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Sedimentary Geology 145 (2001) 215–233

Sedimentary Geology

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An exhumed Palaeozoic underwater scenery: the Visean mud mounds of the eastern Anti-Atlas (Morocco)

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Received 30 May 2000; accepted 15 May 2001

Abstract

About one hundred carbonate mud mounds, covering an area of 440 km^2 in the eastern Anti-Atlas of Morocco, constitute one of the largest mound agglomerations known so far from Lower Carboniferous settings. They occur within a 4000-m-thick succession of shales with intercalated bedded limestones, sandstones, and siltstones. According to conodont and goniatite biostratigraphy, mound formation started in the early *Gnathodus texanus* Zone and terminated during the *G. bilineatus* Zone of the Visean stage. Individual mounds are a few metres to 30 m high, have base diameters of up to 300 m and are concentrated in several parallel, WNW–ESE running belts. From their lithology and facies relationships, four types of mounds can be distinguished: (1) massive crinoidal wacke- or packstones without stromatactis; (2) massive crinoidal wacke- or packstones with rare stromatactis; (3) similar to (2), but allochthonous; and (4) biodetrital (skeletal) grainstone mounds. While carbonate deposition in types (1) to (3) was probably triggered by microbial precipitation, type (4) is the result of a predominantly mechanical accumulation of skeletal debris. Biota in the four types comprise a great variety of invertebrates, among which crinoids, sponges, and bryozoans are most common. Diagenesis of the mound carbonates was dominated by recrystallization of micritic matrix and organic remains and late burial cementation. Oxygen and carbon isotope data of brachiopod and crinoid ossicles, matrix, and early marine cements plot in a large field and do not allow definite conclusions about the composition of the ambient seawater. Microbial activity and the absence or scarcity of green algae, colonial corals and coralline sponges suggest deposition of the mounds in moderate water depth close to the lower limit of the photic zone. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Mud mounds; Visean; Morocco; Reefs; Carboniferous; Palaeoenvironment

1. Introduction

Bioconstructions of Carboniferous age are almost exclusively represented by mud mounds. Although they consist mainly of fine-grained carbonate they have, however, represented a habitat for a large variety of sessile organisms. Impressive examples of mud mounds have been described from Ordovician (Ross et al., 1975; Vennin et al., 1998), Silurian

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PII: S0037-0738(01)00149-X

(Bourque and Gignac, 1983; De Freitas and Dixon, 1995) and Devonian settings (Brachert et al., 1992; Wendt et al., 1997; Kaufmann, 1998), but this type of buildup is most widespread in the Early Carboniferous, in particular, in the Waulsortian facies of England, Ireland and Belgium (Bolton et al., 1982; Lees, 1988; Bridges et al., 1995). The name is derived from the village of Waulsort in the Dinant Syncline of southern Belgium and has subsequently been applied to similar constructions in other parts of the world, including the United States and Canada.

Despite the meticulous examination of many Waulsortian mounds of this period, several aspects of their setting, composition and geometry are still poorly understood. Due to negligible tectonic complications and the lack of vegetation, an ancient underwater scenery of mud mounds and associated deposits is exposed in the eastern Anti-Atlas of Morocco. This exposure provides new insights into the morphology, structure, and depositional environment of these types of carbonate buildups, which seem to have no modern analogues.

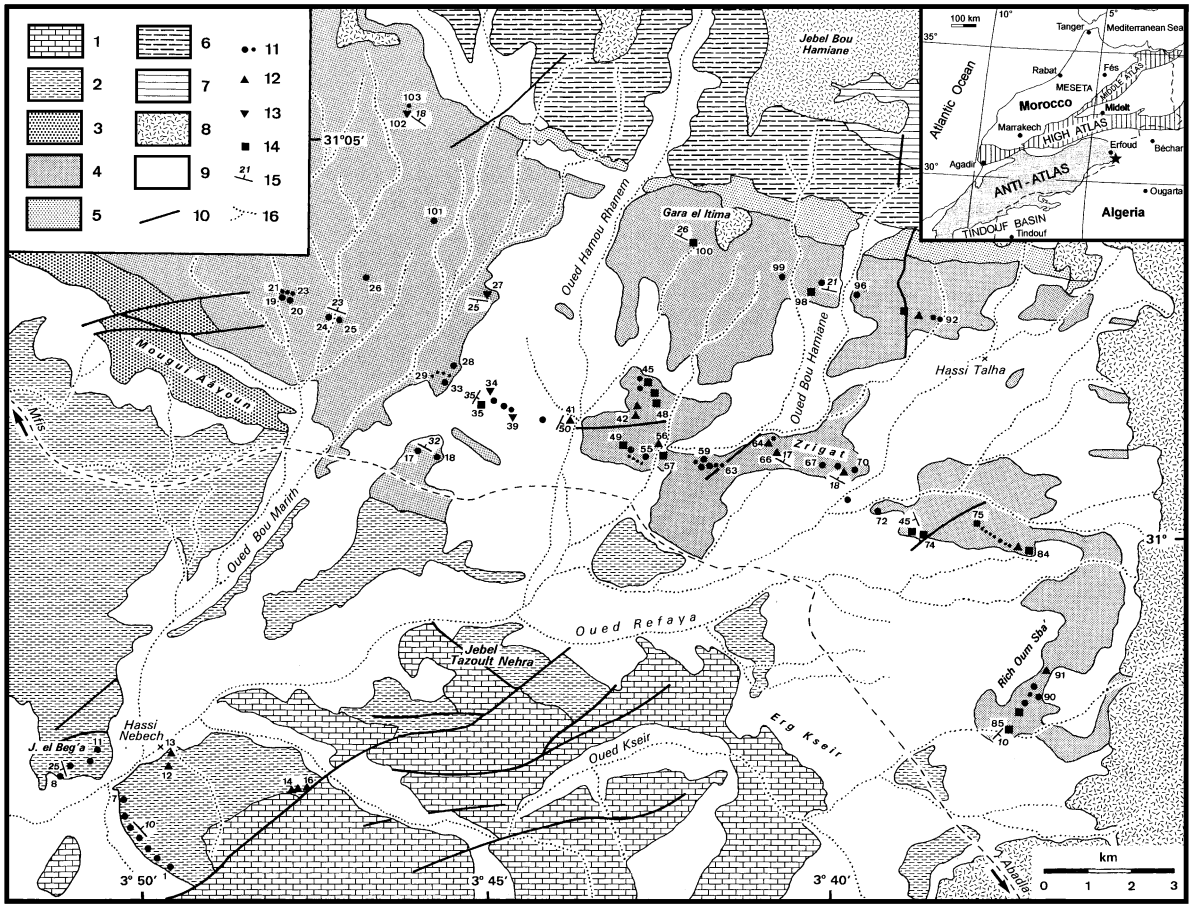

Fig. 1. Geological map of study area showing position of mounds. Geology after Destombes and Hollard (1986, simplified). Symbols: 1 = undivided upper Silurian to upper Famennian, 2 = Oued Znaigui and Merdani Formations, 3 = Mougui Ayoun Formation, 4 = Zrigat Formation, 5 = Itima Formation, 6 = Hamoui Rhanem Formation, 7 = Hassi Mhreimine Formation, 8 = Upper Cretaceous to Quaternary (Hamada), 9 = Quaternary sand and gravel, 10 = faults, 11 = larger and smaller type A mounds, 12 = type B mounds, 13 = type C mounds, 14 = type D mounds, 15 = strike and dip of strata, 16 = dry valleys (oueds). Inset shows location of study area (asterisk).

Fig. 2. Photograph of the mound area of Zrigat. Exhumed mud mounds in right centre (asterisks) and in upper left corner (arrows). Bedded intermound facies mostly covered by sand.

