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Large-scale progradation, demise and rebirth of a high-relief carbonate platform (Triassic, Lombardy Southern Alps, Italy)

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ABSTRACT

The Upper Anisian to Early Carnian succession of the Middle Val Brembana-Pegherolo Massif (Central Southern Alps of Italy) records a complete depositional cycle from platform inception to growth, demise and rebirth. The depositional architecture of this system reflects different evolutionary stages: an inception stage which postdates a previous drowning of an Anisian carbonate platform with progradation of the carbonate platform from the nucleation areas, an aggradational stage with increasing water depth in the basins, a progradational stage where steep slopes comprised of margin-derived breccias develops and a final crisis corresponding to the subaerial exposure of the platform top, followed by the deposition of shales in the basin before the rebirth of a different type of carbonate factory. The record of this evolution reflects the effects of the change in accommodation space (interplay of subsidence and eustacy), which controls the type and storage sites of the sediments produced by the carbonate factory. The effects of the changes in accommodation space are recorded in the shallow water platform as well as in the intraplatform basins, where the sediments, delivered at different rates from the platform top are stored. As a consequence, the aggradational stage corresponds to reduced sedimentation in the basins (i.e. sediments are stored on the platform top) whereas during progradation resedimented limestones are more common in the basin. Subaerial exposure rapidly halted the carbonate production on the platform top, while a major input of shales (probably reflecting a climate change and/or lowering of the base level) is recorded in the basin, where shales onlap the slope of the previous carbonate system. The rebirth of the carbonate factory after subaerial exposure of the platform top is characterized by a different composition of the carbonate factory, probably reflecting changes of the environmental conditions. The step-by-step recording of the evolution of the carbonate system represents an unique opportunity to record a seismic-scale complete evolutionary cycle of a carbonate system in its different sub-environments, from the platform top to the basin.

KEY WORDS: Ladinian, carbonate platform, progradation, subaerial exposure, carbonate slopes

INTRODUCTION

The evolution of a carbonate succession can be subdivided in different stages, as episodes of platform growth can be separated by intervals reflecting reduced or absent carbonate production. The most important parameters which drive the evolution of a carbonate platform are changes in base level (i.e. Kendall & Schlager, 1981; Handford & Loucks; 1993), environmental conditions (e.g. climate, nutrients; Mutti & Hallock, 2003), and the type of the carbonate-producing organisms (as a response to biotic evolution; i.e. Pomar, 2001, 2008), whose interplay affects the efficiency of the carbonate factory as a whole and, eventually, the final geometry of the carbonate platform. The changes in these parameters drive the evolution of carbonate factories, from inception through demise and, in some cases, to the reprisal of a new carbonate factory, similar or different from the previous one.

The evolution from the inception to the demise and renewed return of carbonate production has been documented in subsurface settings and reconstructed by the integration of seismic and core/well data (e.g. Weber et al., 2003). The geometric architecture of these settings is generally well constrained. Nevertheless it is common that too little core data is available to obtain detailed information on the characteristics and distribution of the different carbonate facies and therefore it is difficult to create a large database of facies distribution and lithological-petrophysical characteristics. Well-preserved outcrop analogues which preserve the geometry of a complete evolution of carbonate systems are generally scarce and confined to a few well-known cases, randomly distributed in time and space. Therefore, the identification of new well-constrained examples is required to increase the understanding of the behaviour of carbonate systems having different ages, carbonate-producing biota and depositional settings. Favourable cases should honour a number of requirements, i.e.,

- 1 preservation of the original relationships among the different subenvironments (from platform top to the basin)
- 2 well-exposed geometry
- 3 preserved facies and microfacies
- 4 preserved relationships between deposits related to different evolutionary stages.

A further major point is related to the reconstruction of the interplay between sea-level changes and subsidence (i.e. creation of accommodation space) and carbonate production. The effects of this interplay can be unravelled only in select well-preserved settings.

One example of a carbonate system which fulfils all these requirements is preserved in the Upper Anisian to Lower Carnian succession of the Southern Alps of Lombardy (Middle Val Brembana-Pegherolo Massif, Northern Italy). It consists of a flat-topped, high-relief T-factory (*sensu* Schlager, 2003) platform with steep slopes, which formed after the drowning of the underlying Anisian platform. The evolution of this platform is characterized, after the nucleation stage, at first by aggradation and later by progradation and interfingering with basinal limestones. The top of this platform is marked by a regressive trend responsible for repeated subaerial exposures of the flat-topped platform and by the onlap of shales on the slopes, later followed by a rebirth of the carbonate factory. The geometry and facies distribution of this well-preserved carbonate system allowed us to: 1) reconstruct the relationships of the different facies assemblages in space and time, 2) describe the geometric evolution of a seismic-scale green-house carbonate platform, and 3) reconstruct the response of the carbonate factory to the changes in accommodation space.

GEOLOGICAL SETTING

The Late Anisian to Early Carnian succession of the Southern Alps is characterised by the presence of thick carbonate platform successions separated by basinal troughs and seaways onto which they prograde (Fig. 1). The carbonate system evolves from prevailing attached platforms to the west-south-west (Esino Limestone) to isolated platforms toward the north-east (Dolomites; e.g. Latemar Limestone, Marmolada Limestone, Sciliar Dolomite). In the Lombardy Basin (Fig. 1, 2) the succession (Assereto & Casati, 1965; Forcella & Jadoul, 2000) consists of Late Anisian basinal to peritidal facies ("peritidal dolomite" in Jadoul & Rossi, 1982; Camorelli Limestone in Berra et al., 2005) which, after drowning, are covered by a prograding carbonate platform (Esino Limestone) mainly represented by inner platform facies rimmed by narrow reefal and bioclastic margin facies. The reef facies laterally pass to thick bodies of slope breccias (Rossetti, 1967; Jadoul et al., 1992; Berra 2007) which interfinger with well-bedded resedimented basinal limestones and later with volcanoclastic arenites. In western Lombardy shallow-water facies prevail and basinal limestones were deposited in narrow seaways and troughs. Close to the end of the Ladinian, the basinal facies were generally overlain by shallow-water successions due to the progradation of the Esino Limestone carbonate platform. In the Lozio Basin (Berra, 2007), lower Val Camonica (Costa Volpino) and northern Pegherolo Massif the intraplatform basins persisted until the Carnian as platform progradation was not sufficient to completely fill these wider, open intraplatform basins (Fig. 2). In these areas, the flat-topped Esino Limestone platform reaches a maximum thickness of about 700-800m and rapidly pinches out basinward with steep slopes (about 35°) consisting of clinostratified deposits.

The Late Anisian-Early Carnian basinal succession (Balini et al., 2000), coeval with different stages of evolution of the Esino Limestone, begins with the deposition of marly limestones (Prezzo Limestone) and nodular cherty limestones (Buchenstein Fm.), covered by dark, bedded limestones (referred to by various local stratigraphic names). The calcareous basinal facies are mainly developed in the Grigna Massif (western Lombardy; Perledo-Varenna Limestone), Val Seriana, in the Pegherolo-Menna Massif and in the Concarena-Pizzo Camino Massif (where the basinal limestone is known as Pratotondo Limestone). Volcanoclastic sandstones (Wengen Formation) interfinger, in the widest basins and close to the toe-of-the-slope, with the dark-gray bedded limestone, more commonly in the eastern part of the Central Southern Alps. As the volcanic input is generally scarce in central-western Lombardy basin, the distinction between the pre-volcanic and post-volcanic platforms applied in the Dolomites is not applicable west of the Val Camonica. Where the basinal limestone are not covered by the prograding slope facies of the Esino Limestone (i.e. Pegherolo and Concarena Massifs), the sedimentation shifts to dark shales and siltstones (Carnian, Lozio Shale; Rossetti, 1967; Balini et al., 2000; Berra & Jadoul, 2002; Berra, 2007). In a previous work (Casati & Gnaccolini, 1967) all the silicilastic deposits of the basin facing the Pegherolo Massif were referred to as Wengen Formation. In this paper we separate, due to the different lithological associations, a lower siliciclastic unit consisting of alternating siltstones, shales and calcarenitic to micritic limestones time-equivalent to the Esino Limestone (Wengen Formation) to an upper siliciclastic unit (Lozio Shale) where shales and siltstones dominate and limestones are represented by carbonate mound or micritic layers, covering the slope facies of the Esino Limestone (Lozio Shale).

The overall stratigraphic characteristics of the succession resemble those of many Middle Triassic platform successions studied throughout the Southern Alps (e.g. the Dolomites: Bosellini 1984; Goldhammer et al., 1989; Bosellini & Stefani, 1991; Blendinger, 2001; Esino Limestone in the Lombardy Southern Alps: Assereto et al., 1977; Jadoul et al., 1992; Berra, 2007). Intense syndepositional tectonic activity is documented during the Ladinian in the Dolomites, whereas it is not recorded westward, in the Lombardy Basin. The platforms of the Dolomites (Marmolada Limestone, Latemar Limestone and Sciliar Dolomite; Bosellini, 1984; Bosellini & Stefani, 1991) are generally represented by partly isolated carbonate build-ups, whereas in the Lombardy basins the intraplatform seaways were narrower and most of the platform coalesced toward the south, becoming more similar to the Dolomites toward the north, where partly isolated platforms are present (Concarena, Pizzo Camino, Presolana, Pegherolo). Furthermore, sedimentary deposits in the seaways of the Dolomites include proximal volcanoclastics (including lava flows), which are relatively rare in the Lombardy Basin.

Close to the Ladinian-Carnian boundary, a major sea-level fall is recorded in the Lombardy Basin by a lithostratigraphic unit ("Calcare Rosso", Assereto et al., 1977; Assereto & Kendall, 1977; Assereto & Folk, 1977; 1980; Mutti, 1994; Berra, 2007) characterised by regressive deposits with evidence of subaerial exposures, covering the flat top of the carbonate platform of the Esino Limestone. The Calcare Rosso is thickest and well exposed in Middle Val Brembana, where it consists of up to 60 m of cyclic peritidal limestones characterized by prevailing supratidal facies and evidence of karstification associated with deposition of lenses of carbonate breccias, precipitation of early carbonate-cement and development of mature tepee and paleosols. Eastward (Val Seriana), the Calcare Rosso is represented by a few meters of red to grey paleosols and carbonate breccias, both related to superficial deposition and collapses of karst cavities. Locally, volcanic deposits are present at the top of the Esino Limestone. The subaerial exposure of the Ladinian platforms can be traced throughout the Lombardy Basin and probably all over the Southern Alps (Jadoul et al., 2002), but the precise dating is prevented by the absence of index fossils. Mutti (1994) interprets the Calcare Rosso as a complete third order sequence, bounded at the base and at the top by two major erosional surfaces that represent the sequence boundaries.

The fall in sea level occurring close to the Ladinian-Carnian boundary is well known in shallow-water carbonate platform settings of the western Southern Alps and can be related to a starvation episode in the basin (Berra, 2007).

STRATIGRAPHY

Geometry and facies distribution reflect the entire history of the evolution of the Late Ladinian-Early Carnian carbonate factory in the area between the Middle Val Brembana and the Pegherolo Massif (Lombardy Alps; Fig. 3), where a complete section from the southern to the northern side of the carbonate platform is preserved. The architecture of this carbonate system is described in terms of evolutionary stages: inception, growth, demise and "rebirth" of the carbonate factory.

