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Sedimentary Geology 163 (2004) 237–264
Sedimentary Geology
www.elsevier.com/locate/sedgeo

Temporal–spatial reconstruction of the early Frasnian (Late Devonian) anoxia in NW Africa: new field data from the Ahnet Basin (Algeria)

S. Lüning[a,*], J. Wendt[b], Z. Belka[c], B. Kaufmann[b]

[a] *Department of Geosciences, University of Bremen, P.O. Box 330 440, Geowissenschaften, Klagenfurter Strasse 2, 28334 Bremen D-28359, Germany*
[b] *Geological Institute, University of Tübingen, Sigwartstrasse 10, 72076 Tübingen, Germany*
[c] *Institute for Geological Sciences and Geiseltal Museum, Domstrasse 5, 06106 Halle (Saale), Germany*

Received 23 October 2002; accepted 24 June 2003

Abstract

Anoxic conditions were widespread in NW Africa during the early Frasnian (Late Devonian) that resulted in deposition of organic-rich shales and limestones with total organic carbon (TOC) values of up to 14%. Organic richness and thickness of these sediments vary laterally, and organic-rich vs. organic-poor facies boundaries are likely to have been diachronous. A precise temporal–spatial reconstruction of this anoxic phase in NW Africa is complicated because the organic matter in outcrops is largely oxidised and biostratigraphic resolution in boreholes is generally low due to the lack of recoverable conodonts. This contribution is based on eight outcrop sections at the margin of the central Algerian Ahnet Basin, where detailed spectral gamma-ray measurements were carried out using a handheld instrument. The pre-weathering organic richness in Frasnian outcrop sections is approximated using the characteristic uranium enrichment in the anoxic facies that, based on well studies, is positively correlated with the total organic carbon content. Conodont biostratigraphic results from these sections suggest that the uranium-enriched interval (the anoxic interval) at the basin margin is most common in the basal Frasnian conodont Biozones 1–2, confirming previous results from the Anti Atlas in Morocco. In three of the eight localities studied the basal Frasnian has not been deposited and the Frasnian here commences with distinctly younger uranium-enriched intervals, including Zones 4–11. Well data from the eastern Algerian Berkine Basin is interpreted to indicate a significantly longer anoxic phase there. Million-year-scale diachroneities of the Frasnian anoxia, therefore, clearly exist across the North Africa shelf. It is assumed that the palaeorelief might have been a major factor in controlling the onset, duration, and intensity of anoxia in the region.

Keywords: Frasnian; Algeria; Gamma-ray; Black shale; Source rock; Upper Devonian

1. Introduction

Lower Frasnian black shales have been deposited in many parts of North Africa and form an important hydrocarbon source rock in this region with total organic carbon (TOC) values of up to 14% (Boote

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* Corresponding author.
E-mail address: Sebastian.Luning@gmx.net (S. Lüning).

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doi:10.1016/S0037-0738(03)00210-0

et al., 1998). Similar lowermost Frasnian organic-rich deposits in Europe occur, e.g. in the Rhenish Massif/Harz Mountains (Germany) and the Montagne Noire (France). Most of the data on this organic-rich horizon in North Africa originate from commercial hydrocarbon exploration wells and have remained largely confidential. Only recently a synthesis was compiled (Lüning et al., in press) that allows considerations of the potential mechanisms that led to the accumulation of these vast amounts of organic matter during the early Frasnian of North Africa. The organically richest and thickest Frasnian black shales are developed in central North Africa (Algeria, western Libya) and vertical TOC trends have been interpreted as being

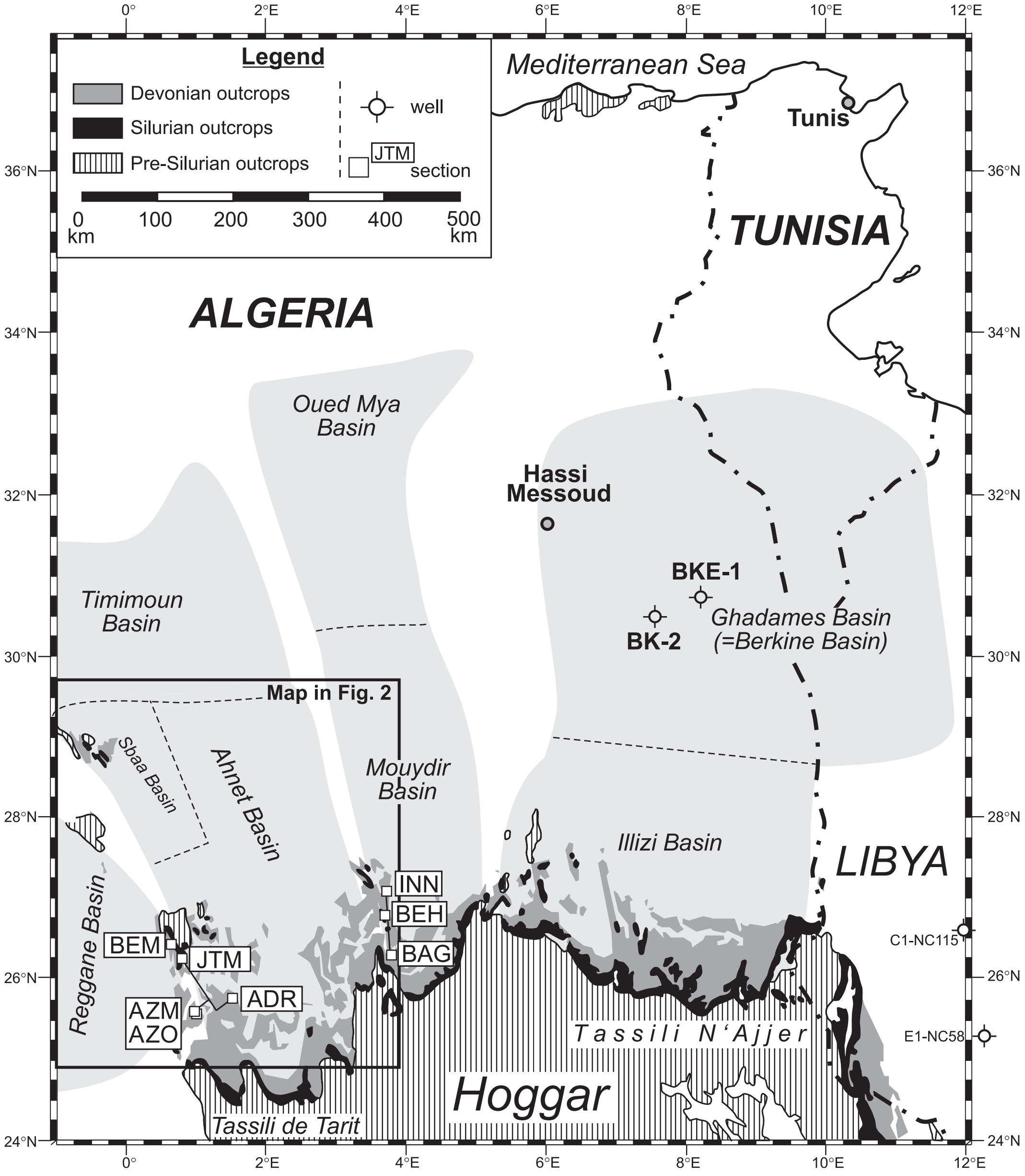


Fig. 1. Locations of the Frasnian sections and wells studied. Outlines of central North African Palaeozoic basins are shaded in grey.

controlled by the rising and falling of an oxygen minimum zone (OMZ) (Lüning et al., in press; Ghori and Mohammed, 2000) during the early Frasnian eustatic transgression. Notably, this early Frasnian anoxic phase ("Frasnes Event" sensu House, 1985) precedes anoxia of the Kellwasser events in the latest Frasnian which are developed in many parts of the world (e.g. Buggisch, 1991; McGhee, 1996), including North Africa where it has been previously studied in Morocco (Schindler, 1990; Wendt and Belka, 1991; Belka and Wendt, 1992; Belka et al., 1999).

The detailed temporal-spatial extent of Frasnian anoxic conditions and facies in North Africa is still unclear. One of the main problems is that high-resolution biostratigraphic data is difficult to obtain from wells where the organic-rich unit is readily identified. This is because Frasnian high-resolution biostratigraphy is based on conodonts for which sample quantities of several kilograms, with preferably carbonate lithologies, are required. These sample volumes usually are not available from cored exploration wells. While such samples can be easily collected in outcrops, identification of the organic-rich interval here is more complicated because the organic matter has often been partly or fully oxidised due to weathering under Saharan arid conditions.

