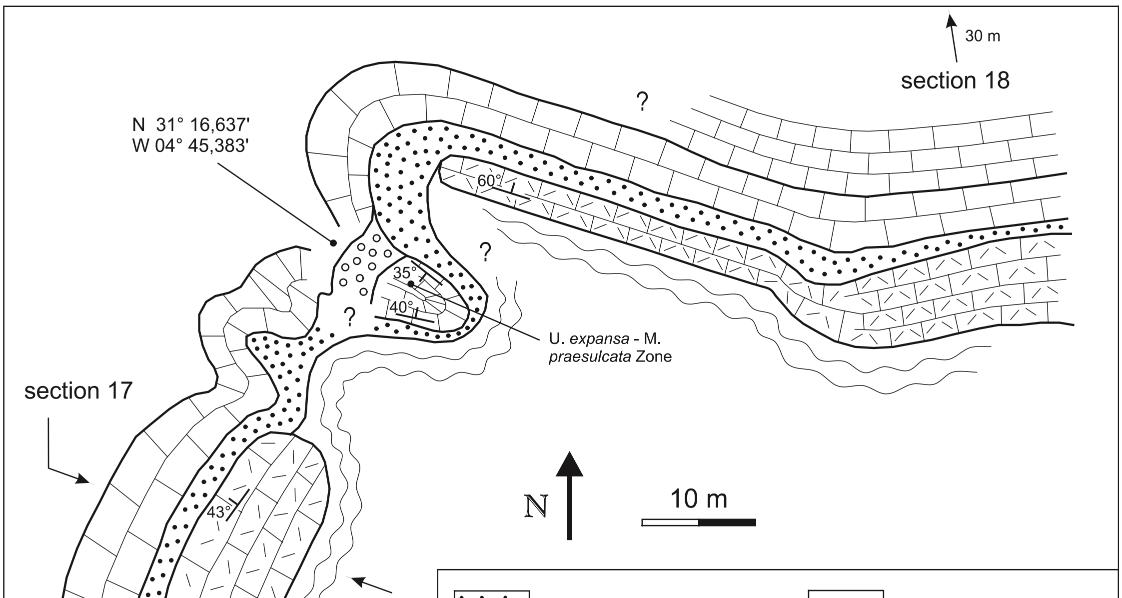


Fig. 28: Map of a location at the western Jebel Rheris, where Eifelian nodular limestones are directly overlain by an upper Famennian palaeosol and crinoidal limestones within about 30 m lateral distance.

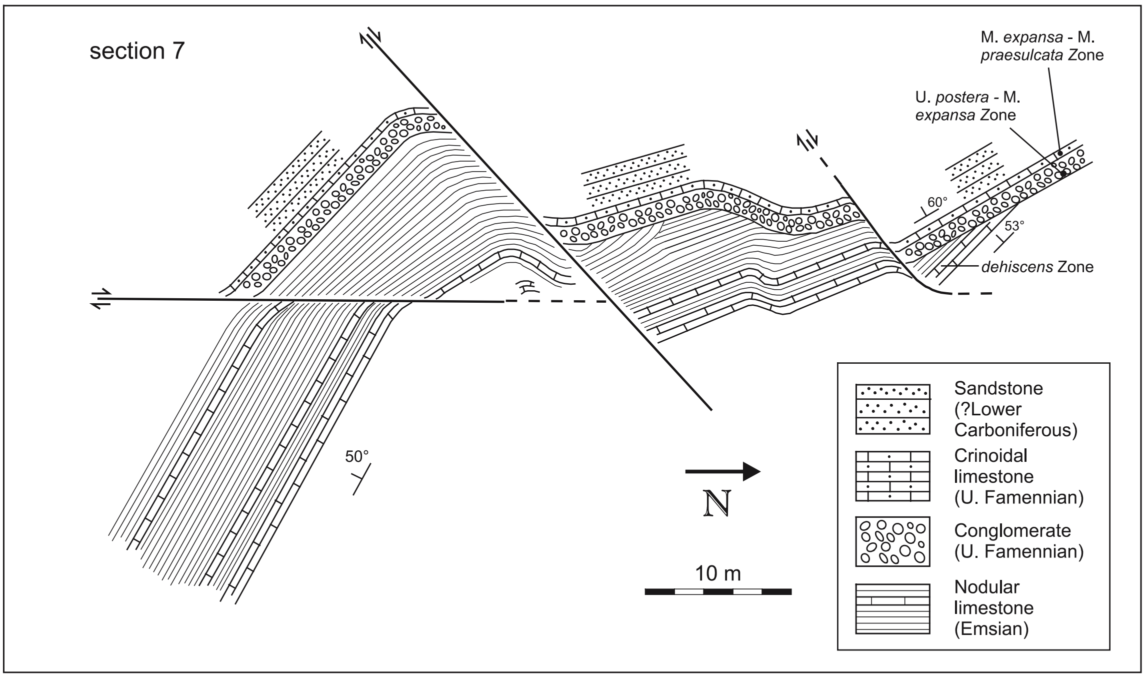


Fig. 29: Map of a Devonian succession cropping out 1300 m NW of the Jebel Rheris. Note angular unconformity between Emsian limestones and a Famennian conglomerate. Faults are probably of Carboniferous age. Conodont data after Spintzyk (1991).

