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The late Norian-Hettangian stratigraphic and paleogeographic evolution of the Bergamasc Alps

Geoitalia, *VI meeting* FIST - Rimini, 2007

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Riassunto

L'escursione permette di osservare, in un rivisitato e aggiornato assetto litostratigrafico, l'evoluzione stratigrafico-sedimentologica dei sistemi deposizionali carbonatici o misti argilloso-carbonatici alla fine del Triassico - inizio Giurassico nel Sudalpino occidentale (Lombardia). Le osservazioni iniziano a partire dalla rivoluzione climatico-paleogeografica del Norico sup., documentata dalla riorganizzazione delle facies, ambienti deposizionali e profonda crisi del sistema deposizionale Dolomia Principale, e proseguono sino alla crisi biologica al limite T/G e alla ripresa della produttività carbonatica nell'Hettangiano. Gli stop dedicati alla potente successione retica permettono di osservare associazioni di facies e una ciclicità a varia scala sviluppata in diversi ambienti di rampa carbonatica o mista e durante diversi trend trasgressivi e regressivi.

Parole chiave:
Norico superiore, Retico, stratigrafia, paleogeografia, limite T/G, analisi di facies, cicli calcareo-marnosi

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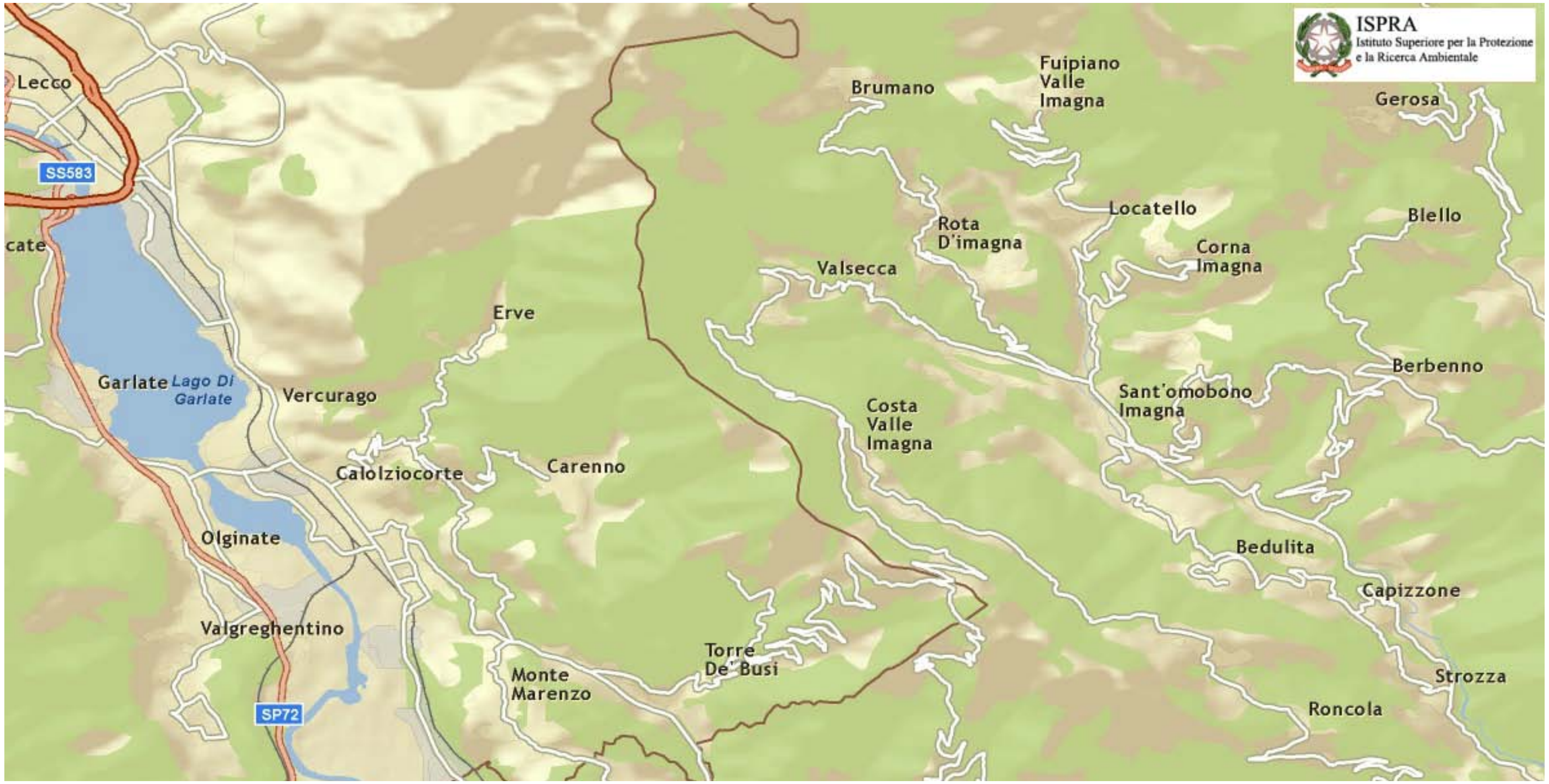
Abstract

The field trip allows the observation and reconstruction of the stratigraphic and paleogeographic evolution during the Late Triassic-Early Jurassic time interval of a thick carbonate to mixed marly-carbonate succession developed on the western Sudalpine passive margin of Lombardy (Southern Alps, North Italy). The itinerary begins with the regional climatic and paleogeographic changes recorded in the upper Norian Dolomia Principale (retrogradation/demise of the carbonate factory also related to a major tectonic event) and continues into the Triassic/Jurassic boundary marked by a biologic-paleogeographic revolution and reorganization of the carbonate productivity from the Rhaetian to the Hettangian times. Several stops are dedicated to the observation of the lithofacies association and the cyclicity of the Rhaetian marly-carbonate succession deposited on different carbonate ramp depositional environments and characterized by several transgressive-regressive trends.



Key words:
Late Norian, Rhaetian, stratigraphy, paleogeography, T/J boundary, facies analysis, marly-carbonate cycles

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1. Introduction

The field trip focuses on the stratigraphic, paleoenvironmental and paleogeographic evolution of the Upper Triassic-Lower Jurassic succession in the Southern Alps of Central Lombardy (Fig. 1).

This succession records the earliest stages of a passive margin evolution, dominated by synsedimentary tectonic, which led to the Early Jurassic opening of the Alpine Tethys. The visited succession is about 1.5 km thick and it belongs to the southern, slightly deformed portion of the Alpine chain (for a more regional geological information see the "*Carta geologica della provincia di Bergamo*", Forcella & Jadoul Ed., 2000), giving the opportunity to observe the evolution and the stratigraphic architecture of the Upper Norian-Lower Hettangian

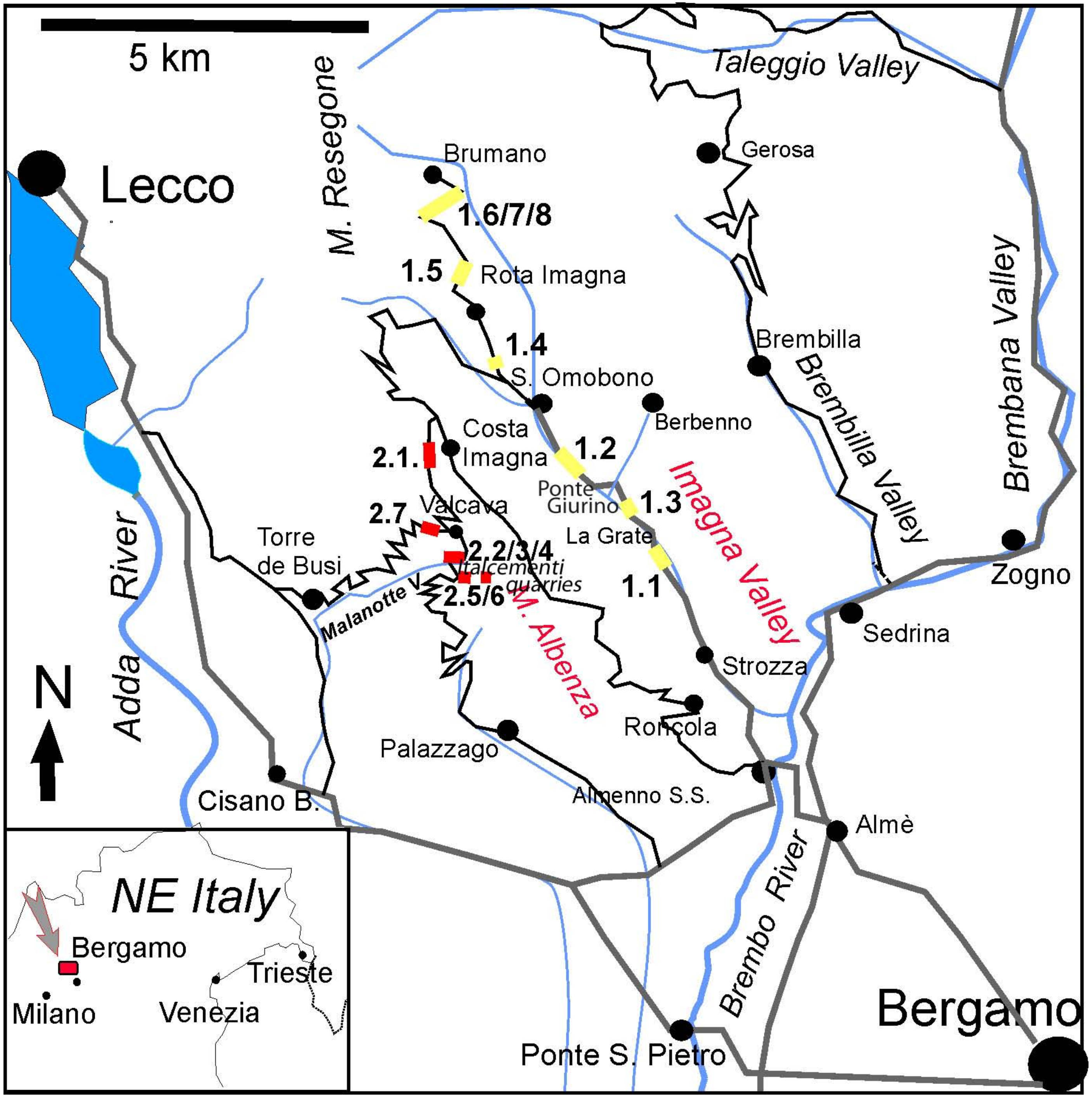

Fig. 1 - Geographical location of the field trip area and stops.

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succession of the Lombardy Basin characterized by a different scale sedimentary cyclicity, several fine siliciclastic, carbonate lithofacies associations and environments mainly developed on a ramp depositional system.

We suggest to visit the whole itinerary in two days (see stops of Fig. 1) but one day itinerary is also possible (in this case skipping 1.1, 1.3, 1,5, 1.8, 2.1, 2.5, 2.6 stops).

The itinerary starts from Bergamo or Dalmine (gates of the A4 highway), follows the direction for “Valle Brembana” until Almè village, cross the Brembo river, the village of Almenno S.S. and enters in the “Valle Imagna”. The first stops (I day) are along the main road to S. Omobono Imagna and then along the secondary road to Brumano village (up to about 900 m in altitude). The second day itinerary starts from S. Omobono Imagna, follows the direction for “Costa Imagna”, here takes the panoramic road up to the top of Mt. Albenza-Valcava (altitude about 1350 m), enters in Valcava village and take the small road in direction for the Italcementi quarry (stops in quarries and along private road from 1200 to 1000 m in altitude). The itinerary returns to Valcava and takes the direction for “Torre dei Busi” and then for “Caprino Bergamasco”, Ponte S. Pietro, Bergamo/Dalmine (Fig.1). The whole car itinerary is about 75 km long.

Topographic maps

Carta Tecnica Regionale 1:10.000 (Regione Lombardia), sheets: C4a5, B4e5, B4e4
Carta Tecnica Regionale 1:50.000 (Regione Lombardia - CT50).

Geological maps

Carta geologica della Provincia di Bergamo alla scala 1:50.000
Foglio geologico 33 “Bergamo”, Carta Geologica d’Italia alla scala 1:100.000 (1954)

2. Stratigraphic and paleogeographic setting

Two depositional systems have been recognized in the upper Carnian to lower Hettangian succession (Jadoul et al., 1994; Gaetani et al., 1998). The lower depositional system (late Carnian to middle Norian) lies on shallow-water carbonates, evaporites and siliciclastics representing a coastal sabkha depositional environment of the S. Giovanni Bianco formation.

It is represented by the shallow-water limestones and intraformational breccias of the Castro formation (Jadoul et al., 1992b), and is covered by the thick carbonate platform of the Dolomia Principale and the coeval intraplatform carbonate basins (Aralalta group; Jadoul, 1985).