PLATFORM INCEPTION (LATE ANISIAN, EARLIEST LADINIAN; LOWER ESINO LIMESTONE)

The demise of the Anisian carbonate platform (Angolo and Camorelli Limestone, Jadoul & Rossi, 1982; Berra et al., 2005) in the Lombardy Basin is marked by a sea-level fall (Gaetani et al., 1998) followed by a rapid marine transgression which leads to the deposition of dark, bedded marly limestones yielding a rich ammonoid fauna (Prezzo Limestone; Balini, 1992). This transgression is rapidly followed by the nucleation of a new carbonate system which persisted throughout the Ladinian. Nucleation occurred on relative highs where the Prezzo Limestone is thinner and rests on the peritidal carbonate facies of the Camorelli Limestone (Fig. 2). During the inception stage it is possible to identify bioclastic-rich margins ("Lumachella di Ghegna"; Tommasi, 1911; 1913) which document the first reef associations of the Esino Limestone platform. From these small highs (Fig. 4a), scattered in the Lombardy Basin, the carbonate factory spreads basinward, gradually enlarging its surface and the sites of carbonate production (Fig. 4). Observations in the inception area (Fig. 4b) provide an understanding of the evolution of the Esino Limestone in the initial stages. The observation of approximately 50 m of slope facies above the Prezzo Limestone suggest that this was the shelf to basin relief close to the nucleation highs (Fig. 4b). The massive, clinostratified slope facies are capped by bedded peritidal limestones which document the aggradation of the Ladinian platform (beginning of the growth stage) after the progradation related to the nucleation stage. A regressive stage in the lower part of the Esino Limestone is locally observed (Assereto et al., 1977). The platform inception is represented by the lower lithozone of the Esino Limestone (lithozone 2 of Jadoul et al., 1992, 50-60 m thick), which consists of well-bedded limestone and dolostones organized in peritidal cycles capped by stromatolitic beds, associated to tepees and dolomitized peritidal-supratidal layers. The regressive trend at the end of the inception stage probably favoured the definitive onset of the carbonate platform of the Esino Limestone, which predates platform aggradation recorded at the beginning of the following stage (platform growth).

PLATFORM GROWTH (LADINIAN; MIDDLE AND UPPER ESINO LIMESTONE)

Most of the Ladinian is characterized by the enlargement from the sites of nucleation of the Ladinian carbonate platform of the Esino Limestone toward the surrounding basinal domains, so that the Esino Limestone interfingers with and covers coeval basinal limestones (Perledo-Varenna Limestone) and carbonate-volcanoclastic deposits (Wengen Formation). The carbonate platform succession can be subdivided into three main facies associations which characterize all the Esino Limestone from the inception to its demise: inner platform facies, reef facies and slope facies (Fig. 5). The growth stage records a general trend characterized by decreased accommodation and increased progradation.

a) bedded to massive inner platform facies

Calcareous, light-coloured, thick-bedded, intra-bioclastic packstone, with dasycladaceans, crinoids and molluscans, oncolitic rudstone and stromatolitic bindstone characterize the inner platform facies. The facies associations in the inner platform (which reaches a total thickness of up to 700-800 m) defines two superimposed lithozones (Jadoul et al., 1992) which cover the lower lithozone (lithozone 2 of Jadoul et al., 1992; reflecting the platform inception stage). The two lithozones, from base to top, are:

middle lithozone of the Esino Limestone (lithozone 4 of Jadoul et al., 1992; 350 to 400 m thick), consisting of thick bedded prevailing subtidal limestones (mainly packstone and wackestone) rich in large oncoids, gastropods, bivalves and green algae, as well as intraclasts and peloids. Stromatolitic limestones are on average a few centimeteres thick and mark the top of shallowing upward cycles, each up to a few meters thick. The lower part of the cycles consists of subtidal thick-bedded to massive packstone and wackestone, capped by fenestral intraclastic-bioclastic packstone and/or stromatolites;

upper lithozone of the Esino Limestone (lithozone 6 of Jadoul et al., 1992; 150 to 350 m thick), consisting of bedded limestones organized in subtidal (characterized by abundant dasycladaceans) and peritidal facies, which are often associated with intertidal-supratidal structures, such as pisoids. The inter-supratidal beds are more common and generally thicker whereas cycles are thinner with respect to those of the underlying middle lithozone. These facies are commonly organized in shallowing-upward cycles whose thickness range from a few decimetres to about a metre. The top of this lithozone corresponds to the top of the Esino Limestone and is marked by a regressive unit with evidence of prolonged subaerial exposures (Calcare Rosso) such as erosional surfaces, collapse breccias, terra rossa deposits and paleosols (Vachè, 1966; Assereto et al., 1977).

The transition between the middle and upper lithozone is gradual. The three lithozones of the Esino Limestone (lower, platform inception stage, and middle and upper, platform growth stage) are present only in the area of nucleation of the Ladinian platform. From these nucleation zones the platform laterally evolves to coeval basinal facies.

The inner platform facies become massive close to the reef area (Fig. 5), where deposition of a large belt (several tens of meters in lateral width) of thick-bedded, bioclastic rudstone to floatstone with crinoids, bivalves and brachiopod occurred. These facies define the belt of higher-energy deposits close to the reef belt. This change in aspect and composition is ascribed to the increased energy of the environment (i.e. effect of storms, tidal channels) and to the bioclastic contribution of the peri-recifal zone. This high-energy deposits are characterised, close to the reef facies of the southern margin of the platform (Val Parina), by the presence of lenses of bioclastic limestones rich in open sea biota (ammonoids and pelagic bivalves) and different brachiopods, which allowed for a good dating of the succession (Jadoul et a., 1992; Fantini Sestini, 1994; Torti & Angiolini, 1997). Biostratigraphic data indicate that the deposition of the Esino Limestone occurred between late Anisian and, at least, Late Ladinian above the inception area, whereas it is possible that the progradation of the Pegherolo Platform lasted until early Carnian, as demonstrated by Balini et al (2000) for the Esino Limestone to the East (Lozio Basin).

The cyclic organization of the inner platform facies in the middle and upper lithozones is different,. The inner platform facies are invariantly organized in shallowing upward cycles characterized by a subtidal lower part capped by stromatolitic bindstones with a fenestral fabric, but the average thickness of the cycles decreases from the lower part (aggrading stage, middle Lithozone) to the upper part (prograding stage, upper Lithozone), from an average of about 1 m to about 0.3 m. The reduction of the cycle thickness from the middle to the upper lithozone suggests a gradually decreasing accommodation from the beginning to the end of the deposition of the Esino Limestone.

b) Massive reefal limestones

The inner platform facies are bordered by a reef belt consisting of massive light-gray limestones. The reef facies (lithozones 3 and 5 of Jadoul et al., 1992) are mainly characterized by massive limestones and patch reefs with metre-size coral framestones with calcisponges and intrabiolcastic packstone associated with *Tubiphytes* and microbial mounds (several meters in diameter; Fig. 5), which also colonize the upper part of the slope. The reefal facies are characterized by a pervasive network of cavities (decimetric to metric) partially or completely filled with isopachous grey to dark gray marine cements (fibrous radial calcite) associated with microbial coatings. These cavities (typically referred to as “evinosponge”, a term introduced by Stoppani, 1858, in the Esino Limestone), previously interpreted as karst-related (Jadoul & Frisia, 1988), have been reinterpreted as reef cavities partially or totally filled by marine isopachous calcite cements (Frisia-Bruni et al., 1989) enveloping microbial crusts (Russo et al., 2006). Similar cavities characterize all the reefal and slope facies of the Ladinian platform in the Western Tethys. The original porosity of the reef facies was very high (up to 45%) as documented by the abundance of cements and internal sediments in the intergranular porosity. Cathodoluminescence and isotope geochemistry (Frisia-Bruni et al., 1989) indicate an early marine origin for these cements.

The reef belt is generally narrow and both the boundaries with the inner platform and slope facies are rapid. Massive reefal limestone can be observed in detail on the southern margin (Middle Val Brembana) whereas toward the north (Mt. Pegherolo) the outcrop conditions do not allow a detailed description of the reef associations (only coral and *Tubiphytes*-bearing limestone are observed; Fig, 5. 6).

Along the southern margin, the reef facies of the Esino Limestone are unconformably covered by the Calcare Rosso. The reef is dominated by mounds (up to 3-4 m high) containing Problematica, calcisponges and Tubiphytes. Corals are relatively rare. The transition with the upper slope is gradual and defined by the decrease in *in-situ* microbial-Tubiphytes associations and the presence of massive breccias with clasts and boulders derived mainly from the reef and upper slope. The abundant early isopachous marine cements filling different types of cavities (both intragranular and intergranular) in the reef and upper slope facies suggests stabilization of the sediments rapidly after deposition, as observed on the slopes of Great Bahama Bank where rapid pervasive cementation occurred in a few hundreds years after deposition (Grammer et al., 1993).

The trajectory of the narrow reef belt is clearly highlighted by the rapid transition from the bedded inner platform facies to the massive, clinostratified slope breccias, which build most of the prograding platform. The reef trajectory of the northern margin of the Pegherolo Massif (Fig. 2) describes two different stages: a first stage where aggradation and progradation are roughly balanced (aggradation/progradation ratio ≈ 1) and a second stage where progradation prevails (aggradation/progradation ratio << 1). The reef defines a narrow climbing belt during the deposition of the middle lithozone, whereas it develops as a time-transgressive, low-angle to sub-horizontal lithozone which marks the toplap surfaces of the slope clinoforms during the deposition of the upper lithozone. This geometry results from the stratigraphic balance between accommodation space and carbonate production. *In situ* reef facies are volumetrically reduced in the Esino Limestone, but reef facies are often recognized as clasts within the slope breccias. This fact suggests that early cementation of the reefal facies and the existence of steep slopes likely favored frequent platform-margin collapse events that fed most of the slope breccias. The presence of early fractures along the slope of the Esino Limestone (Berra & Carminati, submitted), as observed in other early-cemented high-relief platforms (e.g. Frost & Kerans, 2009), further facilitated margin collapses.

c) Slope breccias

The narrow reef belt is bordered basinward by slope deposits, represented by a monotonous succession of massive to crudely bedded, clinostratified, clast-supported intraformational breccia deposits (Fig. 5). Cavities partially or totally filled by isopachous fibrous and botryoidal cements are larger and more common in the upper slope. The maximum size of clasts often exceeds two metres and the average size is centimetric to decimetric. The constant presence of cements in the intergranular voids between the clasts documents the scarcity of fine-grained sediments. When the cavities are not completely filled by cements, laminated internal sediments are present. The presence of ostracods in these laminated internal sediments (which fill the nuclei of the cavities remaining after the precipitation of the isopachous fibrous cements) demonstrate the early syndepositional origin of the cement, confirming geochemical analyses (Frisia-Bruni et al., 1989). The precipitation of these cements was followed by the deposition of the sediments containing ostracods, indicating that the network cavity was still connected with the sea-floor after the first stage of cement deposition. These data support the importance of the early marine carbonate cementation along the submerged slope of the Esino Limestone, as observed in other carbonate platforms (e.g. Grammer et al., 1993; Van Der Kooij et al., 2010). The fact that several clasts derived from the reef and upper slope consist of fine-grained sediments (grainstone/packstone) as well as microbial carbonates and that mud in the intergranular voids of the breccias is generally absent, furthermore supports the important role of the early-diagenetic marine processes (cementation/lithification) able to harden the reef and upper slope facies before the collapse event which generated the breccia bodies. Fine-grained sediment locally fills the intergranular space at the lower slope. In the studied successions clasts are intraformational and generally derive from reef-upper slope facies, as documented by the common occurrence of clasts with *Tubiphytes* bafflestones and coral framestones, together with coarse bioclastic packstone (often yielding gastropods and bivalves). Microbialites and clasts consisting of automicrite are also present, suggesting a contribution to the carbonate factory of the slope itself (slope shedding, Kenter et al., 2005), as observed in other Ladinian platform of the Western Tethys (Keim & Schlager, 1999).

