Rivista Italiana di Paleontologia e Stratigrafia
(*Research in Paleontology and Stratigraphy*)
vol. 123(3): 355-378. **November 2017**

STRATIGRAPHY, SEDIMENTOLOGY AND SYNDEPOSITIONAL TECTONICS OF THE JURASSIC-CRETACEOUS SUCCESSION AT THE TRANSITION BETWEEN PROVENÇAL AND DAUPHINOIS DOMAINS (MARITIME ALPS, NW ITALY)

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To cite this article: Barale L., Bertok C., d'Atri A., Martire L. & Piana F. (2017) - Stratigraphy, sedimentology and syndepositional tectonics of the Jurassic-Cretaceous succession at the transition between Provençal and Dauphinois domains (Maritime Alps, NW Italy). *Riv. It. Paleontol. Strat.*, 123(3): 355-378.

Keywords: syndepositional tectonics; palaeoescarpment; Jurassic-Cretaceous; Dauphinois Domain; Provençal Domain; Maritime Alps.

Abstract. The Provençal and Dauphinois Mesozoic successions cropping out at the southeastern margin of the Argentera Massif (Maritime Alps, NW Italy) were deposited at the transition between the Provençal platform and the Dauphinois basin, marked in the study area by a partly preserved Mesozoic palaeoescarpment. These successions show important lateral variations occurring over relatively short distances, probably related to syndepositional tectonics. Different stratigraphic intervals of the pelagic-hemipelagic Dauphinois succession contain resedimented deposits, made up of both intra- and extrabasinal material, which provide a twofold evidence of syndepositional tectonics indicating both tectonically-triggered gravitational processes and a tectonically-driven evolution of the source areas. Two stages of syndepositional tectonics have been recognized: the first in the earliest Cretaceous, which is related to the deposition of carbonate breccias in the Dauphinois succession and to hydrothermal dolomitization of the Middle Triassic-Jurassic Provençal carbonates, and the second in the Late Cretaceous, which triggered the deposition of different detrital lithozones in the Upper Cretaceous Puriac Limestone. The cited evidence indicates that syndepositional tectonics continued to influence the evolution of the Alpine Tethys European passive margin long after the Late Triassic-Early Jurassic syn-rift stage, which caused the differentiation between the Dauphinois basin and the Provençal platform.

INTRODUCTION

Syndepositional tectonics plays a major role in the evolution of modern passive continental margins, where high-resolution seismic methods and deep-drilling data allow detailed reconstruction of the geometries of faults and sedimentary bodies (e.g., Favre & Stampfli 1992; Karner & Driscoll 2000; Moulin et al. 2005; Péron-Pinvidic et al. 2007; Afilhado et al. 2008; Aslanian et al. 2009). Conversely, in fossil continental margins presently involved in orogenic chains, the direct observation of preserved palaeostructures is rare and the reconstruction of syndepositional tectonics commonly relies on the recognition of indirect evidence, both stratigraphic and sedimentologic. In the case of the Alpine Tethys European palaeomargin, currently incorporated in the Alpine orogen, the effects of Mesozoic syndepositional tectonics have been increasingly recognized in the last decades in several sectors of the Western Alpine chain, often revising previous interpretations that overestimated the role of Alpine deformation in generating complex geometries (e.g., Barféty & Gidon 1983, 1984; Dardeau & De Graciansky 1987; Dardeau 1988; Hibsch et al. 1992; Montenat et al. 1997, 2004; Claudel et al. 1997; Claudel & Dumont 1999; Bertok et al. 2011, 2012; Cardello & Mancktelow 2014).

The Mesozoic stratigraphic successions cropping out at the southeastern margin of the Argentera Crystalline Massif (Maritime Alps, NW Italy) were deposited on the Alpine Tethys European palaeomargin, at the transition between the Provençal platform and the Dauphinois basin. The present-day geological knowledge about these stratigraphic successions substantially derives from studies earlier than 1970, and is summarized in the Geological Map of the Argentera Massif at 1:50,000 (Malaroda

Received: November 09, 2016; accepted: June 27, 2017

1970, explanatory notes by Carraro et al. 1970). The study of the sedimentary successions on the Italian side of the Argentera Massif has been resumed in recent years by Bersezio et al. (2002), Barale et al. (2016a, b) and d'Atri et al. (2016).

Detailed stratigraphic and sedimentologic analyses show that syndepositional tectonics played a key-role in the evolution of this part of the European margin throughout the Mesozoic. The Provençal and Dauphinois successions are characterized by important lateral variations, occurring over relatively short distances. Moreover, different stratigraphic intervals of the pelagic-hemipelagic Dauphinois succession contain resedimented deposits, made up of both intrabasinal and extrabasinal material, which provide a twofold evidence of syndepositional tectonics both pointing to tectonically-triggered gravitational processes and documenting tectonically-driven changes in the source and dispersal of sediments.

The aim of this paper is twofold:

- to describe the Jurassic-Lower Cretaceous Provençal and Dauphinois stratigraphic successions, and the overlying Upper Cretaceous succession, cropping out at the southeastern margin of the Argentera Massif, providing new stratigraphic and sedimentologic interpretations based on original data;
- to document the multiple stratigraphic and sedimentologic evidence of syndepositional tectonics recorded in these successions, reconstructing the major phases of Mesozoic tectonic activity.

METHODS

Geological mapping at 1:10,000 scale was performed to identify the main tectonic and lithostratigraphic units, and to reconstruct primary geometries and stratigraphic relationships. The resulting geological map was recently published at 1:25,000 scale by Barale et al. (2016a). Petrographic studies on 60 uncovered thin sections (30 µm thick) of the collected samples were carried out by optical microscopy and cathodoluminescence (CL) with the aim of characterizing the main microfacies. CL observations were carried out on polished thin sections using CITL 8200 mk3 equipment (operating conditions: 17 kV, 400 µA).

GEOLOGICAL SETTING

The study area is located at the southeastern margin of the Argentera Massif (Maritime Alps, NW Italy), between the Gesso and the upper Vermenagna valleys (Fig. 1). This sector is composed of a set of tectonic units, whose stratigraphic successions have been referred to the Dauphinois and Provençal palaeogeographic domains (d'Atri et al. 2016): the Entracque Unit, the Roaschia Unit, the Limone-Viozene Zone (LiVZ), and the Refrey Zone. They form a SE-NW trending narrow belt, comprised between the Argentera Massif to the SW and the more internal Briançonnais and Western Ligurian Flysch units to the NE (Fig. 1). The Italian side of the Argentera Massif and the adjoining sedimentary successions have been mapped at 1:50,000 by Malaroda (1970; explanatory notes by Carraro et al. 1970). More recently, Barale et al. (2016a) published a detailed map of the study area, which the reader is addressed to for all the cited toponyms and names of lithostratigraphic units.

The Dauphinois and Provençal domains represent the most internal part of the Alpine Tethys European palaeomargin, developed on continental crust. The two domains started to differentiate in the Early Jurassic, in response to the extensional tectonics related to the opening of the Alpine Tethys (e.g., Lemoine et al. 1986; Dardeau 1988; De Graciansky & Lemoine 1988). The stratigraphic successions of the study area (Carraro et al. 1970; Barale et al. 2016a) start with Permian continental siliciclastic deposits, which rest on the crystalline basement of the Argentera Massif, and are characterized by marked thickness changes, reaching a maximum thickness of up to 4000 meters (Faure-Muret 1955; Malaroda 1999). They are followed by Lower Triassic coastal siliciclastic deposits (Valette du Sabion quartzarenites) and Middle Triassic peritidal carbonates (Mont Agnelet Formation). Upper Triassic-Lower Jurassic deposits consist of a thin stratigraphic interval, commonly involved in tectonic slicing. This interval is present in the Roaschia Unit and in the northern part of the Entracque Unit, whereas it is absent in the southern part of the Entracque Unit (see Barale et al. 2016a). It consists of (Malaroda 1957; Carraro et al. 1970; Barale et al. 2016a): red and green shales (Bec Matlas shales, Late Triassic); fine grained limestones and dolomitic limestones, locally with algal lamination, containing beds of flat pebble breccias and bivalve coquinas (Monte Servatun Formation, Rhaetian-Hettangian); bioclastic packstones and wackestones with abundant echinoderm fragments, cephalopods and bivalves (Costa Balmera Limestone, Sinemurian). These units indicate a progressive

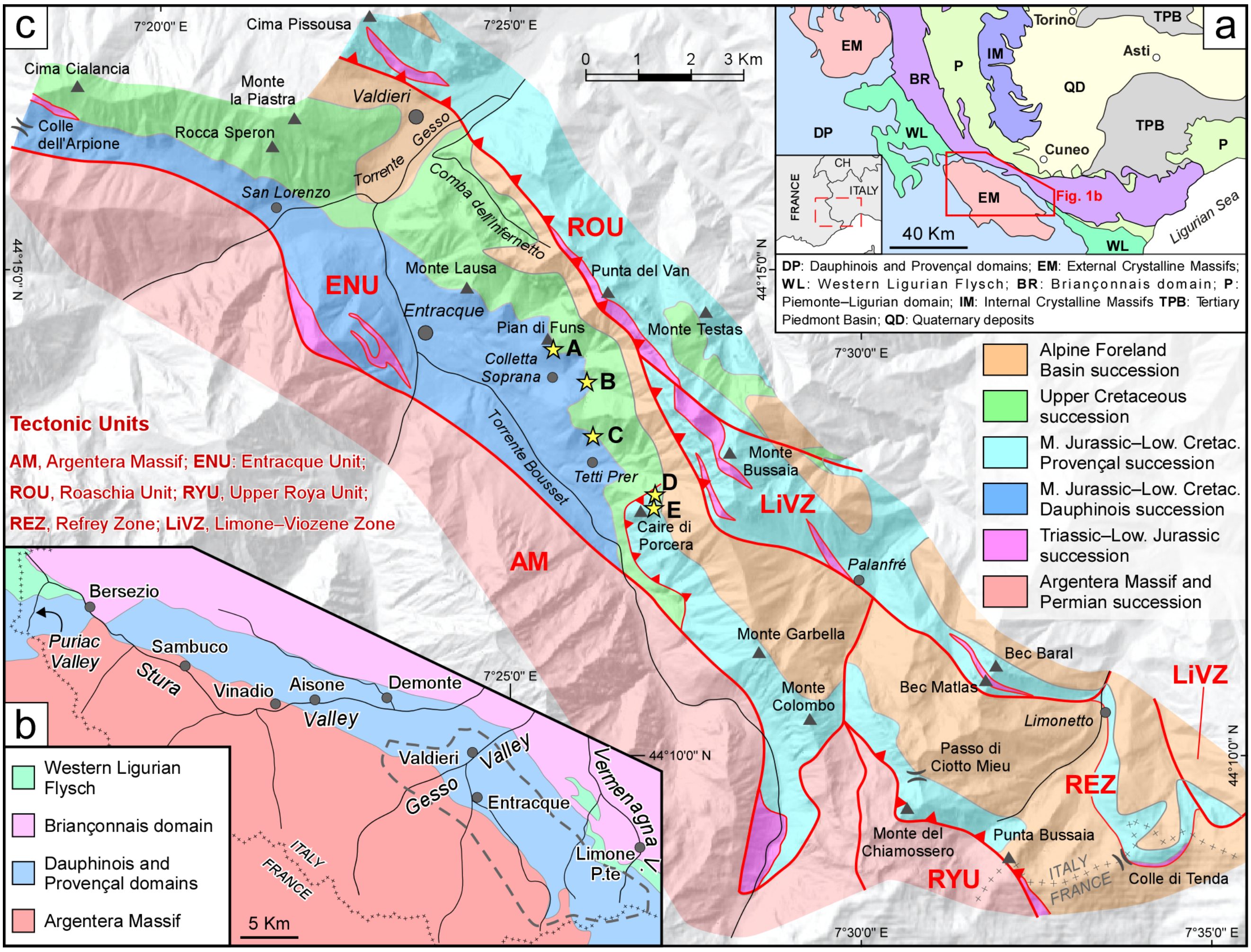

Fig. 1 - a) Schematic geographical and geological map of the SW Alps. The red polygon indicates the position of Fig. 1b. b) Geological scheme of the northeastern side of the Argentera Massif (Stura and Gesso Valleys). The dashed line indicates the study area. c) Geological scheme of the study area, modified from Barale et al. (2016a). The stars indicate the location of the five logs (A, B, C, D, E) of Fig. 4. Hillshade: Sfumo_Europa_WM, Arpa Piemonte (http://webgis.arpa.piemonte.it/ags101free/rest/services/topografia_dati_di_base/Sfumo_Europa_WM/MapServer).

shift from a continental sedimentation (Bec Matlas shales), to inner platform-lagoonal (Monte Servatun Formation) and then to frankly marine, open platform environments (Costa Balmera Limestone).

