Open Research Online

The Open University's repository of research publications and other research outputs

Recognition of massive Upper Cretaceous carbonate bodies as olistoliths using rudist bivalves as internal bedding indicators (Campanian Merfeg Formation, Central Tunisia)

Journal Item

How to cite:

Negra, M. Hédi; Skelton, Peter W.; Gili, Eulàlia; Valdeperas, F. Xavier and Argles, Tom (2016). Recognition of massive Upper Cretaceous carbonate bodies as olistoliths using rudist bivalves as internal bedding indicators (Campanian Merfeg Formation, Central Tunisia). *Cretaceous Research*, 66 pp. 177–193.

For guidance on citations see [FAQs](#).

© 2016 Elsevier Ltd

<https://creativecommons.org/licenses/by-nc-nd/4.0/>

Version: Accepted Manuscript

Link(s) to article on publisher's website:

<http://dx.doi.org/doi:10.1016/j.cretres.2016.06.003>

Copyright and Moral Rights for the articles on this site are retained by the individual authors and/or other copyright owners. For more information on Open Research Online's data [policy](#) on reuse of materials please consult the policies page.

oro.open.ac.uk

Accepted Manuscript

Recognition of massive Upper Cretaceous carbonate bodies as olistoliths using rudist bivalves as internal bedding indicators (Campanian Merfeg Formation, Central Tunisia)

M.Hédi Negra, Peter W. Skelton, Eulàlia Gili, F. Xavier Valldeperas, Tom Argles

PII: S0195-6671(16)30110-0

DOI: [10.1016/j.cretres.2016.06.003](https://doi.org/10.1016/j.cretres.2016.06.003)

Reference: YCRES 3409

To appear in: *Cretaceous Research*

Received Date: 4 March 2016

Revised Date: 10 June 2016

Accepted Date: 10 June 2016

Please cite this article as: Negra, M.H., Skelton, P.W., Gili, E., Valldeperas, F.X., Argles, T., Recognition of massive Upper Cretaceous carbonate bodies as olistoliths using rudist bivalves as internal bedding indicators (Campanian Merfeg Formation, Central Tunisia), *Cretaceous Research* (2016), doi: 10.1016/j.cretres.2016.06.003.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

**Recognition of massive Upper Cretaceous carbonate bodies as olistoliths
using rudist bivalves as internal bedding indicators (Campanian Merfeg
Formation, Central Tunisia)**

M. Hédi Negra[†], Peter W. Skelton^{*}, Eulàlia Gili[‡], F. Xavier Valldeperas[‡], Tom Argles^{*}

[†]Université de Tunis El Manar, Faculté des Sciences de Tunis, Département de Géologie, UR
Pétrologie sédimentaire et cristalline, 2092 El Manar, Tunis, Tunisia (E-mail:
hedinegra@yahoo.fr ; corresponding author)

^{*}Department of Earth, Environment and Ecosystems, The Open University, Milton Keynes
MK7 6AA, UK (E-mail: pwskelto@waitrose.com)

[‡]Departament de Geologia, Universitat Autònoma de Barcelona, Edifici C, Bellaterra, 08193
Barcelona, Spain

ABSTRACT

The Merfeg Formation (upper Campanian) of Central Tunisia crops out around the southwestern periclinal termination of Jebel el Kébar, near Sidi Bouzid. At its base is a massively bedded unit of locally dolomitized, sparsely fossiliferous micritic to microbioclastic limestone that contains several discrete, plurimetric mound-like bodies (lithosomes) of micritic limestone containing locally abundant rudists and corals. The lithosomes are separated laterally from one another by megabreccias and conglomerates containing clasts of similar lithology and are overlain, with sharp contact, by onlapping argillaceous pelagic limestones, within which are intercalated at least two more, somewhat thinner rudist/coral limestone units. This complex of facies is laterally equivalent to thicker, deep platform limestones of the Abiod Formation to the north and east, and to restricted carbonate platform facies of the Berda Formation to the south and west. The lithosomes have previously been interpreted as *in situ* downslope mudmounds that became capped by rudist and coral formations, cemented, and then surrounded by erosively emplaced debris flows. However, our detailed studies of rudist orientations imply variable and in some cases relatively high angles of bedding within the lithosomes with respect to the regional dip of the host strata. Such steep inclinations of internal bedding are unlikely to have been primary. Accordingly, we propose an alternative interpretation that the lithosomes were platform-derived olistoliths, emplaced along with the associated debris flow deposits. Micritic beds, neighbouring the olistoliths are of variable thickness and contain rare large inoceramids and randomly oriented rudists, as well as locally developed microbioclastic beds with planar and small-scale swaley cross stratification. These micritic and microbioclastic beds are, by contrast, interpreted as primary (i.e., non-olistostromal) slope deposits. Whether the proposed catastrophic collapses

of the original platform margin were induced by sea-level fall or seismically triggered (or a combination of the two) remains uncertain.

Key words Olistoliths, rudist limestones, Late Cretaceous, Tunisia.

1. Introduction

A notable feature of the expansive epeiric seas of the Cretaceous Period was episodic progradation of vast carbonate platforms or ramps into neighboring basins in low to mid-palaeolatitudes (Simo, Scott, & Masse, 1993; Skelton, 2003). According to basin configuration and dynamic geological context, the flanking slopes of these platforms or ramps varied from being gentle (frequently less than 3°) to relatively steep (in excess of 10°), hence potentially unstable, especially where accentuated by syn-depositional faulting (Ross & Skelton, 1993). Slope deposits could thus incorporate localized carbonate bodies, hereafter referred to as lithosomes, of either autochthonous or allochthonous origin (e.g., Rosales, Fernández-Mendiola, & Garcia-Mondéjar, 1995; Graziano, 2001; Korbar et al., 2001; Moro & Čosović, 2013 and others cited below); and in some cases distinguishing between the two can be problematical (e.g., Trevisani & Cestari, 2007).

During the Late Cretaceous to Eocene interval, tectonic plate movements gave rise to instabilities that affected platforms and ramps widely around the Mediterranean Tethyan region, and which led, in combination with relative sea-level changes, to various forms of mass transport on their margins and slopes. Examples have been described from northern Syria (Al-Riyami & Robertson, 2000), around the Adriatic margins (Croatia, Korbar et al., 2001; Friuli Basin, Ogata et al., 2014; Maiella platform margin, Mutti, Davoli, Tinterri, & Zavala, 1996, and Stössel, 1999; Apulia, Gargano-Murge region, Borgomano & Philip, 1989, Pieri & Laviano, 1989, and Borgomano, 2000, and the Salento Peninsula, Bosellini & Parente, 1994), in the southern Alps (Doglioni & Bosellini, 1987) and the northern calcareous Alps in Austria (Sanders & Pons, 1999), and in central Tunisia (Negra, 2003).

The response of carbonate deposits to these instabilities was related to their degree of lithification. During tectonic and/or seismic activity, early lithified carbonates deposited on platform and/or distally steepened ramp margins commonly disintegrated into olistoliths and blocks, susceptible to sliding and gravity transportation. Proximally, however, olistoliths may not be clearly distinguishable from autochthonous carbonate lithosomes, particularly where massive, homogeneous bedding and highly bioturbated lithologies may make the recognition of bedding dislocation and rotation difficult. The well exposed and continuous outcrops of the Campanian Merfeg rudist-rich carbonates in Jebel El Kébar (Central Tunisia) provide an instructive example for investigation of this problem.

Jebel el Kébar is located 10 km south of Sidi Bouzid town (Fig. 1A) and it has attracted considerable interest because of the presence of impressively large, mound-like micritic lithosomes that contain locally abundant rudists, corals and associated biota (Khessibi, 1978; Negra, 1984; M'Rabet, Negra, Purser, Sassi, & Ben Ayed, 1986; Negra, 1987; Negra & Philip, 1987; Negra, Purser, & M'Rabet, 1995; Negra & Gili, 2004). These rudist/coral-bearing lithosomes are situated stratigraphically at the base of the upper Campanian Merfeg Formation, the outcrop of which in Jebel el Kébar is limited to the southwestern periclinal closure of the anticline (Fig. 1B), especially along the vertical to overturned SE limb of the fold (Fig. 1C).