2. Geological setting

More than one hundred mud mounds of various sizes and shapes ranging from a few to about 30 m in height occur in an area of 440 km^2 in the Tafilalt Basin of Morocco (Fig. 1). Under the Upper Cretaceous to Quaternary cover of the Hamada du Guir, this basin may have been connected to the Béchar Basin of western Algeria from where similar mounds were described by Bourque et al. (1995). In the southeastern part of the Tafilalt Basin, a complete sequence from the upper Pridolian to the upper Visean is exposed. The Devonian sequence crops out in the southern zone and is fragmented by several WSW–ENE trending faults. The Carboniferous strata dip towards the NNE and are gently folded at their western and eastern extremities. On the basis of an average dip of 20°, a total thickness of the Tournaisian to upper Visean strata of 4000–5000 m can be calculated. Due to their predominantly shaly lithology, these deposits are easily eroded and largely covered by Quaternary sand and gravel. Only the more resistant arenaceous and carbonate members including the mounds stand out from the low-relief topography.

The mounds (previously referred to as "reefs" in the literature) of Jebel Bega in the southwestern part of the study area were first examined by Pareyn (1962) who recognized their stacking and their neighbourhood to fault breccias, and were later briefly mentioned by Hollard (1970). The much more numerous mounds farther north and east in the area of Zrigat have never been studied. They are only mentioned in Pareyn's (1962) monograph on the "Massifs carbonifères du Sahara sud-oranais" and on the 1:200,000 geological map by Destombes and Hollard (1986). A short account on the Zrigat mounds has been given by Belka and Wendt (1994). From their lithologic diversity, number and concentration in a relatively small area they represent one of the largest continuous mound agglomerations known so far from the Lower Carboniferous.

The mounds of this study are represented on the map of Fig. 1, which was compiled using air photographs in combination with 1:100,000 topographic maps and GPS data for each mound. Two disconnected mound areas can be distinguished (Fig. 1): (1) the area of an unnamed mountain southeast of Jebel Bega (mounds 1–7), Jebel Bega (mounds 8–11), and east of Hassi Nebech (mounds 12–16); and (2) the flat hilly area between the Mfis–Abadla track in the south and the escarpment of the Hamada du Guir (culminating in the Jebel Bou Hamiane and Gara el Itima) in the north. In the latter (with the locality Zrigat in the eastern centre, Fig. 2), 87 mounds ranging from a few to about 15 m high crop out. In addition, numerous smaller mounds, only 1–2 m high, are found in the vicinity of the larger ones. The bases of the larger mounds are always covered by recent sand and debris obscuring their relationship to the underlying bedded facies.

3. Stratigraphy

Destombes and Hollard (1986) divided the Lower Carboniferous succession of the southern Tafilalt Basin into several lithostratigraphic units. Mounds ("faciès calcaire construit", "calcaires récifaux et périrécifaux") are mentioned from the lower Visean Merdani Formation and from the upper Visean Zrigat Formation (Fig. 3). The biostratigraphic calibration of these formations by Destombes and Hollard (1986) was mainly based on goniatites some of which, however, were misidentified (Korn, pers. commun., 1999). A thorough biostratigraphic revision of the Lower Carboniferous succession of the Tafilalt Basin, which is the thickest, the most complete and the most fossiliferous one in the eastern Anti-Atlas, would be desirable, but this is beyond the aim of our study. Only the argillaceous Zrigat Formation, which includes the mounds, has been examined by us in more detail (Fig. 4). The dating of the mound and intermound deposits was generally achieved by means of conodonts. A few argillaceous levels in the vicinity of the mounds, in particular in the upper part of the Zrigat Formation, contain late Visean goniatites which have yielded more precise ages. Unfortunately, the conodont zonation of the Visean is still very rough and comprises only four zones for the entire stage (15 Ma according to Gradstein and Ogg, 1996), corresponding to an average duration of each zone of about 3–4 Ma. The conodont and goniatite data show that the Zrigat Formation comprises almost the entire Visean from the *Gnathodus texanus* into the lower part of the *Lochriea nodosa* Zone. Mounds are concentrated in six belts which

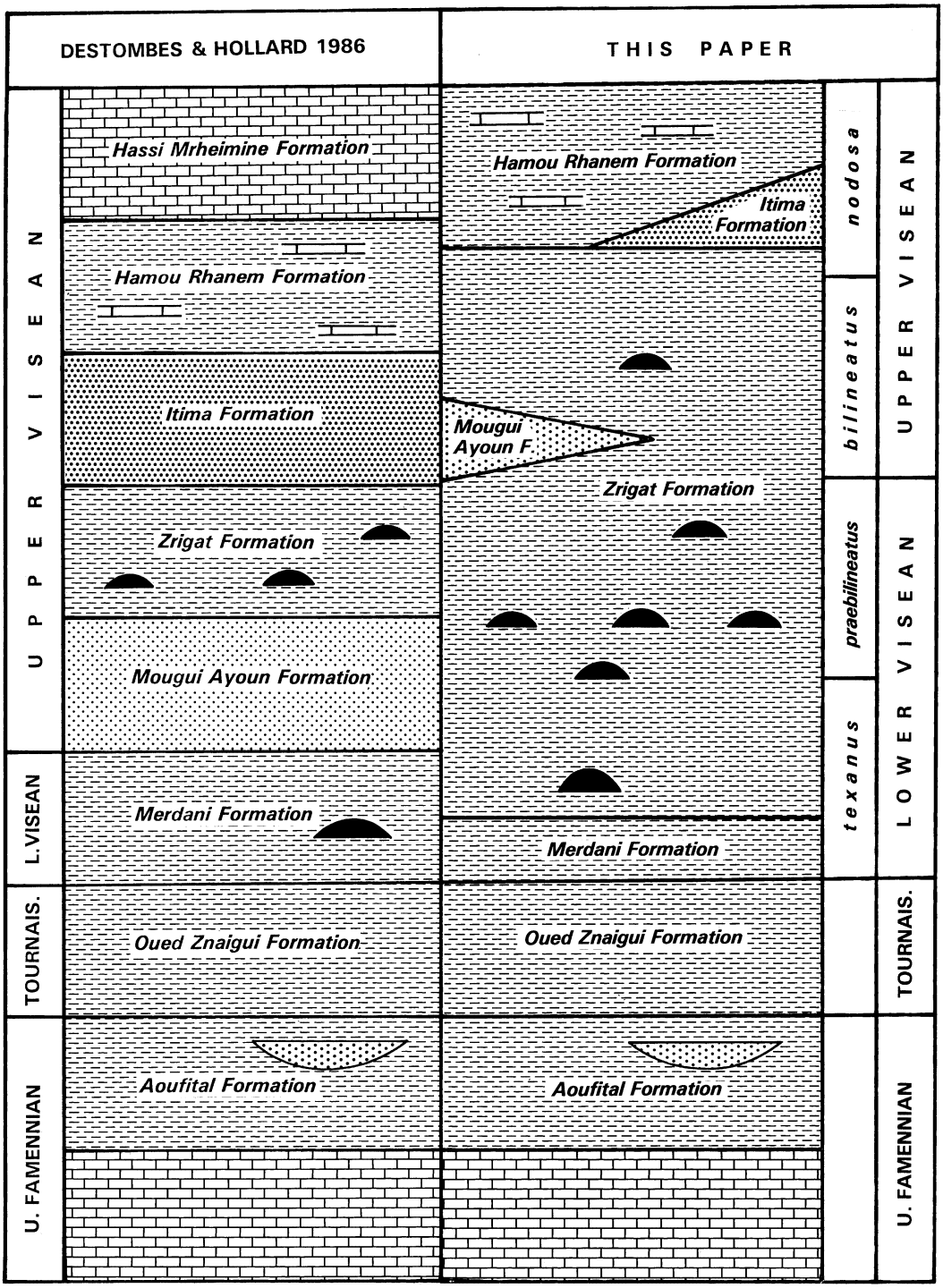

Fig. 3. Litho- and biostratigraphy of the Lower Carboniferous in the Tafilalt Basin.

