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published in

Cretaceous Research
2019

DOI (link to publisher)

[10.1016/j.cretres.2018.11.013](https://doi.org/10.1016/j.cretres.2018.11.013)

document version

Publisher's PDF, also known as Version of record

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citation for published version (APA)

Le Goff, J., Reijmer, J. J. G., Cerepi, A., Loisy, C., Swennen, R., Heba, G., Cavailhes, T., & De Graaf, S. (2019). The dismantling of the Apulian carbonate platform during the late Campanian – early Maastrichtian in Albania. *Cretaceous Research*, 96, 83-106. <https://doi.org/10.1016/j.cretres.2018.11.013>

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The dismantling of the Apulian carbonate platform during the late Campanian – early Maastrichtian in Albania

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ARTICLE INFO

Article history:

Received 4 February 2018

Received in revised form

4 October 2018

Accepted in revised form 18 November 2018

Available online 22 November 2018

Keywords:

Carbonates

Apulia

Mass transport deposits

Upper Cretaceous

Albania

ABSTRACT

The Apulian carbonate margin is widely preserved across the Adriatic domain and has been extensively studied in the south of Italy. In Albania, Oligocene–Pliocene fold-and-thrust tectonics led to widespread exposure of the Apulian Platform and associated Ionian Basin carbonates. However, the portion linking the platform to the basin is missing, preventing a direct reconstruction of the platform margin. Syn-sedimentary folding and faulting are recognized in the uppermost part of both the platform and basinal/slope series. Mass transport deposits (MTDs) occur within the platform succession incorporated into well-bedded intertidal (stromatolites) to shallow-subtidal (rudist packstones) sedimentary sequences. They display significant lateral variability which is accompanied by both rigid and soft deformation structures. Spectacular slumps made up of sediment density flow deposits are recognized in the adjacent Ionian Basin. The lateral extent of basal shear surfaces, syn-sedimentary faults and folds evidenced in the Ionian Basin points toward multiple regional tectonic triggering events affecting the Apulian Platform margin at that time. Bio- and chrono-stratigraphic analyses suggest that the triggers occurred during the late Campanian – early Maastrichtian. Beyond the obvious interest from a stratigraphic point of view, the study of these events recording the dismantling of the Apulian carbonate platform allows for a better understanding of the triggering mechanisms and the sedimentary characteristics of MTDs and slumps at a basinal scale.

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1. Introduction

In modern carbonate environments, margin collapse and slope failure are common features triggering massive sediment movement basinward (Crevello and Schlager, 1980; Mullins and Hine, 1989; Reijmer et al., 1992; Mulder and Cochonat, 1996; Mulder and Alexander, 2001; Correa et al., 2011; Reijmer et al., 2012, 2015; Jo et al., 2015; Principaud et al., 2015; Tournadour et al., 2015; Schnyder et al., 2016). Slope geometries, hydrodynamics (e.g. storms), relative sea-level variations and tectonics are essential factors controlling gravity-driven downslope processes and the

development of mass transport deposits (MTDs), which may include slides, slumps and debris flows (Nardin et al., 1979; Moscardelli and Wood, 2008; Shanmugam, 2016; Qin et al., 2017). The study of MTDs corresponding to paleo-carbonate platform collapse is complicated in outcrop due to the common absence of platform-to-basin transitions and therefore the rare preservation of headwall areas (Spence and Tucker, 1997; Payros et al., 1999; Borgomano, 2000; Hennuy, 2003; Payros and Pujalte, 2008; Reijmer et al., 2015). Slope-rooted MTDs develop strike-parallel headwall scarps leading to downslope movement of large amounts of sediments. Platform-rooted MTDs are less common and understood on carbonate platforms, likely because sediment accumulation occurred in peritidal and shallow-subtidal environments related to gentle or nearly flat depositional profiles. Additionally, fast cementation and lithification processes attributed to

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(sub-) tropical carbonate factories contribute to stabilization of platforms over time (Dravis, 1996; Friedman, 1998). These two processes make shallow carbonate series unlikely to develop syn-depositional reworking and may hamper significant mass-transport basinward.

The carbonate Apulian Platform (Channell et al., 1979) had a considerable impact on the sedimentation in the peri-Adriatic paleogeography from the Early Jurassic till the Late Cretaceous. Platform and slope-to-basinal deposits are presently exposed in the so-called Apulian Foreland along the east coast of Italy, spanning from the Maiella Heights to the Salento Peninsula (Channell et al., 1979; Eberli et al., 1993; Zappaterra, 1994; Borgomano, 2000; Spalluto, 2012). Many authors addressed the tectono-Cretaceous sedimentary evolution of the Apulian Platform and proposed distinct mechanisms for platform-to-basin sediment transfer, including margin erosion due to tectonically induced lowstands, or export of bioclastic sands during highstands (Borgomano, 1987, 2000; Eberli et al., 1993; Graziano, 2001, 2013; Hairabian et al., 2015; Le Goff et al., 2015a). Yet, regional events affecting the entire carbonate platform margin (i.e., from the innermost, intertidal platform setting to the slope/basinal environment) have been left largely unconstrained time wise and geometrically due to the scarcity of outcrops clearly exposing a platform – basin continuity (at least one exception exists in the Maiella Heights; Eberli et al., 1993). Based on a multi-approach analysis using bio-chronostratigraphic criteria and extensive sedimentological investigations of the platform and slope to basinal successions exposed in Albania, we aim to investigate the regional significance of the episodic triggering of MTDs that occur on a large-scale a carbonate platform (100's of km). The present work is based on two already published articles (Le Goff et al., 2015a,b) and focuses on the Campanian – Maastrichtian p.p. MTDs that occur throughout the Apulian domain. This study proposes a new scenario for the Late Cretaceous dismantling of the Apulian Platform margin in the Tethyan realm.

2. Geologic context

The Albanides comprise several NNW-SSE oriented thrust belts that are part of the Alpine Orogenic System (Fig. 1). The three litho-tectonic units that are commonly recognized in the Albanides include, from east to west, i) the internal Albanides, ii) the external Albanides and iii) the Sazani Zone (or pre-Apulian; Renz, 1940). The internal Albanides are mainly composed of metamorphic and volcanoclastic rocks related to the expansion of the Pindos Ocean to the east (Fig. 1A; Degnan and Robertson, 1998; Robertson and Shallo, 2000; Dilek et al., 2005, 2007). The external Albanides comprise allochthonous carbonate units formerly belonging to the Apulian passive margin (carbonate platforms and adjacent basins) and are subdivided into the Krasta-Cukali, Kruja, and Ionian zones. These zones are presently integrated in a thin-skinned fold-and-thrust belt verging westward and abutting against the autochthonous Apulian zone (Meço and Aliaj, 2000; Roure et al., 2004; Vilasi et al., 2006; Lacombe et al., 2009, De Graaf et al., accepted). The Sazani zone, or pre-Apulian zone, is commonly recognized as an extension of the Apulian Platform since no significant discontinuity was documented between these units to date. Its sedimentary record documents striking similarities with time-equivalent carbonate series described from the east-coast of Italy (Channell et al., 1979; Zappaterra, 1994; Borgomano, 2000; Spalluto and Caffau, 2010). The regional geodynamic evolution of the Apulian margin is strongly controlled by the emplacement of ophiolites and related extension which attest to the opening and successive closure of the Tethys during the Triassic and the Late Jurassic respectively. Compressional deformation commenced in the eastern part of the

Adriatic Zone during the Late Jurassic, followed by a progressive migration of the front westward during the Cretaceous. However, the temporal limits of the passive margin conditions of Apulia remain poorly constrained (Robertson and Shallo, 2000; Dilek et al., 2005, 2007; Fantoni and Franciosi, 2009).

The Upper Cretaceous carbonate platform successions preserved in the peri-Adriatic region are mainly made up of well-bedded peritidal to shallow-subtidal limestones, commonly organized in meter-scale cycles (Borgomano, 1987, 2000; Vlahović et al., 2005; Spalluto, 2012; Le Goff et al., 2015b). This monotonous sedimentation pattern is interrupted several times during the Late Cretaceous, namely: i) in Croatia, the Adriatic carbonate platform drowned; an event occurring near to the Cenomanian – Turonian boundary. The platform recovered in the late Turonian showing shallow water carbonates with primitive hippuritids (Korbar and Husinec, 2003). In Italy, a Turonian bauxitic horizon delineates an unconformity between the 'Calcare di Bari' and the 'Calcare di Atlamura' formations, which is interpreted to result from the occurrence of a regional lithospheric bulge (Mindszenty et al., 1995). This major unconformity is coeval with megabreccia accumulation overlain by a pelagic interval in the Ionian Basin succession (Luperto-Sinni and Borgomano, 1989; Bosellini et al., 1999; Graziano, 2013). This unconformity, however, is not identified in Albania (Le Goff et al., 2015b); ii) In the Gargano (Fig. 1B), shallow-water carbonates are replaced by base of slope and pelagic carbonates from the Santonian – early Campanian. A drowning unconformity has been proposed for the marginal successions of the Apulian platform cropping out in the Murge (Ostuni area) during the early – middle Campanian (Borgomano, 2000; Graziano, 2013); iii) in the Murge and Salento areas, soft-sediment deformation structures are observed in Maastrichtian shallow-water limestone beds. At both locations, tectonic processes affected the gentle, variably oriented or uniform paleoslopes, locally associated with restricted intraplatform basins (Spalluto et al., 2007; Mastrogiacomo et al., 2012).