[Fig. 1. hereabouts]

Previous studies of the rudist/coral-bearing lithosomes (cited above) established their lithological character, palaeontological content and stratigraphical position, and devoted special attention to their diagenesis (see also Negra & Loreau, 1988). These studies demonstrated that the lithosomes had undergone early lithification and had been partly eroded

and surrounded by megabreccias and conglomerates during the Late Cretaceous. According to the interpretation developed in these works, they had formed as *in situ* downslope mudmounds that became capped by rudist and coral formations, cemented, then surrounded by erosively emplaced debris flows, and finally buried in pelagic sediments (Negra et al., 1995).

The present study focuses on the orientations of the elongate attached (right) valves of hippuritids within the giant rudist/coral-bearing lithosomes. These orientational data are plotted as equal-area stereographic projections and original bedding within the lithosomes then inferred by reference to the orientations of known autochthonous to parautochthonous hippuritid associations previously investigated by the authors in Santonian platform deposits of the southern Central Pyrenees. The results of this comparison are then used to assess the likely origin of the lithosomes.

2. Geological setting

2.1. Regional palaeogeographical setting

Following a late Cenomanian deepening event (Philip & Floquet, 2000; Caron et al., 2006; Zagrarni, Negra, & Hanini, 2008; Negra, Zagrarni, Hanini, & Strasser, 2011), much of the North African Maghreb domain became occupied by shallow carbonate platform facies, extending especially across central and southern Tunisia (Razgallah et al., 1994). The Cenomanian-Turonian transition was marked by an anoxic event, evidence for which is well expressed in Tunisian successions (Abdallah & Meister, 1996; Robaszynski et al., 1993; Zagrarni, Negra, & Melki, 2003; Zagrarni et al., 2008). It was accompanied by a general demise of carbonate platforms and mass extinction of rudists (Philip & Airaud-Crumiere,

1991). In central and southern Tunisia, the anoxic event was followed by a shallowing trend of deposition accompanied by the re-development of rudist-rich platform carbonates during the early-middle Turonian (Bireno Formation: Zagrarni, 1999; Zagrarni et al., 2003). These shallow marine deposits are overlain by marlstones of late Turonian- early Campanian age, constituting the Aleg Formation. Well-developed in central and southern Tunisia, the latter contains ammonites and planktonic foraminifers associated with echinoids, oysters and benthic foraminifers. This relatively open and deep marine Aleg sedimentation was interrupted during the Coniacian by a more or less generalized shallowing trend mainly expressed by the appearance, at least locally, of platform carbonates, locally rich in rudists and forming the Douleb Member (Bismuth, Boltenhagen, Donze, Le Fevre, & Saint-Marc, 1981). The shallowing seems to have been associated with extensional faulting that created horsts and grabens. This irregular Coniacian topography was sealed during the Santonian-early Campanian interval, by pelagic marlstones of the upper Aleg Formation.

The major tectonic event of Late Cretaceous times occurred during the late Santonian, consisting mainly of compression directly linked with a change in the poles of rotation for the opening of the Atlantic (Guiraud & Bosworth, 1997), which were in turn to lead eventually to the gradual closure of the Tethyan Ocean (Skelton, 2003). Numerous previous sedimentary basin-fills along the southern Tethyan margin, from Morocco to the Syrian Arc, were folded (Guiraud, 1998; Guiraud & Bosworth, 1997). At the same time, in Oman, along the northeastern margin of Arabia, the obduction of ophiolites, which had commenced in the Turonian, was proceeding (Lippard, Skelton, & Gass, 1986; Bechennec, Le Métour, Platel, & Roger, 1995). After the late Santonian tectonic event, several phases of rifting and down-warping or passive margin development occurred during Campanian-Maastrichtian time (Philip & Floquet, 2000).

The Campanian was marked by a new broad transgression, with relatively little tectonic activity in the peri-Tethyan continental platforms (Philip & Floquet, 2000; Bey, Kuss, Premoli Silva, Negra, & Gardin, 2012). From North Africa to Arabia, broad margins flanked the southern side of the Tethys Ocean. The Campanian deposits are predominantly of marine origin and richly fossiliferous.

A general NW-SE structural trend (N140) appears to characterize the main Campanian-Maastrichtian basin orientation. Late Campanian-early Maastrichtian sedimentation (Figs. 1A, 2) was dominated by well-bedded micritic limestones rich in coccoliths and planktonic foraminifers associated with echinoids, inoceramids and benthic foraminifers. These widespread deposits suggest the development of a relatively 'deep platform' frequently fragmented into numerous sub-platforms separated by basins (Negra, 1994). This platform/basin ensemble gave rise to an irregular Campanian topography that was sealed during the late Campanian (*Globotruncanita calcarata* biozone) by predominantly marly sediments. At a global scale, this period around the Campanian-Maastrichtian boundary, corresponds, in several areas, to a maximum of flooding (Matsumoto, 1980).

[Fig. 2 hereabouts]

Some of the 'deep platforms' were directly connected with shallower platforms and/or emerged areas. One significant example of the latter was the Sidi Bouzid-Kasserine island (Negra, 1994 ; Negra et al., 1995; Kadri, Essid, & Merzeraud, 2015) in Central Tunisia

(Figure 1A), which had started to emerge from Turonian times. The transition from emerged areas to deep platforms and basins was generally progressive, in the form of ramps. Hence, regional lateral equivalents to the Merfeg Formation are, to the south, the Berda Formation, consisting of bioclastic carbonates with bird eyes and mud cracks, and, to the north and east, deep-platform deposits of the Abiod Formation (Negra et al., 1995). Massively bedded micritic and microbioclastic limestones incorporating large lithosomes containing rudists and corals, together with conglomerates comprising clasts of similar material, constitute one of the most proximal facies relative to the palaeo-islands (Negra, 1984, 1987, 1994, 2003; M'Rabet et al., 1986; Negra & Philip, 1987, Negra et al., 1995, Negra & Gili, 2004). In Tunisia, the Campanian rudist- and coral-rich facies crop out only in two areas: Jebel el Kébar, in the Sidi Bouzid area (Figure 1A), and Jebel Serraguia, 100km to the south west of Kasserine city. Transition from such proximal facies to well bedded pelagic limestones, which is progressive, is mainly expressed by decreasing proportions of redeposited material. Thus, olistoliths and conglomerates containing shallow marine facies are frequently interbedded within well-bedded pelagic micritic limestones. Size and volume of the redeposited material decreases distally from the shallow areas. In addition, organized gravitational sequences, such as debris-flow deposits and turbidites (Negra, 1994; Negra, 2003) have been identified preferentially toward relatively distal areas.

To summarize, in contrast to the Cenomanian (Gattar), Turonian (Bireno), and Coniacian (Douleb) platforms which were regionally extensive, the Campanian (Abiod) platforms appear to have been fragmented and with variable bathymetries. At least some of these platforms correspond to horsts bounded by Campanian faults, which show NW-SE, N-S or WSW-ENE orientations (Bey et al., 2012).

2.2. Stratigraphical situation and character of the rudist/coral-bearing lithosomes in the Merfeg Formation

In the study area, the upper Campanian Merfeg Formation overlies Coniacian to lower-middle Campanian marlstones of the Aleg Formation and is in turn overlain unconformably by claystones, siltstones and conglomerates of the Mio-Pliocene Béglia and Segui formations (Fig. 2).

The Aleg Formation biota consists mainly of planktonic and benthic foraminifers, irregular echinoids and scarce ammonites. The upper part of the formation includes intercalations of argillaceous limestone, heralding the relatively shallower deposits of the Merfeg Formation. In terms of biostratigraphy, the marlstones and argillaceous limestones of this upper part of the Aleg Formation belong to the *Globotruncanita elevata* Biozone (lower to lower-middle Campanian; Gradstein, Ogg J., Schmitz, & Ogg G.M., 2012, fig. 27.6). Laterally, the ratio of planktonic foraminifers to benthic foraminifers plus ostracodes and debris of inoceramids and echinoderms in this part of the Aleg Formation changes along a SW-NE gradient. Thus, from the Rous el Kébar area, on the SE flank of the anticline, to the SW periclinal closure (Fig. 1B), the ratio changes from 0.7 to 0.3 (Negra et al., 1995). This diminution of the planktonic microfaunal proportion toward the SW and increased relative abundance of varied benthic and neritic fauna and bioclasts suggest shallower conditions of deposition in the SW prior to the deposition of the Merfeg Formation.