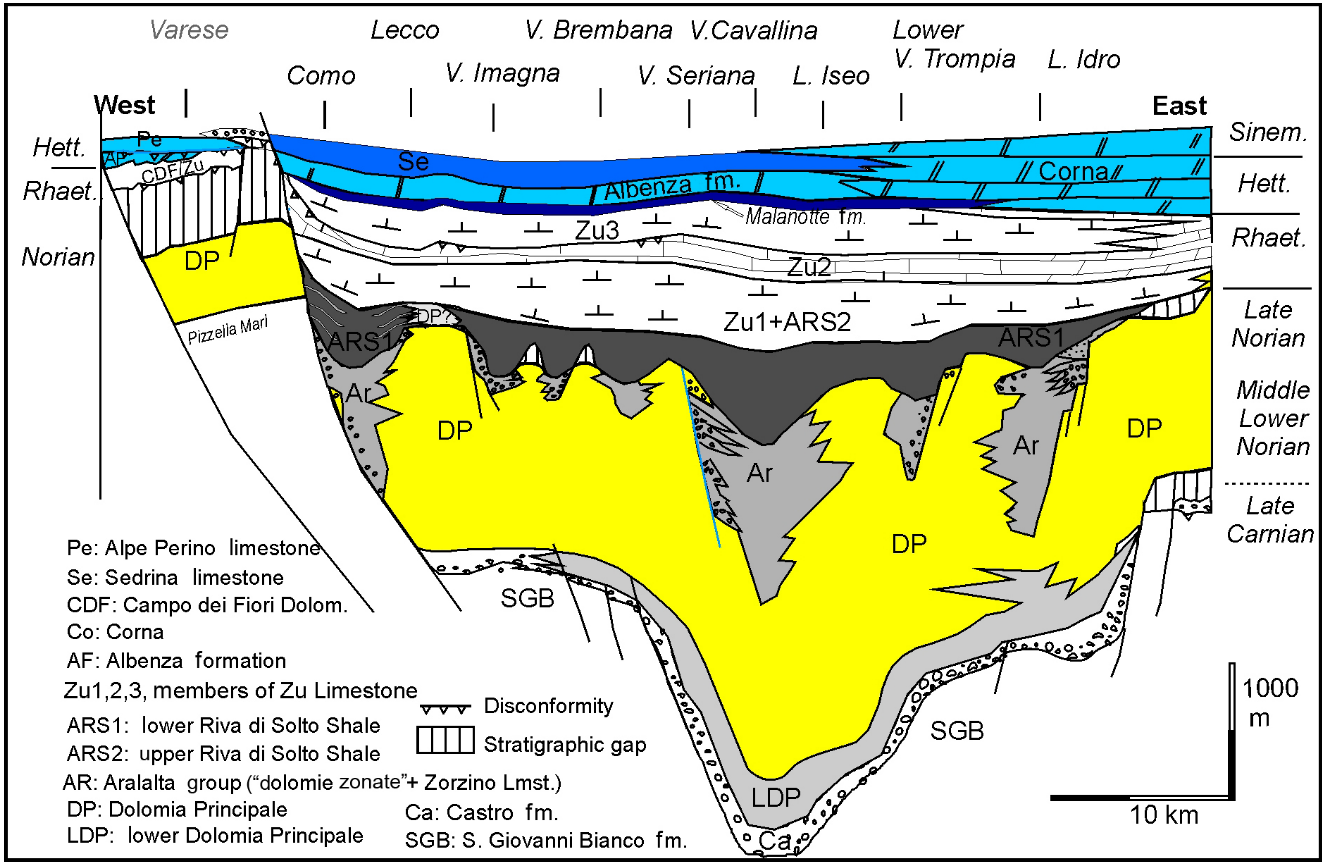

Fig. 2a - Stratigraphic scheme of the Late Triassic-earliest Jurassic succession of Lombardy Basin (modified from Jadoul & Galli, 2008).

The upper depositional system (late Norian-Hettangian) consists, at the base, of a subtidal mixed shale-carbonate ramp depositional environment organized in cycles (Riva di Solto Shale and Zu Limestone) developed on the tilted blocks of the Dolomia Principale due to the Norian rifting event (Jadoul et al., 1992a).

It passes upward into the Hettangian Bahamian-type carbonate platform (Albenza and Malanotte formations, Galli et al., 2007; Jadoul & Galli, 2008).

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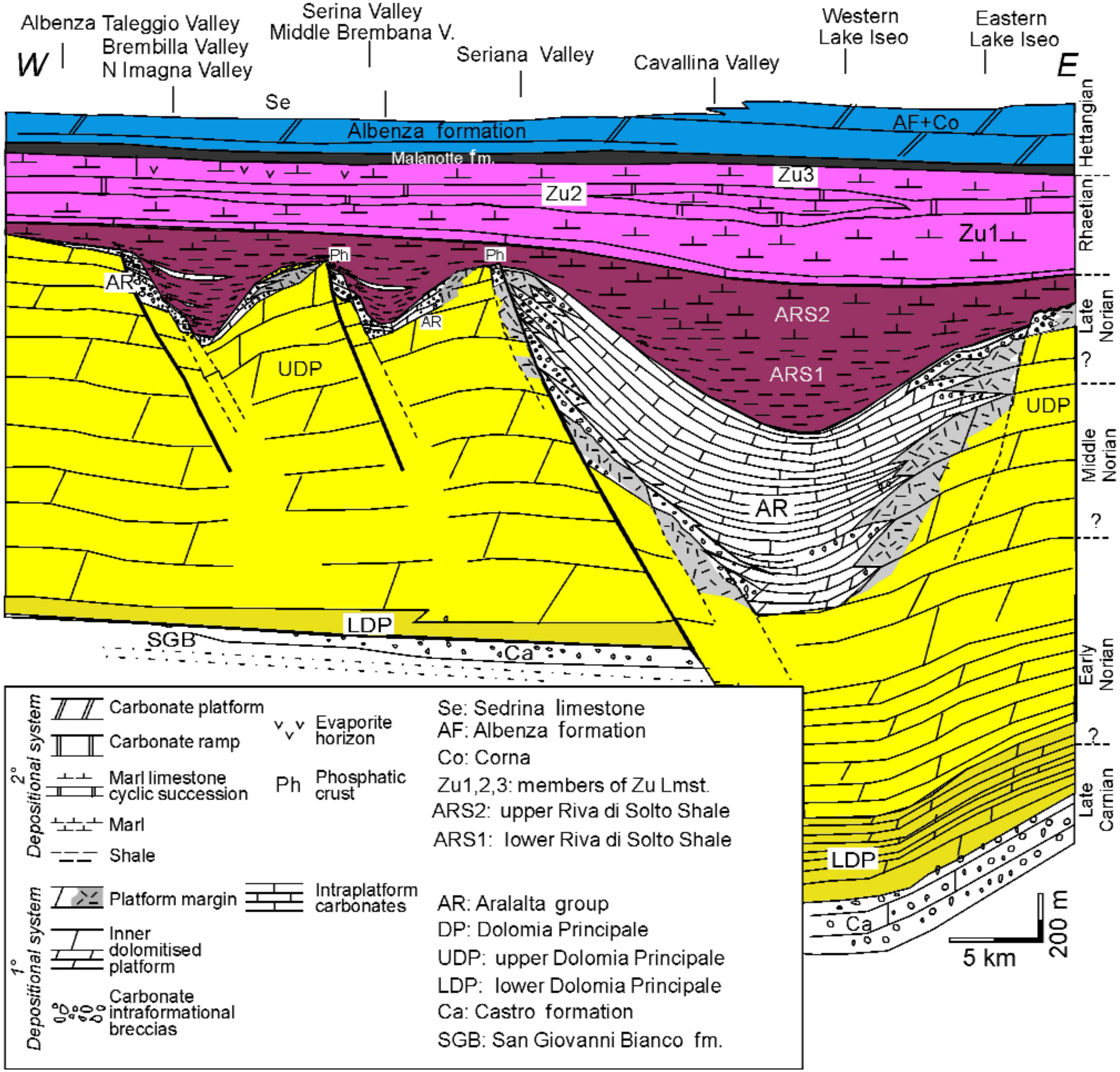

Fig. 2b - Stratigraphic schemes of the Late Triassic-earliest Jurassic succession of the Bergamasc Alps (modified after Jadoul et al., 1994, 2004).

2.1. The upper Carnian-middle Norian dolomitized carbonate platform (Dolomia Principale) and the intraplatform basin carbonates (Aralalta group)

The Dolomia Principale of the western Southern Alps reaches its maximum thickness (up to 3000 m) on the eastern side of Iseo Lake.

In the visited area, the Dolomia Principale deposition started probably during the latest Carnian in restricted shallow-water basins, lagoons and tidal flats, as recorded by 200-300 m thick, dark bedded dolomites with intraformational breccias and microbialites (lower member of Dolomia Principale, Fig. 2).

These subtidal facies are overlain by stacked shallowing upward cycles (5 to 25 m thick), which consist of several dm to m-thick peritidal sequences with Dasycladales and locally tepees, pisoids and flat-pebble breccias at the top. The middle part of the Dolomia Principale is also cross-cut by sedimentary dikes, testifying syndepositional extensional tectonics that will lead to the development of small intraplatform basins.

The intraplatform basin successions (up to 1000 m thick) consist in well-bedded, fine crystalline, dark dolomites, limestones and rare organic-rich, laminated, marly limestones (“dolomie zonate” and Zorzino Limestone of the Aralalta group; Jadoul, 1985; Fig. 2). The depositional processes are dominated by gravity flows and slumpings (Jadoul, 1985). The intraplatform basins are interpreted as half-graben (Picotti & Pini, 1988; Jadoul et al., 1992a; Trombetta, 1992) generally exhibiting two margin types: one is tectonically controlled; the other is a flexural margin. The tectonically controlled margins are located to the west of the basins in central-western Lombardy, and to the east in the Idro Lake area (Jadoul, 1985; Lualdi & Tannoia, 1985; Trombetta,1992). The depocenter shifted from the Idro Lake area towards the Iseo Lake one where the Norian succession is about 3000 m thick (Assereto & Casati, 1965).

The complete development of the Dolomia Principale carbonate platform during the upper Norian records important palaeoenvironmental and geodynamic changes involving the whole western Tethys. The upper Dolomia Principale in Lombardy exhibits margins colonized by peculiar serpulid patch reefs and microbial mounds associated to thick carbonate breccia bodies (Berra & Jadoul, 1996, Zamparelli et al., 1999), the development of which was controlled by synsedimentary tectonic and high subsidence rates. These peculiar buildups at the platform margins have been interpreted as an ecological adaptation to restricted and stressed conditions of the intraplatform basins developed during the upper Norian rifting in the westernmost Tethys (Cirilli et al., 1999). A relative sea level fall at the top of the Dolomia Principale depositional system is recorded by local carbonate platform progradation, meteoric diagenesis or erosional disconformity documented at the top of platform, along with the findings of herbivorous terrestrial reptiles in the coeval uppermost Aralalta group (Wild 1989; Stefani et al., 1991; Renesto S., pers. comm.). A change in circulation pattern and nutrient distribution in marine waters could be ascribed to this sea level fall.

2.2. Crisis of carbonate platform deposition and drowning of the platforms (middle-late Norian)

A sudden crisis of the carbonate production, recorded in both platform and basin facies, characterized the top of the first depositional system. The uppermost Zorzino Limestone consists of a few meters of thin bedded, micritic limestones, micro-turbidites with slumpings, and organic-rich layers yielding vertebrates (reptiles and fishes) and invertebrates (crustaceans, crinoids and rare haermatipic corals) (Tintori et al., 1985; Pinna, 1986). The high concentration of organic matter (OM) and the well-preserved fossils are probably related to both a low sedimentation rate and anoxic bottom condition. Palynological assemblage documents the middle-late Norian boundary in this horizon (Jadoul et al., 1994; 2004, Cirilli et al., 2000).

The carbonate platform succession of structural highs exhibits lenses of dolomitic breccias, marly dolomites with wood and cuticle remains and locally a thin phosphate firm/hard-ground at the top.

2.2.1. The lower Riva di Solto Shale (ARS1, middle-late Norian)

The lower part of ARS (ARS1, 0 to 250 m thick) is only present within the more subsiding areas (Fig. 2). This unit mostly consists in black, thin laminated organic rich shales, marly shales and minor dark grey marls, muddy limestones and paraconglomerates. Slumpings and locally, fossil-rich layers are common in the whole ARS1. The middle-upper portion contains lenticular micritic limestone horizons (up to 18 m thick) intercalated within the shales (stratigraphic marker of Imagna Valley, Stop 1.3). Thin phosphatic firm/hardgrounds with sphalerite, barite, fluorite and celestine mineralizations are locally present (Jadoul et al, 1993).

The palynofacies are characterized by a high proportion of allocthonous continental debris, such as sporomorphs, cuticule and wood remains and of amorphous organic matter (AOM). Palynofacies content in ARS and in the lower member of Zu (Zu1) is quite similar: only a slight decrease in AOM content upwards is documented (Jadoul et al., 1994; 2004, Cirilli et al, 2000).

Shales fill the basins and progressively onlap the margins of structural highs (Albenza, M. Zucco, Catramerio, S. Pellegrino) that are locally characterized by stratigraphic gaps and thin (5 to 15 cm thick) dark crusts of calcium phosphate, with irregular botryoidal features or filling fractures and cavities (Pizzo Formico). Lenticular small carbonate mounds with thick microbial encrustations, associated to serpulids, bivalves, encrusting foraminifers, problematica and dasycladales document local and ephemeral carbonate recolonization around a few paleohights and their slopes ("Artavaggio member" of Jadoul, 1985). This particular lithofacies, often associated to selective, early diagenetic silicization, marks the platform flooding and may correspond to the thick basal black shales (ARS1) deposited in the troughs. Palynological assemblage refers the ARS1 to the middle-late Norian (phase II of Schuurman (1979) and TR zone of Morbey (1975); Buratti et al., (2000).

2.2.2. Palaeoenvironmental meaning of the ARS1

The argillaceous sedimentation of ARS1 marks the sharp transition with the upper depositional system that was probably controlled by climatic changes, such as increased rainfall favoring the fluvial delivery of fine siliciclastics from continental areas. River-estuaries probably run from Europe to the coast of the Tethyan gulf, where the argillaceous sediments were trapped in N-S depressions. Carbonate production decreased, as a consequence of the large siliciclastic influx and the decreased salinity, related to the input of large masses of fresh water.

Deposition of laminated organic rich clays and marls occurred in anoxic sea floors as testified by the abundance of preserved AOM. Sedimentological and paleontological data suggest sea floors located below the photic zone in prevalent anaerobic-subanaerobic conditions.

The local co-occurrence of marine and terrestrial fossils in several horizons of this lithozone indicates emerged areas (where fresh water was available) close to this basin. Geometry and thickness variations of ARS1 inherited the previous palaeogeography. Slumpings and paraconglomerate bodies with intraformational carbonate clasts recorded the bathymetric variations within the basins, the presence of slopes and the persistence of synsedimentary tectonics (Stops 1.2, 1.3 and 1.4). This unit deposited in restricted basins and locally with a distally steepened ramp depositional model.

2.3. The cyclic carbonate ramps with mixed sedimentation

ARS1 is overlain by 500 to 1500 m of limestone-marls asymmetric cycles showing upward gradual carbonate enrichment. This succession is represented by the upper Riva di Solto Shale (ARS2) and by the three members (Zu1, Zu2 and Zu3) of the Zu Limestone Formation. The lower boundary with ARS1 is gradual. The upper boundary of this ramp system (Wright, 1986; Burchette & Wright, 1992) is sharp, from the bioclastic limestones with oncoids and Megalodontids to the well thin-bedded calcilutites (Malanotte formation).

2.3.1. The upper Riva di Solto Shale

This ARS2 unit (up to 350 m thick, late Norian) has a greater extension than ARS1 (Fig. 2). The passage to the overlying Zu1 is marked by the increased occurrence of intercalated limestone (Gnaccolini, 1965) with a transitional zone up to 100 meters in thickness. We propose to set the boundary at the beginning of the up to decameter thick well-organized marl-micritic limestone cycles.