Starting from Early Jurassic, this area differentiated into two distinct sedimentation domains. To the north, the Dauphinois Domain evolved as a subsiding basin, while, to the south, the Provençal Domain remained a platform area where shallow-water sedimentation lasted until the Early Cretaceous. The transition between Dauphinois and Provençal successions is presently located near Caire di Porcera, a few kilometres south of Entracque. This transition, previously considered as a tectonic contact of Alpine age (Carraro et al. 1970), has been recently interpreted as a preserved palaeomorphological feature, i.e. a palaeoescarpment resulting from the erosional remodelling of a submarine Early-Middle Jurassic fault scarp, and progressively covered by slope deposits during the Middle-Late Jurassic (Barale et al. 2016a; d'Atri et al. 2016). In the study area, the Middle Triassic-lowermost Cretaceous Provençal platform carbonates locally show an intense dolomitization, related to a large-scale and deep-rooted hydrothermal system active in the Provençal sector of the European palaeomargin during the latest Berriasian-Valanginian (Barale et al. 2013, 2016b).

During the late Early Cretaceous, the drowning of the Provençal platform led to a relative facies homogenization between the two domains, as suggested by the common stratigraphic evolution, even if characterized by important thickness variations, documented by the deposition of the Marne Nere and Puriac Limestone.

The top of the Mesozoic successions is truncated by a regional discontinuity surface, corresponding to an important hiatus (latest Cretaceous-middle Eocene) due to a prolonged subaerial exposure related to a significant uplift of the Mesozoic European margin during the first stages of Alpine collision (Crampton & Allen 1995). The collision led to the development of the Alpine Foreland Basin, where a middle Eocene-lower Oligocene succession was unconformably deposited, in response to the increasing flexural subsidence (Sinclair 1997; Ford et al. 1999). This succession starts with laterally discontinuous continental to coastal deposits (*Microcodium* Formation; Faure-Muret & Fallot 1954; Varrone & Clari 2003), followed by the middle Eocene Nummulitic Limestone ramp deposits, the upper Eocene hemipelagic *Globigerina* Marl and the upper Eocene-lower Oligocene turbidite succession of the Annot Sandstone (Sinclair 1997; Ford et al. 1999).

Since the Eocene, the palaeo-European continental margin has been progressively involved in the ongoing formation of the Alpine belt (e.g., Dumont et al. 2012). The studied stratigraphic successions underwent three main deformation events which are well recorded at a regional scale: a first, southwestward brittle-ductile thrusting and superposed foldings, followed by northeastward, backvergent folding, in turn followed by southward brittle thrusting and flexural folding (d'Atri et al. 2016, and reference therein). The regional structural setting was achieved in the frame of a transpressional regime, as indicated by the presence of a post-Oligocene NW-SE Alpine transcurrent shear zone (Limone Viozene Zone) which extends for several kilometres from the Western Ligurian Alps to the study area (Piana et al. 2009; d'Atri et al. 2016). In this context, despite the large amount of finite deformation, strain partitioning allowed preservation of most of the primary stratigraphic features and geometrical relationships (Piana et al. 2009, 2014).

The Mesozoic sedimentary rocks of the study area show, in general, a rather high degree of recrystallization; data on the thermal history of these successions are lacking; however, an anchizonal metamorphism can be inferred by extrapolating the data from the adjoining upper Roya Valley (Piana et al. 2014). Due to the scarcity and the general bad preservation of fossils, the chronostratigraphic attribution of most of the lithostratigraphic units is based on regional correlations with better preserved stratigraphic successions of nearby areas. Only locally, the palaeontological and biostratigraphic study of a few but significant fossiliferous intervals has provided direct age information.

JURASSIC-LOWER CRETACEOUS PROVENÇAL SUCCESSION

Garbella Limestone (Middle? Jurassic-Berriasian?)

The Garbella Limestone is a 200-300 metres thick massive limestone succession, only locally showing an ill-defined bedding, with decimetre-thick beds. In the southern sector of the study area (southern Entracque Unit and Refrey Zone) the Garbella Limestone is mainly composed of bioclastic packstones, floatstones, and rudstones, locally associated with coral boundstones (Fig. 3a, b). Fossils are represented by colonial and solitary corals, nerineid gastropods (*Ptygmatis pseudobruntrutana*; Campanino Sturani (1963) also signaled *Nerinea* sp., *Phaneroptyxis moreana*, and *Cryptoplocus* cf. *subpyramidalis*), rudists (Diceratidae), stromatoporoids, echinoderm fragments, benthic foraminifera (Textularidae, Valvulinidae). Beds of oncoidal rudstones, peloidal wackestones and oolitic grainstones are locally present. In the upper part of the unit, a common lithofacies is represented by peloidal-bioclastic mudstones-wackestones with dasycladacean algae (*Clypeina* sp.). In the Roaschia Unit, and in the tectonic slices of Provençal succession presently incorporated in the LiVZ (Bec Matlas-Bec Baral), the above described lithofacies are limited to the upper part (some tens of metres?) of the Garbella Limestone, whereas the lower part is generally formed by bioclastic wackestones/packstones, with abundant crinoid ossicles, along with rare gastropods, bivalves, corals, stromatoporoids and red algae.

The top of the Garbella Limestone is commonly represented by a thin stratigraphic interval (some metres thick) of fenestral and laminated mudstones, locally interbedded with thin layers of greenish clays, associated with flat pebble breccias and oolitic grainstones to packstones. Beds of nerineid gastropod coquina are also present, in which shells are locally completely dissolved and the resulting voids are filled up with a whitish to greenish silty/marly sediment (Fig. 3c); microstalactitic

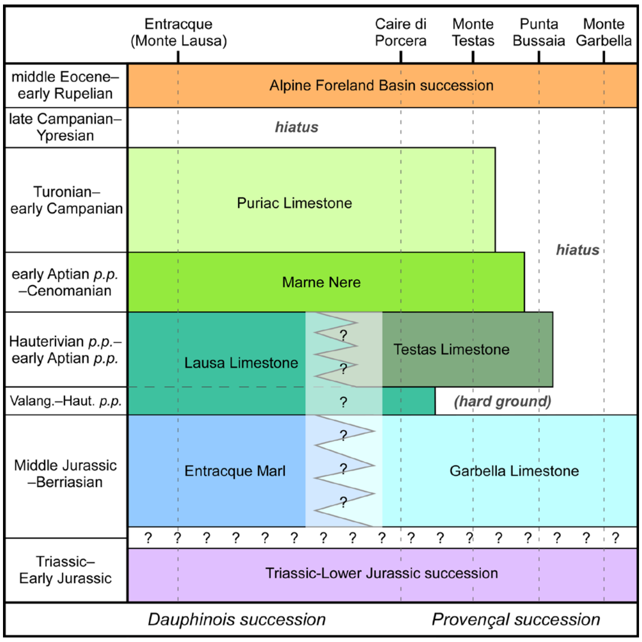

Fig. 2 - Simplified scheme of the stratigraphic relationships between Provençal and Dauphinois successions in the study area. Thicknesses of the rectangles representing lithostratigraphic units are not proportional to their stratigraphic thicknesses nor to time spans.

cements locally predate the sediment infill. At Punta del Van, a grainstone bed composed of subrounded to angular intraclasts, coated grains, benthic foraminifera (*Trocholina* sp.), and abundant ammonite shells is present (Fig. 3d, e). Intraclasts are formed by mudstones, locally with *Clypeina* sp. fragments (Fig. 3e), and peloidal grainstones. Locally (Monte Colombo, Passo Ciotto Mieu), beds of bioclastic mudstone-wackestone with Porocharaceae gyrogonites and stems (sp. aff. *Porochara fusca*), ostracods, and gastropods are also present (Fig. 3f).

The Garbella Limestone is affected for its entire thickness by important phenomena of hydrothermal dolomitization, which locally completely overprinted the primary characters of the rock (Barale et al. 2013, 2016b).

Interpretation. The Garbella Limestone represents a carbonate platform succession and it is mainly formed, in the southern part of the study area, by reefal, peri-reefal, and bioclastic shoal facies (coral-stromatoporoid boundstones, bioclastic rudstones/floatstones and packstones), associated with lagoonal facies (peloidal-*Clypeina* wackestones). Conversely, the succession of the Roaschia unit, dominated by crinoid-rich wackestones/packstones, has been probably deposited on a middle-outer carbonate ramp, possibly evolving into a rimmed platform only toward the top of the unit, where reefal-peri-reefal facies are locally found.

The facies association of the uppermost interval of the Garbella Limestone indicates an inner platform, peritidal environment, in which intertidal/supratidal facies prevail, as indicated by the multiple evidence of periodical emersion: fenestrae, flat pebble breccias, dissolution of aragonitic gastropod shells (probably due to meteoric diagenesis), microstalactitic cements, and nodular fabrics (interpreted to form in peritidal settings as a consequence of bioturbation and periodical desiccation, coupled with early cementation; e.g., Mojon & Strasser 1987). Charophyte-rich beds resulted from deposition in a coastal lagoon environment. The fossil association, dominated by Porocharaceae, indicate a restricted, brackish-water environment (Mojon 1989, 2002). The ammonite-bearing grainstone bed, intercalated within the peritidal facies, can be interpreted as a storm-related, washover deposit, mainly formed by intraclasts (*Clypeina* mudstones) and loose grains ripped out from shallow-water sectors of the platform. The presence and local accumulation of stranded pelagic bioclasts (ammonite shells) in storm-related beds within peritidal or coastal deposits, although unusual, is reported in the literature (e.g., Daber 1968; Stricklin & Smith 1973; Septfontaine 1985; Palma et al. 2013).

The Garbella Limestone has been generically attributed by previous authors to the Middle-Upper Jurassic (Carraro et al. 1970). However, the Middle Jurassic age of the lower part of this unit is only supposed, as it is not supported by biostratigraphic data. The stratigraphic distribution of gastropod species found in the upper part of the unit indicates a Late Jurassic age: *Ptygmatis pseudobruntrutana* is present in the Kimmeridgian-Tithonian (Wieczorek 1998), and *Phaneroptyxis moreana* in the Oxfordian-Tithonian (Sirna & Mastroianni 1993).