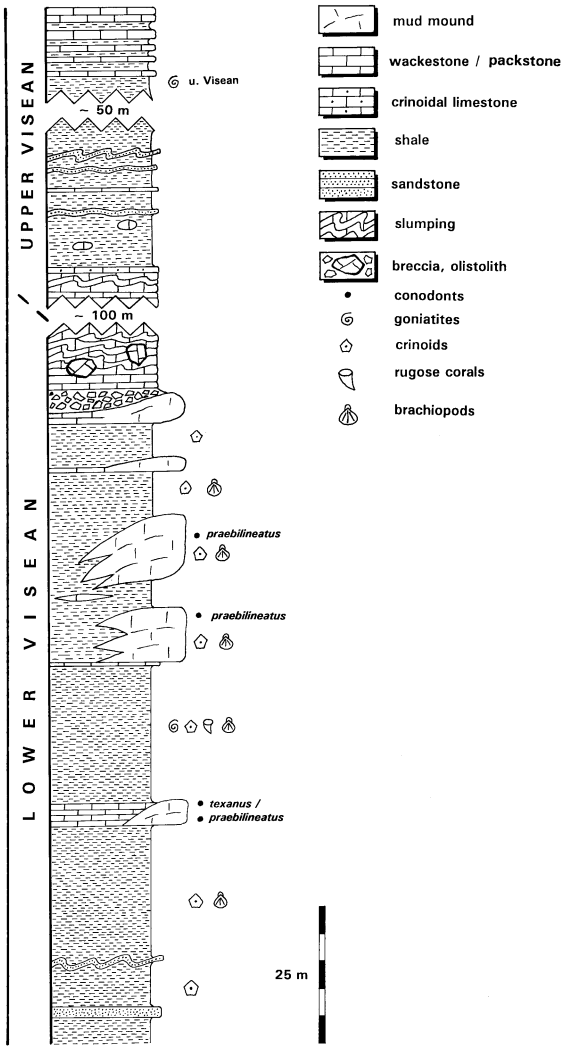

Fig. 4. Section of part of the Zrigat Formation near mounds 19–20.

comprise the interval from the *G. texanus* into the *G. bilineatus* Zone (Fig. 3):

(1) The mounds (1 to 11) of the Jebel Bega–Hassi Nebech area are the oldest. This area was mapped as lower Visean Merdani Formation by Destombes and Hollard (1986). Conodonts recovered from mound as well as from bedded carbonates at Jebel Bega indicate the lower Visean *G. texanus* Zone. The conodont fauna is quite abundant and dominated by two species of *Gnathodus*, *G. pseudosemiglaber* and *G. semiglaber*. In addition, *G. texanus* and a transitional form of *G. texanus* to *G. austini* were identified. Upsection, conodonts are rare, but this is characteristic for the lower and middle part of the Visean worldwide. During this time, conodonts underwent a low-diversity episode and were typically rare in basinal settings (Belka, 1990). The Jebel Bega mounds are underlain by shales and grainstones from which we have obtained conodonts of the upper Tournaisian *Scaliognathus anchoralis* Zone. Clariond (1954) has mentioned upper Tournaisian goniatites from the shales underlying the Jebel Bega mounds. Both lines of evidence suggest that this mound belt was formed during the lower part of the *G. texanus* Zone.

(2) Mounds 17 and 18 constitute a short (600 m) belt which could not be precisely dated, but according to its more southerly position with respect to (3) it must be slightly older than the latter, possibly late *G. texanus* or early *G. praebilineatus* age.

(3) The main belt of the Zrigat mounds is 18.5 km long and extends from mound 19 in the west to mound 84 in the east. Numerous conodont samples from the mounds, as well as from the underlying and overlying intermound lithologies are indicative of the *G. praebilineatus* Zone (Fig. 4). Samples from this belt contain a fauna with *G. preabilineatus*, *L. commutata*, *Vogelgnathus campbelli*, and a gnathodontid element apparently belonging to a new species. In one sample, specimens of *G. praebilineatus* show morphological features which are transitional to *G. bilineatus*. Such transitional forms are known from both the *G. praebilineatus* and the *G. bilineatus* Zone. Because of the lack of *G. bilineatus*, we interpret this fauna as belonging to the *G. praebilineatus* Zone.

(4) The NE–SW trending belt of Rich Oum Sba' (mounds 85–91) can be interpreted as a southward continuation of the Zrigat belt caused by a tectonic flexure. Conodont recovery from these easternmost mounds is poor but suggests a *G. praebilineatus* Zone age as well.

(5) A few scattered mounds (26, 27, 42–48, 101) occur within the approximately 4 km wide zone between (4) and (6) and therefore could be slightly younger than (4). Conodont data from this area are imprecise and allow only a rough attribution to the early Visean.

(6) The northernmost belt comprises mounds 92 to 103. As yet, this belt cannot be firmly dated. A single productive sample contains *G. girtyi girtyi* and can

tentatively be assigned to the *G. bilineatus* Zone of the early upper Visean. Goniatite faunas collected from the shales overlying this belt show that the Zrigat Formation extends into the lower part of the *L. nodosa* Zone (Korn, pers. commun., 1999).

4. Mud mounds

4.1. Morphology

Because they are massive and more resistant to erosion than the surrounding shales, the mounds of belts 2 to 6 stand out from their peneplained surroundings (Figs. 2, 5(A),(B), 6(A)–(C)). Erosion has overprinted almost all original mound surfaces, in particular on the southern faces which, due to the general NNE-dip of the strata, are more exposed and hence more deeply destroyed by fracturing (e.g., mound 50, Fig. 5(B)). Some mounds, however, have preserved primary surfaces, from which, after rotation to the horizontal, their shapes and original slopes can be reconstructed (Figs. 6(C) and 7(B)).

The mounds of belts 2 to 6 do not exceed elevations of 20 m and are commonly only 5–10 m high. Additional amounts removed by erosion seem to have been insignificant. Judging from the diameter of the mounds, the preserved slopes and the distance of the onlapping strata from the actual peaks, only a few metres appear to be missing from the original total elevation. Preserved slopes show gentle dips of 10–20°; in only a few places do dips of up to 37° occur. The most complete mounds display an elongate shape with a length/width ratio of 2:1. Mound 98 shows steeper western and eastern than northern and southern flanks (Fig. 7(B)), but in mound 100, the southern flank is steeper (33–35°) than the northern one (8–11°). The cause of these asymmetries remains uncertain because no uniform relation to bottom currents (see below) can be proved. The exposed bases of the mounds range from a few metres in the small mounds of type A to about 300 m in the largest examples of the same type as well as in type B. The mounds of Jebel Bega reach elevations of up to 30 m (Fig. 5(A)), but their original shape is less evident because of the recent sand cover and widespread rockfalls, which are partly of synsedimentary origin (see below). They have transformed the entire area into a tumble of huge blocks, which also include sandstone boulders of probable Tournaisian age.

4.2. Types

Based on their lithology, shape, and facies relationships, four types of mounds (Fig. 7(A),(B)) can be distinguished in the field. Due to the general NNE dip of the strata, the southern faces of the mounds are more deeply eroded, thus exposing the mound cores. Apart from type C (see below), no obvious regularity in the spatial distribution of the different types can be recognized. Types A, B, and D occur side by side within one and the same belt. Only at Jebel Bega and its southeastern prolongation are type A mounds present alone.

Type A (Figs. 5(A),(B), 6(A), 7(A)) consists of massive or faintly bedded crinoidal wackestone to packstone with various accessory faunal elements. Stromatactoid structures are absent. Intercalation of and lateral transition into debris-flow deposits is locally observed. Mounds 21–23 and 26 are dolomitized. This is the most common mound type and in the Zrigat area, it attains elevations of 15–20 m. The largest mounds occur at Jebel Bega where they reach elevations of up to 30 m. Smaller (1–5 m high) mounds of the same lithology are often intercalated in the over- and underlying strata.

