Geol. Mag. **143** (*3*), *2006, pp. 269–299.* © *2006 Cambridge University Press*
doi:10.1017/S0016756806001737 *Printed in the United Kingdom*

Sedimentary evolution of a Palaeozoic basin and ridge system: the Middle and Upper Devonian of the Ahnet and Mouydir (Algerian Sahara)

JOBST WENDT*†, BERND KAUFMANN*, ZDZISLAW BELKA‡, CHRISTIAN KLUG§ & STEFAN LUBESEDER¶

Institut für Geowissenschaften der Universität, D-72076 Tübingen, Sigwartstrasse 10, Germany
Instytut Geologii Uniwersytet Adama Mickiewicza, ul. Makow Polnych 16, PL 61-606 Poznan, Poland
Paläontologisches Institut und Museum der Universität, Karl-Schmid-Strasse 4, CH-8006 Zürich, Switzerland
School of Earth, Atmospheric and Environmental Sciences, Oxford Road, Manchester M13 9PL, UK

(*Received* 24 February 2005; *accepted* 4 October 2005)

Abstract – The Ahnet and Mouydir regions of southern Algeria are part of one of the world's largest, almost undeformed exposures of Palaeozoic rocks which exemplify a hitherto poorly known early Variscan development of a Devonian basin and ridge system. This area includes a series of intracratonic basins along the northern margin of the West African Craton which consists (from W to E) of the Reggane Basin, Azel Matti Ridge, Ahnet Basin, Foum Belrem Ridge and Mouydir Basin. The depositional and palaeogeographic interpretation is based on 71 sections in this region, which for the first time were biostratigraphically calibrated by means of conodonts, goniatites and brachiopods. The structural evolution during Devonian times was probably controlled by reactivation of ancient N–S- to NW–SE-running faults in the Precambrian basement, which caused differential subsidence and uplift of a previously largely unstructured siliciclastic shelf. A hiatus during Emsian times indicates widespread emergence during this interval. The entire area was flooded during the earliest Eifelian, when the first vestiges of the Azel Matti Ridge become evident by stratigraphic condensation. The palaeogeographic differentiation is most apparent during the Givetian, when a shoal with reduced carbonate sedimentation was established on the Azel Matti Ridge passing towards the west and east into basinal environments of the Reggane and Ahnet basins, respectively. The Foum Belrem Ridge is distinguished by increased subsidence during the early Givetian and by revived uplift during the late Givetian. In the Mouydir Basin further east, up to 1000 m of shales were deposited during the Givetian. The early Frasnian is marked by the ubiquitous sedimentation of black shales and bituminous styliolinites. These lithologies occur repeatedly already during the Middle Devonian and document intermittent anoxic conditions. The basin and ridge topography is levelled by the shallowing-up sequence of up to 1400 m thick upper Frasnian and Famennian shales which grade into a deltaic sequence of uppermost Famennian/Tournaisian sandstones. The up to now only vaguely discriminated lithostratigraphic formations of the Devonian have been biostratigraphically defined in suitable type sections.

Keywords: Devonian, biostratigraphy, palaeogeography, basin evolution, Algerian Sahara.

1. Introduction

The Palaeozoicdeposits which surround the northern margin of the Precambrian Hoggar Massif in southern Algeria include one of the largest, continuous and tectonically almost undeformed exposures of Devonian/ Lower Carboniferous strata in the world. This unique setting is exemplified by the escarpment of Middle Devonian limestones, which in the Ahnet–Mouydir area can be followed in outcrop for about 2000 kilometres and extends over a similar distance into the Illizi Basin further east. Spectacular exposures, a high fossil content, the absence of vegetation and a weak or lacking tectonic overprint challenge stratigraphic and palaeogeographic research under unrivalled conditions which are only aggravated by the desert climate and the remoteness of the area.

The Lower Devonian sandstones represent important reservoir rocks. Their palaeogeography and depositional environment are well known from the work of Beuf *et al.* (1971). The lower Frasnian black shales account for about 10% of the source rocks of the Algerian oil province (Macgregor, 1996; Boote, Clark-Lowes & Traut, 1998). A large amount of information about the Carboniferous can be gathered from the monograph of Conrad (1984), but apart from a few local and mostly outdated studies, the Middle and Upper Devonian of southern Algeria has never been examined in detail. It is the aim of the present article to summarize the stratigraphic and palaeogeographic results which were gathered in southern Algeria from 1992 to 2003. The main scope of our research is to present a

† Author for correspondence: jobst.wendt@uni-tuebingen.de

biostratigraphically well-established depositional and palaeogeographic evolution of a hitherto poorly known Palaeozoic basin and ridge system. This evolution includes the question as to whether the Ahnet and Mouydir basins developed as early as the Devonian or only during the late Variscan phase as stated by Beuf *et al.* (1971, p. 446), Selley (1997) and others. Unfortunately, since the summer of 2003 the area has become virtually inaccessible for foreigners.

2. Geological setting

The West African Craton crops out in the Reguibat (Eglab) shield in the western and in the Hoggar (Touareg) shield in the central Sahara. These Precambrian metamorphic and igneous rocks are covered by an up to 10 km thick pile of continental, fluvial, deltaic and shallow marine deposits, Early Cambrian to Late Carboniferous in age. They were weakly folded and faulted during the Variscan orogeny in Late Carboniferous/Early Permian times (Donzeau, Fabre & Moussine-Pouchkine, 1981). The deformation is most accentuated in the west (Ahnet Basin) and diminishes towards the east (Mouydir and Illizi basins).

In recent plate reconstructions (Golonka, Ross & Scotese, 1994; Scotese, 2001; Golonka, 2002, fig. 12) this sector of Gondwana is located at 30–45° S during the Middle Devonian. Considering the climatic optimum during this interval (Copper, 2002), such a position is feasible. In fact, coral–stromatoporoid buildups of this age are known from the southern border of the Tindouf Basin (Gevin, 1960), from the former Spanish Sahara (Dumestre & Illing, 1967), southeastern Morocco (Fröhlich, 2003) and the Gourara of central Algeria (Wendt & Kaufmann, 1998). A more northerly position of about 20° S was obtained from Givetian limestones in the southern Ahnet Basin by Smith, Moussine-Pouchkine & Ait Kaci Ahmed (1994). Because we assume that the analysed magnetic component (magnetite) of the samples is of late diagenetic rather than of synsedimentary origin, the obtained palaeolatitude value would indicate a Late Carboniferous (pre-Moscovian) and not a Middle Devonian position (Kaufmann & Wendt, 2000). Due to the position of northern Gondwana in high latitudes during Early Palaeozoic times, the sedimentation until the late Early Devonian was almost exclusively siliciclastic, comprising deltaic, fluvial, glacial and shallow marine intervals. The Lower Silurian graptolite shales mark a highstand of sea-level and an open marine interval (Lüning *et al.* 2000) followed by a regression and the deposition of a thick siliciclastic sequence (Tasilis externes of Beuf *et al.* 1971) during Late Silurian/Early Devonian times. The Middle Devonian transgression marks the onset of a new cycle represented by open marine, predominantly carbonatic to shaly sediments. It is followed by a long regressive phase during Late Devonian times. The Carboniferous is characterized

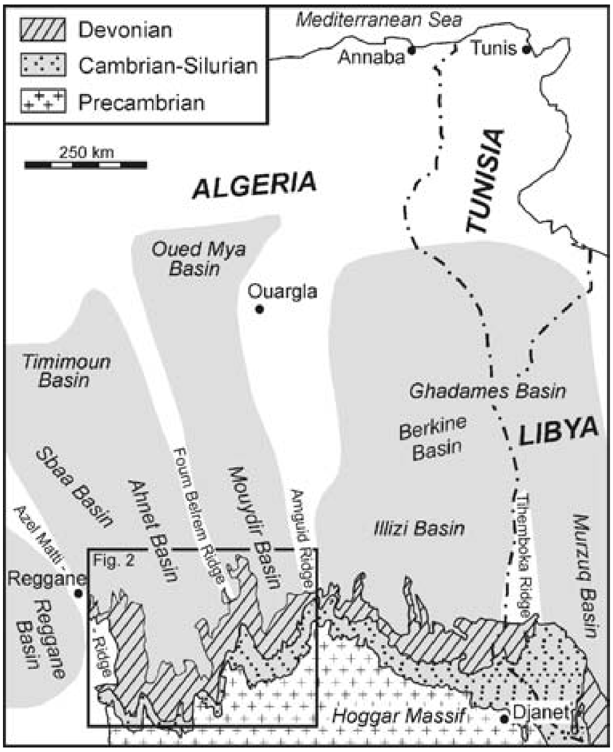

Figure 1. Palaeozoic basins and ridges on the northern margin of the Hoggar Massif (modified after Lüning *et al.* 2004).

by several oscillations of sea-level until the early Moscovian. After the Hercynian orogeny, the southern part of the broad shelf of the Sahara Craton was emergent until Late Cretaceous times.

During the Ordovician to Early Devonian, ancient, mostly N–S- and NW–SE-running, faults in the basement were repeatedly rejuvenated (Beuf *et al.* 1971; Fabre & Kazi Tani, 1987; Haddoum, Guiraud & Moussine-Pouchkine, 2001), thus creating uplifts and depocentres which anticipated the subsequent subdivision of the large shelf north of the craton into several ridges and basins (Sonatrach, 1979). These are, from west to east in southern Algeria and western Libya, the following structural units (Fig. 1): Tindouf Basin, Bou Bernous Ridge (both not shown on Fig. 1), Reggane Basin, Azel Matti (Azzene) Ridge, Ahnet (Oued Djaret) Basin, Foum Belrem (Idjerane) Ridge, Mouydir Basin, Amguid (El Biod) Ridge, Illizi Basin, Tihemboka Ridge and Murzuq Basin.

3. Previous work

The first records of the existence of Devonian rocks in the central Sahara date back to the middle of the 19th century, but these early works are merely of historical interest. Substantial research on the Devonian started in the 1930s (summaries in Follot, 1952 and Legrand, 1967) and was intensified by the discovery of enormous oil and gas resources in the 1950s (summaries in Echikh, 1975; Boote, Clark-Lowes &

Traut, 1998; Traut, Boote & Clark-Lowes, 1998). The first geological map of the southeastern Ahnet was compiled by Monod (1931–32). An outstanding study of the Cambrian to Lower Devonian siliciclastic sequence is the monograph of Beuf *et al.* (1971), based on extensive field studies in the surroundings of the Hoggar Massif. A great step forward in knowledge of the Cambrian to Carboniferous deposits on the northern margin of the massif was the geological mapping (Middle and Upper Devonian by Moussine-Pouchkine), performed in the 1960s and 1970s by the Algerian Ministry of Industry and Energy, the Algerian oil company SONATRACH and BEICIP, consisting of 26 1:200 000 sheets of admirable precision. Short summaries on the Devonian stratigraphy of the area were compiled by Legrand (1967, 1983) and Moussine-Pouchkine (1976). Generalized overviews of the tectonic development and thermal history of the North African basins were published by Logan & Duddy (1998) and Coward & Ries (2003). Structural maps of the Ahnet Basin have been presented by Echikh (1975) and Badsi (1998) but, being without scale, coordinates, localities and legend, they are not very informative.

4. Field-work, material and methods

The Palaeozoic deposits of the Ahnet and Mouydir regions cover a surface of approximately 170 000 km^2 (Fig. 2). During nine expeditions of about one month each, 71 sections in this area, the majority of them including the sequence from the top of the Lower Devonian into the Famennian or Lower Carboniferous, were logged and sampled. The data from each section were verified and re-examined in the field several times during consecutive years in order to minimize biostratigraphic and sedimentary inaccuracies. The biostratigraphic calibration of the sections is based on 1055 (607 productive) conodont samples, 62 goniatite and 49 brachiopod faunas. Results from sections not figured in this article may be obtained from the authors on request. Organic carbon was measured after careful removal of inorganic carbon. In addition, in 12 sections the U, K and Th concentrations of the lower Frasnian hot shales were measured using a portable gamma-ray spectrometer (partly published by Lüning *et al.* 2004). Current directions were calculated from field measurements (total of 4218 from 31 localities) of the orientations of orthoconic nautiloids and foreset beds in cross-bedded sandstones. Spelling of locality names is according to the topographic 1:200 000 map of Algeria.

5. Fauna

5.a. Conodonts

Eifelian conodont faunas of southern Algeria are very poor; only a few long-ranging species of *Polygnathus* and *Icriodus* have been recovered. Among these, *Polygnathus linguiformis linguiformis* is the most frequent and characteristic species of the Eifelian. The greatest abundance of this species, however, has been noted in Givetian carbonates. Early Givetian collections spanning the interval from the *hemiansatus* Zone to the *rhenanus* Zone are particularly prolific. They commonly yield very rich faunas characterized by a great variety of conodont species, which are also known to occur in coeval strata of Morocco and Euramerica. This indicates that the Rheic Ocean did not affect the distribution of conodonts on opposing margins of Gondwana and Euramerica during early Givetian times. The similarity of conodont faunas suggests a connection between both palaeocontinents or their very close palaeogeographic position. This observation is in apparent conflict, however, with Devonian palaeomagnetic data for Gondwana (Tait *et al.* 2000; Stampfli & Borel, 2002). In the upper part of the Givetian, conodonts occur in small numbers and are represented by small-sized polygnathids and icriodids. These faunas generally display a low diversity.

In contrast to the upper Givetian, conodont faunas from the basal Frasnian (Zones 1 and 2) are very abundant and show a high diversity. They are dominated by several species of *Ancyrodella* and *Polygnathus*; representatives of *Icriodus* and *Mesotaxis* are less numerous. Generally, however, the Frasnian faunas of southern Algeria are significantly less diverse and less abundant than coeval faunas of the European Variscides. Their typical feature is the very rare occurrence of *Palmatolepis*. Only a few specimens of *Palmatolepis punctata* have been recovered from carbonate nodules present in Zone 6. This interval as well as Zone 11 yielded the most productive Frasnian faunas. They are moderately rich but commonly represented by only five to six species. Among these, long-ranging taxa such as *Ancyrodella curvata*, *Polygnathus politus*, *Icriodus symmetricus* and *Icriodus alternatus* are most frequent. Representatives of *Ancyrognathus* occur regularly and are distinctive. Their content in the samples is often higher than 10 %.

Famennian conodont faunas are poor and show a very low diversity. Only a few specimens have been found in the middle and upper Famennian. They are represented by shallow-water elements belonging to the genera *Icriodus* and *Pandorinellina*.

Generally there is little variation in CAI (Colour Alteration Index) values of Devonian conodonts in southern Algeria, with a range between 1.5 and 2.5. This indicates that the conodont elements have not been subjected to temperatures greater than about 90–100 °C, and that the Devonian rocks have attained their current rank through depth of burial during Late Carboniferous times. These values correspond well to the maturity level estimated from vitrinite reflectance data (Logan & Duddy, 1998).

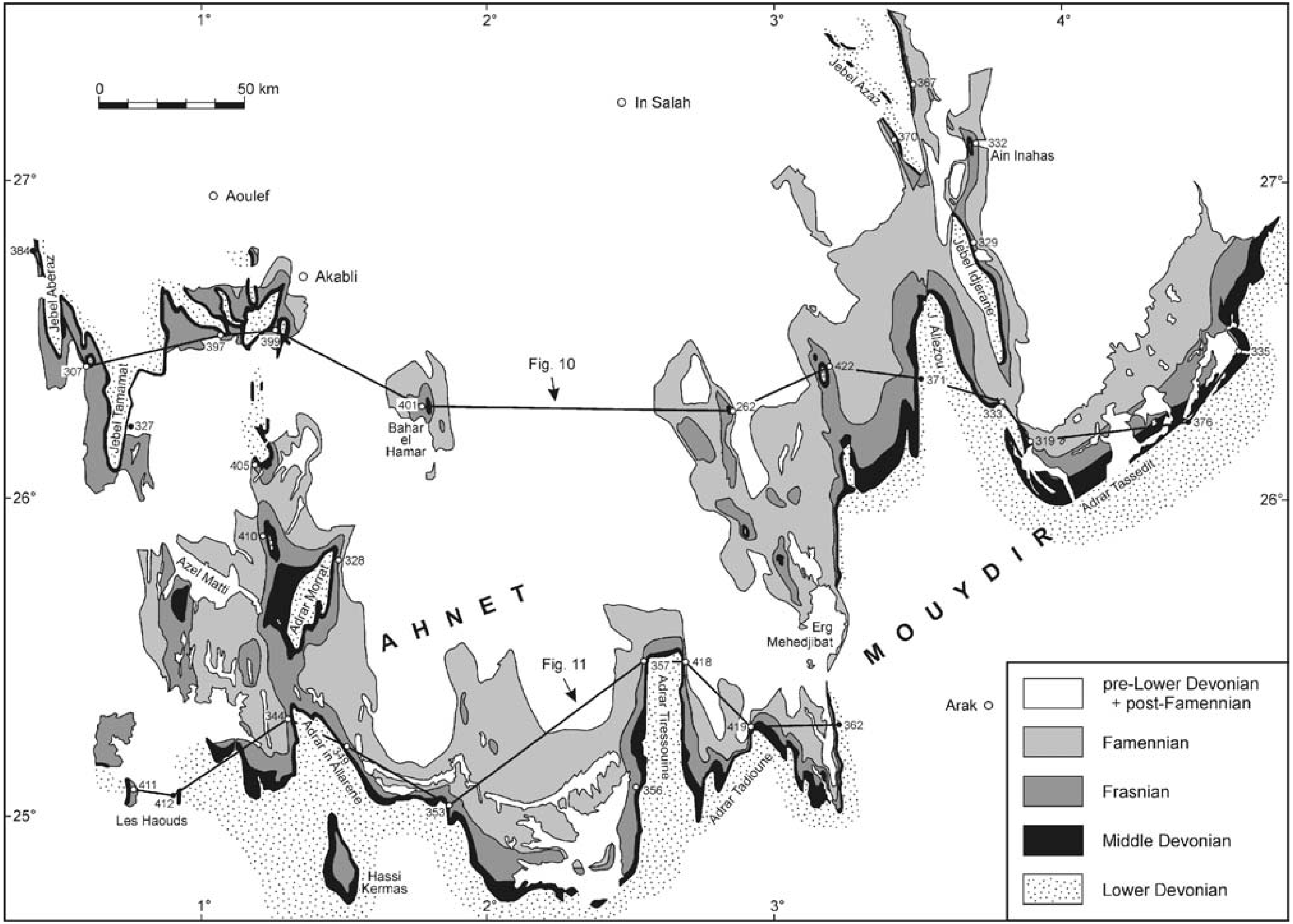

Figure 2. Simplified geological map of the Ahnet and Mouydir (base map from Moussine-Pouchkine, unpub. data 1970) showing the extension of Devonian strata and the locations (numbered small circles and black points) of the sections on Figures 8, 9, 10, 11.