The carbonate series of the Sazani zone (Fig. 2A) in Albania are exposed on the Karaburuni Peninsula and in the Kanali Mountains, a 5-km-wide strip of land oriented in a NW-SE direction and extending for 40 km (Fig. 2B). It exposes a Cretaceous succession that is tilted to the SW and comprises nearly 3000 m of neritic carbonate rocks ranging from the Lower Cretaceous to the Paleocene (?). To the east, the Apulian-related section is bounded by a thrust fault marking overthrusting of the Ionian Basin deposits (Fig. 2B and C). In the Ionian zone, the Upper Cretaceous carbonate succession consists of 300–400 m of re-sedimented deposits with hemipelagites, sediment density flow deposits, debris-flows and slump deposits (Dewever et al., 2007; Vilasi, 2009; Rubert et al., 2012). Precise logging as well as bio-/chronostratigraphic data demonstrate the sedimentation dynamics along the Apulian margin (Rubert et al., 2012; Le Goff et al., 2015a and b).

The platform-to-basin evolution during the Late Cretaceous can be divided into two supersequences (SS): i) SS1 was deposited during the Cenomanian to the Turonian. It comprises a thick aggrading stack of meter-scale, intertidal to shallow-subtidal platform cycles (>600 m) that are marked by stromatolites at the top of each cycle. In the Ionian Basin, few re-sedimentation events associated with SS1 are present as shown by interbedded debrites and hemipelagites (Le Goff et al., 2015a). A complete shutdown of the re-sedimentation dynamics at the end of SS1 is followed by the deposition of phosphorites and hemipelagites in the basin. ii) the platform is re-flooded at the beginning of SS2, during Coniacian – Santonian times, favouring prolific carbonate production dominated by rudists (Peza, 1998). The reflooding of the platform goes hand in hand with increased basinward transfer of sediment (i.e., "highstand shedding" sensu Schlager et al., 1994). Progradation of

Fig. 1. (A) Paleogeographic map of the western-central Tethys during the Cretaceous. Abbreviations: Ap, Apulian carbonate platform; Ad, Adriatic carbonate platform; I, Ionian Basin; G, Gavrovo; NT, Neo-Tethys; the yellow square shows the area of interest; (B) Litho-tectonic map of the peri-Adriatic region, left Italian side is adapted from [Borgomano \(2000\)](#) and structural elements adapted from [Hairabian et al. \(2015\)](#). Carbonate series of the Apulian Platform and the Ionian Basin are represented in dark and light green respectively. Red boxes mark study areas presented in this paper. Letters T., Tragias; P., Piluri; S., Saranda; and K., Ksamil; Z., Zervati; M., Muzina; D., Dhuvjani and V., Vanister are successions detailed in [Le Goff et al. \(2015a\)](#).

Fig. 3. (A) Top: oriented panorama of the uppermost part of the Llogara Pass succession; Bottom: interpretation from the above panorama marking the sedimentary units, bounded with blue and green bold lines, respectively interpreted as basal shear surface and top of the MTDs. Faults and field sections are represented. Note the syn-depositional reworking features highlighted with syn-sedimentary faults, and varying orientations and thicknesses of the beds. The dashed, straight line follows the sea horizon, while the curved dotted line highlight a décollement surface. Locations of panoramas (B) and (C) are indicated; (B) Panorama showing the bedded and MTD units to the SSW. (C) Panorama (top) and interpretation (bottom) of the above panorama showing line drawing of the bedding in MTD1. Ds: Décollement surface; Bs: Bed surface.

Fig. 2. (A) Simplified litho-tectonic map of Albania. Szani (Apulian) zone shown. Modified after Moisiu and Gurabardhi (2004) and Rubert et al. (2012); (B) Location of the Karaburuni Peninsula, Kanali Mountains and Llogara Pass; (C) Detailed map showing stratigraphy, unit numbering (MTD = mass transport deposit; B = bedded units) and field sections studied for sedimentary descriptions.

the slope is documented, while the “backstepping” evolution of the carbonate platform extends into the late Campanian. In the late Campanian – Maastrichtian, MTDs and slumps occur both on the platform and in the basin respectively. The latter are the focus of this study.

3. Methodology

3.1. Facies and stratigraphy

The sedimentary record of the Llogara section was previously described in Le Goff et al. (2015b) its the lower 1218 m. In this study, we performed a detailed sedimentological analysis of the succeeding part (1218–1416 m), which reveals syn-depositional reworking features of the carbonate platform. Outcrop analysis included the description of sedimentary features, the carbonate contents of the individual beds, and textures analysis following the classification of Embry and Klován (1971). In total, 50 hand samples were taken at regular distances throughout the section (section A, Fig. 3A) representing all facies. Another 10 samples cover a syn-depositional deformed sediment interval (section B, Fig. 3A). Fifty thin sections were subjected to petrographic analyses that aimed at revealing the nature of bio- and lithoclasts as well as characterizing textures and diagenetic features. Thin section images were acquired using an automated LEICA DM6000 B digital microscope. Benthic foraminifera associations were used to set the biostratigraphic framework. The results were compared with two biozonation schemes established for carbonate platforms of the Tethyan realm as proposed by Fleury (1980) for the Late Cretaceous of Greece (Gavrovo-Tripolitza Platform) and by Solak et al. (2017) for the Central Taurides in Turkey covering the same time interval. Both schemes were chosen as they provide a very detailed biostratigraphic resolution for the Campanian – Maastrichtian when compared to the Italian counterparts (see Frijia et al., 2015).

$^{87}\text{Sr}/^{86}\text{Sr}$ ratios were determined for four carbonate samples that were retrieved from the Llogara section. Carbonate powders were drilled using a dental microdrill targeting rudist shells. For two samples, the Rb–Sr analyses were performed at the Department of Analytical Chemistry, Ghent University (Belgium). The powders were weighed in a screw-capped Savillex® PFA vial and dissolved in 2 mL of 6 M HCl on a hotplate at 110 °C. The digests were subsequently evaporated to dryness and re-dissolved in 7 M HNO₃. Rb and Sr concentrations were determined using a quadrupole-based Perkin-Elmer SCIEX Elan 6000 ICP-MS instrument using external calibration combined with Y as an internal standard (cf., Vanhaecke et al., 1992). For the two other samples, Sr isotope analysis was carried out at the Scottish Universities Environmental Research Centre (Glasgow, Scotland). Carbonate samples were leached in 1N NH₄Ac prior to acid digestion in 2.5M HCl. Sr was separated in 2.5M HCl using Bio-Rad AG50 W X8 200–400 mesh cation exchange resin. Total procedure blank for Sr samples prepared using this method is < 200 pg. In preparation for mass spectrometry, Sr samples were loaded onto single Ta filaments with 1N phosphoric acid. Sr samples were analysed on a VG Sector 54-30 multi-collector mass spectrometer. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were corrected for a mass fractionation using a $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and an exponential law. The mass-spectrometer was operated in the peak-jumping mode with data collected in 15 blocks of 10 ratios. We rely on both methods for the accuracy and consistency of the data. Numerical ages were obtained by comparison of the results with

the Sr-isotope evolution of global seawater for the Late Cretaceous as reported in Version 4:08/04 (Howarth and McArthur, 1997; McArthur et al., 2001). The results were compared with 15 accurate time constraints (derived from Sr-isotopes) of three slope/basinal sections as reported in Le Goff et al. (2015a).

3.2. Characterization of the deformed intervals

Mullins and Cook (1986) defined slumps as deposits resulting from the movement of semi-consolidated sediment over variable distances along discrete basal shear planes. Mass transport deposits (MTDs) broadly involve sediment packages that underwent submarine mass failure and downslope movement under the influence of gravity (Shanmugam, 2016). The extent and the nature of lower/upper contacts (basal shear surface and top) of the MTD and slump units were carefully mapped in the Kanali Mountains as well as in the two slope/basinal outcrops within the Mali Gjere Mountain belt (Figs. 1 and 2C). Syn-depositional reworking features such as faults, folds and detachment surfaces (Alsop and Marco, 2011) within the units were documented. Axial planes and hinge lines of syn-sedimentary folds were plotted in standard lower hemisphere stereonet and used to restore the direction of the MTDs movement. Platform and slope-to-basinal syn-sedimentary deformations were restored assuming an original depositional dip of 0°. The mean axial plane strike method (MAPS; Alsop and Marco, 2012) was applied to the structural data retrieved from the slope/basinal outcrops to determine the paleo-slope directions.

3.3. Stratigraphic correlations and regional integration

The stratigraphic correlation of the Apulian Platform with the adjacent Ionian Basin was based on the extensive biostratigraphic and chronostratigraphic data from Le Goff et al. (2015a, 2015b).

4. Results

4.1. Facies and stratigraphy of the Apulian carbonate platform

The Llogara Pass succession consists of an alternation of three MTDs and four well-bedded (B) units (Fig. 3A and B). These seven units (B1, MTD1, B2, MTD2, B3, MTD3, B4) have been identified based on their geometrical features. Three separate sections, i.e., A, B and C, were studied (Fig. 3A). Section A is detailed in Fig. 4, while Section B was only sampled and only briefly described due to poor outcropping conditions. Section C is not accessible but large-scale deformational features were described using binocular observations (Fig. 3A and C). Stratigraphy and microfacies observations are reported below and shown in Fig. 5. The facies classification is summarized in Table 1.

