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The role of micrites in the Sinemurian (Lower Jurassic) sponge-microbialite mounds from Foum Tillicht, central High Atlas, Morocco

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ABSTRACT - Microbialites and sponges are the most significant components of the Sinemurian mounds of the Foum Tillicht Range in the central High Atlas of Morocco. Although these spectacularly well-exposed mounds have been reported in literature since the sixties, their genesis and their palaeoenvironmental settings are poorly understood. Recent studies have demonstrated that the characterization of the micritic component (allochthonous vs autochthonous micrite) and its distribution in the mound architecture represent a fundamental tool in reconstructing mound geometries and palaeoenvironmental evolution during their deposition. In this study, three main depositional intervals of the Lower/Upper Sinemurian mounds of the Foum Tillicht locality are recognized and a depositional model is suggested based on the characterization of their micritic component. The proposed depositional model includes a variation of the palaeoenvironmental conditions during deposition of the mounds.

The allochthonous micrite and bioclast-dominated small mounds (ca. 1 m high and 0.5 m wide), observed within the lower depositional interval, suggest a marine palaeoenvironment with well oxygenated marine shallow water and high hydrodynamic conditions as well as, cyclically alternating suboxic/anoxic phases. These small mounds developed during short phases of relatively deeper water conditions. The mound evolution toward larger skeletal-rich (sponge) microbialite mounds indicates an evolution from a relatively fluctuating sea level to a more stable deeper water depositional environment, thus allowing time for the formation of a massive microbialite mound frame. The abundance of peloidal and aphanitic micrite associated with sponge tissue suggests an organic (microbial) origin through heterotrophic activities within a stressed suboxic environment. The decrease of the allochthonous micrite and the intermound deposit abundance involves a reduction of sedimentation rate and water energy. All these findings suggest that the sponge microbialite mounds were deposited within a stressed suboxic to anoxic setting characterized by calm and deep water conditions.

RIASSUNTO - [Il ruolo della micrite nei mound a spugne del Sinemuriano (Giurassico Inferiore) di Foum Tillicht, Alto Atlante centrale, Marocco] - *Le microbialiti e le spugne sono fra i componenti principali dei mound sinemuriani della catena montuosa di Foum Tillicht nell'Alto Atlante centrale in Morocco. Sebbene questi spettacolari mound siano stati descritti a partire dagli anni Sessanta, la loro genesi e la ricostruzione del paleoambiente nel quale si sarebbero sviluppati è ancora controversa. Recentemente, alcuni studi hanno dimostrato che la caratterizzazione della componente micritica (micrite alloctona vs micrite autoctona) dei mound e la relativa distribuzione al suo interno rappresenterebbe uno strumento importante nella ricostruzione della geometria dei mound e dell'evoluzione paleoambientale durante la loro deposizione.*

In questo studio, sono stati descritti tre principali intervalli stratigrafici dei mound che affiorano nella località di Foum Tillicht ed è stato proposto un nuovo modello deposizionale che coinvolge una variazione delle condizioni paleoambientali durante la deposizione dei mound stessi. In particolare, i mound di piccole dimensioni (alti ca. 1 m e larghi ca. 50 cm) dell'intervallo stratigrafico inferiore, dominati da micrite alloctona e bioclasti, sembrano suggerire un paleoambiente marino di acque basse e ben ossigenate e condizioni di alta energia che ciclicamente si alternano a condizioni marine più profonde e meno ossigenate (fino ad anossiche). Questi mound si sarebbero sviluppati durante brevi fasi caratterizzate da acque relativamente più profonde. L'evoluzione di questi mound verso corpi microbialitici di maggiori dimensioni, con abbondanza di bioclasti di spugne, suggerirebbe un ambiente marino fluttuante verso condizioni più stabili e profonde, che avrebbero permesso la fomazione di importanti strutture microbialitiche. L'abbondanza della micrite peloidale e afanitica associata ai tessuti delle spugne, suggerisce un'origine organica (microbica) dovuta ad attività eterotrofica in ambienti stressati da scarsa ossigenazione. La riduzione della micrite alloctona e l'abbondanza dei depositi di intermound coinvolgono anche una riduzione del tasso di sedimentazione e di energia delle acque. Tutte queste evidenze sembrerebbero confermare che i mound microbialitici a frammenti di spugne si depositavano in un contesto subossico-anossico caratterizzato da acque calme e profonde.

INTRODUCTION

Modern and fossil carbonate mounds show distinct morphologies that today are mostly observed in deep marine environments (e.g., Foubert & Henriet, 2009). Although mounds are commonly associated to quiet and deep marine settings (Schlager, 2003), in the fossil record their bathymetric assessment and related palaeoenvironmental reconstruction result more problematic because of their discontinuous record and diagenetic processes (Hebbeln & Samankassou, 2015).

Carbonate mounds have been subdivided into three different categories (James & Bourque, 1992): two organically controlled or biogenic mounds, that include microbial mounds (formed by peloidal or dense micrite resulting from the calcification of benthic microbial association; e.g., Riding, 2002) and skeletal mounds (dominated by branching or encrusting skeletal organisms, such as corals, bryozoans, and sponges), and a third category that includes mud-mounds formed by muddy lenticular or knobby bodies dominated by detrital or inorganic mud accumulation with relatively abundant

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amounts of fossils (James & Bourque, 1992; Schmid et al., 2001), which are often considered as a subtype of reefs.

The geological record of carbonate mounds ranges from the Early Palaeozoic to the Recent and they result abundant in the Phanerozoic strata especially in the sedimentary deposits of Morocco (Bosence et al., 2015; Hebbeln & Samankassou, 2015). During the Jurassic Period, coral reefs and siliceous sponge mounds were exceptionally abundant and reached their abundance peak. Upper Jurassic sponge mounds are well known across Europe and are considered a typical example of sponge-microbial reefs (e.g., Gwinner, 1976; Fluegel & Steiger, 1981; Schmid et al., 2001; Kochman & Matyszkiewicz, 2012), whereas Middle Jurassic sponge mounds have been described in Spain (Giner & Barnolas, 1979) and Morocco (Tomas et al., 2013; Ait Addi, 2015). Although the Lower Jurassic has been considered unfavorable to the formation and growth of reefs and mounds, due to the mass extinction event at the Triassic-Jurassic boundary (Leinfelder et al., 2002), Lower Jurassic carbonate mounds and some sponge mounds have been reported from Morocco (du Dresnay et al., 1978; Neuweiler et al., 2001; Chafiki et al., 2004; Della Porta et al., 2013) and Portugal (Duarte et al., 2000).

Since Early Palaeozoic times the Moroccan margin of Gondwana has been site of intense carbonate precipitation and mud mound formation (e.g., Henriet et al., 2014). Although the upper Silurian units of the Middle Atlas show an ancient example of methane-imprinted carbonate mound of the Moroccan margin (Barbieri et al., 2004), the highest carbonate productivity along this margin is recorded during the Devonian with a peak of carbonate mud mound growth (Hebbeln & Samankassou, 2015). The genesis of the well known Devonian buildups of the eastern Anti Atlas is mostly related to hydrothermal fluids circulation (Franchi et al., 2015a, b, 2016), microbial induced precipitation (Cavalazzi, 2007; Guido et al., 2012, 2013b), methane seepage (Cavalazzi et al., 2007, 2012), and mechanical accumulation of corals and other skeletal components (Kaufmann, 1997; Wendt & Kaufmann, 2006). During the Carboniferous, the (Visean) mounds along the Moroccan margin were mostly related to mechanical accumulation of coral remains coupled with microbial induced precipitation of micritic cements (Wendt et al., 2001; Said et al., 2013). One of the last pulses of carbonate mound productivity (Henriet et al., 2014) along the northern margin of Gondwana was recorded during the Lower Jurassic and particularly during the Sinemurian (Neuweiler et al., 2001; Chafiki et al., 2004; Della Porta et al., 2013, 2015). Spectacularly well-exposed Sinemurian sponge mounds from central High Atlas of northern Morocco were originally described and interpreted as related to sponge activity (Dubar, 1962). More recently, these carbonate buildups, generated by skeletal-biotic framework related to sponge tissue decay and automicrite precipitation, were re-interpreted in terms of siliceous sponge mounds formed in an oxygen minimum zone edge (Neuweiler et al., 2001). However, based on the global mound distribution within the Lower to Upper Sinemurian platform, and on the palaeogeography and basin geodynamics, these micritic sponge mounds have been re-interpreted as developed under deep and open marine conditions within the sub-photic zone below the storm wave base (Chafiki et al., 2004).