Here, we present conodont biostratigraphic data for eight lower Frasnian outcrop sections in the Ahnet

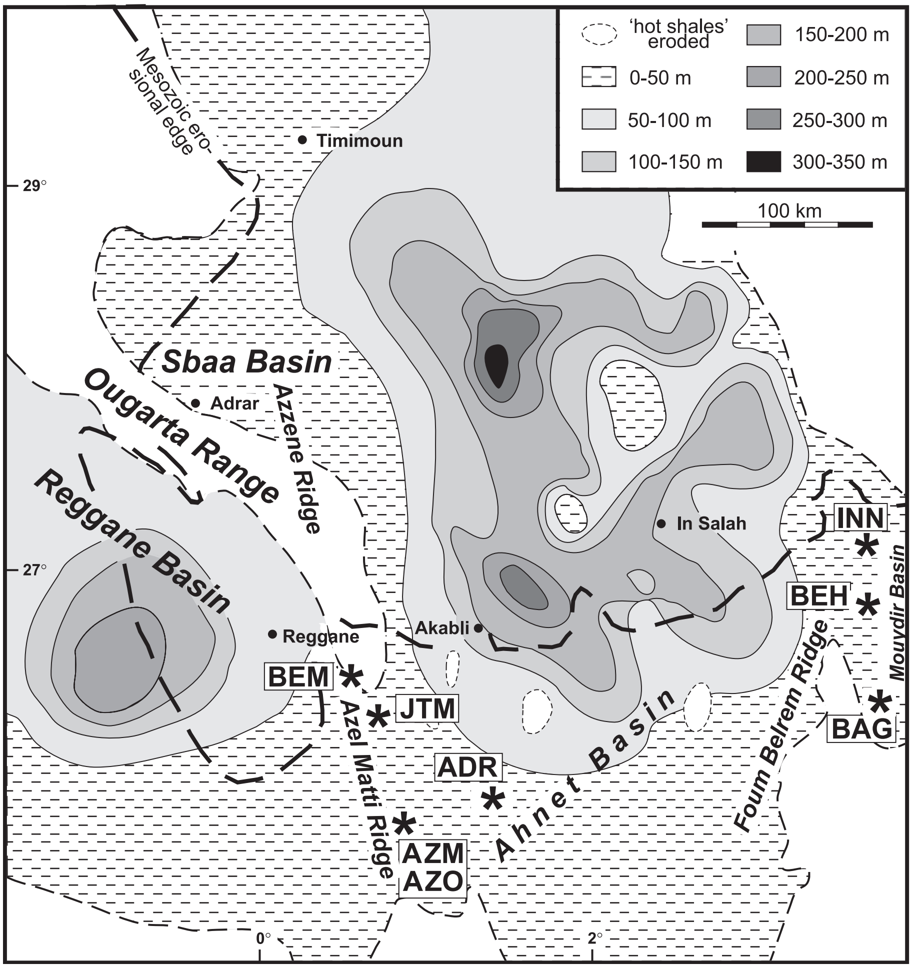


Fig. 2. Frasnian organic-rich shale (>1% TOC) isopach map for the Ahnet and Reggane Basin in W Algeria (after Logan and Duddy, 1998). The Frasnian sections studied at the SW margin of the Ahnet Basin are located outside the hot shale depocentre where the unit is not exposed.

Basin (Algeria) (Figs. 1 and 2) where the (previously) organic-rich unit could be identified in the field based on its characteristic spectral gamma-ray uranium signature that is well known from the wells. Using this approach the biostratigraphic outcrop data were compared with the subsurface for which reliable geochemical data from fresh samples exist (Lüning et al., in press).

2. Material and methods

The eight Frasnian field sections described here are located at the margins of the Algerian Ahnet and Mouydir basins (Figs. 1 and 2). Successions were lithologically logged and samples were collected for conodont biostratigraphic and organic geochemical analyses. For the conodont studies 2–20 samples per section, weighing 3–5 kg each, were taken from carbonate horizons and from concretions that are intercalated with the shale-dominated succession. The samples were processed with a 10% solution of acetic acid up to five times for several weeks, until total dissolution. Conodonts were recovered from the residue using a magnetic separator. They were then picked from the remaining residue under a binocular microscope. A total of 60 samples from five sections were collected for TOC measurements, with the number of samples per section varying between 6 and 21. The samples were pulverised in an agate mortar and organic and inorganic carbon contents were measured using a LECO CS-300 Carbon–Sulphur analyser (precision of measurements ± 3%). For TOC determination, inorganic carbon was carefully removed by repetitive addition of 0.25 N HCl.

Spectral gamma-ray measurements were carried out in all field sections (mainly on bedding planes) with a stratigraphic spacing of 1–2 m, using a portable gamma-ray spectrometer with a NaI(Tl) 3″ × 3″ detector (GRS-2000, GF Instruments, formerly Geofyzika, Brno). Element concentrations are calculated automatically by the instrument from the gamma-ray signal based on calibrations carried out by the

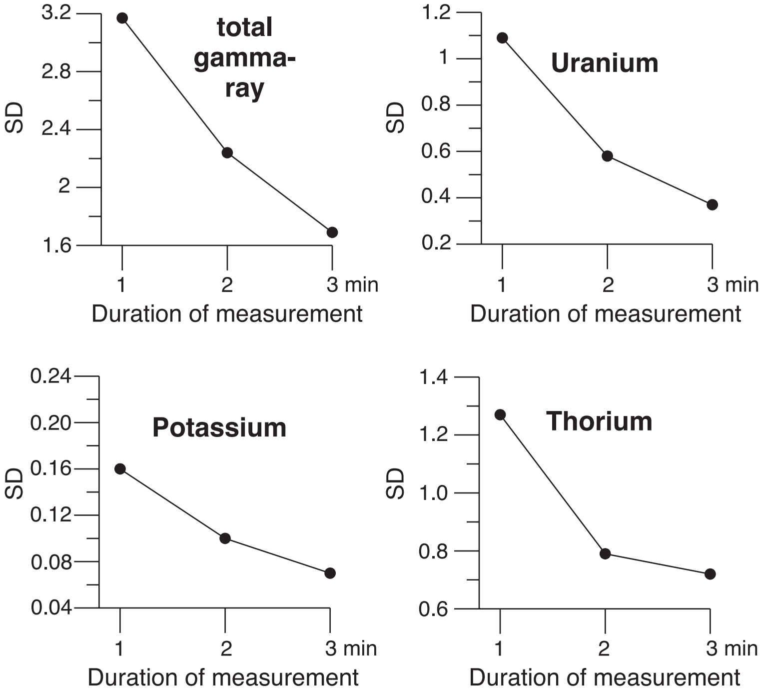


Fig. 3. Spectral gamma-ray test series comprising of 10 measurements each with 1, 2 and 3 min duration (see also Table 1). The standard deviations (S.D.) of the series decreases markedly with increasing measuring durations and reaches a satisfying level of precision at 3 min.

manufacturer on a test pad with known elemental composition. The standard duration used for all measurements was a 3-min interval, chosen on the results of three test series of 10 measurements each, lasting 1, 2 and 3 min, respectively (Fig. 3, Table 1). The measured horizon in this test consisted of green Upper Devonian organically lean, normal/low-radiation shales located several 10 s of metres above the top of the Adrar Morrat section (ADR). The optimum duration for a measurement is naturally a compromise between a high number of datapoints (requires shorter durations) and a precise, reproducable result (requires longer durations), and depends largely on the radiation intensity of the studied lithologies. The test showed that the variability (standard deviation, S.D.) of all measured radiation parameters decreases markedly with increasing duration of the measurement (Fig. 3). An acceptable level of variability is achieved for the 3-min measurement interval (Table 1), so that longer measurements were not considered necessary. Measuring intervals that are significantly shorter than the one selected here were previously used by some authors (e.g. Slatt et al. 1992; Ten Veen and Postma 1996), whereby they carried out five repeat measurements for just a few seconds each, discarding the highest and lowest value and averaging the remaining three values. Such time-saving techniques may be useful for some purposes, e.g. fast discrimination between sandstones and shales (Slatt et al., 1992) or semiquantitative studies. Spectral gamma-ray studies with a strong focus on quantitative aspects, such as the present study, however, generally require longer measuring intervals (e.g. 2 min: Zelt, 1985; Myers and Bristow, 1989; Svendsen and Hartley, 2001; 4–10 min: Myers and Wignall, 1987).

3. Geological setting

During the Palaeozoic several sag basins (Reggane Basin, Ahnet Basin, Mouydir Basin, Illizi Basin) were established on the northern margin of the African Craton (Fig. 1), some of them host significant quantities of hydrocarbons. From Cambrian to Early Devonian times these basins exhibit only little diversified facies patterns and subsidence rates, but from the Middle Devonian they became better individualized and are clearly separated by intervening ridges. The bulk of these deposits are now buried under a thick Mesozoic sedimentary cover. Only along the northern border of the Precambrian Hoggar Massif, the margins of these basins crop out (Fig. 1) enabling a much more detailed reconstruction of facies patterns and palaeogeographies than is possible from subsurface data only. As a result of the Hercynian/Variscan compressional deformation, Cambrian to Namurian strata are folded and faulted exhibiting predominant N–S and NW–SE strike directions (Haddoum et al., 2001) thus allowing a three-dimensional insight into the depositional area.