The Merfeg Formation starts with a ferruginous crust (marking a discontinuity) and is composed of three massively bedded, heterogeneous members (I, II, III), separated by

recessive, thinly bedded, slightly argillaceous limestones with abundant planktonic foraminifers and coccoliths (see fig. 6 in Negra et al., 1995). The planktonic foraminiferal assemblage of the latter beds belong to the *Globotruncana ventricosa* Biozone (of Campanian age according to Bismuth, oral communication, in Negra, 1994; but middle Campanian-early Maastrichtian in Gradstein et al., 2012, Appendix 3). These argillaceous bedded limestones thin as they overlap the mound-like lithosomes within the first member and contain intercalations of conglomeratic and lensoid bioclastic bodies. The third rudist member is overlain by bedded, porcellaneous, silicified micritic limestones that are rich in moulds of *Inoceramus* and chert nodules. The overall thickness of the Merfeg Formation increases from 40 m in the SW periclinal closure to 135 m at Bir ech Chgaïga, but thins again to about half that figure around Rous el Kébar (Fig. 1B). The top of the porcellaneous limestones is eroded and unconformably overlain by the Béglia and Segui formations.

The present study concentrated on the first massively bedded member (I) of the Merfeg Formation, which contains the large mound-like lithosomes. Three main facies can be recognized in this member:

2.2.1. Massively bedded micrites

The most widely distributed facies, which forms the lower part of much of the member flanking the areas occupied by blocks and associated conglomerates and the entire thickness of the member in some areas, comprises massively bedded white micrites and locally developed microbioclastic limestones. Scanning electron photomicrographs (Figure 3A) show evidence of neomorphic recrystallisation, including neogenic microspar and interlocking nanofabrics (M'Rabet et al., 1986; Negra & Loreau, 1988; Negra et al., 1995), in

contrast to the overlying argillaceous limestones (Fig. 3B). Dolomitization is locally present, especially in lower parts of the member, and in places is associated with marked ferruginous weathering in large nodules or semi-continuous bands. Body fossils are generally sparse. Pelagic microfossils are lacking, in contrast to the argillaceous micrites overlying the member. However, irregular echinoids (Figure 4A) are relatively common in the basal few metres of the member, forming an effective marker bed for the base of the Merfeg Formation in the study area. Rudists are locally present, though only as scattered individual valves and in random orientations, suggesting that they are entirely allochthonous. Prominent among these is the large recumbent form, *Pseudosabinia* (Figure 4B) and their inferred downslope redistribution is similar to that observed in co-eval slope deposits in the Gargano Peninsula of SE Italy by Borgomano and Philip (1989). Other localized macrofauna include large inoceramids (*I. cf. goldfussi* d'Orbigny; Negra & Philip, 1987; Figure 4C herein), as well as rare regular echinoids (*Salenia* sp., pers. comm., Andrew Smith, Natural History Museum, London, 2001). Localized planar lamination with numerous burrows, including *Ophiomorpha*, can be seen on weathered surfaces within patches of ferruginous concretionary growth in bedded microbioclastic limestones at Rous el Kébar (Figure 4D; see also fig. 5C, D in Negra et al., 1995). The orientation of this lamination, together with the way-up indications of low angle truncations (possible small-scale swaley-like cross-stratification; Figure 4E) and the backfills of burrows that cut through the depositional laminations, are here consistent with the regional dip.

[Figs. 3 and 4 hereabouts]

2.2.2. Rudist- and coral-rich limestones

The largest examples of the latter – the principal objects of study in this paper – are exposed in the Bir ech Chgaïga sector of the SE flank of Jebel el Kébar (Fig. 5), where the SE fold limb is overturned with a subvertical regional dip, though accompanied locally by upright subsidiary synclines, as also clearly shown in a natural section to the west, in Oued Dakhla (Fig. 6A). The largest of the exposed lithosomes (the conjoined Blocks 1-2 in Fig. 5) exceeds 50 m in stratigraphical height and can be followed along strike for nearly 300 m. Its basal contact on the Aleg Formation (Fig. 7A, B) is broadly flat, though with some basal undulations up to 4 m in amplitude. The basal ferruginous crust runs along the contact, which also incorporates small localized lenses of conglomerate.

[Fig. 5 and 6 hereabouts]

2.2.3. Conglomerates

The mound-like lithosomes are separated laterally from one another, with sharp contacts, by bouldery conglomerates, which, together with the bedded argillaceous limestones, show onlap onto the bodies (Fig. 7C, D). At the NE end of Rous el Kébar, Member I passes entirely into conglomerate with rounded clasts (Fig. 6B, C). Conglomerates include boulders of varied size (millimetric to plurimetric diameter) and composition (Negra, 1984; Negra et al., 1987; Negra, 2003). Certain blocks are micritic and derive from adjacent “mud-mounds” (Negra, 2003) or from carbonates deposited on paleoslopes. Others are bioclastic and sometimes rich in entire joined rudists and corals. The genesis of all types of blocks imply an early lithification of rudist limestones (Negra, 1986; M’Rabet et al., 1986; Negra et al., 1988; Negra, 2003). The matrix enveloping the varied blocks

which is composed of pelagic micritic limestone rich in planktonic foraminifera, suggest resedimentation processes in pelagic depositional environments (Negra, 2003).

[Fig. 7 hereabouts]

The rudist/coral lithosomes (facies 2) are largely composed of yellow-weathering, cream-coloured wackestone and micrite. No obvious bedding is observable within the lithosomes, though parallel joints with metre-scale spacing are visible in some examples, oriented at a steep angle with respect to the regional bedding (Fig. 7B).

The most abundant macrofossils within the rudist/coral-bearing lithosomes are rudists and, secondly, corals (Negra & Philip, 1987). Isolated rudists and corals and their angular fragments are scattered through most of the lithosomes, but the majority of complete specimens are concentrated locally in bouquets and clusters (Fig. 8A, B). By far the commonest rudist species are the two hippuritids, *Hippurites colliciatius* Woodward (Fig. 8A, B) and *Vaccinites vesiculosus* (Woodward) (Fig. 8C, D); '*V. braciensis* Sladić-Trifunović', cited by Negra and Philip (1987), is now regarded as a junior synonym of the latter species (see Laviano & Gallo Maresca, 1992). We have also observed scattered specimens of the multiple-fold hippuritid *Pironea corrugata* (Woodward), the radiolitids *Joufia cappadociensis* (Cox) (Fig. 8E) and '*Rajka*' sp. (now considered a junior synonym of *Biradiolites*), and the large canaliculate form *Pseudosabinia* sp. (previously illustrated in Fig. 4B). In addition, Negra and Philip (1987) recorded the presence of the radiolitid *Pseudopolyconites* sp. According to the SIS dating of Steuber and Schlüter (2012; see their fig. 5), *V. vesiculosus* ranges from the topmost Santonian to the lowermost part of the upper Campanian (within their '*Hippuritella lapeirousei* Interval Zone'). Although this range

overlaps at its top with the lower part of the *Globotruncana ventricosa* Biozone, to which the overlying argillaceous limestones belong (see above), it also leaves open the possibility of the rudist/coral-bearing lithosomes considerably pre-dating those overlying autochthonous deposits.

[Fig. 8 hereabouts].

According to Negra et al. (1995, p. 407), rudists and corals are most abundant at the stratigraphical tops of the mounds, but this distributional pattern is not consistent. In the largest lithosome (the conjoined Blocks 1 and 2; Figs. 5, 7A), for example, rudists are mostly concentrated towards its SW end. The same lithology and fossil content is observed in the blocks in the surrounding conglomerate. Some mega-blocks approach the mound-like lithosomes in size (Fig. 6). The conglomerate has a pale micritic matrix and is frequently capped by a distinctly finer-grained microconglomerate. Macrofossils are relatively scarce in the overlying argillaceous limestones, though several specimens of an irregular echinoid (*Vomeraster subverrucosus* (Gauthier), pers. comm., Andrew Smith, Natural History Museum, London, 2001) were encountered in the area of the SW periclinal closure.