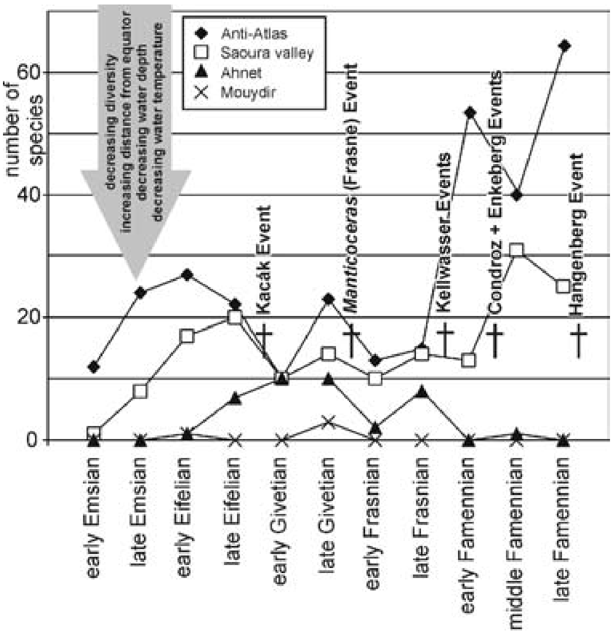

Figure 3. Diversity of Devonian ammonoid faunas in Algeria and SE Morocco (Anti-Atlas), based on all available (mostly own) data (Belka *et al.* 1999; Göddertz, 1987; Klug, 2001, 2002; Petter, 1959, 1960 and others).

5.b. Cephalopods

Apart from conodonts, goniatites are the best index fossils, which have considerably completed the biostratigraphic calibration of our sections. Their diversity (Fig. 3) differs significantly compared to the faunas reported from the eastern Anti-Atlas of Morocco (Klug, 2002) and the Saoura Valley in Algeria (Petter, 1959, 1960; Göddertz, 1987). The total lack of goniatites in Lower Devonian deposits of the Ahnet and Mouydir region is a consequence of the restricted water depth and the concomitant siliciclastic lithology. Water depth was probably still too low during the early Eifelian, accounting for the record of only one cosmopolitan species (*Pinacites jugleri*) by Moussine-Pouchkine (1976, p. 142). Ecological conditions became more favourable during the late Eifelian and the Givetian, as is indicated by more common and diverse faunas which are dominated by abundant tornoceratids, agoniatites and pharciceratids. Some specimens of the Givetian *Sellagoniatites discoides* attain diameters of up to 400 mm in the western Ahnet. The goniatite abundance decreases again in the early Frasnian and reaches a last moderate peak in the late Frasnian, which is, however, exemplified by only one locality in the northern Ahnet (299).

We could not find any goniatites in the Famennian, in contrast to Petter (1959) and Moussine-Pouchkine (1976), who mentioned the occurrence of *Sporadoceras* in the northern Ahnet. Further north, at Jebel Hèche (Sbaa Basin), in the Saoura valley (Ougarta Basin) and in the eastern Anti-Atlas, however, the Famennian is well documented by a great abundance of goniatites and clymenids (Petter, 1959, 1960; Korn, 1999). From the above data it becomes clear that the limiting factor for the distribution of ammonoids is water depth and that the availability of ecological niches was higher in both the Saoura Valley and in the eastern Anti-Atlas than in the Ahnet-Mouydir. Orthoconic nautiloids are common in the Givetian and to a lesser degree in the lower Frasnian, where they have been used for palaeocurrent analyses (see Section 10).

5.c. Brachiopods

Brachiopods are very common throughout our sections but, because of their lower biostratigraphic value, only specimens from the Lower Devonian were specifically determined. These faunas show a high diversity and close relationships to coeval ones from Libya (Massa, 1988), the central and eastern Anti-Atlas (Morocco), Asturias and Aragon (Spain) and Bohemia (P. Carls, Braunschweig, pers. comm.). Moussine-Pouchkine (1976) and Legrand (1967, 1983) mentioned a great number of Devonian brachiopod species, however, without assigning them to individual levels and localities. The majority of these species are probably also present in our faunas. Because all our specimens were collected according to horizon, their systematic study would be a challenge for the future.

5.d. Other groups

Middle Devonian and lower Frasnian limestones contain a great number of small solitary rugose corals, often associated with gastropods and rare pelecypods. *Buchiola* is common in Frasnian shales and occasionally preserved with articulated shells. The disappearance of this tiny pelecypod has been used for an approximate determination of the Frasnian–Famennian boundary. Only a few isolated specimens of colonial Rugosa (generally *Hexagonaria*), small stromatoporoids and chaetetids have been found. Trilobites are rare and mostly represented by genera of the long-ranging phacopids. Styliolinids are very common in the majority of Middle Devonian and lower Frasnian mudstones and are often accumulated to form almost matrix-free grainstones (see Section 6.d). Tentaculitids, however, are restricted to the Lower Devonian sandstones and the upper Frasnian Grès de Mehden Yahia. Crinoid remains often occur in rock-forming quantities and are locally preserved as up to 15 cm long stems lacking, however, cups and holdfasts. Scattered fish remains were found in several Middle and Upper Devonian samples and are most common in Famennian rocks (Fig. 6c). An upper Famennian fauna of chondrichtyan teeth was described by Ginter, Hairapetian & Klug (2002).

6. Stratigraphy

The biostratigraphy is based on conodonts and goniatites, the time resolution of which is by far

https://doi.org/10.1017/S0016756806001737 Published online by Cambridge University Press

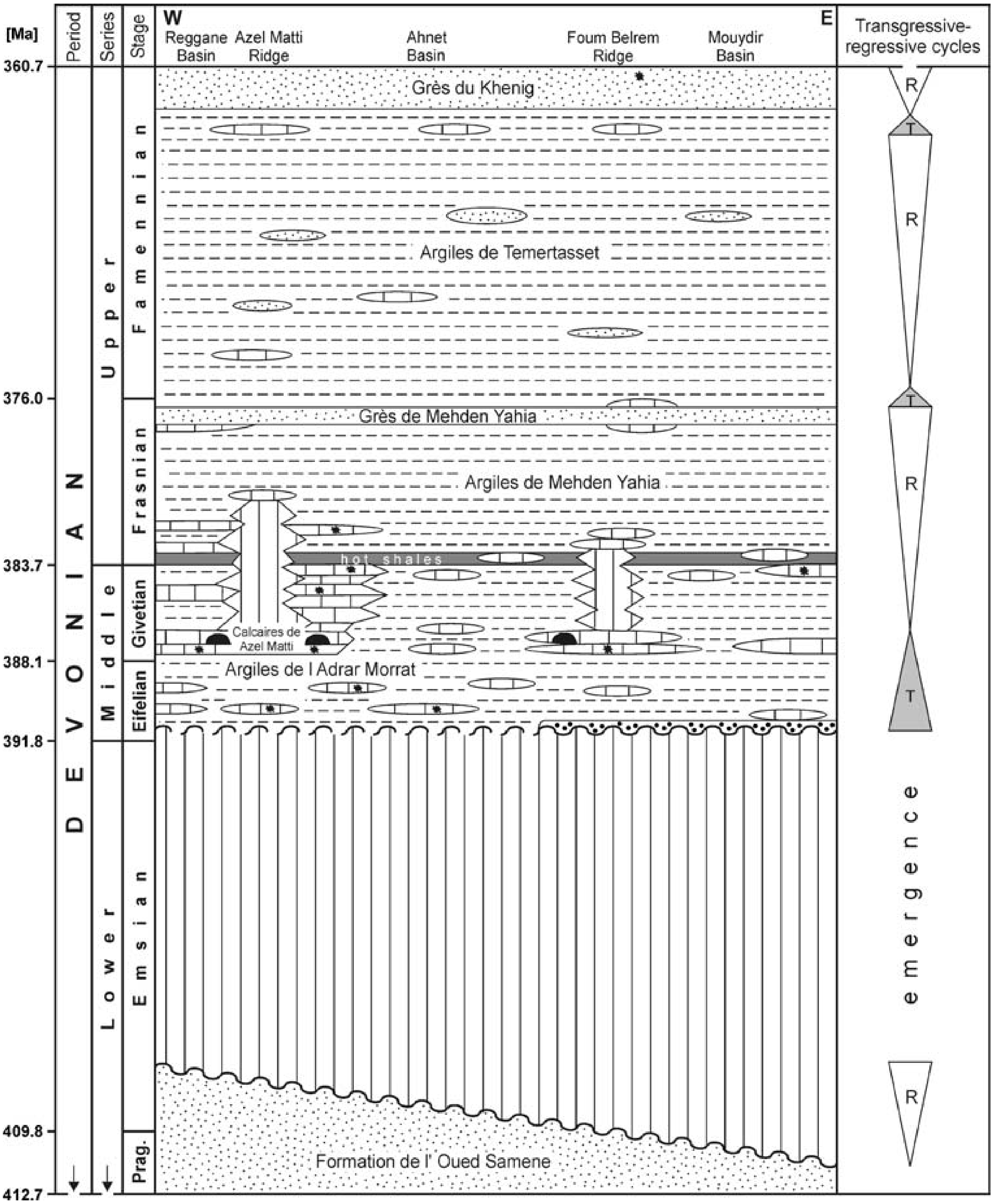

Figure 4. Synoptic view of Pragian to Famennian formations. Vertical hachure – hiatus. For legend see Figure 10. Radiometric ages after Kaufmann & Trapp (2004). Only upper part of Formation de l'Oued Samene and lower part of Grès du Khenig are included; lithology of both formations is simplified.

superior to the biozonation by chitinozoans and spores (Richardson & McGregor, 1986). On the 1:200 000 geological maps and in relevant publications, various formation names in the Devonian are used which have never been properly defined. Their main characters and the type sections are summarized and figured here for the first time (Figs. 4, 5a, 8, 9; Table 1).

6.a. Lower Devonian

A progressive shallowing during the latest Silurian and the Early Devonian caused the shedding of great amounts of siliciclastic detritus from the central parts of the West African Craton towards the north. Depositional unconformities across this boundary in

https://doi.org/10.1017/S0016756806001737 Published online by Cambridge University Press

Table 1. Principal characteristics of Devonian formations in the Ahnet-Mouydir area

	Formation de l'Oued Samene	Argiles de l'Adrar Morrat	Calcaires de l'Azel Matti	Argiles de Mehden Yahia	Grès de Mehden Yahia	Argiles de Temertasset	Grès du Khenig
Type locality	Oued Samene	Adrar Morrat	Gara Azel Matti	Mehden Yahia	Mehden Yahia	Oued Temertasset	Hassi el Krenig
Total thickness	140–220 m	0–140 m	2–45 m	170–700 m	3–120 m	350–1100 m	50–250 m
Type section (this paper)	Oued Samene (undescribed)	Ain Inahas (Fig. 9)	Adrar Morrat N (Fig. 8)	Adrar Morrat N (Fig. 8)	Adrar Morrat N (Fig. 8)	Ain Behaga (Fig. 9)	Hassi el Krenig (Conrad, 1984)
Thickness at type section	?	50 m	18 m	170 m	95 m	500 m	100 m
Lithology	Sandstone with shale intercalations	Grey shale, limestone & dolomite intercalations	Limestone with shale intercalations, mud buildups	Dark shale, thin limestone and sandstone levels, hot shale at base	Sandstone with shale intercalations	Varicoloured shale, sandstone & limestone intercalations	Sandstone with shale intercalations
Fossils	B, T, Tr	B, C, Cr, G, Ga, O, R, S, T	B, C, Cr, G, Ga, O, P, R, S, T	C, G, P, O, S	B, Ga, Te	B, C, P, V	B, Cr, G, Ga, Pl, T, Tr
Age	Pragian–Emsian	Eifelian	Late Eifelian–early Frasnian	Frasnian	Latest Frasnian (Zone 13)	Famennian	Latest Famennian/ Tournaisian
References	Beuf *et al.* 1968, 1971; Legrand, 1983	Bertrand-Sarfati, Fabre & Moussine-Pouchkine, 1977	Legrand, 1967; Bertrand-Sarfati, Fabre & Moussine-Pouchkine, 1977	Bertrand-Sarfati, Fabre & Moussine-Pouchkine, 1977	Moussine-Pouchkine, 1976; Bertrand-Sarfati, Fabre & Moussine-Pouchkine, 1977	Legrand, 1967; Moussine-Pouchkine, 1976	Moussine-Pouchkine, 1976; Conrad, 1984; Legrand-Blain, 2002

Abbreviations: B – brachiopods, C – conodonts, Cr – crinoids, G – goniatites, Ga – gastropods, O – orthoconic nautiloids, P – pelecypods, Pl – plants, R – rugose corals, S – styliolinids, T – trilobites, Te – tentaculitids, Tr – trace fossils, V – vertebrates.

the Ahnet and Mouydir have sometimes been related to the 'Caledonian orogeny' (Beuf *et al.* 1968; Biju-Duval *et al.* 1968; Logan & Duddy, 1998; Fekirine & Abdallah, 1998; Polonio *et al.* 2005 and others). In the eastern part of the Illizi Basin, that is, toward the Tihemboka Ridge, an angular unconformity between Upper Silurian and Lower Devonian sandstones has been observed (Boudjema, 1987).

Lower Devonian deposits are continental/fluvial in the south, passing into deltaic/shallow marine sandstones with argillaceous intercalations towards the north and northwest. As is shown by the unidirectional S–N to SE–NW currents on both the northern and the southern margins of the Hoggar Massif, this part of the Precambrian basement was submerged during Early Devonian times (Beuf *et al.* 1968, 1969, 1971). The sequence consists of a great variety of cross-bedded sandstones, conglomerates, siltstones, shales and rare oolitic intercalations. It shows only minor variations in thickness, oscillating between 140 and 220 metres. So far, correlation of sections in the Ahnet and Mouydir has only been achieved lithostratigraphically (Beuf *et al.* 1968) though graptolites, brachiopods and trilobites (Legrand, 1967, 1983), tentaculitids and trace fossils are common at various levels. The Lower Devonian sandstones are capped by the lower Eifelian transgression. This hiatus is best documented and longest on the Foum Belrem Ridge and adjacent areas (Figs 4, 9, 10, 11, 16). From this area, the siliciclastic lithology increases in thickness towards the northwest and comprises also lower Emsian equivalents. A significant marker bed at the base of the Lower Devonian sandstones is the Upper Silurian (Ludlowian) orthoceratid limestone on the northern Azel Matti Ridge (Biju-Duval *et al.* 1968) which extends to the northwest (southern Morocco) and west (Mauretania) over an area of about 300 000 km^2 (Wendt, 1995). The Lower Devonian clastic sequence was labelled with various formation names by Legrand (1967, 1983, 1985): Formation argilo-gréseuse de l'Azzel Matti, Grès de la Sebkha Mekerhane, Grès de Foum Immeden, Grès du Djebel Idjerane, Grès de l´Adrar Tassedit. However, none of these has ever been defined, which makes them rather *nomina nuda*. In accordance with the 1:200 000 geological maps, we use the term Formation de l'Oued Samene in our stratigraphic columns (Figs 4, 8, 9).

In the Tassili n'Ajjer (southern part of the Illizi Basin), a shale unit (Formation d'Orsine) of supposed Siegenian age (= late Pragian/early Emsian in the modern sense) caps the upper member ('Barre supérieur') of the Oued Samene Formation (Dubois, Beuf & Biju Duval, 1967). Our brachiopod datings from the top of the cliff-forming sandstones have yielded Pragian ages on the Foum Belrem Ridge and in the Mouydir Basin and early Emsian ages on the Azel Matti Ridge, thus indicating for the first time a major gap and a subaerial exposure during the Emsian. Sections in which this

https://doi.org/10.1017/S0016756806001737 Published online by Cambridge University Press

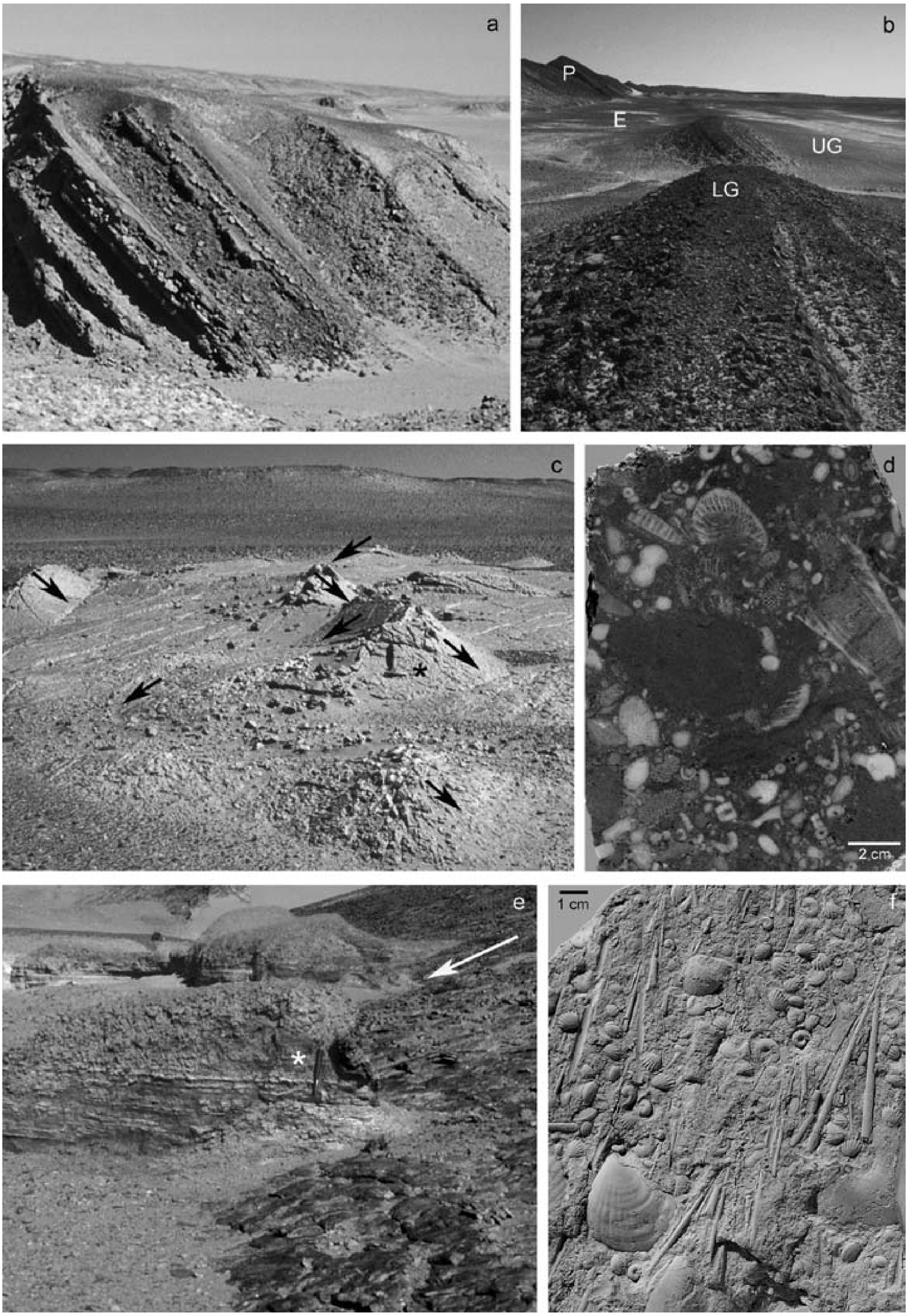

Figure 5. (a) Type section of the Calcaires de l'Azel Matti at Adrar Morrat N (328) comprising units 5–33 on Figure 8. Thickness of exposed beds is about 30 m. (b) Devonian section at Ain Tidjoubar (372). P – Pragian sandstones, E – Eifelian shales, LG – lower Givetian limestone escarpment (5 m thick), UG – upper Givetian shales. (c) Slumped bed of lower Givetian (*rhenanus* Zone) limestone at Gour bou Kreis (422). Arrows indicate opposing dips of individual slumpfolds. In the background escarpment of the upper Frasnian Grès de Mehden Yahia. Hammer at ∗ is 32 cm long. (d) Polished vertical slab of upper Givetian coral–crinoid floatstone (sample 271/7)

https://doi.org/10.1017/S0016756806001737 Published online by Cambridge University Press

gap has been documented by brachiopods include Ain Kahla (367; Fig. 9), Ain Bagline (333), Oued In Sormar (319, both on Fig. 10), In Heguis S (418; Fig. 11), Hassi Bel Rezaim (227) and Tin Khelifa (366). Towards the Ahnet Basin and Azel Matti Ridge, this hiatus appears shorter. Thus, an early Emsian age for the top of the Formation de l'Oued Samene was proved by brachiopods at Bled el Mas (307; Fig. 10) and Jebel Tamamat W (390). Unfortunately, the precise contact between the Lower Devonian sandstones and the lower Eifelian shales is mostly concealed. A more detailed biostratigraphic and depositional examination of the Lower Devonian, however, was beyond the aim of our studies.