Type B (Figs. 6(B) and 7(A)) is similar to type A, but distinguished by infrequent typical stromatactis cavities (Fig. 6(D)). The latter are generally small (several centimetres across), rarely decimetres in size. These mounds are up to 15 m high and have base diameters of 50–300 m. The mound slopes appear more gentle than those of type A.

Type C (Fig. 7(A)) is lithologically identical to type B but the orientation of stromatactis cavities show that it is allochthonous. Geopetal fillings reveal rotations of the mounds up to 90° with respect to the under- and overlying mudstones. Only four mounds (27, 34, 39, and 102) belong to this type. They are aligned in a NNW–SSE direction, suggesting that they are derived from the same source area. It cannot be excluded that some mounds of type B are also allochthonous, because their relationships to underlying strata could not be clearly established.

Type D (Figs. 6(C) and 7(B)) consists of bioclastic (generally crinoidal) grainstone or packstone, in some

A

B

places (mounds 84–86, 95) associated with ooids. Stromatactis cavities are absent. Some mounds show a faint cross-bedding, indicating currents from the north. Elevations are generally in the order of a few metres, but may attain 30 m (mound 49). Where preserved, flanks show slopes of up to 35°. Mounds 49 and 84 show a lateral transition of crinoidal grainstones into debris-flow breccias. This type corresponds to the biodetrital mounds of Bosence and Bridges (1995) or to the skeletal mounds of James and Bourque (1992).

4.3. Lithofacies

The main sedimentological features of the mound and intermound facies are summarized in Table 1. This compilation shows that the mounds consist of wackestones and packstones, with the exception of type D (which is not a mud mound) where grainstones prevail.

Note that *ooids* (Fig. 8(A)) are restricted to mound type D and the intermound lithologies and point to a source not related to that of mud mounds. The diameters of the ooids range from 0.9 to 1.2 mm; the internal structure shows numerous laminae and a radial pattern of calcite crystals suggesting a primary (Mg?) calcitic composition.

Apart from skeletal remains (see below), *peloids* (Fig. 8(B)) are the most common constituent in the majority of the mud mounds, but are almost lacking in the intermound facies. Their size shows a wide range from 0.03 to 0.35 mm in diameter, suggesting that these particles are of various origins. Most abundant are peloids of 0.03–0.06 mm size, which exhibit diffuse margins and merge into the fine-grained cement or the microsparitic matrix, giving the matrix a clotted appearance. It has been argued by numerous authors (e.g., Pratt, 1995; Pickard, 1996) that these peloids are not true allochems but rather precipitates within a microbial mat or biofilm. This interpretation is supported by the fact that this kind of peloid is restricted to mound types A, B, and C, but is absent from type D, as well as from the intermound strata. Larger peloids with diameters of 0.12–0.35 mm are generally associated with intraclasts and can be considered as true allochems, likely faecal pellets.

In contrast to the rare micrite envelopes which penetrate into skeletal fragments and are best observed in crinoid remains (Fig. 8(C)), *microbial crusts* are encrustations on allochems. They consist of dark, mostly structureless, sometimes faintly laminated micrite (Fig. 8(D)). Similar but thicker micritic crusts line stromatactis cavities and may also be of microbial origin.

Stromatactis, spar-filled cavities which are the most typical and widespread feature of carbonate mud mounds, are surprisingly rare in the Visean mud mounds of the Tafilalt area and are restricted to mound types B and C. They are represented as isolated features, not networks as in most other mud mounds. In general, they are filled with one generation of blocky calcite cement only and show the typical flat base and digitate roof (Fig. 6(D)). Such an outline (in combination with other geopetal patterns) shows that mound type C is clearly allochthonous. For the origin of the stromatactis cavities, we favour the interpretation of Lees (1964) who considered them as left behind after the decomposition of soft organic matter, possibly microbial mats.

A coarse *bedding*, preserving the form of growth surfaces of the mounds, is observed in mound types A, B, and C, and is best expressed in type A (Figs. 5(A) and 6(A)). From the centroclinal strike of these bedding planes, the primary inclinations of mound surfaces can be traced (Fig. 7(B)). Mound type D exhibits a more regular bedding, occasionally also a faint cross-bedding indicating sediment transport. Some calcareous intermound strata show indistinct graded bedding, but sole marks typical of turbiditic sequences are very rare. Slumps have been found in several sandstone and mudstone levels in intermound strata (Fig. 4). Similar gravitational deformation of decimetre-thick wackestone and packstone units, but of more limited extent, are obvious in some strata onlapping some major mud mounds (e.g., mound 66, Fig. 7(A)). The axes of these slumpfolds run more or less parallel to the mound surfaces, thus documenting the still existing relief of the underlying mound after

Fig. 5. Type A mounds. (A) Erosional remnant of mound (no. 9) at Jebel Bega. Indistinct bedding reflects gentle slope on left and steeper on right flank. Person (1.85 m) for scale (arrowed). (B) View from mound 55 (steep flanks are an erosional feature) to mound 50 (type A, approximately 15 m high).

termination of its growth. Locally, a younger generation of small (1–2 m high) mounds was directly established on this gravitationally deformed substrate (Fig. 7(A)).

Some mounds of type A (9, 24, 71) and D (49, 84) pass laterally into or are overlain by bioclastic wackestone-supported *breccias* which bear all the characteristics of debrites (Fig. 6(F)). The angular to poorly