Between the different episodes of breccia deposition, evidence of reduced sedimentation is suggested by thin microbial and automicrite layers or, typically during the aggradational stage, by centimetric to decimetric lenses of pelagic daonellid bivalves (Fig. 5). These low-sedimentation layers mark the faint clinostratified bedding in the prograding slope facies. The grain size of the breccias decreases from the upper slope to the toe of the slope and locally it is possible to observe a crude fining upward trend within a single clinostratified depositional event. The collapse events of the reef and upper slope produced mainly coarse clast-supported breccias and consequently the breccias bodies at the toe of the slope rapidly pinch out. These features, along with the heterogeneous composition of the clasts, their lithofacies and the high-angle of depositional surfaces (increasing, during the progradation, from some 25° at the upper slope to about 35° a dip which lasts for most of the progradational stage; Fig. 3) fit a model for their origin of accumulation of coarse, non-cohesive and (almost) mud-free sediments (Kenter, 1990; Harris, 1994) produced by falls of unstable portions of the upper slope and reef belt, as observed in several platforms in the geological record, both in outcrop and subsurface (Kenter et al., 2005; 2010; Collins et al; 2006) . According to the present-day difference in altitude between the distal part of the slope facies and the platform top, basinal paleowater depths reach their maximum (about 500-550 m) during the progradation stage.

d) Basinal facies

The transition from the slope facies to the basinal succession is marked by the pinch out of the clinostratified slope breccias within dark, well-bedded fine-grained calcarenites, mudstones and sandstones-siltstones that characterize the sedimentation in the open basin facing the carbonate platform. The distal part of the clinoforms (mainly consisting of light-gray calcirudites in decimetric beds) is characterized by a lower angle with respect to the middle-upper part of the slope (Fig. 4c). Whereas the slope deposits are similar during all the evolution of the Esino Limestone, the lithology of the basinal deposits changes through time, so that the slope breccia deposits interfinger with and rest on different lithostratigraphic units during the evolution of the carbonate system (Fig. 7). In the first stage the massive slope breccias cover the marly calcilutites of the Prezzo Limestone and later interfinger with up to 20 m of the planar to nodular cherty limestones (yielding ammonoids and rich in sponge spiculae, radiolarians and locally fishes; Tintori, personal comm.) with thin tufitic layers (Buchenstein Fm.). During the Ladinian the cherty basinal facies are substituted by dark, laminated, intraclastic packstones (Perledo-Varenna Fm.), in planar thin beds (average thickness around 10–20 cm, only rarely massive beds occur) commonly showing normal grading. Composition and sedimentary structures indicate that the bedded calcareous deposits of this unit were mainly resedimented from the shallow part of the carbonate factory. The dark colour as well as the presence of well-preserved laminations and scarce burrowings indicates that the sea-bottom was from anoxic to dysoxic. The carbonate deposits of the Perledo-Varenna Limestone are thicker close to the toe of the prograding slope facies and thin out basinward, suggesting that they built a toe-of-the-slope fan which interfingered with the slope breccias. Locally, intraformational paraconglomerate beds up to a few decimetres thick as well as slump overfolds and cm-thick layers of clast supported slope breccias with centimetric clasts occur. Locally the Perledo Varenna interfingers with or is substituted by the Wengen Formation (consisting of sandy to shaly volcanoclastic deposits alternating with thin-bedded resedimented limestones), which records the clastic input from the erosion of volcanic edifices at the border of the basin or locally submarine volcanic activity (Jadoul & Rossi, 1982). The transition between the two units is gradual. Clastic input is clearly coeval with the progradation of the Esino Limestone, as the Wengen Formation interfingers with the slope breccias of the Esino Limestone, mainly north of the Pegherolo Massif (Fig. 7)

The evolution of the basinal sedimentation reflects different evolutionary stages. The abundance of pelagic organisms and calcilutites suggests a reduced efficiency of the carbonate platform in exporting sediments basinward at the time of the deposition of the Buchenstein Formation. Facies associations in the overlying Perledo-Varenna Limestone reflect an increase in the sediment delivery from the platform toward the basin. The changes in depositional rates and facies assemblages of the basinal succession can therefore be framed within the overall evolutionary trend of the Esino platform, characterized by a first stage of aggradation stage (with reduced progradation and sediment delivery) followed by a major progradation pulse (which persisted until the demise of the Esino Limestone).

PLATFORM DEMISE (EARLIEST CARNIAN?)

The deposition of the Esino Limestone came to a sudden end close to the Ladinian-Carnian boundary throughout the Lombardy Basin (Assereto et al., 1977; Jadoul & Rossi, 1982; Gaetani et al., 1998) with the end of the progradational stage (Berra, 2007). The end of the Ladinian carbonate system (Esino Limestone) is recorded by different facies assemblages either at the platform top or at the slope.

a) Platform top

The platform demise is well-recorded at the top of the Esino Limestone in middle Val Brembana. The massive reef facies are unconformably capped by bedded peritidal-supratidal limestones (Fig. 8). The unconformity at the top of the Esino Limestone (Assereto et al., 1977) consists of a subaerial exposure surface with evidence of paleokarst and carbonate dissolution. Paleosols and vadose cements are also present. This erosional surface is locally associated with sedimentary dykes which cut into the underlying reef facies for a depth of about 5-10 meters, associated with a network of cavities filled by early cements and internal sediments. The dykes are filled with reddish and marly limestones. The Calcare Rosso facies, overlying the unconformity surface, show rapid lateral changes, both in facies association and thickness. On the southern margin of the studied Esino Limestone platform (middle Val Brembana), bedded peritidal-supratidal limestones cover the Esino Limestone and several erosional surfaces (often associated with paleosols) are present within the Calcare Rosso, that reaches a thickness of about 60 m. Tepee structures (Assereto & Kendall, 1977) which alternate with red marls are common. Above the prograding part of the Esino Limestone (north of the Pegherolo Mt.) the boundary between the Esino Limestone and the “Calcare Rosso” is not well defined and paleosols are less frequent in peritidal sediments of the Calcare Rosso (about 50 m thick) with respect to the southern margin. The thickness of the Calcare Rosso decreases to a few meters (3-5 m) above the inner platform facies of the Esino Limestone (i.e. in correspondence to the nucleation zones of the Esino Limestone), where the regressive facies are represented by intraformational residual breccias and reddish pelites. Data from the platform top (where the toplap of the prograding slope breccias occurred) suggest that the demise of the Esino Limestone carbonate platform can be ascribed to a rapid sea-level fall, which changed the environmental conditions, thus reducing the efficiency of the carbonate factory, as observed in other coeval carbonate platforms in the Lombardy Basin (Berra, 2007). The “Calcare Rosso” thus reflects the changes in the carbonate production on the platform top, triggered by a regressive trend at the top of the Esino Limestone (Assereto & Kendall, 1977; Assereto et al., 1977; Mutti, 1992; Gaetani et al., 1998; Berra, 2007).

b) Slope and basin

The change in sedimentation and environment on the platform top has a counterpart in the basin and along the slope. The open basinal setting is only partly preserved in the study area due to Alpine tectonics, whereas the shelf-break is eroded. Nevertheless it is possible to follow the effect of the change along the middle-lower slope (Fig. 9). The slope facies, mainly represented by a monotonous massive unit consisting of reef-derived early-cemented breccias, continuously prograde for about 4 km to the north. The end of the progradation is marked by the onlap of shales with intercalation of siltstones (Lozio Shale), which unconformably rest on the last pulses of progradation of the Esino Limestone carbonate platform (Fig. 9). Poor outcrop prevents the determination of whether the onlap surface postdates the deposition of the last breccia event or if a last event of breccia deposition occurred after the beginning of the deposition of the shales. Despite this uncertainty, it is possible to consider the end of the deposition of the slope breccias as rapid, occurring immediately before or during the first period of deposition of the Lozio Shale. The onlap surface is well exposed at different paleodepth, determined by geometric constraints from the position of the toplap surface of the prograding wedge: about 350-400 m at the Valleve Quarry and 250-300 m at Monte Cavallo. These geometric constraints indicate at least 450-550 meters of relief from the shelf to basin at the end of the progradation of the carbonate platform. The clast-supported slope breccias, with clasts up to 1 m in size (Fig. 9c) are directly onlapped, in the lower slope, by shales, which mantle the irregular top surface of the slope breccias. The present-day angle between the platform slope and the shales is on average around 25°. As basinal sediments, originally deposited roughly horizontally, commonly dip towards the basin due to differential compaction when they onlap former slopes (Carminati & Santantonio; 2005), it is possible to reconstruct an original angle between the originally horizontal shales and the carbonate slope slightly higher, around 30-35° (Fig. 9b). This angle is compatible with the obtained dip of about 35° for the slope as deduced from geometric constraints. The contact between the breccia clasts and the shales (Fig. 9) is sharp and marked by pyrite, Fe-rich crust and hard-grounds, which supports the existence of a significant hiatus on this onlap surface. The onlapping shales do not contains clasts of the slope facies of the Esino Limestone, suggesting that the process of breccia production decreased rapidly, with the onlap of the Lozio Shale. In the middle slope, between the Lozio Shale and the typical slope breccias of the Esino Limestone it is possible to observe the presence of a thin (up to 3 m thick) drape of dark, muddy calcareous slope breccias, that pinches out both basinward and toward the upper slope (Fig. 10). Within the Lozio Shale asymmetrical ripple marks rarely occur. The position of these structures with respect to the top of the Esino Limestone indicate a paleo-water depth of at least 200 m (deeper than the expected storm-weather wave base) supporting an origin related to the existence of bottom currents or to deposition related to muddy turbidity currents rather than waves.

Burrowing in the Lozio Shale is generally reduced and limited to a few layers, pointing to prevailing dysoxic conditions. Carbonate sedimentation during the first stages of deposition of the Lozio Shale is extremely reduced and consists of dark mudstone lenses embedded in the Lozio Shale, thus recording the presence of a less-efficient and partly different carbonate factory, which exported a reduced amount of carbonates during the deposition of the Lozio Shale. The composition and texture of these limestone reflect a change in the nature of the carbonate factory after the progradation of the Esino Limestone. Clasts from these dark muddy limestones are also present in mud-supported deposits which locally intercalate within the shale (Fig. 10). The thickness of these intraformational breccia layers generally ranges from about half a meters (close to the slope of the Esino Limestone) to a few centimeters toward the basin. In the more basinal domain the Lozio Shale directly covers the Perledo-Varenna Limestone (Valleve Quarry): the transition between the two units is rapid, marked by about 5 meters of intercalating shales and limestone.

Within the shales quartz-rich siltstones intercalate. This facies suggests the erosion of a distal continental basement, supporting the possible origin from the European continent of the clastic material delivered in the northern part of the Lombardy Basin, as suggested by Berra & Jadoul (2002). Toward the south, the deposition of the Lozio Shale did not occur, as the carbonate highs probably prevented the delivery of shales toward the south. Here, the clastic input during the Carnian is dominated by volcanoclastic deposits (Val Sabbia Sandstone) which were fed from south by the Southern Mobile Belt of Brusca et al. (1981).

The sharp contact between Esino Limestone and Lozio Shale at the slope of the platform, the rapid transition between Perledo-Varenna Limestone and Lozio Shale and the presence of the thin carbonate unit between Esino Limestone and Lozio Shale in the middle slope suggest a relatively rapid switch-off of the carbonate input in the basin, ascribed to the decreased productivity on the subaerially-exposed platform top.

PLATFORM REBIRTH (EARLY CARNIAN)

The exposure of the platform top, marked by a reduction in the efficiency of the carbonate factory, is followed by a gradual reprise of the carbonate production. The physiographic setting of the basin has changed and the shelf to basin relief is reduced, due to the deposition of the Lozio Shale, which grasually fills the intraplatform basin. The creation of accommodation space on the platform top and the rebirth of the carbonate factory is recorded by the deposition of cyclic peritidal limestone (Breno Formation), whereas a gradual increase of carbonates in the Lozio Shale can be envisaged in the basin, mainly close to the former slopes of the Esino Limestone.

a) Platform top

After the subaerial exposure of the platform top and the deposition of the different facies of the Calcare Rosso, a reprise of the carbonate production is recorded by the deposition, on the flat top of the Esino Limestone, of cyclic peritidal limestones (Breno Limestone). In the Pegherolo Massif the thickness of the Breno Fm. is roughly constant (about 70 m), whereas toward the south (Middle Val Brembana) the thickness generally increases (as observed for the underlying Calcare Rosso; Assereto et al., 1977)

Peritidal cycles of the Breno Formation are characterized by an intertidal-supratidal part more developed with respect to the Esino Limestone (Assereto et al., 1977). This facies association suggests that sediment production overpasses the creation of accommodation space. A general drowning of the Breno Limestone is recorded by the transition to subtidal facies with marly intercalations of the overlying Calcare Metallifero Bergamasco which gradually evolves in the Gorno Formation (Casati & Gnaccolini, 1967; Assereto et al, 1977).

b) **Slope**

Carbonate sedimentation at the slope is recorded by the presence of the fine-grained muddy limestone beds which intercalate with dark shales on the lower slope (Fig. 11). In the middle-upper slope the first evidence of in-situ carbonate production is recorded by meter-thick carbonate mounds alternating and interfingering with dark shales. These low-relief mounds reach a few tens of meters in width and 0.5 to 3 m in height. Lithologically, they consist of fine-grained limestones (mainly wackestone) containing calcisponges, gastropods, crinoids, corals (both solitary and colonial) and problematica. Calcimicrobes have been observed in thin sections (Fig. 11). The mounds generally grow close to the slope of the Esino Limestone and pinches out in the shales that onlap the slope. Laterally to the mounds, intraformational breccias supported by a matrix of shales and marls with carbonate clasts derived from the mounds are present. The clasts generally show soft-sediment deformations, suggesting that they were not lithified at the time of deposition. Transport and selection of the clasts is reduced and the low-relief mounds laterally pass to mound-derived breccias.