6.b. Eifelian

On the Foum Belrem Ridge and adjacent areas, the lower Eifelian (*costatus* Zone) is a major transgression and marks the onset of a fully marine sedimentation of shales and carbonates. The 0.1–0.5 m thick transgression conglomerate (Fig. 9, sections 329 and 367) contains well-rounded, locally imbricated, pebbles of Lower Devonian sandstones, ironstones, phosphorites and corroded quartz grains in a calcareous matrix (Fig. 6a) with brachiopod coquinas, and caps an eroded surface with an up to 1 m relief. This gap is obvious in the eastern part of the study area from Ain Kahla (367) in the northeast to Hassi Kermas (414) in the southwest. It is best exemplified on the Foum Belrem Ridge (329, 333, 319, 362), from where it can be traced into the southern Ahnet Basin (418, 419, 356). The conglomerate proper could be dated by conodonts only in one section (367), where it yielded a latest Emsian to earliest Eifelian age. This is in agreement with the age of the overlying bed in several other sections (early Eifelian *costatus* Zone; in two sections its lowermost part). The upper boundary of the Eifelian is mostly gradual, showing a transition into limestones of the lowermost Givetian.

The major part of the Eifelian consists of silty greenish shales with some thin interlayers of fine-grained sandstones and calcareous mudstones (Figs 8, 9, 10, 11) which have yielded only a few biostratigraphic data. Therefore, it cannot be excluded that, in the western part of the study area, the lower Eifelian shales may locally extend into the upper Emsian.

Thicker bundles of skeletal wackestones (Fig. 6b) are generally restricted to the upper Eifelian or may, in places of strong condensation, comprise the entire Eifelian (Fig. 9). The thickness of the Eifelian strata varies considerably between 0–5 m on the Foum Belrem Ridge (258, 362, 363, 366, 420; Fig. 11) and 140 m in the eastern Reggane Basin (384; Figs 10, 12). Bertrand-Sarfati, Fabre & Moussine-Pouchkine (1977, Fig. 7) have introduced the term 'Argiles de l'Adrar Morrat' for the Eifelian/lower Givetian shales. Though we cannot confirm the suggested stratigraphic range and diachronism of this formation, we use it as a general term for the Eifelian shales in our study.

6.c. Givetian

In the entire Ahnet and Mouydir areas the Givetian limestones constitute a more or less prominent escarpment (Fig. 5a, b) which generally includes both upper Eifelian and lowermost Frasnian equivalents. The sequence consists of well-bedded, dark, partly bituminous mudstones and wackestones which contain a great variety of skeletal remains (goniatites, orthoconic nautiloids, gastropods, pelecypods, brachiopods, bryozoans, styliolinids, trilobites, crinoids, solitary rugose corals; compare Fig. 5d). Stromatoporoids, tabulate and colonial rugose corals are extremely rare and have been found only in a few places (e.g. 358, 370, 414, 410, 332; Figs 8, 9). The entire fauna indicates a shallow, open marine environment which passes laterally, with an insignificant relief, into basinal areas with prevailing shale sedimentation. Conodont data show that the sedimentation in the basinal areas during the Givetian was probably continuous. On the ridges, however, a hiatus between the Givetian and the Frasnian is observed which may comprise up to ten conodont zones (equivalent to about 4 Ma). In the area of the Azel Matti mud mounds (288), this hiatus is even longer (12 conodont zones), showing that they represented more prominent submarine highs than the surrounding ridge proper. The average interval of non-deposition on the Azel Matti Ridge is longer than on the Foum Belrem Ridge. The data compiled on Figure 7 include only those locations in which this gap is well documented biostratigraphically, but it can be argued that it is more widespread. There is no evidence of emergence during this interval. Figures 13 and 14 give only a distorted image of the considerable variations in thickness and lithology between ridges and basins because they comprise the entire Givetian and entire Frasnian, respectively. The angular unconformity at the Givetian/Frasnian boundary at Oued Ouzdaf N (295; Fig. 5e) suggests that the contrasting thickness variations in the Middle Devonian are the effect of synsedimentary block faulting which can only

at Jebel Azaz 2. Compare section in Figure 9, unit 7. (e) Angular unconformity between tilted lower Givetian (*rhenanus* Zone) skeletal limestones (right, arrow indicates dip of surface) and onlapping, flat lying lower Frasnian shales (left) at Oued Ouzdaf N (295). Hammer at ∗ is 32 cm long. (f) Bedding plane of upper Frasnian (Zone 11) Kellwasser Limestone at Illirhene (299). Note parallel aligned orthoconic nautiloids indicating currents from SW, numerous tiny goniatites (*Tornoceras*, *Aulatornoceras*, *Lobotornoceras*, *Manticoceras*, *Costamanticoceras*, *Virginoceras*), small pelagic pelecypods (*Buchiola*) and big (undetermined) pelecypods.

https://doi.org/10.1017/S0016756806001737 Published online by Cambridge University Press

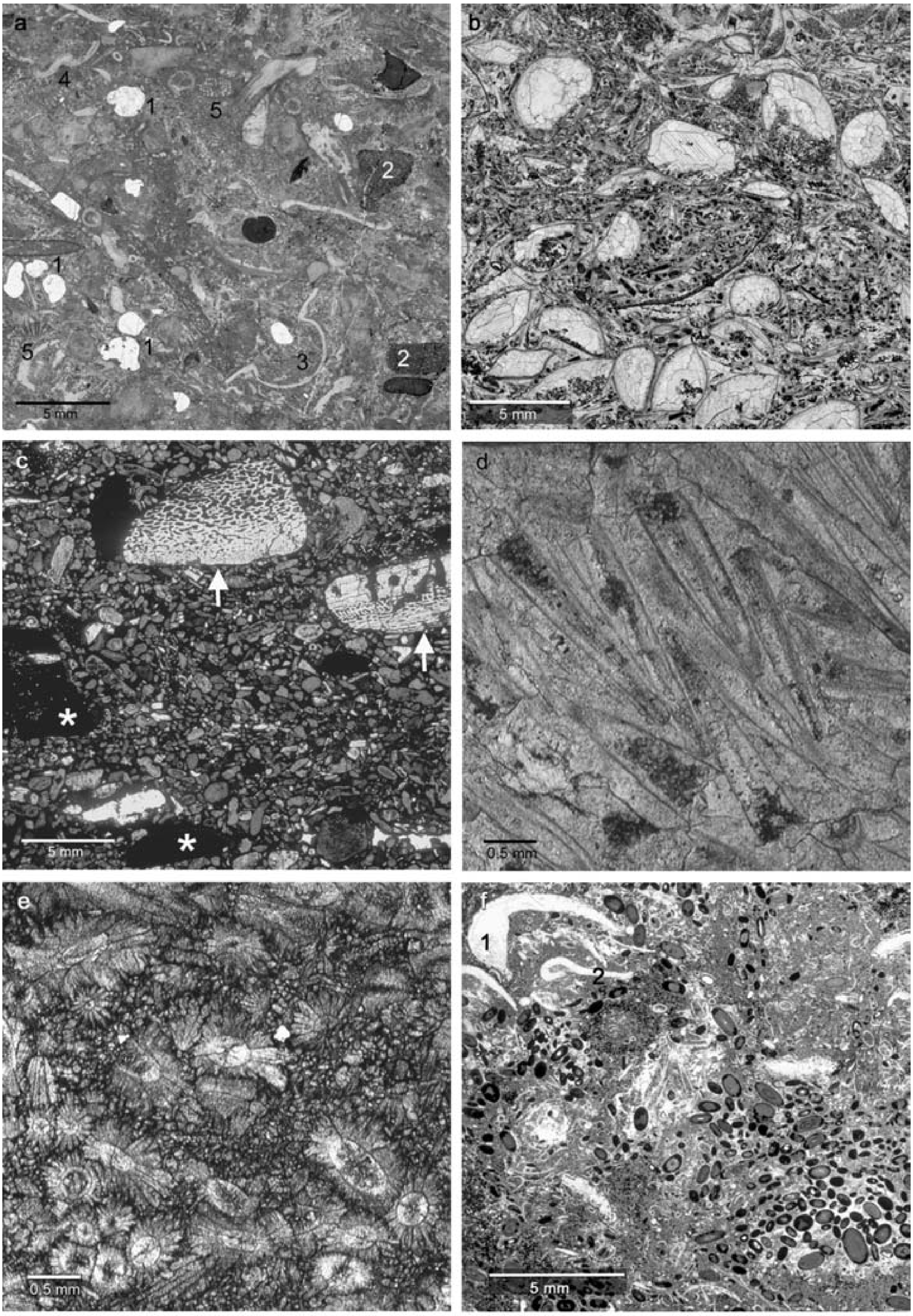

Figure 6. (a) Thin-section of lower Eifelian transgression conglomerate at Ain Bagline (333) with corroded quartz grains (1), phosphatized grains (2), trilobite (3), brachiopod (4) and bryozoan (5) remains. Sample 312/5. Compare section in Figure 10. (b) Thin-section of Eifelian packstone with thin-shelled brachiopods. Ain Behaga (329). Sample 267/8. Compare with section in Figure 9, between units 7 and 9. (c) Thin-section of iron-stained upper Famennian sandstone with phosphorite clasts (∗) and fish (placoderm?) remains (arrowed). Tes Ereghet (258). Sample 256/18. (d) Thin-section of lower Frasnian bituminous grainstone with densely packed,

https://doi.org/10.1017/S0016756806001737 Published online by Cambridge University Press

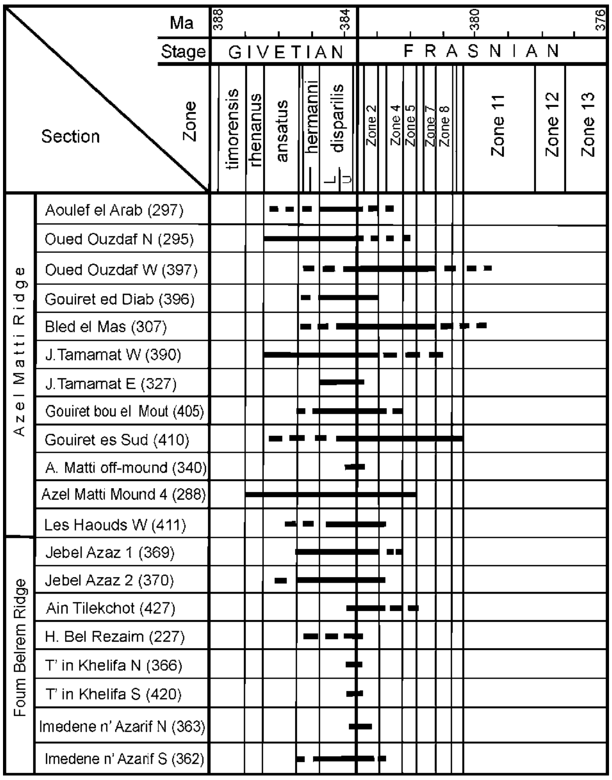

Figure 7. Biostratigraphically documented (solid bars) and possible (broken bars) duration of the hiatus at the Givetian–Frasnian boundary on the Azel Matti and Foum Belrem ridges. Radiometric ages after Kaufmann & Trapp (2004).

accidentally be detected in the field. The N–S-running Oued Kerane Fault between the Azel Matti Ridge and the Ahnet Basin which is visible on seismic lines (T. Djebbar, unpub. M.Sc. thesis, Univ. London, 1995) may be one of these structural elements which were inherited from Precambrian lineaments.

Gautier & Chudeau (1907) were the first to mention the spectacular mud buildups, which were constructed during the early Givetian on the central and marginal ridge (Figs 13, 16; Moussine-Pouchkine, 1971; Wendt, Belka & Moussine-Pouchkine, 1993; Belka, 1994; Wendt *et al.* 1997; Wendt & Kaufmann, 1998; Kaufmann & Wendt, 2000). The mud mounds are up to 30 m high and sometimes grouped into clusters. The mud ridges are up to 8.5 km long (Gouiret es Sud) and up to 100 m high. All the buildups are denuded of the onlapping and overlying lower Frasnian shales and thus give an impressive image of an ancient Devonian seafloor.

Givetian thickness variations exhibit a more contrasting pattern than Eifelian ones. They range from 2 m in the western Ahnet (307) to about 1000 m in the eastern Mouydir (376; Figs 10, 13). The latter value may be somewhat exaggerated due to an average calculation derived from the insignificant dip of the strata (8–11°). In this area, a siliciclastic intercalation in the upper Givetian shales ('Grès de l'Oued Iris') was mentioned by Bertrand-Sarfati, Fabre & Moussine-Pouchkine (1977, Fig. 7). We did not find this lithology in our sections, but we cannot exclude that some sandy levels are intercalated in equivalent strata which are largely covered by Quaternary deposits. Bertrand-Sarfati, Fabre & Moussine-Pouchkine (1977, Fig. 7) have labelled the Middle Devonian limestones 'Calcaires de l'Azel Matti'. Because at the type locality (340) this sequence is strongly reduced (5 m) and incomplete, we propose Adrar Morrat N (328; Figs 5a, 8) as a more appropriate and biostratigraphically much better documented type section.

6.d. Frasnian

The Frasnian sequence shows a laterally rather consistent subdivision into three units (from base to top): (1) some tens of metres of bituminous styliolinid grainstones and packstones with interlayers of black shales and limestone nodules, (2) a several hundred metres thick pile of polychrome clays (Argiles de Mehden Yahia) and (3) thin-bedded, medium-grained, partly cross-bedded, brownish sandstones and clays (Grès de Mehden Yahia). The presence of all Frasnian conodont zones has been proved by our samples, but the biostratigraphic record is much more complete in the lower (Zones 1–10) than in the upper (Zones 11–13) Frasnian. The entire sequence represents a shallowing-up cycle with goniatites and myriad pelagic styliolinids in the lower, and neritic tentaculitids and brachiopods in the upper unit.