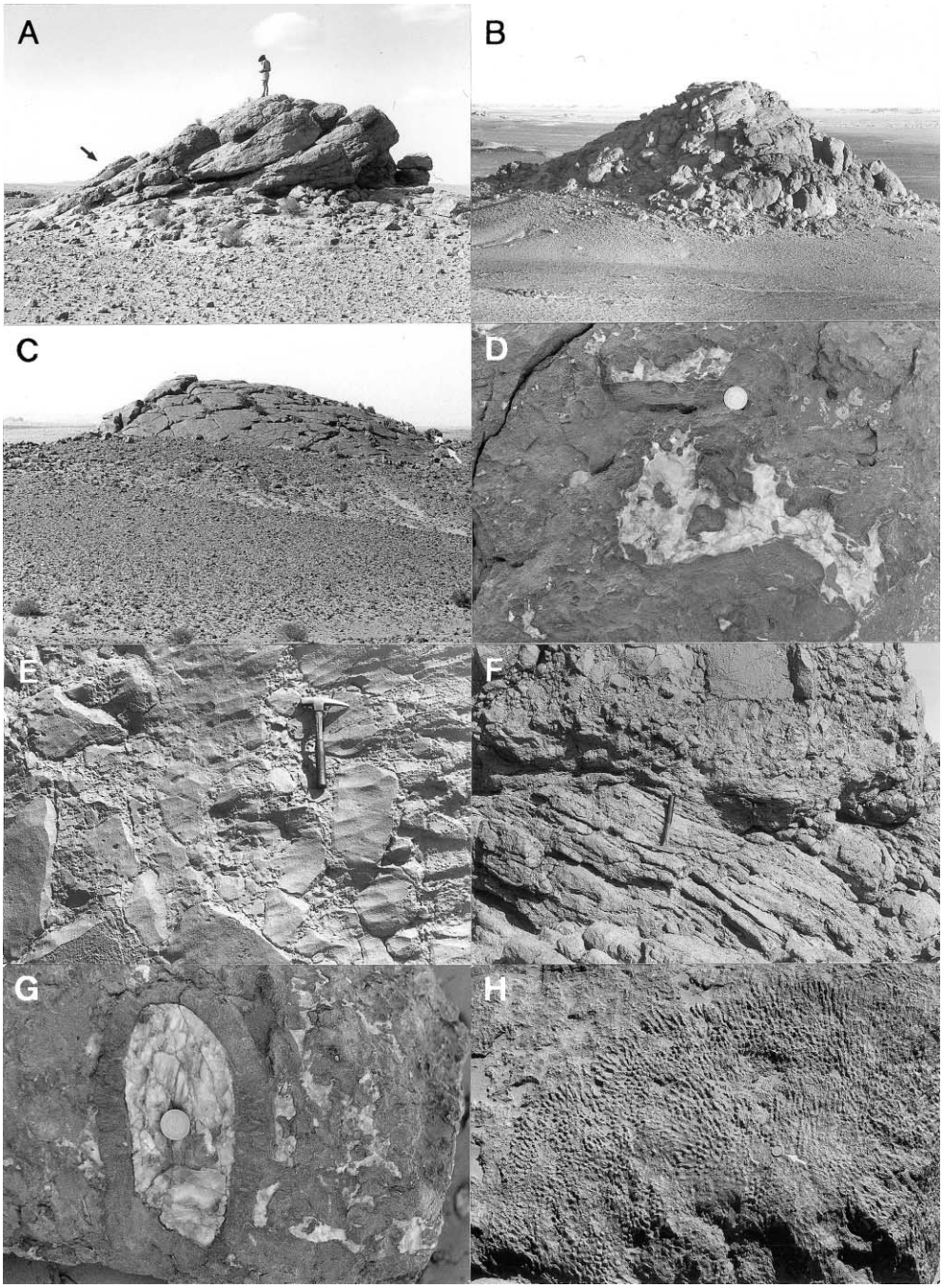

Table 1
Relative abundance of sedimentological features in mound types A–D and in intermound strata

Lithology	Mound type				Intermound
	A	B	C	D	
Mudstone					□
Wackestone	■	■	■		○
Packstone	■	●	●	●	□
Grainstone				■	□
Sandstone					□
Siltstone/shale					■
Ooids				□	○
Microbial peloids	□	●	●		
Other peloids	●	●	●	□	□
Intraclasts	□	●	□	□	●
Lithoclasts	□	□	□	□	○
Micrite envelopes	○	○		○	○
Microbial crusts	□	□	□	●–○	●
Fibrous cement		○	○		
Syntaxial cement	○	○		●	□
Blocky cement	●	■	■	●	●
Dolomitic cement	○	□	□		
Dolomitization	□			○	□
Stromatactis		□	□		
Planar bedding	□	○	○	●	■
Cross-bedding				□	○
Graded bedding					○
Debris-flow deposits	□			□	○
Slumping					□

■ = very common, ● = common, □ = rare, ○ = very rare, faint.

rounded clasts range from a few millimetres to several decimetres in size. Clast lithology is similar to that of the adjacent mounds and suggests that the mounds were the source of the transported material. Breccias with larger components up to 3 m across were observed at several sites at Jebel Bega, in particular near the eastern extremity of the mountain (Fig. 6(E)). In this case, all clasts are angular and show no evidence of significant lateral transport, and matrix sediment is minor. We interpret this breccia, which is in sedimentary contact to the adjacent mound 11, as a submarine rockfall close to a steep fault scarp.

4.4. Biota

The distribution and relative abundance of skeletal remains of mound and intermound strata (Table 2) were compiled from field observations and thin sections.

Apart from two fragments of dasycladacean thalli in one sample from mound 25 (type A), indubitable remains of *calcareous algae* have not been found. Rather common are fragments of *Fasciella fusa* (Kulik) (Fig. 8(E)), a problematic genus which is generally attributed to the Rhodophyta. Mamet (1991), however, did not exclude a chlorophyte affinity. Other Problematica, which occur sporadically in mound types B and D, include *Aphralysia*, interpreted by Belka (1981) as a foraminifer, but by Mamet and Roux (1975) as a chlorophyte, as well as *Stacheoides* and *Rothpletzella*.

A variety of vase- to ball-shaped *demosponges*, some up to 0.5 m in diameter, have been encountered in all environments and are most common in type B and C mounds (Fig. 6(G)). Within the mounds, they are generally in situ but appear transported where found in the intermound strata. Their preservation within the mounds suggests rapid burial by the accumulation of mud. Millimetre-sized spicules occur in mound types B and C as well as in the intermound facies. An undeterminable pharetronid was found in a thin section from mound 13 (type B) and a chaetetid in the shales underlying mound 19. These two exceptional discoveries confirm that coralline sponges did not significantly contribute to mound construction here.

Small cylindrical *worm tubes* are observed in mound types B and C only. The tubes are several millimetres long with internal diameters of 0.5–1.5 mm and external diameters of 1.5–4 mm (Fig. 8(F)). The inner surface is well-defined while the outer is faint and grades into the surrounding matrix. The tube wall is darker, probably due to a higher organic

Fig. 6. (A) Example of type A mound (no. 33). Note wedging-out of thick-bedded mound strata toward left with remnant of onlapping crinoidal grainstone covering mound flank (arrowed). (B) Example of type B mound (no. 66), approximately 15 m high. Intermound beds covered by gravel. (C) Exhumed flank of type D mound (no. 98). Person (kneeling) for scale (arrowed). Compare Fig. 7(B). (D) Stromatactis cavity, filled with one generation of blocky spar. Type B mound (no. 69). Coin diameter is 24 mm. (E) Synsedimentary fault–scarp breccia with angular clasts near mound 11 at Jebel Bega. (F) Debrite overlying well-bedded crinoidal wackestones which onlap type A mound south of Jebel Bega. (G) Transverse section of large demosponge. Type B mound (no. 69). Coin diameter is 24 mm. (H) Large colony of *Lithostrotion*. Type A mound (no. 17). Coin (24 mm in diameter, arrowed) for scale.

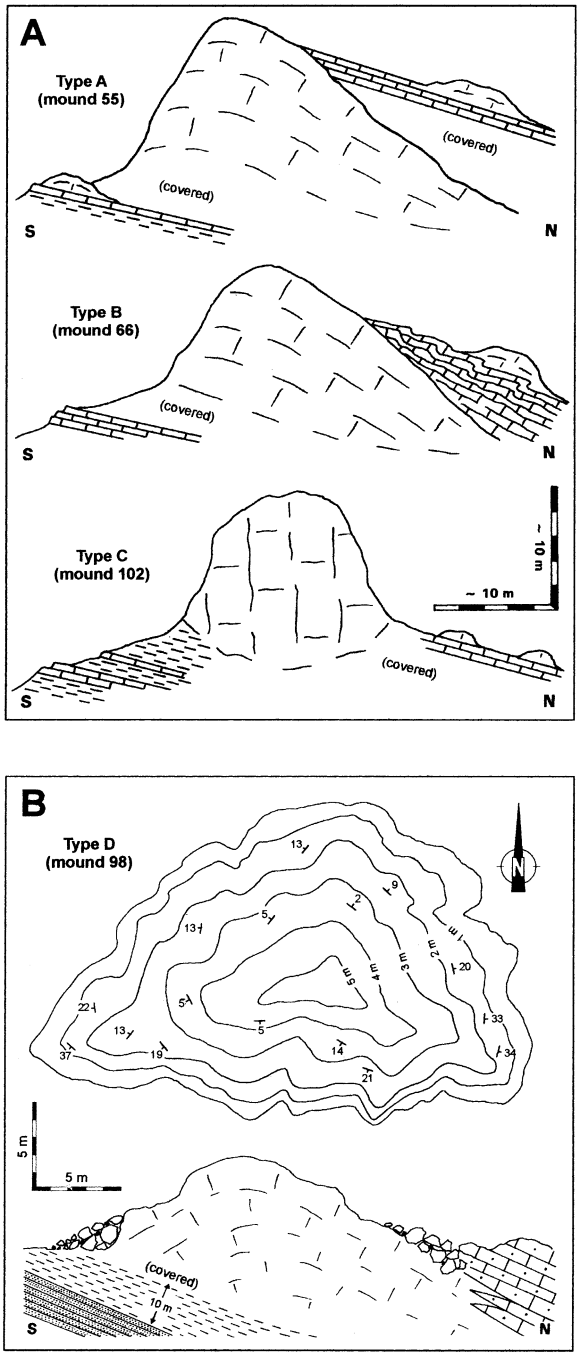

Fig. 7. (A) Simplified sketches of type A, B, and C mounds. (B) Topographic map and profile of mound 98 (type D). Note interfingering and onlapping of crinoidal grainstones and more steeply dipping eastern/western than northern/southern flanks. Compare with Fig. 6(C).