The ARS2 is characterized by *Bactrillum* bearing laminated shales, marls, marly limestones and calcilutites, locally bioturbated and fossiliferous, arranged in 6 to 30 m thick asymmetric cycles deposited on a mid-outer ramp. The fine terrigenous sediments at the base of the cycle show well-developed parallel laminations. Rare paraconglomerates are present at the base of the cycles. Thin bioclastic calcarenites with prevalent bivalves, often micronized or affected by micro borings are commonly intercalated within marls and shales. These layers are interpreted as storm wave episodes (Masetti et al., 1989). The palynological assemblage is referred to the upper phase 2 of Schuurman (late Norian) (Jadoul et al., 1994; 2004). The depositional environment of this cyclic unit is interpreted as distal ramp.

2.3.2. The lower Zu Limestone (Zu1 member)

The cyclic organization of this lithofacies is similar to that of ARS2, but shows less black shale intercalations and slumpings. This unit (200 to 500 m thick) is characterized by the upward increase of fossil content and limestone intercalations (7 to 20 m thick). Thin bioclastic lenses commonly alternate with laminated marls and marly limestones: bivalves, echinoids and brachiopods are the most common fossils. The microfacies consist of bioturbated mudstone, wackestone and rare intrabioclastic packstone with foraminifers (*Aulotortus* spp., *Agathammina* spp., *Glomospirella* spp. and rare *Triasina* sp.). In Zu1 member of Imagna Valley at least two horizons, characterized by vuggy carbonates, evaporite pseudomorphs (replaced by chalcedony, celestine and feldspar) and planar stromatolites are present.

Asymmetric and subordinate symmetric cycles (3-4 m up to 30 m thick) are well developed. High energy, bio-intraclastic floatstone with clay chips and less common bioturbation mark the top of some cycles. The upper Zu1 documents a further carbonate increase and local shallowing/shoaling upward trends. In structural high areas the succession ARS2-Zu1 is generally reduced and it is difficult to distinguish the two units that directly overlie the Dolomia Principale.

Palynofacies are always characterized by high proportion of continental organic matter (miospores and palynomacerals) and by moderate to low percentage of AOM (Jadoul et al., 1994; 2004, Cirilli et al., 2000).

Lithofacies, microfacies and palynofacies associations of Zu1 identify prevalent low-energy subtidal environments. Sea bottoms were oxygenated and carbonate mud deposition was still associated with periodic terrigenous input. Carbonate mud was produced *in situ* in the middle-outer part of the carbonate ramp and exported towards the basin during the regional carbonate platform progradations.

2.3.3. The middle Zu Limestone (lower coral limestone, Zu2 member)

Zu2 represents a carbonate platform succession, which spreads throughout the Lombardy Basin with different facies and thickness, and thus useful as a stratigraphic marker of 50 to 100 m in thickness (Fig. 2). In the western-central Lombardy the lithofacies organization documents the evolution of a prograding carbonate ramp from mid to inner conditions. The stacking pattern of the facies identifies some major cycles (15 to 20m thick), with shallowing-shoaling upward trend, locally recorded by peritidal facies with fenestrae, dolomitized limestones, stromatolites and/or oolitic grainstone (Stops 1.7 and 1.8). Carbonates are dominant around paleohighs of the early Norian whereas in the subsiding/deeper areas marls intercalations persist.

The carbonates were mainly deposited below the fair-weather wave base and they consist in subtidal bioturbated mudstones/wackestones with scattered coral framestones (e.g. *Rethiophyllia* spp. frequently present also in marly horizons) and foraminiferal packstone, bafflestone with calcisponge and porostromata (Lakew, 1990). Bioclastic calcarenites, locally rich in echinoids, are common at the base of the cycles.

In the most subsiding/deeper part of the basin (Val Taleggio and Val Cavallina-Iseo) the more well-bedded, muddy lithofacies prevails representing the prevalence of outer ramp environments below storm wave (Burchette & Wright, 1992).

The shallowing upward trend at the top of the Zu2 represents the progradation of the inner ramp system characterized by local dolomitized peloidal and oolitic facies, ending with a disconformity at the top (Stop 1.8).

The two episodes of carbonate enrichment represented by the Zu1 and 2 could be related both to a decreased terrigenous input and to an increased carbonate production, probably connected to sea level fluctuations.

2.3.4. The upper Zu Limestone and the second coral limestone (Zu3 member)

This unit is present in the whole Bergamasc Alps and it records a new transgressive-regressive cycle developed along a mid-inner carbonate ramp, characterized by fine cyclic terrigenous input. The thickness of Zu3 member ranges from 120 to over 200 m.

Three lithozones have been recognized, each representing a different evolutive stage of the ramp depositional system:

- Zu3a consists of a 7.5 to 15 m thick marly limestones, shallowing and coarsening upward asymmetric cycles that exhibit local iron-oxides crusts at top of the carbonate banks and rare evaporitic facies within the basal marly horizons;

- Zu3b is represented by alternated grey to greenish marls and black marly shales grading to marly limestones and micritic limestones. Evaporitic facies within the middle part of cycles, and mammillary, iron-oxide thin crusts (hardgrounds) at the top of the cycles often characterize the facies association of the mid-ramp in less subsiding areas (Mt. Albenza, Stop 2.2);
- Zu3c corresponds to the upper (40-50 m thick) calcareous part of the succession (second coral limestone marker), recording the second regional carbonate platform progradation (inner ramp facies associations, Stop 2.3) with patch-reefs and local evidences of meteoric diagenesis at the top (Lakew, 1990; 1994).

Palynofacies from Zu3 contain a high total amount of OM. The percentage of continental derived organic debris (miospores and palynomacerals) is high. An increase in marine OM (dinoflagellate cysts, foraminifer linings and algal spores) is recorded in the uppermost part of the Zu3c. The AOM is generally from low preserved to absent. Both facies and palynofacies arrangement indicate general well-oxygenated conditions of the depositional environment. In such conditions the good preservation rate of particulate OM is indicative of high sedimentation rate, denoting that the OM can quickly be buried beneath the oxidizing water-sediment interface and be preserved also in well-oxygenated conditions. The quantitative analysis of palynological assemblages from ARS and Zu shows a progressive upwards increase of xerophytic elements, which become dominant in the Zu3. The rapid increase of xerophytic sporomorphs and the decrease in AOM suggest a shifting towards warmer and probably dryer climate, during the deposition of the upper portion of Zu Limestone (Jadoul et al., 1994; 2004). The top of Zu3c is marked by a paraconformity (Stop 2.4) interpreted as a regional drowning unconformity at the top of the last Zu platform progradation.

2.3.5. The late Norian-Rhaetian high-frequency cyclicity (IV and V order)

The ARS2 and Zu Limestone consist in thickening-upward, subtidal cycles organized in a composite hierarchy (Fig. 3). Decimeter limestone-marl couplets are arranged in meter-scale asymmetric cycles grouped in bundles; such bundles are assumedly related to fourth order cycles (Masetti et al., 1989). These fourth order cycles, 3 to 30 m thick, are formed by three parts: a lower argillaceous unit (black shale or marl); a middle, rhythmic part composed of limestone-marl couplets, where the carbonate semicouplets show a general thickening-up arrangement and a wholly carbonate unit that marks the upper part of each cycle. Cycle tops are usually sharp, although they can be locally gradational, giving rise to a partially symmetric organization (more typical in the Iseo Lake successions). The fifth order cycles (1 to 3 m thick) display an inner arrangement similar to the described major hierarchy. Variations in this general trend are shown in Fig. 3, according to the depth of the depositional environment.

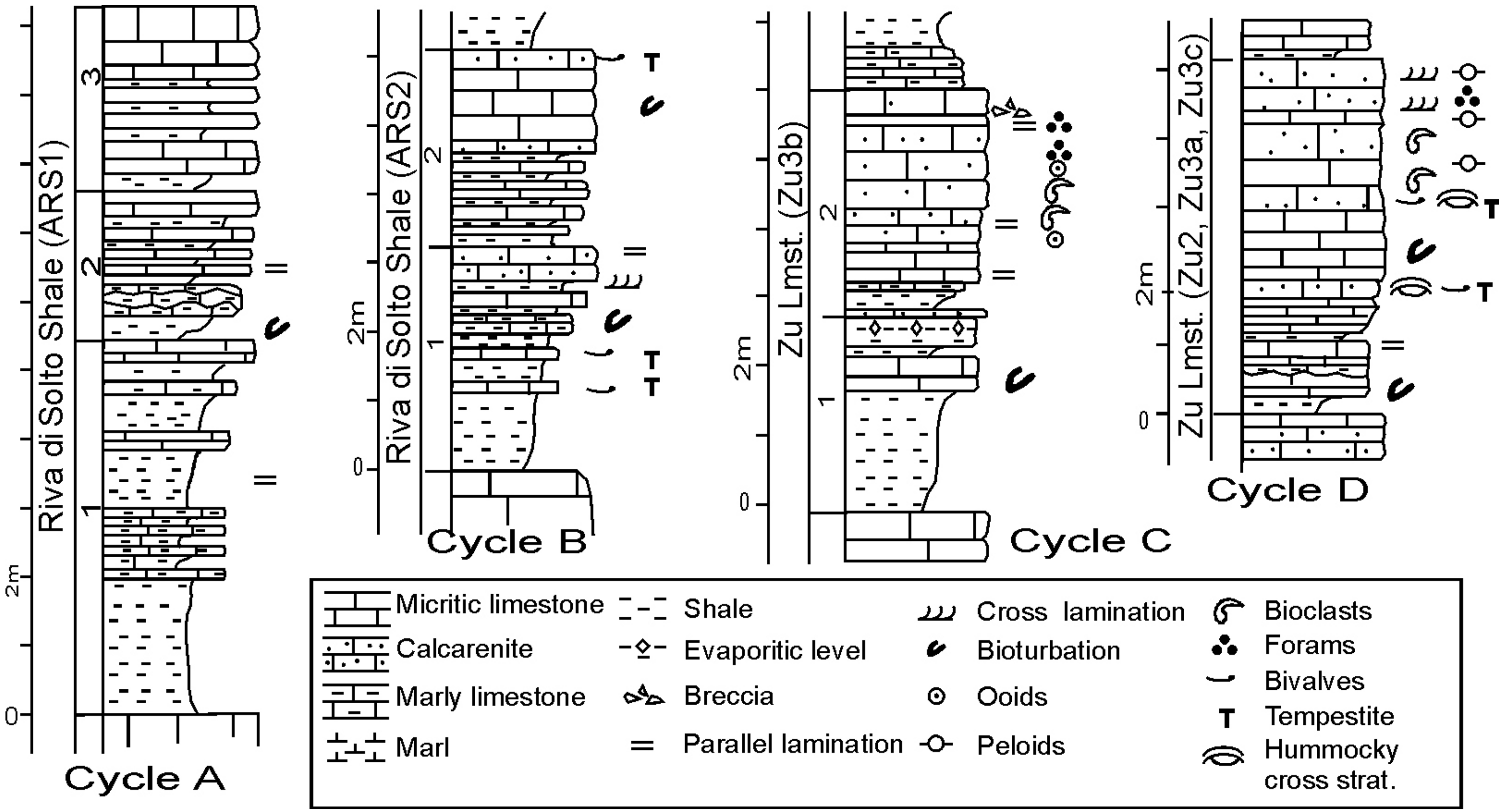

Fig. 3 - Fourth order asymmetric cycles of the Norian-Rhaetian succession. Numbers in vertical columns refer to higher frequency cycles (modified from Jadoul et al., 1994).

A-type cycle characterizes the deepest portions of the basin, corresponding to ARS1 and 2. It is wholly muddy, up to 30 m thick. The lower part consists of black shales poor in fossils. The middle unit is made by dm-scale laminated shales/marl couplets, whereas dark micritic limestone with thin marly layers represents the cycle top. Occasionally slumps and paraconglomerates occur. The depositional environment can be referred to relatively deep (below storm wave base) and poorly oxygenated seafloor within intraplatform troughs and in the outer-slope ramp environments.

B-type cycle is entirely muddy and differs from A-type on the basis of a higher carbonate/shale ratio and of the presence of thin bioclastic storm layers. The faunal assemblage evolves up-cycle: the basal shale/marl contains small endobiontic bivalves, the upper part of the cycle is characterized by larger epibiontic ones. The palynofacies from A and B-type cycles show a high percentage of terrestrial allochthonous material as common background indicative of the proximity of source areas. Dark brownish AOM and large fragments of poorly rounded and sorted inertinite, subordinate vitrinite and abundant pyrite dominate the palynofacies from argillaceous intervals. These palynofacies confirm oxygen-depleted bottoms. In B-type cycles, the palynofacies are characterized by minor amount of AOM and high proportion of sporomorphs and poorly sorted rounded equidimensional inertinite. In the uppermost part of this cycle a blooming of fungi is associated with small fragments of poorly sorted and rounded equidimensional inertinite, which reveal more oxygenated sea floors. This B-cycle was deposited in a low-energy, outer deep ramp environment, where the shallower sea floor allowed the deposition of thin bioclastic storm layers (Jadoul et al., 1994; 2004).

C-type cycle, typical of Zu3b, exhibits a coarsening and shallowing upward evolution. The lower portion of the cycle consists in bioturbated marls bearing poor associations of small bivalves organized in thin storm layers. The central part is composed by an irregular alternation of black marls, yellow/reddish dolostones with carniola-type breccias and fine grained storm layers showing swaley and hummocky cross-stratification. The upper calcareous unit consists of cross-bedded grainstones capped by peloidal limestone. These fine-grained beds could be interpreted as i) inner ramp facies overlying cross-bedded sands during the progradational evolution of the cycle or ii) deeper ramp deposits corresponding to a retrogradational phase. The top of the cycle is sharp and marked by a metallic oxide crust probably related to a non-depositional hiatus between two adjacent cycles. The increasing tempestite proximality, and the coarsening-up trend can be referred to a shallowing-up evolution of these cycles. Palynofacies parameters show that various signatures can be recorded across the cycle. These differences concern the relative abundance of the organic constituents and their preservation rate (Jadoul et al., 1994; 2004), which point to an analogous shallowing upward trend as evidenced by facies analysis. The depositional environment is referred to the mid-inner sectors of ramp.

D-type cycle shows the same trend of the C-type, but the lower marly facies are replaced by thin marly interlayers and bioturbated or laminated fine wackestones/packstones. The cycle is almost entirely characterized by fine to coarse packstones and locally grainstones. In the upper part, bioclastic packstones and coral-rich boundstones may be intercalated. Palynofacies are characterized by high amount of both marine and terrestrial OM, the relative percentages of which vary across the cycle: the amount of marine elements decreases upward within the cycle, while terrestrial fraction increases.
This cyclic organization is typical of the Zu2, Zu3a and Zu3c deposited in the more proximal, inner portion of the carbonate ramp.