A Berriasian age can be speculated for the uppermost interval of the unit, represented by peritidal deposits, based on the correlation with the successions of the southern part of the Maritime Alps (Nice Arc), where the Middle-Upper Jurassic platform carbonates are followed by an interval of peritidal and lagoonal sediments of lower-middle Berriasian age (Lanteaume 1968; Dardeau & Pascal 1982; Barale et al. 2016c). This attribution is consistent with the presence of charophyte remains attributed to *Porochara fusca*, as this species has a large

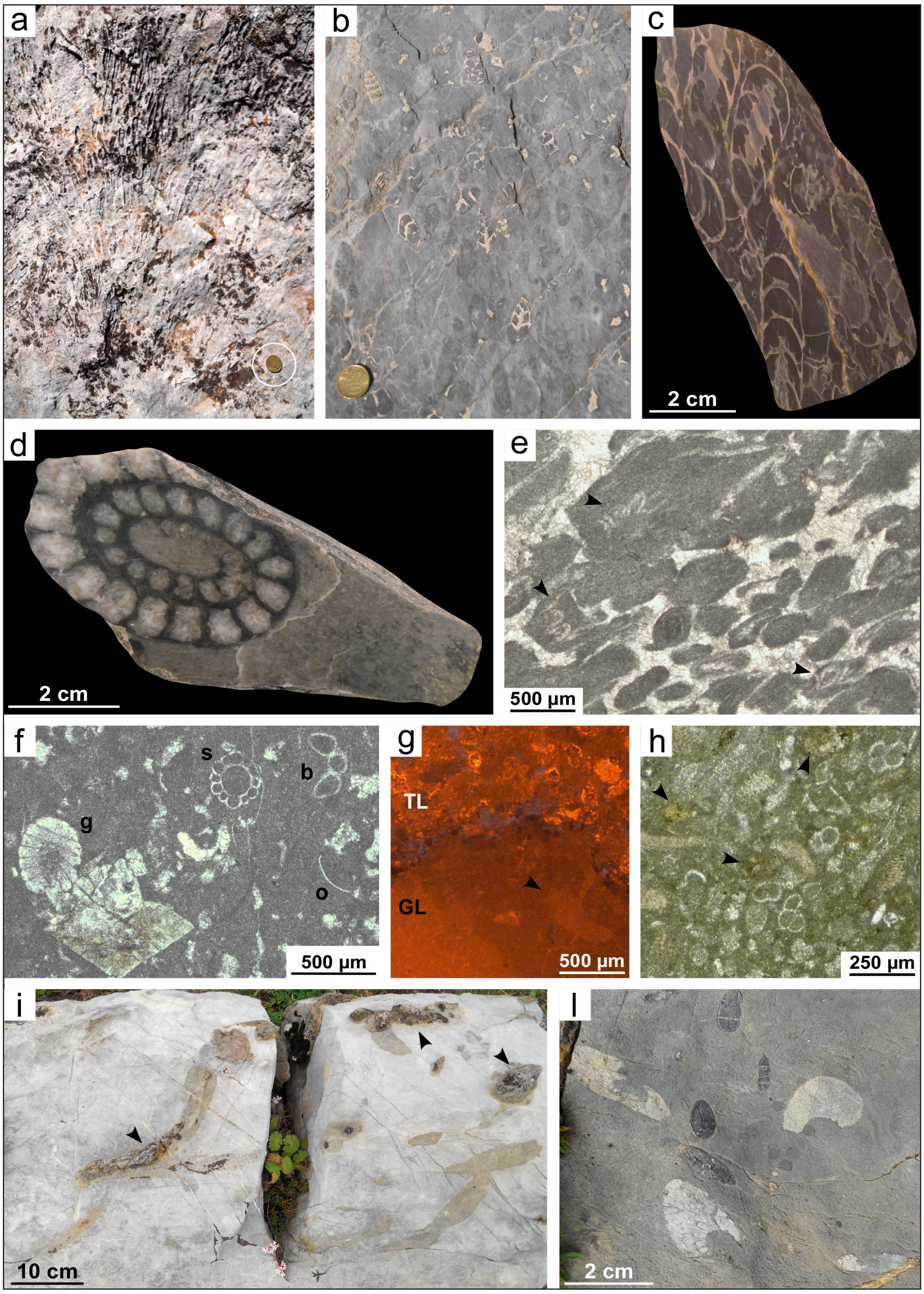

Fig. 3 - Jurassic-Lower Cretaceous Provençal succession. a) Garbella Limestone: coral boundstone affected by selective dolomitization of the matrix (encircled coin for scale). Vallone degli Alberghi, Palanfré. b) Garbella Limestone: bioclastic rudstone with dolomitized nerineid gastropods. Monte del Chiamossero. c) Nerineid gastropod coquina from the top interval of the Garbella Limestone. Voids, derived from the dissolution of gastropod shells, are filled by a yellowish marly sediment. Monte Testas. d) Ammonite shell in a grainstone composed of platform-derived intraclasts and loose grains, from the upper interval of the Garbella Limestone. Punta del Van. e) Thin section photomicrograph (plane light) of the grainstone in (d), mostly composed of mudstone intraclasts, some of which contain *Clypeina* fragments (arrow tips). f) Thin section photomicrograph (plane light) of a bioclastic wackestone with Porocharaceae remains (g: gyrogonite, s: stem, b: branchlet) from the upper interval of the Garbella Limestone; an ostracod shell (o) is also visible. Note the brown, euhedral dolomite crystal growing on the matrix. Monte Colombo. g) Cathodoluminescence photomicrograph of the discontinuity surface separating the Garbella Limestone (GL) from the Testas Limestone (TL), encrusted by phosphates (lilac-blue luminescence) and Fe-oxyhydroxides (non luminescent). The arrow tip indicates a probable sponge boring. Monte Testas. h) Testas Limestone: thin section photomicrograph (plane light) of a bioclastic packstone with echinoderm fragments, planktonic foraminifera (*Hedbergella* sp.), and phosphatic grains (arrow tips). Punta del Van. i) Cross-section of a bioturbated bed of Testas Limestone, showing *Thalassinoides* burrows filled with a crinoid-rich packstone. Silicified nodules are locally developed along the burrows (arrow tips). Monte Testas. l) Detail of the bioclastic-lithoclastic conglomerate interval in the upper part of the Testas Limestone, containing reworked ammonite moulds and belemnite rostra. Punta del Van.

stratigraphic distribution spanning the Bathonian-Berriasian (Mojon 1989; Schudack 1993; Pereira et al. 2003).

Testas Limestone (Hauterivian p.p.?-early Aptian p.p.?)

In the northern sector of the study area (Roaschia Unit) the Testas Limestone overlies a hard ground surface developed at the top of the Garbella Limestone (Fig. 2), commonly mineralized and patchily coated by a millimetre-thick crust of phosphates and Fe-oxyhydroxides (Fig. 3g) and locally colonized by large serpulids (10-15 centimetres long and 3-4 millimetres in diameter). Above, a few metres of bioclastic, crinoid-rich, wackestones and packstones are present (Fig. 3h), containing planktonic foraminifera (*Hedbergella* sp.), fragments of large tube worms, ammonite moulds, and partly silicified belemnite rostra, locally iso-oriented. These deposits are bioturbated (*Thalassinoides*) and contain decimetre-sized silicified nodules, commonly developed along burrows (Fig. 3i); phosphates are present as millimetre-sized grains, as filling of foraminifera chambers, and as impregnations on minor discontinuity surfaces. In the upper part of the unit, a bioclastic-lithoclastic conglomerate interval, 100-120 cm thick, is present, with phosphatized lithoclasts, belemnites, reworked ammonite moulds (*Barremites* sp. and *Melchiorites* sp., figured in Barale 2014) and solitary corals (Fig. 3l). The conglomerate lies on a mineralized hard ground, coated by Fe-oxides and phosphates, and characterized by the presence of decimetre-long fractures and burrows.

In the southern sector of the study area, the Testas Limestone consists of a thin interval (0-2 metres) of marly limestones containing abundant segmented belemnites and echinoderm fragments. This interval is only locally present (Carraro et al. 1970; Barale et al. 2016a), lying on the dolomitized Jurassic succession (Punta Bussaia), or on the thin interval of pebbly limestones attributed to the lower member of the Lausa Limestone (Caire di Porcera, Monte del Chiamossero).

Interpretation. The Testas Limestone can be interpreted as the result of pelagic sedimentation, in an open- marine shelf environment. The basal discontinuity surface, represented in the Roaschia Unit by a mineralized hard ground, marks the drowning of the Jurassic-Berriasian platform (Garbella Limestone). The presence of repeated discontinuity surfaces and the abundance of phosphates indicate the condensed character of this unit. Condensation was probably related to sediment winnowing by bottom currents, whose action is also confirmed by the local iso-orientation of belemnite rostra on bedding surfaces. The lateral thickness variations of these deposits can be attributed to a palaeotopographic control, with sediment deposition limited to more depressed sectors of the shelf.

The Testas Limestone probably has an Early Cretaceous age as it is comprised between the Middle? Jurassic-Berriasian? Garbella Limestone and the early Aptian p.p.-Cenomanian Marne Nere. For this unit, a Hauterivian p.p.-early Aptian p.p. age is proposed, by comparison with the condensed Lower Cretaceous successions of the southeastern Maritime Alps. In this area, after drowning of the Jurassic-Berriasian carbonate platform, a condensed open-marine succession deposited in the early Hauterivian p.p.-early Aptian p.p., until a switch to marly sedimentation during the early Aptian (Bigot et al. 1967; Lanteaume 1968, 1990; Pasquini et al. 2004; Barale et al. 2016c).

Bioclastic-lithoclastic conglomerates in the upper part of the Testas Limestone can be correlated with analogous deposits occurring in the Lower Cretaceous successions of the southeastern Maritime Alps, corresponding to an important Barremian condensation episode and representing a reliable key interval in this region (e.g., Faure-Muret 1955; Bigot et al. 1967; Lanteaume 1968, 1990; Delanoy 1992; Pasquini et al. 2004; Barale et al. 2016c). A Barremian age is consistent with the presence of reworked *Melchiorites* sp. and *Barremites* sp., as the first genus has a Barremian-early Albian stratigraphic distribution, and the second is Barremian (Wright et al. 1996).