DISCUSSION

The depositional architecture of the Late Anisian to Carnian succession of the Pegherolo Massif-middle Val Brembana reflects a coherent stratigraphic evolution, consisting of different stages, related to changes in the creation of the accommodation space and in carbonate productivity (Tab. 1). The onset of the carbonate factory in the Late Anisian postdates a major sea-level rise documented by the drowning of the shallow-water carbonate factory of the Camorelli Limestone (Jadoul & Rossi, 1982; Gaetani et al., 1998; Berra et al., 2005) and the deposition of the basinal, ammonoid-brearing Prezzo Limestone. The beginning of the deposition of the Esino Limestone on relative highs (where the Prezzo Limestone is thinnest or, locally, absent) is characterized by a progradation of slope facies toward a basin with reduced water depth (some 50 m, Fig. 4b). As short term, frequent subaerial exposures are observed in the Lower Lithozone of the Esino Limestone, we suggest that the creation of accommodation space was reduced during this first stage. The transition to the aggrading stage (middle lithozone) suggests an increased creation of accommodation space on the platform top (Fig. 2).

In the inner platform area, the reduced bed and cycle thickness in the Upper Lithozone points to a decrease of the rate of creation of space for sediment storage. At this time, the aggradation/progradation ratio decreases and a rapid progradation of slope facies, consisting of coarse calcareous breccias, is observed. The origin of the Ladinian slope breccias is still matter of debate. In some of the coeval Ladinian platform deposits of the Dolomites, clinostratified deposits on build-up flanks contain lenses of breccias produced in situ by translational sliding and fragmentation of automicrite in early diagenetic stages, with displacive growth of fibrous calcite cements (Blendinger, 2001). The internal organization of the slope breccias at Monte Pegherolo, enriched in reef-derived facies, suggests deposition from mass flows which were probably triggered by submarine rock falls (probably generated when the reef margin became too steep and/or during severe storms) leading to the progradation of the platform. Slope instability appears to be related to oversteepening of the margin due to high growth rates of the reef dwelling organisms as no evidence of significant, persistent tectonic activity is recorded. A similar origin of the slope breccias has been suggested for the coeval facies of the Latemar and Rosengartner-Catinaccio platforms in the Dolomites (Harris, 1994; Maurer, 2000), for the Concarena platform (Berra, 2007) and for the Carboniferous platforms of western Kazakhstan (Tengiz oil field, Weber et al., 2003; Collins et al., 2006; Kenter et al., 2010).

A decrease in the rate of creation of accommodation space on the platform top during the progradation stage is confirmed by a seismic-scale toplap geometry of the prograding clinostratified breccias, which indicates that the sediments produced on the platform top and reef were exported basinward as reduced space was available for sediment storage on the flat-topped prograding platform. The effect of the changes in rate of creation of accommodation space in the different evolutionary stages of the Esino Limestone on the platform top is mirrored in the basin (Tab. 1). The stage of platform inception (lower lithofacies) and the prevailing aggradation stage (thick inner platform cycles and prevailing aggradation of the slope facies; middle lithozone of Jadoul et al., 1992) likely correspond to the deposition of the units characterized by low sedimentation rates (Prezzo Lst. and Buchenstein Fm.), whereas the progradation stage is recorded in the basin by thick resedimented limestones (Perledo-Varenna Fm.; Fig. 7). The local and episodic volcanoclastic input (Wengen Fm.) probably reflects volcanic activity in the surrounding of the depositional basin, with a probable input from N-NE. The increased basinal delivery of limestone is ascribed to the decreased accommodation space for sediment storage on the platform top.

The end of the breccia production and slope progradation is related to the subaerial exposure of the platform top, marked by karst surfaces, paleosols and terra rossa deposits (Calcare Rosso). The subaerial exposure switched off the production of breccias and marked the end of the progradation, as documented in other coeval platform in the Lombardy Basin (Berra, 2007). The changes in thickness and facies of the Calcare Rosso from the core of the Esino Limestone platform to its rims (Assereto et al., 1977; Jadoul et al., 1992) reflect changes in accommodation space, which are ascribed to a different subsidence in the different part of the carbonate system. A higher subsidence is documented at the prograding part of the platform with respect to the inner platform which rests upon the nucleation area. The difference in subsidence, reflected by thickness and facies changes of the Calcare Rosso from the rims of the Ladinian Esino Limestone at the end of the progradation (about 60 m thick) to the innermost part of the platform (thickness reduced to a few meters), can be explained by syndepositional tectonics or by compaction-driven subsidence. As evidence of tectonic activity (e.g. sharp thickness and facies changes) are missing, the cause of the observed differential subsidence can be ascribed to the variation in thickness of the basinal units (Prezzo Limestone, Buchestein Fm., Perledo-Varenna Limestone, Wengen Fm.) which underlie the Esino Limestone. In the core of the platform the basinal facies are reduced to 5-20 m of marly limestones (Prezzo Limestone), whereas below the last prograding clinoforms at least 150-200 m of fine-grained basinal limestones are preserved (Prezzo Fm., Buchenstein Fm., Wengen Fm., Perledo-Varenna Fm.). The presence of thick basinal facies may explain the higher subsidence on the outer part of the platform, due to the compaction of the basinal sediments, which increase their thickness (and, thus, produce a higher total compaction) from the core of the platform to its rims (Doglioni and Goldhammer 1988; Berra &, Carminati, submitted).

In the basinal succession a partial interfingering of the Lozio Shale with the uppermost part of the Perledo-Varenna Limestone (about 5 m of transition between the two units) is observed, suggesting that the crisis of the carbonate factory occurred simultaneously with the beginning of the input of shales. The input of shale, rarely with fine sandstone intercalations, can be ascribed to a progradation of deltaic bodies from north, due to a lowering of the base level and/or to a change in the climate conditions on the European margin, with increased rainfall and higher delivery of shales (Berra & Jadoul, 2002). The importance of climate change in controlling the delivery of shales in marginal basins at specific latitudes has been documented by Perlmutter & Mattews (1989) and observed in the Southern Alps and Austroalpine close to the Norian-Rhaetian boundary, where a major input of shales postdates the final crisis of the Dolomia Principale/Hauptdolomit carbonate platform (Berra et al., 2010). The deposition of the Lozio Shale is responsible for the filling of the intraplatform basin by fine-grained siliciclastics, with a gradual reduction of the paleo-water depth. Sediment delivery from the platform top is reduced to absent, as only thin and muddy fine-grained carbonates intercalate in the Lozio Shale, whereas carbonate mounds develop in the shales close to the upper slope of the previous platform (Esino Limestone). The mounds of the Lozio Shale indicate that, after the crisis of the carbonate platform of the Esino Limestone, the reprise of carbonate production is related to a different type of carbonate factory. Laterally, these mounds evolve to thin lenses of mound-derived breccias. The sedimentological features of these breccias document that the processes that controlled their deposition were different from those that produced the mud-free breccias of the prograding slopes of the Esino Limestone (Fig. 10). The abundance of mud suggests that these mounds grew in quiet water, likely below fair weather wave base. The presence of coral colonies and calcimicrobes such as *Cayeuxia* (Fig. 11) suggests that deposition probably occurred above the base of the photic zone, when the basin was partly filled by shales.

The decreased carbonate input in the basin reflects a reduced production on the platform top, which likely corresponds to the deposition of the Calcare Rosso, when dissolution phenomena and long periods of subaerial exposure highly reduced the efficiency in exporting sediments of the carbonate factory. Furthermore, the input of shales likely increased the quantity of nutrients in the sea-water, probably reducing the efficiency of the carbonate factory.

The complex geometry preserved in the prograding platform of the Middle Val Brembana and Pegherolo Massif can be interpreted in term of chronostratigraphic evolution. A possible, qualitative chronostratigraphic reconstruction of the Pegherolo massif is presented. In the proposed reconstruction (Fig. 12), it is possible to define the different distribution of sediments in the two major stages in the platform growth, one characterized by a higher aggradation/progradation ratio followed by a second one where the progradation is much more higher. Due to the decrease of the accommodation space on the platform top, the inner platform facies halt their deposition whereas the progradation of the reef and the slope facies continues basinward, creating a time-transgressive deposition of the slope facies when accommodation on the platform top ceased.

Out data indicate that carbonate production, controlled by “health” and “size” of the carbonate factory, sharply decreased due to the co-occurrence of subaerial exposure of the platform top (creating a hiatus on the platform top, documented by the abundant paleosols and by the early-diagenetic history of and supratidal facies of the “Calcare Rosso”) and input of shales (possibly responsible for the increase of nutrients). The shutting down of the carbonate factory of the Esino Limestone and a shift to a different carbonate factory is recorded at the slope by the development of muddy mounds and by the absence of reef-derived breccias which dominate in the prograding slope of the Esino Limestone.

CONCLUSION

The geometry and facies distribution of the Late Anisian-Early Carnian succession of the Middle Val Brembana-Pegherolo Massif indicate that the evolution of the studied carbonate systems is driven by the interplay between changes in accommodation space and in the nature of the carbonate factory. Whereas the nucleation of a carbonate systems highly relies on the original morphology of the basin, the nature of the carbonate factory plays the major role in the development of the final architecture of carbonate systems. If the efficiency and composition of a carbonate factory is roughly constant, the shift from different depositional architecture (i.e. aggradational vs. progradational as in the case of the Pegherolo Massif) is exclusively controlled by 1) the changes in the base level and 2) the size of the carbonate factory. These changes do not control only the geometry of the platform but also the amount of sediment which is exported basinward, as recorded by the basinal successions. Major changes in the carbonate factory are instead triggered by environmental changes. In the studied succession, the shutting down of the Esino Limestone carbonate factory is due to a sea-level fall which is responsible for the exposure of the platform top. The effect of this exposure (which reduced significantly the area of the carbonate factory) on the crisis of the carbonate factory was probably enhanced by the coeval input of a large amount of shales which likely affected the composition of the sea-water (e.g. increased nutrients), further reducing the efficiency of the carbonate factory. The interplay between reduced productivity area and changes in the environmental conditions were efficient in shifting carbonate productivity from a flat-topped, high-relief platform with early-cemented reefs which fed the slope breccias to a new factory (different for facies, volume and composition of the reef assemblages) represented by muddy, low-energy mounds.

The opportunity to observe different superimposed carbonate depositional systems preserved from inner platform to basin is not common in outcrop. The Ladinian succession of the Middle Val Brembana-Pegherolo Massif represents a favorable example which can give important indications on the way a high-relief, flat-topped carbonate factory reacts to changes in base level and in environmental conditions.