3. Rudist orientations within the rudist/coral-bearing lithosomes

Given the lack of obvious bedding within the rudist/coral lithosomes, but the abundance of hippuritid rudists, it was decided to plot the orientations of the latter in order to check for any consistent pattern from which original bedding orientation within the lithosomes might be inferred. Before reviewing the results of this survey, it is necessary to summarize current

understanding of the typical life positions and modes of taphonomic re-orientation of these rudists.

3.1. Palaeoecology and taphonomy of hippuritid rudists

Field observations of hippuritid rudists preserved in life position show that they typically grew upwards, either vertically or with a somewhat inclined orientation, thereby raising their suspension-feeding systems from the substrate as obligate ‘elevators’ in the ecological morphotype terminology of Skelton and Gili (2002). In most cases, their tubular right (attached) valves became more or less implanted in the sediment that accumulated around them, yielding sediment-supported, ‘constratal’ growth fabrics (Gili, Masse, & Skelton, 1995a; Skelton, Gili, Vicens, & Obrador, 1995b; Vilardell & Gili, 2003). The original direction of growth and life-orientation of specimens shown in vertical section can be confirmed from observation of the tabulae in their lower valves (Fig. 9), since the latter, besides being concave towards the commissure, usually grew with an approximately horizontal attitude in the manner of hammocks slung between the inner surfaces of the valve walls (Skelton & Gili, 2002). Consequently, only specimens exhibiting concave-upwards, approximately bed-parallel tabulae should be considered as preserved in life position. Specimens that grew vertically display tabulae with symmetrical curvature (Fig. 9A), while those with inclined growth tended to produce asymmetrically curved tabulae (with the maximum inflection of curvature displaced towards the opposite side from the direction of inclination; Fig. 9B).

[Fig. 9 hereabouts]

362

363 The clustering density and preferred orientation of the shells, when in life position, seems to
364 have varied according to species. Dense clusters of vertically oriented small slender shells of
365 *Hippurites colliciatius* Woodward and *Hippuritella vasseuri* (Douvillé) have been described
366 from the Maiella carbonate platform, Italy (Stössel & Bernouilli, 2000) and Gosau, Austria
367 (Götz, 2003), respectively. Large, solitary to locally clustered cylindrical forms such as
368 *Vaccinites* also tended to grow vertically, sometimes partially stabilized by other individuals
369 (Steuber, Yilmaz, & Löser, 1998; Schumann, 2000) or by neighboring corals (Gili et al.,
370 1995b; Skelton et al., 1997). By contrast, slender cylindrical *Hippurites socialis* Douvillé and
371 *Hippurites praecessor* Douvillé, for example, most commonly grew in relatively loose
372 clusters, with a preferred inclined orientation (Grosheny & Philip, 1989; Gili, 1992; Skelton et
373 al., 1995; Vilardell & Gili, 2003; see also Fig. 9B). In experimental flume tank and field
374 studies of water flow patterns around models of hippuritids, Gili and LaBarbera (1998; 2001)
375 found that the cap (equivalent to the left valve) of model shells oriented vertically or inclined
376 upstream was bathed only by water from the mainstream flow. Flow around models inclined
377 downstream, however, showed distinct differences from the other orientations. Hippuritid
378 models inclined downstream generate intense rising vortices in their lee that lift water off the
379 substrate and up onto their caps, which are thus bathed in a mixture of water from both the
380 mainstream flow and the surface of the sediment. A downstream inclined orientation
381 accordingly permitted hippuritids to exploit resources (food particles) unavailable to vertically
382 oriented rudists. The conclusions of these experimental studies are consistent with the
383 preferentially inclined growth of hippuritids – verified by the bed-parallel orientation of their
384 tabulae (e.g., Fig. 9B) – away from the inferred predominant current direction in the southern
385 Central Pyrenees (Gili, 1992; Skelton et al., 1995; Vilardell & Gili, 2003). However, a
386 detailed palaeoecological and taphonomic study of one of the hippuritid lithosomes in this

area (Skelton et al., 1995) showed that most of the shells there had been re-oriented (as again confirmed by inspection of their tabulae) so as to lie densely stacked more or less parallel with the bedding. This taphonomic fabric, termed ‘dense horizontal fabric’ in Skelton et al. (1995), was shown to be due to current-induced removal of sediment and the domino-like toppling of shells during occasional storms. Moreover, the toppling direction of the secondarily oriented shells conformed with the direction of growth of the originally inclined specimens, suggesting a causal relationship: the inclined growth could be interpreted as a response to predominant fair-weather currents sharing the same trends as the storm surges.

Specimens with geniculate growth additionally reveal the ability of hippuritids to re-attain elevation through growth when displaced from their upright position (Skelton & Gili, 2002; Vicens & Gili, 1995; Steuber, 1997). The resumption of upward growth by geniculation can be recognized by the re-orientation of tabulae, which re-established an approximately horizontal orientation, while the shell wall underwent curved upward growth (e.g., Skelton & Gili, 2002, Pl. 1, fig. 2). Geniculation was usually a response to toppling by occasional current-induced displacement. However, some shells show a multigeniculate horn-shape evidently reflecting chronic instability that necessitated repetitive recovery growth (Steuber, 1999).

A variety of preserved attitudes with respect to bedding was thus possible in autochthonous to parautochthonous associations of hippuritids, ranging from upright to inclined life orientation (with or without curvature or geniculation) to more or less bed-parallel in the case of secondarily toppled shells (Figs. 10A and 10B). Nevertheless, bulk data from specimens displaying such a spectrum of preserved orientations can be expected to show a mean pole

oriented approximately normal to bedding, with tight clustering of data for vertically grown individuals to looser clustering for those with variably inclined growth, together with a scatter of bed-parallel orientations shown by toppled shells.

[Fig. 10 hereabouts]

3.2. Conventions for plotting orientations of rudists

The orientations of the elongate right (attached) valves of hippuritids within the rudist/coral-bearing lithosomes were plotted as equal-area stereographic lower hemisphere projections, using the Stereonet 4.9.5a plotting software of Allmendinger (1995). For each individual, the present 3-dimensional orientation of the apical to commissure-centre axis of the right valve was plotted, using different symbols according to whether the commissure was directed upwards or downwards (Fig. 11), for both *Hippurites colliciatatus* and *Vaccinites vesiculosus*. For curved valves, the orientation of only the latest-formed part (towards the commissure) was used, as this would indicate the final attitude of those specimens that had been preserved in life position, and data from such geniculate shells were tagged.

[Fig. 11 hereabouts]

All the plotted orientations were then stereographically rotated to correct for the regional dip at the site of each lithosome (allowing also for the overturn of the southern fold limb), so as to reveal the preserved orientations of the rudists prior to folding of the Merfeg strata. Mean

orientations were then identified for consistently clustered rudist data points inferred to represent individuals preserved in life position (as explained in the previous section), to serve as proxies for the poles to the original bedding of their host sediment. Other specimens, with more widely dispersed orientations, can be assumed to represent toppled shells. Finally, original host-sediment bedding orientations inferred from the rudist data were compared with the corrected regional bedding orientation to test for any deviation from concordance.

Rudist orientation data were collected in four sets, for Blocks 1 to 4. Sets 1 and 2 relate to the largest lithosome, at Bir-ech-Chgaïga (Fig. 5), set 1 being derived from its SW termination, which is separated from Block 2 by a gravel-covered path, where the rudists are most abundant. Sets 3 and 4 come from the lithosomes successively along strike to the NE, the latter being exposed in Oued el Khécha (Fig. 5).

3.3. Results and analysis

Figures 12A, C and 13A, C show the stereographic projections of the 'raw', unrotated hippuritid orientational data for Blocks 1-4, respectively. The same data are then shown rotated so as to correct for the regional dip of the overturned host strata in Figures 12B, D + E and 13B, D, respectively. Also included for the conjoined Blocks 1 and 2 in Figures 12B and C-E is the mean orientation in each block of prominent parallel joints that are possibly interpretable as bedding (Figure 7B). Finally, Figure 13E shows for Block 4 the effect of a second rotation to orientate vertically the pole to bedding estimated from the rudist orientations, illustrating the clustering of individuals interpreted to have been preserved more

or less in life position around that pole, as well as the scatter of data (grey points) around the (restored) horizontal plane representing specimens presumed to have been toppled.