(1) Generally the lower Frasnian (Zones 1–2), 15–30 m thick, bituminous limestones and shales overlie the Givetian sequence conformably, but on the ridges a biostratigraphically well-documented hiatus between both stages is evident (see Section 6.c). The limestones consist almost exclusively of parallel-aligned styliolinids (Fig. 6d, e), the orientations of which, however, differ drastically in one and the same level and therefore cannot be used as palaeocurrent indicators (Wendt, 1995). In addition, small goniatites, orthoconic nautiloids and the pelagic pelecypod *Buchiola* are common faunal elements. Coeval hot shales with intercalated

parallel aligned styliolinids. Off-mound Azel Matti (288). Sample 63c. (e) Thin-section of lower Frasnian (Zone 2) bituminous grainstone. Note centrifugally grown 'rosette' cement crystals surrounding styliolinid shells. Gour bou Kreis (422). Sample 421/15. (f) Thin-section of lower Eifelian (*costatus* Zone) skeletal mudstone with scattered and poorly sorted iron ooids. 1 – brachiopod, 2 – trilobite. Gouiret es Sud (410), sample 410/3. Compare with section in Figure 8, first limestone bed above unit 4.

https://doi.org/10.1017/S0016756806001737 Published online by Cambridge University Press

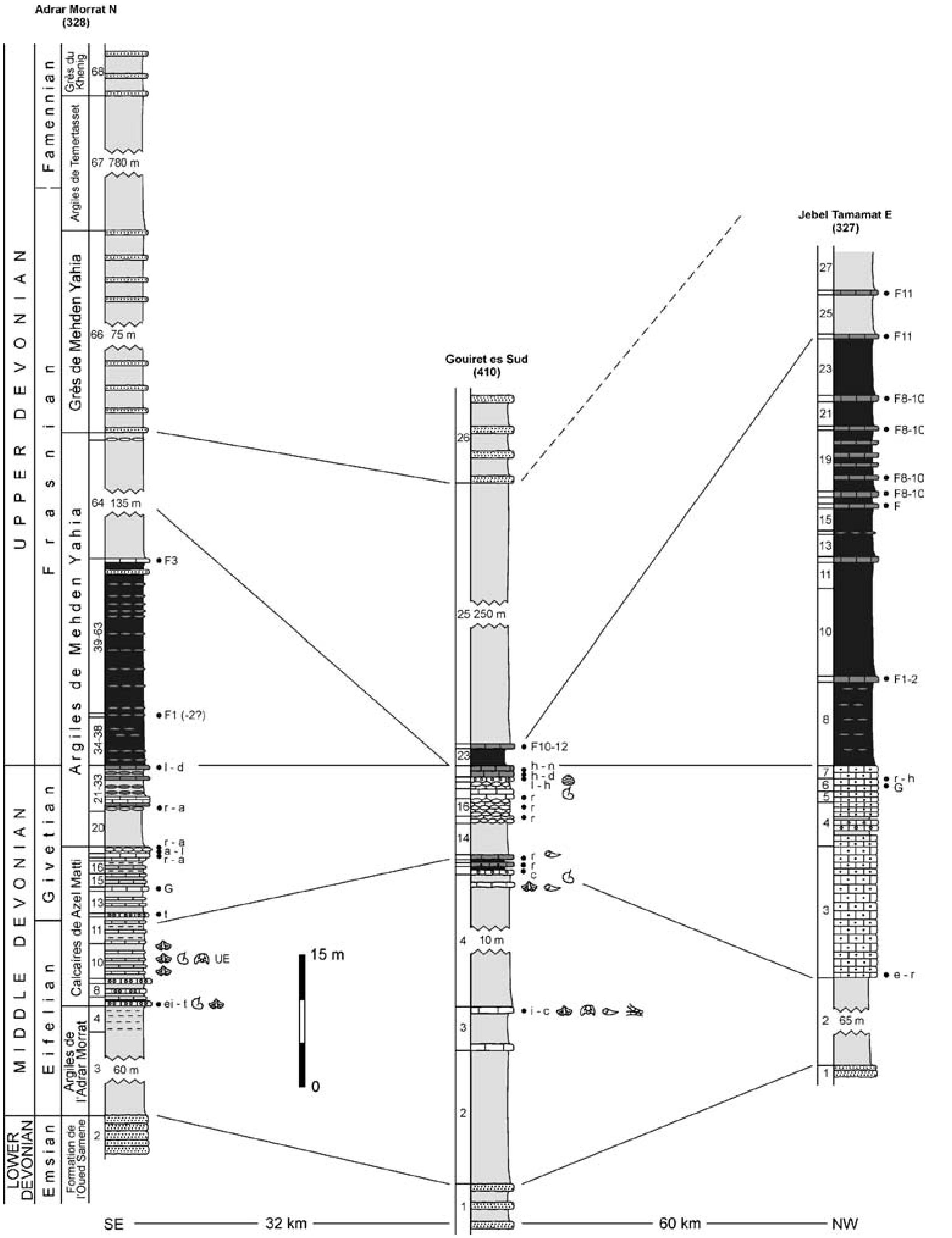

Figure 8. Correlation of sections on the Azel Matti Ridge. Note strong thickness reduction of lower Frasnian at Gouiret es Sud (410). For legend see Figure 10; for location of sections see Figure 2.

bituminous limestones are common also in the eastern Anti-Atlas of Morocco (Wendt & Belka, 1991; Belka *et al.* 1999) and indicate a widespread interval of anoxic conditions (Frasne Event of House, 1985) in both ridge and basinal settings.

https://doi.org/10.1017/S0016756806001737 Published online by Cambridge University Press

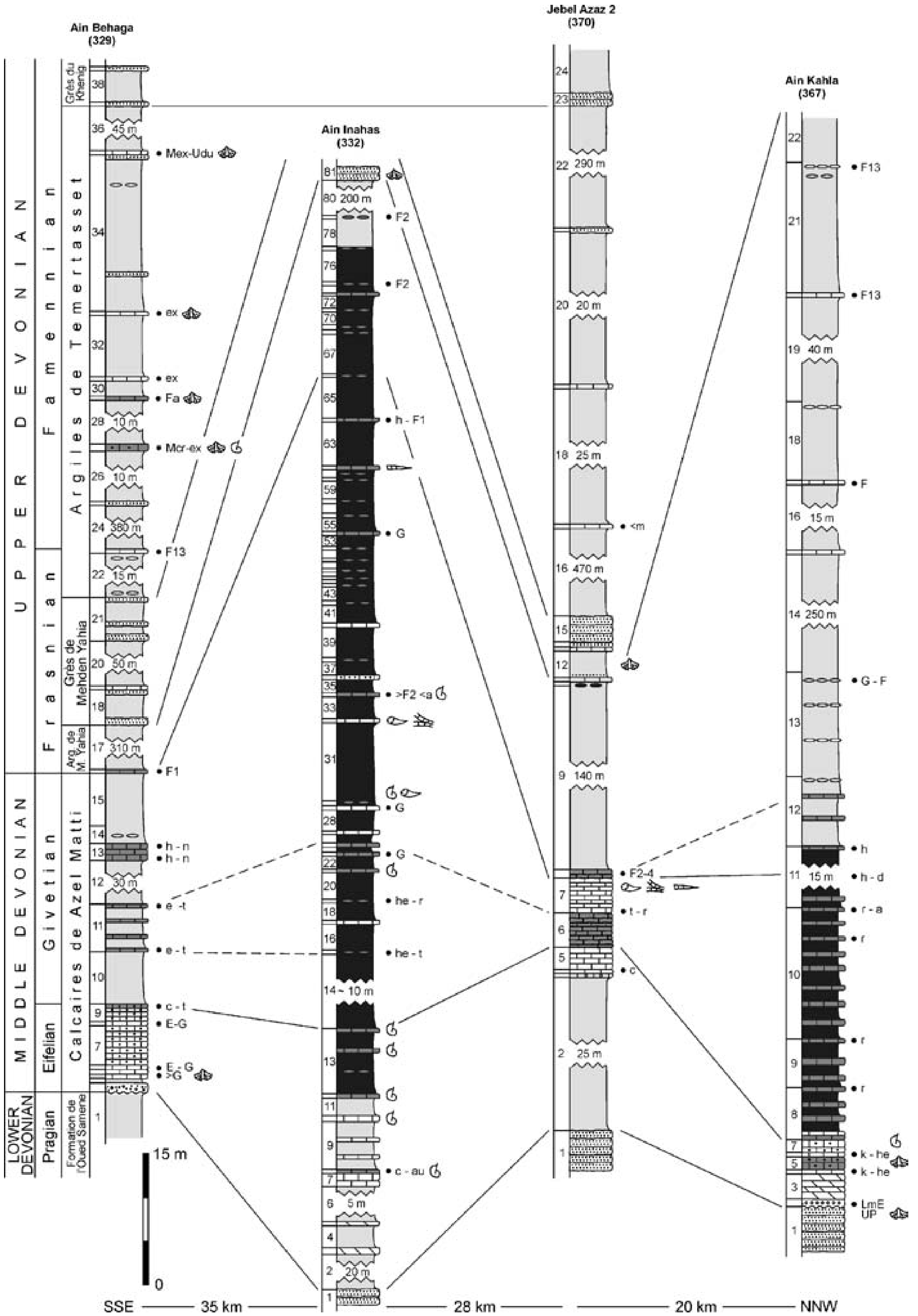

Figure 9. Correlation of sections in the northern Mouydir. Note strong thickness reduction of Givetian at Jebel Azaz 2 (Foum Belrem Ridge). For legend see Figure 10, for location of sections see Figure 2.

(2) The Argiles de Mehden Yahia are a monotonous sequence of varicoloured (black, brown, grey, green, red, pink) clays with rare calcareous mudstone levels, ironstone nodules and layers and some millimetre-thin, fine-grained sandstone interlayers. The latter are characterized by

https://doi.org/10.1017/S0016756806001737 Published online by Cambridge University Press

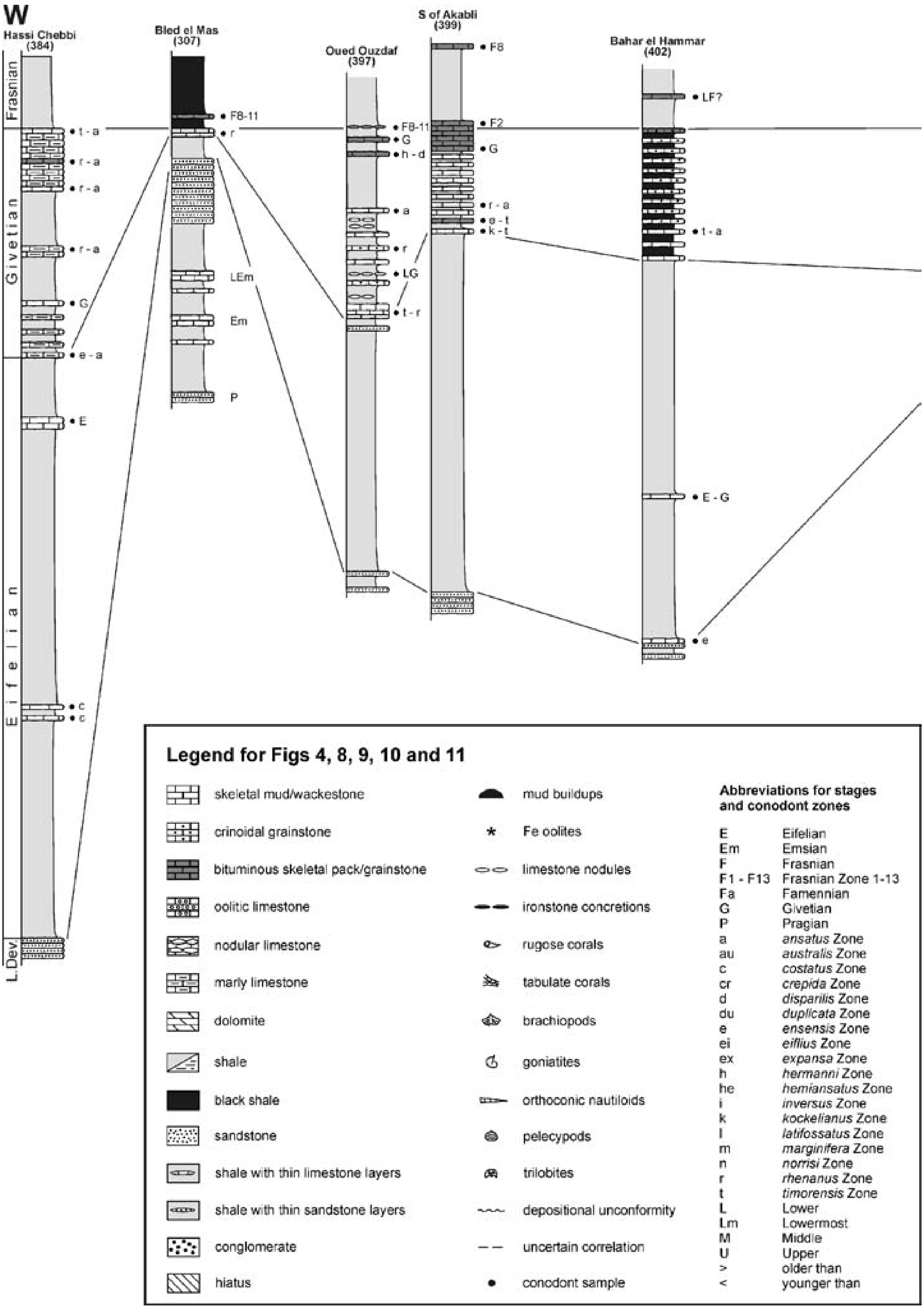

Figure 10. For caption see facing page.

low-angle cross-bedding capped by erosional (storm) events (T. Aigner, Tübingen, pers. comm.). The limestones have yielded conodont faunas pertaining to the upper Frasnian (Zones 11–13), but a clear separation from unit 1 has been achieved only in a few sections. South of

https://doi.org/10.1017/S0016756806001737 Published online by Cambridge University Press

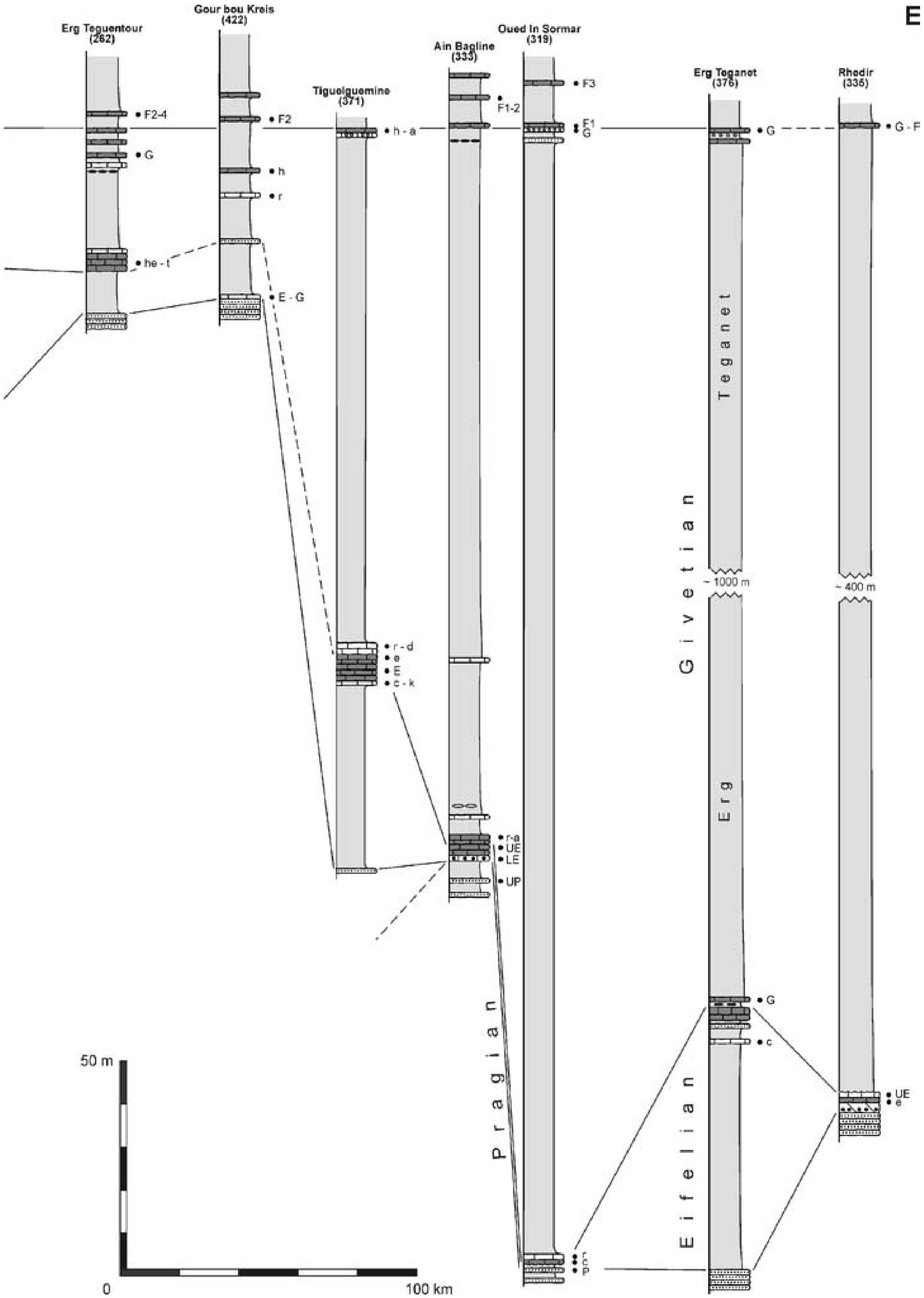

Figure 10. W–E transect through the northern Ahnet–northern Mouydir from the Reggane Basin (384) into the Mouydir Basin. Note extreme increase of Givetian thickness in the eastern Mouydir (376, 335). Continuous lines – biostratigraphic correlations; broken lines – lithostratigraphic correlations. For location of sections see Figure 2.

https://doi.org/10.1017/S0016756806001737 Published online by Cambridge University Press

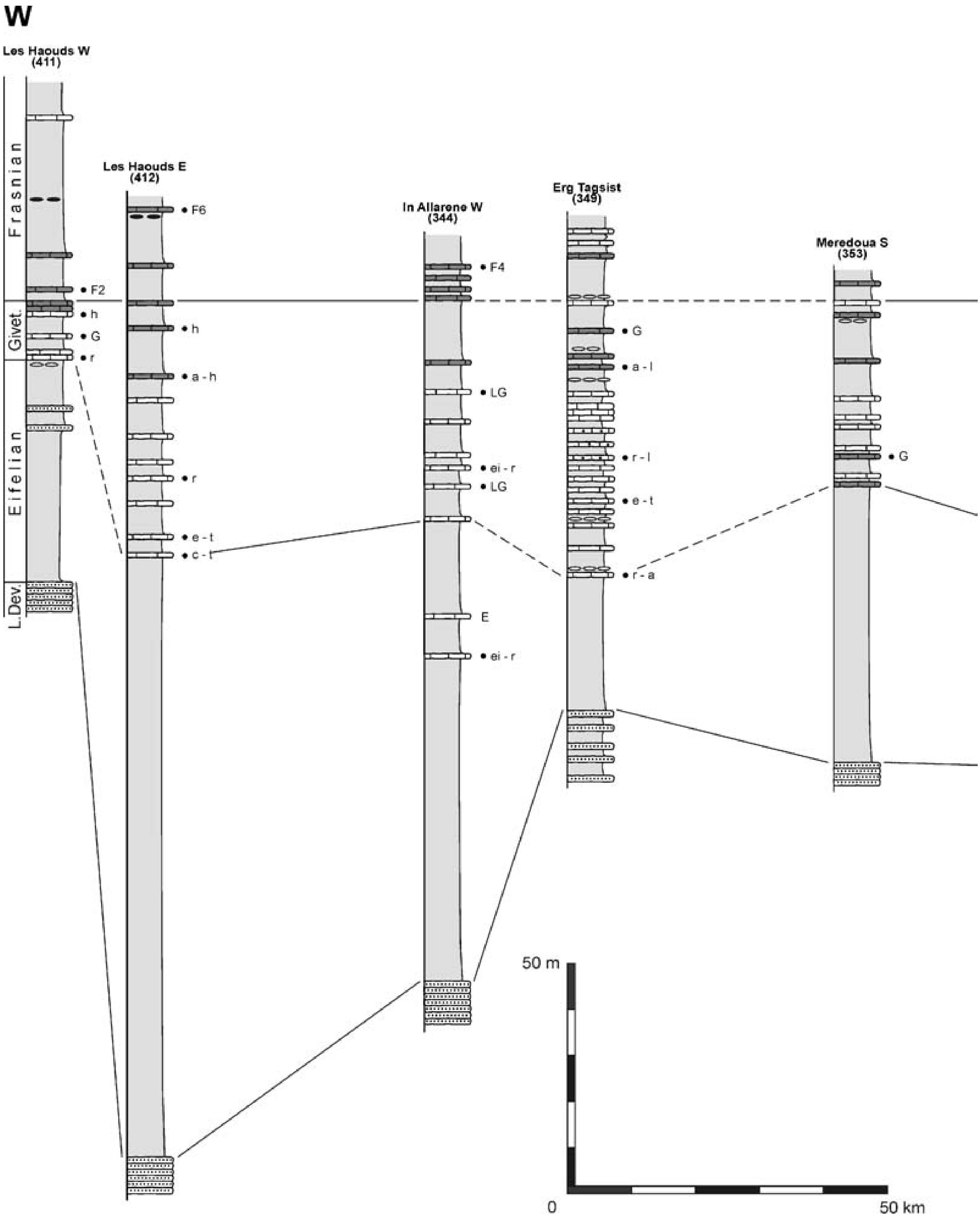

Figure 11. For caption see facing page.