JURASSIC-LOWER CRETACEOUS DAUPHINOIS SUCCESSION

The Jurassic-Lower Cretaceous Dauphinois succession of the Entracque area (Fig. 1) has been previously subdivided by Carraro et al. (1970) and Malaroda (1970) into two units, namely:

- a lower marly unit (300-400 m), with breccia beds at the top, basically correlated to the Middle-Upper Jurassic "Terre Nere" of the classic Dauphinois succession;

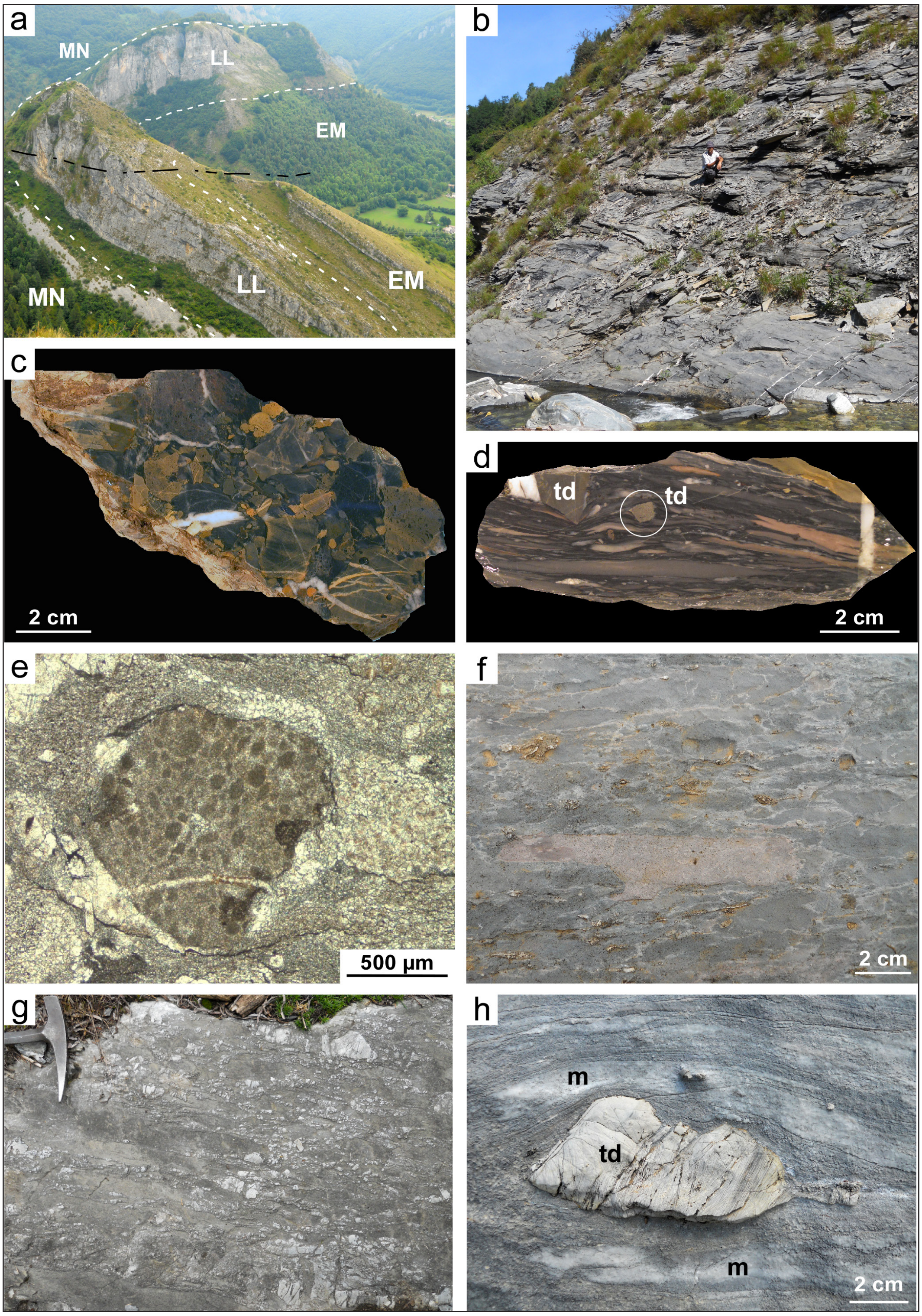

Fig. 4 - Jurassic-Lower Cretaceous Dauphinois succession. a) Panoramic view of Monte Stramondin (foreground) and Pian dei Funs (background), taken from Monte Lausa. The image shows the Entracque Marl (EM), Lausa Limestone (LL) and Marne Nere (MN) units folded in the Monte Lausa-Monte La Piastra anticline (the image is roughly perpendicular to the axial plane, whose trace is indicated by the black dashed line). b) Dark shales in the lower interval of the Entracque Marl, cropping out along the Bousset River southeast of Entracque. c) Hand sample of breccia from the upper interval of the Entracque Marl, mainly composed of dolostone clasts from the Middle Triassic Mont Agnelet Formation. Bec Cavallera, near Tetti Prer. d) Hand sample of breccia from the upper interval of the Entracque Marl, with stretched mudstone clasts and angular clasts of Middle Triassic dolostones (Mont Agnelet Formation; td). Monte Stramondin. e) Clast of peloidal packstone in a breccia bed of the upper interval of the Entracque Marl. Monte Viver, southeast of Entracque. f) Breccia bed in the lower interval of the Lausa Limestone, mainly composed of grey and pinkish mudstone clasts. Monte Stramondin. g) Breccia bed with clasts of coarsely crystalline dolostone in the lower interval of the Lausa Limestone. Tetti Tancias, near Colletta Soprana. h) Breccia bed in the lower interval of the Lausa Limestone, with a clast of Middle Triassic dolostone (Mont Agnelet Formation; td) surrounded by stretched mudstone clasts (m). Caire dell'Uglia, near Colletta Soprana.

- an upper limestone unit, with breccia beds at the base, corresponding, according to these authors, to the Upper Jurassic "Barre Tithonique" and the Lower Cretaceous "Neocomiano a Cefalopodi".

In this paper, the distinction between a lower marly unit (Entracque Marl) and an upper calcareous unit (Lausa Limestone) is maintained (Fig. 2, 4a), but a different chronostratigraphic attribution is proposed for the two intervals (see below).

Entracque Marl (Middle? Jurassic-Berriasian?)

The Entracque Marl consists of a marly-shaly succession, whose thickness can be estimated at some hundred metres, with some uncertainty owing to poor exposure and tectonic deformation.

This unit mainly consists of dark grey marls, calcareous marls and shales (Fig. 4b), with rare thin beds of bioclastic mudstones and wackestones containing echinoderm fragments, bivalve shells, and other bioclasts. The upper part (uppermost 100 metres) is characterized by the presence of breccia beds, a few centimetres to a few decimetres thick. Breccia beds become more and more abundant toward the top; the interbedded marly intervals progressively decrease in thickness and eventually disappear marking the transition to the overlying Lausa Limestone. Breccias are generally clast-supported, with subrounded to subangular clasts (Fig. 4c, d), millimetre-sized in the lower part of the breccia interval, up to centimetre-sized in the upper part. Larger clasts (10-15 cm) have been observed in outcrops close to the Caire di Porcera palaeoescarpment (south of Tetti Prer). Clasts are composed of:

- finely to medium crystalline dolostones, macroscopically showing a gray or beige colour; some of these clasts are crossed by calcite veins which end at the edge of the clast without continuing in the matrix;
- ooidal-peloidal grainstones, peloidal packstones (Fig. 4e), and bioclastic wackestones;
- grayish or pinkish mudstones (Fig. 4d), appearing in thin section as a rather homogeneous microspar mosaic, with rare recrystallized bioclasts.

The first two lithotypes prevail in the lower part of the breccia interval, whereas mudstone clasts largely prevail in the upper part. Rare rounded grains of polycrystalline quartz are also presents. Bioclasts are mainly represented by echinoderm fragments, benthic foraminifera and belemnite rostra.

Interpretation. The Entracque Marl is the result of an essentially hemipelagic sedimentation; breccia beds in the upper interval indicate an increasing importance of resedimentation processes toward the top of the unit. Carbonate breccias of Tithonian age are widespread in the pelagic successions of the Dauphinois Basin and have been interpreted as deep-water depositional lobes derived from gravity flow originated by the mobilization of slope sediments (e.g., Courjault et al. 2011; Ferry et al. 2015). The carbonate breccias observed in the Entracque sector likely represent a more proximal equivalent, which deposited close to the margin of the Provençal platform.

Macroscopic and petrographic characters of the finely to medium crystalline dolostone clasts indicate a probable origin from the erosion of the Middle Triassic Mont Agnelet Formation. Clasts of ooidal-peloidal grainstones and peloidal packstones could derive from Middle Jurassic-lowermost Cretaceous, early-lithified platform deposits of the Provençal domain, or from the Middle Triassic-Early Jurassic succession, in which similar facies are present (Carraro et al. 1970). Polycrystalline quartz grains may derive from the Lower Triassic Valette du Sabion quartzarenites, or from the crystalline basement (clasts of crystalline rocks in these beds have been actually reported by Carraro et al. 1970). The origin of grayish and pinkish mudstone clasts is more problematic, as similar facies are not known in the coeval Provençal sediments nor in the pre-Jurassic succession. These are probably intraformational clasts derived from redeposition of consolidated or semi-consolidated slope sediments. Breccia beds rich in mudstone clasts can be thus interpreted as the result of debris flows representing the downslope transformation of slope sediment slumpings (e.g., Colacicchi & Baldanza 1986; Tucker & Wright 1990).

Lausa Limestone (Valanginian?-early Aptian p.p.)

The Lausa Limestone is an essentially calcareous unit, reaching a maximum thickness of 50-60 metres (Fig. 4a, 5). The lower interval of this unit is mostly composed of polymictic, clast-supported carbonate breccias, showing an ill-defined, dm-thick bedding, locally alternating with fine grained limestones. Clasts are subangular to

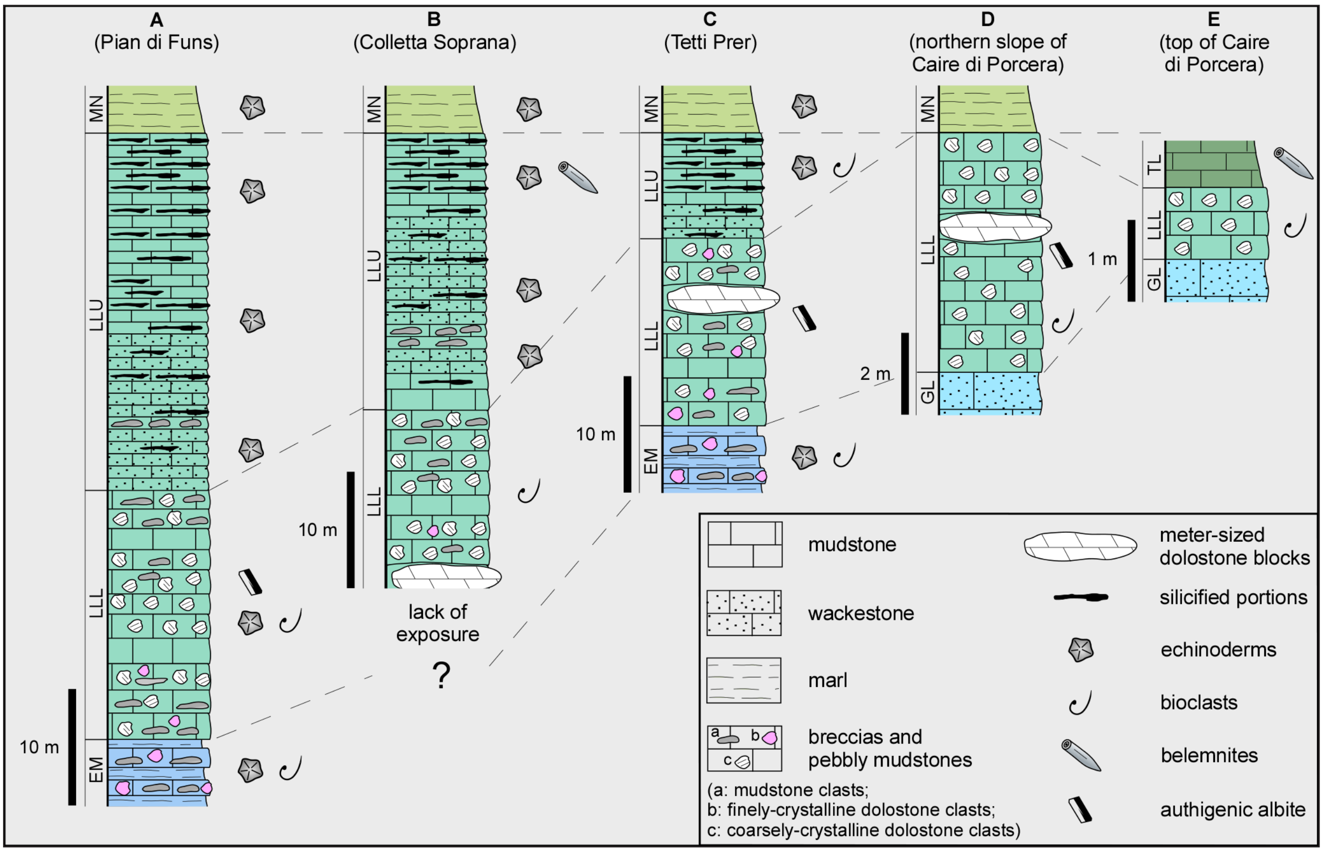

Fig. 5 - Schematic logs of the Lausa Limestone south of Entracque. Log A refers to the southern side of Pian dei Funs, log B to the lower Pautafol Valley (near Colletta Soprana), log C to the southern side of Caire dell'Uglia (near Tetti Prer), log D to the northern slope of Caire di Porcera and log D to the top of Caire di Porcera (see position of localities in Fig. 1). EM: Entracque Marl; LLL: Lausa Limestone, lower interval; LLU: Lausa Limestone, upper interval; MN: Marne Nere; GL: Garbella Limestone; TL: Testas Limestone. The location of the five logs is indicated in Fig. 1c. Please note the variation of the vertical scale among logs A-C, log D, and log E.

subrounded, vary in size from some millimetres to a few decimetres, and are composed of grayish or pinkish mudstones (Fig. 4f), coarsely crystalline dolostones (Fig. 4g) and subordinate finely to medium crystalline dolostones (Fig. 4h). The matrix is a mudstone, commonly recrystallized to a microspar-pseudospar mosaic, containing echinoderm fragments and other recrystallized bioclasts. Mudstone and finely crystalline dolostone clasts are analogous to those observed in the underlying Entracque Marl. Coarsely crystalline dolostone clasts have a whitish colour and are composed of subhedral to euhedral dolomite crystals, commonly showing sweeping extinction and characterized by a homogeneous, orange-red cathodoluminescence.