[Figures 12 and 13 hereabouts]

Figures 12B, D, E and 13B, D reveal that after correction for the regional tectonic tilt, the hippuritids – both *Vaccinites* and *Hippurites* – predominantly ‘face’ (i.e., have their commissures directed) towards the South-West (as previously noted for uncorrected orientational data by Negra, 1987, Fig. 3 therein) in Blocks 1-3, or towards the West in the case of Block 4. In each case, the mean pole for the corrected autochthonous rudist data shows a shallow declination towards the NE (or to the East in the case of Block 4), implying an inferred bedding orientation dipping steeply (up to $\sim 70^\circ$) to the SW (or to the West, for Block 4) according to the argument based on rudist life positions rehearsed earlier.

Significantly, while the orientations of *Hippurites* specimens show some expected scatter, relating to the variable inclination of individuals in autochthonously preserved clusters (e.g., Fig. 14A), those of *Vaccinites* specimens show relatively greater consistency, presumably reflecting typically upright implantation of their large, elongate shells during growth, similarly to examples in the Santonian of the southern Central Pyrenees investigated by Gili et al. (1995b) and Skelton, Gili, Rosen, and Valdeperas (1997). Even geniculate specimens of the latter (e.g., Fig. 14B) re-attained closely similar orientations in the latest-formed parts of their shells (Fig. 13E). On the other hand, the more scattered data points assumed to represent toppled shells show, as expected, a tendency to cluster around the girdle for the inferred

bedding (grey points in Fig. 13E). Also worth noting is that the mean rudist poles for Blocks 1 and 2 are close to those for the parallel joints observed within them (Figs. 7B, 12B, E), although that for Block 3, by contrast, is clearly divergent (Fig. 13A, B), suggesting that the joints observed in the latter may indeed be tectonic. Additional corroboration for the inferred bedding orientations in the conjoined Blocks 1 and 2 comes from associated articulated specimens of the large recumbent canaliculate rudist *Pseudosabinia* (Fig. 14C), which would have lain prone on the sediment surface in life.

[Fig. 14 hereabouts]

Finally, mention should be made of some additional measurements of commissural plane orientations made on articulated specimens of *Inoceramus* cf., *goldfussi* preserved in porous white clotted micrites (Block 5) along strike to the West of Blocks 1/2 (Figs. 4C and 12F). In contrast to the rudist orientational data discussed above, the mean pole for the commissural planes of these large flat clams lies remarkably close to that for the host fold limb, suggesting concordant bedding there.

4. Discussion

The hippuritid orientational data discussed above imply bedding dips within the investigated lithosomes of up to $\sim 70^\circ$ with respect to the original regional bedding of the basal member (I) of the Merfeg Formation. Moreover, this inferred bedding – further corroborated by the

orientations of associated recumbent *Pseudosabinia* – matches prominent parallel joints within the largest lithosome (conjoined Blocks 1 and 2), which probably thus indeed represent bedding. It is inconceivable that such a steep bedding orientation for the accumulating lime sediments in which elevator rudists became passively implanted could have been primary, contrary to the earlier interpretation of the lithosomes as *in situ* mudmounds colonized by rudists and corals (Negra, 1987; Negra et al., 1995). Hence the lithosomes are re-interpreted here as allochthonous blocks (olistoliths) calved from a nearby platform margin. The similarity of the sense of bedding rotation in the investigated blocks – with internal bedding tilting down to the SW or W with respect to the original horizontal – implies rotational slumping and sliding from a source area in that general direction (Fig. 15). Smaller blocks, by contrast, would have been able to roll, hence their more haphazard orientations in the bouldery conglomerates that surround the blocks. In other words, the former ‘mounds’ can now be regarded as the largest components of a gigantic debris-flow, otherwise already attested by the widespread platform-derived conglomerates (Negra, 2003).

[Fig. 15 hereabouts]

The inferred rotational slumping and sliding of the rudist and coral-bearing blocks from a carbonate platform source area to the SW (or W) is consistent with the palaeogeographical context outlined earlier (Fig. 1A), based on regional facies distributions, analysis of planktonic/benthic foraminiferal ratios in the underlying Aleg Formation and indications of slope instability in the laterally equivalent Merfeg and Abiod formations (Negra et al., 1995), the sedimentology of the conglomerates (Negra, 2003) and the evidence for micrite diagenesis and early lithification within the blocks (Negra, 1984; M'Rabet et al., 1986; Negra & Loreau,

1988). Nevertheless, the presence of a zone between Oued Dakhla and Jebel Fraiou (Fig. 1B) that lacks such mega-blocks allows the possibility that the two areas could have been sourced from different parts of the parent platform. The massively bedded micrites and locally developed microbioclastic limestones with *Inoceramus*, irregular echinoids and tempestite horizons (Negra & Zagrarni, 2007), by contrast, appear to represent primary accumulations of locally generated or transported sediments on the paleoslope.

5. Conclusions

The approach adopted herein of using plots of rudist orientations to infer internal bedding in the lithosomes has thus proved its worth for (re-)interpreting how the latter originated, so can be recommended for the analysis of comparable slope deposits elsewhere.

The colossal scale and regional extent of the debris flows in the basal Merfeg member (I), in particular, beg the question of how they were triggered. Numerical modeling of the compositionally similar Maiella carbonate platform in Italy by Rusciadelli, Sciarra, and Mangifesta (2003) suggests that emersion alone, despite creating considerable lithostatic stresses, might not have been sufficient to have caused its collapse. The additional involvement of seismic shocks thus seems likely – like the proverbial straw that breaks the camel's back – and evidence for contemporaneous collapses elsewhere and for some tectonic activity in the region indeed exists (M'Rabet et al., 1986; Negra, 2003; Bey et al., 2012).

As a final speculation, we suppose that collapse on this scale would have generated widespread tsunamis, offering the possibility for testing the scenario that we propose by searching for evidence of coeval tsunami deposits in surrounding regions.

Acknowledgements

The research on which this study is based was funded by NATO Collaborative Linkage Grant (Mediterranean Dialogue countries) EST.CLG.977089 to M.H.N., E.G. and P.W.S., on ‘Genesis of rudist and coral formations in El Kébar, Tunisia’ (2000-2002). In addition, comparative studies of rudist palaeoecology in the southern Central Pyrenees were supported by Spanish DGI Project no. PB 97-0135-C02-02. We are very grateful for the identification of echinoids by Andrew Smith (NHM). Albert Casanelles Gili is thanked for drawing the cartoons of Figs. 10, 11 and 15. Jalel Jaballah is also thanked for the improvement of some figures. For our stereographic projections of the rudist orientations, we used the free-download ‘Stereonet’ software produced by Richard Allmendinger. We address our thanks to two anonymous reviewers who have revised our paper and contributed to improve its content.

References

Abdallah, H. and Meister, C. (1996) La limite Cénomanién-Turonien en Tunisie du Centre - Sud. Extension du faciès Bahloul (Cénomanién supérieur – Turonien inférieur) : biostratigraphie, paléoenvironnements. *Comptes Rendus de l'Académie des Sciences de Paris*, **322** (IIa), 39-46.

Allmendinger, R. (1995) Stereonet for Macintosh, distributed via:
<ftp://www.geo.cornell.edu/pub/rwa> (last visited, 02/03/2015)

Bechennec, F., Le Métour, J., Platel, J.-P. and Roger, J. (1995) Doming and down-warping of the Arabian Platform in Oman in relation to Eoalpine tectonics. In: *Middle East Petroleum Geosciences, GEO'94* (Ed. M.I. Al-Husseini), Vol.1, pp. 167-178. Gulf PetroLink, Bahrain,

Bey, S., Kuss, J., Premoli Silva, I., Negra, M.H. and Gardin, S. (2012) Fault-controlled stratigraphy of the Late Cretaceous Abiod Formation at Ain Medheker (Northeast Tunisia). *Cretaceous Research*, **34**, 10-25.

Bismuth, H., Boltenhagen, C., Donze, P., Le Fevre, J. and Saint-Marc, P. (1981) Le Crétacé moyen et supérieur du Jebel Semmama (Tunisie du Centre-Nord): microbiostratigraphie et évolution sédimentologique. *Bull. Centres Rech. Explor.-Prod. Elf Aquitaine. Pau*, **5**, 193-267.