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FIGURES

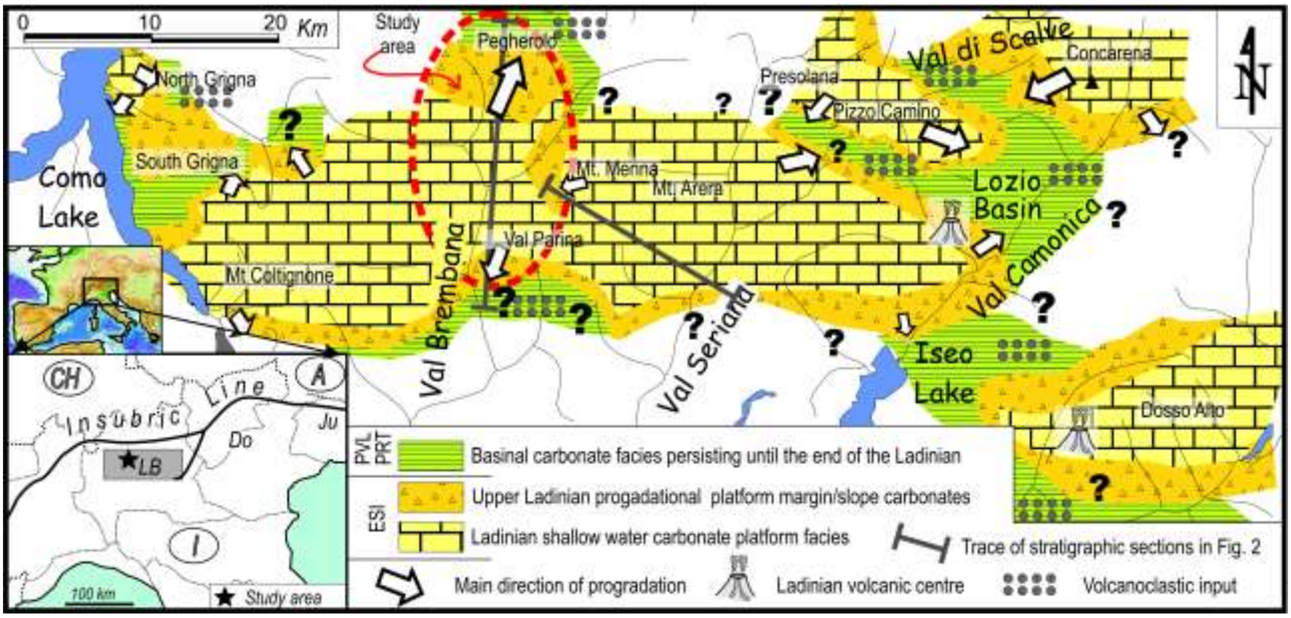

Fig. 1 – Paleogeographic distribution of the carbonate highs and intraplatform basins in the Lombardy Basin at the end of the deposition of the Esino Limestone. In the inset: LB: Lombardy Basin; Do: Dolomites; Ju: Julian Alps

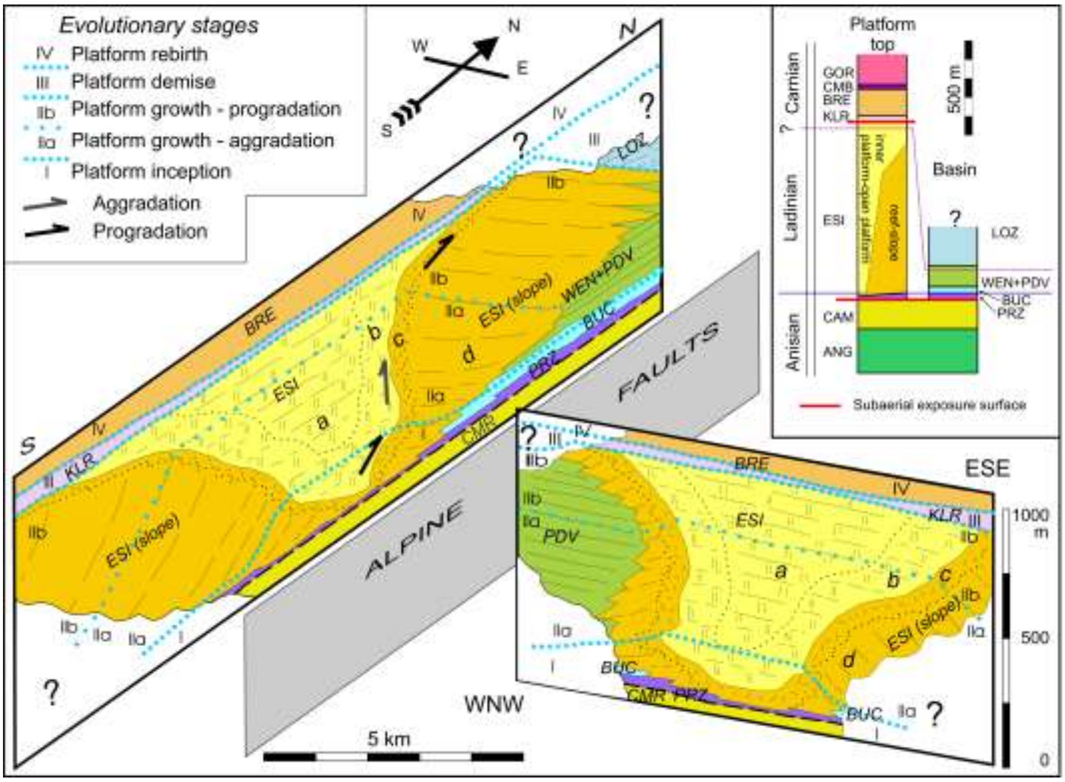

Fig. 2 – Schematic facies distribution along two stratigraphic sections across the study area (Pegherolo Massif – Middle Val Brembana). The trace of the stratigraphic sections is indicated in Fig. 1. On the top right, a simplified stratigraphic diagram summarizes the stratigraphy in basinal (right) and platform top (left) settings. ANG: Angolo Limestone; CAM: Camorelli Limestone; PRZ: Prezzo Limestone; BUC: Buchenstein Fm.; PDV: Perledo-Varenna Limestone; WEN: Wengen Formation; ESI: Esino Limestone, consisting of: a) bedded inner platform facies; b) massive bioclastic facies (open platform); c) reef belt; d) slope breccias; KLR: Calcare Rosso; LOZ: Lozio Shale; BRE: Breno Formation; CMB: Calcare Metallifero Bergamasco; GOR: Gorno Formation.

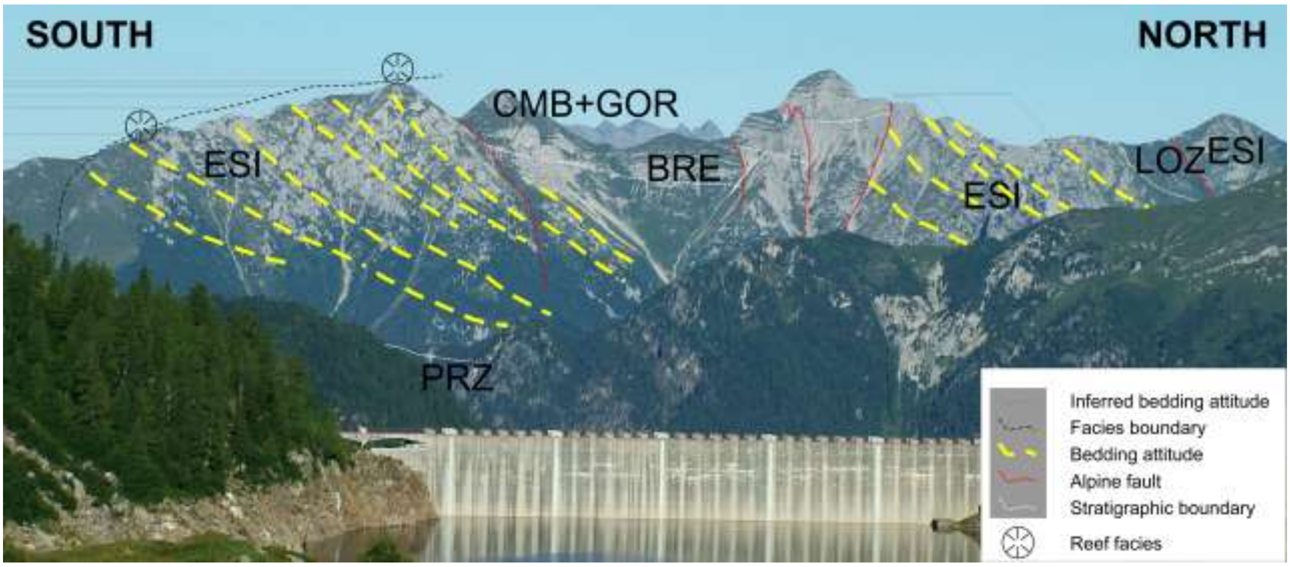

Fig. 3 – Panoramic view of the prograding platform of the Pegherolo Massif from East.

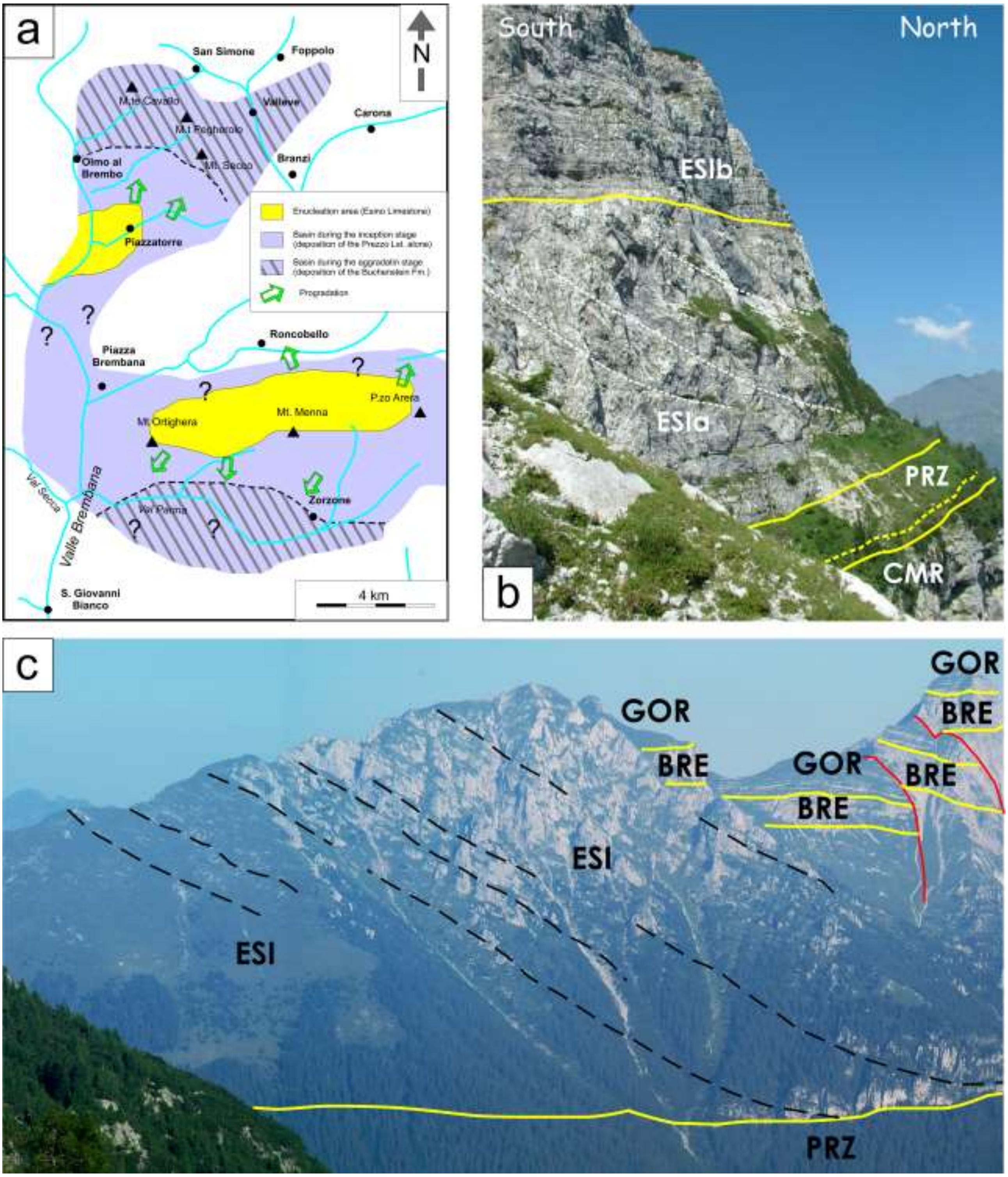

Fig. 4 – Paleogeography and stratigraphic setting of the Esino Limestone during the deposition of the lower lithozone: a) paleogeographic reconstruction of the enucleation areas of the Esino Limestone, with the distribution of the surrounding basinal facies (the distribution of the Buchenstein Fm., corresponding to the aggradation stage is indicated); b) geometry of the basal part of the Esino Limestone prograding from the nucleation area (northern Arera Mt.); c) view or the southernmost part of the Pegherolo Massif, with the geometry of the aggrading stage, immediately predating the major progradation of the platform.