Close to the Caire di Porcera palaeoescarpment (Tetti Prer, Colletta Soprana), metre-sized masses of dolostones are locally present, whose colour (yellow on fresh surfaces and brown on weathered ones) and differential weathering make them stand out from the encasing limestone (Fig. 6a, b). These masses consist of coarsely to very coarsely crystalline, subhedral to euhedral dolomite crystals, commonly showing sweeping extinction. Concentrations of Fe-oxides along crystal boundaries and cleavage planes are probably responsible for the yellow-brown colour of the rock.

A thin stratigraphic interval (a few metres thick), is locally present on the northern side of Caire di Porcera (Fig. 5), where it rests on the palaeoslope surface connecting the Provençal Platform to the Dauphinois basin (Barale et al. 2016a; d'Atri et al. 2016). It consists of decimetre-thick beds of pebbly mudstones with scattered clasts of white dolostone. Clasts range in size from a few millimetres to some decimetres; rare metre-sized blocks are also present (Fig. 6c, d). They consist of subhedral to euhedral dolomite crystals, commonly showing sweeping extinction and characterized by a homogeneous, orange-red cathodoluminescence (Fig. 6e, f). This interval is locally overlain by belemnite-

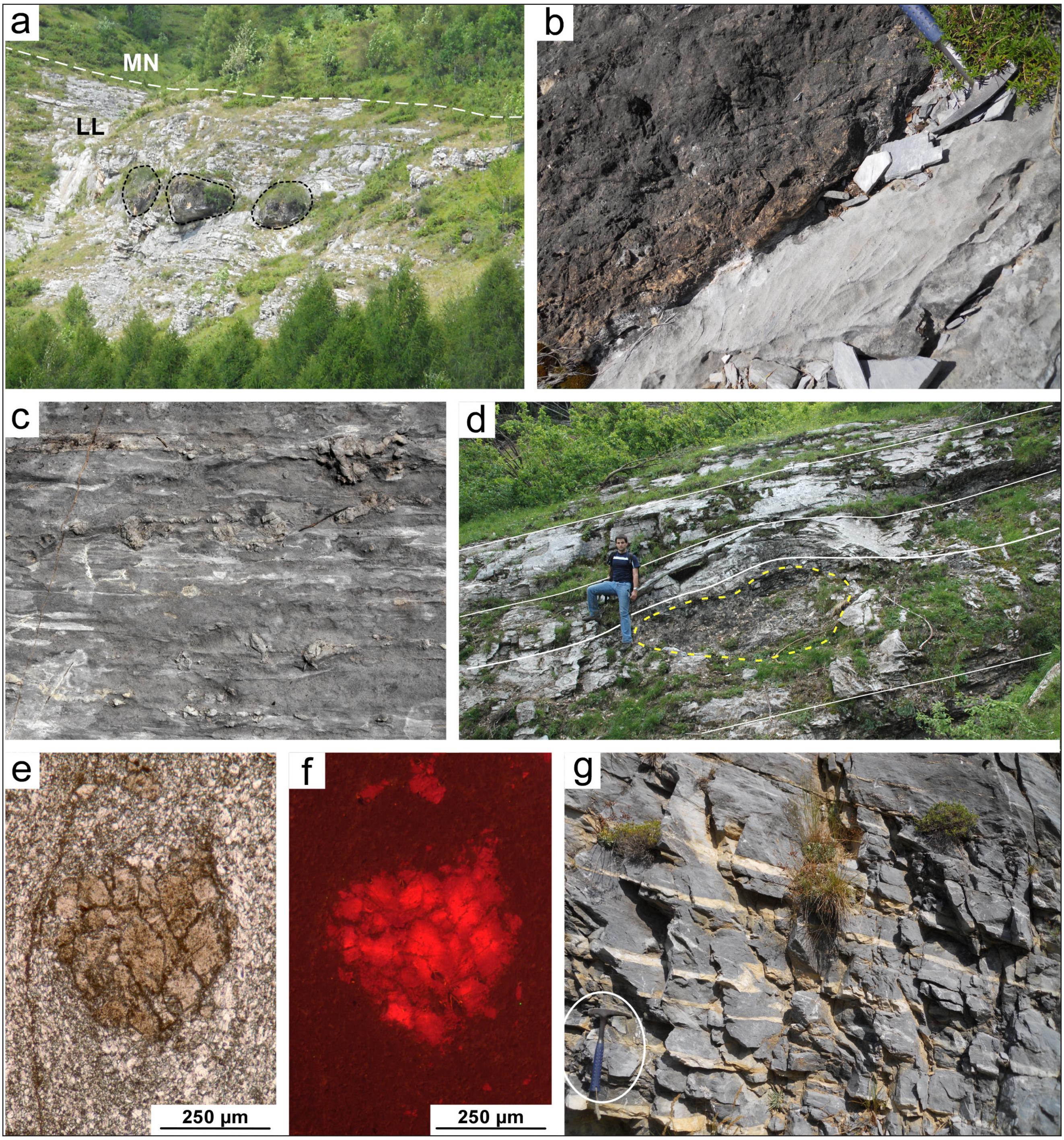

Fig. 6 - Lausa Limestone. a) Metre-sized masses of brown dolostone (black dashed lines) in the lower interval of the Lausa Limestone at Tetti Prer (LL: Lausa Limestone; MN: Marne Nere). b) Detail of the contact between one of the masses of brown dolostone in (a) and the encasing limestone. c) Clasts of coarsely crystalline dolostone in the pebbly mudstones cropping out on the northern side of Caire di Porcera. d) Metre-sized block of coarsely crystalline dolostone (dashed line) within the pebbly mudstone interval cropping out on the northern side of Caire di Porcera (white lines indicate the bedding). e), f) Millimetre-sized clast of coarsely crystalline dolostone in the pebbly mudstones cropping out on the northern side of Caire di Porcera (thin section photomicrographs; e, plane light; f, cathodoluminescence). g) Bioclastic mudstones with cm-thick, white-coloured silicified portions in the upper interval of the Lausa Limestone (encircled hammer for scale). Tetti Tancias, near Colletta Soprana.

bearing marly limestones of the Hauterivian p.p.?-lower Aptian p.p.? Testas Limestone, or directly by the lower Aptian p.p.-Cenomanian Marne Nere unit (see below).

The upper interval of the Lausa Limestone is made up of thin to medium bedded grey micritic limestones and crinoid-rich wackestones. They contain abundant bedding-parallel silicified portions, some centimetre thick and up to a few metres wide, with highly irregular shape on plan view, showing a white, grey or brownish colour on weathered surfaces (Fig. 6g). Carbonate breccia beds, 10-20 cm thick and entirely composed of centimetre-sized mudstone clasts, are locally present. This interval is about 30-40 metres thick near Entracque (Monte Lausa, Pian di Funs), and progressively thins out toward the south (Fig. 5). The boundary between the Lausa Limestone and the overlying Marne Nere is very sharp, though no unconformity can be recognized between the two units.

Interpretation. The lower interval of the Lausa Limestone is the result of repeated resedimentation events, indicating a relative instability of the marginal sectors of the basin. Breccia beds are very similar to those of the underlying Entracque Marl, and the same considerations can be made as to the origin of limestone and finely crystalline dolostone clasts. On the other hand, the coarsely crystalline dolostone clasts, which do not occur in the Entracque Marl, are strongly comparable, from a macroscopic and petrographic point of view, to the dolomitized Garbella Limestone of the Provençal succession, and probably derived from their erosion.

One of the most intriguing features of this breccia interval is represented by the metre-sized dolostone masses observed at Tetti Prer and Colletta Soprana, some of which (Tetti Prer) have been mapped as "carnieules" by Malaroda (1970). These masses are here interpreted as dolostone blocks, derived from the dolomitized Garbella Limestone. Indeed, the petrographic characteristic of the dolostone masses are very similar to those of the hydrothermal Provençal dolostones and smaller dolostone clasts of dolomitized Garbella Limestone are present in the same stratigraphic interval as the large dolostone masses. In conclusion, the lower breccia interval of the Lausa Limestone contains abundant clasts derived from the dolomitized Provençal succession and varying in size from millimetre-sized grains to metre-sized blocks. They probably derive from rockfall processes, possibly triggered by seismic events, affecting the dolomitized rocks exposed on unstable surfaces. Polymictic breccias containing both extraformational dolostone clasts and intraformational mudstone clasts probably derived from the redeposition, by debris flow processes, of semi-consolidated, fine-grained slope sediments containing dolostone clasts.

The pebbly mudstones which locally overlie the Garbella Limestone are interpreted as slope deposits draping the Caire di Porcera palaeoslope, laterally equivalent to the breccia beds in the lower interval of the Lausa Limestone (Fig. 5), deposited in the adjoining Dauphinois basin. The upper interval of the Lausa Limestone marks the recovery of a pelagic sedimentation, only rarely interrupted by resedimentation events resulting in the deposition of thin breccia beds.