Following marginal-marine to fluvial-siliciclastic sedimentation during the Early Devonian (Tassili externe or Assejrad and Oued Samene Formations of Beuf et al., 1971), fully marine conditions prevailed from the late Emsian/early Eifelian. Middle Devonian ramp carbonates (Calcaires de Azel Matti of Bertrand-

Table 1
Data table for the spectral gamma-ray test series that was used to evaluate the variability of measured values for different measuring durations

Run	1 min				2 min				3 min			
	Total	K	U	Th	Total	K	U	Th	Total	K	U	Th
1	75.1	1.5	4.6	10.3	77.6	1.5	6.2	11.5	82.0	1.6	4.2	15.2
2	76.4	1.6	6.0	9.4	83.1	1.5	5.4	12.7	80.4	1.6	4.6	14.1
3	84.3	1.4	3.5	11.8	78.5	1.5	5.0	12.5	79.2	1.5	4.5	14.6
4	77.0	1.5	4.8	9.0	82.5	1.6	4.8	12.7	80.1	1.6	3.8	15.4
5	79.2	1.4	6.6	8.2	79.1	1.6	4.6	13.7	80.4	1.4	4.8	13.9
6	83.2	1.7	5.6	10.0	82.9	1.6	5.0	12.7	82.6	1.5	4.9	13.9
7	74.4	1.2	5.0	11.7	84.1	1.5	4.3	12.9	82.7	1.5	4.9	13.1
8	77.5	1.4	6.7	7.8	82.2	1.8	4.5	12.4	79.7	1.5	5.1	13.2
9	78.1	1.5	4.6	10.6	80.1	1.5	5.4	14.6	80.2	1.5	4.3	14.4
10	81.4	1.8	3.4	10.5	78.4	1.4	5.9	13.3	76.7	1.4	4.5	14.5
S.D.	3.17	0.16	1.09	1.27	2.24	0.10	0.58	0.79	1.69	0.07	0.37	0.72

Sarfati et al., 1977) constitute a prominent, 2–20 m high (present-day) escarpment which can be traced in outcrop for over 2000 km from the eastern Reggane Basin in the west into the Illizi Basin in the east (Wendt and Kaufmann, 1998; Kaufmann and Wendt, 2000). A pronounced eustatic sea-level rise at the Givetian–Frasnian boundary, corresponding to the initial phase of the transgressive–regressive cycle IIb of Johnson et al. (1985), led to hemipelagic deposition of predominantly black shales with intercalated thin-bedded, styliolinid-dominated bituminous limestones, limestone concretions and cm-thin layers of cross-stratified fine-grained sandstones. At some levels the shales are weathered grey, reddish or greenish whereby no stratigraphically controlled colour patterns and no relationship with gamma-ray uranium signals appear to exist. The physical appearance of the shales varies from firm to soft, and is partly even powdery. Notably, high uranium values have been recorded in both firm and powdery shales, indicating that even the strongly weathered shales seem to retain (at least part of) their original uranium. The fauna of the shales is of low diversity and comprises almost exclusively abundant styliolinids and *Buchiola* (a pelagic bivalve). Limestone intercalations contain abundant styliolinids, frequent orthoconic cephalopods, goniatites, brachiopods, gastropods and very rare small tabulate as well as solitary rugose corals. The thin sandstone layers generally show an eroded upper surface and sole marks and are probably the result of intermittent storm activities (tempestites). This formation, which in outcrop attains thicknesses of several hundred metres, is termed Argiles de Mehden Yahia (Bertrand-Sarfati et al., 1977) or Argiles de Temertasset (Legrand, 1983) or, in subsurface sections, Argiles Frasniens and Argiles Frasniens Radioactives (e.g. Askri et al., 1995; Daniels and Emme, 1995). Towards the end of the Frasnian, the siliciclastic input becomes more pronounced, in particular in the eastern Ahnet and in the Mouydir Basin. These Grès de Mehden Yahia contain typical shallow-water organisms such as brachiopods and thick-shelled tentaculites.

The pelagic ridges, which separate the above mentioned basins are characterized by strongly reduced depositional thicknesses and obvious gaps. The Azzene Ridge (in the north) and Azel Matti Ridge separate the Reggane Basin from the Ahnet Basin; the Foum Belrem Ridge (= Idjerane Ridge) (Fig. 2) separates the latter from the Mouydir Basin. With respect to these palaeogeographic units, the examined sections can be summarized as follows:

3.1. Bled El Mass (BEM section)

This area comprises the flank of a plunging anticline, in the core of which Silurian shales are deeply eroded forming a large circular depression. The strongly condensed upper Emsian/Eifelian limestones and the upper hiatus (comprising the upper Eifelian to lower Frasnian) are therefore interpreted as indicating a swell position (Azel Matti Ridge) during the Middle Devonian to early Frasnian. In contrast, the extremely thick (630 m) overlying Frasnian shales clearly reflect a strongly increased subsidence and a basinal position of this section during the late Frasnian (Fig. 4).

3.2. Azel Matti mound (AZM)

A similar ridge position (Azel Matti Ridge) during the Givetian and earliest Frasnian is evident in the Azel Matti area (Figs. 1 and 2), which is characterized by the occurrence of spectacular lower Givetian mud mounds (Wendt et al. 1997). The age of the basal Frasnian shales which onlap the mounds reveals a pronounced hiatus during the middle Givetian to early Frasnian and suggests that the mounds persisted as topographic highs during this interval (Fig. 5).

3.3. Azel Matti off-mound (AZO)

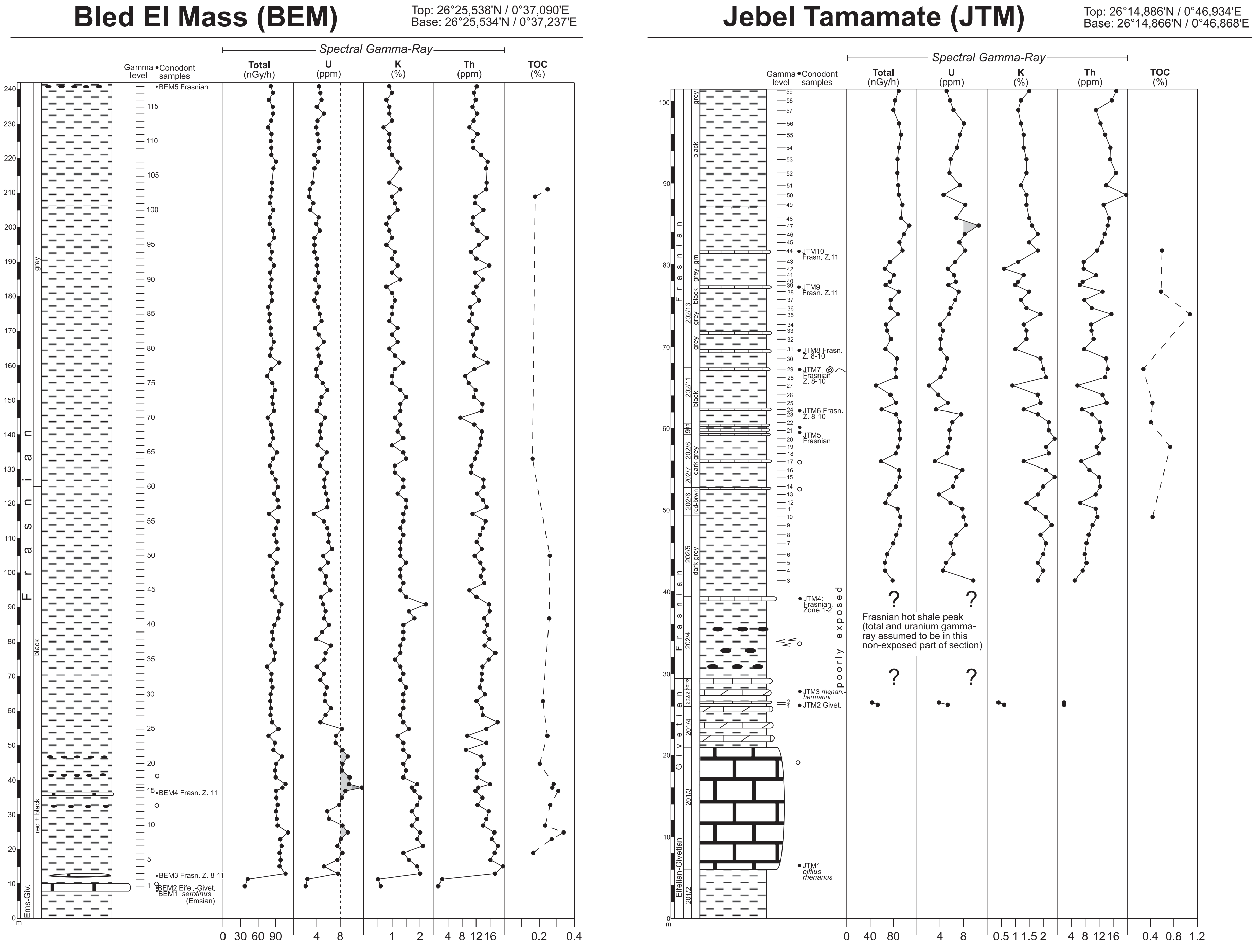
In the off-mound areas the lower Frasnian is stratigraphically more complete, commencing in section AZO with conodont Zone 3 (Fig. 5).

3.4. Jebel Tamamate (JTM)

An increased thickness of Middle Devonian limestones and Frasnian shales, the top of which could not be precisely established, assign an intermediate ridge-basin-position to this section (Fig. 4).