Whatever the depositional environment, mounds may result from different builders but they have a common and essential component which is a dense peloidal crust (Leinfelder, 1993). To better understand the nature and evolution of these mounds, it is necessary to understand the origin of their autochthonous micrite and the features controlling vertical antigravity accretion (e.g., Wood, 2001; Riding & Tomas, 2006). The autochthonous micrite has been interpreted as resulting from the microbial metabolic activity (Reitner et al., 1996; Guido et al., 2011, 2012, 2014). In addition, several Authors suggested the

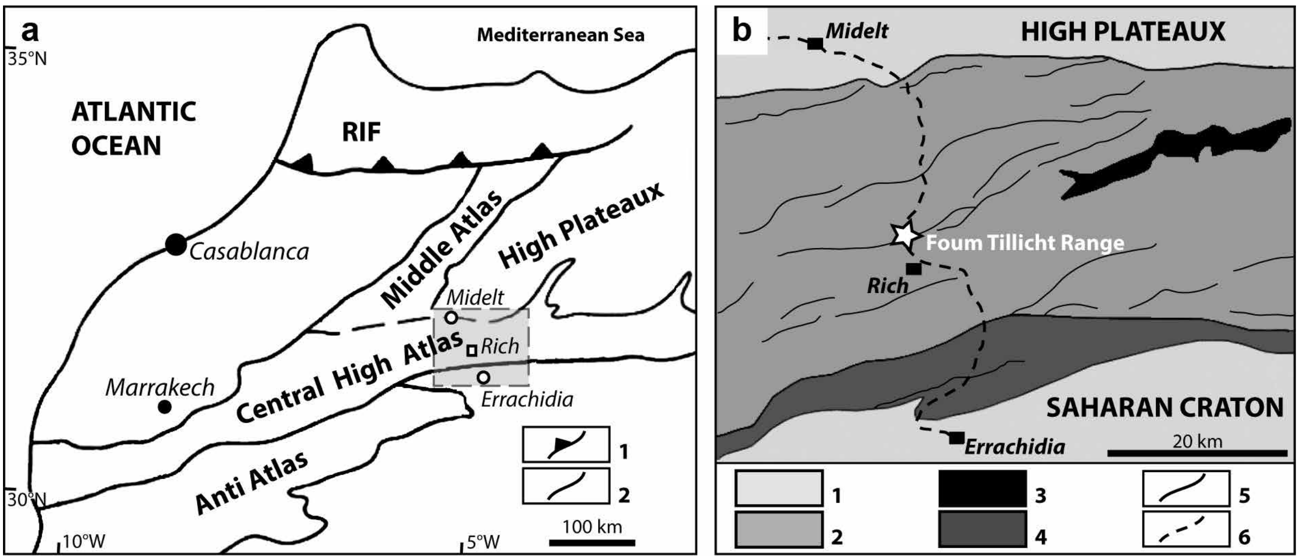

Fig. 1 - Location map of the study area. a) Simplified structural provinces of northern Morocco. The studied area (grey boxed area), lying in the High Atlas, is shown in detail in b. 1: convergent plate boundary; 2: structural province boundaries. b) Simplified geologic map of the study area and Foum Tillicht locality (star). Modified from Lachkar et al. (2009). 1: stable blocks; 2: central basin complex; 3: El bour Mouguer Palaeozoic basement; 4: southern platform complex; 5: fault and Early Jurassic ridges; 6: main road nr. 21.

role of the autochthonous micrite within the mounds as the main factor controlling the growth, evolution and stabilization of high carbonate reliefs (Della Porta, 2013; Guido et al., 2016).

The origin of the autochthonous micrite within the carbonate buildups has been attributed to the activity of benthic microorganisms that can provide different types of microbialites (Wood, 2001), with products including: 1) growth of calcified cyanobacteria (Riding, 2002), binding activity of locally derived micrite by coccoid cyanobacteria generating stromatolites (e.g., Pratt, 1982; Chafetz, 1986); 2) precipitation from prokaryotic-eukaryotic communities forming clotted and fenestrae thrombolites (e.g., Reid et al., 1995; Feldman & McKenzie, 1998); and 3) products resulting from the physiological activity or decay of phototrophic or heterotrophic microorganisms or sponges forming biolithite (e.g., Pickard, 1996; Reitner et al., 1996; Pratt, 2000).

This study aims to document the Sinemurian sponge-microbialite mounds of Foum Tillicht Range, located between the cities of Midelt and Errachidia, in the central High Atlas (Morocco). The objectives include: 1) the investigation and the possible correlation between the depositional geometry and the amount of autochthonous micrite; and 2) the proposal of a growth model of the mounds based on their palaeoenvironmental changes.

GEOLOGICAL SETTING OF THE STUDY AREA

The central High Atlas forms the western margin of the Maghrebian Tethys realm of an inverted pre-existing Mesozoic rift basin, mainly filled with Triassic and Jurassic sediments (Jacobshagen et al., 1988; Beauchamp et al., 1996). This basin developed on a fault block controlled by NE-SW oriented faults, in response to a widespread Triassic-Jurassic intracontinental rifting related to the opening of the Atlantic system and proceeding westward to the enlargement of the Tethyan realm (Manspeizer et al., 1978).

Sinemurian sponge microbialite mounds (Chafiki et al., 2004; Chafiki, 2005) crop out in the eastern part of the central High Atlas and are part of the Foum Tillicht section located in the northern flank of Foum Tillicht ridge about 12 km North of the Rich village (Fig. 1).

The studied Sinemurian mound series crop out over a sequence with a total thickness of about 280 m. They mostly occur on the top of the Idikel Formation (Fig. 2). The upper member of the Idikel Formation is a massive, brachiopod-rich limestone including three lithostratigraphic units (Chafiki, 2005). The lower lithostratigraphic unit consists of about 60 m thick wavy-nodular limestone, followed by a middle unit of about 50 m wavy nodular fairground limestone with an *Arnioceras-Asteroceras* ammonite association at its top referred to the early Late Sinemurian (Neuweiler et al., 2001; Chafiki et al., 2004; El Harriri et al., 2010). These two lithostratigraphic units represent the pre-mound sequence, their tops being composed of an abundant ferruginous brachiopod shell bed accumulation (Tomasovych et al., 2006). Small microbialite mounds occur in the upper unit, consisting of about 160 m of a finely stratified limestone, and in the Aberdouz