Meter-scale, coarsening- and shallowing-up cycles, composed of subtidal carbonates similar to C and D-type cycles, have been described in several papers. The only interpretation of muddy asymmetric cycles without any coarsening-upward trend (cycles A and B, Fig. 3) was published in Masetti et al. (1989) and Burchell et al. (1990), and applied to the same succession previously described. According to these authors, the asymmetric carbonate signal was linked to eustatic fluctuations controlling productivity and accommodation at the top of the platforms, which represent carbonate mud productivity areas. The exportation of carbonate mud to the basin was negligible in the deepening phase and increased during the shallowing evolution and the consequent decreasing in accommodation at the platform top. A subaerial exposure of large platform areas “killed” the carbonate factory, pausing the carbonate mud supply to the basins. The same eustatic fluctuations could generate coarsening- and shallowing-up cycles in the uppermost portion of the ramps. A rough estimate suggested approximately 10^5 years as the order of magnitude for each cycle duration. Basing on conodont biostratigraphy, the Brumano-Albenza composite section illustrated in Stops 1.6, 1.7 and 2.2-2,4 (Figs. 9, 11, 12) has been recently considered as representative of the whole Rhaetian (Rigo et al., 2009; Muttoni et al., 2010). Since (at least) 50-55 high-frequency cycles are recognizable with a approximate duration of 10^5 years, the Rhaetian stage should be ca. 4 My long.

2.4. The platform drowning at the T/J boundary (Malanotte formation)

The thin-bedded Malanotte formation (Stops 2.4, 2.5, 2.6 and 2.7) consists of 15 to 30 m thick micritic limestones, poor in fossils. It represents a regional stratigraphic marker in the central Lombardy developed between two shallow water carbonates units (Zu3 member and Albenza formation - dolomia a Conchodon *Auctorum* – Jadoul & Galli, 2008). At the base of the formation, bioturbations on the bedding surfaces and small slumpings are present, whereas at the top oolitic-bioclastic fine calcarenites alternate with mudstones yielding sponge spiculae, rare radiolaria and small chert nodules. The lithofacies evolution documents a major transgression with monotonous outer carbonate ramp facies associations at the base and a gradual transition to shallower platform environments toward the top. The relative sea level rise and low sedimentation rates controlled the deposition of the Malanotte formation and created the accommodation space for the Albenza platform progradation. Palynological and C-isotope studies carried out on several sections enabled the location of the T/J boundary in the lowermost part of this formation (Galli, 2002; Galli et al., 2005; 2007).

2.5. The early Hettangian Albenza formation

This unit documents the last and most conspicuous regional carbonate platform progradation in the Lombardy Basin, occurred during the early Hettangian. Its thickness ranges from about 100 m to over 250 m in the Iseo Lake area. The lower part of the Albenza formation consists of grey oolitic grainstones with micritized lithoclasts, bioclasts, which represent the platform shoals prograding margin on top of the Malanotte formation (Stop 2.7). The upper part of this Bahamian-type carbonate platform consists of fine peloidal packstones and oolitic grainstones.

FIRST DAY

The upper Norian-lower Rhaetian fine siliciclastic to carbonate high-frequency cycles of the western Bergamasc Alps.

Field trip stops (from 1.1 to 1.8) are located in Fig. 1 and Fig. 4.

Stop 1.1

This stop (Fig. 5) shows the stratigraphic setting of the lower Imagna Valley and the Mt. Albenza characterized by the upper Norian (relatively reduced in thickness) succession lacking, at the top of the Dolomia Principale, of the bioconstructed facies and of the slope and (or) basinal successions (Aralalta group and the overlying facies of the basal ARS). The deposition possibly occurred at the margin of a Norian structural high.

Along the Imagna Valley road, near Caschiettino-Ponte della Grate (Fig.1), one of the best-exposed and complete sections of the ARS2 crops out (Fig. 5A). The uppermost Dolomia Principale represents the base of the section. Since the deposition occurs at the top of

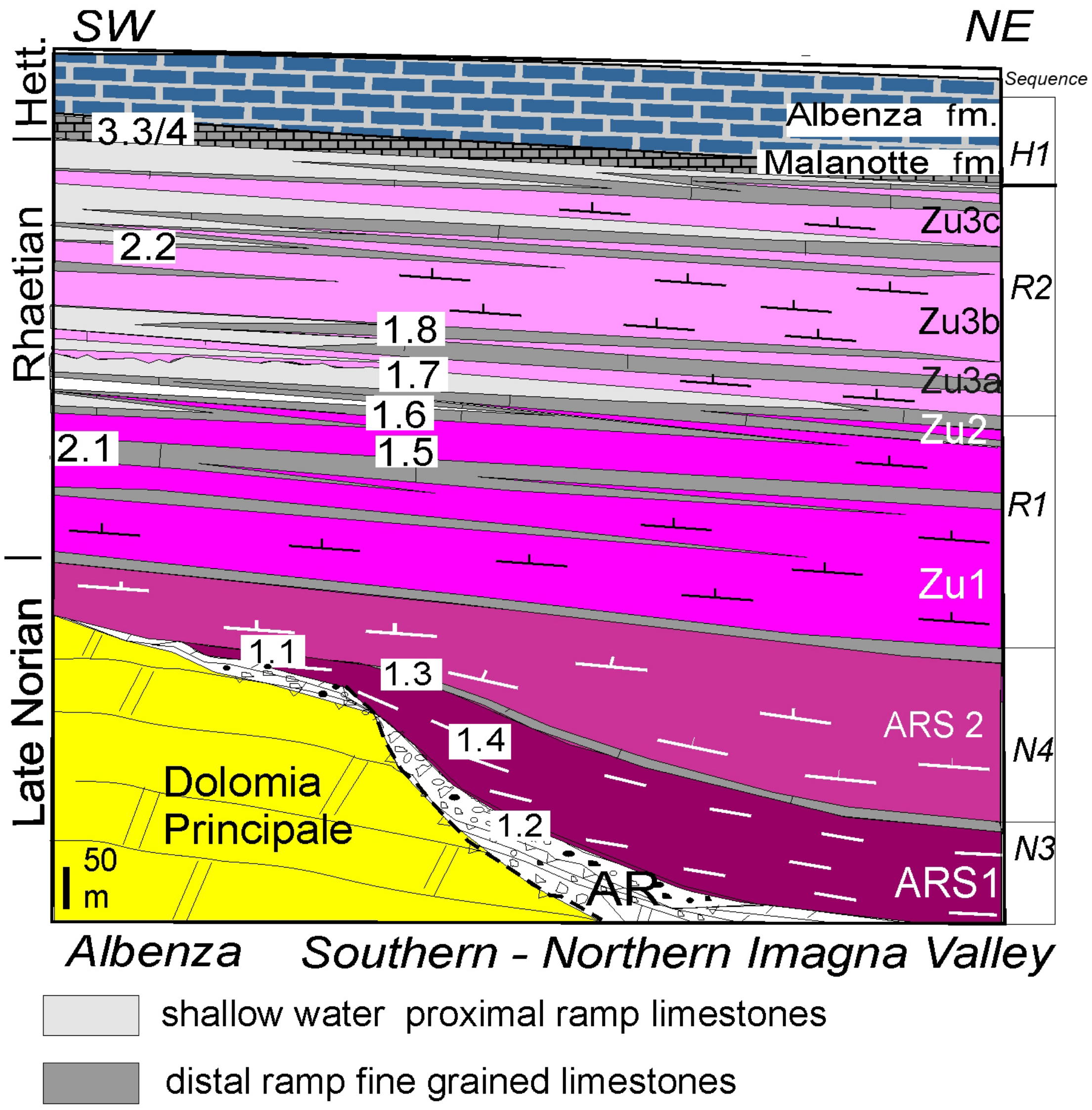

Fig. 4 - Late Norian-Hettangian stratigraphic setting of the visited area with different ramp depositional systems developed on the "Albenza high" and western Imagna-Taleggio Basin and the stratigraphic location of the field trip stops.

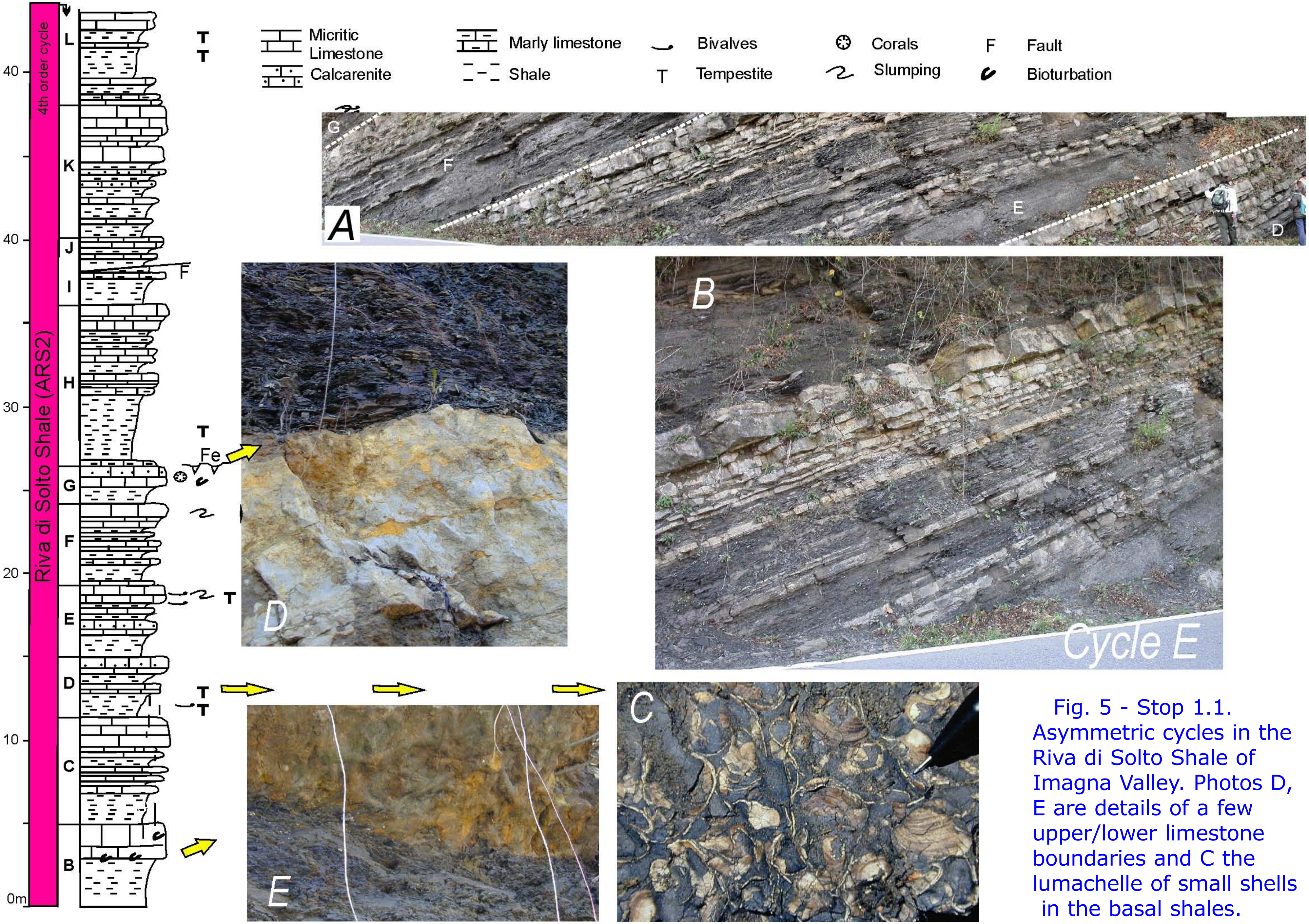

Fig. 5 - Stop 1.1. Asymmetric cycles in the Riva di Solto Shale of Imagna Valley. Photos D, E are details of a few upper/lower limestone boundaries and C the lumachelle of small shells in the basal shales.

a structural high, the ARS1 was not deposited. The whole section (about 60 m thick) consists in 13 cycles asymmetric of fourth order (B-type; Fig. 3). Each fourth order cycle can be further subdivided in smaller-scale fifth order cycles (Fig. 5B). The ARS2 fourth order cycles are mainly muddy and do not exhibit an evident coarsening-up trend clearly referable to a shoaling-up evolution of the depositional environment.

The typical cycle is characterized by a lower portion consisting of dark shales containing thin layers rich in monospecific assemblages of small bivalves (Fig. 5C), indicative of restricted environmental conditions. *Bactrillum* are also common. Toward the top of the cycle, limestones become more abundant: marls and limestones prevail with respect to shales.

Bedding is sometimes reworked by burrows (mainly *Thalassinoides*) introducing limestone into marls and vice-versa and deformed by synsedimentary structures such as slumping and loading. The boundaries between beds are usually transitional, and in particular the lower contacts of calcareous layers do not show erosional features. These layers are often bioturbated and consequently massive, but in some cases they are composed of many amalgamated events.

Palynofacies are dominated by brownish AOM associated with low to moderate percentage of sporomorphs, equidimensional inertinite, dispersed spheroidal and angular crystals of pyrite. Diagenetic and weathering pattern are indicative of a primary nature of the lithological alternations in the central part of the cycle. The palynofacies study of similar cycles in other sections (Laxolo, Imagna Valley) shows a rapid decrease in palynomorphs specimen and a blooming fungal filaments associated to poorly sorted and rounded equidimensional inertinite. The palynofacies variation across the cycle shows a trend from disoxic-anoxic conditions in the lower part (testified by preserved AOM and pyrite) to more oxygenated conditions at the top where the OM is degraded by fungi, bacteria and burrowers (Jadoul et al., 1994; 2004).

Cyclicity seems related to the amount of shale *versus* limestones, documenting both an intrabasinal and extrabasinal source of the sediments. According to the fact that limestones are almost absent at the base of the cycle and shales are absent at the top, it is possible to recognize that the mechanisms that controlled the cyclicity was able to control both the extrabasinal input and the intrabasinal carbonate production. It is therefore possible to suggest that the delivery of shales was probably related to humid conditions, which favored the transport of fine-grained terrigenous material from the European continent to the Tethyan gulf by fresh water, thus lowering the salinity in the Lombardy Basin that prevents a large productivity of limestones.