3.5. Adrar Morrat (ADR)

The thick Middle Devonian (70 m of Eifelian shales, 30 m of Givetian limestone/shale alternation) and lower Frasnian (170 m shales) indicate a typical basin


Bled El Mass (BEM)

Top: 26°25,538'N / 0°37,090'E
Base: 26°25,534'N / 0°37,237'E

Jebel Tamamate (JTM)

Top: 26°14,886'N / 0°46,934'E
Base: 26°14,866'N / 0°46,868'E

Fig. 4. Lithologies, conodont biostratigraphy, spectral gamma-ray and organic-richness of the studied field sections (location map in Fig. 2). Legend for sections in Fig. 7.

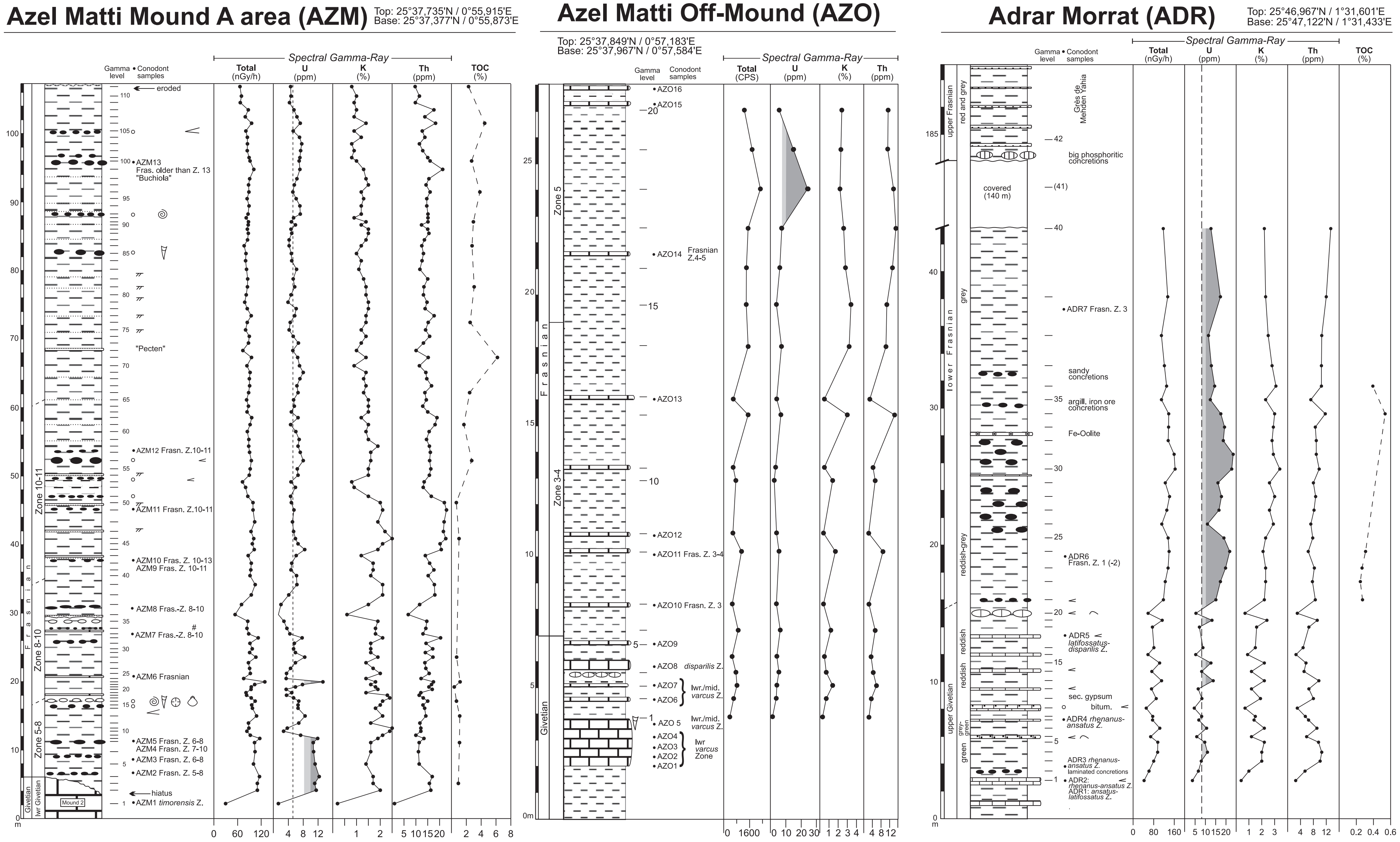


Fig. 5. Lithologies, conodont biostratigraphy, spectral gamma-ray and organic-richness of the studied field sections (location map in Fig. 2). Legend for sections in Fig. 7.

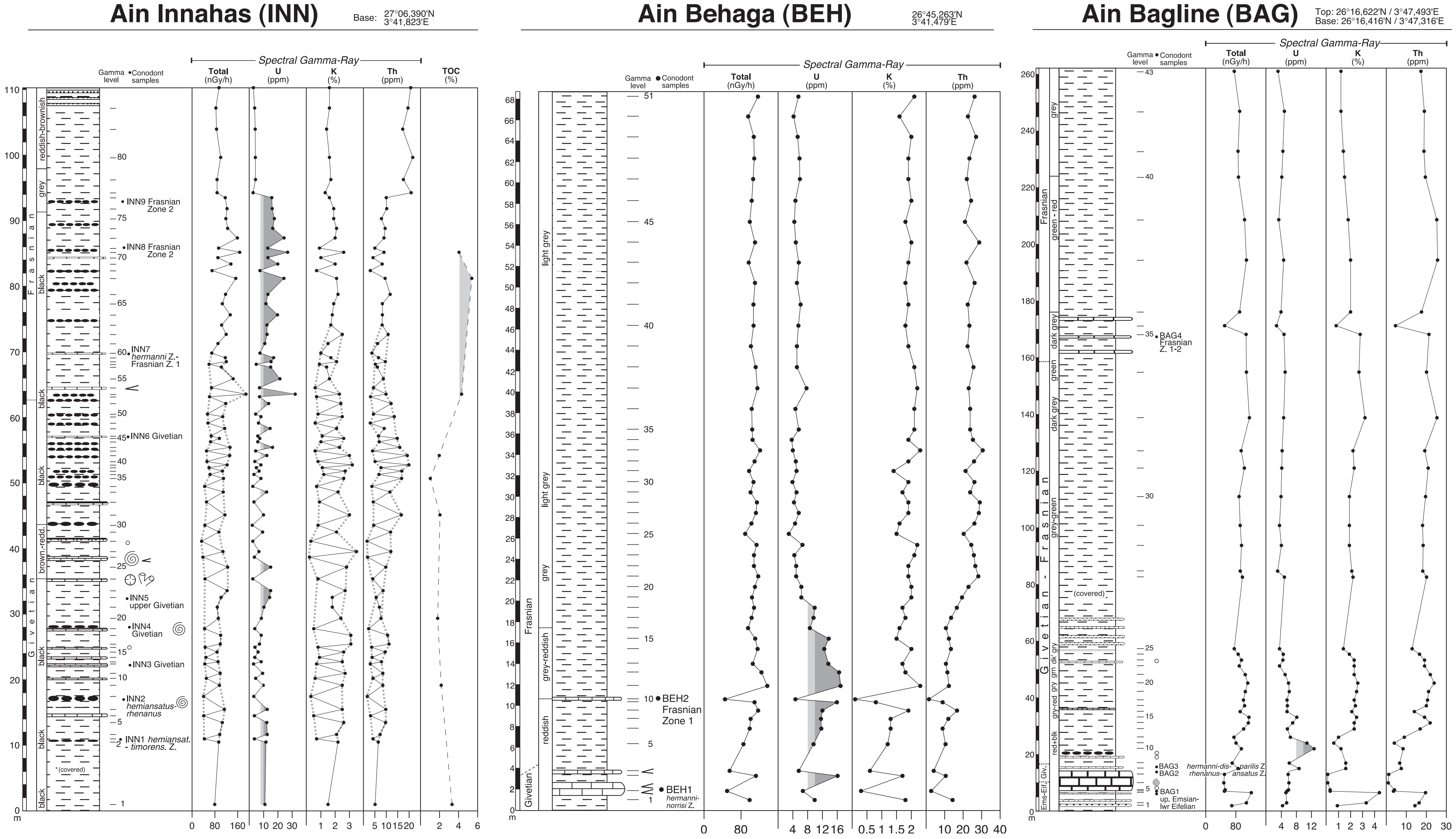


Fig. 6. Lithologies, conodont biostratigraphy, spectral gamma-ray and organic-richness of the studied field sections (location map in Fig. 2). Legend for sections in Fig. 7.

position of this section. The upper Frasnian sandstone unit of the Grès de Mehden Yahia is well exposed but, apart from undeterminable brachiopods and orthoconic cephalopods in insoluble phosphoritic concretions, did not yield any diagnostic organic remains (Fig. 5).

3.6. Ain Innahas (INN)

This is a typical basinal succession as indicated by a relatively thick (80 m) Middle Devonian succession of black shales with intercalated 5–30 cm thick limestone beds. The basal portion of the Frasnian consists of black shales with numerous limestone concretions, passing into reddish–brownish shales with thin sandstone levels. The total thickness of the Frasnian until the base of the Grès de Mehden Yahia is about 350 m (Fig. 6).