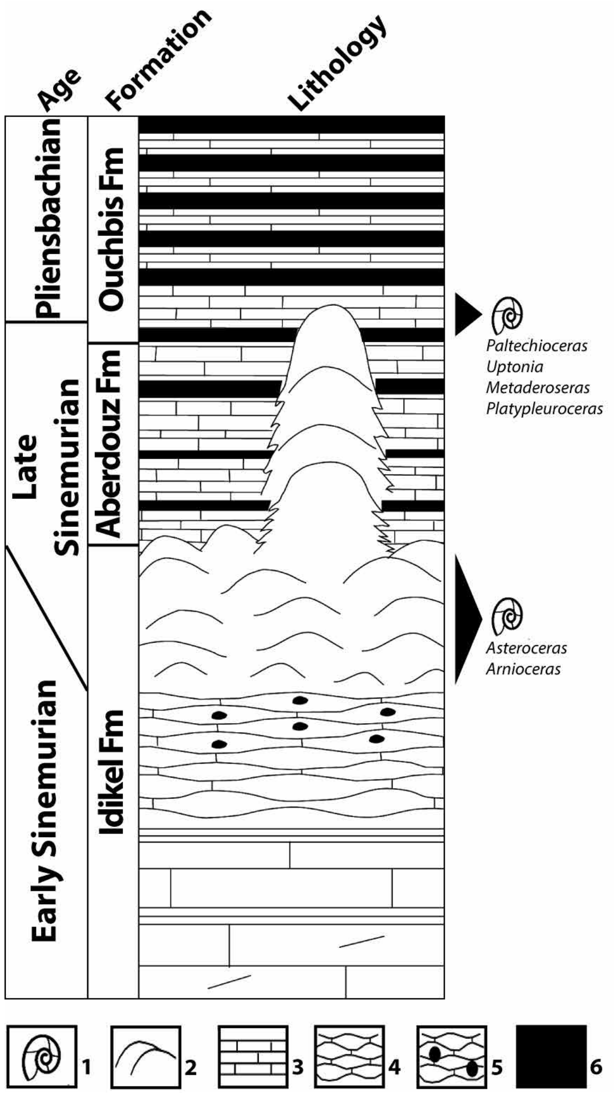

Fig. 2 - Lower-Upper Sinemurian lithostratigraphic column including mounds from Foum Tillicht locality. Modified from Chafiki et al. (2004). 1: ammonites; 2: microbial mounds; 3: limestone; 4: wavy to nodular limestone; 5: fairground limestone; 6: marls.

Formation, that includes a thin-bedded limestone, attributed to the Late Sinemurian (El Hariri et al., 1996). At the base of the Ouchbis Formation, which is constituted by rhythmic series of micritic limestone and marl, some mounds are still present. The Ouchbis Formation represents the post-mound sequence and it is attributed to the Lower Pliensbachian (Carixian) (Studer, 1980). Having been identified as hemipelagic, these deposits seem to interfere with the late stages of sponge mound retrogradation (Neuweiler et al., 2001; Chafiki et al., 2004). Therefore, the first appearance of the sponge microbialite mounds may be attributed to the top of the Idikel Formation corresponding to the Lower-Upper Sinemurian boundary. These mounds locally evolve in the Aberdouz Formation, while the last observed mounds occur embedded in the sediments of the Ouchbis Formation associated to the Upper Sinemurian-Lower Carixian transition.

MATERIAL AND METHODS

The studied Sinemurian sponge microbialite mound sequence, with sub-vertical arrangement, is entirely encased in its host rocks. The inspection of some 2D-mound outcrop suggests a simple, domical shaped mound morphology and the presence of two main facies: a micritic core facies and a laterally synchronous, well-bedded inter-mound facies. The well exposed mounds show three different lithological intervals that were described and sampled (Fig. 3). The lower interval is characterized by small sized sponge microbialite mounds separated by well bedded inter-mound strata. The middle interval shows a size increase and frequency of the mounds, wheras the upper interval is typified by sub-vertical lenticular mounds. Ten, 21 and 17 samples were collected from the lower, middle and upper intervals, respectively.

From each sample, standard petrographic thin sections (48 mm long, 28 mm wide and 30 μm thick) were prepared in order to document the mound facies evolution. Uncovered thin sections were analyzed with Axioplan Imaging II microscope (Zeiss) equipped with an AxioCam HRc digital camera, under plane and cross-polarized light. Mineralogical and chemical composition was determined by an EDAX Genesis 4000 energy-dispersive X-ray spectrometer linked to a FEI-Philips ESEM-FEG Quanta 200F scanning electron microscope. The analyzed samples were previously polished with 0.25 μm diamond-impregnated surfaces, then gently etched (0.05% HCl, 1 min) and carbon coated (ca. 250 Å coating thickness). Working conditions and detector constants were as follows: voltage 15 kV, tilt angle 0°, take-off angle 36.01°, beam current factor 1.0, resolution at MN-Ka 154 eV, Be window thickness 15 μm, nominal dead layer of 0.15 μm, maximum counts per second threshold value 6,000. These working conditions coupled with a spot size of 0.1 μm allow to analyze a Ca-carbonate volume of few μm^3 with a minimum detectability limit for the major measured elements (Mg, Al, Si, S, K, Ca, Mn, Fe, Sr, Ba) lower than 0.1 weight percent. The data were corrected by ZAF technique employing EDAX 9900 software. The quantitative analysis of the microfacies were performed by point counting on forty eight polished thin sections (200 points were counted per thin section).

All studied samples (hand samples and thin sections) are stored in the Geological Sample Repository at the Cadi Ayyad University in Marrakech, Morocco.

RESULTS

Palaeontological and sedimentological study

Three different intervals have been recognized on the base of sedimentological and palaeontological studies of the Foum Tillicht Sinemurian section (Fig. 3a) in agreement with the subdivision proposed by Neuweiler et al. (2001).

The lower interval (25 m thick) consists of relatively small size mounds (1 m maximum height observed in outcrop) (Fig. 3b). Sponge mounds consist of boundstones of lyssakine sponges in association with commensalic terebellids and the problematic organism such as *Radiomura*. These small mounds can be easily recognized throughout the whole interval due to their characteristic lens shaped morphology and lack of internal bedding deposits, and they are also overlapped by large inter-mound bedded sediments. The bedded strata show four main facies: 1) packstones with lithoclastic rimmed by erosion surfaces; 2) packstones with thin-shelled bivalves; 3) bioclastic packstones with clotted peloidal, lithoclasts and *Tubiphytes*; and 4) cortoid packstones and grainstones with ooids, calcareous sponges, dasycladacean algae, coral fragments, gastropods, and lithoclasts. An increase of the grain sizes (~10 μm) was observed within the inter-mound facies.

The middle interval (135 m thick) includes isolated larger mounds (from 2 to 5 m high) locally associated with more than 6 m high caotic accumulations of mounds with different shapes (Fig. 3c). These mounds are surrounded by planar and cross-bedded inter-mound deposits. This interval consists of boundstone with siliceous sponge in life position embedded in detrital micrite, that transitionally increases the bioclastic (bivalves, brachiopods, ostracods, and gastropods) component. Poorly preserved benthic foraminifera, including rotaliids, *Frondicularia* sp., *Nodosaria* spp., *Lenticulina* cf. *muensteri* (Roemer, 1839), are also present (R. Barbieri, personal communication, 2016). Thrombolitic and leiolitic structures associated to sponges can be easily recognized in the outcrop as they are made of dark clotted peloidal micrite and embedded in a gray fine micrite. These arborescent and dendritic microbialites commonly are associated to annelids (Fig. 4a-b). Sponges are represented by hexactinellids (Fig. 4c) and dish-shaped lithistids (Fig. 4d) with a minor contribution of calcareous sponges, bryozoans, and polychaetes (*Terebella* and *Serpula*). The grayish to dark gray leiolites commonly appear massive and structureless, and, at the base of the mounds, are associated to thrombolites.