Table 2
Relative abundance of skeletal remains in mound types A–D and in intermound strata

Taxa	Mound type				Intermound
	A	B	C	D	
Red algae (?)	□	□	●		□
Foraminifera	○	△	△	○	○
Demospongea	□	●	●	□	□
Coralline sponges		△			
Sponge spicules		□	□–●		□
Worm tubes		□	●		
Tabulata	△				△
Solitary Rugosa	△–□	□	□		●
Colonial Rugosa	○			△	●
Brachiopoda	□			△	□
Bryozoa	□–●	□	□	●	●
Pelecypoda		△		△	
Gastropoda		△		△	△
Cephalopoda		△	△		□
Crinoidea	■	●	●	■	■
Echinoidea	△	△			△
Ostracoda	○	○			
Conodonta	○	○	○	△	○
Trace fossils					○

■ = very common, ● = common, □ = rare, ○ = very rare, △ = iso-isolated specimens.

content, and consists of a clotted micrite with some calcite grains and sponge spicules. The tubes thus resemble *Terebellina*, an agglutinated polychaete worm tube which has been mentioned from Lower Carboniferous (Warnke, 1994; Pratt, 1995) as well as from Upper Triassic (Wendt et al., 1989) and Upper Jurassic sponge-rich mud mounds (e.g., Schorr and Koch, 1985).

Corals: One specimen of *Michelinia* and two favositids were found in three intermound localities. A few colonies of *Lithostrotion* were observed in mound types A and D (Fig. 6(H)); the same or a related genus is more common in the intermound facies. Solitary Rugosa are always present but rare; at Jebel Bega, some of them attain a length of 0.5 m. In the shales underlying the main mound generations near mounds 19–20 (Fig. 4), a more diverse fauna of Rugosa was collected which comprises *Cyathaxonia* and *Dibunophyllum*, as well as lophophyllids, hapsiphyllids, and caniniids, which indicate moderate water depths of some tens of metres (Kullmann, 1997).

Brachiopods are rare and have not been found in mound types B and C. Rare single-valved and fragmented specimens were collected from the shales underlying mounds 19–20 (Fig. 4). The fauna comprises the following taxa: *Spirifer taigensis* (Besnossova), *Neospirifer fascicostatus* (Menchikoff), *Crenispirifer* sp., *Actinoconchus lamellosus* (Leveille), *Schellwienella* sp. and *Linoproductus* sp.

Fenestrate *bryozoans* are common in the majority of the mounds as well as in the intermound facies. Much rarer are ramose and massive Trepostomata.

Some scattered indeterminable *cephalopods* were found in mound types B and C. A more abundant fauna was collected from the shales underlying mound 99. This goniatite fauna appears almost monospecific and contains *Goniatites* cf. *stenumbilicatus* Kullmann, indicating a late Visean age (corresponding to part of the *G. bilineatus* Zone).

Crinoids are by far the most common skeletal elements in the mound as well as in intermound strata. Stem fragments in the intermound strata are sometimes still partially articulated and current-oriented indicating N–S currents. Holdfasts have never been observed and only a few indeterminable calyces were found. We assume that the abundance of crinoid fragments in the bedded facies underlying the mounds is derived from thickets which may have served as a substrate for the foundation of the mounds.

Overall, there is no principle difference in the faunal composition between mound types A to D, which can be distinguished only by their microfacies and depositional features. In contrast to the mounds, the intermound facies appears more fossiliferous, because of the ease in which solitary and colonial Rugosa and goniatites weather out from the shales in the vicinity of the mounds.

4.5. Diagenesis

Diagenesis of the mud mounds include sparse early marine cementation, alteration of micrite matrix and bioclasts, and late burial cementation (Table 1). Surprisingly, a first wall-lining generation of isopachous, fibrous calcite cement, so characteristic of stromatactoid cavities in Palaeozoic mud mounds, is rare or so thin that it cannot be sampled. Likewise, a sequence of shallow-burial dog-tooth cements followed by bright-cathodoluminescent cements is absent. Most cavities are filled by clear, ferroan, blocky calcite cement. The reason for the scarcity of

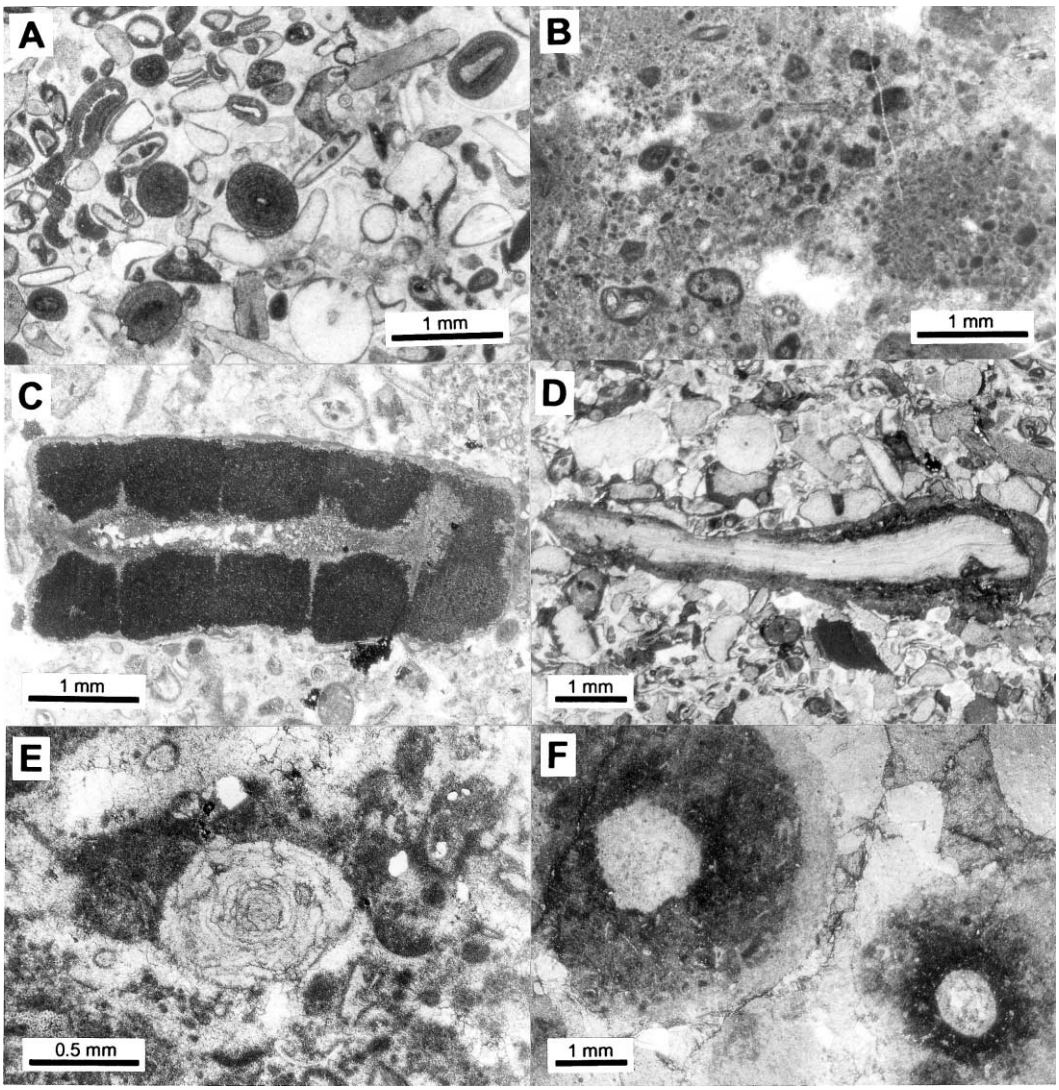

Fig. 8. Microfacies. (A) Oolitic, bioclastic grainstone. Type D mound (no. 85, thin section M 743/1). (B) Peloidal texture. Type C mound (no. 39, thin section M 736b). (C) Crinoid ossicle with micrite envelope (crossed-nicols). Type D mound (no. 84, thin section M 720). (D) Crinoidal grainstone with brachiopod valve surrounded by microbial crust. Type D mound (no. 84, thin section M 747). (E) Microproblematicum *Fasciella fusa*, possibly a red alga. Type B mound (no. 69, thin section M 756a). (F) Worm tubes (cf. *Terebellina*). Type C mound (no. 102, thin section M 726/3a).

early marine and shallow-burial cement is uncertain. Possibly, the stromatactoid cavities represented restricted diagenetic environments with permeability too low for high rates of circulating porewater required for early marine cementation. This interpretation is favoured by the lack of interconnection between individual cavities as observed in the field (Fig. 6(D)).