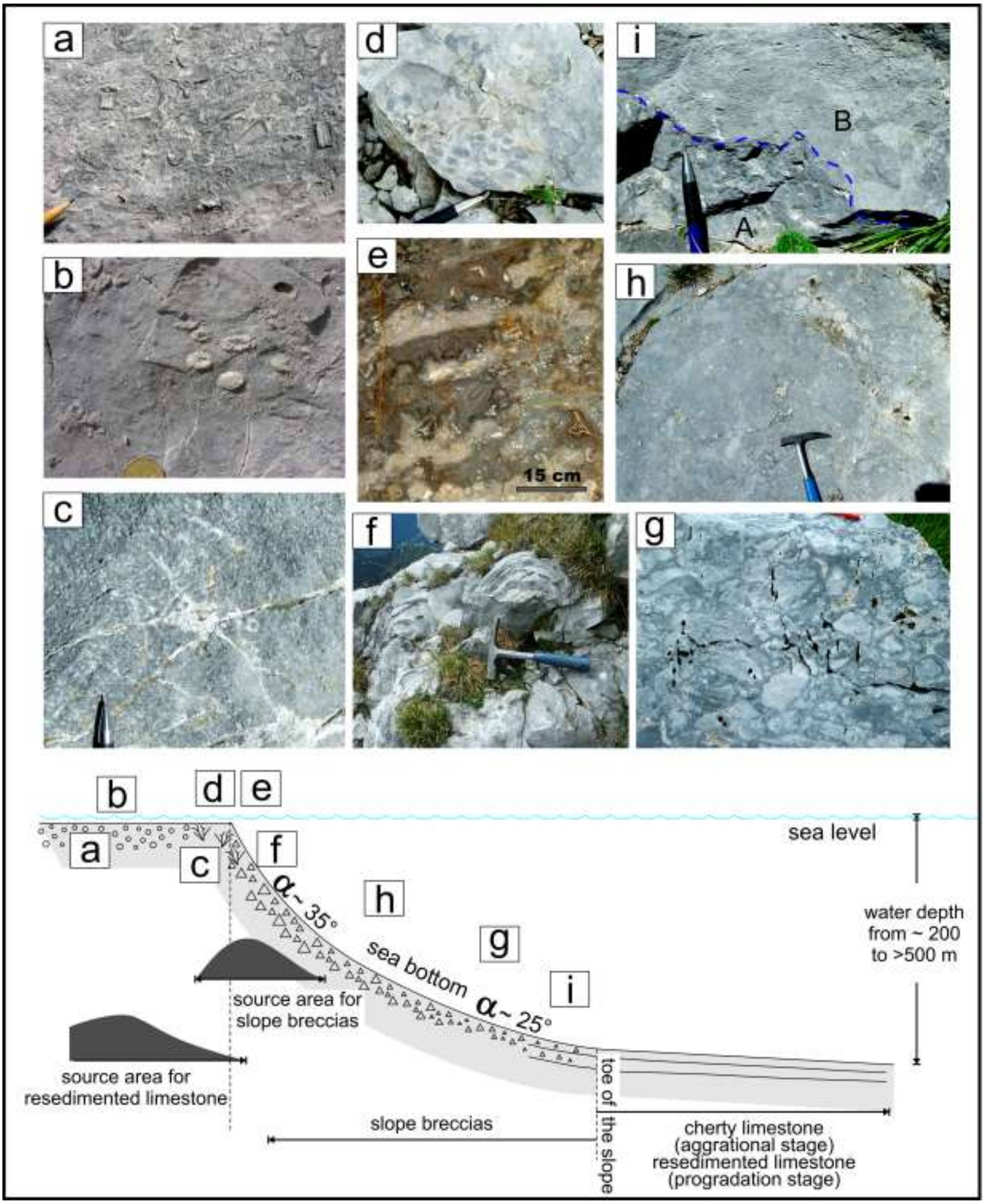

Fig. 5 – Ideal profile and facies distribution along the depositional profile (from platform rim to the basin) during the growth stage (lower part of the figure). a) bioclastic rudstone yielding abundant crinoids and bivalves, open platfor/backreef facies; b) bioclastic sand with small coral colonies, backreef facies; c) *Tubiphytes* in the reef facies; d) coral framestone, reef facies; e) microbialitic mound with abundant cavities filled by marine isopachous fibrous radiaxial calcite, upper slope facies; f) large cavity filled with marine isopachous cement, upper slope; g, h) mud-free slope breccias, stabilized by early, marine fibrous radiaxial calcite cements, slope facies; i) sharp contact between slope breccias (A) and a bivalve (daonellids) coquina (B) which marks the interval between two breccia flows. Letters in boxes in the slope model (base of the figure) indicate the approximate position of the pictures along the depositional profile.

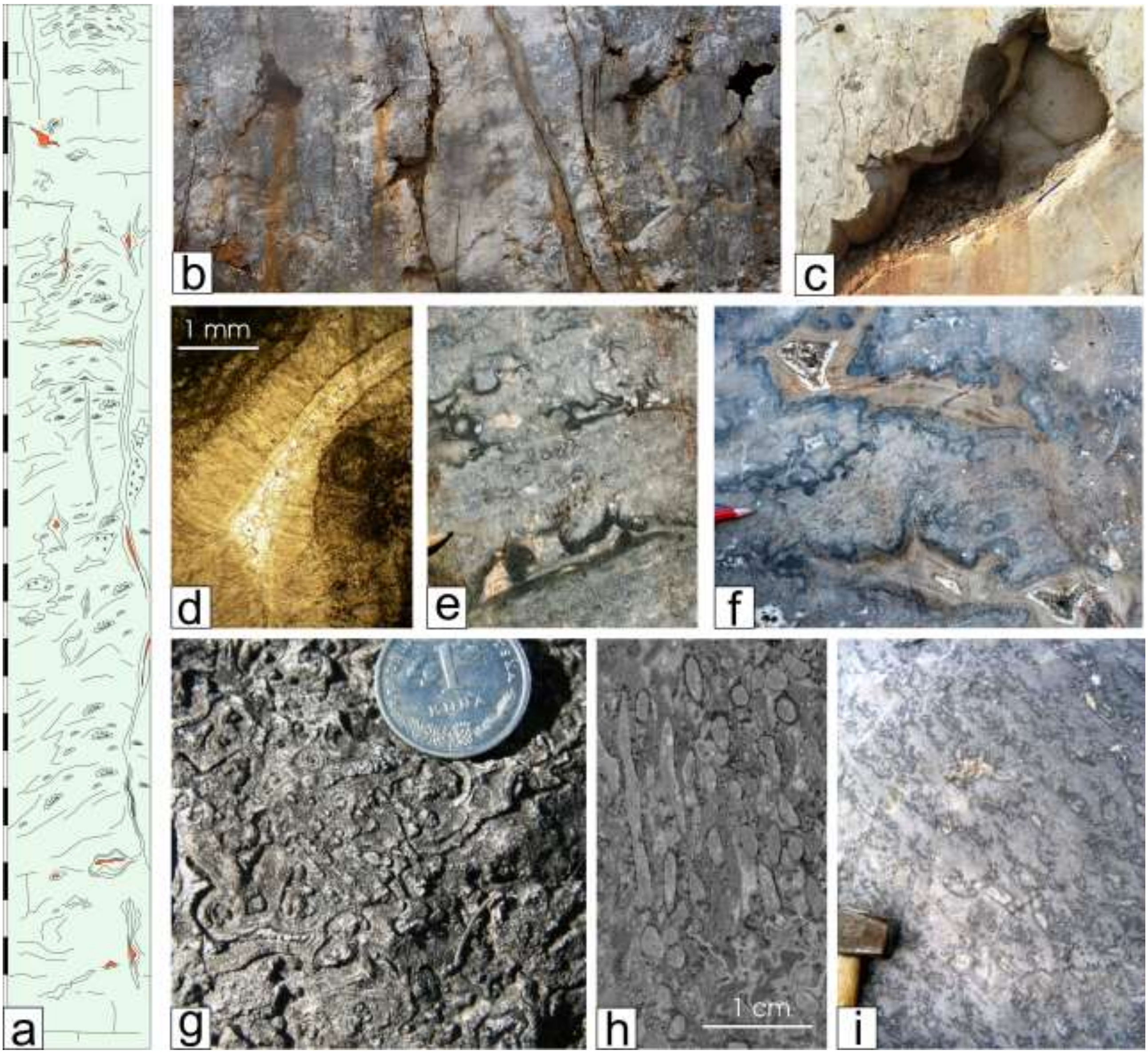

Fig. 6 – Characteristics of the reef facies of the Esino Limestone. a) stratigraphic log of the reef facies (legend as in Fig. 8); b) massive aspect of the reef facies on the in Middle Val Brembana. Note the presence of large cavities partly filled by cements; c) detail of a large cavity coated by marine isopachous cements; d) microphotograph (thin section) of marine isopachous fibrous radiaxial cements in the reef facies; e, f) small cavities (stromatactis-type in ‘e’) in the reef facies, with micritized dark boundaries and filled by marine fibrous radiaxial calcite; g) massive calcimicrobial limestone with cavities filled by marine isopachous fibrous cements; h) serpulid colony; i) massive laminar microbial boundstone with cement-filled cavities.

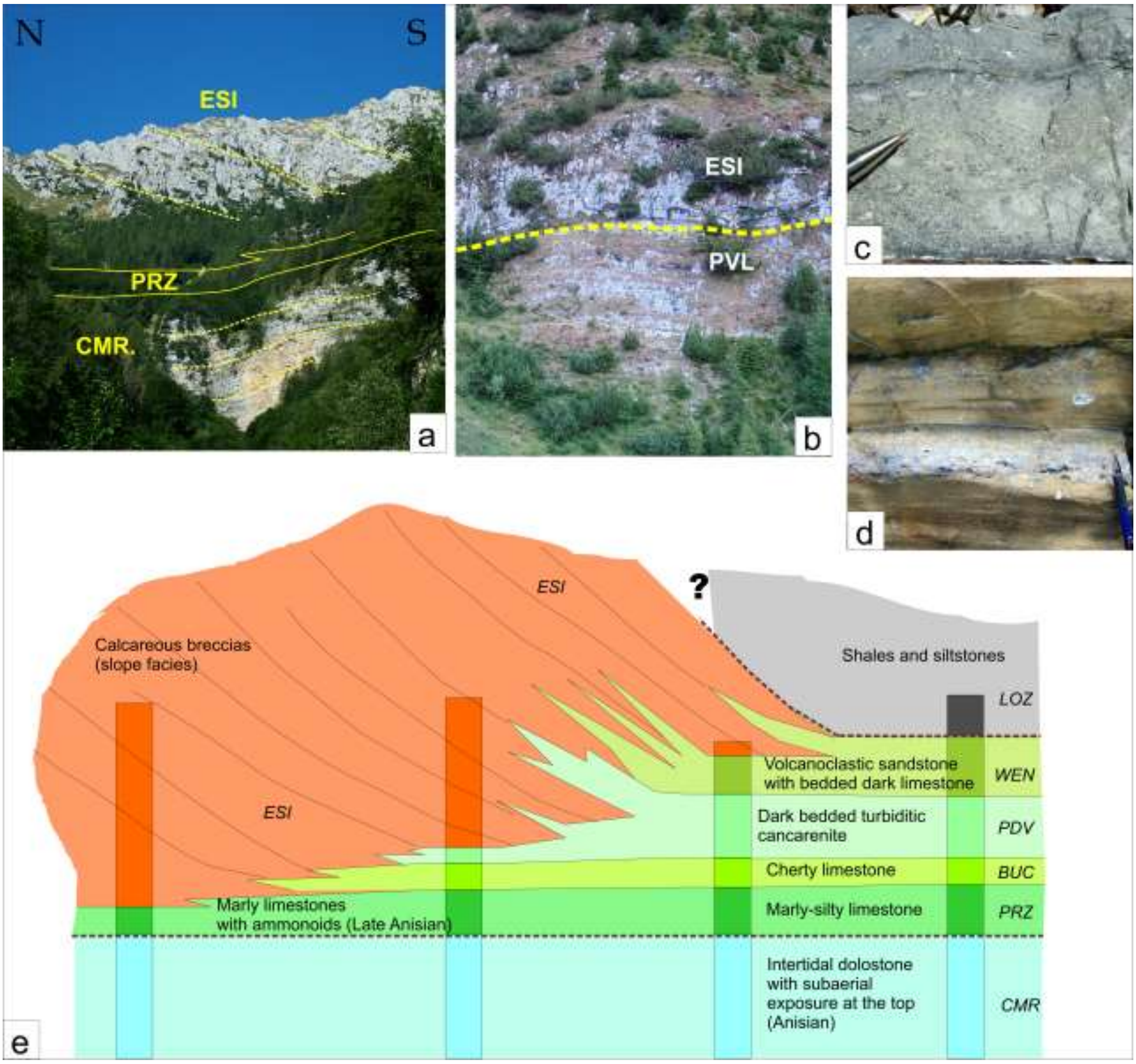

Fig. 7 – Vertical and lateral distribution of the basinal facies during the different stages of the platform growth; a) Geometry of the transition between prograding slope breccias and basinal units, south of Monte Pegherolo; b) detail of the transition between the bedded basinal limestone of the Perledo-Varenna Limestone and the prograding slope breccias of the Esino Limestone, Valleve; c) aspect of the platform-derived resedimented limestone of the Perledo Varenna limestone; d) fine-grained marly siliciclastics of the Wengen Formation with lenses of calcareous rudstone; e) schematic distribution of the slope facies during the different stages of the deposition of the Esino Limestone (CAM: Camorelli Limestone; PRZ: Prezzo Limestone; BUC: Buchenstein Fm.; PDV: Perledo-Varenna Limestone; WEN: Wengen Formation; ESI: Esino Limestone).