Chronostratigraphic attribution of Entracque Marl and Lausa Limestone

The transition between the Entracque Marl and the Lausa Limestone corresponds to a sharp change in the composition of carbonate breccias. Clasts of coarsely crystalline dolostones, interpreted as dolomitized Garbella Limestone, abound in the lower part of the Lausa Limestone, whereas they are not present in the upper interval of the Entracque Marl. The breccia beds in the lower interval of the Lausa Limestone are here interpreted as laterally equivalent to the thin interval of pebbly mudstones which locally overlie the Garbella Limestone on the Caire di Porcera palaeoslope. This pebbly mudstone interval overlies the Middle? Jurassic-Berriasian? Garbella Limestone and is in turn overlain by the Hauterivian p.p.?-early Aptian? Testas Limestone (Fig. 2). Thus, a Valanginian?-Hauterivian p.p.? age is inferred for it and for the laterally equivalent breccias which compose the base of the Lausa Limestone; a Berriasian? age is proposed for the top of the underlying Entracque Marl. The carbonate-rich unit known as "Barre Tithonique" (Gignoux and Moret 1938) in the typical Dauphinois succession and dated to the upper Kimmeridgian-lowermost Berriasian (e.g., Debrand-Passard et al. 1984; Séguret et al. 2001; Courjault et al. 2011; with references therein), is therefore not present. In the Puriac Valley, about 40 km towards WNW from the study area (see Fig. 1b), the "Barre Tithonique" is represented by about 50 metres of Kimmeridgian fine-grained limestones, and a few metres of Tithonian carbonate breccias and fine-grained limestones (Sturani 1962). This unit becomes progressively thinner towards the east (i.e., towards the study area), whereas it grows thicker westward, i.e., towards the centre of the Dauphinois Basin (Sturani 1962; Dardeau 1983). This could be interpreted as a lateral pinchout of the whole unit towards the margin of the

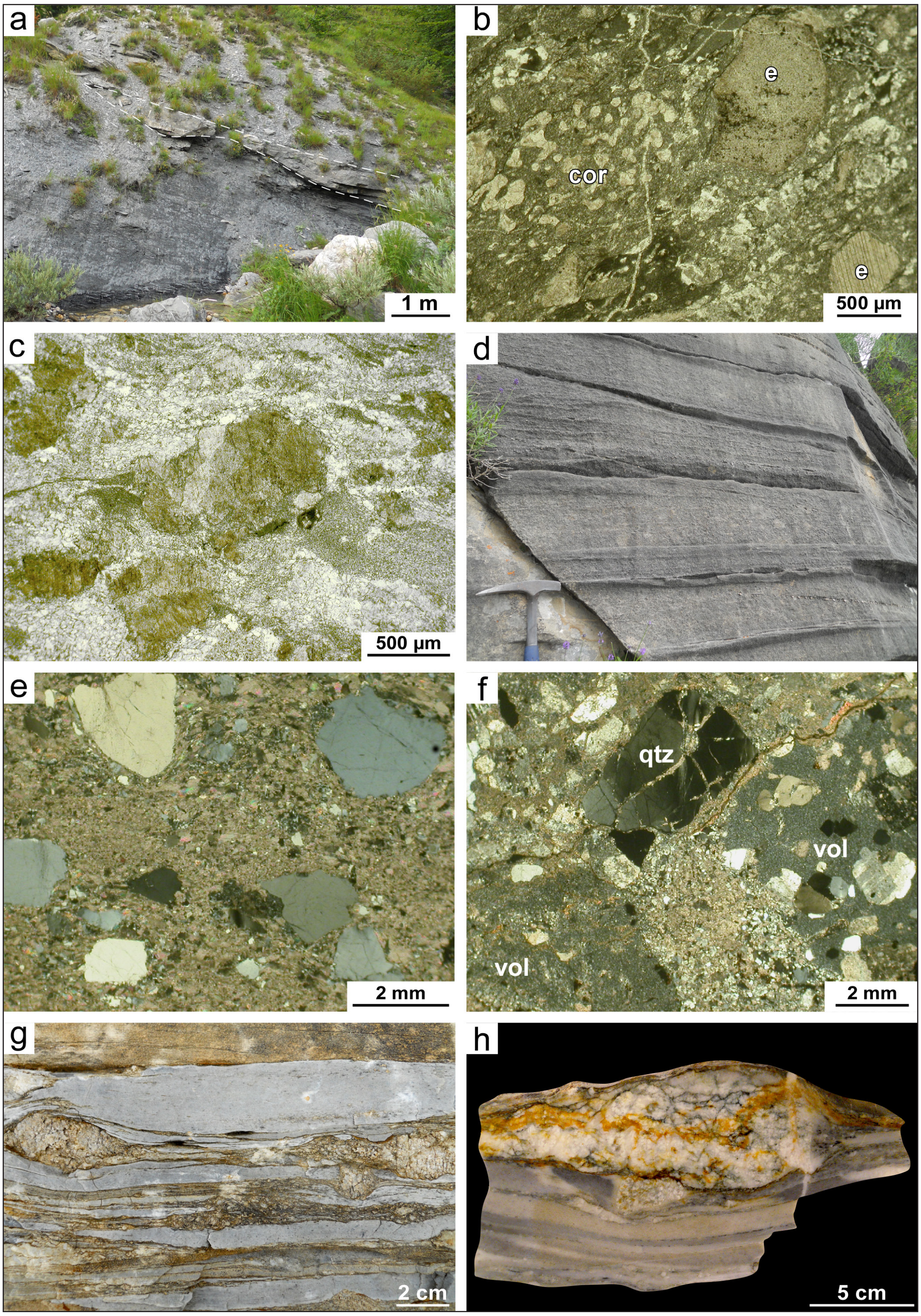

Fig. 7 - Cretaceous succession a) Lenticular packstone bed (dashed line) in the lower interval of the Marne Nere. Balmere Valley, near Colletta Soprana. b) Thin section photomicrograph (plane light) of the packstone bed in (a), showing a coral fragments (cor) and two echinoderm fragments (e). c) Puriac Limestone, reworked dolomite lithozone: thin section photomicrograph (plane light) of a lithoclastic packstone composed of subrounded grains of coarsely crystalline dolostone. Barricate, upper Stura Valley. d) Puriac Limestone, siliciclastic lithozone: metre-thick interval derived from amalgamation of several lithoarenite beds, locally showing parallel lamination. Monte La Piastra. e) Puriac Limestone, siliciclastic lithozone: thin section photomicrograph (crossed polars) of an arenite layer, mainly composed of monocrystalline quartz grains. Comba dell'Infernetto. f) Puriac Limestone, siliciclastic lithozone: thin section photomicrograph (crossed polars) of a microconglomeratic layer, composed of clasts of volcanites (vol) and quartz (qtz). Comba dell'Infernetto. g) Puriac Limestone, siliciclastic lithozone: alternation of cm-thick layers of sandy-limestones and lithoarenites with granitoid pebbles. Comba dell'Infernetto. h) Puriac Limestone, siliciclastic lithozone: grey-coloured sandy limestones containing a granitoid pebble, about 15 cm long. Comba dell'Infernetto.

basin, and would explain its absence in the Entracque area. The base of the Entracque Marl is not observable; by analogy with the marly successions of the upper Stura Valley (Terre Nere; Carraro et al. 1970), a Middle? Jurassic age is here proposed for the lower part of this unit.

The boundary between the Lausa Limestone and the overlying Marne Nere corresponds to a sharp change from calcareous to marly sedimentation. An analogous switch in sediment composition occurred in the early Aptian in the hemipelagic successions of the Dauphinois Basin (e.g., Cotillon et al. 2000; Cotillon 2010) and of the western Tethys in general (e.g., Southern Alps, Erba et al. 1999; Bersezio et al. 2002; Lukeneder 2010; Apennines, Coccioni et al. 1992; Cecca et al. 1995), and has been attributed to the crisis of nannoconids (Erba 1994), an important group of calcareous nannofossils that bloomed at the Jurassic/Cretaceous boundary and gave rise to the ubiquitous uppermost Jurassic-Lower Cretaceous Maiolica lithofacies (e.g., Wieczorek 1988). Thus, the top of the Lausa Limestone can be reliably attributed to the earliest Aptian and a Valanginian?-early Aptian p.p. age is proposed on the whole for this unit. The Lausa Limestone thus corresponds to the Lower Cretaceous fine-grained limestone unit which characterizes the Dauphinois successions on the northern and nortwestern side of the Argentera Massif, known in the literature as "Neocomiano a Cefalopodi" ("Néocomien à Céphalopodes"; Gignoux et al. 1936; Sturani 1962; Carraro et al. 1970; Gidon et al. 1977).

APTIAN-UPPER CRETACEOUS SUCCESSION

Marne Nere (early Aptian p.p.-Cenomanian)

This unit is a monotonous succession of dark-coloured shales and marls, characterized by a marked slaty cleavage. Fossils are rare (echinoderm fragments and other indeterminable bioclasts); in the Puriac Valley, at the northwestern termination of the Argentera Massif (see Fig. 1b), the upper part of this unit yielded a planktonic foraminifera association of late Cenomanian age (Bersezio et al. 2002). South-east of Entracque (Vallone delle Balmere, near Colletta Soprana), a lenticular bed, about 10 metres wide and with a maximum thickness of 60 cm, was observed a few metres above the base of the unit. It shows an erosional concave base and a nearly flat top (Fig. 7a). The base of the bed is represented by a centimetre-thick microbreccia layer, grading upward into a packstone. The microbreccia consists of millimetre-sized, subangular clasts of peloidal grainstones, coarsely crystalline dolostones and reddish, Fe-oxide-impregnated mudstones. Abundant bioclasts are also present (Fig. 7b): coral fragments, echinoderm fragments, dasycladacean algae, bryozoans.

The thickness of the Marne Nere is of 70-80 metres near Entracque (Monte Lausa, Pian di Funs), and progressively thins out towards the South. In the sector corresponding to the Jurassic Provençal Platform, this unit is only locally present (Fig. 2; see also Barale et al. 2016a), with a thickness varying from a few metres (Monte del Chiamossero) to 20-25 metres in the Roaschia Unit (Monte Testas).

Interpretation. This unit resulted from hemipelagic sedimentation in a slope environment, punctuated by sporadic resedimentation events. Lateral discontinuity and thickness variations are likely related to the Cretaceous palaeotopography, with sediment deposition occurring only in relatively depressed sectors.

The lenticular packstone bed can be interpreted as the fill of a small-scale erosional channel (gutter) by resedimented material. Non-channelized beds of resedimented bioclastic wackestones in the Marne Nere unit have been also observed in the high Stura Valley by Bersezio et al. (2002). Shallow-water bioclasts (corals, dasycladacean algae) point to the presence of a shallow-water area, occasionally shedding resedimented material to the slope. In the Aptian-Cenomanian, however, both Provençal and Dauphinois Domains were characterized by hemipelagic sedimentation and no shallow-water facies of this age are known in outcrop. Consequently, the shallow-water area should have been placed elsewhere, possibly in correspondence of the present-day Argentera Massif. A shallow-water area have been hypothesized to exist in that position also later, in the Late Cretaceous, shedding shallow-water bioclasts into the Puriac Limestone succession of the upper Stura Valley (Sturani 1962; Bersezio et al. 2002). The origin of reddish mudstone clasts is unknown. They could represent clasts of mineralized hard grounds, or palaeosols. Instead, coarsely crystalline dolostone clasts probably derived from the dolomitized Garbella Limestone.

Puriac Limestone (Turonian-early Campanian; Bersezio et al. 2002)

The Puriac limestone is a thick succession of limestones (bioclastic mudstones and wackestones) and marly limestones, in centimetre- to decimetre-thick beds with thin marly interbeds. It is characterized by the presence of various detrital lithozones of different composition (from carbonate to siliciclastic). Variations in clast composition are both vertical and lateral, indicating an evolution of the source areas during time but also a spatial differentiation due to the basin morphology. In the studied sector, fossils are rare and generally poorly preserved (echinoderm fragments, *Inoceramus* prisms, and planktonic foraminifera), and then a precise dating of this unit is not possible. In the high Stura Valley, the Puriac Limestone is dated to the late Turonian-early Campanian, resting on an erosional unconformity locally followed by early-middle Turonian chaotic deposits (Bersezio et al. 2002). In the study area, neither unconformity nor chaotic deposits have been observed at the base of the Puriac Limestone, which is therefore attributed to the Turonian-early Campanian.

The thickness of the Puriac Limestone is of the order of some hundred metres, but it is difficult to assess it with more precision because in the whole study area the succession is affected by complex folding and repetition by internal thrusts. South of Entracque, the Puriac Limestone progressively thins out and onlaps the Caire di Porcera palaeoslope. In the sector corresponding to the Jurassic Provençal Platform, the Puriac Limestone shows important lateral variations (Fig. 2): in the Roaschia Unit it reaches a maximum thickness of about 100 metres (Monte Testas), whereas it is completely lacking in the southern sector (Vallone del Sabbione-Colle di Tenda), either due to non-deposition or to later erosion.