Aoulef (299) we discovered a 10 cm thick bed of bituminous limestone crowded with goniatites, orthoconic nautiloids, *Buchiola*, tentaculitids, ostracods and rare fish remains (Fig. 5f). The association of *Tornoceras*, *Aulatornoceras*, *Lobotornoceras*, *Manticoceras*, *Costamanticoceras* and *Virginoceras* as well as the conodont fauna indicates a late Frasnian age (conodont Zone

https://doi.org/10.1017/S0016756806001737 Published online by Cambridge University Press

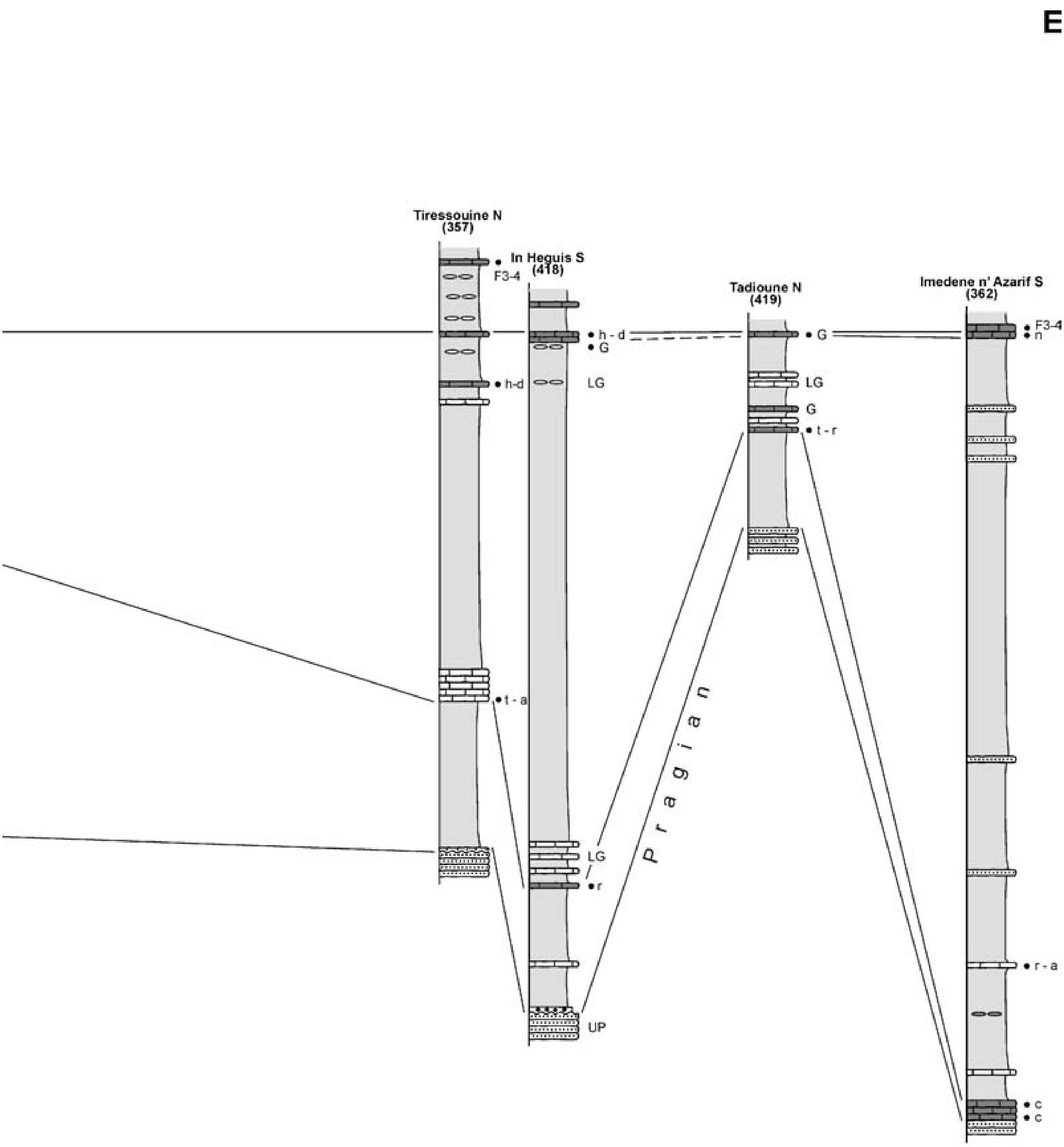

Figure 11. W–E transect through the southern Ahnet–southern Mouydir. For legend see Figure 10; for location of sections see Figure 2.

11, *Archoceras varicosum* Zone after Becker *in* Weddige, 1996). Thus, this level in age, fauna and lithology corresponds to the basal part of the Kellwasser facies in the eastern Anti-Atlas of Morocco, which has been dated as the lower part of the same zone (Belka, Dopieralska & Skompski, 2002). This is the first record of Kellwasser Limestone in southern

https://doi.org/10.1017/S0016756806001737 Published online by Cambridge University Press

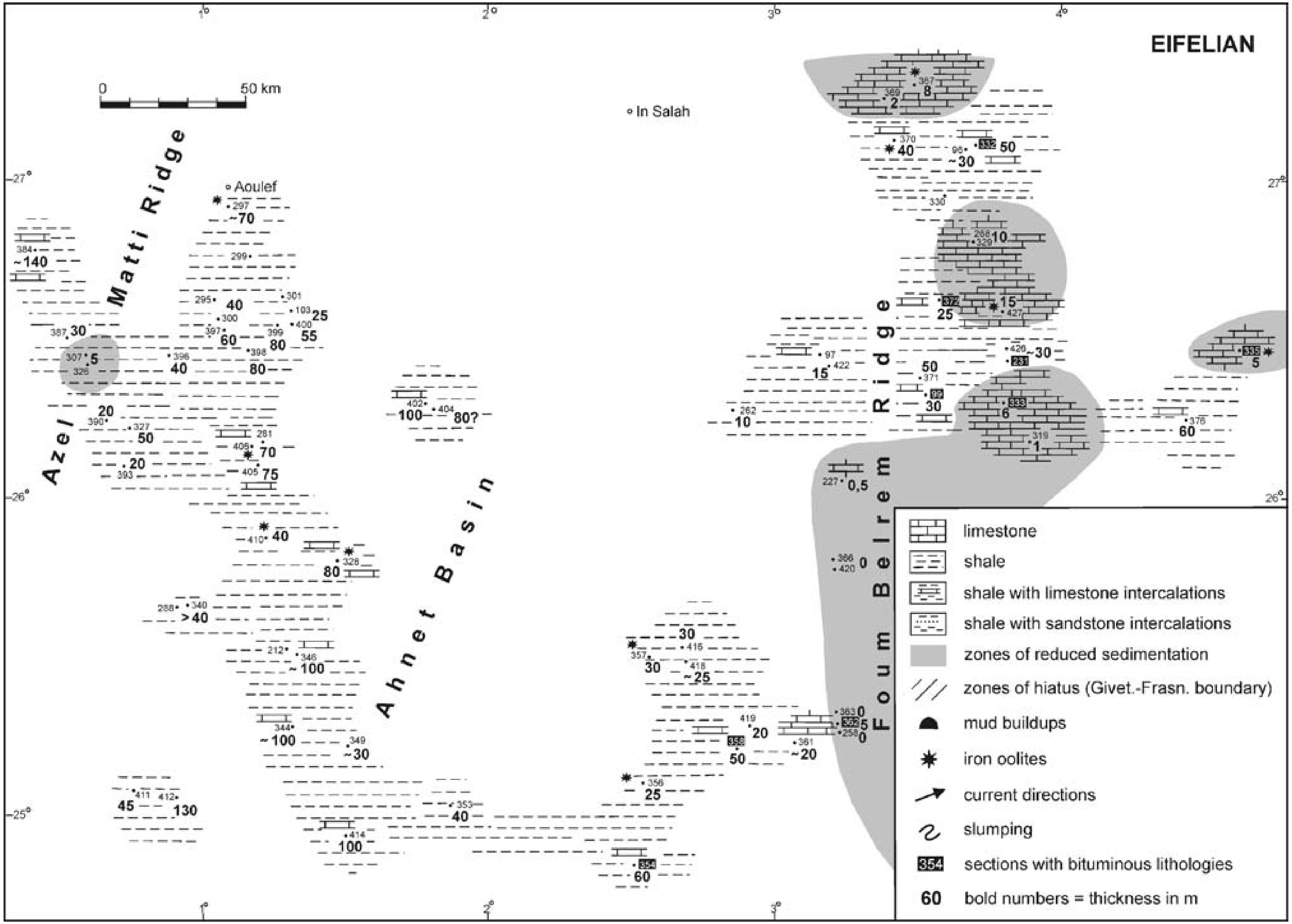

Figure 12. Facies pattern of the Eifelian.

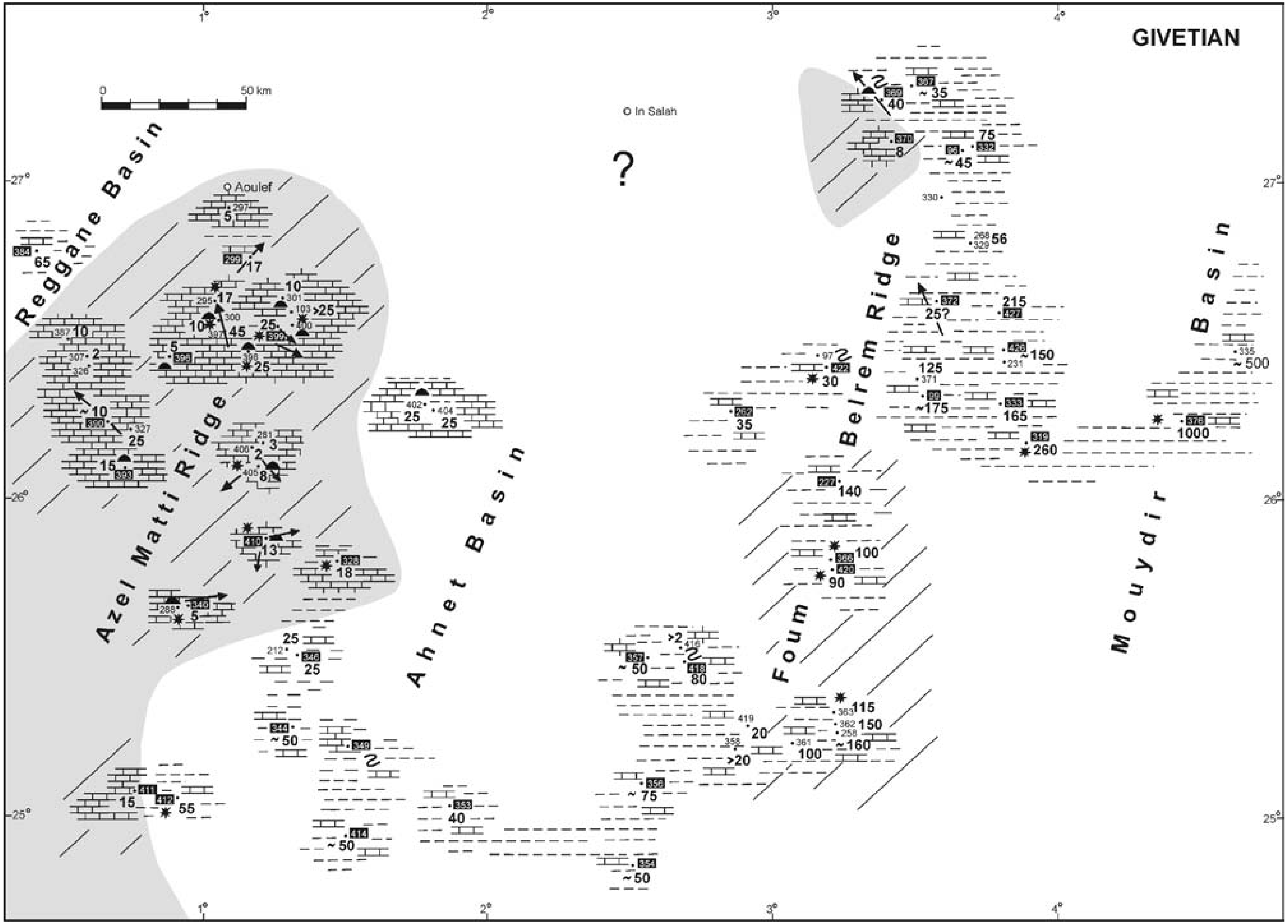

Figure 13. Facies pattern of the Givetian. For legend see Figure 12.

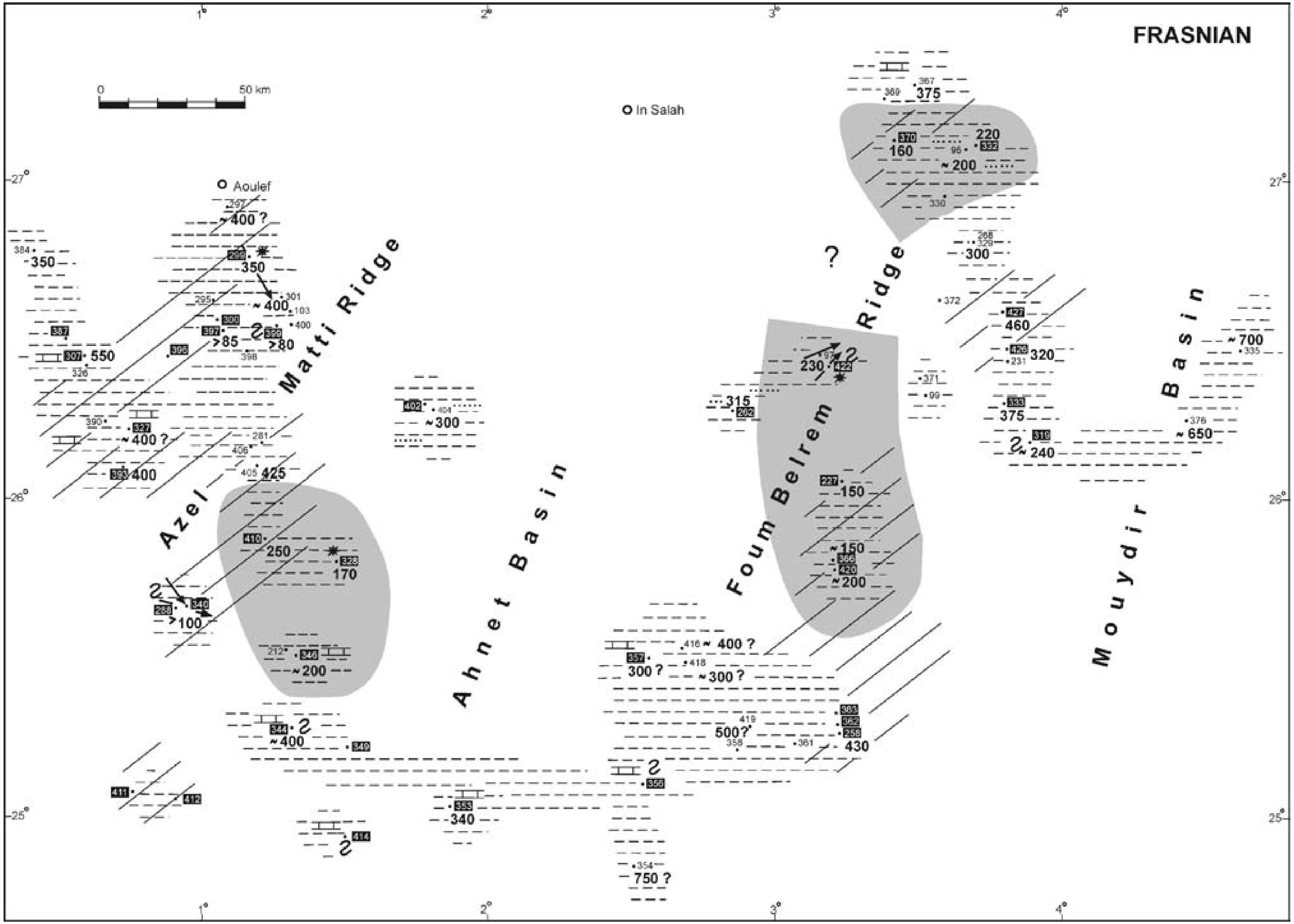

Figure 14. Facies pattern of the Frasnian. For legend see Figure 12.

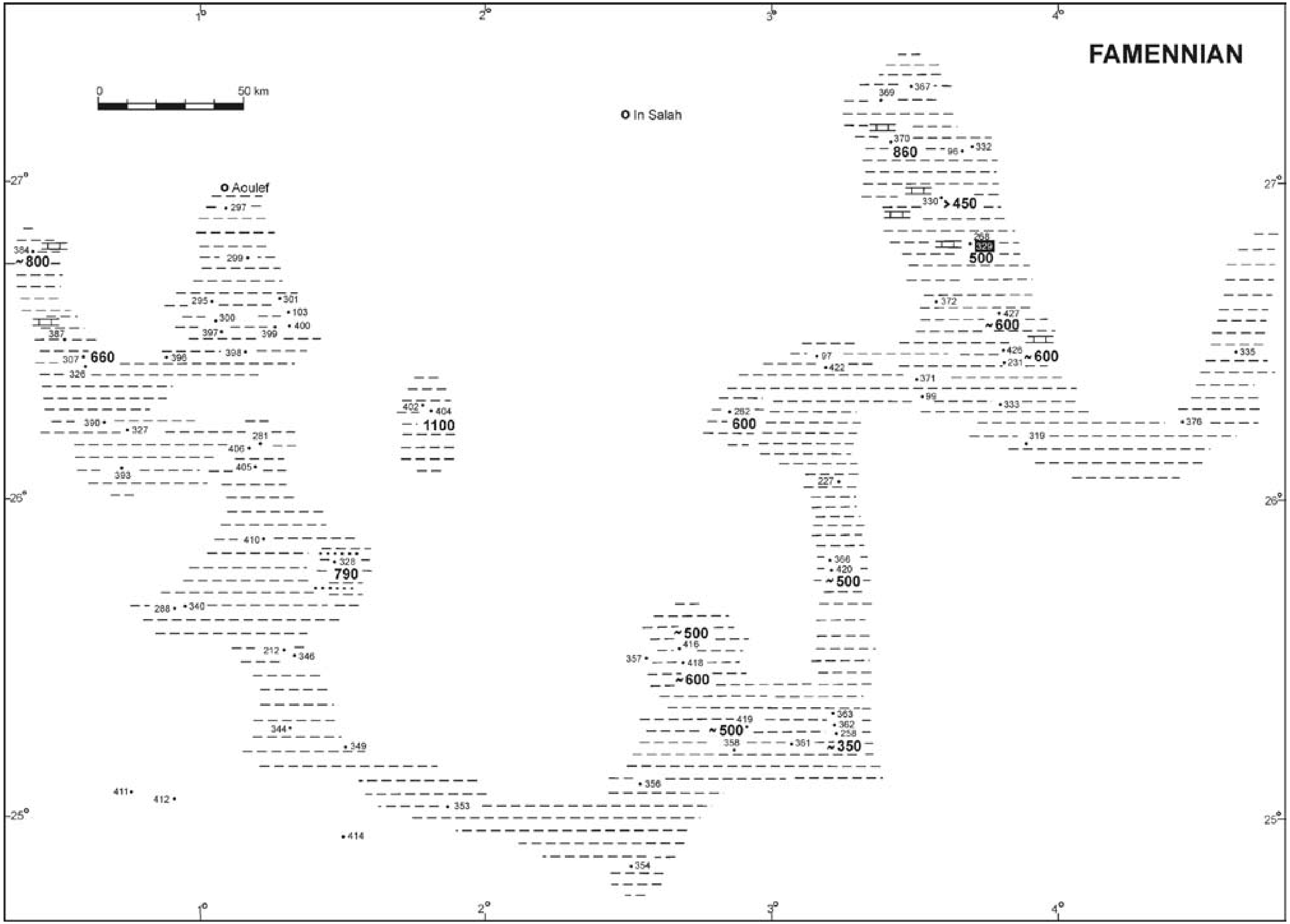

Figure 15. Facies pattern of the Famennian (uppermost Famennian/lower Tournaisian Grès du Khenig excluded). For legend see Figure 12.