During the arid portion of the cycle, shales were trapped on the European continent, whereas the normal marine conditions in the Lombardy Basin favored the production and accumulation of limestones. The time series (Claps, in Jadoul et al., 1994) show that all the over imposed fluctuations (lithologic couplets, basic fifth order and fourth order cycles) exhibit a thickening-up tendency, which is reflected in an asymmetric trend. The spectral analysis permits to discard a stochastic mechanism in producing the described cyclicity. The studied section represents the first case where obliquity is identified as dominant over the precession cycle, which so far has been recognized as the common expression of Milankovitch periodicity recorded in supplier platforms. Considering that the obliquity control is stronger at the middle latitude and that the Tethyan gulf was placed more southward, it is possible to suggest that the “Rhaetian Kossen facies” and the climatic changes (from arid to relatively humid marine conditions) on the European continent locally influenced the Tethys gulf sedimentation with periodic input of shales transported by rivers.

Stops 1.2, 1.3 and 1.4. These stops are different from the previous one for the major thickness of the Norian succession and for (tectonically controlled) slope facies belonging to the Aralalta group (uppermost breccias of the Dolomia Principale and “dolomie zonate”) and to the basal ARS. This succession characterizes the stratigraphic and tectonic evolution of the eastern margin of the Mt. Albenza structural high and of the overlooking basin of the Northern Imagna Valley.

Stop 1.2

Along the road from the Ponte Giurino pitch to the S. Omobono Valley, the uppermost Dolomia Principale is cropping out. It is represented by lenses of polygenic and dolomitized chaotic breccias (Fig. 6 and Fig. 7) often with matrix support characterizing lenticular and canalized bodies at the top of the Dolomia Principale. Breccias are also intercalated with fine blackish well-bedded dolomites (“dolomie zonate”) locally characterized by slumpings and lenticular geometries (Fig. 6). In the breccias, bioconstructed dolomites typical of numerous margin of the Dolomia Principale have not been observed. This absence could document the formation of an inner tectonic-controlled slope margin not colonized and limited by bioconstructions (e.g. serpulids, microbialites; Berra and Jadoul, 1994).

Fig. 6 - Stop 1.2. **A, B** Panoramic view of a thick channelized dolomitic breccia at the top of the Dolomia Principale. **C:** Large syndepositional fold (slumping) involving bedded fine grained dolostones interbedded with breccias (“dolomie zonate”). **D, E:** Details of dolomitic breccias with polygenic clasts and boulders of “dolomie zonate” and Dolomia Principale.

Stop 1.3

The stop gives the opportunity to observe the first thick horizon of micritic carbonates of the ARS1, representing a stratigraphic marker of the entire Imagna Valley. Along the Imagna Valley road, we can observe a different ARS succession, separated by a fault from that of Stop 1.1. A thick A- type cycle (Fig. 3) at the top of the ARS1 and the boundary with the ARS2 are cropping out. The base consists of black shales, marls with slumpings (Fig. 7B) and large clay chips, covered by laminated marls and marly limestones.

The top of the cycle is characterized by a 17 to 20 m thick micritic carbonate horizon (stratigraphic marker in Imagna Valley) (Fig. 7A) represented by monotonous dark grey mudstones with thin marly interlayers. Near the top fine matrix-supported paraconglomerates are present. The top of the cycle is characterized by a paraconformity (Fig. 7C) exhibiting small intraformational breccia lenses (boundary ARS1/ARS2). In other outcrops of the Imagna Valley this boundary is also marked by a low angle unconformity. The overlying marls and marly limestone succession is characterized by rhythmic and planar arrangement of laminae (1 to 20 mm thick). The organic matter analyses are described in A-type cycle (chapter 2.3.5). The palynofacies from this interval show cyclic pattern, each of 7-9 laminae. Each light-dark couplet shows in the dark laminae an enrichment in AOM (up to 60%), which often masks the sporomorphs, associated with pyrite and, in the light ones an increase of fungal remains and inertinite (Jadoul et al., 1994; 2004).

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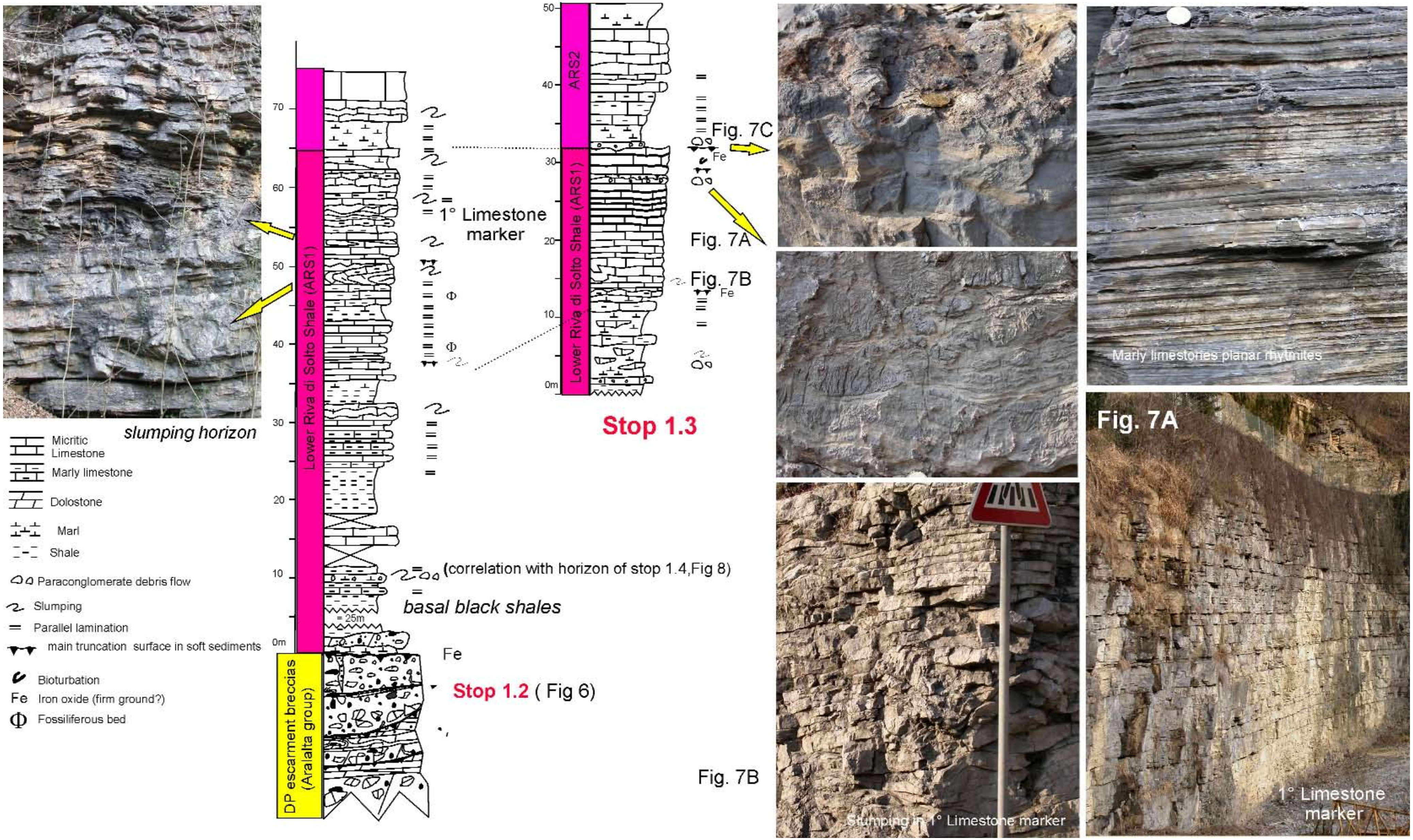

Fig. 7 - The ARS1 stratigraphic section of Ponte Giurino with several sin depositional deformations (slumping), the stratigraphic boundary with the slope-escarpment breccias of the upper Dolomia Principale/"dolomie zonate" (stop 1.2), and the "Zorzino type" limestone marker (stop 1.3) of Ponte Giurino representing the ARS1/ARS2 boundary in the Imagna-Taleggio basin.

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Stop 1.4

This stop, located at the beginning of the provincial road for Rota Imagna, leads to see a thin calcilutite horizon (Fig. 8A) intercalated at the base of ARS1. Varve-type laminations are present and interested by a few reactivation surfaces (minor erosional disconformities and local folding (from centimeter to decimeter scale). This sinsedimentary structures are interpreted as slope gravitational deformations and are very frequent on the southwestern margin of the Imagna-Taleggio basin. They are possibly related to a regional elevated seismo-tectonic activity during the ARS1 time deposition (Figs. 2b and 4 show paleofaults/escarpments that westward delimit the half-graben geometry of upper Norian AR, ARS; more details in Jadoul et al., 1992a).

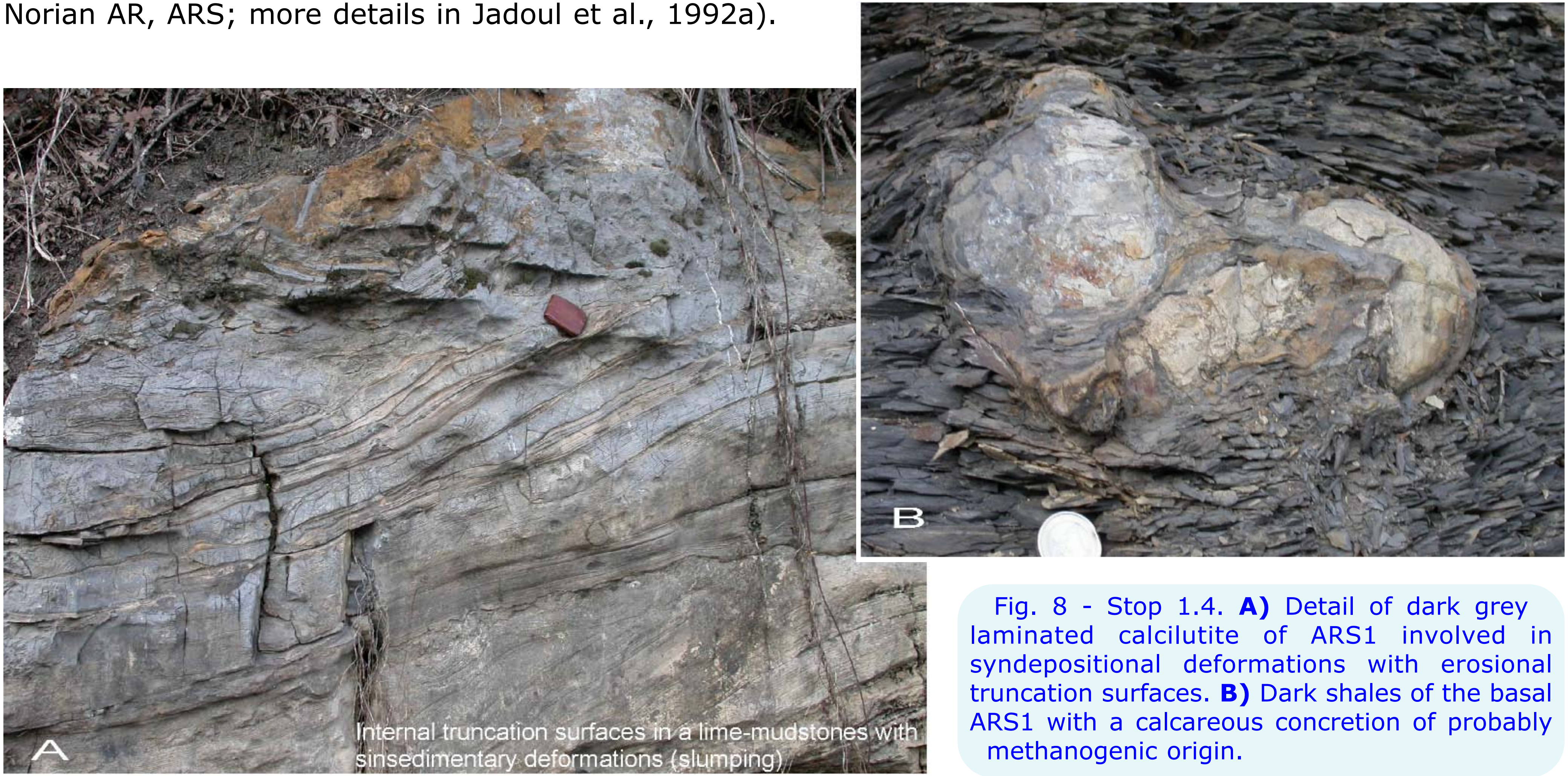

Fig. 8 - Stop 1.4. **A)** Detail of dark grey laminated calcilutite of ARS1 involved in syndepositional deformations with erosional truncation surfaces. **B)** Dark shales of the basal ARS1 with a calcareous concretion of probably methanogenic origin.