4.1.1. Stratigraphy of units along the reference section A

4.1.1.1. Unit B1 (1310 m). Le Goff et al. (2015b) provided a detailed description of the B1 unit consisting of a regularly stacked 1220 m thick interval of intertidal (stromatolites, restricted lagoonal) and shallow-subtidal (rudist-dominated) carbonate platform deposits. These deposits are organized in meter-scale cycles interpreted to result from high frequency/low amplitude sea-level variations during the Late Cretaceous (Cenomanian to middle – late Campanian; Le Goff et al., 2015b). Only the uppermost part (1220–1310 m) has been documented in this study. Do note that due to the

Fig. 4. Lithostratigraphic column of the uppermost part of the Llogara Pass section (1300–1416 m). Facies are classified into four associations (see Table 1). Sampling points are indicated along the succession. Determination of CsB (Crétacé supérieur Biozone; Fleury, 1980) and assemblages from Solak et al. (2017) are indicated to the right, as well as chronostratigraphic data derived from strontium isotopes. M, W, P, G, F, R, and B stand for mudstone, wackestone, packstone, grainstone, floatstone, rudstone and bindstone, respectively.

Table 1

Facies identified at the Llogara Pass succession with indication of sedimentary features, nature of grains and cements observed, as well as the corresponding depositional environment.

Facies – type	Sedimentary features	Carbonate grains	Diagenesis	Depositional environment	Facies association
fA0: Conglomerate	Erosive base	Fine cobble to medium boulder (fauna-rich, grainstone) embedded in bioclastic packstone	Dissolution and likely contemporaneous karstification	Supratidal	A Emersion facies
fA1 Breccia fB1: Stromatolitic bindstone	Irregular base Common binding of bioclastic shells; frequent bird's-eye-type vugs	Intra- and extraclasts Major: <i>Thaumatoporella parvovesicularifera</i> , <i>Decastronema kotori</i> , ostracod shells and peloids, microbial coating Minor: rudist and echinoid clasts	Karstification Dolomitic rhomb molds. Sediment and spar-fill (drusy and blocky cementation) of vugs. Fibrous and dogtooth cements frequently observed in <i>Thaumatoporella parvovesicularifera</i> (Fig. 5B)	Supratidal Intertidal Schlagintweit et al. (2015)	B Intertidal facies
fB2: Mudstone – Wackestone	Occasional binding laminations, sporadic dwellings and bioturbations	Major: <i>Thaumatoporella parvovesicularifera</i> , <i>Decastronema kotori</i> , ostracod shells and peloids. Minor: rudist and echinoid clasts, benthic foraminifera (Miliolidae, <i>Rhapydionina</i> sp.), microbial coating	Fibrous and dogtooth cements frequently observed in <i>Thaumatoporella parvovesicularifera</i>	Intertidal Schlagintweit et al. (2015)	
fC1: Bioclastic/Benthic foraminifera Packstone	Poorly-sorted grains embedded in a muddy matrix, outsized clasts	Major: Rudist debris, benthic foraminifera (Miliolidae, <i>Cuneolina</i> sp., <i>Moncharmontia apenninica</i>), ostracod shells. Minor: Sponge spicules and echinoid debris, <i>Thaumatoporella parvovesicularifera</i> , peloids and lithoclasts	Micritisation of the matrix. Moldic porosity commonly filled with drusy and blocky cements. Spar-fill in dolomite rhomb molds	Shallow-subtidal	C Shallow-subtidal facies
fC3: Bioclastic Packstone to Grainstone (Fig. 5A)	Sorting and abrasion of the grains, frequent orientation of the grains	Major: Rudist and echinoid debris, sponge spicules. Minor: Benthic foraminifera (<i>Dicyclina schlumbergeri</i>)	Intergranular porosity filled with drusy and blocky calcite. Selective dissolution (Fig. 5A)	Shallow-subtidal	
fD2: Laminated Grainstone	Disconformable ravinement surface. Large-scale laminations and alignment of rudists.	Decimeter-size rudist organisms, minor echinoid debris.	Selected dissolution of inner aragonitic part of rudist shells.	Reef, subtidal to outer shelf	D Subtidal facies

presence of MTDs the thicknesses of the units succeeding unit B1, vary from location to location.

From 1220 to 1300 m, two microfacies types are present: i) bioclastic grainstone (fC3, Table 1) with moderately to well-sorted bioclasts (100 μ m–250 μ m in size) showing horizontal layering of the grains. Rudist fragments predominate and are associated with sponge spicules and benthic foraminifera (rotaliinids), along with minor peloids and lithoclasts. Intergranular voids are predominantly filled with blocky calcite, although drusy cements also occur; ii) bioclastic (rudist-dominated) packstones with poorly-sorted, cm-sized rudists and echinoderms clasts (fC1, Table 1). Small (<100 μ m) rhombohedral moulds of dolomite are common in the matrix pointing to dolomite precipitation and subsequent dissolution.

The following 1300–1305.5 m interval shows meter-thick bioclastic beds (packstones and grainstones, fC1 to fC3) with millimeter to centimeter-sized rudist fragments (up to 5 cm in size; Fig. 4). Circular molds resulting from the partial dissolution of rudists are also present. Bird's-eye-type vugs occur at the top of the beds. The occurrence of ostracods and benthic foraminifera (Miliolidae, *Cuneolina* sp., *Dicyclina schlumbergeri*, *Nezzazatinella* sp. and *Rotorbinella scarsellai*) suggests a shallow-subtidal depositional setting (Fig. 4). Molds in relation to selective dissolution of dolomite occur evenly scattered in the micritic matrix. The topmost part of the unit (1305.5–1310 m) contains thicker beds (up to 1.5 m)

with poorly consolidated, fine-grained packstones. Indurated crusts with bird's-eye-type vugs that commonly are enlarged by dissolution cap each bed. A 20 cm thick layer marks the top of unit B1 showing cm-sized intraclasts and breccia fragments. This brecciated interval which shows an irregular base is interpreted as an emersion horizon (fA1, Fig. 4).

4.1.1.2. Unit MTD1 (15.0 m). Unit MTD1 displays syn-depositional reworking features specific to MTDs that are described in paragraph 4.2. Exposures along section A offered the possibility to study and sample the unit in detail.

From 1310 to 1319 m, MTDs shows a uniform chalky aspect. It contains scattered bioclasts (mm to cm in size) and lack bedding or flow features (Fig. 6C). Microscopic observations reveal the presence of ostracods, benthic foraminifera (Miliolidae) as well as a cyanophyceae (*Decastronema kotori*, Radoičić) and *Thaumatoporella parvovesicularifera* (Fig. 5B). Rudist fragments occur randomly scattered throughout the interval. Some samples are entirely composed of poorly-sorted rudist debris (Fig. 4, samples 005; 006).

4.1.1.3. Unit B2 (47.5 m). The basal interval (approximately 5 m thick) is exclusively composed of reworked rudists, reaching 10 cm in size, showing a distinct stacking/imbrication pattern (Fig. 6D). Thin-section petrography shows a dominance of rudist and minor

Fig. 5. Microphotographs of selected samples (A) sample 008: coarse, well-rounded rudist fragments (Rd), up to 3 mm, Polarized Light (XPL); (B) sample 004: specimens of *Thaumatoporella parvovesicularifera* (Tp) scattered in a micritic matrix. Note the selective dissolution and the presence of intragranular acicular (Ac) and dogtooth cements (Dc), Plane Polarizing Light (PPL); (C) sample 014: specimen of *Moncharmontia apenninica* (Ma) occurring adjacent to surrounded by *Decastronema kotori* (Radoičić; Dk), Plane Polarizing Light (PPL); (D) sample 019: specimen of *Dicyclina schlumbergeri* (Ds). Note the presence of angular rudist debris, Plane Polarizing Light (PPL); (E) sample 029: specimen of *Accordiella conica* (Aco). Note the numerous calcite cemented rhombohedral molds of dolomite (Dm) scattered in a finely grained micritic matrix, Plane Polarizing Light (PPL); (F) sample 010: Detail of a bird's-eye-type vug and drust (void-filling) cementation; (G) sample 014: specimen of *Rotorbinella scarsellai* and *Decastronema kotori*. Abbreviations: Vo, void; MI, Miliolidae.

Fig. 6. Photographs of selected facies in the field. (A) Stromatolite showing syn-depositional reworking features (immediately below MTD2) with a close-up (B) on imbricated lithoclasts of stromatolites embedded in a muddy matrix; (C) Mud-supported packstone showing shell fragments of shallow-water organisms; (D) Clast-supported rudist rudstone disconformably overlying MTD1.

echinoid fragments along with sponge spicules (sample 008; Fig. 5A). This bed is continuously traceable from section A to B, and is represented in blue shade in Figs. 3A and 4. On the top of it, carbonate layers consist of bioclastic packstones (fc1, Fig. 4) with ostracods and a *Thaumatoporella parvovesicularifera* - *Decastronema kotori* assemblage. This facies is commonly associated with dolomite molds filled by (blocky) calcite. A stromatolitic bindstone (fb1) showing clear microbial laminations occurs higher in the sequence (Fig. 4). Unit B2 furthermore contains stacks of meter-thick limestone beds (Fig. 3C). Thin-section analysis shows a '*Thaumatoporella parvovesicularifera* - *Decastronema kotori*' association (fb1 and fb2), which according to Schlagintweit et al. (2015) reflects an inner-platform setting including shallow-subtidal and intertidal environments.

The upper part of B2 is comprised of bioturbated mudstones – wackestones (fb2). Thin sections show dolomite molds filled by calcite within the decimeter-thick bioclastic packstone layers (Fig. 4). The presence of the '*Thaumatoporella parvovesicularifera* – *Decastronema kotori*' association typifies every sample (012–016). Microbial coatings occur (samples 015–016) binding ostracod shells and/or benthic foraminifera (*Rotorbinella scarsellai*, *Moncharmontia apenninica*, Fig. 5C and G). The uppermost part of unit B2 consists of an alternation of stromatolitic bindstone (fb1), bioturbated mud-to wackestone (fb2), and bioclastic lithologies (fc1 and fc3) with cm sized rudist debris. A decimeter thick layer with up to one centimeter large lithoclasts (intraclasts?) marks the top. It

shows karstification features within a syn-sedimentary breccia features suggesting emersion.