Stable oxygen and carbon isotope data of brachiopod shells, normally indicative for isotopic compositions of ancient seawater, plot in a large field of $\delta^{18}O = -6.0‰$ to $-0.9‰$ PDB and $\delta^{13}C = -3.7‰$ to $+4.9‰$ PDB (Fig. 9). Such a high scattering of values does not allow any reliable statements about the stable-isotopic composition of the ambient seawater. However, the heaviest (and hence, the least

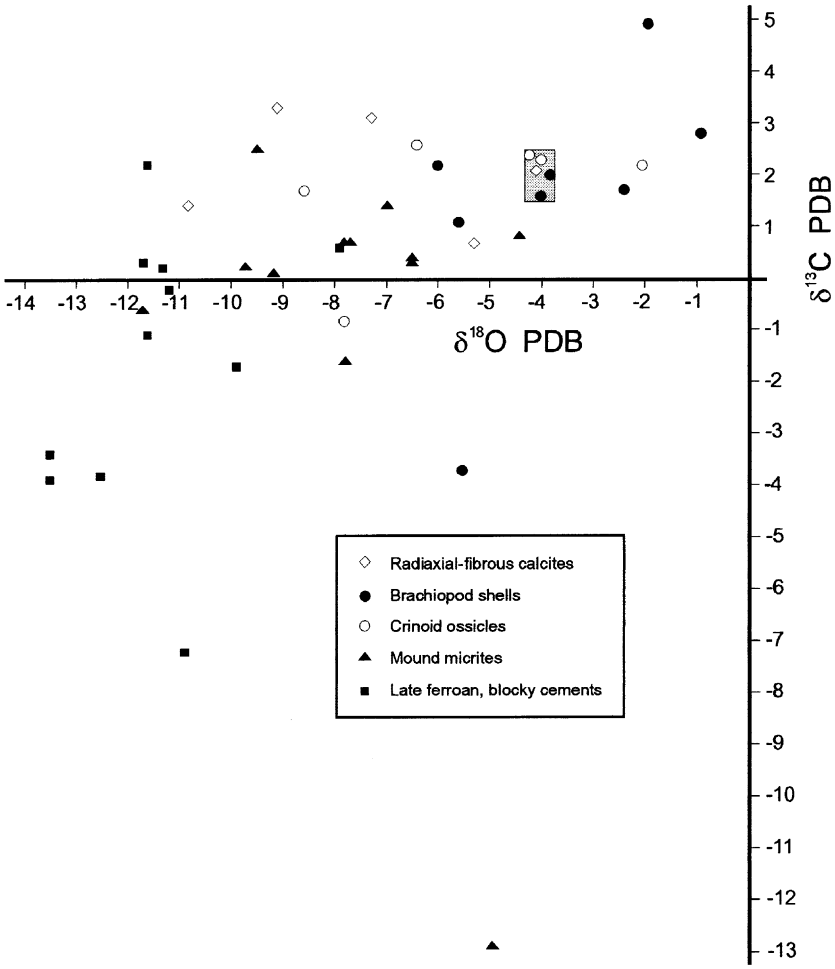

Fig. 9. $\delta^{18}O$ and $\delta^{13}C$ plots of calcite cements, micrites, and skeletal components of the Visean mud mounds in the Tafilalt Basin. Shaded rectangle marks the suggested stable-isotopic composition of Visean seawater in the eastern Anti-Atlas.

diagenetically altered) values of one of the rare fibrous marine cements and two crinoid ossicles lie within the brachiopod field between $\delta^{18}O = -4.2‰$ to $-4.0‰$ PDB and $\delta^{13}C = +2.1‰$ to $+2.4‰$ PDB (Fig. 9). Together with two neighbouring brachiopod values, a narrow field of $\delta^{18}O = -4.2‰$ to $-3.8‰$ PDB and $\delta^{13}C = +1.6‰$ to $+2.4‰$ PDB (Fig. 9) is suggested as a rough estimate of the stable-isotopic composition of Visean seawater in the eastern Anti-Atlas. It corresponds approximately to upper Visean brachiopod values of western Europe (Bruckschen and Veizer, 1997).

Most carbonate components, especially micrite matrix, bioclasts (with the exception of brachiopod shells and crinoid ossicles) and fibrous marine cements have been subjected to strong diagenetic alteration. This is revealed by a rather uniform dull to moderate cathodoluminescence and significant Fe uptake indicated by potassium ferricyanide staining. This is expected in the deep-burial realm. Stable-isotope values of fibrous cements, micrite matrix, and crinoid ossicles plot in a field of $\delta^{18}O = -11.7‰$ to $-4.0‰$ PDB and $\delta^{13}C = -1.6‰$ to $+3.3‰$ PDB (with the exception of a single deviation value of $\delta^{13}C = -12.9‰$

PDB) (Fig. 9). The carbon signature suggests that the system was buffered by the host rock, while the oxygen signature points to a variable amount of diagenetic alteration by hot diagenetic fluids.

With few exceptions, clear, ferroan, blocky calcite cement fills the stromatactoid cavities. Deep-blue potassium ferricyanide stain indicates Fe concentrations in excess of 1000 ppm (Kaufmann, 1997; p. 945). Such a high Fe content is the result of strongly reducing redox conditions with Fe^{2+} in solution most likely derived from clay minerals. Stable-isotope analyses plot in a field of strongly depleted $\delta^{18}O$ values (−13.5‰ to −7.9‰ PDB) and slightly depleted $\delta^{13}C$ values (−7.2‰ to +2.2‰ PDB). $\delta^{18}O$ values are 3.7–9.5‰ lighter than the estimated marine composition (see above). By simply assuming increased porewater temperature as the main controlling factor for the depleted $\delta^{18}O$ values, estimates for the precipitation temperatures and the burial depth can be made (e.g., Lavoie and Bourque, 1993; Kaufmann, 1997). According to the oxygen–isotope fractionation curve of Friedman and O'Neil (1977), a 10 °C increase in temperature causes a negative $\delta^{18}O$ shift of about 2.0‰. The observed shift of 3.7–9.5‰ thus corresponds to an increase in temperature of 18.5–47.5 °C. Assuming a normal geothermal gradient of 30 °C/km in the Tafilalt Basin, 600–1600 m of burial are required to accommodate the oxygen–isotope values of the ferroan blocky calcite cement. Based on stratigraphic reconstruction, such a burial depth certainly was reached during the Visean. The decrease in $\delta^{13}C$ is probably caused by thermocatalytic decarboxylation of organic matter in burial depths of several hundred metres (Irwin et al., 1977), which releases ^{12}C-enriched CO_2 into porewaters.