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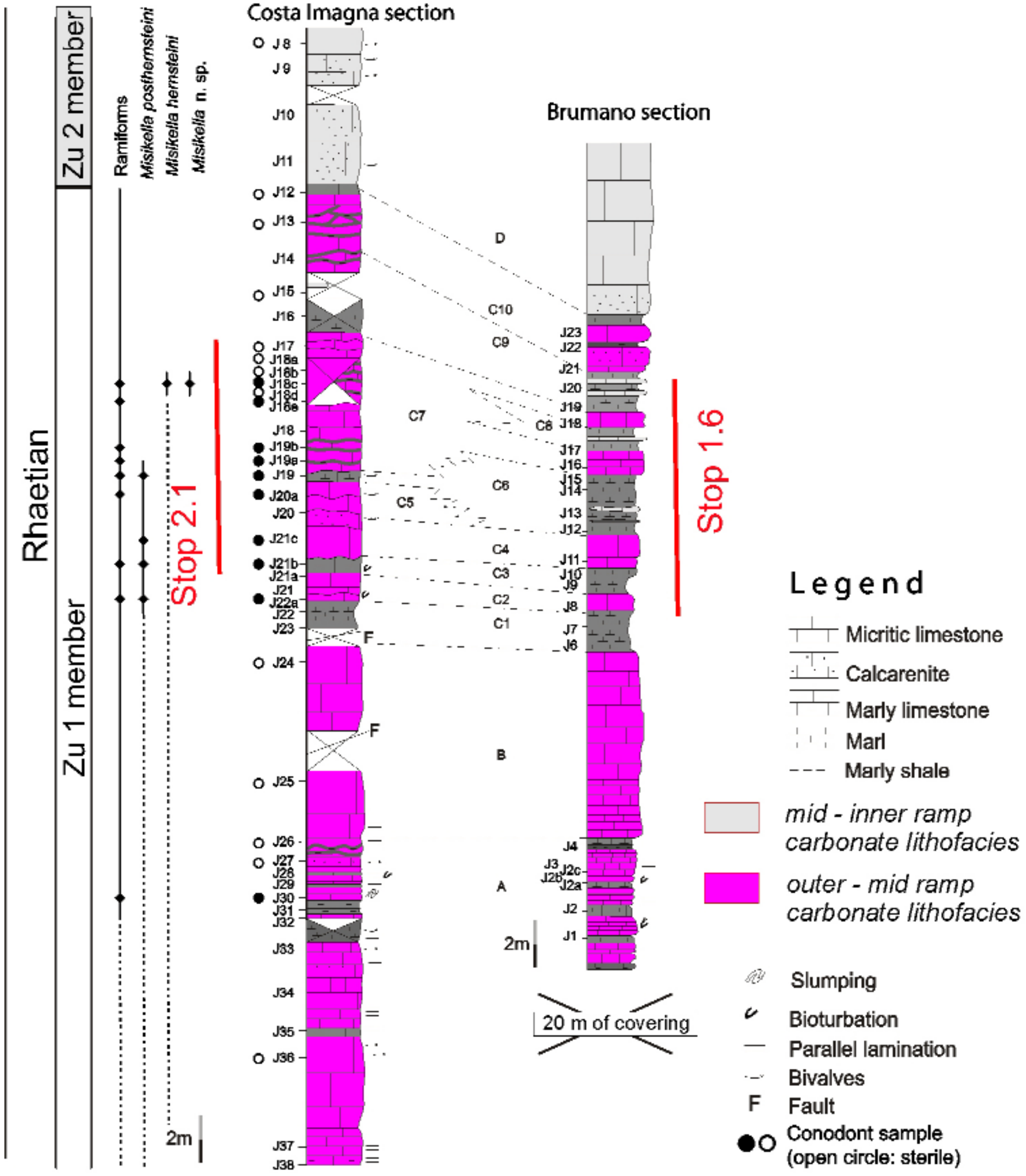
Stop 1.5

This stop is developed along the road to Brumano. Upstream of Rota Imagna the lower Zu Limestone is cropping out. The succession consists of monotonous alternations of shaly marls, marly limestones and micritic limestones stratified at the top. The cyclicity of the lower Zu Limestone is less clear respect to the upper Zu Limestone. Symmetric cycles are also present. Fossiliferous carbonates are more frequent upwards.

Brumano section has been recently studied for conodont analyses to better understand the age of the base of the Zu1 member, which represents the lower part of the Zu Limestone Formation. The Brumano section consists of two outcrops separated by about 20 m of covering (Fig. 9).

The upper outcrop might be physically correlated to the Costa Imagna section, which is well-calibrated with conodont biostratigraphy (see Stop 2.1, Fig. 9 and Fig. 10). For this reason the upper stretch of Brumano section has not been studied under biostratigraphic point of view. Particular attention has been instead focused on the lower outcrop of the Brumano section where already from the lowermost sample (J282), a specimen of *Misikella posthernsteini* along with a *Misikella hernsteini* occurs, confirming the Rhaetian age of the base of the Zu1 member. The joint occurrence of these two species marks out the *M. hernsteini-M. posthernsteini* Subzone, the lower part of the *M. posthernsteini* Assemblage-Zone *sensu* Kozur and Mock (1991), Rhaetian in age and corresponding to the *Paracochloceras suessi* and *“Choristoceras” haueri* ammonoid Tethyan Zones proposed by Krystyn (1987, 1990), recently confirmed by Krystyn et al. (2007). The presence of the *Misikella posthernsteini* together with *Misikella hernsteini* characterized the investigated Brumano section. In the upper part of the lower Brumano outcrop, *Misikella koessenensis* occurs. *Misikella koessenensis* usually is more frequent, but however not common, in the upper Rhaetian and it is a typical component of the fauna of the *Misikella koessenensis* conodont Subzones described by Kozur and Mock (1991), that is the upper part of the *Misikella posthernsteini* Assemblage Zone (Fig. 10). The lower boundary of *Misikella koessenensis* Subzone is marked by the disappearance of *Misikella hernsteini* that means the FO (First Occurrence) of *Misikella koessenensis* does not define the base of its homonymous Subzone. According to Moix et al. (2007), *Misikella koessenensis* appears already in the lower part of the *Misikella hernsteini-Parvigondolella andrusovi* Zone (uppermost Sevatian, upper Norian), even if extremely rare, and still present up to the whole *Misikella posthernsteini* Zone.



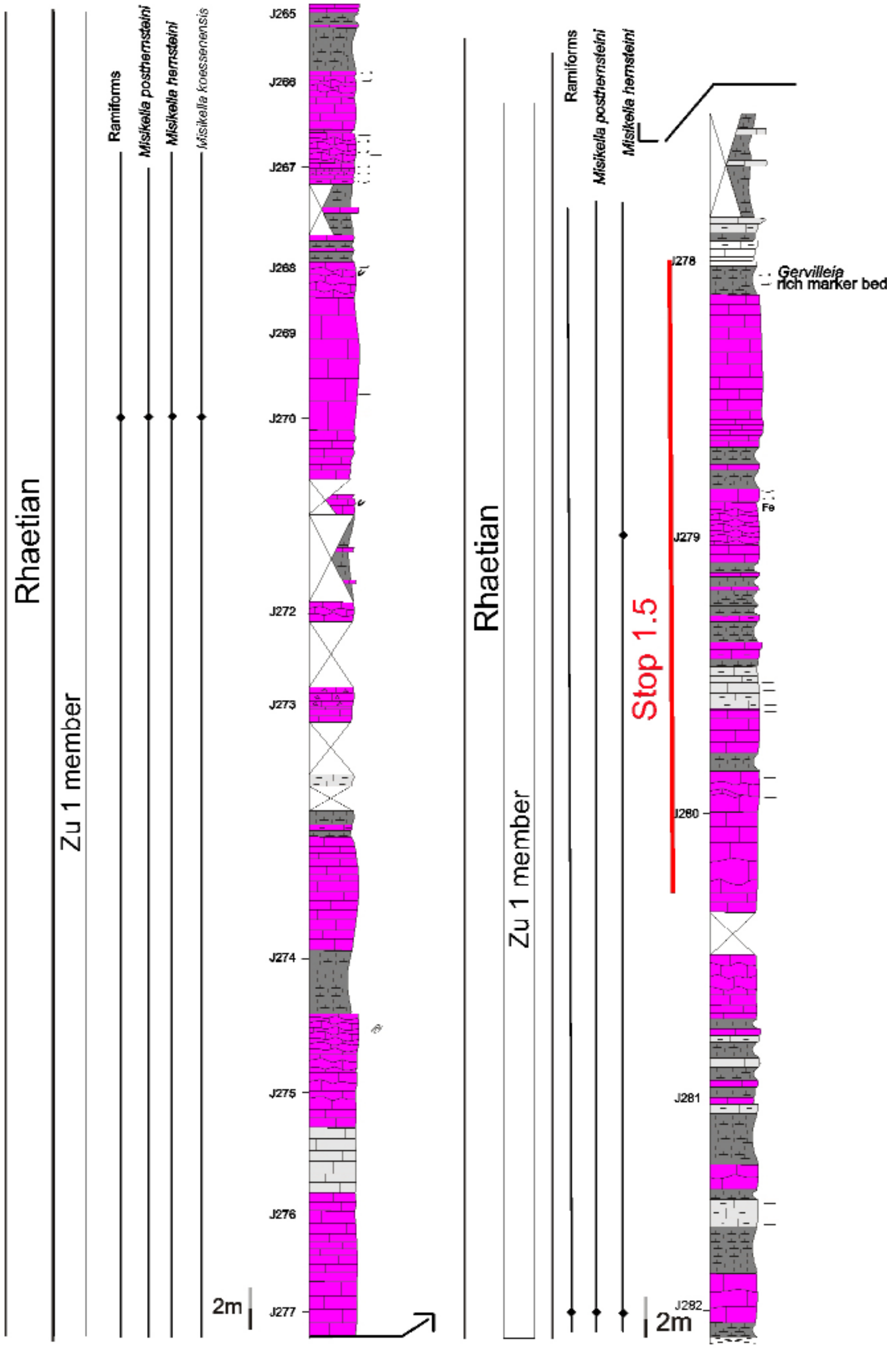


Fig. 9 - Stratigraphic correlation between the thick Zu1 section of Brumano (sampled for magnetostratigraphy, stop 1.6 and conodont biostratigraphy for the Norian/Rhaetian boundary, stop 1.5) and the Costa Imagna section (conodont biostratigraphy below the Zu1/2 boundary, Stop 2.1).

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Stage		Ammonoid Zone	Conodont Zone by Kozur & Mock, 1991	
Lias		*Psiloceras planorbis*	*Neohindeodella detrei* Zone	
Rhaetian	upper	*Choristoceras marshi*	*Misikella ultima* Zone	
		Choristoceras ammonitiforme	*Misikella posthernsteini* Assemblage Zone	*Misikella koessenensis* Subzone
	lower	*Vandaites stuerzenbaumi*		
		"Choristoceras" haueri		*Misikella hernsteini - Misikella posthernsteini* Subzone
		Parachocloceras suessi	*Misikella hernsteini - Parvigondolella andrusovi* Assemblage Zone	
Norian (Sevatian)		*Sagenites reticolatus*		

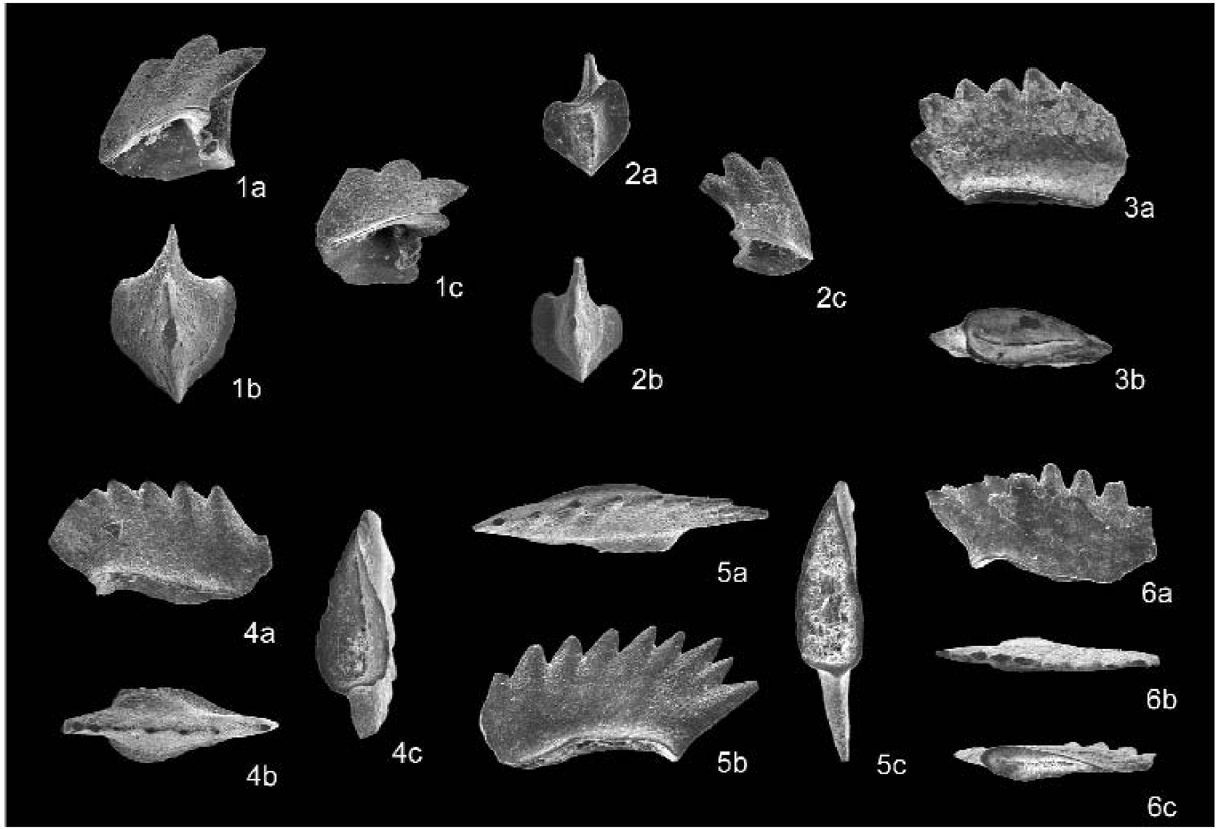

Fig. 10 - Conodont biostratigraphy (Stop 1.5 and Stop 2.1) and SEM conodont micrographs of Costa Imagna lower Zu Limestone (Zu1) section (Fig.9):
1, 2) Misikella posthernsteini Kozur and Mock, 1974, sample J 22a;
3, 4, 5) Misikella hernsteini (Mostler), 1967; Zu Limestones Fm., Zu 1 member, sample J 18c;
6) Misikella n. sp. A; sample J 18c.
Major details in the text.

Stop 1.6

The succession continues along the Rota Imagna-Brumano road, where the remaining Zu Limestone succession crops out (Fig. 11). In correspondence of a lateral valley it is possible to observe the top of Zu1 member characterized by a few marly horizons rich in fossils. The Zu1-Zu2 transition (Fig. 9 and Fig. 11) consists of meter to decameter marl-limestones cycles. Marls contain large bivalves (*Homomia sp., Cardita sp., Trigonia sp.*). The overlying bioturbated limestones at the top of the cycles yield corals, brachiopods, crinoids and foraminifers, phosphate clasts and quartz grains. The Zu2 is characterized by a sharp decrease of the fine siliciclastic content (Fig. 11).

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Stop 1.7

This stop and the next one are focused on the thick Rhaetian carbonate platform (Zu2 member).
Three minor subdivisions can be recognized within the Zu2.

a) Lower Zu2: the platform succession is characterized by a 18 m thick, shallowing upward and, in part, coarsening upward carbonate cycle (D-type cycle; Fig. 3) consisting of mudstones-wackestones and associated *Retiophyllia spp*. patch reefs at the base. Bioclastic packstones with sponge, echinoids, *Microtubus* sp., *Porostromata* and foraminifers (among which *Triasina hantkeni*) and mudstones overlying fine breccias are more common at the top (Fig. 11).

b) Middle Zu2: it is characterized by intra-bioclastic packstones with fenestrae, covering marly limestones with chert nodules and interspersed corals. Towards the top of this part of the succession, the trend is still shallowing and coarsening upward and the facies commonly consist of intra-bioclastic, foraminiferal packstones, bioclastic storm-layers and oolitic grainstones. Cross laminations and wave ripples are quite common.