The upper interval (140 m thick) includes massive lens-shaped mounds (5 to 7 m high) with a sub-vertical arrangement generating a decametric dome structure (Fig. 3d). Despite the homogeneity of thin-bedded mound surfaces, the palaeontological association of this interval mainly consists of bryozoans and sponges (Fig. 4e-f) with microbialites and few solitary corals toward the top of the interval. Ferruginous surfaces with an ammonite association of *Paltechioceras, Uptonia, Metaderoceras* and *Plalypleuroceras* have been observed at the top of this interval. The inter-mound strata, less abundant in this interval, are composed by well stratified bioclastic wackestones that separate, overlap and locally incorporate the mounds. A decrease in grain-size (from ~10 to 4 μm) was observed within the inter-mounds from the base to the top of the section.

Facies and microfacies observations

The thin section analysis enabled to observe that the skeletal component of the sponge microbialite mounds mainly consists of calcareous and siliceous sponges, bryozoans, bivalves, echinoderms, *Serpula* and *Terebella* and problematic organisms such as *Radiomura*. Whereas the allochthonous micrite (detrital) is quite ubiquitous and generally fills the cavities, the autochthonous micrite shows often thrombolitic and clotted peloidal or pelodal fabric. The carbonates at Foum Tillicht locality

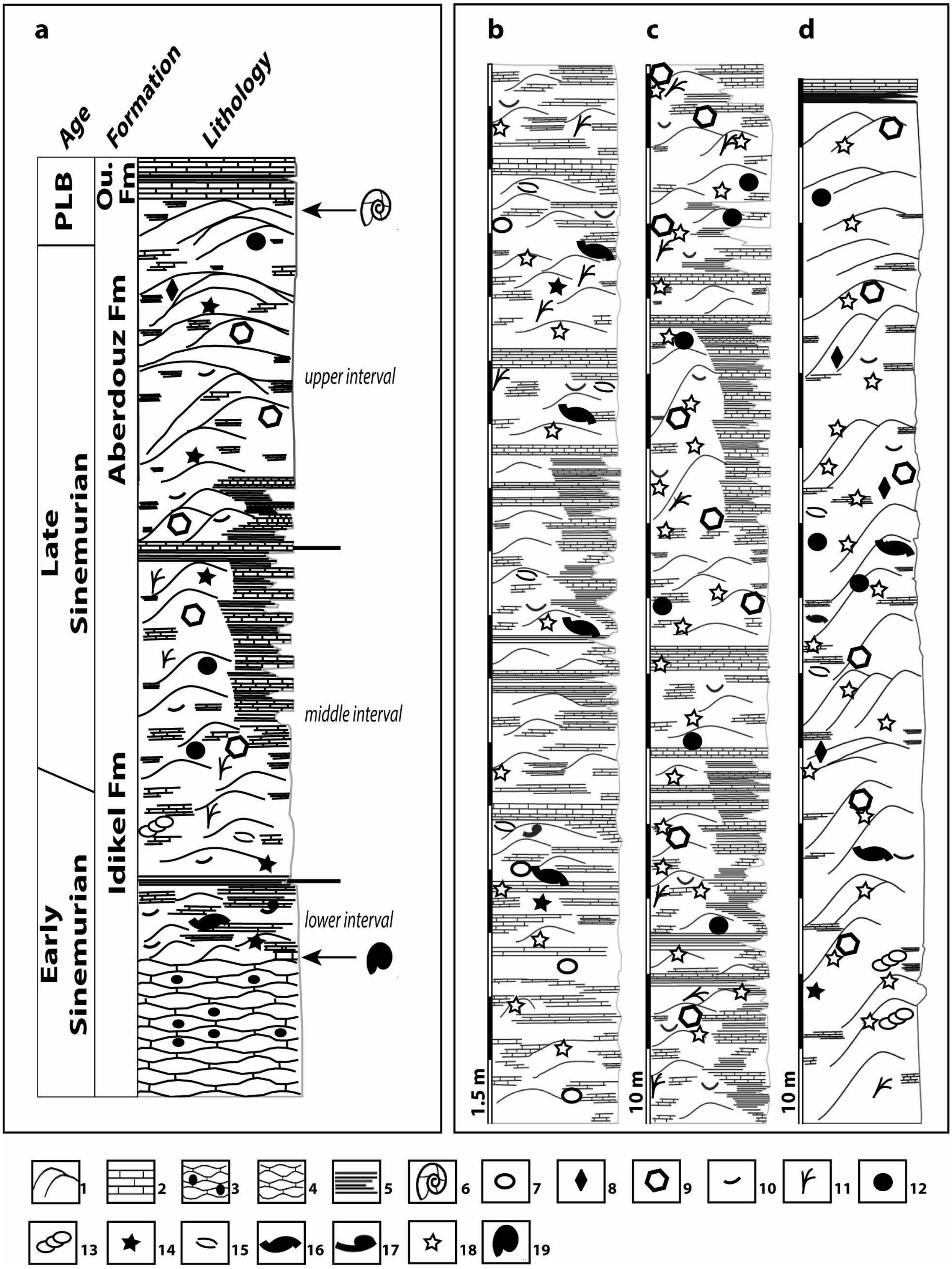

Fig. 3 - Stratigraphic sections of the studied outcrops. a) A synthetic stratigraphic survey of the Lower-Upper Sinemurian sponge microbialite mounds at Foum Tillicht locality. PLB: Pliensbachian; Ou.: Ouchbis. b-d) The three different columns represent a detailed stratigraphic survey of the lower, middle and upper intervals, respectively. 1: carbonate mounds; 2: limestone; 3: fairground limestone; 4: wavy to nodular limestone; 5: marls; 6: *Paltechioceras, Uptonia, Metaderoceras, Plalypleuroceras* ammonite association; 7: gastropods; 8: corals; 9: hexactinellids; 10: sponges; 11: thrombolites; 12: bryozoans; 13: foraminiferans; 14: echinoderms; 15: ostracods; 16: bivalves; 17: brachiopods; 18: collected samples; 19: *Asteroceras, Arnioceras* ammonite association.