4.1.1.4. Unit MTD2 (8.2 m). The lower part of unit MTD2 consists of a rudist-dominated packstone with discrete breccia intervals. The upper part shows coarse lithified clasts (up to 3 cm) consisting of two microfacies: i) one (sample 018) with ostracod shells and *Thaumatoporella parvovesicularifera* scattered in a micritized matrix, the latter showing numerous dolomite molds filled by calcite cements; and ii) a second with intact, cm-scale, *Dicyclina schlumbergeri* embedded with poorly sorted rudist and echinoid fragments that occurs in the uppermost part of MTD2 (sample 019, Figs. 4 and 5D).

4.1.1.5. Unit B3 (8.1 m). The base of unit B3 comprises a grainstone rich in rudists and ostracod shells (fc3). *Decastronema kotori* and *Thaumatoporella parvovesicularifera* are present, the latter typically showing evidence of reworking and/or compaction (e.g. deformed, occasionally flattened or with dislocated shapes). Non-biogenic elements consist of rounded peloids and lithoclasts showing wackestone-type internal texture and rhombohedral molds. The main part of the unit B3 consists of a sequence dominated by bioclastic packstones (fc1) containing mainly rudist debris. Minor stromatolitic facies (fb1) occurs at 1385 m within the section (Fig. 4). Algal coating occurs in association with horizontal fenestral vugs infilled by calcite cements (Fig. 5F).

4.1.1.6. Unit MTD3 (11.3 m). Unit MTD3 shows two specific intervals. The lower one is composed of meter-thick bioclastic beds, showing evidence of syn-sedimentary folding (see Section 4.2). The base of the unit shows mm to pluri-cm rudist debris scattered in a chalky matrix. Thin-sections of five closely spaced samples (Fig. 4) show abundant rudist debris, diversely sorted and abraded, and abundant echinoid fragments, peloids and lithoclasts. *Rhapydionina* sp. (1399 m, sample 025), characteristics for intertidal platform settings (Landrein et al., 2001; Fleury, 2018), was found in this unit.

4.1.1.7. Unit B4 (15.9 m). A bed-confined conglomerate lies immediately above unit MTD3 (Fig. 4) showing evidence of contemporaneous karstification (fA0). The conglomerate consists of fine cobble to medium boulder sized transported blocks that are closely packed at the base and loosely scattered in a bioclastic packstone matrix at the top (Fig. 7D). The top of the conglomerate is marked by a bioclastic facies (fC1) with diverse benthic foraminifera such as *Cuneolina* sp., *Dicyclina schlumbergeri*, *Accordiella conica* (Figs. 4 and 5E), *Moncharmontia apenninica*, *Rotorbinella scarsellai*, and heteroclidids. Minor drusy calcite infill is present in molds of dolomitic rhombs.

Decimeter to meter thick stromatolites (fB1) alternating with bioclastic packstones (fC1) comprise the remaining part of unit B4 (starting from 1410 m). Thin sections reveal *Thaumatoporella parvovesicularifera* and ostracods (samples 031, 032 and 033), *Dicastronema kotori* (sample 031) and benthic foraminifera (Miliolidae, sample 031). Dolomite rhomb molds are common (sample 031 and 032). The uppermost bed consists of a brecciated horizon (fA1) capped by a stromatolite (fB1).

4.1.2. Stratigraphy of unit MTD1 to B2 along section B

In section B, two intervals could be identified within unit MTD1: i) a lower interval, ca. 65 m thick, with meter-thick beds lacking clear top and basal contacts and showing slightly irregular orientations, suggesting syn-depositional reworking. To the SSW, the unit abruptly terminates against a fault (Fig. 3A). Microscopic analysis revealed three microfacies types: a) grainstones mainly composed of rudist fragments, fairly to well-sorted and sub-rounded to rounded, and minor echinoid fragments; b) packstones with shallow-water benthic foraminifera such as Miliolidae, *Cuneolina* sp., *Moncharmontia apenninica*, *Cuvillierinella* sp. associated with *Thaumatoporella parvovesicularifera*, peloids, and a few rudist fragments; c) bindstones characterized by microbial coatings and a '*Thaumatoporella parvovesicularifera* - *Dicastronema kotori*' facies association (Schlagintweit et al., 2015). Ostracod shells, rudists and undifferentiated bioclasts are also present; ii) an uppermost interval (~6 m thick) lying unconformably on i) and showing coarse reworked rudist fragments showing imbrication (Fig. 3A).

4.1.3. Facies and facies associations

Four facies associations (FA) characterize the well-bedded units of the Llogara outcrop (Table 1): i) FA-A groups microbrecciated intervals reaching up to 20 cm in thickness at the base of MTDs, and conglomerate facies solely observed in the top of MTD3. Subaerial exposures of the platform are invoked to explain the presence of lithoclasts as well as karstified features occurring in this facies association (Eberli et al., 1993; Spalluto and Caffau, 2010). Although under-represented comparing to other facies, these occurrences may have significant temporal implications (i.e. hiatuses in sedimentation or significant erosion); ii) FA-B groups fenestral and bioturbated mudstones as well as facies with microbial laminations. Bird's-eye vugs suggest alternating periods of wetting and drying (Shinn, 1968), while dolomite precipitation as evidenced by small dolomitic rhombs, can either be microbially induced or

resulting from confinement by impermeable layers (Röhl and Strasser, 1995; Strasser et al., 1995). These features point toward a restricted, intertidal environment characteristic of a tidal flat (Spalluto, 2012); iii) FA-C includes foraminiferal packstones and bioclastic (rudist-dominated) grainstones. Benthic microfauna occur associated with ostracods, sponge spicules, echinoid fragments and peloids. These microfacies are commonly encountered in shallow-subtidal (lagoonal) environments (Spalluto, 2012; Solak et al., 2017); iv) The few external platform setting sediments that were encountered are laminated rudstones capping the first MTD that reflects high-energetic conditions corresponding to FA-D, and possibly matching with an open shelf setting (Carannante et al., 1998, 2000; Simone et al., 2003). This bed is recognized in section A and B (Fig. 3A).

4.1.4. Chronostratigraphic analysis

$^{87}\text{Sr}/^{86}\text{Sr}$ data obtained from bulk samples range from 0.70752 to 0.70780, indicating ages spanning from early-middle Campanian (sample 008) to late Maastrichtian (sample 032) according to the LOWESS look-up table (Table 2).

4.2. Sedimentary architecture of MTDs (platform) and slumps (basin)

Both the platform and slope/basin environments show reworked intervals with deformation features that provide evidence for downslope movements. In idealized models, extensional features are identified in the headwall domain (normal faults) and contraction features in the toe domain (compressional folds and thrusts; Bull et al., 2009; Alsop and Marco, 2013). Our observations focus on the uppermost part of the succession that exposes syn-sedimentary deformations, restricted to three units (MTD1, 2 and 3) on the platform, and three units in the Ionian Basin (S1, S2a-b, S3). Variations in bed thickness, folding and bed amalgamation indicate that the deformations occurred after initial sediment accumulation but prior to complete lithification (Owen, 1987).

4.2.1. Geometrical characteristics of MTDs on the carbonate platform

The following section focuses on the thickness variability and syn-sedimentary features of MTD1, 2 and 3, and discusses the restored geometries based on structural data. The following three datasets were obtained: i) orientations of undeformed beds (B units) and syn-sedimentary deformed beds in MTDs; ii) structural features that facilitated downslope movements, i.e. basal shear surfaces and faults; iii) data related to syn-sedimentary folding, i.e., hinge lines and axial surfaces (Alsop and Marco, 2011, 2014).

Spotting the MTD units in the stratigraphy is relatively straightforward, given the fact that they are sandwiched between undeformed units. However, depicting the variety of deformational features within these units is not an easy task considering the presence of multiple reworked units showing considerable lateral variability. An upscaling approach was used, starting with observations of meter-scale features along section A, before making outcrop-scale observations (i.e., hectometer-scale features) along section B. In a final step, features extending the size of the Kanali Mountains (i.e. kilometer-scale features) were measured along section C (Fig. 3C). Key points are mentioned in the text and aim at guiding the reader through the deformational features shown in Fig. 3A.

4.2.1.1. Meter-scale features, section A. Unit MTD1 shows SSW dipping layered packstone-type limestone beds, which are separated from a NNE dipping structureless deposit (consisting of amalgamated layers) by a sub-vertical normal to listric fault (Fig. 3,

Fig. 7. Outcrop photographs (A) Erosive contact of MTD3 on the well-bedded carbonate series of B3; (B) close-up of the deformations observed at the base of MTD3; (C) Panorama of the upper part of the succession. Dip azimuths/dips of the bedding, basal shear surfaces (BSS, blue lines), top of the MTDs (green lines) and faults (red lines) are indicated. MTDs are

Table 2

$^{87}\text{Sr}/^{86}\text{Sr}$ ratios and corresponding numerical ages calculated for four carbonate samples retrieved from the Upper Cretaceous section of Llogara (uppermost part). The numerical ages are derived from the LOWESS look-up table version 4:08/04 (Howarth and McArthur, 1997; McArthur et al., 2001). Lower and upper confidences limit appear next to the age, respectively written in blue and red. e.: early; m.: middle; l., late.