Stop 1.8

This stop is focused on the shallow water regressive platform carbonates at the top of the Zu2 member and the overlying the marly-limestone cycles of the upper Zu (Zu3a lithozone of Jadoul et al., 1994; 2004).

c) The upper Zu2 (Fig. 11): it consists of two major shallowing and coarsening upward cycles (D-type) with bioturbated mudstones and wackestones at the base and, upward, bioclastic packstones, oolitic grainstones and thin planar stromatolitic bindstones. Small encrusted *Porostromata* colonies and bioclastic lenses with brachiopods (*Rhaetina gregaria*) characterize the base of the prograding oolitic shoals. Erosional surfaces, current ripples, cross bedding and sedimentary dikes characterize the top of this member that is also partially dolomitized and shows a local disconformity at the top with breccia pockets and oolitic grainstones). The overlying succession records the recovery of marl/limestone cycles (Zu3a) (Fig. 11). The first cycle is still transitional, with prograding oolitic shoals at the top. The arrangement of the overlying asymmetric cycle differs in the minor fossil content and for the predominant laminated mudstones, dolomitized marls and ochre, vuggy marly limestones (C-type cycles; Fig. 3). These facies represent the lower Zu3, which is observed in detail in the Stop 2.2. The facies evolution of Zu2 illustrates a general shallowing trend related to the prograding carbonate ramp system on the Imagna-Taleggio depression (Fig. 4). The eustasy-controlled shallowing trend also allowed the development of inner-middle ramp facies on the Albenza-Imagna sector (top of the succession) and local subaerial exposures. The overlying, cyclic lower Zu3 facies record a progressive crisis of carbonate production in the ramp system polluted by terrigenous input (Fig. 4).

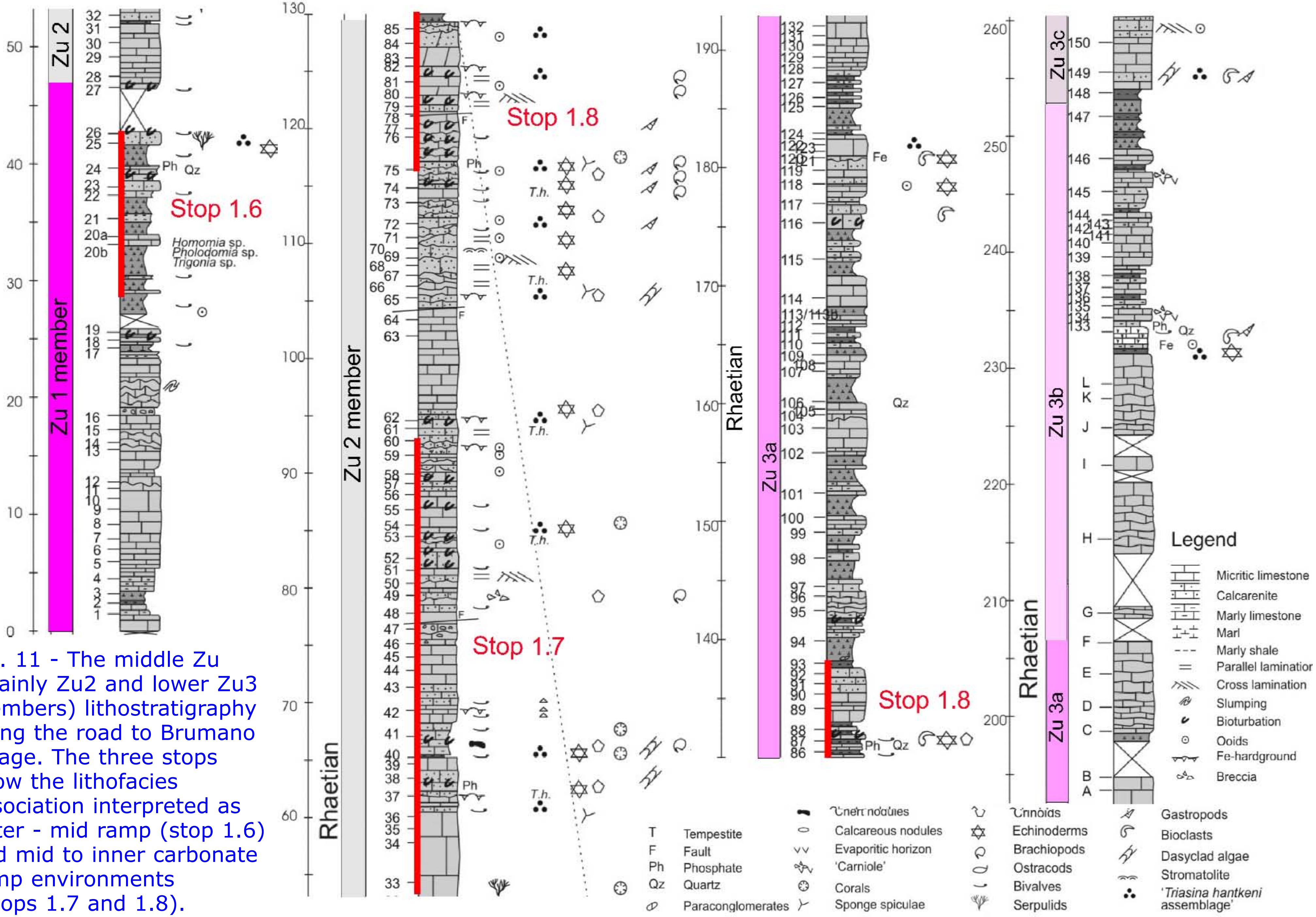

Fig. 11 - The middle Zu (mainly Zu2 and lower Zu3 members) lithostratigraphy along the road to Brumano village. The three stops show the lithofacies association interpreted as outer - mid ramp (stop 1.6) and mid to inner carbonate ramp environments (Stops 1.7 and 1.8).

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SECOND DAY

The Rhaetian marly to carbonate ramp cycles and the T/J stratigraphic boundary.

Field trip stops (from 2.1 to 2.7) are located in Fig. 1 and Fig. 4.

Stop 2.1

Along the Costa Imagna-Valcava road the Upper Triassic succession is cropping out (Fig. 9). It represents the sedimentation occurred in the structural high of the Mt. Albenza, as testified by the absence of the ARS1 and by the very thick ARS2 succession. Close to the village Costa, the middle-upper Zu Limestone and the boundary with the platform carbonates of the Zu2 member are cropping out. The lower Zu Limestone is typically cyclic, with mainly carbonate cycles less thick than previous outcrops described in stops 1.5 and 1.6. Several samples have been collected and worked for conodont investigations from both the Zu1 and Zu2 members of the Costa Imagna section (Fig. 9). As expected, the lithozone D, corresponding to the lowermost Zu2 member of the Zu Limestone Formation failed to give in conodonts due to the progressive establishment of shallow-water environment. The Zu1 member, which is equivalent to the other lithozones (A-C), instead, yielded a useful conodont fauna mainly composed of the species *Misikella posthernsteini* Kozur and Mock, *Misikella hernsteini* (Mostler) and *Misikella* n. sp. A. Also some ramiform elements have been recovered in some samples. The conodont distributions are illustrated in Fig. 9. According to Kozur & Mock (1991), the joint occurrence of *Misikella posthernsteini* Kozur and Mock and *Misikella hernsteini* (Mostler) characterized the *M. hernsteini-M. posthernsteini* Subzone that is the lower part of the *M. posthernsteini* Assemblage-Zone (Kozur & Mock, 1991; Fig. 10). The stratigraphic range of the *M. hernsteini - M. posthernsteini* Subzone is equivalent to the *Paracochloceras suessi* and “*Choristoceras*” *haueri* ammonoid Tethyan Zones proposed by Krystyn (1987, 1990). Recently the FAD (First Appearance Datum) of *Misikella posthernsteini* has been well calibrated with the FO of the ammonoid *Paracochloceras suessi*, which is largely used to mark the Norian/Rhaetian boundary and which has been proposed as a possible biomarker for the base of the Rhaetian (Krystyn et al., 2007). Thus, if the FAD of *Misikella posthernsteini* is used to define the boundary between Norian and Rhaetian stages, then the upper part of the Zu1 member, which corresponds to the *M. hernsteini - M. posthernsteini* Subzone, is lower Rhaetian in age.

Stop 2.2 and 2.3. They are focused on the upper Rhaetian stratigraphy along the private Italcementi road on the SW side of Mt. Albenza between 1000 and 1100 m in altitude (photo cover of this guide, Figs. 12, 13).

Stop 2.2

Along the road to an abandoned quarry, the succession from the upper Zu Limestone to the Albenza fm. is well cropping out. The upper Zu (Zu3 member, from 120 to over 200 m thick) is subdivided into three lithozones (Jadoul et al., 1994) that document the lithofacies association and the stratigraphic architecture of the typical end Triassic carbonate ramps with fine siliciclastic inputs (Lakew, 1990; Galli et al., 2007). The lower one (Zu3a) consists in marls, marly and micritic limestones arranged in 7.5 to 15 m thick asymmetric cycles, rarely characterized by shallowing- and coarsening-upward trend (from fine peloidal packstones to ooidal or bio-intraclastic grainstone). They locally exhibit thin iron-oxide crusts at the top. The middle lithozone (Zu3b) is represented by thinner cycles (4 to 9 m thick) consisting of grey to greenish marls and black marly shales, grading into marly lime-mudstones and peloidal wackestones to packstones. Evaporitic facies and bioclastic, iron-rich packstone (tempestites) characterize the middle part of the cycles, while iron-oxide crusts (hardgrounds/firmgrounds) are frequently present at the top of the cycles (Figs. 12 and 13).

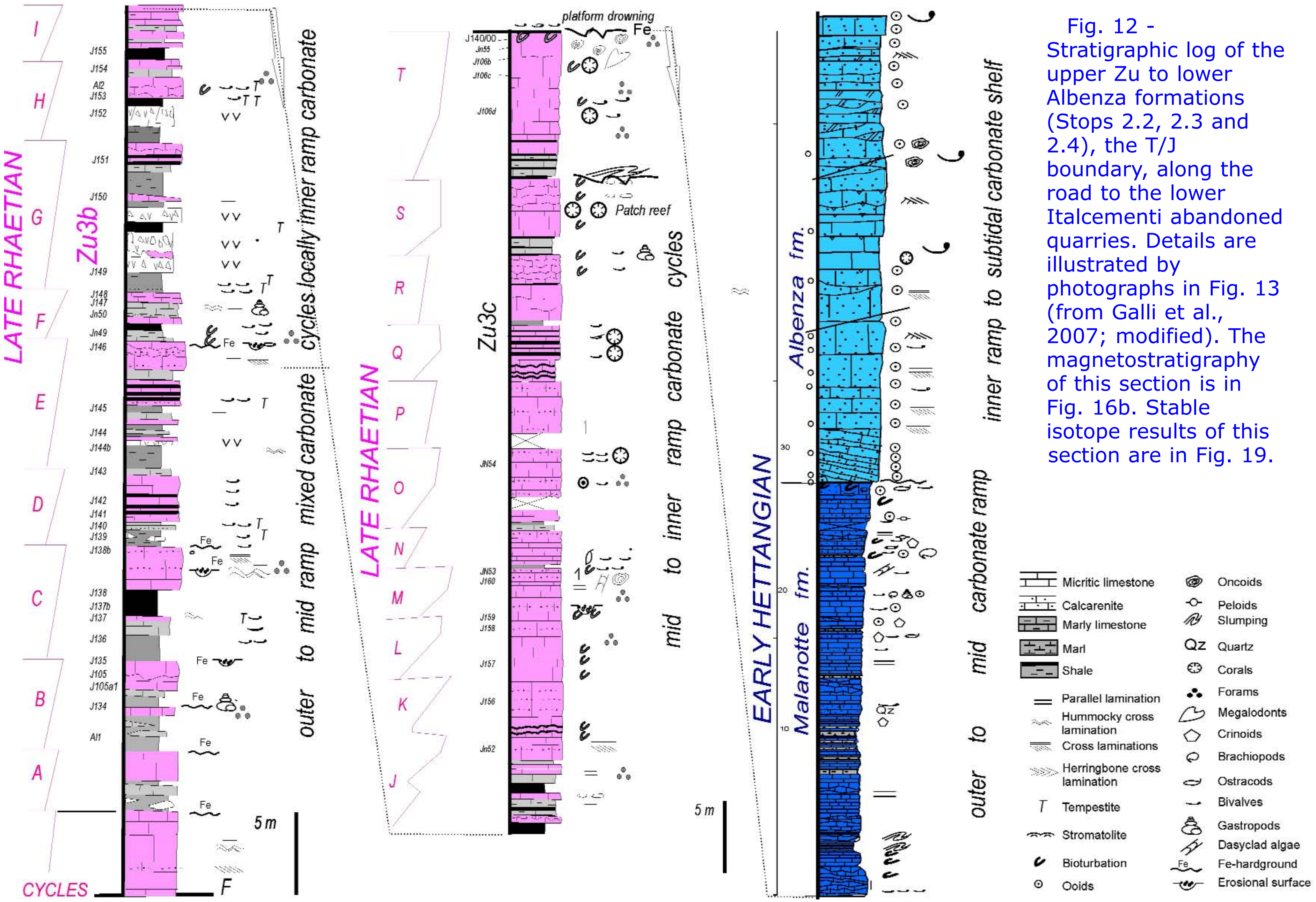

Fig. 12 - Stratigraphic log of the upper Zu to lower Albenza formations (Stops 2.2, 2.3 and 2.4), the T/J boundary, along the road to the lower Italcementi abandoned quarries. Details are illustrated by photographs in Fig. 13 (from Galli et al., 2007; modified). The magnetostratigraphy of this section is in Fig. 16b. Stable isotope results of this section are in Fig. 19.