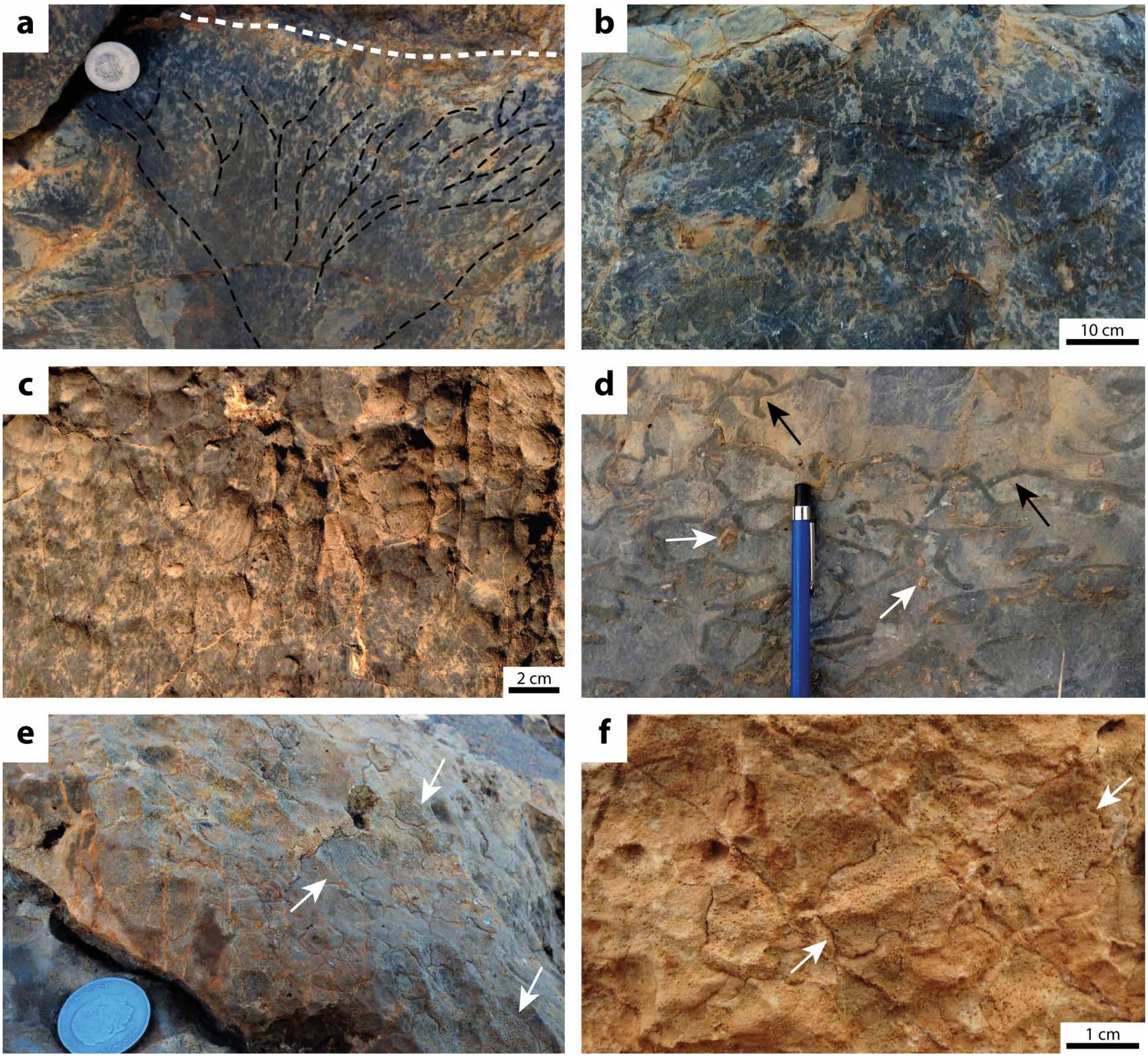

Fig. 4 - Outcrop photographs of the sponge microbialite mounds of Foum Tillicht locality. a) Dendritic to arborescent thrombolites (dashed line) made of dark micrite embedded in light grey micrite (coin for scale: 2.3 cm of diameter). b) Dendritic dark micrite forming thrombolite clumps embedded in light grey micrite. c) Siliceous sponge associated with dark micrite clots (mound 1.5 m of height). d) Outcrop of dish-shaped siliceous sponges, lithistids (black arrows) within light micrite rich in encrusting bioclastics (white arrows). e-f) Mound (about 3 m of height) mainly composed of autochthonous micrite with abundant bryozoans (white arrows).

are represented by two main facies types: massive, mainly micritic, domical to lens-shaped mound and lateral synchronous well bedded inter-mound. Three different microfacies were observed in the inter-mound: 1) mudstone to wackestone of fine detrital micrite (Fig. 5a-b); 2) wackestone to packstone dominated by coquinoid with abundant brachiopods and foreground surfaces; and 3) packstone to grainstone dominated by brachiopod, echinoderm, and bivalve and bioclasts.

The microfacies, observed in the lower interval, are mainly represented by wackestone to packstone with large *Terebella*, allochthonous micrite (detrital micrite) and subordinately peloidal micrite. In the middle interval a thrombolitic bindstone to bafflestone frequently occurs and consists of clotted peloidal micrite associated to *Terebella* and *Serpula*. Fenestrae also occur (Fig. 5c). Toward the top the sediments are fine and well sorted. The microfacies is mainly constituted of boundstones dominated by peloidal micrite and hexactinellids; lithistids and calcareous sponges are also common. The sponges are mainly encrusted by bryozoans, *Serpula*, *Radiomura* and *Terebella* (Fig. 5d).

The quantitative analyses of the mound facies were performed by counting point on the five most common components: detrital micrite, autochthonous micrite (including peloidal and aphanitic textures), hexactinellids, other sponges (lithistids, calcareous sponges and sponge spicules), and skeletal grains (e.g., bryozoans, terebellids, serpulids) and problematic organisms (Fig. 6). The data agree with the bio-sedimentological observations and