3.7. Ain Behaga (BEH)

The Middle Devonian limestones in this section comprise only the lower Givetian, the upper part of which is argillaceous, overlain by two styliolinid limestone layers. The Frasnian, of which only the basal portion is well enough exposed for sampling, is 380 m thick and consists of monotonous black shales terminated by some thin-bedded sandstones (Grès de Mehden Yahia) which during this study could be dated by conodonts as upper Frasnian (Zone 13) (Fig. 6).

3.8. Ain Bagline (BAG)

The 8 m thick limestone escarpment at the base comprises the entire Middle Devonian indicating a ridge position (Foum Belrem or Idjerane Ridge) with reduced sedimentation at this time. The Givetian/Frasnian boundary could not exactly be traced, but the great thickness of the Frasnian shales (about 500 m) not only points to an increased subsidence rate but also to a levelling of the preceding topography with the onset of the Late Devonian (Fig. 6).

4. Spectral gamma-ray characteristics and organic richness

The spectral gamma-ray data in most sections is characterised by a prominent uranium-enriched interval up to 45 m thick (Figs. 4–8), often just above the top of the Givetian strata. The maximum uranium concentrations of the peaks in the individual sections vary between 12 and 32 ppm. Two U cut-offs of 8 and 10 ppm have been marked in the sections and in the correlation panel. Typically, this uranium-enriched shale unit is overlain by a monotonous shale series that on the spectral gamma-ray log is expressed by normal-radiation values (sections BEM, BEH and BAG). A characteristic baseline value for this monotonous unit is 5 ppm uranium (e.g. in sections AZM, BEM, BEH, BAG). In these monotonous shales the K and Th spectral gamma-ray curves often subtly follow the U curve, mainly because the detrital U, K and Th contents are all lower in carbonates as compared to shales. The spectral gamma-ray data of section INN contains a bimodal set of values for Givetian shales (higher values) and intercalated dark limestone concretions (lower values) just below the lower Frasnian U peak (Fig. 6).

The early Frasnian U peak is a well-known phenomenon in hydrocarbon exploration wells in Algeria, S Tunisia and W Libya (Lüning et al., in press) (Fig. 9). The U peak generally coincides with elevated TOC values, so that the peak can be used as a reliable proxy for elevated organic contents in this interval of the Frasnian shales of North Africa (Lüning et al., in press).

The close relationship of U and TOC in type I/II organic-rich strata is based on the fact that in seawater U^{6+} is carried in solution as uranyl carbonate complexes that 'precipitate' under oxygen-depleted, reducing conditions during deposition (Wignall and Myers, 1988; Postma and ten Veen, 1999). The authigenic U^{4+} enrichment in organic-rich shales is independent of the purely detrital K and Th, as evidenced by the general decoupling of the U peak vs. the K and Th spectral gamma-ray signals in the Frasnian field sections (Figs. 4–6) and by the well wireline log data from the same interval in the western Algerian Berkine Basin (Fig. 10). Uranium also occurs in the detrital fraction but U_{detr} concentrations in sediments usually co-vary with those of K and Th (e.g. Wignall and Myers, 1988).

In three of the five sections that were geochemically studied (BEM, JTM, ADR; Figs. 4 and 5) the TOC values are very low and rarely exceed 0.5%, even in the uranium-rich intervals. It is assumed that in these sections the organic matter has been largely

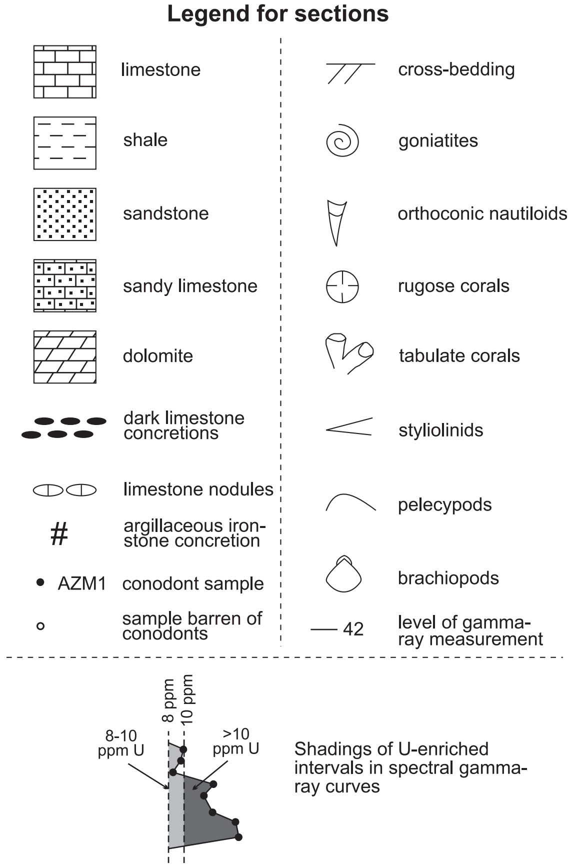


Fig. 7. Legend for field sections in Figs. 4, 5, 6 and 8.

oxidised due to weathering because age-and facies equivalent, U-rich strata in the subsurface of Algeria are known to be organically rich with maximum TOC values often greater than 7% (Figs. 9 and 10). Notably, in two of the field sections analysed (AZM, INN; Figs. 5 and 6) TOC values in some levels exceed 5%, indicating that, in places, the organic matter has partly escaped weathering-induced oxidisation. Consequently, trends in TOC content as observed in these sections do usually not reflect original trends because of vertical variations in the intensity of weathering. Clearly, the TOC values recorded only represent minimum values. This may explain why the gamma-ray-peak in section AZM is atypically associated with only relatively low TOC-values (1%). Notably, higher organic richnesses occur in the upper, non-U-enriched part of this section, however possibly indicating the presence of more terrigenous organic matter here. A more convincing relationship with regard to pre-weathering conditions has been recorded in section INN where the maximum TOC values coincide with the U-enriched interval (Fig. 6).

The presence of the characteristic basal Frasnian U peak suggests that U at least in part escaped the destructive weathering processes. This may be related to the lack of water in the Sahara which prevents any soluble, oxidised U^{6+} to be carried away from the weathered sediment (Dr. Steven Petsch, personal communication, 2003). A linear relationship between (U-dominated) gamma-ray intensity and organic richness has been documented for the Frasnian hot shale in W Algerian exploration wells from which fresh shale samples were available. In Fig. 11 a gamma/TOC plot of the Frasnian hot shale in the Berkine Basin well BKE-1 (Fig. 10) is illustrated in which the best fit line allows to approximate the TOC using the total gamma-ray. The U-enriched shale interval in the Frasnian field sections is interpreted here as representing the (now weathered but formerly organically rich) Frasnian "hot shale" based on the consistent basal Frasnian stratigraphic position (see below) and the positive gamma/TOC relationship in wells. Notably, the "hot shale" only comprises the organically richest parts of the succession so that strata with lower, but still elevated (>1%) Corg values are not covered by the U-peaks marked in Figs. 4, 5, 6 and 8.

The relict uranium and organic matter content of Frasnian black shales in outcrops depends mainly on the three factors (1) original organic richness/original uranium content, (2) duration and intensity of weathering, and (3) organic carbon loss during burial and thermal maturation (Raiswell and Berner, 1987). In some Palaeozoic black shales diagenetic mobilisation and re-deposition of uranium have taken place, e.g. in the tectonically strongly deformed and heated Silurian graptolithic black shales of Thuringia, which contain diagenetically migrated, mineable uranium accumulations (Hähne and Altmann, 1993), and in the Ordovician black shales of Wales (Lev et al., 2000). Also the Frasnian strata in NW Africa were subjected to deformational processes, however, less intense. The characteristic presence of the Frasnian uranium peaks in the measured sections indicates that major diagenetic effects in the uranium distribution can be neglected for the field area studied. Note, however, that weath-