Precise biostratigraphic dating shows that upper Famennian layers above the unconformities in the investigated area are of four different ages (Tab. 12): In the northernmost part in section 7, a basal conglomerate of the Upper *postera* – Middle *expansa* Zone overlies Emsian limestones. At the northeastern Jebel Rheris (section 4), a 10 m thick conglomerate of the Middle – Upper *expansa* Zone was deposited on upper Givetian rocks. In sections 16 and 17 at the western edge of the mountain and north of Lalla

Locality	Age of layers below unconformity	Age of layers above unconformity	Tilting angle
section 10	Emsian	Frasnian (Zone 10)	15°
section 11	middle Famennian (U. *crepida* - *marginifera* Zone)	middle Famennian (U. *crepida* - trachytera Zone)	25°
section 7	Lower Emsian (*dehiscens* Zone)	upper Famennian (U. *postera* - M. *expansa* Zone)	20°
section 4	Givetian	upper Famennian (M. - U. *expansa* Zone)	?
section 16	Frasnian	upper Famennian (M. *expansa* - M. *praesulcata* Zone)	?
section 17	Givetian	upper Famennian (U. *expansa* - M. *praesulcata* Zone)	?
L. Mimouna (N flank of syncline)	Silurian	upper Famennian (U. *expansa* - M. *praesulcata* Zone)	?
L. Mimouna (S flank of syncline)	Silurian	upper Famennian (U. *praesulcata* Zone)	?

Tab. 12: Unconformities in Devonian sections of the Jebel Rheris area.

Mimouna (northern flank of the syncline), sediments of the Upper *expansa* – Middle *praesulcata* Zone unconformably overlie older rocks and finally at the southern flank of the syncline north of Lalla Mimouna, limestones of the Upper *praesulcata* Zone overlie Silurian shales. Because the hinterland was situated N and NW of the Jebel Rheris it could be expected that the transgressive layers become successively younger towards this direction. However, this is not the case, so an inhomogeneous topography is inferred. For example while the area of section 7 was flooded, the areas of section 16 and 17, which are situated basinward of section 7, were still above sea level. In general, the stratigraphic gap increases towards WNW, which indicates that the intensity of uplift was higher in this direction. Angular unconformities, e.g. in section 7, where Lower Devonian pelagic sediments are capped by upper Famennian conglomerates show that at least parts of the hiatuses were caused by Upper Devonian erosion and not only by emergence or non-deposition.

Neptunian dikes at the northern Jebel Rheris are ESE – WNW oriented, the fault plane of the normal fault (chapter 8.1.1) strikes ca. E – W. These directions indicate that a N – S oriented extensional regime prevailed in the Jebel Rheris area during the Late Devonian, which might have been related to the subsiding Mader basin in the S, causing flexures at its margins.

8.2 Carboniferous

The eastern Anti-Atlas was folded during the Variscan orogeny; the fold axes generally run in NW – SE and E – W direction (Choubert 1952, Piqué & Bouabdelli 2000). According to Piqué (1989), the age of the Variscan deformation in the eastern Anti-Atlas is not accurately determined, however, it probably took place in the Namurian / Late Carboniferous (e.g. Michard et al. 1982). The Jebel Rheris was stronger affected by deformation than most other localities of the eastern Anti-Atlas: Three large synclines and two anticlines developed with NW – SE running axes. The anticline in the centre of the mountain is folded on a smaller scale, whereby the limbs of the folds sometimes are inverted. At one location in the centre, Emsian and Eifelian rocks are thrusted against Givetian rocks. Smaller scale faulting occurs for example at the eastern edge of the Jebel Rheris and in section 7, where three normal faults can be recognised (Fig. 29); here, one fault cuts an other which shows that faulting occurred during two generations.

After the main folding phase of the Jebel Rheris, a major normal fault developed at its southern edge (Fig. 4), which can be traced over several kilometres. After Spintzyk (1991), the fault plane dips subvertical towards the N. In the faulting zone, where Cambrian sandstones in the S are in contact with folded Devonian rocks, hydrothermal activity led to the precipitation of ore, mostly galenite (Agard 1958).