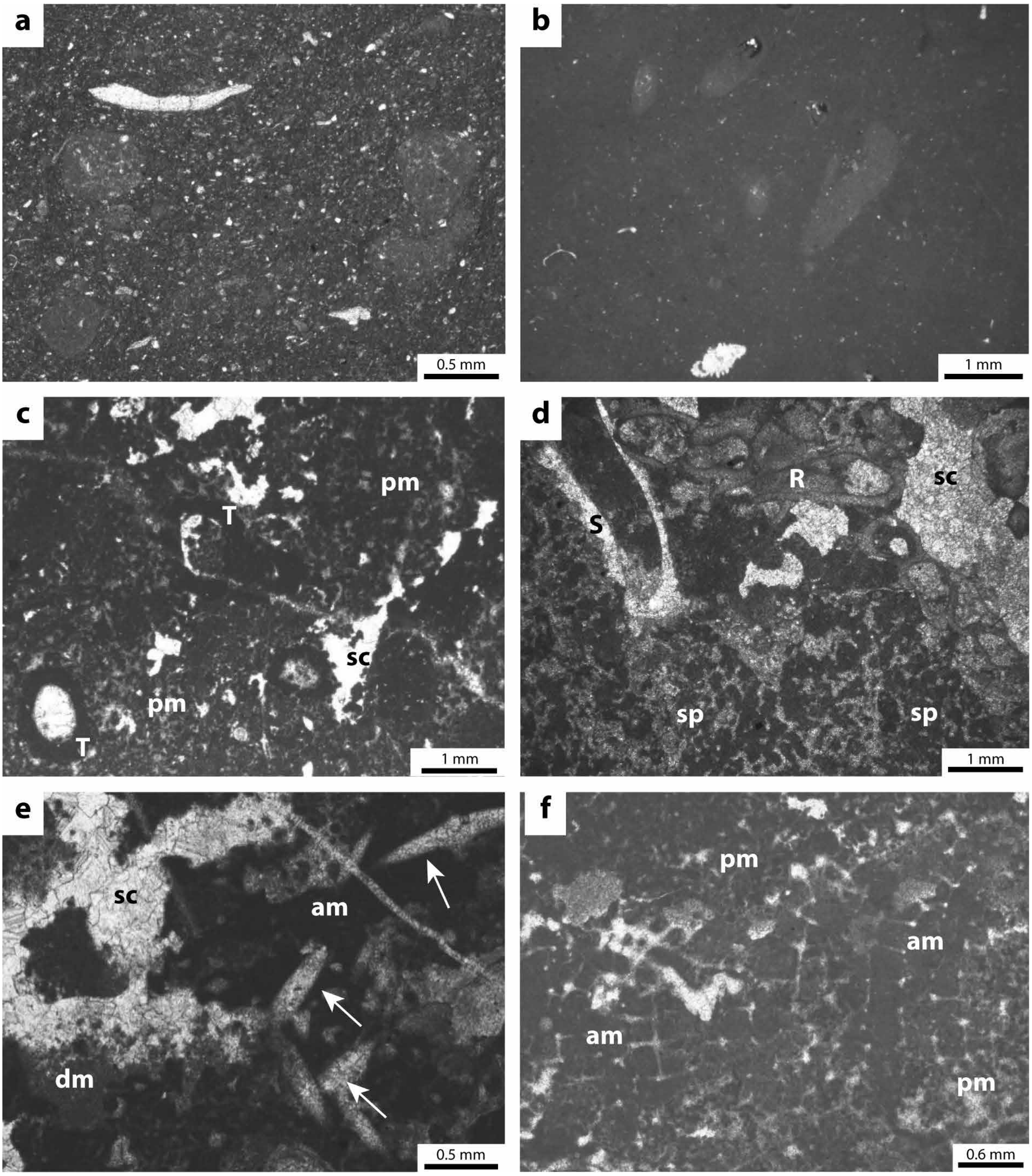

Fig. 5 - Microfacies observed in the three intervals of the Sinemurian mounds of Foum Tillicht Range. a-b) Inter-mounds; c-d) mounds. a) Mudstone/wackestone of the lower interval (sample FT4) composed of detrital micrite with larger grain sizes than those observed in the upper interval (b). b) Mudstone of the upper interval (sample FT40). c) Boundstone composed of peloidal micrite (pm) with abundant *Terebella* (T) and microcavities filled with sparry calcite (sc) (sample FT15). d) Boundstone composed of sponges tissue (sp), *Serpula* (S), problematica *Radiomura* (R), and cavities filled with sparry calcite (sc) (sample FT41). e) Boundstone composed of aphanitic micrite (am) with calcified triaxon spicules (white arrows), and large cavities geopetally filled with detrital micrite (dm) and sparry calcite (sc) (sample FT23). f) Boundstone composed of hexactinellid tissue with peloidal (pm) and aphanitic micrite (am) (sample FT44).

confirm the subdivision of the Foum Tillicht mound sequence in three intervals as previously described.

The samples from the lower interval are composed mainly of wackestone to packstone with abundant detrital micrite and minor contribution of peloidal micrite. Peloidal micritic boundstones with *Terebella* were also observed within this interval. Ostracod, bivalve, and gastropod bioclasts appear embedded into detrital micrite.

The micritic matrix is composed mainly of allochthonous micrite (detrital) representing more than 60% of the component, followed by 15% of autochthonous micrite, mainly peloidal in texture. The skeletal grains account for 19% and are dominated by *Terebella*. Hexactinellids account for 4% and other sponges for 2% (Fig. 6).

The samples from the middle interval are composed mainly of peloidal micritic boundstones rich in siliceous sponges. This interval is characterized by a significant increase of autochthonous micrite (Fig. 6b). About 40% of the micrite is represented by autochthonous micrite; hexactinellids represent about 4%, other sponges are also relatively common (18%). The skeletal grains represent about 24% of the mound fabric. *Terebella* is often related to peloidal micrite while aphanitic micrite is mainly observed in association with hexactinellids. The detrital micrite is present in subordinate amounts (14%) and seems mainly filling the cavities and embedding the sponges.

The samples from the upper interval are composed mainly of peloidal micritic boundstones rich in siliceous sponge and annelids encrusted by bryozoans (Fig. 5f). The microfacies is composed at least by 45% of autochthonous micrite and about 20% of skeletal grains including large bryozoans and encrusting organisms (*Serpula* and *Terebella*). The automicrite appears dark and dense with mainly an aphanitic texture. Hexactinellids represent the 9% and other sponge 13% of the mound fabric. Detrital micrite with fine bioclasts fills cavities and represents 13% of the microfacies components.

Micro-morphological and chemical analyses of micrite

The autochthonous micrite often with thrombolitic texture associated to siliceous sponges occurs as a very fine micrite. This fraction observed with scanning electron microscope (SEM) shows an agglutinated fabric with abundant tiny spherical particle overgrowth (Fig. 7a). The detrital micrite is constituted of equidimensional calcitic elements (Fig. 7b). Honeycomb-like meshworks were observed scattered within the autochthonous micrite, they consist of subsferical calcitic bodies with diameters ranging from 3 to 10 µm (Fig. 7c-d).

The chemical analyses (EDX) reveal that the detrital micrite is made of calcite and silicate minerals (Al-K-Fe-Mg), whereas the autochthonous micrite consists only of calcite.

The elemental chemical analyses (EDX) reveal that the detrital micrite result made of calcite and silicate minerals (Al-K-Fe-Mg), whereas the autochthonous micrite is made only of calcite.

DISCUSSION

Role of the micrite in the Sinemurian sponge-microbialite mounds

The microbialites in the Sinemurian sponge mounds mainly exhibit thrombolitic and leiolitic fabrics. The term micrite was introduced by Folk (1959), who defined micrite as crypto- to microcrystalline crystal texture with a grain-size of less than 4 µm generated by lithified lime mud derived from mechanical deposition. However, the term micrite is most common referring to a rock composed of fine-grained calcite crystals for in situ precipitated or for the accumulation of pre-existing carbonate particles (Fluegel, 2010). Two different types of micrite are recognizable: autochthonous micrite, which may exhibit both dense microcrystalline micrite (aphanitic micrite) or peloidal/clotted peloidal microfabric, and allochthonous micrite (detrital micrite). The clotted peloidal and peloidal textures are very common in the microbial fabrics, they consist mainly of very small peloids commonly densely packed, exhibiting a clotted fabric generally surrounded by fenestral microspar matrix (Riding, 2000). The clotted fabric, typically formed by an irregular sponge-like network of micrite, is widespread in thrombolites (Pratt & James, 1989) and has been referred to as structure "grumeleuse" or clotted (Cayeux, 1935). Precise origins and specific processes of clotted-peloidal fabric is unclear, although Chafetz (1986) regarded peloids as calcified bacterial aggregates rimmed by euhedral calcite crystals. Common peloids of ancient reefs and stromatolites appear to be microbial precipitates (Fluegel & Steiger, 1981; Reid, 1987; Sun & Wright, 1989). Leinfelder & Schmid (2000) attributed the peloidal micrite to in situ precipitation mediated by microbial biofilms during organic matter degradation. The aphanitic micrite indicates a peloidal fabric locally passing to a more homogeneous texture composed of a mixture of micrite and micro spar or by only one of these mineral components. The aphanitic micrite is recognized

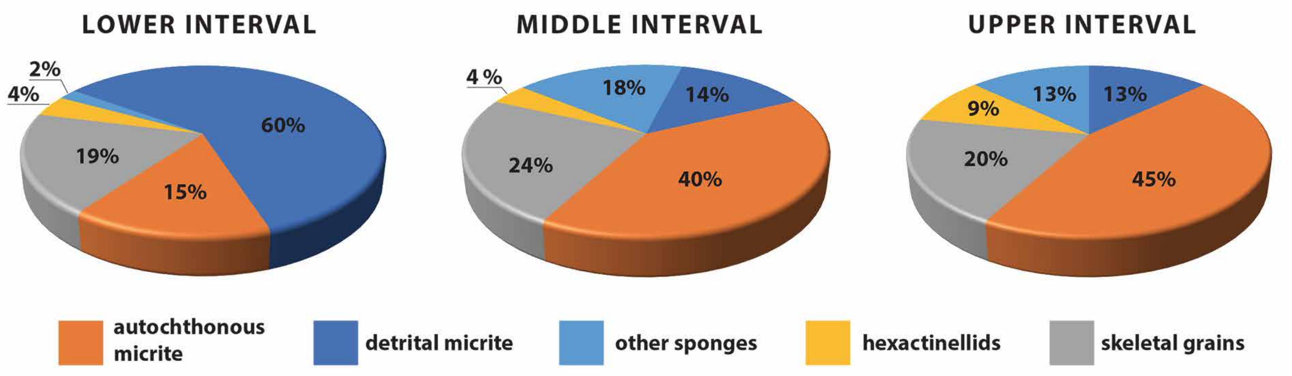

Fig. 6 - Quantitative data of micrite types and skeletal components of the lower, middle and upper interval within the Foum Tillicht sponge-microbialite mounds. Note the inverse correlation between the autochthonous micrite and the detrital micrite.