Borgomano, J.R.F. (2000) The Upper Cretaceous carbonates of the Gargano-Murge Region, Southern Italy: a model of platform-to-basin transition: *AAPG, Bull*, v. **84**, p.1561-1588.

Borgomano, J. and **Philip, J.** (1989) The rudist carbonate build-ups and the gravitary carbonates of the Gargano-Apulian margin (southern Italy, upper Senonian). *Mem. Soc. Geol. It.*, **40**, 125-132.

Bosellini, A. and **Parente, M.** (1994) The Apulia Platform margin in the Salento Peninsula (southern Italy). *Giornale di Geologia*, **56**, pp.167-177.

Boukadi, N. and **Bedir, M.** (1996) L'halocinèse en Tunisie: contexte tectonique et chronologie des événements. *C. R. Acad. Sc. Paris*, **322**, série IIa, 587-594.

Burollet, P. F. (1956) Contribution à l'étude stratigraphique de la Tunisie centrale. *Ann. Mines Géol. (Tunis)*, **18**, 345 pp.

Caron, M., Dall'Agnolo, S., Accarie, H., Barrera, E., Kauffman, E.G., Amédro, F., Robaszynski, F. (2006) High-resolution stratigraphy of the Cenomanian–Turonian boundary interval at Pueblo (USA) and Wadi Bahloul (Tunisia): stable isotope and bio-events correlation. *Geobios* 39, 171–200.

Gili, E. (1992) Palaeoecological significance of of rudist constructions: a case study from les Collades de Basturs (Upper Cretaceous, south-central Pyrenees). *Geologica Romana*, **28**, 319-325.

Gili, E. and LaBarbera, M. (1998) Hydrodynamic behaviour of hippuritid rudist shells: ecological consequences. *Geobios, Mémoire special*, **22**, 137-145.

Gili, E. and LaBarbera, M. (2001) Movimiento del fluido alrededor de las conchas de los hipurítidos: efectos de la orientación de las conchas en el suministro y concentración de partículas en las corrientes de alimentación. *Geotemas*, **3**, 281-284.

Gili, E., Masse, J.-P., and Skelton, P.W. (1995a) Rudists as gregarious sediment-dwellers, not reef-builders, on Cretaceous carbonate platforms. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **118**, 245-267.

Gili, E., Skelton, P.W., Vicens, E. and Obrador, A. (1995b) Corals to rudists – an environmentally induced assemblage succession. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **119**, 127-136.

Gradstein, F., Ogg, J., Schmitz, M.D. and Ogg, G.M. (Eds.) (2012) *The Geologic Time Scale 2012*. Elsevier, Amsterdam. 1144 pp.

632

633 **Graziano, R.** (2001) The Cretaceous megabreccias of the Gargano Promontory (Apulia,
634 southern Italy): their stratigraphic and genetic meaning in the evolutionary framework of the
635 Apulia Carbonate Platform. *Terra Nova*, **13**, 110-116.

636

637 **Grosheny, D. and Philip, J.** (1989) Dynamique biosédimentaire de bancs à rudistes dans un
638 environnement perideltaïque: la formation de La Cadière d'Azur (Santonien, SE France).
639 *Bulletin de la Société Géologique de France* (8), t. V, **6**, 1253-1269.

640

641 **Götz, S.** (2003) Larval Settlement and Ontogenetic Development of *Hippuritella vasseuri*
642 (Douvillé) (Hippuritoidea, Bivalvia). *Geologia Croatica*, **56**, 123-131.

643

644 **Guiraud, R.** (1998) Mesozoic rifting and basin inversion along the northern African Tethyan
645 margin: an overview. In: *Petroleum Geology of North Africa* (Eds. D.S. Macgregor, R.T.J.
646 Moody and D.D. Clark-Lowes), *Geological Society of London, Special publication*, **133**, 215-
647 227.

648

649 **Guiraud, R. and Bosworth, W.** (1997) Senonian basin inversion and rejuvenation of rifting
650 in Africa and Arabia: synthesis and implication to plate – scale tectonics. *Tectonophysics*,
651 **282**, 39-82.

652

Kadri , A., Essid, E. M. and Merzeraud, G. (2015) Limit emerged boundaries of "Kasserine Island" changed during the Upper Cretaceous-Eocene (Central Tunisia). *J. of African Earth Sc.*, **111**, 244-257.

Khessibi, M. (1978) *Etudes géologiques du secteur de Maknassy-Mezzouna et du Jebel Kébar (Tunisie centrale)*. Doctoral thesis, Université de Lyon, France, 175 pp.

Korbar, T., Fuček, L., Husinec, A., Vlahović, I., Oštrić, N., Matičec, D. and Jelaska, V. (2001) Cenomanian carbonate facies and rudists along shallow intra-platform basin margin – the island of Cres (Adriatic Sea, Croatia). *Facies*, **45**, 39-58.

Laviano, A. and Gallo Maresca, M. (1992) Palaeontological characters of the species *Vaccinites vesiculosus* (Woodward). *Geologica Romana*, **28**, 49-59.

Lippard, S.J., Shelton, A.W. and Gass, I.G. (1986) *The ophiolite of Northern Oman. The Geological Society of London, Memoir 11*, 178 pp.

Matsumoto, T. (1980) Inter-regional correlation of transgressions and regressions in the Cretaceous period. *Cretaceous Research*, **1**, 259-373.

Moro, A. and Čosović, V. (2013) Upper Turonian–Santonian slope limestones of the islands of Premuda, Ist and Silba (Adriatic coast, Croatia). *Geologia Croatica*, **66**, 1-13.

M'Rabet, A., Negra, M. H., Purser, B. H., Sassi, S. and Ben Ayed, N. (1986) Micrite diagenesis in Senonian rudist build-ups in Central Tunisia. In: *Reef Diagenesis* (Eds. J. H. Schroeder and B. H. Purser), pp. 210-223, Springer, Berlin.

Mutti, E., Davoli, G., Tinterri, R., & Zavala, C. (1996) The importance of fluvio-deltaic systems dominated by catastrophic flooding in tectonically active basins. *Memorie di Scienze Geologiche*, **48**, 233-291.

Negra, M. H. (1984) *Paléoenvironnement et diagenèse des faciès récifaux à rudistes du Jebel Kébar, Tunisie centrale*. Doctoral thesis, Université de Paris, Orsay, France, 290 pp.

Negra, M. H. (1987) Paléoenvironnement et conditions de genèse du complexe sénonien récifal à rudistes du Jebel el Kebar, Tunisie centrale. *Bull. Soc. Géol. France*, (8), **3**, 317-326.

Negra, M. H. (1994) *Les dépôts de plate-forme à bassin du Crétacé supérieur en Tunisie centro-septentrionale. Sédimentation et Diagenèse des series du Crétacé supérieur (formation Abiod et faciès associés). Stratigraphie, Sédimentation, Diagenèse et Intérêt pétrolier*. Doctorat Es-Sciences thesis, Université de Tunis, 548 pp.

694

695 **Negra, M. H.** (2003) Upper Cretaceous platform-derived conglomerates in Central Tunisia:
696 Significance and genesis mode, In: North African Cretaceous Carbonate Platform Systems
697 (Eds. E. Gili, M.H. Negra and P.W. Skelton), *Nato Science Series IV/28*, pp.129-141.

698

699 **Negra, M. H.** and **Gili, E.** (2004) The role of rudists in micrite production and stabilisation.
700 Example of the Upper Cretaceous rudist formations in Jebel el Kebar, Central Tunisia. *Cour.*
701 *Forsch.-Inst. Senkenberg*, **247**, 193-205.

702

703 **Negra, M. H.** and **Loreau, J. P.** (1988) Nanostructures comparées et diagenèse polyphasée
704 des micrites dans des ‘mud-mounds’ à rudistes; exemple du Sénonien supérieur du Jebel el
705 Kébar, Tunisie centrale. *Géologie Méditerranéenne*, **15**, 143-157.

706

707 **Negra, M. H.** and **Philip, J.** (1987) Stratigraphie et paléontologie des formations à rudistes et
708 grands foraminifères du Campanien du Jebel Kébar (Tunisie Centrale). *Géologie*
709 *Méditerranéenne*, **12/13** (for 1985/6), 49-57.