Sample number	Stratigraphic position (m)	Unit	$^{87}\text{Sr}/^{86}\text{Sr}$	Standard deviation 2σ	Age (My)	Stage
032	1412	B4	0.70780	0.00002	66.62/67.98/69.28	l. Maastrichtian
022	1399	B3	0.70760	0.00150	75.82/75.95/76.06	l. Campanian
008	1324	MTD1	0.70752	0.00120	80.14/80.47/80.84	m. Campanian
005	1314	MTD1	0.70770	0.00002	71.14/71.98/72.72	e. Maastrichtian

Table 3

Name of the different units identified at the Llogara Pass succession with their associated thickness from sections A, B, and C and their lateral extension across the sections (see Fig. 3A). AB is the calculated thickening from section A to section B. Same holds for AC. Stratigraphic positions are given along the Section A (reference). NO, Not Outcropping.

Unit	Stratigraphic position (m) in Section A	Section A	Section B	Section C	A → B	A → C	Extension (m)
B4	1400.1–1416	15.9	NO	NO	NO	NO	
MTD3	1388.8–1400.1	11.3	15.0	NO	×1.3	NO	2807
B3	1380.7–1388.8	8.1	4.4	NO	×0.5	NO	–
MTD2	1372.5–1380.7	8.2	13.0	NO	×1.6	NO	2995
B2	1325–1372.5	47.5	42.7	NO	×0.9	NO	–
MTD1	1310–1325	15.0	65.0	>150	×4.3	>×10	7500
B1	0–1310	1310.0	1260.0	1170.0	×0.9	×0.9	–

key point 1). A thickening trend of unit MTD1 is noticeable eastward, pointing to erosion of unit B1 (Fig. 3, key point 2). MTD2 is regularly bedded in the west (203/37 orientation, Fig. 7C), which abruptly changes into a chaotic pattern after a fault cutting through the bedding at an angle of 25–30° (Fig. 7C). Beds pinch out against the fault plane and suggest normal displacement (Fig. 7F). A layer of brecciated rocks also marks the fault. Further to the NNE, the unit quickly shifts into a single interval made up of carbonate breccias. Fluid escape structures suggesting dewatering processes of unconsolidated sediments are present. Bindstone fragments embedded in a micritic matrix make up the bed located immediately below MTD2 (Fig. 6A and B). These features may point to dewatering processes enhanced by differential lithification kinetics between poorly consolidated carbonate mud and cemented stromatolites at the time of reworking. Internal ramp surfaces with a similar orientation and dip angle as the underlying bedded unit B3 mark the internal structure of the MTD3 unit (red lines in Fig. 7C). Overturned folded beds embedded in 2–3 m thick intervals are present. The folds exhibit hinge lines parallel to the ramp surfaces, as evidenced by a recumbent fold in Fig. 7E. Scouring of the original bedding is also shown in Fig. 7A. Brecciated carbonate rocks are exposed near the basal shear surface while blocks and disrupted bedding occur higher-up in unit MTD3 (Fig. 7B). Mineralization is typically absent along faults planes, and deformed beds are distinctively fracture-free.

4.2.1.2. Hectometer-scale features, section B. A normal fault cutting through the regular bedding and affecting MTD1 and B1 marks the outcrop (Fig. 3, key point 3). The 70 m wide olistolith (Fig. 3, key point 4) consists exclusively of fA1, fC1 and fC3, deposited in intertidal to shallow-subtidal depositional environments. Tilted beds composing the olistolith show a toplap contact with unit B2 (Fig. 3A), which is interpreted as an erosional unconformity. The rudist-rich bed unconformable lying on top of MTD1 is continuous across the section and is affected by a normal fault (Fig. 3, key point 5), strongly suggesting a late tectonic origin. The damage zone related to this fault is shown in Fig. 3, key point 6. MTD2 and 3 display significant thickening toward the NNE due to erosion of the

underlying units B2 and B3 respectively (Fig. 3A and B). MTD2 thickens by 160% and MTD3 by 130% to the NNE (Fig. 3, key point 7; Table 3). Accordingly, the “B” units show drastic thickness reduction as illustrated by unit B3, which passes from 8.1 m to 4.4 m in thickness over 500 m distance following a SSW to NNE direction (Fig. 3, Table 3). Both MTD2 and 3 can be traced over a significant distance (>2.8 km; Fig. 2C, Table 3).

4.2.1.3. Kilometer-scale features, section C. Syn-depositional reworking of thick sediment packages occurs in the NW of the study area (Figs. 2C and 3C, section C). A décollement surface that develops over several hundreds of meters is identified in MTD1, showing a clear movement (and transport) of carbonate series. A series of folded and discontinuous carbonate sequences mark the landscape (Fig. 3C). A 150 m high cliff exposes a series of carbonate layers with highly variable bedding orientations that differ from the overall bedding recorded in the B-units (Fig. 3C). The continuity of units MTD1, 2 and 3 could be traced on satellite images. Unit MTD1 displays a ten-fold thickness increase when moving from section A to section C to the NW, i.e., basinward (Fig. 2C). Conversely, thickness variations of MTD1, 2 and 3 towards the SSE are limited to 10–15 m (Fig. 2C).

4.2.1.4. Paleoslope. Facies-types fA0 to fD2 (Table 1), typical of emersive to subtidal environments (Fig. 4, Table 1) suggest a peritidal setting typifying an inner-shelf environment within the Tethyan realm. The inferred slope angle in this setting was very gentle to nil. The bedding orientation in the undisturbed B units was used to restore the paleoslope angle of repose. However, some disparities were detected along the succession that might be due to either tectonic processes during the Oligo-Pliocene, or syn-sedimentary deformation induced by the triggering of the MTDs. When attributing a 0° inclination to the B1 unit, restored angles for units B2 and B3 shows an increasing dip of the platform beds to the NNW (Fig. 7C). This is in agreement with paleogeographic reconstructions suggesting sediment shedding from the Apulian Platform to the east (Zapatero, 1994; Degnan and Robertson, 1998). Reconstruction of the fault-plane orientation affecting MTD1 with

sandwiched between unfolded units. See inset on the top right for stratigraphic position. Note that (A) and (C) are two different outcrop locations along the shoreline (Fig. 2C); (D) Closer view of the conglomerate evidenced at the top of MTD3. Lb: Lithified block; (E) Detail of a recumbent fold evidenced in MTD3; (F) Normal fault affecting well-bedded carbonate beds (MTD2).

respect to the paleoslope angle results in an original dip angle of approximately 30°. It resulted in a tilting of the olistolith (Fig. 3A) to the NNE as shown by the orientation of the beds in Fig. 3A (key point 4). The northwards thickening of the MTD1, as documented in Fig. 2C and Table 3, suggests significant sediment reworking by means of fault movements to the north. Bedding planes within unit B2 show minor variations in both their orientation and dip. This suggests the restoration of normal platform environmental and sedimentation settings following the triggering and deposition of MTD1. Transitory steepening of the platform could also explain the settling of the rudist-rich interval at the top of MTD1, which is the only evidence of true subtidal conditions (Table 1; Fig. 3). However, the predominance of intertidal facies reported at the top of unit B2 (Fig. 4) suggests a rapid re-establishment of an inner platform setting with a flat depositional profile. Of major interest in unit MTD2 is the orientation of the fault scar (~25–30°), which has a similar orientation as the fault measured in MTD1. Plane orientations measured in unit B3 revealed local disparities, as documented by local buckling shown in Fig. 7C, but not affecting the continuity of the layers. Evidences of scouring and dismantling of the regular bedding suggest significant and similar syn-depositional reworking as for MTD1, 2, and 3.

4.2.2. Slump deposits in the Ionian Basin, sedimentological and structural evidences and restoration of the paleoslope

In the Ionian Basin, syn-sedimentary deformations are identified by undeformed sediment density flow deposits capping the deformed beds of slumped units (Le Goff et al., 2015a). They show varying morphologies, which likely depend on numerous factors such as degree of lithification of the deposits, water content and angle of repose of the deposits.

4.2.2.1. Facies and stratigraphy. The Upper Cretaceous succession outcropping in the Mali Gjere Mountains (Fig. 8A and B) shows three to four slumps (S1, S2a–b, S3) that are continuously exposed over a distance of 41 km from NW to SE. Two of them (S1 and S3) display syn-sedimentary deformed layers. As for S2, only the basal shear surface is clearly exposed, making it difficult to infer downslope movement using the deformation style of the layers. Thickness variations of the slump units are minor throughout the studied area. In both the Muzina and Dhuvjani localities (6.5 km apart), the thickness of the first slump unit (S1) is ca. 40 m while the third slump unit (S3) reaches 15 m in thickness (Fig. 8A and B). Platform and slope-derived material compose the re-sedimented facies (calciturbidites and calcidebrites) that underwent syn-depositional reworking. The units reveal a more proximal character (thicker beds and coarser clasts) than the well-bedded units below and above, which consist of density flow deposits. Paleontological investigations of S1 at the Muzina section revealed the presence of shallow-water derived skeletal grains such as bioclasts, bryozoans, corals, Orbitoides and Miliolidae. Pelagic foraminifera were found in the micritic matrix as well as reworked lithoclasts, including specimens of *Abathomphalus intermedius*, *Rugoglobigerina* sp., *Globotruncanita stuartiformis*, *Globotruncanita angula*, *Globotruncanita stuarti*, *Globotruncana falsostuarti*, *Globotruncana arca*, *Contusotruncana* (Rosita) *contusa*, and *Racemiguembelina fructicosa*. Higher up in the succession, i.e., unit B2 to B4, platform-derived debris consists of broken bivalves, echinoderms, bryozoans, benthic foraminifera, and planktonic foraminifera, e.g., *Globotruncana* sp., and *Globotruncanita stuarti*. The ages derived

from Sr-isotopes in Le Goff et al. (2015a) date S1 as latest Campanian, while S2 and S3 are of Maastrichtian age.