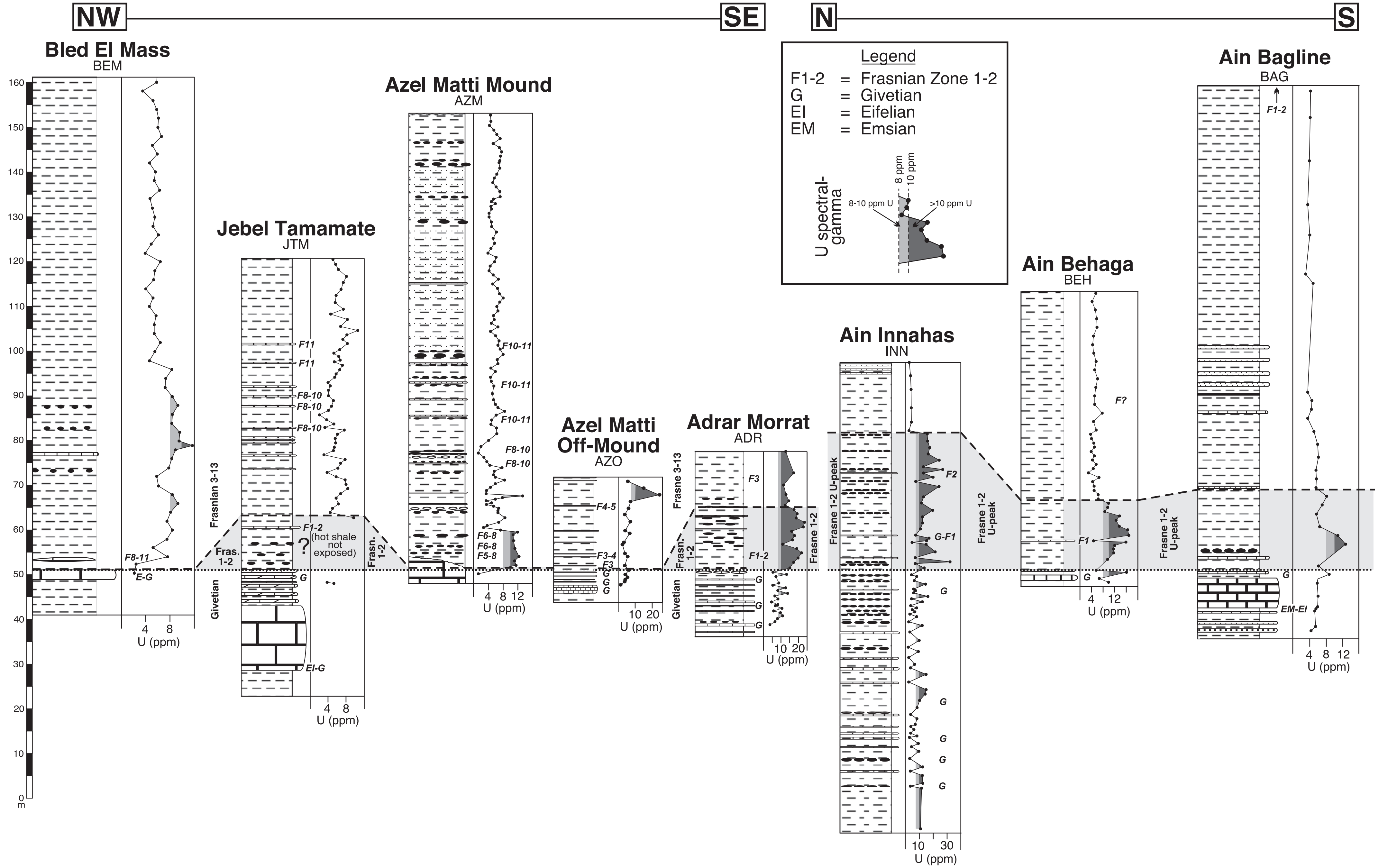


Fig. 8. Correlation of the basal Frasnian uranium peak and conodont biostratigraphic data across the studied sections. The biostratigraphic data available suggests that the U enriched interval was deposited during Frasnian Zones 1–2, with the exception of section AZM where a hiatus exists. Location map in Fig. 1, legend for lithologies in Fig. 7.

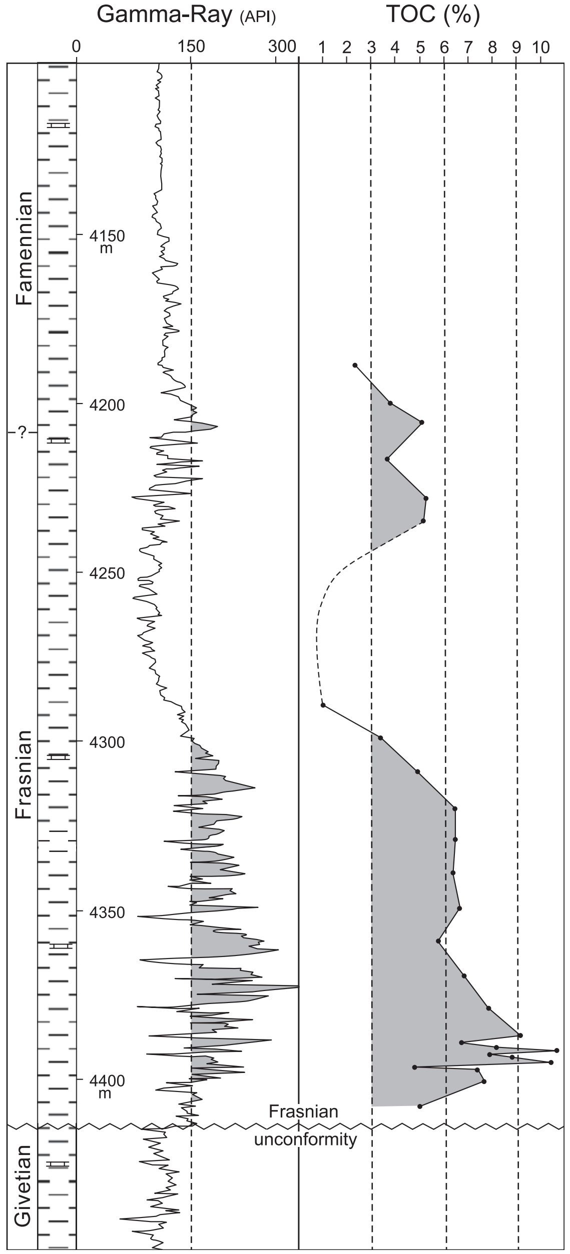


Fig. 9. Frasnian and Frasnian–Famennian boundary (?) hot shales in well BK-2 (Berkine Basin, eastern Algeria, Fig. 1) (from Lüning et al., in press).

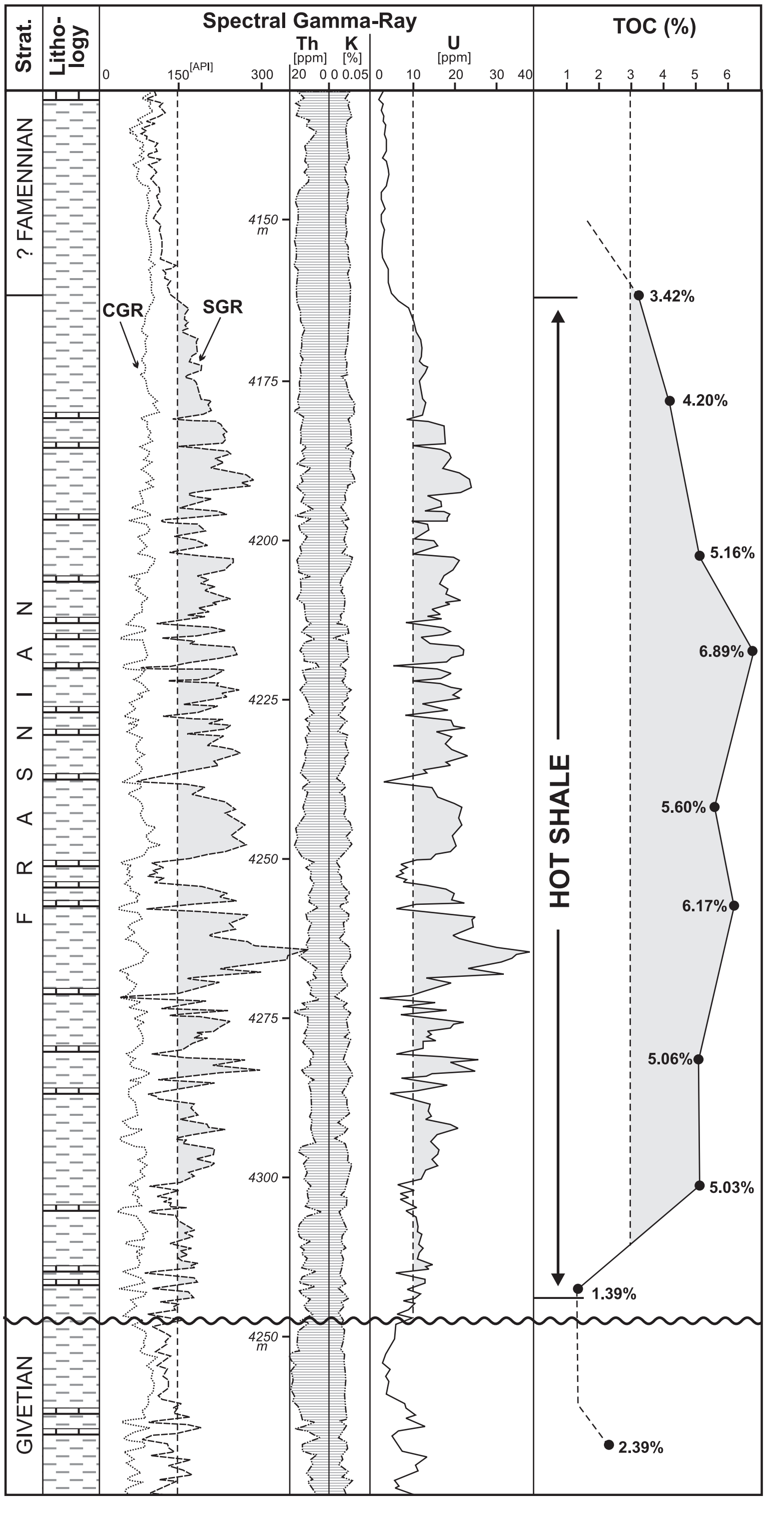
ering intensities are likely to have differed in the individual sections, potentially complicating direct numerical comparisons of the U signals between the individual sections.