710

711 **Negra, M. H., Purser, B. H.** and **M'Rabet, A.** (1995) Sedimentation, diagenesis and
712 syntectonic erosion of Upper Cretaceous rudist mounds in central Tunisia. *Spec. Publs int.*
713 *Ass. Sediment.*, **23**, 401-419.

714

Negra, M.H. and Zagrarni, M.F. (2007) Upper Cretaceous tempestites in rudist-rich facies, Tunisia. Cretaceous Rudists and Carbonate Platforms: Environmental Feedback. *SEPM Spec. Publ.*, **87**, ISBN 978-1-56576-127-8, p.45-56.

Negra, M.H., Zagrarni, M.F., Hanini, A. and Strasser, A. (2011) The filament event near the Cenomanian-Turonian boundary in Tunisia. *Bull. Soc. géol. France*, **182**, 507-519.

Ogata, K., Pogačnik, Ž., Gini, G.A., Tunis, G., Festa, A., Camerlenghi, A. and Rebesco, M. (2014) The carbonate mass transport deposits of the Paleogene Friuli Basin (Italy/Slovenia): Internal anatomy and inferred genetic processes. *Marine Geology*, **356**, 88–110.

Philip, J. and Airaud-Crumière, C. (1991) The demise of the rudist-bearing carbonate platforms at the Cenomanian/Turonian boundary; a global control. *Coral Reefs*, **10**, 115-125.

Philip, J. and Floquet, M. (2000), Late Cenomanian; Early Campanian; Late Maastrichtian. Explanatory Notes. In: *Peri-Tethys, Paleogeographical Atlas* (Eds. J. Dercourt, M. Gaetani, B. Vrielynck, E. Barrier, B. Bijou-Duval, M.F. Brunet, J.P. Cadet, S. Crasquin and M. Sandulescu). CCGM/CGMW, Paris.

Pieri, P. & Laviano, A. (1989) Tettonica e sedimentazione nei depositi senoniani delle Murge sud-orientali (Ostuni). *Boll. Soc. Geol. It.*, **108**, 351-356.

737

738 **Razgallah, S., Philip, J., Thomel, G., Zaghib-Turki, D., Chaabani, F., Ben Hajali, N.**

739 **and M'Rabet, A.** (1994) La limite Cénomanién – Turonien en Tunisie centrale et

740 méridionale: biostratigraphie et paléoenvironnements. *Cretaceous Research*, **15**, 507-533.

741

742 **Robaszynski, F., Hardenbol, J., Caron, M., Amedro, F., Dupuis, C., Gonzales – Dunozo,**

743 **J.M., Linares, D. and Gartner, S.** (1993) Sequence stratigraphy in a distal environment: the

744 Cenomanian of the Kalaat Senan Region (Central Tunisia). *Bulletin du Centre de Recherche*

745 *Exploration – Production Elf-Aquitaine*, **17** (2), 395-433.

746

747 **Rosales, I., Mehl, D., Fernández-Mendiola, P.A. and García-Mondéjar, J.** (1995) An

748 unusual poriferan community in the Albian of Islares (north Spain): palaeoenvironmental and

749 tectonic implications. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **119**, 47-61.

750

751 **Rusciadelli, G., Sciarra, N. and Mangifesta, M.** (2003) 2D modelling of large-scale

752 platform margin collapses along an ancient carbonate platform edge (Maiella Mt., Central

753 Apennines, Italy): geological model and conceptual framework. *Palaeogeogr.,*

754 *Palaeoclimatol., Palaeoecol.*, **200**, 107-126.

755

756 **Sanders, D. and Pons J.M.P.** (1999) Stratigraphy, sedimentology, and models of

757 development. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **148**, 249-284.

758

Schumann, D. (2000) Paleocology of late Cretaceous rudist settlements in Central Oman.
In: *Middle East models of Jurassic/Cretaceous carbonate systems* (Eds A.S. Alsharhan and
R.W. Scott), *SEPM Spec. Publ.*, **69**, 245-262.

Simo, J.A.T., R.W. Scott and J.-P. Masse, eds. (1993) Cretaceous carbonate platforms: an
overview. Cretaceous carbonate platforms. *AAPG Memoir*, **56**, 479 p.

Skelton, P. W. (2003, ed.) *The Cretaceous World*. The Open University and Cambridge
University Press, Cambridge, UK, pp. 360.

Skelton P.W. and Gili, E. (2002) Palaeoecological classification of rudist morphotypes.
Proc. 1st Int. Conf. on Rudists (Beograd, 1988), "Rudists", *UGSY, Mem. Publ.* 265-285.
[Reprints of this paper were issued in 1991, but the full volume itself was not published until
2004.]

Skelton, P.W., Gili, E., Vicens, E. and Obrador, A. (1995) The growth fabric of gregarious
rudist elevators (hippuritids) in a Santonian carbonate platform in the southern Central
Pyrenees. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **119**, 107-126.

Skelton, P.W., Gili, E., Rosen, B.R. and Valdeperas, F.X. (1997) Corals and rudists in the
late Cretaceous: a critique of the hypotheses of competitive displacement. *Boletín de la Real
Sociedad española de Historia natural (Sec. Geol.)*, **92**, 225-239.

781

782 **Steuber, T.** (1997) Hippuritid rudist bivalves in siliciclastic settings – functional adaptations,
783 growth rates and strategies. *8th International Coral Reef Symposium, Panama City,*
784 *Proceedings*, **2**, 1761-1766.

785

786 **Steuber, T.** (1999) Cretaceous rudists of Boeotia, central Greece. *Special Papers in*
787 *Palaeontology*, **61**, 229 pp.

788

789 **Steuber, T. and Schlüter, M** (2012) Strontium-isotope stratigraphy of Upper Cretaceous
790 rudist bivalves: Biozones, evolutionary patterns and sea-level change calibrated to numerical
791 ages. *Earth-Science Reviews*, **114**, 42–60.

792

793 **Steuber, T., Yilmaz, C., and Löser, H.** (1998) Growth rates of early Campanian rudists in a
794 siliciclastic-calcareous setting (Pontid Mts., North-Central Turkey). *Geobios, Mémoire spécial*,
795 **22**, 385-401.

796

797 **Stössel, I.** (1999) Rudists and carbonate platform evolution: the Late Cretaceous Maiella
798 carbonate platform margin, Abruzzi, Italy. *Memorie di Scienze Geologiche*, **51**, 333-413.

799

800 **Stössel I. and Bernoulli, D.** (2000) Rudist lithosome development on the Maiella Carbonate
801 Platform Margin. In: *Carbonate Platform Systems: components and interactions* (Eds E.

Insalaco, P.W: Skelton, and T.J. Palmer), *Geological Society, London, Spec. Publ.*, **178**, 177-190.

Trevisani, E. and Cestari, R. (2007) Upper Cretaceous rudist bivalves from basinal highs (Venetian Prealps, northern Italy). *SEPM Spec. Publ.*, **87**, p.71-80.

Vicens, E. and Gili, E. (1995) Características morfológicas y paleoecológicas de los hipurítidos. *Revista Española de Paleontología*, **10**, 130-139.

Vilardell, O. and Gili, E. (2003) Quantitative study of an hippuritid rudist lithosome in a Santonian carbonate platform in the southern Central Pyrenees. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **200**, 31-41.

Zagrarni, M.F. (1999) *Sédimentologie, stratigraphie séquentielle et diagenèse des faciès du Crétacé supérieur du Jebel Biréno. Paléogéographies des plates-formes carbonatées du Cénomanién supérieur–Coniacien en Tunisie centrale*. PhD Thesis, University of Tunis II.

Zagrarni, M.F., Negra, M.H. and Melki, S. (2003) Turonian rudist-coral limestones in Jebel Biréno, Central Tunisia. In: *North African Cretaceous Carbonate Platform Systems* (Eds. E. Gili, M.H. Negra and P.W. Skelton), *Nato Science Series IV/28*, pp.111-128.

Zagrarni, M.F., Negra, M.H., Hanini, A. (2008) Cenomanian-Turonian facies and sequence stratigraphy, Bahloul Formation, Tunisia. *Sedimentary Geology*, **204**, 18-35.