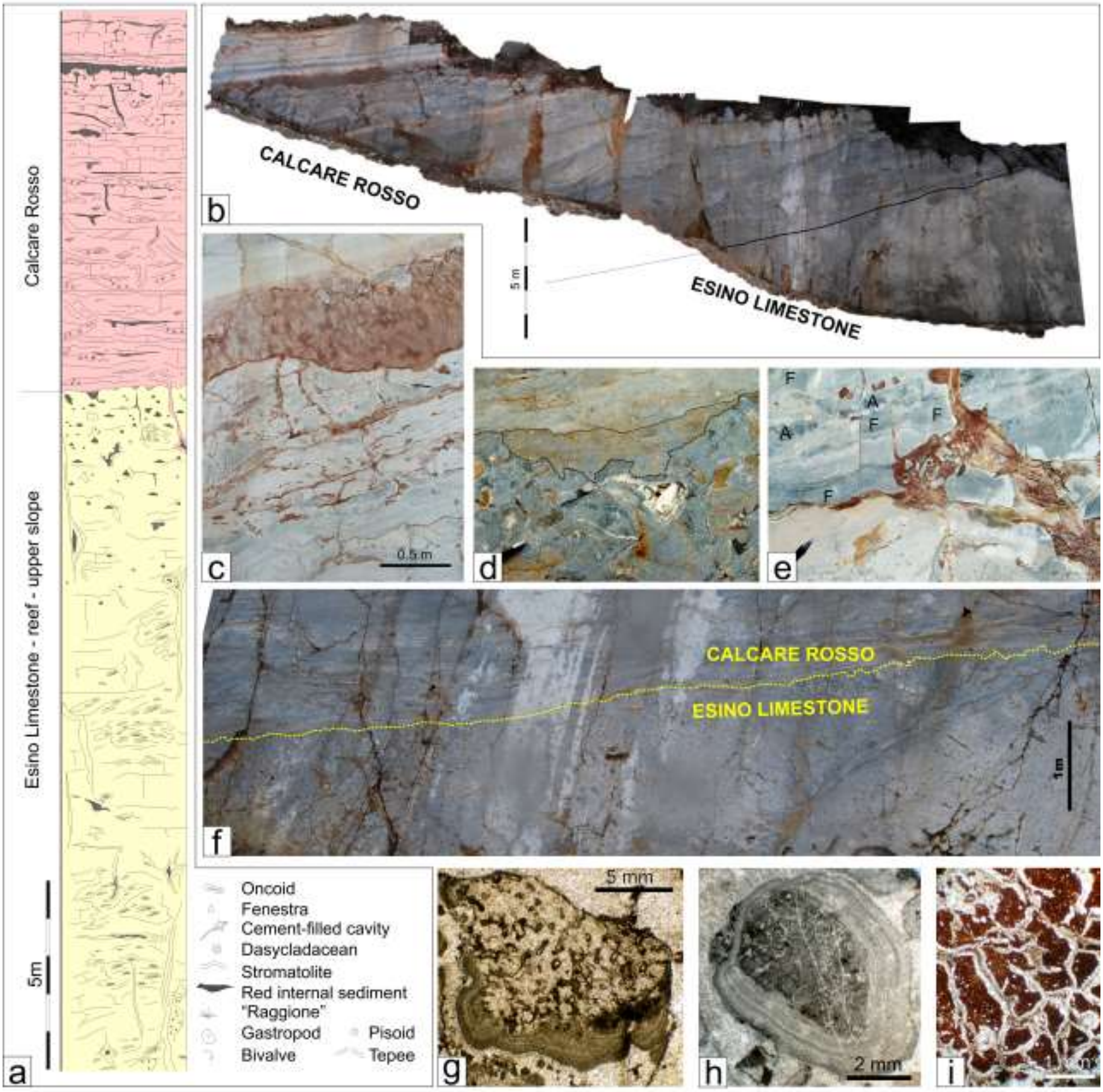

Fig. 8 – Facies association reflecting the demise of the carbonate platform of the Esino Limestone on the platform top (Cespedosio Quarry). a) stratigraphic log of the transition between Esino Limestone and Calcare Rosso; b) view of the studied section (the road to Gamba Quarry); c) detail of a paleosols within the Calcare Rosso (top right in ‘a’); d) detail of the unconformable contact between the Esino Limestone and Calcare Rosso (the dashed line marks the disconformity between the two units). Note the presence of cavities filled by brownish internal sediments within the Esino Limestone, interpreted as evidence of karst; e) dissolution cavities (epikarst) in peritidal limestone filled by terra rossa and angular clasts of the host rock, with abundant fibrous (F) and acicular (A) cements, Calcare Rosso; f) close-up view of the contact between Esino Limestone and Calcare Rosso: note the massive facies of the Esino Limestone (rich in cavities filled by internal sediments from the Calcare Rosso) and the layered facies of the Calcare Rosso, strongly affected by post-depositional deformation; g) pendant vacose cements in the Calcare Rosso; h) pisoidal grain; i) pedorelicts within a paleokarst cavity (each pedorelict presents a rim of calcite).

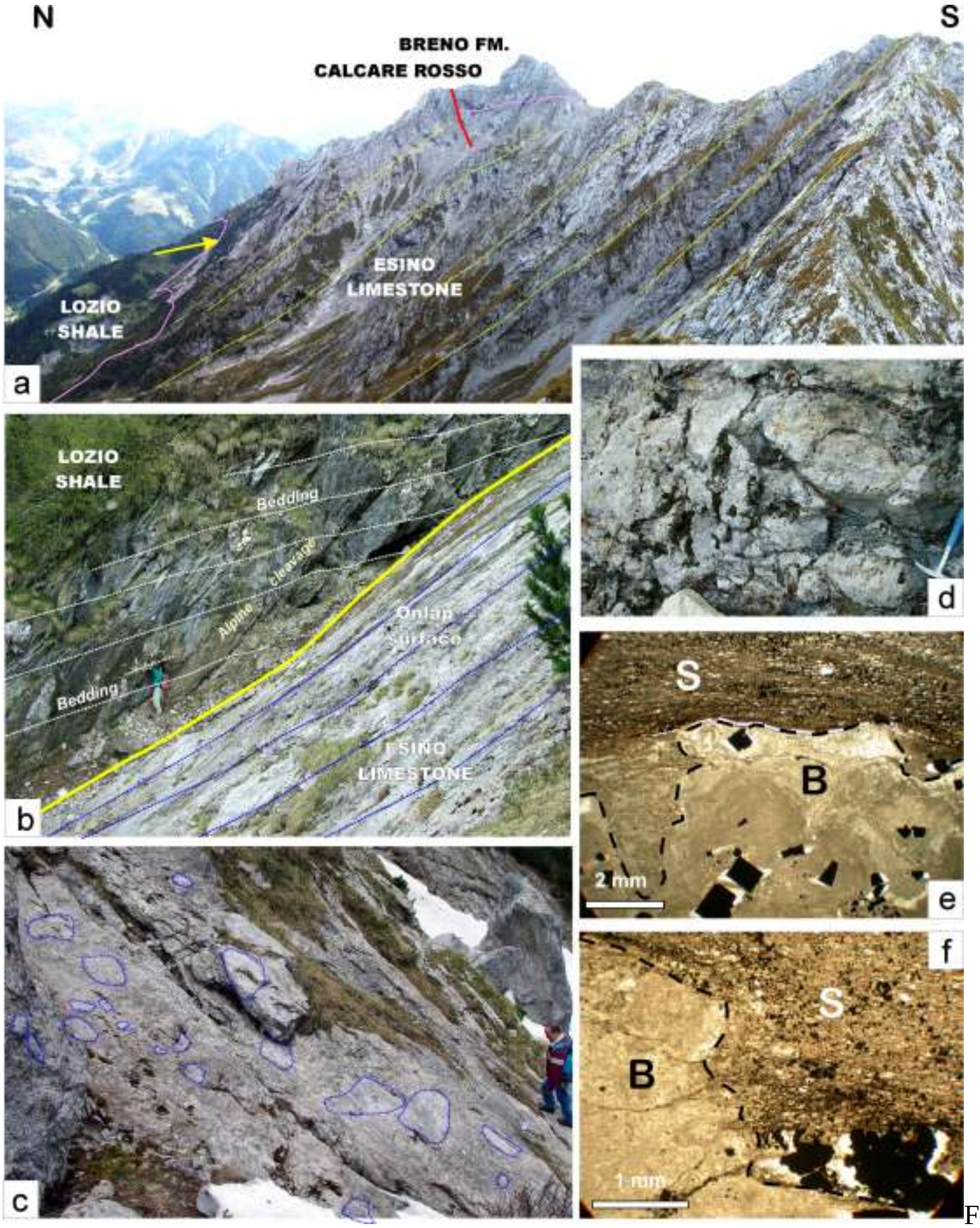

Fig. 9 – Facies association reflecting the demise of the carbonate platform of the Esino Limestone along the slope. a) view of the northern slope of the Esino Limestone (north of Mt. Pegherolo): note the clinostratified slope and the flat-lying younger units (Breno Formation, Early Carnian) on the former platform top of the Esino Limestone. The arrow points to the position of fig. ‘b’; b) detail of the onlap surface represented by the last clinostratified breccias of the slope of the Esino Limestone; c) distribution of breccia boulders on the onlap surface; d) detail of the onlap surface: note the shale that fills the intergranular voids between the unsorted breccia boulders at the top of the Esino Limestone; e, f) microphotographs of the contact between the calcareous breccia boulders (B, Esino Limestone) and the shales (S, Lozio Shale). Note the abundant pyrite.