4.2.2.2. Sedimentary structures. At Muzina and Dhuvjani, S1 displays flat basal shear and top surfaces. An overall chaotic bedding pattern characterizes this unit, which shows significant variation in both dip direction and angle of the beds (Fig. 8C and D). Deposits with coarse clasts (up to a few cm) form the uppermost part of S1, showing an irregular base and a flat top. This interval is regarded as the healing-stage deposit, filling the topography created on the top surface of the MTD (HSD, Fig. 8C). Slump S3 evidences an increase in syn-sedimentary deformation toward the top of the unit as documented by a narrowing of interlimb angles and large-scale fluid escape features (Fig. 8E). At Muzina, buckling of the beds with a wavelength 15–20 m occur at the base of S3 resulting in low amplitude, gentle folds that are progressively disrupted upwards resulting in water escape features along with an apparent disorganized bedding pattern. The variability in bed orientation and dip of the relatively “undeformed units” (i.e., B3 and B4) ranges at Dhuvjani from 023/12 to 349/28 in unit B3, and from 039/26 to 024/22 in unit B4 near Muzina. Underlying basal shear surfaces are identified for every slump unit based on the contact with the undeformed, well-bedded units. Additionally, faults are evidenced within the syn-sedimentary deformed packages. At Muzina, normal faulting commonly occurs in the crest of overturned folds and follows the straightened limb, showing gliding of meter-to pluri-meter thick bed packages (see closer view in Fig. 8C). Mean vectors calculated for each set of faults result in the following dip directions for Muzina and Dhuvjani respectively: i) 77.8° and 63.3° for unit S1 and ii) 71.3° and 43.0° for S3, the latter being based on only a few data. The data suggest a preferential dip direction of the faults to the ENE. The deformed beds show steeper angles than the original bedding, suggesting syn-sedimentary deformation (Fig. 8C). Sediment reworking processes are shown by intense folding due to downslope movement of unconsolidated layers (recumbent and overturned folds) in unit S1. This is also shown in the stereonet projections, while these displays a widely dispersed orientation of hinge lines and poles to the axial surfaces (Fig. 9A and C). At Muzina, axial surfaces have similar strike directions and reversed dip angles compared to the faults. At Dhuvjani, most of the axial surfaces are similar in both dip azimuth and dip angle as the faults (Fig. 9).

Folding-related data in unit S3 evidence a partitioning of hinge lines and poles-to-axial surfaces. Hinge lines are predominantly NW trending with gently to steeply inclined plunges (14–75°) at Dhuvjani. South to SE-trending hinge lines occur at Muzina, but inclined plunge lines were not present ($\leq 43^\circ$). At Muzina, poles-to-axial surfaces mainly plot to the ENE. This data population is also evidenced at Dhuvjani in addition to a population plotting to the SW, resulting in a bimodal fold facing direction. Whereas the ENE-dipping population follows the orientation of the faults, the second SW-dipping population shows a trend opposite to the faults.

4.2.2.3. Paleoslope restoration. Mean vectors of the axial surfaces of the folds are calculated from rose diagram distributions using the Mean Axial Plane Strike method (MAPS; Alsop and Marco, 2012). Axial surfaces from Muzina suggest a mean dip azimuth direction to the west for both S1 and S3 (268.6° and 277.5°, Fig. 9E and F), while the data retrieved from Dhuvjani show a NNE direction for S1 and NNW for S3 (10.4° and 334.7° Fig. 9G and H). The mean strike of axial

Fig. 8. (A) Panorama of the Upper Cretaceous basinal succession in the Muzina outcrop, with units that are described in the text. A schematic log of the succession is displayed to the left. Blue and green lines stand for basal shear surfaces and top of the slumps respectively. Modified from Le Goff et al. (2015a); (B) Panorama of the individual units within the Upper Cretaceous succession of the Dhuvjani outcrop. Numerical ages, which were derived from the LOWESS look-up table version 4:08/04 (after Le Goff et al., 2015a), are shown along with their sampling locations. To the right a simplified geological map of Albania is given with location of the outcrops (red square). (C), (D), (E) close-ups of MTD1, 2 and 3 in Muzina outcrop, see (A) for location. Abbreviations: HSD, healing stage deposits, F&R, flat and ramp.

Fig. 9. Equal area lower hemisphere projection of the structural data retrieved from the basinal Muzina and Dhuvjani outcrops. Raw data are represented in the upper stereonet (A to D) and restored angles after rotation relative to the stratification of the underlying undeformed bedded unit for each slump unit are represented in the lower stereonet (E to H). Bedded units underlying and overlying slump units are represented in blue dashed and solid lines respectively. Faults are plotted as red lines. Data related to folding appear as red dots (hinge lines) and blue boxes (poles to the axial surfaces). Rotation parameters are indicated to the bottom right of the stereonet and related to azimuth, plunge of the rotation axis, and magnitude of rotation. Rose diagrams and mean vectors are calculated for the axial surfaces data sets showing preferential dip azimuth direction. Abbreviations: Mv AS, Mean vector Axial Surfaces; TD, Transport Direction.

surfaces is calculated as oriented normal to the mean dip azimuth direction. The downslope direction is inferred from the upward-facing characteristics of the axial surfaces (Alsop and Marco, 2012).

For S1, downslope directions calculated for both localities vary significantly from E (88.6° , Muzina) to SSW (194.4° , Dhuvjani). The slump S3 reveals a 45° dip orientation difference for Muzina and Dhuvjani, suggesting that its transport direction varied from ENE to ESE (Fig. 9E–H).

5. Interpretation and discussion

5.1. Facies and depositional environments in the inner platform domain

Facies and facies associations show striking similarities with the tropical-type flat-topped platform environments of the Late Cretaceous characterized by i) a rudist factory that developed at shallow depths with individual build-ups distributed in a subtidal silty-sand plain environment (Borgomano and Philip, 1987; Simone et al., 2003); ii) a restricted, foramol-type lagoon that acted as a recipient for bioclastic debris through episodic storms (Carannante et al., 1998; Moro et al., 2002); iii) a peritidal domain dominated by microbial sediment binding and mud ponds, subjected to episodic emersions (Simone et al., 2012; Schlagintweit et al., 2015); iv) a supratidal environment showing evidence of subaerial brecciation and karstification (Spalluto et al., 2007). These paleoenvironments and associated facies are extensively described in Italy (Chiocchini and Mancinelli, 1977, 2008; Eberli et al., 1993; Spalluto, 2012), the peri-Adriatic Realm (Vlahović et al., 2005; Brlek et al., 2013) and the Tethyan Realm (Tasli et al., 2006; Solak et al., 2017).

The classification of Le Goff et al. (2015b) was adapted to describe the facies variations along the Apulian Margin in Albania. The spatial facies distribution along the depositional profile is extensively described in the aforementioned article and will not be repeated here. The newly acquired data were integrated with this study, but focuses on the uppermost Cretaceous succession. Thus, facies A1 – A2 (Le Goff et al., 2015b) and fA0, fA1 (this study) forms facies association A; facies B1 to B4 and fB1, fB2 (this study), forms association B and facies C1 to C3 and fC1, fC3 (this study), form association C; facies D1 and fD2 (this study) forms association D.

5.2. Age of the deposits

5.2.1. Biostratigraphy

In the Fleury (1980) biozonation, CsB5 (Crétacé supérieur Biozone 5) is positioned between the last occurrence of *Murgella lata* (lower Campanian) and the last occurrence of *Moncharmontia apenninica* (upper Campanian p.p.). Associated foraminifera include *Accordiella conica*, *Rotorbinella scarsellai* and *Reticulinella* sp. Although our analysis did not recover *Murgella lata*, it does show the presence of *Moncharmontia apenninica*, *Accordiella conica* and *Rotorbinella scarsellai*. This assemblage is in accordance with CsB5, whereas the presence of *Rhapydionina* sp. in MTD3 could correspond to the onset of CsB6 (upper Campanian – lower Maastrichtian p.p.). Solak et al. (2017) recently assigned a late Campanian age to the *Rotalispira scarsellai* – *Murciella* gr. *cuvillieri* zone (their ‘Assemblage II’) in the central Taurides Mountains of central Turkey. In the latter study, the identified facies and biota strikingly resemble those recognized in the Llogara section, among them, *Moncharmontia apenninica*,

Rotalispira scarsellai, *Nezzazatinella* sp., *Accordiella conica*, *Rhapydionina* sp., *Decastronema kotori*, *Thaumatoporella* sp., and ostracods. None of the larger hyaline foraminifera of ‘Assemblage III’ (Maastrichtian) of Solak et al. (2017) were present in our samples.

When comparing the planktonic biota identified in the rock record (S1 – B4) in the Ionian Basin with the biozonation of Caron (1983), extended in Bolli et al. (1985), detailed chronostratigraphic attributions can be made. Foraminifera and their total extension zones are given as follow: *Globotruncana arca* (uppermost Santonian – upper Maastrichtian); *Globotruncana falsostuarta* (Maastrichtian); *Globotruncanita stuartiformis* (Campanian – Maastrichtian); *Globotruncanita stuarti* (uppermost Campanian – Maastrichtian); *Contusotruncana* (Rosita) *contusa* (upper Maastrichtian); and *Abathomphalus intermedius* (upper Maastrichtian). Concomitant ages obtained for the planktonic foraminifera suggest a late Campanian to Maastrichtian age for the triggering of the slumps, and a significant reworking of the Campanian record.