5. Biostratigraphy

Palynomorphs that are routinely used for biostratigraphic dating in exploration wells do not provide a satisfying time resolution because the Frasnian palynomorph scheme in North Africa consists of 1–3 zones only (e.g. Paris et al., 1985; Streel et al., 1988; Abdesselam-Rouighi, 1996). In contrast, conodonts potentially allow high-resolution biostratigraphic dating in the Upper Devonian (Fig. 12). Conodonts, however, are not very frequent in shale-dominated successions such as the Frasnian in North Africa. In order to achieve high resolution stratigraphic data from such a lithology sample sizes of several kilograms are generally necessary. Unfortunately, large samples cannot be retrieved from hydrocarbon exploration wells. Cutting samples originate from larger, rather undefined intervals and are often of only small quantities. Cores are rarely taken from hydrocarbon source rock intervals, and when existing, removal and destruction of rather large samples can usually not be justified for conodont analysis. Therefore, in this study, the stratigraphic analysis was almost exclusively carried out from outcrop samples and the age data were then correlated with the subsurface by using typical gamma-ray signatures, namely the uranium peaks, taking into account that the uranium-enriched interval may also be diachronous.

In this contribution we use the conodont zonal scheme of Klapper (1997) who, based on graphic correlation, developed a quantitative chronostratigraphic framework for the Frasnian and subdivided this stage into 13 conodont zones. The scheme provides the best possible stratigraphic resolution and has already been replicated in several Devonian sections worldwide (see Klapper and Becker, 1999; Belka et al., 1999). In the basal part of this scheme a conodont zone represents around 200,000 years (Fig. 12). This allows a very precise correlation of sections and detailed analysis of the sedimentary evolution.

In the studied sections only about half of all samples yielded identifiable conodont elements. The recovery rate was low, generally below 10 elements/kg. The most productive were samples of the Frasnian Zone 11. Conodont fauna includes taxa that were cosmopolitan during the Middle and Late Devonian, but it is less diverse than time-equivalent faunas of the


Strat.
Litho-logy
Spectral Gamma-Ray
0
150[API]
300
Th [ppm]
20 0
K [%]
0 0.05
U [ppm]
0 10 20 30 40
TOC (%)
1 2 3 4 5 6
? FAMENNIAN
F R A S N I A N
GIVETIAN
CGR
SGR
4150 m
4175
4200
4225
4250
4275
4300
4250 m
HOT SHALE
3.42%
4.20%
5.16%
6.89%
5.60%
6.17%
5.06%
5.03%
1.39%
2.39%

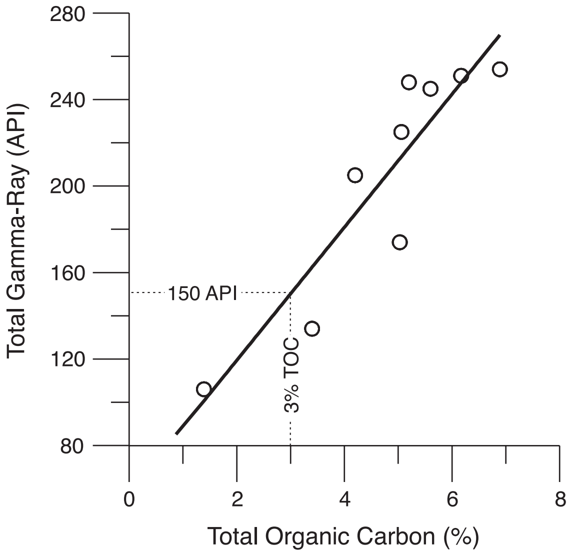


Fig. 11. Gamma-ray/TOC crossplot of the Frasnian hot shale in the Algerian Berkine Basin well BKE-1. The best fit line allows to estimate organic richness based on total gamma-ray values. API=unit for gamma-ray intensity.

European Variscides. In the Frasnian, a typical feature is the very rare occurrence of *Palmatolepis* and the dominance of polygnathids and icriodids, which commonly co-occur with ancyrodellids and relatively frequent ancyrognathids.

The sections investigated range in age from the Emsian to the late Frasnian. Though the Middle Devonian contains more carbonate horizons than the Frasnian, the low conodont recovery here allows only a rough stratigraphic subdivision. The stratigraphic resolution in the Frasnian portion is significantly higher, but the low-diversity fauna usually makes identification of single conodont zones impossible.

The Frasnian shale-dominated succession commences with the strongly uranium-enriched interval that often spans Frasnian conodont Zones 1 and 2 (Fig. 8). Most probably it represents the originally organically richest black shales deposited during the peak anoxic phase at the beginning of Frasnian time. Notably, in three sections (AZO, AZM and BEM, Fig. 8), there is a stratigraphic gap and parts of the lower Frasnian are missing. Characteristic U-enriched intervals occur above these gaps in all three of these sections and the peaks roughly fall into Frasnian Zones 5–11. Due to insufficient biostratigraphic resolution it remains unclear whether these U peaks are contemporaneous or have different ages. Nevertheless, they indicate the (possibly local) return of anoxic conditions after the main Zones 1–2 anoxic phase had terminated. The greater hiatus in the Azel Matti Mound section (AZM) in comparison to the Off-Mound section (AZO) is not related to any erosional event. It is due to marine onlap of Frasnian shales on the Givetian mud mounds (Wendt et al., 1993, 1997) exhibiting a pronounced and spectacular morphology over the sea floor still during Frasnian times.

6. Discussion

6.1. Diachroneity of the Frasnian anoxia in North Africa

The sections studied indicate the presence of a major anoxic phase during Frasnian Zones 1 and 2 at the margin of the Ahnet Basin. Younger anoxic phases also occur in some of these sections but could not be confidently correlated, as of yet. The present day basin morphology of the Saharan Palaeozoic basins did already partly exist during the Late Devonian as documented by the Frasnian hot shale isopach map of the Ahnet Basin (Fig. 2), so that a deepening facies shift must have occurred towards the centres of the basins.

Generally, in the basin centres the Frasnian hot shales (>3% TOC) attain great thicknesses, e.g. in the Berkine Basin well BK-2 (Fig. 9) of partly more than 200 m, representing more than half of the total Frasnian section here. In contrast, the U-enriched intervals in the studied sections at the basin margin only represent a small percentage of the total Frasnian succession, possibly mostly not exceeding 5–10%.

Fig. 10. Frasnian hot shale in well BKE-1 (Berkine Basin, eastern Algeria, Fig. 1). The organic-rich ("hot") shale interval is marked by a characteristic gamma-ray peak which according to spectral gamma-ray data is almost entirely due to an enrichment in uranium. CGR = Computed gamma-ray (Th + K), SGR = Spectral gamma-ray (Th + K + U).

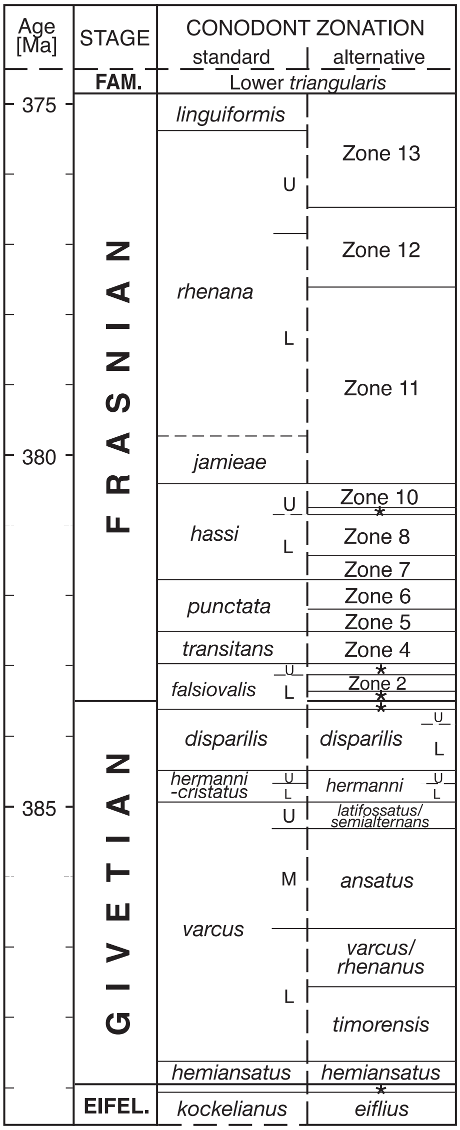


Fig. 12. Frasnian conodont biozonal scheme of Klapper (1997) used in this study (right column) and correlation with the standard zonation (left column) of Ziegler and Sandberg (1990). Correlation is based on Sandberg et al. (1989) and Klapper and Becker (1999). Calibration with absolute ages is based on Kaufmann (2002). *Conodont zones not labelled are (in ascending order): *ensensis*, *norrisi*, Zones 1, 3 and 9.

Similar maximum thicknesses as in BK-2 were reported by Logan and Duddy (1998) from the depocentres of the Ahnet Basin (Fig. 2), although notably, their illustrated organic-rich unit included all strata with TOC greater than 1%. If major hiatuses are assumed to be absent, these greater thicknesses of uranium-enriched strata that represent greater percentual proportions of the total Frasnian successions may be taken as evidence that anoxia in the Berkine Basin depocentre lasted significantly longer than at the basin margins.