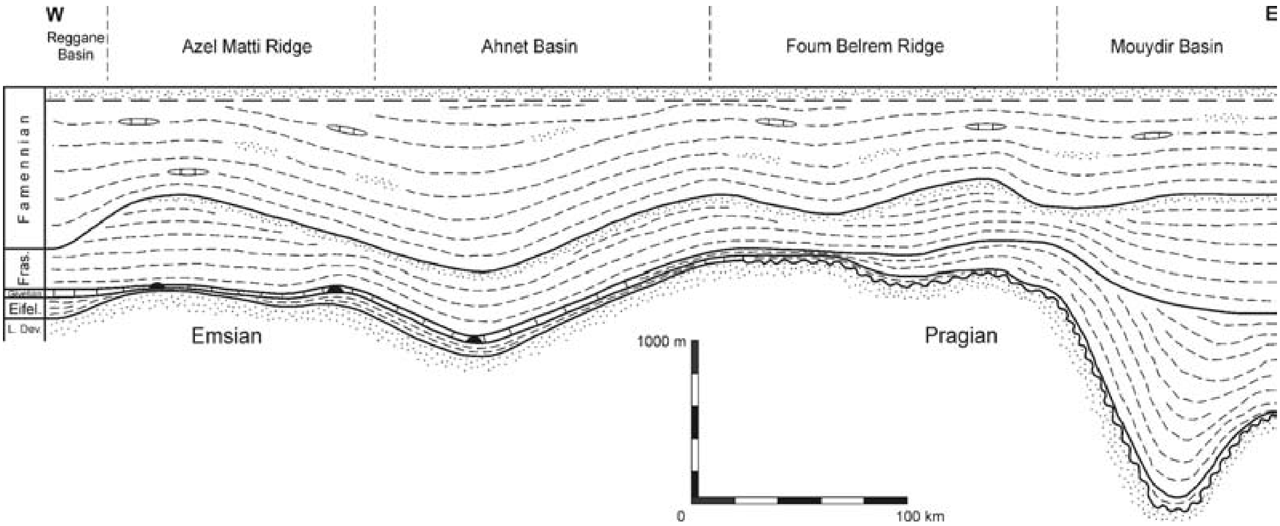

Figure 16. Schematic cross-section from the Reggane into the Mouydir basin, flattened at the base of the uppermost Famennian Grès du Khenig, approximately along the transect of Figure 10. Solid lines – chronostratigraphic boundaries; broken line – lithostratigraphic boundary. Legend as in Figure 10.

Algeria. Significantly, it was found only in the northernmost part of the study area, while further south this interval is represented by shales deposited under well-oxygenated conditions. We found this lithology also further north, at Hassi Fegaguira (Sbaa Basin) and in the Ougarta Basin.

(3) The Grès de Mehden Yahia form one or several low escarpments in the otherwise totally flat scenery of the Upper Devonian shales. The thickness of this unit varies considerably, between 3 m (at 262 and 370; Fig. 9) and 120 m (at 333 and 404), but does not show obvious relationships to the previous submarine topography. In the extreme west (384, 307) this formation was not observed, either due to an insignificant thickness or its total absence. It cannot be excluded that the highest thickness values of the Grès de Mehden Yahia are distorted by the inclusion of younger (lower Famennian) levels. In general the sandstones contain numerous brachiopods and tentaculitids, but a more precise age than late Frasnian cannot be derived from these faunas. At Ain Behaga (329; Fig. 9), the Grès de Mehden Yahia are overlain by a calcareous mudstone layer which has yielded conodonts of latest Frasnian (Zone 13) age. Because the same sandstones at Ain Kahla (367; Fig. 9) and at Jebel Tamamat S (393) are underlain by limestones attributed to the same conodont zone, it can be assumed that the Grès de Mehden Yahia in the Mouydir and the Ahnet are virtually coeval. The inclusion of the entire Frasnian in this lithology as shown by Bertrand-Sarfati, Fabre & Moussine-Pouchkine (1977) is disproved by our data.

6.e. Famennian

The grey and reddish, mostly flat-lying, Famennian Argiles de Temertasset (= Argiles de Khenig of Conrad, 1984) are largely covered by Quaternary deposits allowing only a few reliable thickness measurements. They range from 500 m in the northern Mouydir (329) to about 1100 m in the northern Ahnet (404). The sequence is well exposed north of Ain Tiouendjiguine (330), at Ain Behaga (329; Fig. 9), Adrar Morrat N (328; Fig. 8) and Tes Ereghet (258). Here and in several other sections, up to five skeletal (ubiquitous brachiopods, common pelecypods and orthoconic nautiloids, ostracods, rare bellerophontids and crinoids) calcareous packstone layers are intercalated in the monotonous shale sequence. The majority of them are late Famennian (*expansa* Zone) in age. Older limestone intercalations were sampled at Bled el Mas (307, *crepida* Zone) and at Ain Tiouendjguine (330, Upper *rhomboidea* to Upper *marginifera* Zone). These calcareous levels represent short open marine intervals in an otherwise restricted mudflat regime which was too shallow to allow the existence of goniatites, but from Hassi Fegaguira (Sbaa Basin), about 250 km northwest of Aoulef, Famennian goniatites and clymenids were recorded by Petter (1959, 1960). The limited water depth is also documented by moulds of undeterminable pelecypods in the shales and thin sandstone layers with brachiopod coquinas and occasional wave ripples (e.g. in 328). Short intervals of high turbulence are documented by 0.1–0.2 m thick conglomerate layers with phosphatized pebbles and fish remains which may be accumulated to form veritable bonebeds (Fig. 6c). The frequent lenticular intercalations of other, mineralized (hematite, azurite) coarse pebbles, however, must not be mistaken as a proof for emergence

https://doi.org/10.1017/S0016756806001737 Published online by Cambridge University Press

during the Famennian. They are the remainders of early Pleistocene alluvial terraces which infiltrated superficial cracks and fault-fissures in a landscape similar to the present one.

6.f. Upper Famennian–Tournaisian

The Argiles de Temertasset grade into a sequence of coarse- to medium-grained sandstones with intercalated siltstones and shales which form several prominent escarpments (Grès du Khenig). We measured a maximum thickness of 250 m at Tirechchoumine (403), considerably more than the 100 m in Conrad (1984) from the same section. Thickness at the type locality is 100 m; at Hassi-Tin-Entenai, 50 km SW of Tirechchoumine, only 50 m were recorded (Conrad, 1984). The brachiopod fauna indicates a rough Tournaisian age for the Grès du Khenig which can be more precisely bracketed by our conodont faunas from the upper Argiles de Temertasset (upper Famennian *expansa* Zone) and from a crinoidal limestone layer at the base of the Argiles de Teguentour at Jebel Azaz 2 (370), which has yielded a late Tournaisian age (*anchoralis* Zone). Several sections in the Ahnet and Mouydir were carefully examined by Conrad (1984), who reported brachiopods, gastropods, crinoids, trilobites, trace fossils (*Spirophyton*, *Skolithos*), plant remains and rare goniatites.

7. Bituminous lithologies

As is shown by the widespread distribution of organic-rich limestones and shales (Kellwasser facies), the content of total organic carbon (TOC) in sediments increased at a global scale during late Frasnian/early Famennian times. Equivalent lithologies are common in North America and in the Variscan realm of central and western Europe (Racki, 1999; Joachimski *et al.* 2002; Bond, Wignall & Racki, 2004 and others). In the eastern Anti-Atlas of Morocco, the bituminous lithology occurs already in the Frasnian conodont Zone 1 and continues up to the top of Zone 4 (Frasne Event: Belka *et al.* 1999). A second, much more prominent interval of organic-rich sediments (Kellwasser facies) begins in Zone 11 and ranges into the Lower *rhomboidea* Zone of the lower Famennian (Wendt & Belka, 1991; Belka, Dopieralska & Skompski, 2002). In southern Algeria, however, we found Kellwasser equivalents only at Hassi Fegaguira (Sbaa Basin) and in one place in the northern Ahnet (see Section 6.d).

A detailed examination of the geochemistry and trace element composition of the bituminous facies of Middle and early Late Devonian age in southern Algeria is beyond the aims of our work. It should be noted, however, that in this area, organic-rich limestones occur repeatedly much earlier (and locally also later) than during the intervals of the Frasne and Kellwasser events, that is to say, from the lower Eifelian into the upper Famennian. TOC values obtained from 105 samples in 11 sections show variable amounts of 0.1–1.3 % in the carbonates and 4–6 % in the shales. These values are of course considerably depleted by recent weathering, but nevertheless they reflect an intermittently high organic productivity and preservation. In the Eifelian, the occurrence of bituminous limestones is restricted to the southeastern Ahnet and the Mouydir (10 sections) and is found only in the triangle from Adrar Tiressouine (354) in the south to Ain Inahas (332; Fig. 9) in the north and Rhedir (335) in the east. They occur in both the highly reduced, purely calcareous sequences (e.g. 362, 333, 335; Figs 10, 11) and in the predominantly shaly, up to ten times thicker sequences with only sporadic calcareous intercalations (e.g. 354, 358, 332; Fig. 9). With a few exceptions in the extreme northwest (384), in the centre (404) and in the east (329, 335) of the study area, intercalations of bituminous limestones are almost ubiquitous in the Givetian (42 sections), but they show no obvious relation to the submarine topography. The same, non-diagnostic, pattern is observed in the lower Frasnian (36 sections), while in the upper Frasnian, that is, towards the mass extinction event at the Frasnian/Famennian boundary, bituminous limestones become very rare (5 sections), due to widespread well-oxygenated shallow water conditions. Higher up, this lithology was found only in two levels of a single locality (329; Fig. 9) of late Famennian (*expansa* Zone) age. This trend with an acme of organic productivity during the early Frasnian (Fig. 4) is emphasized by the ubiquitous deposition of organic-rich shales (Frasne Event) with up to 6 % TOC in the study area and up to 14 % in the Berkine Basin (Lüning *et al.* 2004).

The great majority of the bituminous carbonates are grainstones with a negligible amount of matrix and consist exclusively of myriad densely packed styliolinids (Figs 6d, e). The conical shells are mostly parallel aligned and often stuck into one another (cone-in-cone structures). These patterns document a high organic productivity and the deposition of the planktonic organisms as 'marine snow' and by local eddies (Wendt, 1995). Much scarcer are other types of bituminous skeletal limestones, which consist mostly of crinoid ossicles associated with rare brachiopod and trilobite remains.

These data show that in the Ahnet and Mouydir areas, widespread euxinic conditions, caused by repeated high organic productivity and lack of circulation, existed at various intervals from the early Eifelian into the late Frasnian (and in one place into the late Famennian). A unique situation is found at Ain Inahas (332; Fig. 9), where the entire sequence from the upper Eifelian into the lower Frasnian consists of black shales with intercalated bituminous limestones documenting a sort of 'black hole' with constant euxinic conditions. With a few exceptions (307, 327, 393, 299, 410; compare

Figs 9, 10), the water column during the late Frasnian and the Famennian was too well oxygenated to allow deposition of organic-rich limestones.

8. Ironstones

The occurrence of iron-rich levels in Devonian rocks of southern Algeria and western Libya has long been known (Sacal, 1963; Goudarzi, 1970; Bertrand-Sarfati, Fabre & Moussine-Pouchkine, 1977; Chauvel & Massa, 1981). In two more detailed, petrographic and geochemical studies, Guerrak (1987*a*,*b*) distinguished nine iron-oolitic levels in the Devonian of the Ahnet and Mouydir. They were said to attain thicknesses of 0.8 to 5 m and were correlated over tens of kilometres. Guerrak (1987*b*) interpreted them as related to sedimentary cycles which were caused by eustatic sea-level changes or epeirogenic movements.

Our observations are hardly compatible with these data, neither by the number of individual levels, nor by their thickness and regional extent. We found six individual levels with scattered iron ooids in Eifelian to lower Tournaisian rocks which are 0.1 to 0.5 m, rarely 1 m, thick. They occur in the lower Eifelian (10 sections), upper Eifelian (1 section), the lower Givetian (9 sections), the upper Givetian (8 sections), the lower Frasnian (3 sections; compare Figs 12–14) and the uppermost Famennian/lower Tournaisian (2 sections). Though most of them are biostratigraphically well dated, their correlation over several tens of kilometres appears hazardous and their relation to sea-level changes remains speculative. The limonitic and chamositic oolites were shed into skeletal mud- and grainstones (Fig. 6f) which were deposited on structural highs as well as in basinal areas. In the Givetian (Fig. 13), the distribution of oolites shows a preference to areas of reduced carbonate deposition on the Azel Matti Ridge (zone B; see Section 11.c). On the Foum Belrem Ridge the occurrence of iron oolites is also related to intervals of low and discontinuous sedimentation during the late Givetian (363, 420, 366, 227). The same is true for two localities in the eastern Mouydir (319, 376). The oolite levels in these six localities may be biostratigraphically coeval. Oolitic intercalations in the Eifelian and Frasnian, however, are found in both ridge and basin environments. Thus, the provenance of the ooids remains enigmatic, because their occurrence is apparently not related to the submarine topography.

Limonitic/hematitic infiltrations and stainings are widespread on the top of the Lower Devonian sandstones of the Oued Samene Formation and are evidence of a long interval of subaerial exposure and erosion during the late Early Devonian. The lower Eifelian transgression conglomerate often contains reworked pebbles of iron-stained sandstones and clay ironstones. The latter constitute common, 1–10 cm thick, intercalations or pebble layers in Eifelian to lowermost Tournaisian shales but are without any stratigraphic and palaeogeographic significance. According to Guerrak (1988), the source of the iron must be sought in the uplifted and deeply eroded Precambrian shields of Niger and Congo, from where it was transported onto the wide shelf areas by rivers.

9. Slumping

Phenomena of slumping and sliding are useful tools in palaeogeographic reconstructions because they indicate the presence of submarine slopes of faint to moderate inclination (> 1–4°). Theoretically, the axes of slumpfolds run perpendicular to the equivalent slope direction. In the study area, gravitational deformation of semi-lithified sediment is only sporadically observed and does not exhibit clear relationships to the large-scale submarine topography which is revealed by the facies patterns and subsidence rates. The significance of the obtained data is limited due to the small number of localities (8 in the Givetian, 7 in the Frasnian; some shown on Figs 13 and 14) and measurements (44 in the Givetian, 4 in the Frasnian). Slumping phenomena have not been observed in pre-Givetian and post-lower Frasnian rocks. Individual slumpfolds are longitudinally not consistent (a few to about 20 metres long) and exhibit a great divergence of directions. Generally, the sediment displacement was 'frozen' at an initial stage, as is shown by only moderately undulating beds which are under- and overlain by undeformed ones. More spectacular slumping phenomena with up to vertical fold limbs were observed in Givetian strata of Erg Tagsist (349) and Gour bou Kreis (422; Fig. 5c). The more common slumping structures in the vicinity of mud buildups are not considered in this context because they are strictly related to the local buildup topography (Wendt & Kaufmann, 1998).

10. Current directions

Current directions in lime- and dolostones are most obviously represented by preferred orientations of conical or rod-shaped organic remains (orthoconic nautiloids, tentaculitids, crinoid stems; Wendt, 1995). First reports on current data pre-dating the lower Givetian mud buildups were published by Wendt & Kaufmann (1998). Figures 13 and 14 show the majority of current directions, which are compiled from a total of 3684 measurements in 19 localities in the Givetian and from 534 measurements in 12 localities in the Frasnian. No data were obtained from pre-Givetian and post-Frasnian rocks.

Lower Devonian current directions show a rather consistent pattern reflecting a discharge of streams which probably originated in the Niger and Congo shields in the south (Beuf *et al.* 1971, pls 11, 12). Only in the shaly-calcareous facies of the northern Mouydir (369, 372) do similar northerly to northwesterly

https://doi.org/10.1017/S0016756806001737 Published online by Cambridge University Press

directions persist into the lower Givetian. In contrast, a puzzling pattern of current directions was obtained in the predominantly calcareous facies of the same interval on the Azel Matti Ridge (Fig. 13). The majority of the diagrams show unidirectional orientations; some of them, however, exhibit a high degree of dispersion. It can be argued that during a precursor phase of buildup construction in the lowermost Givetian, an irregular seafloor topography caused these highly diverging orientations. This may also be the reason for the inconsistent pattern in the lower Frasnian (Fig. 14) which, due to the scarcity of suitable shells, is established on a poorer database. Some levels of the upper Frasnian Grès de Mehden Yahia contain numerous current-oriented tentaculitids which, however, due to an intense recent reworking of these strata, could never be observed in place.