The biostratigraphic resolution obtained in the platform section remains a major obstacle to confidently assign the same age for the triggering of MTDs. This reflects the larger uncertainties in the biozonation of shallow-water benthic foraminifera when compared with their planktonic counterparts during the Late Cretaceous. The rapid evolution of the planktonic foraminifera during this period combined with their diversity and broad distribution (i.e., absence of endemism more common to benthic foraminifera) may explain these disparities. Hence, our results obtained for the platform section is the best resolution that could be achieved based on this dataset. Higher resolution of the biostratigraphy possibly be reached through additional sampling and targeted identification of *Rhapydioninidae*, which commonly flourish in these restricted (at times emersive) environments (Fleury, 2018). The identification of macro-organisms such as rudists might also be a solution to refine the stratigraphic framework, although they are rarely found in living position in this part of the section (mostly scattered clasts).

5.2.2. Chronostratigraphy

Two out of four numerical ages derived from the strontium isotope analyses show age assignments that differ from the biostratigraphic data. The ages are either too young (71.98 Ma, early Maastrichtian) or too old (80.47 Ma, early Campanian). Both i) analytical and ii) sedimentological explanations could be given to explain these discrepancies; i) the original isotopic signature of the rudist shells was overprinted by signals derived from other cements. Sampling rudist fragments engulfed in a muddy facies (e.g., packstones) with a microdrill uneasy, and small fractions of bulk and other carbonate phases may also be sampled to some extent, each possessing to a specific diagenetic signature. This is particularly prevalent in platform-derived samples that underwent several emersive phases at the platform top; ii) Syn-sedimentary reworking also appears as a possible explanation for age discrepancies, as sample 005 was sampled in MTD1. However, the late Campanian (sample 022) and late Maastrichtian (032) ages obtained for the samples retrieved at the top of the succession agree with the biostratigraphical framework.

The ages derived from Sr-isotope analysis in the Ionian Basin (published in Le Goff et al., 2015a) are consistent with the stratigraphic framework established in Albania. They allowed the correlation of the Upper Cretaceous successions along and across the two westernmost thrust belts of the Ionian Basin (i.e., Çika and Kurveleshi, Fig. 1B).

5.3. Correlation of inner platform domain (Apulian Platform) with the slope deposits of the Ionian Basin

5.3.1. Outcrop scale

5.3.1.1. Apulian carbonate platform. Integrated meter-, hectometer- and kilometer-scale observations of the platform outcrop revealed

rigid and soft deformations structures of sedimentary beds. Syn-sedimentary faults clearly affected the carbonate deposits but are not readily associated with specific systematics due to the paucity of slip-sense indicators and mineralization. Overturned and recumbent folds as well as water-escape features account for the soft deformations of carbonate beds encountered in the field (Fig. 7).

Deformation features provided evidence for reworking processes affecting three specific units (MTD1 to 3, Fig. 3), each of which are capped by undeformed deposits. Well-bedded series of shallow-subtidal and intertidal rocks cover each syn-sedimentary deformed unit and point to the re-establishment of a flat, shallow-water and low energy environment after each catastrophic event (Table 1; Fig. 3).

Although late tectonic deformation is present locally (Fig. 3), syn-sedimentary reworking can be confidently inferred for MTD1 to 3, and correspond to three major events occurring in a 3 to 5 Ma interval during the late Campanian – early Maastrichtian.

The geometry of MTD1 (Fig. 3) allowed for reconstructing a ramp-flat-ramp model of deformation (Fig. 10). This would explain

Fig. 10. Proposed ramp-flat-ramp model for the development of MTDs on the Apulian Platform leading to massive re-sedimentation in the adjacent Ionian Basin. The normal faults mechanically create increased accommodation space basinward for sediment reworking and accumulation. Note the erosion (stage d) and the sealing of syn-sedimentary deformations with platform sedimentation.

both the nature of syn-sedimentary faults and the destruction of the layers caused by a structural roll-over (Fig. 10). The ‘normal’ fault evidenced in MTD2 and the ramp faults measured in MTD3 also match such a structural model.

5.3.1.2. Ionian Basin. In the basin, basal shear surfaces mark the base of every slump unit while faults affect the continuity of syn-sedimentary folded beds and bed packages. Slump transport directions were determined using the mean axial plane strike method (MAPS; Alsop and Marco, 2012), which is based on the assessment of layer parallel shearing (LPS) or layer normal shearing (LNS) governing the paleoslope system. Alsop and Holdworth (2007) showed that axial surfaces predictably strike normal or parallel to the downslope direction depending on whether LNS or LPS govern them, respectively. Only the bimodal fold facing distribution evidenced at Dhuvjani (Fig. 9D) is a feature that can be used to assess fold vergence at a high angle to the flow direction, i.e., reflecting the lobe shape of the slump. However, both sets of axial surfaces occur randomly throughout the outcrop, suggesting that there is no clear vergence symmetry. The same holds for Muzina (S1) where the data set displays a wide range of axial surface directions, which shows the dispersion of fold vergence.

Folding-related data (axial planes and hinge lines) and faults identified in the slumps within the Dhuvjani and Muzina successions are not randomly distributed. An overall eastward to southward direction of the slump displacement stands out from the restored orientations with respect to bedding (Fig. 9). This agrees with a downslope movement initiated along the Apulian edge, which was situated to the west.

5.3.2. System scale

Based on i) time constraints set by bio- and chronostratigraphic data; ii) well-identifiable and timewise relatively closely spaced re-sedimentation events (Figs. 3 and 8), and iii) the specific geometries of the syn-sedimentary deformed units, we suggest a genetic relationship between the MTDs identified in the Apulian platform section of the Kanali Mountains, and the slumps described in the adjacent Ionian Basin (Fig. 11).

The deformation styles within the studied sediments significantly change when moving from the platform toward the downslope environment. While the original stack of syn-sedimentary deformed sediments is locally preserved on the platform outcrop (Figs. 3 and 7C), the reworked beds in the Ionian Basin appear more contorted, exposing intense deformations at a bed scale (Fig. 8). These discrepancies of sediment consistency could be explained by cementation and lithification kinetics. Tropical shallow-water carbonates have a high cementation potential compared to basinal sediments due to a variety of factors such as mineralogy, temperature, exposure to fresh-water vadose and meteoric-marine mixing diagenesis, and wave agitation (Dravis, 1979, 1996; Friedman, 1998; Grammer et al., 1999; Melim et al., 2002; Christ et al., 2015). Rapid lithification of intertidal deposits such as stromatolitic bindstone (fB1) is evidenced in Fig. 6. Syn-sedimentary normal faults affecting the flat depositional profile mechanically create additional accommodation space allowing for sediment reworking and formation of MTDs. At the system scale, this characteristic might reflect the rigid versus soft mechanical behaviour of sediment on the platform and the slope/basin environments, respectively.

The MTD and slump units make up to 33% of the Upper Cretaceous succession in the Ionian Basin for the succession at Tragias (Fig. 11). Volumes of resedimented material were calculated from the area exposed in the outcrops and considering an average thickness for each unit. Those volumes correspond to minimum values because the precise boundaries of the units are difficult to estimate. The estimated volumes for MTD1 and MTD3 are $5 \times 10^8 \text{ m}^3$ and $3 \times 10^7 \text{ m}^3$ of shallow-water sediments respectively calculated for the platform outcrop of the Kanali Mountains (i.e., 200 km²; Fig. 3). The slope/basinal outcrops of the Mali Gjere Mountains (i.e., 400 km²) showed $5 \times 10^9 \text{ m}^3$ and $2 \times 10^9 \text{ m}^3$ (i.e., 2–5 km³) of resedimented density flow deposits for S1 and S3 respectively. These volumes are comparable with sediment failures calculated in other carbonate basins. Hennuy (2003) estimated minimum volumes of resedimented carbonate units resulting from the tectonic dismantling of the South Provence Platform (Turonian – Coniacian) and for four individual units (RSC 1 to 4) calculated volumes of outer shelf material ranging from $1 \times 10^8 \text{ m}^3$ to $9 \times 10^9 \text{ m}^3$.

5.3.3. Regional scale and triggering mechanisms

Identifying pre-conditioning and triggering factors of MTDs in ancient system requires a careful appraisal of syn-sedimentary reworking features when evaluating the characteristics and dynamics of the system. MTDs identified on the Apulian platform document rigid and soft reworking of exclusive shallow-water carbonate layers that were deposited in a peritidal setting with supposedly very gently slopes ($<1^\circ$) at the time of deposition. Contorted layers are limited to three discrete and continuous intervals (MTDs) thickening basinward. Scouring and brecciating processes occur at the basal shear surface of MTDs. Faulting is evidenced for two out of three MTDs (Fig. 3). Displacement of lithified blocks is documented (Fig. 7A and B) attesting that significant reworking processes affected the indurated carbonate rocks.

Consequently, liquefaction and fluidization of sediments resulting from the loss of shear resistance caused by increasing pore water pressure cannot be inferred as the only process controlling syn-depositional reworking. Internal triggering factors such as wave action, rapid change in ground water level, or overloading of sediment, all leading to liquefaction, can be discarded (Spalluto et al., 2007). Although storms play a major role in coastal erosion, and may induce of significant scouring of (un-)lithified sediments, they will not result in faulting and significant reworking of carbonate series. Slope instabilities are regularly invoked as potential triggers of MTDs (Spence and Tucker, 1997; Reijmer et al., 2012, 2015; Alves, 2015). Several authors argued that tectonically triggered syn-sedimentary deformations and associated deposits, e.g., slumps, could develop on very gentle slopes dipping less than 1° (Field et al., 1982; Garcia-Tortosa et al., 2011; Alsop and Marco, 2013). In all these case studies, slumping sheets are initiated in alternating clayey-silty lithologies in (paleo-)lake or river delta environments. Of importance is also that early and shallow-burial diagenesis taking place in shallow-water, tropical carbonate environments result in rapid cementation when compared to their siliciclastic counterparts, thus increasing the shear strength of the slope and decreasing failure susceptibility (Harris et al., 1985; Spence and Tucker, 1997).