Reworked dolomite lithozone. A dolomite-bearing lithozone characterizes the Puriac Limestone throughout the Stura Valley and in the ridge separating it from the Gesso Valley (Cima Cialancia, Monte La Piastra) (Sturani 1962, 1963; Malaroda 1970). This lithozone commonly characterizes the lower part of the Puriac Limestone and has been dated to the late Turonian p.p.-Santonian p.p. in the upper Stura Valley (Sturani 1963). However, in the middle Stura Valley, between Bersezio and Aisone, this lithozone shows a different vertical distribution, locally characterizing nearly the whole thickness of the Puriac Limestone (Monte Bersaio, near Sambuco; Sturani 1963; Malaroda 1970).

The lithozone consists of centimetre- to decimetre-thick beds, commonly with an erosional base, locally showing a normal grading of dolomite grains; plane parallel and cross laminations have been locally observed. The rock is a lithoclastic packstone containing dolomite grains, mudstone clasts and rare echinoderm fragments, in a recrystallized matrix. Dolomite constitutes up to the 30-40 % of the rock volume and occur both as submillimetric, sub-angular crystal fragments and as millimetre- to centimetre-sized, sub-angular to sub-rounded, polycrystalline clasts (Fig. 7c), consisting of subhedral dolomite crystals, brownish in thin section, 300 to 800 µm in size, locally showing sweeping extinction. Mudstone clasts show a microsparitic texture and contain rare bioclasts, locally recognizable as fragments of dasycladacean algae (*Clypeina* sp.).

Reworked dolomite lithozone - Interpretation. Petrographic analysis clearly discloses the clastic nature of dolomite, represented by worn crystal fragments and subrounded polycrystalline clasts. However, the presence of dolomite in the Puriac Limestone was reported by previous authors as "dolomitization" (Sturani 1963; Carraro et al. 1970; Malaroda 1970; Bersezio et al. 2002). This misinterpretation is due to the particular characteristics of the dolomite-bearing rocks: indeed, a large part of this interval only contains submillimetric, monocrystalline dolomite grains that, without a more detailed investigation, could be mistaken for *in situ* grown crystals.

The dolomite-bearing beds are thus the result of resedimentation processes. Two possible sources of dolomite clasts were available in the Late Cretaceous: the Middle Triassic Mont Agnelet Formation and the dolomitized Garbella Limestone, whose dolomitization dates back to the earliest Cretaceous (Barale et al. 2013, 2016b). The petrographic features of the clasts, i.e. the crystal size, the brown colour and the sweeping extinction are closely comparable to those of the dolomitized Garbella Limestone, whereas do not fit the characters of the Middle Triassic dolostones, which show a markedly smaller crystal size. Moreover, dolomite clasts are associated with clasts of *Clypeina*-bearing mudstones, which is a common lithofacies of the Garbella Limestone.

Siliciclastic lithozone. A siliciclastic lithozone characterizes the uppermost part of the Puriac Limestone along the whole NE margin of the Argentera Massif (Gubler et al. 1961; Sturani 1962, 1963; Malaroda 1963; Friès 1999; Bersezio et al. 2002). It progressively increases in thickness from the upper Stura Valley (Puriac Valley), where it only corresponds to the uppermost tens of metres of the Puriac Limestone (Sturani 1962; Bersezio et al. 2002) and has been dated to the Santonian p.p.-early Campanian (Bersezio et al. 2002), to the Valdieri-Entracque sector, where it represents at least the upper third of the unit. South of Entracque, the siliciclastic component in the Puriac Limestone abruptly disappears.

This lithozone is composed of lithoarenites and sandy limestones, interbedded with limestones and marly limestones. Lithoarenites are medium to very coarse, locally microconglomeratic, and form centimetre- to decimetre-thick beds with erosional base, normal grading, parallel lamination and, locally, ripple cross lamination at the top. Metre-thick lithoarenite intervals derived from amalgamation of several beds can be locally observed (Fig. 7d). Grains are represented by monocrystalline quartz, lithoclasts (mainly volcanic rocks, with minor granitoids and recrystallized limestones), and polycrystalline quartz with undulose extinction (likely derived from metamorphic rocks) (Fig. 7e, f). In cathodoluminescence, quartz grains show a dull to moderate blue-violet luminescence (typical of quartz from high-grade metamorphic, plutonic or volcanic rocks; Ramseyer et al. 1988; Götze et al. 2001), or a rapidly decaying, blue-green luminescence (typical of hydrothermal vein quartz; Ramseyer et al. 1988; Götze et al. 2001). Clasts of volcanic rocks have rhyolite and rhyodacite composition, and contain quartz phenocrysts with corrosion gulfs in a microcrystalline groundmass. Locally, slightly coarser groundmasses probably indicate a sub-volcanic origin. Elongated limestone blocks, up to one metre long, are locally present within the lithoarenite beds. Sandy limestones form decimetre-thick beds, locally showing normal grading of the arenitic grains, and have the same composition and grain size of the above described lithoarenites. In the lower Comba dell'Infernetto valley, near Valdieri, these facies are associated with matrix-supported conglomerates, in centimetre- to decimetre-thick beds, with a sandy limestone or arenite matrix. Clasts are centimetre-sized (locally up to 15 cm), subrounded to rounded, and are mainly composed of granitoids, migmatites and rhyolites (Fig. 7g, h).

Siliciclastic lithozone - Interpretation. This lithozone records an important input of resedimented materials in the Puriac Limestone basin. Resedimentation was due to gravity flows, likely represented by turbidity currents in the case of lithoarenite beds and debris flows in the case of sandy limestones and matrix-supported conglomerates.

The provenance of the siliciclastic material is still an open question. Palaeocurrent analysis carried out by Friès (1999) in arenite beds of the Puriac Limestone at the NW termination of the Argentera Massif indicates a provenance from SSW. The author thus argued the derivation of the siliciclastic inputs from a not specified area situated some tens of kilometres to the south (Maures-Estérel Massif?). However, the Upper Cretaceous successions cropping out in intermediate position between the study area and the Maures-Estérel Massif did not register similar siliciclastic inputs (Debrand-Passard & Courbouleix 1984; Debrand-Passard et al. 1984). Conversely, Malaroda (1963) indicated the Argentera Massif as the source of the siliciclastic inputs. The Argentera Massif basement includes all the lithotypes present as clasts in the Puriac Limestone. Granitoid clasts are closely comparable to the "migmatitic granitoid gneiss" (Lombardo et al. 2011; anatexites of Carraro et al. 1970), the most common lithotype of the Argentera basement, as already suggested by Malaroda (1963). On the other hand, clasts of volcanic and subvolcanic rock could derive from the Permian rhyolites and the related hypoabissal rocks locally present at the SE and NE margin of the Argentera Massif (Faure-Muret 1955; Malaroda 1957). The scarcity and the limited extent of the present-day outcropping rhyolites (Faure-Muret 1955; Malaroda 1957) do not necessarily rule out that some larger masses of permian rhyolites, now totally removed by erosion, were exposed and actively eroded in the Late Cretaceous.

Well rounded granitoid pebbles are common in the Puriac Limestone conglomerates: clast rounding can result from either fluvial transport, permanence in a gravelly beach environment, intense weathering of granitoid rocks (corestones: e.g., Ryan et al. 2005), or a combination of these processes, all pointing to an emerged source area. Recrystallized carbonate clasts, locally present in arenite and conglomerate beds, probably represent intraformational clasts, ripped out by gravity flows, even if an extraformational origin can not be ruled out.

Discussion

Cretaceous syndepositional tectonics

The main phases of syndepositional tectonics which influenced the deposition of the Dauphinois and Provençal successions in the study area have been recognized on the basis of multiple evidence, namely:

- sedimentologic evidence, related to the presence of resedimented intervals in the hemipelagic Entracque Marl, Lausa Limestone and Puriac Limestone units;
- stratigraphic evidence, based on the geometries and thickness variations of the sedimentary bodies;
- diagenetic evidence, represented by the fault-related hydrothermal dolomitization of Provençal carbonates (reported in Barale et al. 2013, 2016b).

Facies analysis confirms that the southern part of the study area was a shallow water domain from at least the Middle Jurassic to the earliest Cretaceous whereas in the northern part a deeper water, slope environment is documented. This environmental change takes place at Caire di Porcera, which is thus a key area where since the Middle Jurassic the boundary between the Provençal and Dauphinois Domains was located (Barale et al. 2016a; d'Atri et al. 2016). The occurrence of breccia beds in the Entracque Marl and the Lausa Limestone of the Dauphinois succession shows that such boundary was unstable and affected by gravitational processes. These carbonate breccias are polymictic and include both intraformational and extraformational clasts represented by lithoclasts of older formations and document that the platform-basin boundary was not a depositional slope but an escarpment where older formations had been exhumed. As to depositional processes, these breccias are interpreted as debris flow deposits, which are known to be the result of the failure of slope deposits when the shear stress acting on sediments overcomes their shear strength (Spence & Tucker 1997). Many triggering mechanisms have been proposed, including relative sea level changes, seismic shocks, slope oversteepening, differential compaction, cyclical loading by storm waves, gas-hydrate dissociation, and bolide impacts (e.g. Haq 1993; Spence & Tucker 1997; Drzewiecki & Simó 2002). In the study case, some of the mechanism proposed in the literature can be confidently ruled out (e.g., gas hydrate dissociation, bolide impact). The abundance of extraformational clasts derived from the Triassic-Early Jurassic succession suggests that tectonic triggers (slope oversteepening or seismic shocks) are the most probable. The presence of clasts of veined rocks documents that the Triassic-Early Jurassic succession was already veined and thus had been affected by fracturing before its erosion and redeposition as clasts in the breccia beds. The erosion of older terms of the stratigraphic succession implies their exposure at the seafloor, likely along fault-related palaeoescarpments. Furthermore, the size reduction of clasts and thinning of breccia beds northwards, and, concomitantly, the thickening of the whole stratigraphic succession, further suggest the existence of a palaeoslope, onto which the Dauphinois succession onlapped, at Caire di Porcera (see Barale et al. 2016a; d'Atri et al. 2016). The decreasing abundance of clasts derived from the Middle Triassic Mont Agnelet Formation toward the top of the Entracque Marl, replaced by a greater abundance of intrabasinal mud-supported slope sediments, could be related to the progressive covering of the original palaeoescarpment surfaces by slope sediments, preserving the Triassic succession from further erosion. Breccia beds are present in the uppermost part of the Entracque Marl (Middle? Jurassic-Berriasian?) and in the lower part of the Lausa Limestone (Valanginian?-early Aptian?), and thus the breccia interval can be essentially attributed to the lowermost Cretaceous.