4.6. Thermal maturation

The predominantly siliciclastic Lower Carboniferous sequence of the Tafilalt Basin constitutes the upper part of the Palaeozoic sequence of the eastern Anti-Atlas and thus its thermal overprint is less than that of the Devonian (Belka, 1991). New conodont CAI data obtained from the Visean mud mounds and carbonate interbeds reveal a thermal maturity trend with a decrease in CAI towards the northeastern part of the basin. The highest CAI values of 3–3.5 are recorded in the south, in the carbonates of the *G. texanus* Zone, exposed in the area around Jebel Bega. Towards the north, the rocks of the *G. praebilineatus* Zone, which comprise the third Zrigat belt yield values of CAI 2.5–3. At the western end of this belt, however, conodonts have values of CAI 3, whereas in an easterly direction, at Zrigat proper, the CAI values are slightly lower and range from 2.5 to 3. Only a single value of 2.5 is available from mound 94 in the youngest belt, which is attributed to the *G. bilineatus* Zone.

This thermal maturity trend with a decrease in CAI up-sequence, confirms the interpretation of Belka (1991) that the thermal maturity pattern recognized in the Palaeozoic of the eastern Anti-Atlas is due simply to depth of burial. Regional data suggest that it must have been attained prior to late Variscan basin inversion. Assuming that the unloading began after the Westphalian C (Belka, 1991), the period for burial and heating of the Visean strata was thus no longer than 35 Ma. Hence, a range of burial palaeotemperatures between 100 and 170 °C can be estimated for the Visean strata of the Tafilalt Basin. The least degree of burial is displayed by rocks in the northeastern part of the basin.

5. Discussion and conclusions

5.1. Conditions of mound growth

In contrast to most other mid-Palaeozoic mud mounds, the Visean mounds of the eastern Anti-Atlas are intercalated in a predominantly shaly basinal sequence. Though the base of the prominent mounds is always concealed by Quaternary sand or gravel, it can be suspected that they were not established directly upon clayey sediment. The substrate of small (1–2 m high) mounds is often better exposed and consists of stratified crinoidal wackestones or packstones, which in turn onlap or underlie the larger mounds. Therefore, it can be assumed that the debris of crinoid thickets, which apparently flourished at repeated sea level lowstands (see below), formed suitable substrates for mound growth. This growth was achieved by a rapid in situ precipitation of fine-grained carbonate, which in mound types A, B and C were probably of microbial origin. This source of carbonate production is suggested by the predomi-

nantly peloidal or clotted fabric of the mound micrites and by interpreted microbial encrustations of skeletal grains. We suspect that these cavities represent the open space left behind after the decay of microbial matter. It seems very unlikely that siliceous sponges, often invoked for the formation of stromatactis (Bourque and Gignac, 1983; Davies and Nassichuk, 1990; Bourque and Boulvain, 1993; Warnke, 1994) previously occupied these spaces. Sponge remains are by far too rare in the mound micrites to support such an interpretation (Pratt, 1986). Moreover, sponges never show the outlines and shapes of stromatactis.

Once deposition of mound carbonates had initiated, it continued without noticeable vertical and lateral differentiation. Because of the scarceness of flank debris, the mounds could not prograde laterally like many reefs and platforms. Therefore, a more or less conical shape was the only possible growth form of these mud mounds.

Sessile organisms, in particular fenestrate bryozans, and to a lesser degree demosponges, crinoids, polychaetes, and problematic microorganisms settled on the mound surfaces or were engulfed by the carbonate precipitation, but did not significantly contribute to mound accretion. The apparent lack of vertical and lateral organic zonation within the mounds may be explained by the limited size of the mounds, which did not offer particular ecologic niches and/or bathymetric gradients.

The mounds were probably constructed within the lower range of the photic zone where photosynthetic calcimicrobes were still active, but other photosynthesis-dependent organisms such as calcareous (in particular green) algae were absent or scarce. For these reasons, a water depth of several tens to a maximum of about one hundred metres seems feasible. Nowhere did the mound tops reach higher levels within the photic zone in which coral-sponge/green algae dominated associations could develop (equivalent to phase D in Lees and Miller, 1985).

This model can be applied to mound types A to C only. Type D mounds are totally different and do not represent mounds in the strict sense. As stated above, this type consists of well-sorted grainstones with only minor amounts of micritic matrix, yet a conical shape was produced. It is the result of a mere mechanical accumulation of carbonate grains, probably near the storm wave base.

5.2. Sedimentary environment

A thorough bio- and sequence-stratigraphic study of the rather monotonous 4000-m-thick basinal succession is made difficult by the widespread cover of Quaternary sand and gravel. These shale and siltstone units with some intercalated crinoidal packstones and grainstones crop out only in some dry valleys (oueds) and in the vicinity of the mounds. Nevertheless, there is clear evidence for a cyclic development of mud mounds. They are concentrated within four (if not more) belts, the exact biostratigraphic attribution of which could not be established with utmost precision because of the relatively long range of Visean conodont zones. We interpret these belts as related to lowstands within several shallowing-upward cycles.

Shales with uncommon mud- and sandstone intercalations represent deep-water deposits which, apart from rare radiolarians, calcispheres and sponge spicules are almost devoid of skeletal remains. Towards the top of each cycle, the shales become more fossiliferous (brachiopods, corals, and others) and intercalations of crinoid wackestones and packstones appear which, in turn, may have formed the substrate for mound construction.

The spatial coexistence of mound types A, B, and D (C is discussed below) in the same facies belt is enigmatic. One would expect a bathymetric gradient as the principal reason for the lithologic diversity of the mounds, but this seems not to be the case. Rather, it can be speculated that adjacent mounds have slightly different ages and that the hydrodynamic regime changed within time intervals which cannot be resolved biostratigraphically. Another possibility is that differing biota between mound types indicate a self-organized ecological overprint. The finer details of development could have been controlled especially with respect to which biota dominates and by the order of colonization. This could account for the fact that there is a similarity in the mounds, but there are distinct types nearby one another. Data about current directions at the intervals of mound formation are scarce. Orientation of crinoid stems in the intermound facies (total of 122 measurements) in the vicinity of mounds 19–20 shows a pronounced N–S maximum. Groove casts and ripple marks in sandstone levels of the upper Zrigat and Itima Formations indicate N–S

to NW–SE current directions (Döring, pers. commun., 1999).

On the other hand, mound type C is allochthonous, i.e., these blocks are derived from an unknown source. Their almost linear arrangement suggests such a source either in the north, covered by younger deposits and the present Cretaceous cover of the Hamada du Guir, or in the south where Visean deposits are largely eroded. It can be speculated that these large blocks were detached from fault scarps similar to, but larger than those observed at Jebel Bega, but it seems unlikely that they have travelled over long distances. Such a transport requires a gentle slope of the seafloor, which is also indicated by slumping phenomena in some intermound sandstones and limestones (Fig. 4).

Little is known about depositional patterns during Visean times at a wider regional scale. Between a depocenter in the west (Tindouf Basin) and another in the east (Béchar Basin), deposits of this interval are largely eroded and make palaeogeographical reconstructions speculative. It is possible that the Tafilalt Basin was nothing else than the western prolongation of the Béchar Basin. The peculiarity of the Tafilalt mounds is their basinal setting and their facies diversity whose origin is not yet fully understood.

Acknowledgements

The project was supported by the Deutsche Forschungsgemeinschaft (DFG; grant We 239/15-1). We are indebted to Mohamed Dahmani and Atmane Fadile (Ministère de l'Energie et des Mines, Rabat and Midelt, Morocco) for the issue of a permission to work and to export samples. Sascha Döring, Jörg Hayer, Christian Klug, Oliver Wendt, and Renate Kostrewa (all Tübingen) helped during field work. Stable-isotope analyses were performed by Michael M. Joachimski (Erlangen). Noor Farsan (Heidelberg) determined the brachiopods, Dieter Korn (Tübingen) the goniatites, and Jürgen Kullmann (Tübingen) the rugose corals. Technical assistance was provided by Wolfgang Gerber, Indra Gill-Kopp, Ute Mann, Martin Rücklin, Bernhard Siethoff, and Gitta Wahl (all Tübingen). Finally, we thank editors David Kopaska-Merkel and Douglas Haywick and more especially journal reviewers Michael A. Gibson, Brian R. Pratt, and Mohamed H. Negra for their thorough and constructive reviews.

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