In Italy, time-equivalent deposits also show post-sedimentary reworking of the peritidal environments; in the Murge area (Altamura Formation, Italy; Spalluto et al., 2007) and in the Salento area (Mastrogiacomo et al., 2012). However, the identified décollement

Fig. 11. Correlation of the Apulian Platform section in Llogara (left) with the slope/basinal sections of the Ionian Basin (2.5 magnification) with a focus on the dismantling of the carbonate platform (red squares). Platform and slope/basinal sections from Le Goff et al. (2015a,b). The uppermost part of the Llogara succession as well as the facies classification for the platform section are from this study. Note the actual position of each section within the inset (top right). Note the datum (red line), which correlates the platform and the basin sections. Letters in the inset correspond to the first letter of the slope/basin outcrops.

Fig. 13. Conceptual paleogeographic model showing the coeval eastward migration of the thrust front to the East and the resulting tectonic dismantling of the Apulian Platform to the west, leading to massive sediment shedding (MTDs and slumps) in the Ionian Basin. Adapted after Mutti et al. (2003).

surfaces and recumbent and overturned folds could not be linked to carbonate series in the Ionian Basin because of a lack of outcrop exposures. The authors relate the settling of slump sheets to the action of i) variably oriented or ii) uniform local paleoslopes. The former is attributed to seismic events; the latter, when concurred by significant facies change attesting paleoenvironmental deepening, is associated to the tectonically-controlled inception of intra-shelf basins leading to listric faults and block faulting. In the present study, MTDs are clearly shed toward the Ionian Basin; the thickening trends of the units and the movement of MTDs to the west as well as the orientation of faults show this unequivocally. Thus, this scenario differs from the infill of intra-shelf basins as proposed by Spalluto et al. (2007) and Mastrogriacomo et al. (2012) for the Salento and Murge areas.

The similar stratigraphic and paleo-environmental setting of the Murge/Salento and the Sazani zone, which are 175 km apart, suggests a tectonic reorganization at a regional scale of the Apulian platform at that time. This could agree with the inception of intra-shelf basins in the other parts of Apulia (i.e. the Murge, Salento; Mastrogriacomo et al., 2012; Festa et al., 2018) and MTDs shed basinward in the marginal parts. Among external triggers for MTDs, seismic events emerge as the most likely candidate to facilitate massive sediment transfer basinward through a near-surface ramp-flat-ramp fault system (Figs. 10 and 11).

Recent studies have highlighted the significance of MTDs and slump deposits on the Apulian Platform and in the adjacent Ionian Basin (Jablonska et al., 2016; Korneva et al., 2016). The link between massive platform shedding and resulting slope/basinal deposits is often difficult to demonstrate due to outcrop scarcity and late tectonic deformation (Payros et al., 1999; Floquet and Hennuy, 2001, 2003; Reijmer et al., 2015). The same holds for the continuity of the Apulian platform in the region during the Late Cretaceous, a link that formally has not been demonstrated to exist between Italy and Albania. In Italy, NW-SE (dip-slip) and ESE-WSW to E-W

(strike-slip) trending faults are commonly invoked as structural features involved in syn-sedimentary deformations of the Apulian series in the Murge and Gargano regions (Festa, 2003; Spalluto et al., 2007; Korneva et al., 2016). Syn-sedimentary folds in the Ionian Basin and the migration of the slumps to the ESE agree with the NW-SE dip-slip direction. Alternative interpretations for downslope movements of MTDs relate to destabilization processes associated with slope-rooted headwall scarps. As demonstrated by high-quality multibeam data of modern carbonate environments, MTDs are prone to develop *slope-oriented* flanks, or *lateral margins* that are orientated perpendicular to *headwall scarps* and to the platform margin (Bull et al., 2009; Principaud et al., 2015; Tournadour et al., 2015; Wunsch et al., 2017). However, the number of MTDs and slumps identified in both platform and slope/basinal succession discussed in our study do match. This strongly suggests that large scale processes of tectonic origin affected both environments.

The Vlora-Elbasan Transfer-Zone (Figs. 1 and 2A) is commonly interpreted as a deep-seated SW-NE oriented basement fault, that presently separates the external Albanides thrust sheets from the Peri-Adriatic Depression (Swennen et al., 1998; Roure et al., 2004; Vilasi, 2009). This fault could have been active during the Late Cretaceous, similarly to the Mattinata Transfer Fault in the Gargano Promontory (Borgomano, 2000; Hairabian et al., 2015). However, relating this fault activity to re-sedimentation processes is not straightforward, and up to now no evidence has been found in Albania to support this hypothesis.

The late Campanian to Maastrichtian dismantling of the Apulian platform characterizes the Late Cretaceous evolution of Apulia, and likely reflects the progressive narrowing of the Tethyan oceanic domain (Dercourt et al., 1986). The emplacement of the Mirdita ophiolites and subsequent closure of the Korabi-Pelagonian Ocean to the east of the Apulian Platform are commonly assigned to the Late Jurassic. The development of the Apulian margin in a passive

Fig. 12. Integrated representation of outcrop, system and regional scale sedimentary features of the Apulian margin during the Campanian – Maastrichtian. Black rectangles in the models refer to the outcrop pictures given on the left. Notice that three dismantling events of the carbonate platform were evidenced, corresponding to a repetition of stages 2 and 3. For the paleogeographic reconstruction on the Italian side, the data is compiled from Borgomano (2000); Spalluto et al. (2007); Spalluto and Caffau (2010); Mastrogriacomo et al. (2012) and Hairabian et al. (2015).

margin setting persisted during the Cretaceous (Dercourt et al., 2000; Robertson and Shallo, 2000; Fantoni and Franciosi, 2009). The data presented in this study agree with an incipient compressive deformation superimposed on a passive margin setting. It also concurs with the initiation of a convergent margin system induced by thrust loading of the Kruja, Krasta, Mirdita and Korabi sedimentary units (Figs. 12 and 13). The growing orogenic wedge (Roure et al., 2004) progressively migrated westward inducing flexural subsidence of the Ionian Basin accompanied by normal faults classical of a foredeep setting (Mutti et al., 2003). The westward migration of the foredeep induced an extensional regime at the eastern margin of Apulia favouring the emplacement of MTDs on the platform and slumps in the basin as discussed in this study (Fig. 13).

6. Conclusion

Carbonate platform and slope/basin successions were studied in the Albanian fold-and-thrust belt. The transitional part between both settings of the Upper Cretaceous system, likely fault-bounded, is not preserved. Sedimentological investigations revealed soft-sediment (bed amalgamation, folding) and rigid deformations structures (brecciation, block displacement associated to faulting) in the peritidal-dominated platform deposits. These structures are condensed in three intervals (mass transport deposits, MTDs) separated by a basal shear surface and a top from well-bedded, undeformed units of similar lithologies. In the Ionian Basin, detachment surfaces and folding structures within deformed strata suggest a displacement of the slump sheets toward the east to southeast, which agrees with the position of the Apulian margin at that time. Bio and chronostratigraphic data suggest that MTDs and slumps originate from the same events constrained to the Campanian-Maastrichtian. As their initiation in inner platform environment does not match with slope instabilities, we suggest that solely tectonic triggers could induce normal faulting generating both soft and rigid deformations of the platform deposits, inducing a massive basinward movement of consolidated and unconsolidated carbonates (i.e., characterized by soft-sediment deformations and disaggregation of the previously lithified sediments). A ramp-flat-ramp system of platform dismantling is proposed to explain this sediment transfer. Syn-sedimentary deformations observed in Albania could record the same tectonic events as in the Murge and Salento areas, where similar syn-depositional reworking features have been previously identified in the peritidal-dominated deposits of the Apulian carbonate platform. Repeated tectonic triggers (late Campanian – early Maastrichtian) initiated the dismantling of the Apulian carbonate platform resulting in massive reworking and shedding of carbonate sediments (MTDs and slumps) from shallow to deep water settings.

Acknowledgements

We thank Prof. R. Ellam and Dr. Hamdy El Desouky for carrying out the Sr-isotope analysis respectively at the Scottish Universities Environmental Research Centre (Glasgow, Scotland), and the Department of Analytical Chemistry, Ghent University (Belgium). We thank Bernard Martin (Université de Bordeaux - EPOC) for the thin section preparation. We thank the EA 4592 'Géoressources et Environnement' (ENSEGID Bordeaux-INP), France, and KU Leuven, Belgium, who funded the PhD studies and sedimentological investigations, and to the College of Petroleum Engineering & Geosciences of the King Fahd University of Petroleum & Minerals (CPG-KFUPM), Saudi Arabia, for their partial Post-doc support and funding the fieldwork related to the structural geology analysis. The authors thank Kristaq Muska and the Geological Department of the

Polytechnic University of Tirana, Albania, for their providing biostratigraphic data of the area and various numerical topographic and geological maps. Journal reviewers P. Harries, J. Borgomano, J.P. Masse and an anonymous reviewer are gratefully thanked for their insightful reviews and suggestions that significantly improved the quality of the manuscript.

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