11. Facies pattern and palaeogeography

11.a. Lower Devonian

One of the crucial questions of our research has been if and to what extent the basin and ridge topography of the Ahnet and Mouydir was already sketched during the Middle and Late Devonian. During the Early Devonian one can observe a gradual transition from a continentally predominated regime in the southeast (central and eastern parts of the Hoggar Massif, Tassili n'Ajjers), across a mixed continental–marine zone in the western part of the Hoggar Massif and in the areas of the later Mouydir Basin, into a predominantly marine environment in the northwestern Ahnet Basin (Beuf *et al.* 1971, pl. 30). In the Illizi Basin the Lochkovian and Pragian are again continental (Henniche *et al.* 2001). On the Foum Belrem Ridge, weak epeirogenetic movements, inherited from Precambrian lineaments, caused minor variations in thickness and lithology. As shown by the eroded and iron-stained top of the Lower Devonian (Pragian to lower Emsian) sandstones and the lower Eifelian transgression conglomerate, the entire area was emergent during the Emsian. It should be noted that this stage with a duration of 18 Ma is the longest one of the Devonian (Kaufmann & Trapp, 2004). A similar gap has also been observed further northeast on the western slope of the Tihemboka Ridge (Moreau-Benoit, Coquel & Latreche, 1993; Abdesselam-Rouighi, 1996).

11.b. Eifelian

During the early Eifelian the peneplained land areas were flooded and covered with up to 140 m of green shales with some intercalated skeletal limestones (Fig. 12). Only in a small area on the western flank of the Jebel Tamamat anticline (= Bled el Mas, 307, 326) is the Azel Matti Ridge already contoured as is shown by the deposition of only 5 m of shales. The Foum Belrem Ridge, however, is clearly outlined by a broad N–S-trending belt of strongly reduced (362, 319, 333, 427, 329, 367, 369, 335) or even lacking (258, 363, 420, 366) Eifelian deposits. Iron oolites occur in both ridge (367, 427, 335) and basinal (297, 406, 328, 356, 357) environments. Bituminous limestones were found only in the Mouydir area, but their distribution is not restricted to basinal environments (see Section 7).

11.c. Givetian

From northwest to southeast/east, three different depositional areas can be distinguished. Zone A is represented by one section only (384). Considerable contrasts in thickness and lithology compared to the northwestern margin of zone B suggest that this area belongs to the eastern margin of the Reggane Basin (Fig. 13).

In the western Ahnet (zone B), skeletal, often bituminous, limestones become more frequent at the Eifelian/Givetian transition and persist intermittently throughout the Givetian/lower Frasnian. This zone, which extends from Les Haouds W (411) in the south to Aoulef (297) in the north, is the Azel Matti Ridge, characterized by sedimentation of 2–25 m of limestones with thin shale intercalations. During a short interval within the early Givetian, spectacular carbonate mud mounds and ridges were constructed in this area (Moussine-Pouchkine, 1971; Wendt *et al.* 1997). It cannot be excluded that this structural high continues into the northern Mouydir, but a possible connection between both areas is concealed over an about 200 km wide zone south of In Salah, in which Middle Devonian deposits are deeply buried. Such an assumption is supported by the discovery of a W–E-running high in this area (Djoua Ridge) on seismic lines (T. Djebbar, unpub. M.Sc. thesis, Univ. London, 1995). At Jebel Azaz in the northern Mouydir (369), a 5 km long dolomitized mud ridge is exposed which represents the same environment and age as the mud buildups on the Azel Matti Ridge. Current directions on this ridge show highly diverging patterns which may be the result of an irregular bottom topography. Two Givetian levels with iron oolites can be discerned in this zone.

The eastern sector (zone C = Ahnet Basin and Foum Belrem Ridge) is distinguished by a predominance of shales with minor intercalations of skeletal, often bituminous, limestones, and represents a deeper subtidal environment. Thicknesses in the northeastern part of this zone are not significantly higher than in zone A (25–80 m) but increase considerably to the east where amounts of up to 1000 m (376) were measured. Rare slumping phenomena indicate gently dipping slopes towards SE–E. This relief was created during the early Givetian and is probably related to synsedimentary tectonics. Direct evidence of the latter has been found only in one section on the Azel Matti

Ridge (295), where lower Givetian (*rhenanus* Zone) crinoidal limestones are capped by an erosional surface and covered by lower Frasnian shales with an angular unconformity of 15° (Fig. 5e).

With thicknesses of 115–160 m and a pure clay sedimentation, a N–S-trending zone of the Foum Belrem Ridge (227, 366, 420, 363, 362, 258) shows a surprising increase of subsidence during the early Givetian. Upper Givetian deposits in this area, however, are again reduced to a few metres with a hiatus on top representing a typical shoal (Fig. 7). Some iron–oolitic intercalations occur in this area and patchily further east.

11.d. Frasnian

A gradual levelling of the basin and ridge topography is achieved during the Frasnian, but the available biostratigraphic data are too scarce to document this evolution on a regional scale stepwise through the entire interval. The zones of reduced sedimentation during the late Givetian can be traced into the early Frasnian (Fig. 14). The Azel Matti Ridge with the lower Givetian mud buildups is characterized by a ubiquitous gap at the Givetian/Frasnian boundary (Fig. 7). The different duration of non-deposition at this boundary may be an effect of an irregular, undulating topography of the seafloor on which minor amounts of sediment accumulated in local depressions, whereas adjacent structural highs remained sediment-free. This phenomenon is best documented by the lower Givetian mud mounds which persisted as the most prominent topographic features into the early Frasnian (Wendt *et al.* 1997). Thicknesses of the lower Frasnian (Zones 1–10) range between 3 m (410) and 40 m (327; Fig. 8).

A second structural high is the S–N-running Foum Belrem Ridge (258 to 227) which, after an interval of increased subsidence during the early and middle Givetian, is again characterized by a strongly reduced sedimentation or even non-deposition during the late Givetian/early Frasnian. The hiatus on this boundary is shorter than on the Azel Matti Ridge and comprises only two to six conodont zones (Fig. 7). The northern prolongation of the Foum Belrem Ridge is concealed by Quaternary deposits, but at Jebel Azaz (369, 370) a similar gap at the Givetian/Frasnian boundary was detected, indicating a northward continuation of the ridge. In the Ahnet Basin west and the Mouydir Basin east of this ridge, the mixed shale–carbonate sedimentation during the Frasnian is continuous and attains thicknesses of several hundred metres.

In the upper Frasnian (Zones 11–13), a thick pile (up to 500 m) of polychrome shales (Argiles de Mehden Yahia) was deposited over the entire area, showing that the pre-existent basin and ridge topography was virtually levelled. Only two areas, one on the southern Azel Matti Ridge, the other in the central and northern parts of the Foum Belrem Ridge, are distinguished by reduced thicknesses (Fig. 14), indicating that the previously existing highs had still a faint effect. During the latest Frasnian (Zone 13) a continuous sheet of fine-grained sandstones with interbedded clays (Grès de Mehden Yahia) covered the entire area. Elevated thicknesses in the east (120 m at 333, 90 m at 427) compared to 20–30 m on the former Azel Matti Ridge suggest an eastern to southeastern source of a prodelta fan deposit.

11.e. Famennian–Tournaisian

After the short siliciclastic influx of the Grès de Mehden Yahia during the latest Frasnian, the monotonous shale sedimentation (Argiles de Temertasset) continues into the latest Famennian. The homogeneous facies pattern indicates rapid subsidence of a shallow marine mudflat with partly restricted circulation (Fig. 15). Sporadic thin intercalations of brachiopod coquinas, most common during the late Famennian (*expansa* Zone), document short intermittent open marine conditions. The upper Famennian deposition of clays and siltstones is gradually substituted by an increasing siliciclastic influx (Grès du Khenig). Conrad, Massa & Weyant (1986) mentioned lower subsidence rates on the Azel Matti Ridge ('Bled-el-Mas High') and in the western Ahnet Basin compared to the eastern Ahnet and Mouydir basins during the late Famennian/early Tournaisian. These data would show a still-weak persistence of the previous basin and ridge topography. According to Conrad (1984), the up to 250 m thick Grès du Khenig represent a fluvial environment in the south (Hoggar, Mouydir) passing into a deltaic and, to the north, into a more open marine, neritic setting.

12. Depositional cycles

For the establishment of a well-documented relative sea-level curve, our sections are affected by the usual disadvantages: those on the ridges are well dated but incomplete, while the basinal ones have yielded insufficient biostratigraphic data. Nevertheless, the sedimentary development of the Ahnet and Mouydir during Devonian times clearly exhibits one major transgressive and two major regressive cycles (Fig. 4). They can only roughly be correlated with the eustatic sea-level curve of Johnson & Sandberg (1988) and the depositional cycles of Johnson, Klapper & Elrick (1996) and are most probably overprinted by regional tectonic pulses.

The sandstones of the Formation de l'Oued Samene mark the end of a regressive cycle which culminated in emergence during the Emsian. The hiatus is longest and best documented in the eastern part of the study area (Foum Belrem Ridge, Mouydir Basin), and less evident further west in the Ahnet Basin and on the Azel Matti Ridge (e.g. Bled el Mass). The onset of the subsequent transgressive cycle is

https://doi.org/10.1017/S0016756806001737 Published online by Cambridge University Press

early Eifelian (*costatus* Zone) in age, later than in Euramerica (Johnson & Sandberg, 1988), but more or less coeval to a sea-level rise (Chotec Event) in southeast Morocco (Kaufmann, 1998). This sea-level highstand persisted into the Givetian and reached its maximum during the *ansatus* Zone, concomitant with a transgressive pulse (Taghanic Event) in SE Morocco (Kaufmann, 1998). We interpret the lacunary sedimentation in the middle/upper Givetian on the Azel Matti and Foum Belrem ridges (Fig. 7) as the onset of a regressive phase. The anoxic interval of the lower Frasnian (Zones 1–2) hot shales and styliolinid limestones has generally been interpreted as a transgressive phase (House, 1985; Lüning *et al.* 2004 and others). Recent examinations of this level in Morocco, however, have yielded less radiogenic Nd-signatures in conodonts than those recorded from the under- and overlying strata. These data point to a regressive regime at that time (J. Dopieralska, Poznan, Poland, pers. comm.). Such an interpretation is supported by a prominent positive ^{13}C excursion during the earliest Frasnian in Poland, Germany, Austria and France, which also appears related to a sea-level fall (Buggisch & Joachimski, in press). It should be noted that the similar anoxic lithology of the upper Frasnian Kellwasser Event in Morocco (which in the study area is represented only in one place) has recently also been interpreted as regressive (Dopieralska, 2003). In the Ahnet and Mouydir, the regression continued during the remainder of the stage and terminated with the prodelta deposits of the upper Frasnian Grès de Meden Yahia.

The subsequent short transgressive phase, which does not display a pronounced deepening, is only documented by scattered fully marine limestones of latest Frasnian age on the Foum Belrem Ridge. The complete lack of ammonoids and the depositional features of the Famennian shales indicate an environment of a shallow mudflat or lagoon and a long-lasting regressive phase which is only interrupted by a short open marine ingression during the late Famennian (*expansa* Zone). This pulse can be correlated with a highstand of sea-level in southeast Morocco (Wendt & Belka, 1991). The regressive phase was terminated with the progradation of the uppermost Famennian/Tournaisian Grès de Khenig, before the onset of a new transgressive cycle in the uppermost Tournaisian (Argiles de Teguentour, not shown on Fig. 4).

13. Conclusions

On the basis of 71 precisely logged and sampled sections, the biostratigraphic evolution of the Ahnet and Mouydir during the Devonian has been documented for the first time. A basin and ridge topography is faintly outlined in the Early Devonian and most accentuated during the Middle Devonian. From west to east, five palaeogeographic realms can be distinguished: Reggane Basin, Azel Matti Ridge, Ahnet Basin, Foum Belrem Ridge and Mouydir Basin (Fig. 16). Subsidence rates in these realms vary considerably in space and time. They are characterized by the following steps of depositional and structural evolution.

(1) The Early Devonian is a period of a widespread uniform facies distribution exemplified by only minor differences in thickness and sedimentary environment. The transition from a continental regime in the south into a shallow marine siliciclastic open shelf in the north documents a gradual deepening in this direction. New brachiopod data indicate a hiatus during the Emsian which is longest and best documented on the Foum Belrem Ridge and adjacent areas. This gap is the result of uplift and emergence and shows the premature existence of this structural high.

(2) The early Eifelian (*costatus* Zone) transgression marks the onset of a fully marine regime in the entire area, characterized by the deposition of shales with intercalated skeletal limestones. Eifelian thicknesses range between 0 and 140 m and show only minor differences in subsidence and submarine relief. The Foum Belrem Ridge and adjacent areas, however, are clearly distinguished by non-deposition or by highly condensed carbonate sedimentation.

(3) Carbonate deposition is most widespread during the Givetian on the Azel Matti Ridge, represented by a limestone–shale sequence which oscillates in thickness between 2 and 25 m. This ridge may have extended into the northern Mouydir where a similar sequence is exposed, but the 200 km wide intermediate zone is deeply buried. Spectacular mud mounds and ridges were constructed during a short interval of the early Givetian on the central and marginal ridge. The irregular topography offered many niches for the existence of ammonoids which exhibit a higher diversity in the Givetian than during preceding and subsequent intervals. However, their diversity is significantly reduced compared to the more open marine settings in northwest Algeria (Saoura Valley) and in the eastern Anti-Atlas of Morocco.

(4) Towards the Reggane Basin in the northwest and the Ahnet Basin in the east/southeast, Middle Devonian deposits of the Azel Matti Ridge pass into basinal shales with some intercalated skeletal limestones. On this ridge and on the Foum Belrem Ridge, a hiatus of variable duration, caused by non-deposition across the Givetian/Frasnian boundary, is evident. In the basinal areas sedimentation was probably continuous, but the biostratigraphic record is poorer than on the submarine highs. Subsidence during

the Givetian was strongest in the Mouydir Basin where up to 1000 m of shales were deposited.

(5) A highstand of sea-level is reached during the early Givetian, followed by a regression during the late Givetian and Frasnian. It is documented by depositional gaps in the late Givetian followed by sedimentation of black shales and bituminous limestones during the earliest Frasnian. This anoxic interval is most obvious on the Azel Matti and Foum Belrem ridges, but was also observed in the southern Azel Matti Basin.

(6) During the late Frasnian and the Famennian, the pre-existing basin and ridge topography is levelled by more uniform subsidence and the deposition of varicoloured shales in a shallow mudflat or lagoonal regime which persists into the late Famennian. As a consequence of the reduced water depth, ammonoids are virtually lacking in upper Frasnian and Famennian deposits.

(7) The monotonous shale sedimentation during the Late Devonian is briefly interrupted in the latest Frasnian when deltaic sandstones (Grès de Mehden Yahia) prograded from the south/southeast. The Late Devonian regressive phase is shortly suspended by two ingressions at the Frasnian/Famennian boundary and during the late Famennian (*expansa* Zone). The regression is terminated by the progradation of another deltaic fan (Grès du Khenig) from the southeast during the latest Famennian/Tournaisian.

(8) Bituminous limestones and shales are widespread in both ridge and basin environments from the lower Eifelian into the lower Frasnian and indicate intermittent anoxic conditions. Actual TOC concentrations reach 6% which, however, are depleted by recent weathering. Organic-rich limestones were very sporadically found also in the upper Frasnian and upper Famennian shale sequence.

(9) Thin Fe-oolitic mudstones occur at six levels from the lower Eifelian to the lower Frasnian and in the uppermost Famennian/Tournaisian. They were found mostly in ridge settings, more sporadically also in basinal settings. Their occurrence in both environments is too restricted locally and too inconsistent laterally to explain a relationship to sea-level changes.

(10) The submarine topography and the contrasting differences in uplift and subsidence are probably related to a reactivation of ancient faults in the Precambrian basement. Direct effects of the synsedimentary tectonics were observed only in one place in the northern Ahnet, but may be more common.

Acknowledgements. This work was funded by the Deutsche Forschungsgemeinschaft (DFG, grants We 239/15.1-4). The extensive field-work would not have been possible without the strenuous assistance of our collaborators J. Bauer, J. Chevallier, S. Fröhlich, J. Hayer, S. Kirn, D. Müller-Lorch, J. Rath, S. Walker (all Tübingen), M. Jochmann (Longyearbyen, Norway), R. Kostrewa (Mwanza, Tansania), M. Lopez-Correa (Erlangen) and S. Lüning (Bremen). Two short field trips were financially supported by SONATRACH and organized by K. Boumendjel and H. Naili (Boumerdès, Algeria). Lower Devonian brachiopods were determined by P. Carls (Braunschweig), some goniatites by D. Korn (Berlin). Technical assistance was offered by B. Baldorj, W. Gerber, P. Jeisecke, A. Lawrynowicz, H. Vollmer (deceased), R. Riehle (all Tübingen) and H. Lanz (Zürich, Switherland). The manuscript benefited from the comments of R. Eschard (Institut Français du Pétrole, Rueil Malmaison, France) and an anonymous reviewer. We are grateful to these persons and organizations for their assistance in making this project possible.

References

ABDESSELAM-ROUIGHI, F. 1996. Biostratigraphie des spores du Dévonien de la synéclise Illizi-Ghadamès (Algérie). *Bulletin du Service Géologique de l'Algérie* **7**, 171–209.

BADSI, M. 1998. Fracturation naturelle des roches: application au Bassin de l'Ahnet (Algérie). *Thèse présentée à l'Institut Français du Pétrole pour obténir le grade de docteur, Université Paris VI*, 271 pp.

BELKA, Z. 1994. Carbonate mud buildups in the Devonian of the Central Sahara: evidences for submarine hydrothermal venting. *Przeglad Geologiczny* **5**, 341–6 (in Polish).

BELKA, Z., DOPIERALSKA, J. & SKOMPSKI, S. 2002. Conodont stratigraphy of the Late Devonian Kellwasser facies in the eastern Anti-Atlas, Morocco. In *Eighth International Conodont Symposium held in Europe ECOS VIII* (ed. M.-F. Perret Mirouse), p. 20. Strata, Série 1, vol. 12.

BELKA, Z., KLUG, C., KAUFMANN, B., KORN, D., DÖRING, S., FEIST, R. & WENDT, J. 1999. Devonian conodont and ammonoid succession of the eastern Tafilalt (Ouidane Chebbi section), Anti-Atlas, Morocco. *Acta Geologica Polonica* **49**, 1–23.

BERTRAND-SARFATI, J., FABRE, J. & MOUSSINE-POUCHKINE, A. 1977. Géodynamique des aires cratoniques: Quelques exemples sahariens. *Bulletin des Centres de Recherche Exploration-Production Elf-Aquitaine* **1**, 217–31.

BEUF, S., BIJU-DUVAL, B., DE CHARPAL, O. & GARIEL, O. 1969. Homogénéité des directions des paléocourants du Dévonien inférieur au Sahara central. *Comptes Rendus de l'Académie des Sciences, Série D* **268**, 2026–9.

BEUF, S., BIJU-DUVAL, B., DE CHARPAL, O., GARIEL, O., BENNACEF, A., BLACK, R., ARENE, J., BOISSONNAS, J., CHACHAU, F., GUERANGE, B. & GRAVELLE, M. 1968. Une conséquence directe de la structure du bouclier Africain: L'ébauche des bassins de l'Ahnet et du Mouydir au Paléozoique inférieur. *Publications du Service Géologique de l'Algérie, Nouvelle Série, Bulletin* **38**, 105–34.