FIGURE CAPTIONS

Fig. 1. (A) Location map, showing general situation and Campanian palaeogeographical context of strata in the Jebel el Kébar anticline. (B) Geological map of SW periclinal termination of Jebel el Kébar. (C) Diagrammatic section across SE limb of anticline and subsidiary syncline at Bir-ech-Chgaïga (section line X-Y in (B)).

Fig. 2 Summary stratigraphical log of formations exposed at study area in Jebel el Kébar.

Fig. 3 (A) SEM photograph of matrix of Unit 1 rudist limestone, showing anhedral to subhedral micritic grains partly surrounded by a sparitic cement. (B) SEM photograph of bedded argillaceous limestone onlapping the Unit 1 rudist limestones, showing abundant nanofossils, predominantly coccoliths and their debris.

Figure 4. Macrofossils and sedimentary structures in massively bedded white micrites and microbioclastic limestones of Merfeg Formation: (A) Section of irregular echinoid in the basal bed (Oued Dakhla); (B) *Pseudosabiania*, fragment of coiled left valve (J. Fraiou); (C) *Inoceramus* cf. *goldfussi* d'Orbigny (west of Bir-ech-Chgaïga); (D) *Ophiomorpha* (Rous el-

Kébar); (E) Possible swaley-like cross stratification (Rous el-Kébar). Scale bars in A, B, D are 10 mm; length hammer head in C is 150 mm.

Fig. 5. Detailed map showing the geometry of the rudist- and coral-rich limestones of the Merfeg Formation in the Bir-ech-Chgaïga sector of the Jebel el Kébar anticline, southern limb (see Fig 1B for location). Key to stratigraphical units: (a) Aleg marlstones; (b, e, f) rudist limestones I, II and III, respectively; (c) intraformational conglomerates; (d) pelagic argillaceous limestones; (g) bedded micritic limestones; (h) Mio-Pliocene silts and clays. Numbers in white circles refer to Blocks 1, 2, 3 and 5 discussed in text. Red arrows indicate directions towards Oued Dakhla (to the SW) and Oued el Khécha, including Block 4 (to the NE). X-Y shows section line for Fig. 1C.

Fig. 6. (A) Natural section along eastern wall of Oued Dakhla (see Fig. 1B for location), showing overturned southern limb of anticline at right (south), with allochthonous megablock in lower part of Merfeg Formation (arrowed) and Aleg Formation in its core, as well as roof syncline to the north. (B) Field photo showing conglomerates containing varied-sized pebbles. Rous el Kébar area. (C) Detailed view showing a rudist-rich “block” enveloped by a micritic matrix.

Fig. 7. (A, B) Block 2 of the largest mound-like rudist- and coral-rich lithosome at Bir-ech-Chgaïga, viewed from the north (i.e., from stratigraphically beneath it), with vertical joints interpreted here as bedding indicated in (B) together with person in white circle for scale. (C, D) Onlap of flanking beds on rudist- and coral-rich lithosome (Block 3) at Bir-ech-Chgaïga, with bedding relationships indicated in (D). See Fig. 5 for locations.

869

870 Fig. 8 Rudists in the Merfeg Formation, Jebel el Kébar: (A) cluster of slender hippuritids
871 (*Hippurites colliciatus* Woodward) in isolated block (Rous-el-Kébar); (B) cluster of *H.*
872 *colliciatus* right (attached) valves viewed in transverse section (Rous-el-Kébar); (C) pair of
873 *Vaccinites vesiculosus* (Woodward) in longitudinal section (Oued el Khécha, Block 4); (D)
874 *V. vesiculosus*, articulated shell (Jebel Fraiou); (E) *Joufia cappadociensis* (Cox) (Bir-ech-
875 Chgaïga, Block 2). See Fig. 1B for localities. Length of hammer head in A and C is 150 mm;
876 Scale bars in B, D and E is 10 mm.

877

878 Fig. 9 (A) Hippuritid specimens showing symmetrical concavity of tabulae towards the
879 commissure, including base of body chamber, here filled by white micrite (*H. colliciatus*,
880 Rous-el-Kébar); (B) Oblique, bed-parallel tabulae in *H. socialis* specimens preserved in
881 inclined life position (Vilanoveta, southern Central Pyrenees; see Skelton et al., 1995). Scale
882 bars are 10 mm.

883

884 Fig. 10 Summary cartoons showing typical hippuritid orientations with respect to bedding and
885 currents, including accidentally toppled shells and specimens with geniculate recovery
886 growth. (A) Rudist shells implanted in the sediment forming upright growth fabrics. (B)
887 Slender cylindrical shells with a downstream inclined orientation

888 Fig. 11 Diagram explaining conventions for stereographic plotting of rudist orientations: (A)
889 projection of rudist orientation poles onto equatorial plane; (B) resulting stereographic
890 projection (but note that equal area plots are used in this work, so the explanatory cartoon in
891 (A) is slightly simplified for ease of understanding).

892

Fig. 12 Stereographic projections of orientation data for Blocks 1, 2 and 5: (A) Block 1, uncorrected hippuritid orientations; (B) Block 1 data rotated to correct for regional dip, with pole and plane of parallel joints (bedding?) added; (C) Block 2, uncorrected hippuritid orientations together with mean pole for joints (apparent bedding) within block; (D) Block 2 data rotated to correct for regional dip; (E) Block 2 data as in (D), with points for hippuritids preserved in life position shown in grey, together with their mean vector and implied bedding plane, with that inferred from joints for comparison, and points for rudists interpreted as toppled shown coloured; (F) Block 5 poles to commissural planes of *Inoceramus* specimens, rotated to correct for regional dip.

Fig. 13 Stereographic projections of orientation data: (A) Block 3, uncorrected rudist orientations; (B) Block 3 data rotated to correct for regional dip; (C) Block 4, uncorrected rudist orientations; (D, E) Block 4 data rotated first to correct for regional dip (D), then again to set pole for block bedding (estimated from fallen rudists) to vertical (E).

Fig. 14 (A) Cluster of *Hippurites colliciatus* photographed *in situ* in Block 1, showing fanned orientations around a general commissural ‘facing’ direction towards the SW (to the right); (B) Geniculate example of *Vaccinites vesiculosus* in Block 4; (C) articulated specimen of *Pseudosabiania* preserved on apparent bedding surface within Block 1. Length of hammer shaft in A and B is 350 mm; Scale bar in C (bottom left) is 10 mm.

Fig. 15 Model for emplacement of blocks of rudist-rich limestone as olistoliths derived from platform, illustrating expected sense of rotation of elevator rudists.

- Vaccinites (up)
 ● Hippurites (up)
 + Vaccinites (down)
 + Hippurites (down)
- Pole to apparent bedding measured in block
 ● Pole to regional bedding
 ● *Inoceramus* (pole to commissure)
- Mean vector of poles to commissures (with 95% confidence contour)
 + Data used to calculate mean rudist orientation
 + Data points omitted from calculation: all lie close to bedding plane in block (fallen rudists?)
- Mean vector of poles for hippuritids preserved in life position

Highlights

As classically known, the Late Cretaceous is a period of obvious tectonic instabilities at least around the Mediterranean Tethyan region. Tectonic plate movements in combination with sea-level changes which gave rise to instabilities have led to various forms of mass transport on platform and ramp margins and slopes. In many situations, the recognition of bedding dislocation and rotation is difficult; our study introduces the methodology of rudists orientation measurement as a tool to discriminate between in situ and olistholitic deposits.

The example of Jebel el Kebar that constituted for us a nice demonstrative example with high-quality and continuous outcrops which help a lot to study the vertical stacking of the rudist-rich carbonates and also to follow the frequent and rapid lateral facies changes.

Our approach was based on the study of the orientations of the elongate right (attached) valves of hippuritids within the rudist/coral-bearing lithosomes. These orientations were plotted as equal-area stereographic lower hemisphere projections, using the Stereonet 4.9.5a plotting software of Allmendinger (1995).

We tried to establish a model which reconstitutes the different episodes of sedimentation since the installation of rudists on the sea floor until the last feature of the rudist-rich layer observed today on the field

This approach which provided significant results in the studied area, could be used as a tool guide to solve certain problems in geological series, linked to resedimentation processes, layers polarity, etc. In fact, our paper emphasizes the relevance of our method to the analysis of comparable slope deposits elsewhere, so to broaden its interest.