The hydrothermal dolomitization affecting the Middle Triassic-Berriasian? Provençal succession (Barale et al. 2013, 2016b), is itself another evidence of an earliest Cretaceous tectonic activity. Dolomitization, in fact, occurred in the latest Berriasian-Valanginian and was related to a polyphase circulation of hot fluids through active faults and associated fracture networks (Barale et al. 2013, 2016b). The superposition of pelagic, more or less

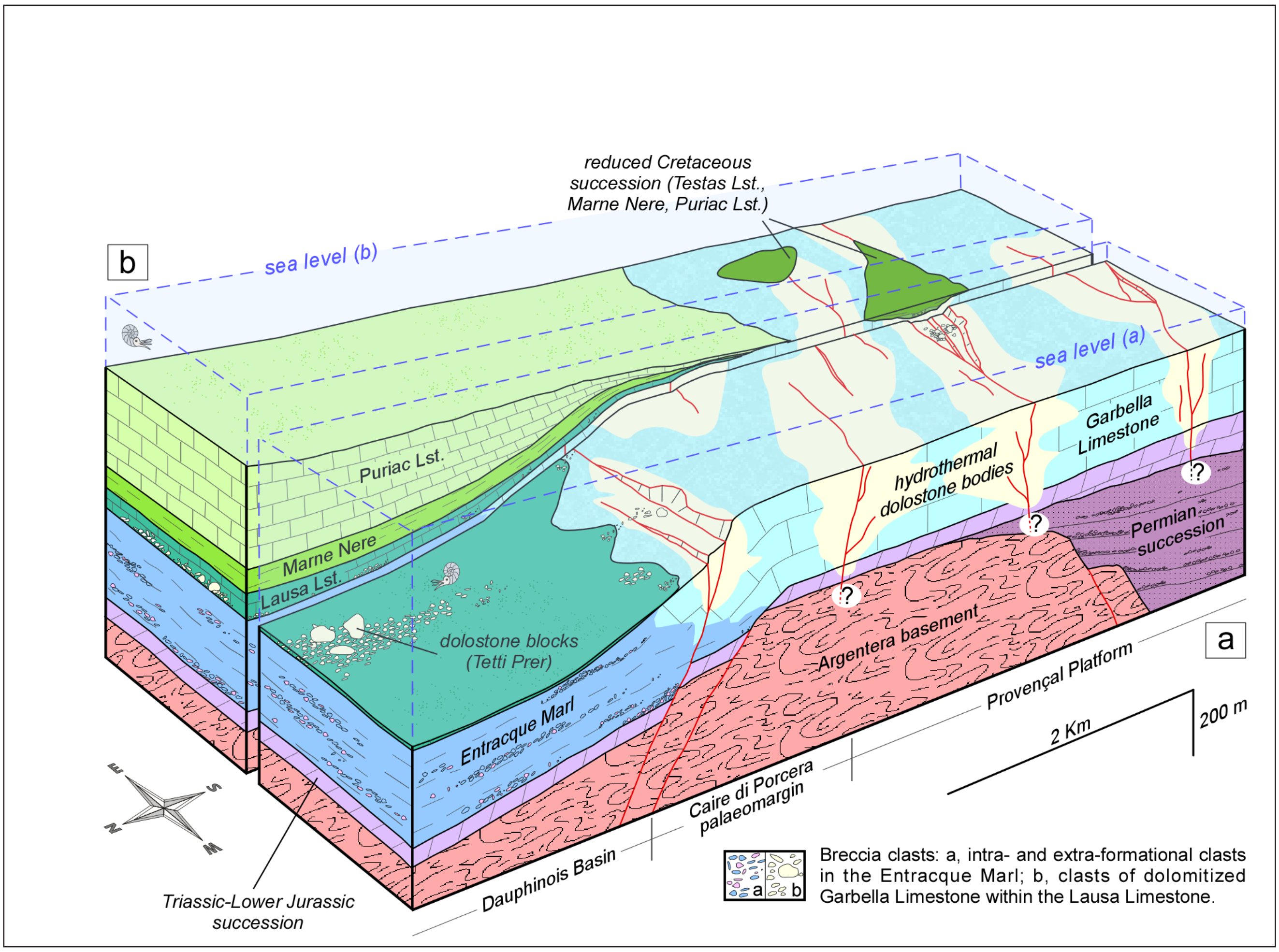

Fig. 8 - Composite 3D sketch showing the evolution of the Dauphinois and Provençal successions in correspondence of the Caire di Porcera palaeomargin from the earliest Cretaceous (a, beginning of the deposition of the Lausa Limestone) to the latest Cretaceous (b, end of the deposition of the Puriac Limestone). See text for further details.

condensed, Hauterivian-Cenomanian sediments (Testas Limestone, Marne Nere) over the Berriasian peritidal facies of the top of the Garbella Limestone, and the lateral thickness variations of the post-Berriasian succession document a drowning of the Provençal Domain and sedimentation over a complex palaeotopography and further support an earliest Cretaceous tectonic phase.

This earliest Cretaceous tectonics probably acted on the Caire di Porcera palaeoslope and its lateral equivalents and created new palaeoescarpment surfaces, exposing to erosion the hydrothermally dolomitized Garbella Limestone and triggering gravity flows along the slope which originated the breccias beds in the lower part of the Lausa Limestone (Fig. 8a). Since the late Early Cretaceous, and throughout the Late Cretaceous, the deposition of a rather thick succession in the Dauphinois basin (Lausa Limestone, Marne Nere and Puriac Limestone), while almost no deposition took place on the Provençal platform, caused the progressive reduction of the morphological expression of the Caire di Porcera palaeoescarpment (Fig. 8b).

An earliest Cretaceous (Valanginian) tectonics is well documented throughout the Dauphinois Basin, and particularly on its southern and southwestern margins (e.g., De Graciansky & Lemoine 1988; Bulot et al. 1997; Wilpshaar et al. 1997). This tectonic phase has been linked to the rifting and the first opening stages of the North Atlantic Ocean (Dardeau 1988; De Graciansky & Lemoine 1988). It was essentially related to E-W or NW-SE trending extensional structures (Joseph et al. 1989; Hibsch et al. 1992; Masse et al. 2009). Valanginian faults gave rise to a complex palaeotopography reflected in the important lateral variations of facies and thickness in the Lower Cretaceous successions of these sectors (Debelmas & Kerckhove 1980; Dardeau & De Graciansky 1987; Joseph et al. 1989; Hibsch et al. 1992; Montenat et al. 1997; Masse et al. 2009).

Another, later, phase of syndepositional tectonics is documented by clastic inputs in the Upper Cretaceous Puriac Limestone. In the Stura Valley, the lower part of the succession contains abundant dolostone clasts, which derived from the erosion of the dolomitized Garbella Limestone. The age of this lithozone is late Turonian p.p.-Santonian p.p. in the high Stura Valley (Sturani 1963). A change in the clastic input occurs in the upper part of the Puriac Limestone, i.e. in the Santonian p.p.-early Campanian (Bersezio et al. 2002), and consist of siliciclastic sand and gravel size material, which could derive from the erosion of uplifted tectonic slices of Argentera-type basement. These clastic inputs indicate the progressive denudation of Upper Jurassic dolomitized rocks at first, and of crystalline rocks later, which implies important displacements along syndepositional faults during Late Cretaceous. Tectonic activity could have also played a role in triggering the gravity flows responsible for the mobilization and resedimentation into the basinal Puriac Limestone of the clastic material, at least partly derived from subaerial erosion, as documented by the high degree of roundness. The absence of clastic inputs in the Puriac Limestone succession which has been deposited south of Entracque documents that Late Cretaceous tectonic activity did not affect the sector of the Caire di Porcera palaeoslope.

A Late Cretaceous syndepositional tectonic activity can be thus inferred in the study area from the late Turonian to the Santonian-Campanian boundary. A middle Turonian-early Coniacian tectonic phase is well documented by sedimentologic evidence in the adjoining southern Provence basin, located southward of the Provençal platform (Floquet & Hennuy 2003), whereas the Santonian-Campanian boundary corresponds to an important syndepositional tectonic activity registered throughout the Vocontian Basin, which triggered a massive siliciclastic input into the basinal successions (Friés 1999).

Implications for the Cretaceous geodynamic evolution

The classic models of the Mesozoic evolution of the European Tethyan palaeomargin (e.g., Tricart 1984; Lemoine et al. 1986) envisage a first phase of extensional tectonics, essentially Late Triassic-Early Jurassic. It caused the horst-and-graben structuration of the European palaeomargin (Lemoine et al. 1986; Faure & Megard-Galli 1988; De Graciansky & Lemoine 1988; Tricart et al. 1988; Masini et al. 2013), and, in the study area, the differentiation between a basinal area (Dauphinois) to the NW and a platform area (Provençal) to the SE. This rifting phase was followed by an oceanic spreading phase and a long period of passive thermal subsidence of the margin, ending in the Late Cretaceous with the onset of compressional tectonics leading to the oceanic closure (e.g., Boillot et al. 1984). Nonetheless, the stratigraphic record of the study area documents that syndepositional tectonic activity continued to influence the evolution of the margin even after the Early Jurassic, with two main tectonic phases of earliest Cretaceous and Late Cretaceous age.

An analogous evolution has been documented in the Briançonnais Domain (Claudel & Dumont 1999; Bertok et al. 2011), where Middle-Late Jurassic syndepositional tectonics played a major role in the evolution of the palaeomargin, locally resulting more important than the Early Jurassic syn-rift phase in terms of displacements and generation of palaeotopography. Moreover, multiple evidence of Early Cretaceous transtensional tectonics was described in the adjoining External Ligurian Briançonnais Domain (Bertok et al. 2012), pointing to the existence at that time of a large deformation zone, cutting transversely across different domains of the Alpine Tethys European palaeomargin (Dauphinois/Provençal and Briançonnais).

This reconstruction is consistent with the regional geodynamic context, as different palaeogeographic schemes place the whole area, during the Cretaceous, along a regional transform system, running from the Bay of Biscay to the Alpine Tethys through the Pyrenean region and the Provence (e.g., Stampfli et al. 2002; Golonka 2004; Handy et al. 2010). Moreover, the position of this supposed Cretaceous deformation zone, cutting across Provençal/Dauphinois and External Ligurian Briançonnais domains, roughly coincides with the present-day Ligurian Transfer (d'Atri et al. 2016), a large shearing corridor that represents the boundary between the Maritime-Ligurian Alps and the rest of the Western Alps. It is thus possible that this first-order Alpine kinematic transfer zone partly set on a pre-existing, Cretaceous, long-lived crustal weakness zone.

CONCLUSIONS

A multidisciplinary study, including stratigraphy, facies analysis, transmitted light and cathodoluminescence petrography, allowed to improve the knowledge about the palaeoenvironmental setting of the Jurassic-Cretaceous Dauphinois and Provençal successions cropping out at the southeastern margin of the Argentera Massif, and to investigate the times and modes of their Mesozoic evolution. The main results of this study are the following:

- the Jurassic-Lower Cretaceous Dauphinois succession and the overlying Upper Cretaceous hemipelagic succession contain several resedimented intervals, which document both tectonically-triggered gravitational processes and a tectonically-driven evolution of the source areas;
- stratigraphic, sedimentologic, and diagenetic evidence document two phases of syndepositional tectonics younger than the Jurassic rifting phase, which occurred in the earliest Cretaceous (Valanginian) and in the Late Cretaceous (from late Turonian to Santonian-Campanian boundary).

Acknowledgements. The authors thank two anonymous reviewers and the Editor Fabrizio Berra for useful comments and suggestions which improved the text. The Maritime Alps Natural Park is kindly acknowledged for allowing fieldwork within the Park territory, and for providing accommodation in Park facilities. Carles Martín-Closas (Departament d'Estratigrafia, Paleontologia i Geociències Marines, Universitat de Barcelona) is thanked for the determination of charophyte gyrogonites. Andrea Sacchetto is acknowledged for sharing fieldwork in the early phases of the research. The research was supported by the University of Torino (ex 60% funds; Doctoral School of Sciences and Innovative Technologies funds) and by the Italian CNR (National Research Council), Istituto di Geoscienze e Georisorse, Unità di Torino. Funds related to the ProGeoPiemonte Project (financed by Compagnia di San Paolo and University of Torino) have also been utilized. A financial contribution by the Italian Association for Sedimentary Geology (GeoSed) (Contributo Giovani 2011 to L. Barale) is gratefully acknowledged.

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