BEUF, S., BIJU-DUVAL, B., DE CHARPAL, O., ROGNON, P., GARIEL, O. & BENNACEF, A. 1971. *Les grès du*

Paléozoique inférieur au Sahara. Sédimentation et discontinuités. Évolution structurale d'un craton. Paris: Éditions Technip, 464 pp.

BIJU-DUVAL, B., DE CHARPAL, O., BEUF, S. & BENNACEF, A. 1968. Lithostratigraphie du Dévonien inférieur dans l'Ahnet et le Mouydir (Sahara central). *Publications du Service Géologique de l'Algérie, Nouvelle Série, Bulletin* **38**, 83–104.

BOND, D., WIGNALL, P. B. & RACKI, G. 2004. Extent and duration of marine anoxia during the Frasnian–Famennian (Late Devonian) mass extinction in Poland, Germany, Austria and France. *Geological Magazine* **141**, 173–93.

BOOTE, D. R. D., CLARK-LOWES, D. D. & TRAUT, M. W. 1998. Palaeozoic petroleum systems of North Africa. In *Petroleum Geology of North Africa* (eds D. S. Macgregor, R. T. J. Moody and D. D. Clark-Lowes), pp. 7–68. Geological Society of London, Special Publication no. 132.

BOUDJEMA, A. 1987. Évolution structurale du bassin pétrolier 'triasique' du Sahara nord orientale (Algérie). *Thèse de Doctorat en Sciences, Université Paris XI*, XVII + 290 pp. Paris: Éditions Technip.

BUGGISCH, W. & JOACHIMSKI, M. M. In press. Carbon isotope stratigraphy of the Devonian of central and southern Europe. *Palaeogeography, Palaeoclimatology, Palaeoecology*.

CHAUVEL, J.-J. & MASSA, D. 1981. Paléozoique de Libye occidentale. Constantes géologiques et pétrographiques. Signification des niveaux ferrugineux oolithiques. *Compagnie Française des Pétroles, Notes et Mémoires* **16**, 25–60.

CONRAD, J. 1984. Les séries carbonifères du Sahara central algérien. Stratigraphie, sédimentation, évolution structurale. *Thèse de Doctorat d'État ès-Sciences naturelles, Université Aix-Marseille*, 370 pp.

CONRAD, J., MASSA, D. & WEYANT, M. 1986. Late Devonian regression and early Carboniferous transgression on the northern African platform. *Annales de la Societé Géologique de Belgique* **109**, 113–22.

COPPER, P. 2002. Silurian and Devonian reefs: 80 million years of global greenhouse between two ice ages. In *Phanerozoic reef patterns* (eds W. Kiessling, E. Flügel and J. Golonka), pp. 181–238. SEPM Special Publication no. 72. Tulsa, Oklahoma: Society for Sedimentary Geology.

COWARD, M. P. & RIES, A. C. 2003. Tectonic development of North African basins. In *Petroleum Geology of Africa: New Themes and Developing Technologies* (eds T. Arthur, D. S. Macgregor and N. R. Cameron), pp. 61–83. Geological Society of London, Special Publication no. 207.

DONZEAU, M., FABRE, J. & MOUSSINE-POUCHKINE, A. 1981. Comportement de la dalle saharienne et orogenèse varisque; essai d'interprétation. *Bulletin de la Societé d'Histoire Naturelle de l'Afrique du Nord* **69**, 137–72.

DOPIERALSKA, J. 2003. Neodymium isotopic composition of conodonts as palaeoceanographic proxy in the Variscan oceanic system. *Dissertation zur Erlangung des naturwissenschaftlichen Doktorgrades der Justus-von Liebig-Universität Gießen*, 111 pp. http://geb.uni-giessen.de/geb/volltexte/2003/1168/pdf/DopieralskaJolanta-2003-06-26.pdf

DUBOIS, P., BEUF, S. & BIJU DUVAL, B. 1967. Lithostratigraphie du Dévonien inférieur gréseux du Tassili n'Ajjer. *Mémoires du Bureau de Recherches Géologiques et Minières* **33**, 227–35.

DUMESTRE, A. & ILLING, L. V. 1967. Middle Devonian reefs in Spanish Sahara. In *International Symposium on the Devonian System 2* (ed. D. H. Oswald), pp. 333–50. Calgary: Alberta Society of Petroleum Geologists.

ECHIKH, K. 1975. *Géologie des provinces pétrolifères de l'Algérie*. Alger: Société Nationale d'Édition et de Diffusion, 173 pp.

FABRE, J. & KAZI TANI, N. 1987. Part de l'héritage dans la déformation phanérozoique du Sahara central et occidental. In *Current Research in African Earth Sciences* (ed. G. Matheis and H. Schandelmeier), pp. 241–4. Rotterdam, Boston: A. A. Balkema.

FEKIRINE, B. & ABDALLAH, H. 1998. Palaeozoic lithofacies correlatives and sequence stratigraphy of the Saharan Platform, Algeria. In *Petroleum geology of North Africa* (eds D. S. Macgregor, R. T. J. Moody and D. D. Clark-Lowes), pp. 97–108. Geological Society of London, Special Publication no. 132.

FOLLOT, J. 1952. Ahnet et Mouydir. *XIXème Congrès Géologique International. Monographies Régionales. 1. série, Algérie 1*. Alger, 80 pp.

FRÖHLICH, S. 2003. Facies pattern and genesis of the Jebel Rheris biostromes (Givetian, eastern Anti-Atlas, Morocco). *Facies* **49**, 209–20.

GAUTIER, E. F. & CHUDEAU, R. 1907. Esquisse géologique du Tidikelt et du Mouidir-Ahnet (Sahara). *Bulletin de la Societé Géologique de France, Série 4* **7**, 195–218.

GEVIN, P. 1960. Études et reconnaissances géologiques sur l'axe cristallin Yetti-Eglab et ses bordures sédimentaires. Première partie. Bordures sédimentaires. *Publications du Service de la Carte Géologique de l'Algérie, Nouvelle Série, Bulletin* **23**, 328 pp.

GINTER, M., HAIRAPETIAN, V. & KLUG, C. 2002. Famennian chondrichthyans from the shelves of North Gondwana. *Acta Geologica Polonica* **52**, 169–215.

GÖDDERTZ, B. 1987. Devonische Goniatiten aus SW-Algerien und ihre stratigraphische Einordnung in die Conodonten-Abfolge. *Palaeontographica* **A 197**, 127–220.

GOLONKA, J. 2002. Plate-tectonic maps of the Phanerozoic. In *Phanerozoic reef patterns* (eds W. Kiessling, E. Flügel and J. Golonka), pp. 21–75. Society of Economic Paleontologists and Mineralogists, Special Publication no. 72.

GOLONKA, J., ROSS, M. I. & SCOTESE, C. R. 1994. Phanerozoic paleogeographic and paleoclimatic modelling maps. In *Pangea: Global environments and resources* (eds A. F. Embry, B. Beauchamp and D. J. Glass), pp. 1–47. Calgary: Canadian Society of Petroleum Geologists.

GOUDARZI, G. H. 1970. Geology and mineral resources of Libya – a reconnaissance. *U. S. Geological Survey Professional Paper* **660**, viii + 104 pp.

GUERRAK, S. 1987*a*. Paleozoic oolitic ironstones of the Algerian Sahara: a review. *Journal of African Earth Sciences* **6**, 1–8.

GUERRAK, S. 1987*b*. Metallogenesis of cratonic oolitic ironstone deposits in the Bled el Mass, Azzel Matti, Ahnet and Mouydir basins, Central Sahara, Algeria. *Geologische Rundschau* **76**, 903–22.

GUERRAK, S. 1988. Paleozoic marine sedimentation and associated oolitic iron-rich deposits, Tassilis N'Ajjer and Illizi Basin, Saharan platform, Algeria. *Eclogae Geologicae Helvetiae* **81**, 457–85.

HADDOUM, H., GUIRAUD, R. & MOUSSINE-POUCHKINE, A. 2001. Hercynian compressional deformations of the Ahnet-Mouydir Basin, Algerian Saharan Platform: far-field stress effects of the Late Palaeozoic orogeny. *Terra Nova* **13**, 220–6.

HENNICHE, M., ESCHARD, R., HAMEL, A. & PROUST, J. 2001. Sedimentary architecture of the fluvial Devonian reservoirs in the Illizi Basin (Algeria). *American Association of Petroleum Geologists, 2001 Annual Meeting, Extended Abstracts*, 85.

HOUSE, M. R. 1985. Correlation of mid-Palaeozoic ammonoid evolutionary events with global sedimentary perturbations. *Nature* **313**, 17–22.

JOACHIMSKI, M. M., PANCOST, R. D., FREEMAN, K. H., OSTERTAG-HENNING, C. & BUGGISCH, W. 2002. Carbon isotope geochemistry of the Frasnian–Famennian transition. *Palaeogeography, Palaeoclimatology, Palaeoecology* **181**, 91–109.

JOHNSON, J. G., KLAPPER, G. & ELRICK, M. 1996. Devonian transgressive–regressive cycles and biostratigraphy, northern Antelope Range, Nevada: Establishment of reference horizons for global cycles. *Palaios* **11**, 3–14.

JOHNSON, J. G. & SANDBERG, C. A. 1988. Devonian eustatic events in the western United States and their biostratigraphic responses. In *Devonian of the World, Volume 3: Paleontology, Paleoecology and Biostratigraphy* (eds N. J. McMillan, A. F. Embry and D. J. Glass), pp. 171–8. Calgary: Canadian Society of Petroleum Geologists.

KAUFMANN, B. 1998. Facies, stratigraphy and diagenesis of Middle Devonian reef- and mud-mounds in the Mader (eastern Anti-Atlas, Morocco). *Acta Geologica Polonica* **48**, 43–106.

KAUFMANN, B. & TRAPP, E. 2004. Kalibrierung der Devon-Zeitskala – eine Synthese aus U–Pb, ID-TIMS-Datierungen und relativer, zeitlinearer Conodonten-Stratigraphie. In *74. Jahrestagung der Paläontologischen Gesellschaft, Göttingen 02. bis 08. Oktober 2004, Kurzfassungen der Vorträge und Poster* (eds J. Reitner, M. Reich and G. Schmidt), pp. 121–4. Göttingen: Universitätsdrucke.

KAUFMANN, B. & WENDT, J. 2000. Calcite cement successions in Middle Devonian (Givetian) carbonate mud buildups of the southern Ahnet Basin (Algerian Sahara). *Carbonates and Evaporites* **15**, 149–61.

KLUG, C. 2001. Early Emsian ammonoids from the eastern Anti-Atlas (Morocco) and their succession. *Paläontologische Zeitschrift* **74**, 479–515.

KLUG, C. 2002. Quantitative stratigraphy and taxonomy of late Emsian and Eifelian ammonoids of the eastern Anti-Atlas (Morocco). *Courier Forschungsinstitut Senckenberg* **238**, 1–109.

KORN, D. 1999. Famennian ammonoid stratigraphy of the Ma'der and Tafilalt (eastern Anti-Atlas, Morocco). In *North Gondwana: Mid-Palaeozoic terranes, stratigraphy and biota* (eds R. Feist, J. A. Talent and A. Daurer), pp. 147–79. *Abhandlungen der Geologischen Bundesanstalt Wien* **54**.

LEGRAND, P. 1967. Le Dévonien du Sahara algérien. In *International Symposium on the Devonian System 1* (ed. D. H. Oswald), pp. 245–84. Calgary: Alberta Society of Petroleum Geologists.

LEGRAND, P. 1983. Aperçu sur l'histoire géologique de l'Algérie paléozoique: Le Paléozoique inférieur et le Dévonien. *Lexique Stratigraphique International, Nouvelle Série* **1**, 96–108.

LEGRAND, P. 1985. Lower Palaeozoic rocks of Algeria. In *Lower Palaeozoic of north-western and west-central Africa* (ed. C. H. Holland), pp. 6–89. Chichester, New York, Brisbane, Toronto, Singapore: John Wiley & Sons.

LEGRAND-BLAIN, M. 2002. Le Strunien et le Tournaisien au Sahara algérien: limites, echelles lithostratigraphiques et biostratigraphiques régionales. *Mémoires du Service de la Carte Géologique d'Algérie* **11**, 61–85.

LOGAN, P. & DUDDY, I. 1998. An investigation of the thermal history of the Ahnet and Reggane Basins, Central Algeria, and the consequences for hydrocarbon generation and accumulation. In *Petroleum Geology of North Africa* (eds D. S. Macgregor, R. T. J. Moody and D. D. Clark-Lowes), pp. 131–55. Geological Society of London, Special Publication no. 132.

LÜNING, S., CRAIG, J., LOYDELL, D. K., STORCH, P. & FITCHES, B. 2000. Lower Silurian 'hot shales' in North Africa and Arabia: regional distribution and depositional model. *Earth-Science Reviews* **49**, 121–200.

LÜNING, S., WENDT, J., BELKA, Z. & KAUFMANN, B. 2004. Temporal–spatial reconstruction of the early Frasnian (Late Devonian) anoxia in NW Africa: new field data from the Ahnet Basin (Algeria). *Sedimentary Geology* **163**, 237–64.

MACGREGOR, D. S. 1996. The hydrocarbon systems of North Africa. *Marine and Petroleum Geology* **13**, 329–40.

MASSA, D. 1988. Paléozoique de Libye occidentale. Stratigraphie et paléogéographie. *Thèse de Doctorat, Faculté des Sciences et Techniques, Université de Nice*, 518 pp.

MONOD, T. 1932. L'Adrar Ahnet. Contribution à l'étude physique d'un district saharien (en collaboration avec Jaques Bourcart). *Révue de Géographie Physique et de Géologie Dynamique* **4–5**, 1–136.

MOREAU-BENOIT, A., COQUEL, R. & LATRECHE, S. 1993. Étude palynologique du Dévonien du Bassin d'Illizi (Sahara oriental algérien). Approche biostratigraphique. *Geobios* **26**, 3–31.

MOUSSINE-POUCHKINE, A. 1971. Les constructions recifales du Dévonien moyen du Pays Bas de l'Ahnet (Sahara Central, Algérie). *Bulletin de la Societé d'Histoire Naturelle de l'Afrique du Nord* **63**, 79–88.

MOUSSINE-POUCHKINE, A. 1976. Le Dévonien. In *Introduction à la Géologie du Sahara Algérien* (ed. J. Fabre), pp. 119–69. Alger: Societé Nationale d'Édition et de Diffusion.

PETTER, G. 1959. Goniatites dévoniennes du Sahara. *Publications du Service de la Carte Géologique de l'Algérie, Nouvelle Série, Paléontologie, Mémoire* **2**, 313 pp.

PETTER, G. 1960. Clymènies du Sahara. *Publications du Service de la Carte Géologique de l'Algérie, Nouvelle Série*, *Paléontologie*, *Mémoire* **6**, 58 pp.

POLONIO, I., ESCHARD, R., FERRANDO, R., CHAMBERS, A. & FIGARI, E. 2005. Stratigraphic analyses of the Lower Devonian sequences, Reggane Basin, southeastern Algeria. *2nd North African/Mediterranean Petroleum & Geosciences Conference & Exhibition, Algiers*, *10–13 April 2005* **B30**, 1–4.

RACKI, G. 1999. The Frasnian–Famennian biotic crisis: How many (if any) bolide impacts? *Geologische Rundschau* **87**, 617–32.

RICHARDSON, J. B. & MCGREGOR, D. C. 1986. Silurian and Devonian spore zones of the Old Red Sandstone Continent and adjacent regions. *Geological Survey of Canada Bulletin* **364**, 1–79.

SACAL, V. 1963. Microfaciès du Paléozoique saharien. *Compagnie Française des Pétroles. Notes et Mémoires* **6**, 1–30.

SCOTESE, C. R. 2001. Atlas of earth history, volume 1, Paleogeography, PALAEOMAP project. Arlington, Texas: A & M University Press, 52 pp.

SELLEY, R. C. 1997. The basins of Northwest Africa: Structural evolution. In *African Basins* (ed. R. C. Selley), pp. 17–26. Amsterdam: Elsevier.

SMITH, B., MOUSSINE-POUCHKINE, A. & AIT KACI AHMED, A. 1994. Palaeomagnetic investigation of Middle Devonian limestones of Algeria and the Gondwana reconstruction. *Geophysical Journal International* **119**, 166–86.

SONATRACH. 1979. Géologie de l'Algérie. Provinces pétrolières. Geology of Algeria. The hydrocarbon-bearing provinces. In *Well evaluation conference* (ed. J. L. Chardac), pp. 1–26. Paris: Schlumberger.

STAMPFLI, G. M. & BOREL, G. D. 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. *Earth and Planetary Science Letters* **196**, 17–33.

TAIT, J., SCHÄTZ, M., BACHTADSE, V. & SOFFEL, V. 2000. Palaeomagnetism and Palaeozoic palaeogeography of Gondwana and European terranes. In *Orogenic Processes: Quantification and Modelling in the Variscan Belt* (eds W. Franke, V. Haak, O. Oncken and D. Tanner), pp. 21–34. Geological Society of London, Special Publication no. 179.

TRAUT, M. W., BOOTE, D. R. D. & CLARK-LOWES, D. D. 1998. Exploration history of the Palaeozoic petroleum systems of North Africa. In *Petroleum Geology of North Africa* (eds D. S. Macgregor, R. T. J. Moody and D. D. Clark-Lowes), pp. 69–78. Geological Society of London, Special Publication no. 132.

WEDDIGE, K. (ed.) 1996. Devon-Korrelationstabelle. *Senckenbergiana Lethaea* **76**, 267–86.

WENDT, J. 1995. Shell directions as a tool in palaeocurrent analysis. *Sedimentary Geology* **95**, 161–86.

WENDT, J. & BELKA, Z. 1991. Age and depositional environment of Upper Devonian (early Frasnian to early Famennian) black shales and limestones (Kellwasser facies) in the eastern Anti-Atlas, Morocco. *Facies* **25**, 51–90.

WENDT, J., BELKA, Z., KAUFMANN, B., KOSTREWA, R. & HAYER, J. 1997. The world's most spectacular carbonate mud mounds (Middle Devonian, Algerian Sahara). *Journal of Sedimentary Research* **67**, 424–36.

WENDT, J., BELKA, Z. & MOUSSINE-POUCHKINE, A. 1993. New architectures of deep-water carbonate mud buildups: Evolution of mud mounds into mud ridges (Middle Devonian, Algerian Sahara). *Geology* **21**, 723–6.

WENDT, J. & KAUFMANN, B. 1998. Mud buildups on a Middle Devonian carbonate ramp (Algerian Sahara). In *Carbonate Ramps* (eds V. P. Wright and T. P. Burchette), pp. 397–415. Geological Society of London, Special Publication no. 149.