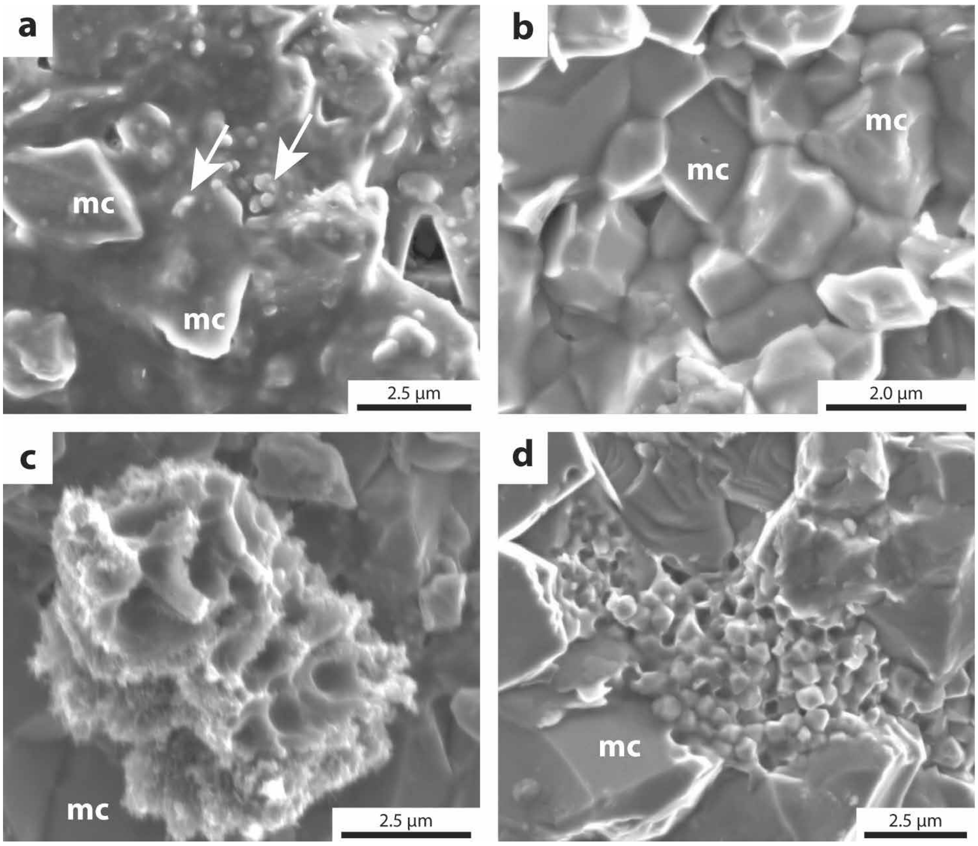

Fig. 7 - Scanning electron microscopy (SEM) photomicrographs of the micritic fraction. a) Autochthonous micrite with tiny spherical particles (white arrows) overgrowing calcitic minerals. b) Detrital micrite with well defined and equidimensional crystals. c-d) Honeycomb-like pattern of equidimensional sub-polygonal to -spherical aggregates of microcrystals (less than 1 µm in diameter) within autochthonous micrite. mc: micrite crystals.

by dark fine micritic grains showing a lack of all particles including undifferentiated microfossils but generally enclosing sponge spicules (Riding, 2000; Guido et al., 2013a). The detrital or allochthonous micrite derived mainly from physical processes as erosion and transport of preexisting carbonate (Fluegel, 2010), represents a poorly sorted and typically finer grained detrital wackestone to packstone fabrics.

The main complexity of microbial carbonate studies consists of recognition of organisms and processes involved (Riding, 2000). In this respect, the geometry and biotic composition of the mounds change from the base to the top in the studied Foum Tillicht succession and allowed its subdivision into three intervals. The lower interval consists of small mounds composed mainly of light gray detrital micrite dominated by bio-intraclastic components with minor microbialites and skeletal parts. This biotic association does not allow the formation of a suitable framework and small sized mounds developed. The amount of detrital micrite suggests high sediment input during this phase of mound growth, with the deposition of significant inter-mound strata.

At the base of the middle interval, dendritic clump and arborescent thrombolites are associated to the calcareous and siliceous sponges. Thrombolites are easily recognizable for their mesoclot structures, with unlayered mesoscale fabric and mm-scale cavities (Aitken, 1967). Thrombolites are characterized by homogeneous dense micrite with clotted peloidal fabric forming aggregates surrounded by fenestrate microspar matrix (Tomas et al., 2013). The clotted peloidal micrite displays agglutinated to branching morphology resulting from complex dissolution/precipitation reactions mediated by the metabolic activity of anoxygenic bacterial communities (Petrash et al., 2012), associated with extracellular polymeric substance (EPS) (Fig. 7). This interval is characterized by bryozoans, hexactinellids, and aphanitic autochthonous micrite enclosing sponge spicules. Chafiki et al. (2004) interpreted this interval as sponge-microbial boundstone, while Neuweiler et al. (2001) describe it as bio-organic construction relating to episodic biostromes of dish-shaped lithistid sponges. Here, the main framework supporting the mound growth is represented by the skeletal components. The microbialites, resulting from degradation of organic matter by heterotrophic bacteria, contribute in binding and stabilizing the mound framework (e.g., Krumbien et al., 1977; Chafetz, 1986; Paerl et al., 2001).

The upper interval is quite similar to the middle one with a more abundant skeletal component. The micrite shows dark dense aphanitic texture (Fig. 6e-f). Generally, sponges are present in all three intervals albeit with irregular distribution. Their distribution seems to be controlled by sedimentation rate and water energy: tabular shapes occur in areas of large sediment input, while dish-shaped sponges occur in low sedimentation rate and energy (Leinfelder & Keupp, 1995; Della Porta et al., 2013, 2015).