Therefore, from a shelf-wide perspective the Frasnian organic-rich sedimentary body has to be considered as diachronous on a scale of a few million years. Unfortunately, no conodont biostratigraphic data is available for the basin centre wells and biostratigraphy here is based on less precise palynomorphs. It is proposed that the main anoxic phase (Zones 1–2) and the younger anoxic periods documented here for the Ahnet Basin margin sections progressively increase in intensity and duration towards the deeper parts of the basins. In the depocentres anoxia dominates during most of the Frasnian, with few or no oxic interludes.

Deposition of the lowermost Frasnian hot shales in the studied Ahnet field sections coincides with an intense transgression which is known from many parts of the world (Frasne Event sensu House, 1985; IIb transgression sensu Johnson et al., 1985) (Fig. 13). This earliest Frasnian transgression may have raised and intensified an oxygen minimum zone that subsequently impinged onto the North African shelf (Lüning et al., in press). The transgression is likely to have led to sediment starvation because detritus became trapped in river mouths, forming backstepping depositional geometries, preventing dilution of the organic matter on the shelf (see also discussion in Murphy et al., 2000). Once the transgression slowed down the (generally organic-poor) detritus influx into the basin reestablished, so that anoxic conditions disappeared at the basin margins and only persisted in the basin centres. Such an origin of the lower Frasnian organic-rich strata in NW Africa generally corresponds to the transgressive black shale model proposed by Wignall (1991).

6.2. Comparison with Morocco and other parts of the world

Organic-rich deposits related to the earliest Frasnian transgression were also deposited in Morocco, as documented by Wendt and Belka (1991) from out-

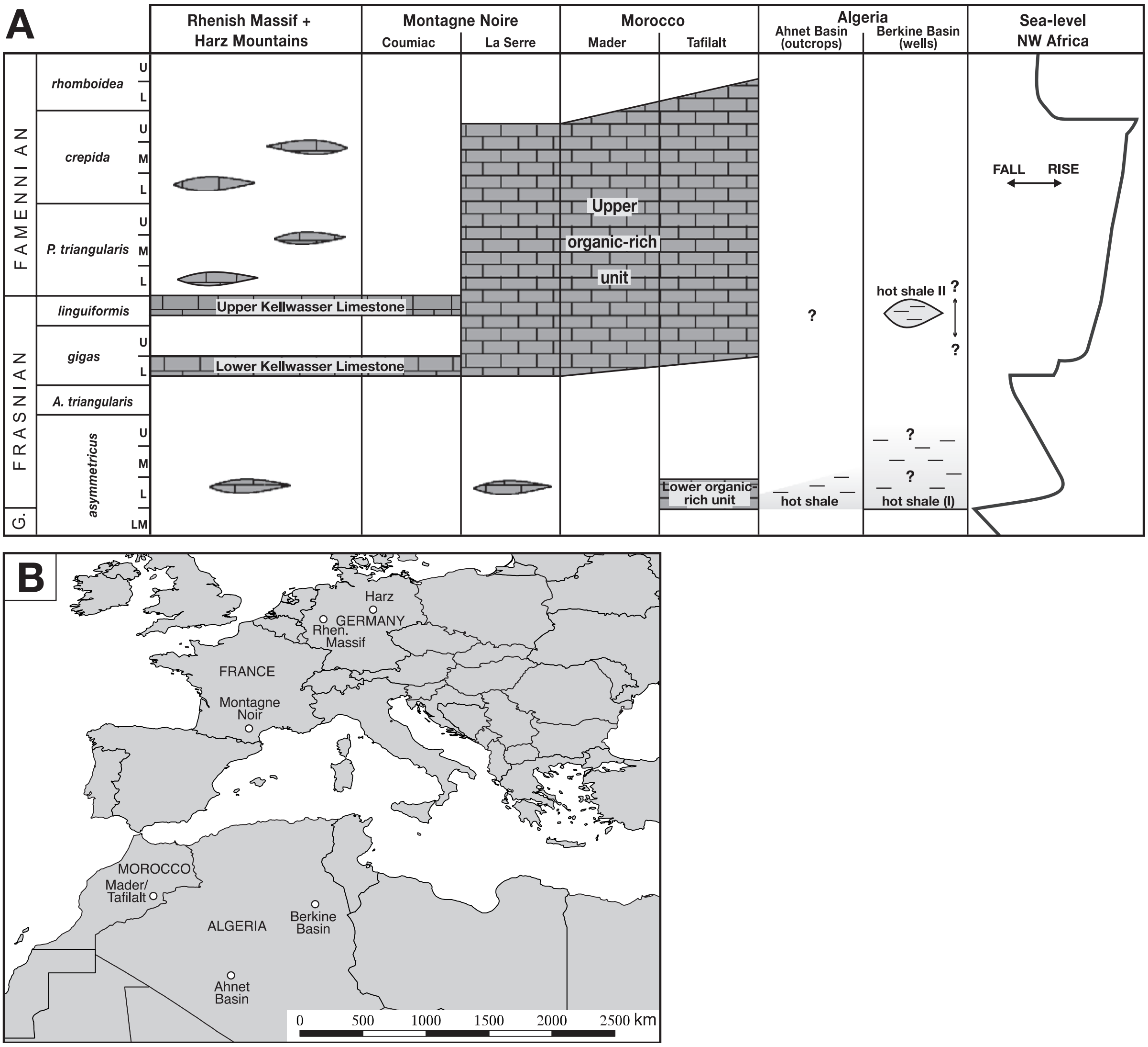


Fig. 13. (A) Deposition of Frasnian organic-rich strata (grey units) in NW Africa and in selected European regions (modified after Wendt and Belka, 1991). (B) Localities illustrated in (A). While at the basin margin (Ahnet field sections) oxygen-poor conditions are proven to have existed only during the lowermost part of the Frasnian (conodont Biozones 1 + 2, Fig. 12), anoxia is assumed to have continued for longer in the shelfal depocentres, e.g. in parts of the Berkine Basin. A second organic-rich shale unit around the Frasnian/Famennian boundary in the Berkine Basin may correspond to the Kellwasser phase.

crops in the eastern Anti Atlas. This so-called Frasnes Event (sensu House, 1985; see also Ebert, 1993; House, 2002) characterized by the presence of oxygen depleted water on the sea floor ranges in the Anti Atlas from Zone 1 to the lower part of Zone 4 (Belka et al., 1999).

Other comparable lowermost Frasnian organic-rich deposits are known, e.g. from the Rhenish Massif/ Harz Mountains (Germany) and the Montagne Noire (France) (Fig. 13, Wendt and Belka, 1991), highlighting the interregional importance of this earliest Frasnian anoxic event. Strata from this early Frasnian anoxic phase form the second most important Palaeozoic hydrocarbon source rock in North Africa (Lüning et al., in press).

6.3. Kellwasser events

Another significant anoxic event in NW Africa developed around the Frasnian–Famennian boundary and is part of the prominent 'Kellwasser' phase that is associated with mass extinctions and deposition of organic-rich facies in many parts of the world (e.g. McGhee, 1996). A second hot shale ("hot shale II", Fig. 9) is developed in the depocentre of the Berkine Basin at around this level, which however, has been only roughly dated by palynomorphs. A genetic link with the organic-rich (Kellwasser) facies in the eastern Anti-Atlas in Morocco (Schindler, 1990; Wendt and Belka, 1991; Belka and Wendt, 1992; Belka et al., 1999) is assumed (Fig. 13).

7. Conclusions

The lower Frasnian organic-rich shales and limestones in NW Africa were deposited during a pronounced anoxic phase, that in the marginal zones was restricted to the basal Frasnian Biozones 1–2 and, locally, to a few shorter younger oxygen-depleted periods during Zones 5–11. In the depocentres, however, anoxic conditions appear to have lasted significantly longer. This interpretation is based on conodont biostratigraphic data from eight Frasnian field sections in the central Algerian Ahnet Basin. A precise temporal–spatial reconstruction of this anoxic phase in NW Africa is complicated by the fact that the organic matter in Frasnian outcrops is largely oxidised by weathering and biostratigraphic resolution in wells is generally low due to the low number of retrievable conodonts. In the present study the anoxic interval, and therefore the pre-weathering organic rich interval, has been identified in outcrops guided by a characteristic uranium enrichment, that in wells is positively correlated with the total organic carbon content. In the central parts of the Frasnian depocentre of the Berkine Basin in eastern Algeria, a second anoxic phase exists, that may correspond to the Kellwasser Event around the Frasnian–Famennian boundary (e.g. Buggisch, 1991; McGhee, 1996).

Acknowledgements

Houria Naili (Sonatrach) and the Sonatrach management are thanked for support and permission to publish the well logs. We are grateful for useful discussions to Dr. Adrian Immenhauser (Vrije Univ. Amsterdam). Technical assistance has been provided by Jochen Rath, Stefan Lubeseder (Univ. Tübingen), C. Müller and J. Holstein (both Univ. Bremen). The study was funded by the German Research Foundation (JW: We 239/15-3, SL: Lu 654/1-1, 1-2). Photographs of the studied field sections are posted at http://www.blackshale.com/pics/frasne.htm. The paper benefited from constructive review by Trans Van Buchem (IFP) and an anonymous colleague.

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