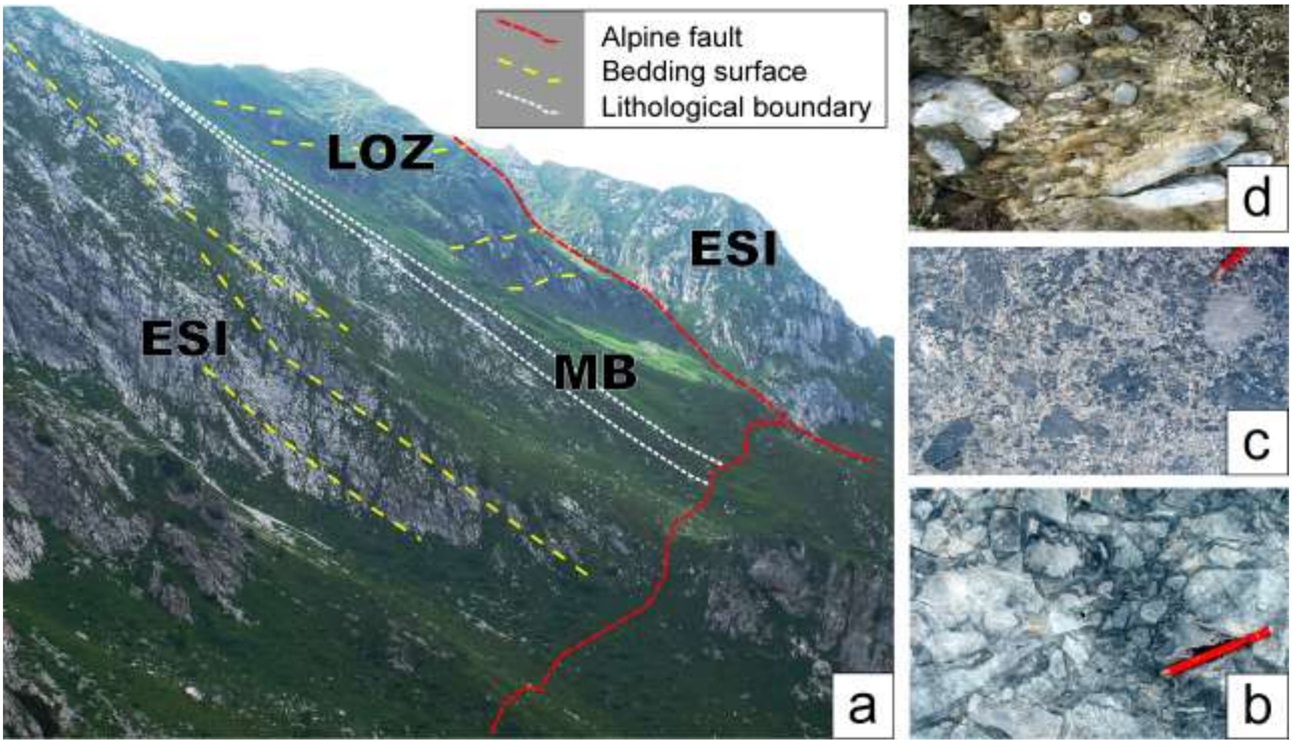

Fig. 10 – View and coarse facies of at the transition between Esino Limestone and Lozio Shale. a) panoramic view of the transition between Esino Limestone and Lozio Shale at the middle-upper slope, Monte Cavallo: note the pinch out of the fine-grained, bedded limestones deposited above the last clinoforms of the Esino Limestone(ESI: Esino Limestone, MB: Muddy breccia deposits; LOZ: Lozio Shale); b) typical clast-supported mud-free breccias from the clinoforms of the Esino Limestone: note the abundance of fibrous early marine cements filling the intergranular porosity, documenting the early lithification of the clasts at the moment of deposition; c) muddy breccias between the the Esino Limestone and the Lozio Shale: the dark clasts show irregular borders, documenting their plastic behavior at the moment of deposition; d) fine-grained limestone clasts embedded in a shaly-silty matrix, typical of the deposits at the borders of the mounds within the Lozio Shale.

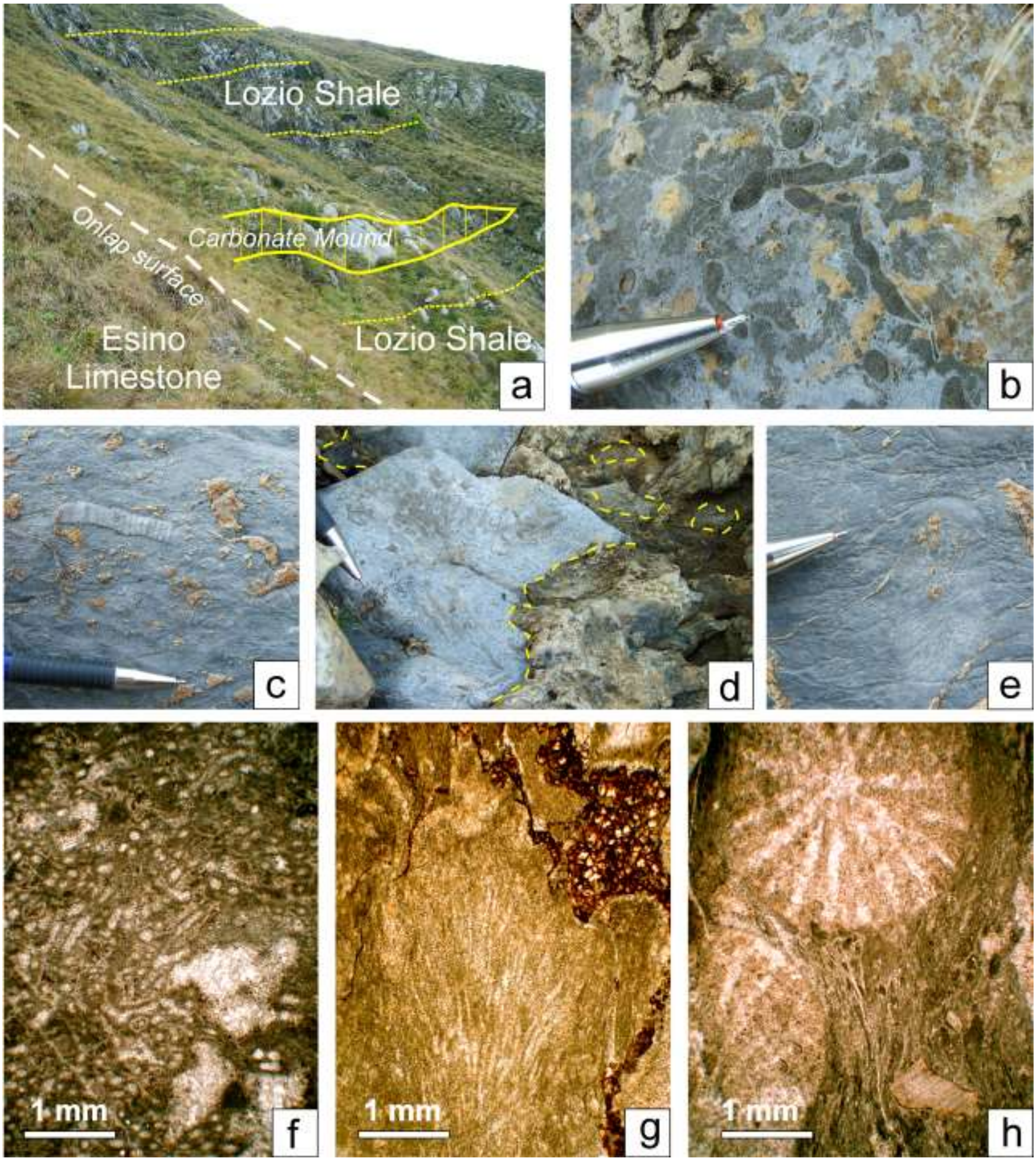

Fig. 11 – Facies reflecting the “rebirth” of the carbonate factory close to Monte Cavallo: a) view of the onlap of the Lozio Shale on the slope of the Esino Limestone, with the intercalation of a meter-thick carbonate mound which pinches out in the shales; b) calcisponge in the carbonate mound; c) crinoids ossicles; d) muddy breccias with shaly matrix lateral to the carbonate mound. Note the different composition with respect to the slope breccias of the Esino Limestone and the presence of the muddy matrix.; e) large solitary coral; f) thin section of a calcimicrobial limestone from the carbonate mounds (*Girvanella*); g) calcimicrobial limestone (probably *Cayeuxia*), thin section; h) coral framestone from the microbial mounds in the Lozio Shale.

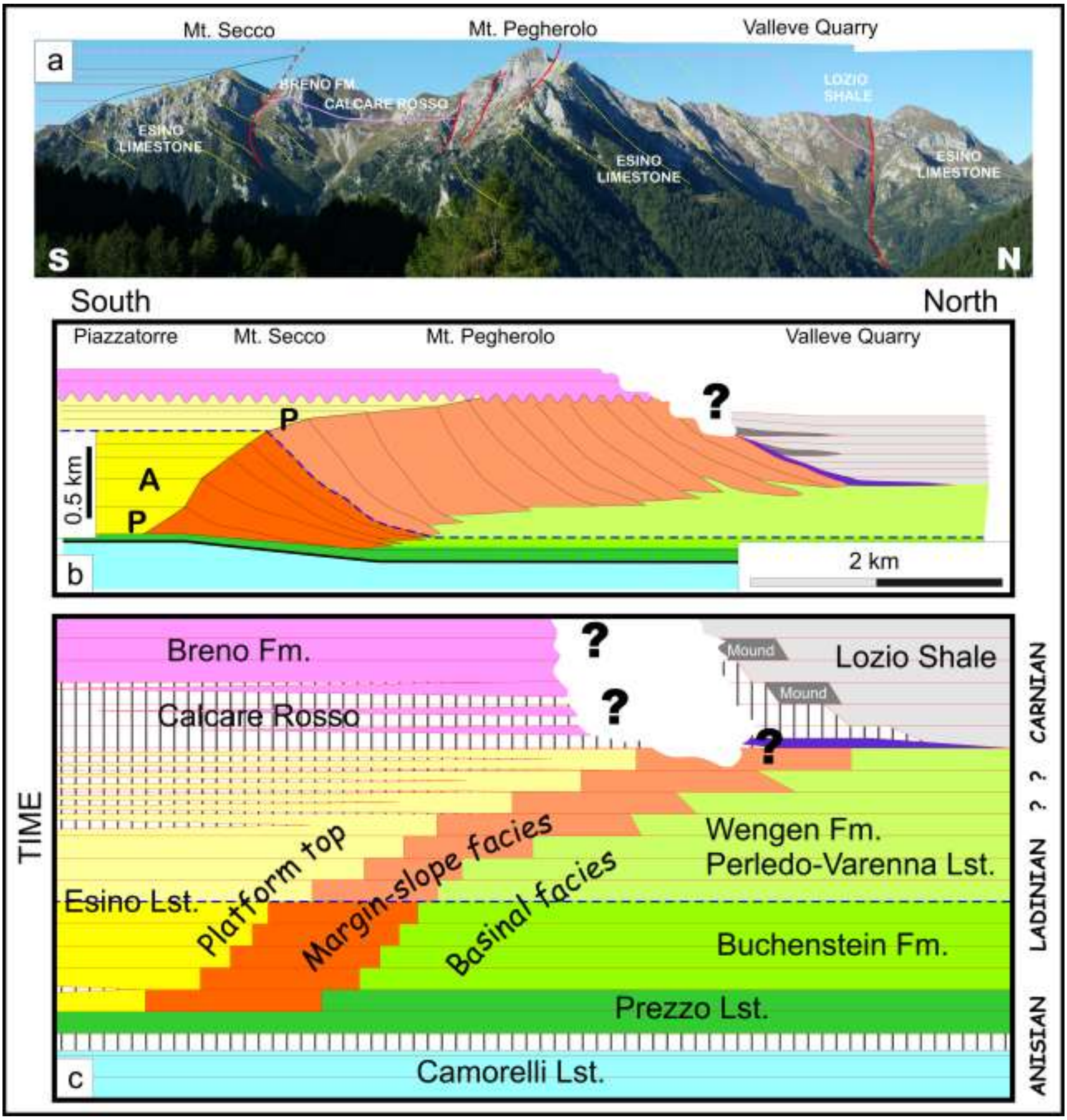

Fig. 12 – Panoramic view of the northern side of the Pegherolo platform from N-E (Foppolo). (a), closely comparable with the schematic cross-section (b) and the qualitative chronostratigraphic section of northward prograding margin of the Pegherolo Massif (A: aggradation; P: progradation) (c). The chronostratigraphic section evidences the changes through time of sediment accumulation on the platform top and the depositional hiatus (dark vertical lines) along the slope, related to the demise of the Esino Limestone platform during the subaerial exposure of the platform top. Time scale is relative.

Tab. 1 – Synthetic table of the lateral and vertical facies distribution and stratigraphic evolution in the studied succession, with the evolutionary interpretation of each stage (wkst: wackestone, pkst: packstone; SU: shallowing upward; lst: limestone).