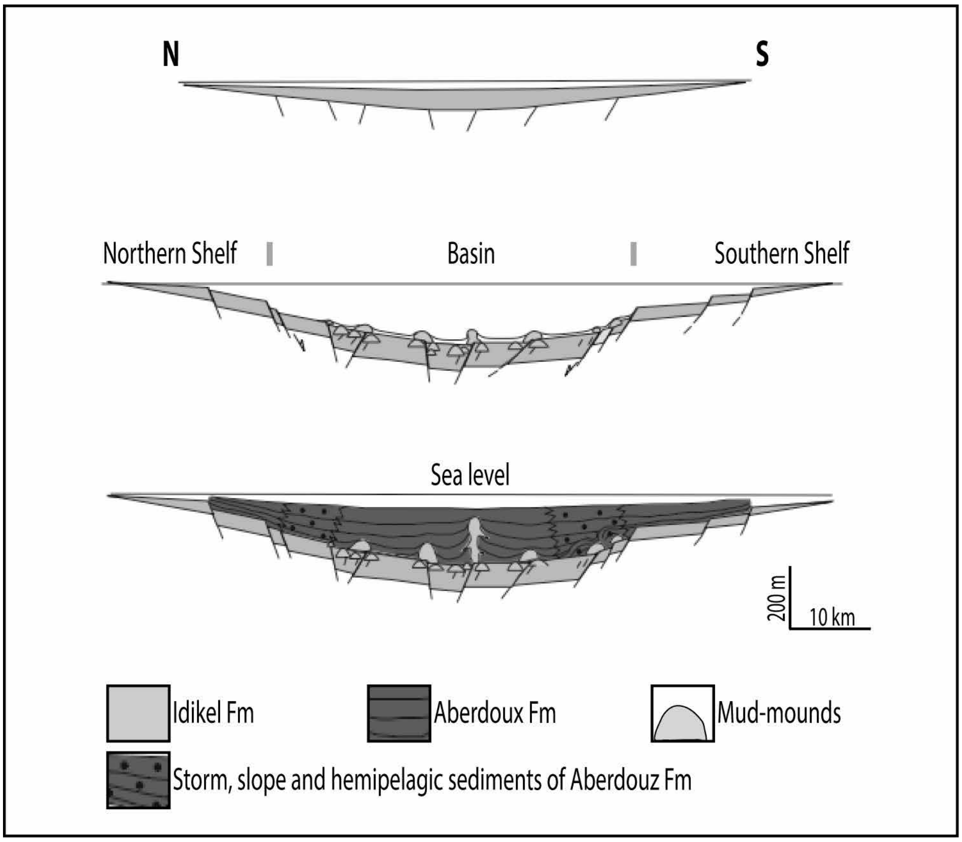

Fig. 8 - Geodynamic model of the development of the Sinemurian mounds along the Midelt Errachidia section. a) Lower Sinemurian stable carbonate platform. b) Lower-Upper Sinemurian breakup of the platform and onset of the mounds. c) Upper Sinemurian sediments buried the build-ups. Modified from Chafiki et al. (2004).

The inter-mound frequency within the sequence decreases from the lower to the upper interval. This evolution can be explained with a variation in sedimentation rate and water-energy in the depositional environment. In deep sea depositional environment, the detrital micrite input is low, allowing the microbial communities to induce autochthonous micrite precipitation. When the sea level decreases, the detrital micrite input increases so that the inter-mound facies becomes more common.

Palaeoenvironmental evolution

In the lower interval of the sponge-microbialites succession of the Sinemurian the detrital nature of the inter-mounds probably reflects relatively shallow (50 to 100 m of deep) and well oxygenated seawater conditions preventing the mound growth. On the other hand, the small mounds formed during the sea level rising so that the development of suboxic/anoxic conditions triggered the sponge/microbial colonization. During this phase, metazoans provided sufficient organic matter supply for heterotrophic microbial activities. At the same time, bacterial metabolic processes induced autochthonous micrite precipitation forming hard substrate for metazoan colonization. This association allowed the deposition of the mounds, that stopped to grow when oxygenated shallow water and high detrital input destabilized the delicate equilibrium of the mound ecosystems. Neuweiler et al. (2001) described the morphology of the lower interval as indicator of multiple stages of mound accretion and erosion, attributing it to the hydromechanical deposition. A similar mound morphology was described by Tomas et al. (2013) for the Middle Jurassic microbial mound of the Amellago Canyon (Central High Atlas, Morocco), and this morphology was interpreted as the response to sea level oscillations.

In comparison to the lower interval, the middle and upper intervals are characterized by more frequent and larger sized (2-5 m) mounds. This difference in mound size had been interpreted as due to the variation of the palaeoenvironmental conditions: deep and suboxic water settings persisted for longer time compared to the lower interval with the formation of larger mounds. This interpretation is in agreement with the detrital micrite size that shows a very fine texture, suggesting a deposition in a more quiet and deeper environment.

The sizes of sub-vertical mounds increase towards the upper interval associated to a remarkable rise of skeletal components and microbial cementation. The limited presence of detrital micrite and the occurrence of lithistid and hexactinellid sponges are indicative of low-energy and suboxic/anoxic conditions (Krautter, 1997).

Depositional model

According to their fabrics, fossil associations, and trophic structures, the studied Sinemurian sponge mounds have been proposed as reefal sponge mounds thriving heterotrophic consumption and microbial mineralization at subphotic levels (Neuweiler et al., 2001). Based on the subsiding geodynamic model, Warme (1988) indicates that the mounds were growing and concentrated on the central part of the basin, on a structural high (at about 100 m water depth), within an oxygen minimum zone. Another model for the genesis of these Sinemurian mounds was proposed by Chafiki et al. (2004) (Fig. 8). According to this model, the Sinemurian mounds developed in open and deep sea conditions within the storm wave base and their rise and growth (and burying) was related to sea floor morphologic changes. In this case, the rise and growth of mounds would correspond to the main breakup of the platform towards the Lower-Upper Sinemurian boundary, then the vertical swelling could be related to the subsidence and carbonate sedimentation.

According to the model proposed by Chafiki et al. (2004) and the data collected in the present study, we suggest that frequency and shape of the mounds could be related to rhythmic changes or fluctuations of the sea level (Fig. 8). The onset of the lower interval and the sponge-microbial mounds can be related to the rhythmic deepening and shallowing trends. Moreover, the formation of small-scale sequences of mounds can be explained by the fluctuation of the sea level.

During the deposition of the middle interval, the sea level fluctuations change in frequency and amplitude, and become deeper and more stable, leading enough time for microbial heterotrophic processes inducing the microbialite formation and the development of the larger sized mounds. The transgressive stage implied new accommodation space and involved the formation and development of a significant framework. Additionally, the deposition in deep sea could be confirmed by the scarcity of detrital inputs and by the abundance of aphanitic micrite. The upper interval shows a clear evidence of sea level increasing. Actually, the big and well-sorted mound lenses, composed of dark aphanitic micrite, indicate a deposition within deep water conditions and stressed suboxic environment. The remarkable vertical mound accretion observed within this interval proves an unrestricted accommodation space.

CONCLUSIONS

New evidences obtained through micrite characterization enabled to contribute to the reconstruction of the evolution and depositional geometry of the Sinemurian carbonate mounds of the Foum Tillicht section. The rise, growth, and burial of the studied mounds have been related to changes of the sea floor morphology. The mound growth was controlled by two main factors: 1) the biotic association and micrite types; and 2) the sea level fluctuations. The geobiological characterization confirmed the distinction of three different intervals. The lower interval consists mainly of relatively small size microbial mounds separated by large inter-mound bedded sediments. This interval is dominated by the detrital (allochthonous) micrite, skeletal grains are mainly composed of *Terebella*. Hexactinellids represent only 4% and other sponges 2%. The middle interval is dominated by larger and complex mounds where the autochthonous micrite dominates (40%) and the contribution of the detrital micrite decreases to 14%. Also the upper interval is characterized by massive, big, but sub-vertical mound-lense structures, composed mainly of autochthonous micrite and a relevant contribution of the skeletal components.

The autochthonous micrite occurs mainly as clotted peloidal or aphanitic textures. The peloidal to clotted peloidal microfabric lacks any trace of microfossils, and shows abundant scattered corpuscles and honeycomb-like structures. These evidences suggest a microbial induced precipitation, mediated by heterotrophic activities in stressed dysoxic environment. The aphanitic fabric of the micrite associated to siliceous sponges is related to microbial inducing mineralization or to organomineralization processes due to organic matter decay. The amount of autochthonous syndepositional cemented micrite, detrital micrite and skeletal component is related to the sea level variation. During the deposition of the lower interval shallow and well oxygenated water conditions favored the deposition of detrital micrite and the growth of small mounds, while deep water and suboxic/anoxic conditions prevailed during the middle and upper intervals. These conditions stimulated the heterotrophic microbial activities and autochthonous micrite development favoring the onset of larger mounds.

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