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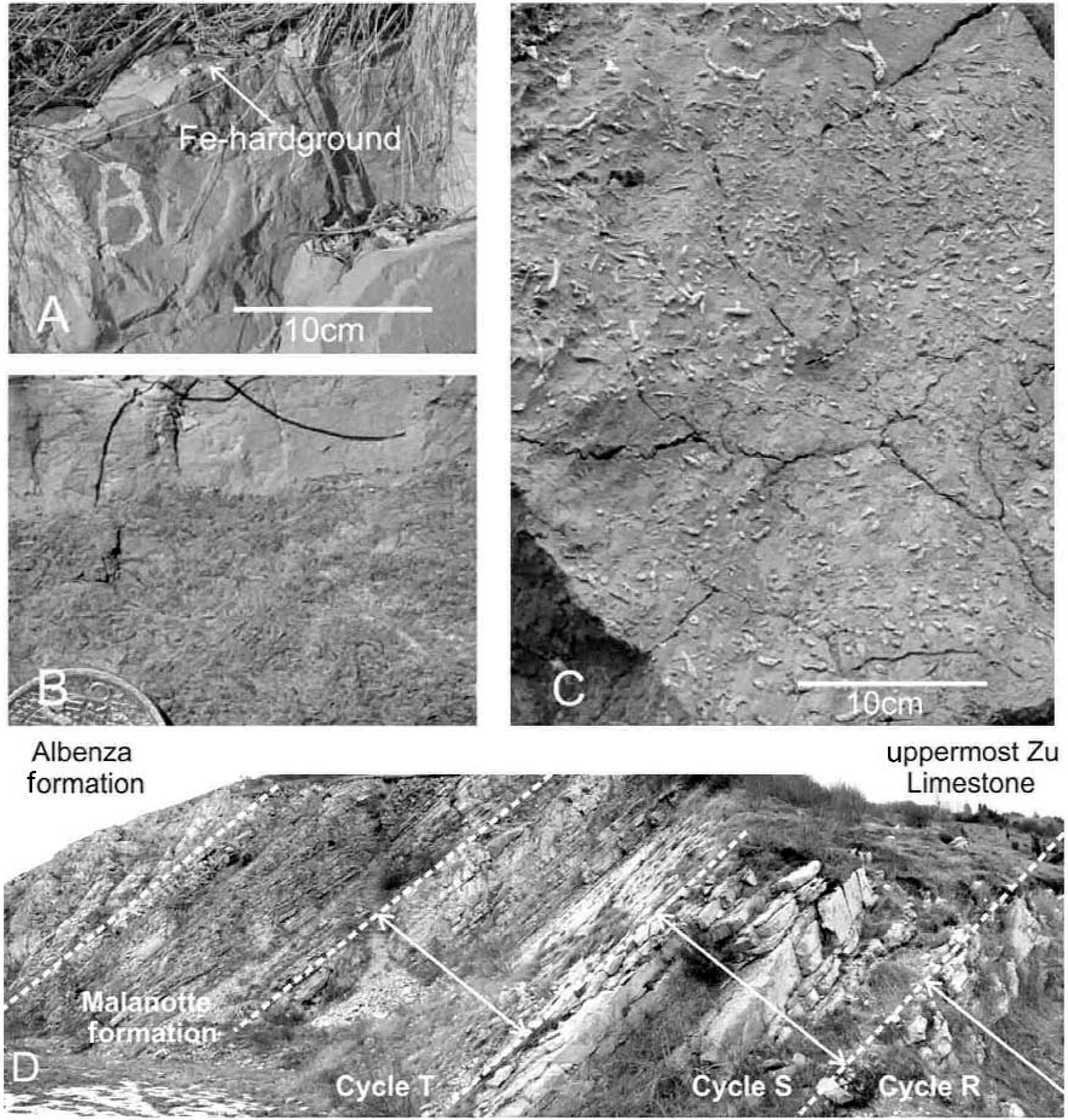

Fig. 13 - The cyclic succession of the upper Zu (Zu3) in the Italcementi quarry section (Fig. 12).
A) Fe-hardground at the top of Cycle B;
B) tempestite in the middle of cycle E (Fig. 12);
C) coral (Retiophyllia) patch reef in Cycle S;
D) view of the uppermost Zu cycles, the sharp boundaries to the basinal Malanotte limestones and to the overlying shallow water Albenza carbonates (from Galli et al., 2007, modified).

Palynofacies contain high percentage and high species diversity of sporomorphs often in tetrad status, associated with other terrestrial phytoclasts (tracheids, cuticules and wood remains). A peak of xerophytic sporomorphs is recorded in the carniole-type horizons (Jadoul et al., 1994; 2004).

Facies association of this succession is interpreted as a mid ramp environment. In the Albenza area this terrigenous-carbonate sedimentation records also hypersaline and restricted conditions and hiatuses at the top of several asymmetric cycles (Zu3a and Zu3b).

Stop 2.3

The upper lithozone (Zu3c; Fig. 12) consists of 40–50 m of mainly bioturbated wackestones to shallow water packstones and grainstones. The fossil assemblages are very rich at the top of Zu3 carbonate succession: benthic foraminifers, corals, calcisponges, bryozoans, problematica and encrusting organisms (Lakew, 1990) are common, together with corals and calcispongia patch-reefs, with large megalodontids and oncoidal limestones (Fig. 14A and Fig. 14B).

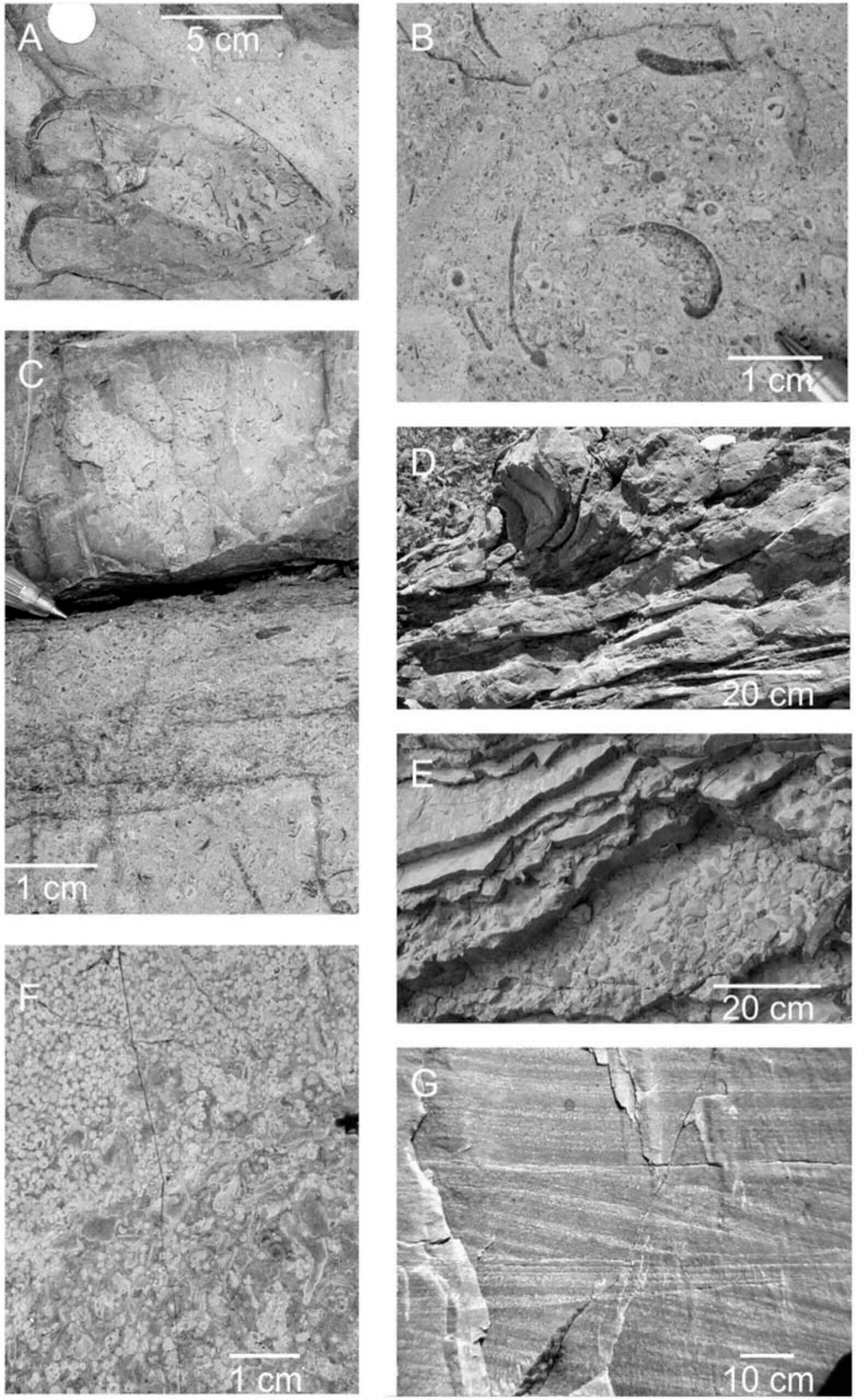

Fig. 14 - Large megalodontid **(A)** and bioclastic-oncoidal limestone **(B)** in the last rhaetian carbonate cycle T (Figs. 12, 13). **(C)** Close-up view of the T/J boundary in the Italcementi abandoned quarry (Fig. 12). The drowning unconformity at the top of the Zu is represented by a thin bioclastic layer. The overlying subtidal limestones (Malanotte fm.) present bioturbation along the bedding planes (**E**) and slumpings **(D)**.
The lower Albenza fm. is characterized by oolitic grainstone, rudstone with ooids, aggregated, microbial coated grains and intraclasts **(F)**, frequently with cross laminations and selective dolomitization (white bands) **(G)**, Italcementi quarry section (from Galli et al., 2007).

The rich foraminiferal assemblage (Fig. 15) is dominated by *Triasina hantkeni* Majzon, with common *Gandinella falsofriedli* (Salaj, Borza and Samuel), *Aulotortus sinuosus* Weynschenk and *Auloconus permodiscoides* (Oberhauser). *Thaumatoporella parvovesiculifera* (Raineri), *Austrocolomia* sp., *Ammobaculites* sp., *Planiinvoluta* sp. and Nodosariidae are also present. Moreover, the microfacies is characterized by bivalves, crinoids, gastropods, calcisponges (*Sphintozoa*), coprolites (*Parafavreina* sp.), ostracods, corals and dasycladacean algae. The rich and diversified benthic foraminiferal assemblage and the reef communities and other reef-associated organisms, including the calcified sponges, disappear at the top of the Zu Limestone.

Palynofacies show an increase in marine OM (i.e. dinoflagellate cysts, foraminifer linings and algal spores), reflecting high productivity, low rate of terrigenous pollution and shallow water normal marine conditions.
Zu3c identifies the second, regional progradation of the carbonate platform. Facies organization of Zu3c documents the latest Rhaetian carbonate inner ramp progradation in central Lombardy characterized by a shallowing and shoaling upward trend. This regression could be related to a relative sea level fall at the end of Triassic, confirmed also by the evidence of a local meteoric diagenesis at the top of the Zu3 member (Lakew, 1994).

The above mentioned section in the Italcementi Quarry has been studied for magnetostratigraphy (Figs. 16a, b) in conjunction with the nearby Costa Imagna and Brumano sections (Muttoni et al., 2010). These composite magnetostratigraphic data straddling from the base of the Rhaetian to the T/J boundary have been correlated to published data from the Tethyan marine Pizzo Mondello section (Muttoni et al., 2004) and the Newark astronomical polarity time scale (Kent and Olsen, 1999). This correlation framework indicated (1) a position of the Norian/Rhaetian boundary (as defined at Brumano and Pizzo Mondello by the first appearance of *Misikella posthernsteini*) within Newark magnetozones E17r–E19r in the ~207–210 Ma time interval, and (2) a position of the Triassic/Jurassic boundary (T/J) interval (placed at Italcementi Quarry at the acme of *Kraeuselisporites reissingeri* and coincident with a negative carbon isotope excursion) correlative to just above Newark magnetozone E23r and just below the oldest CAMP lavas dated at ~202 Ma. For further information, see Muttoni et al. (2010).

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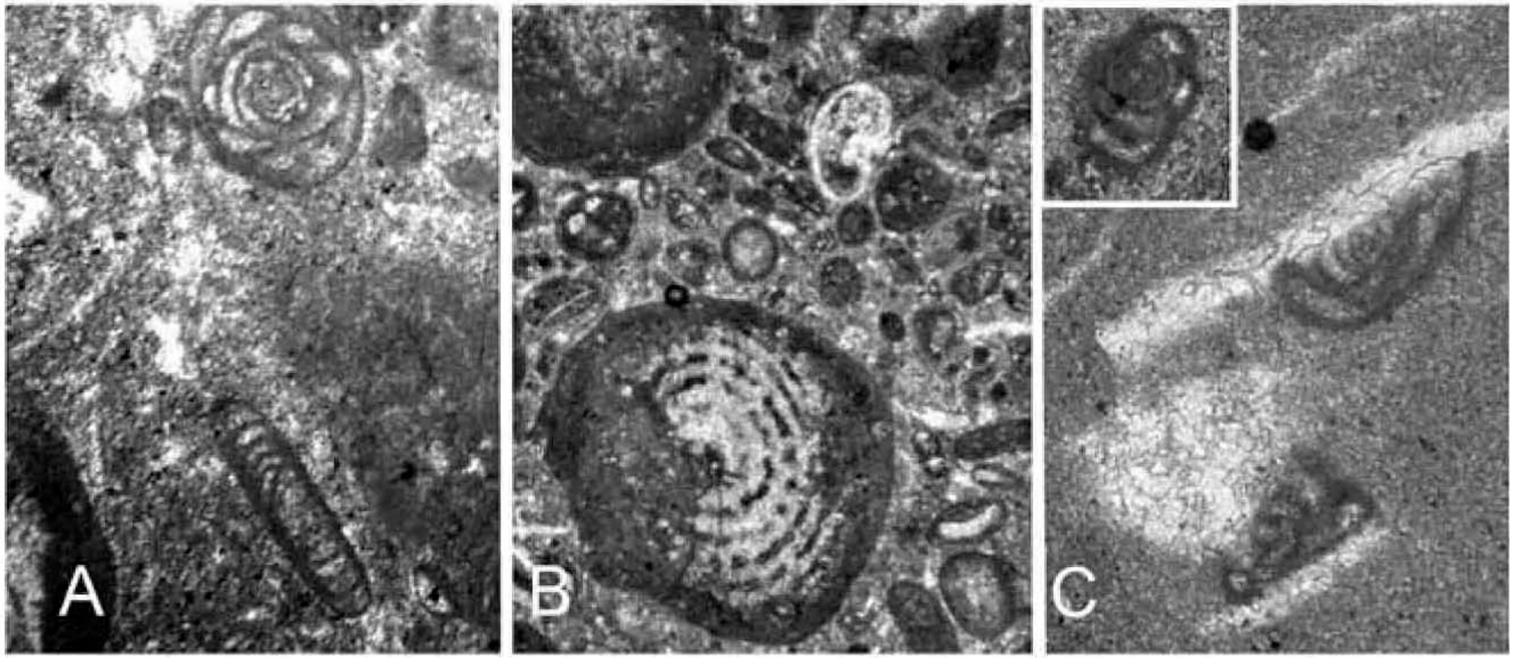
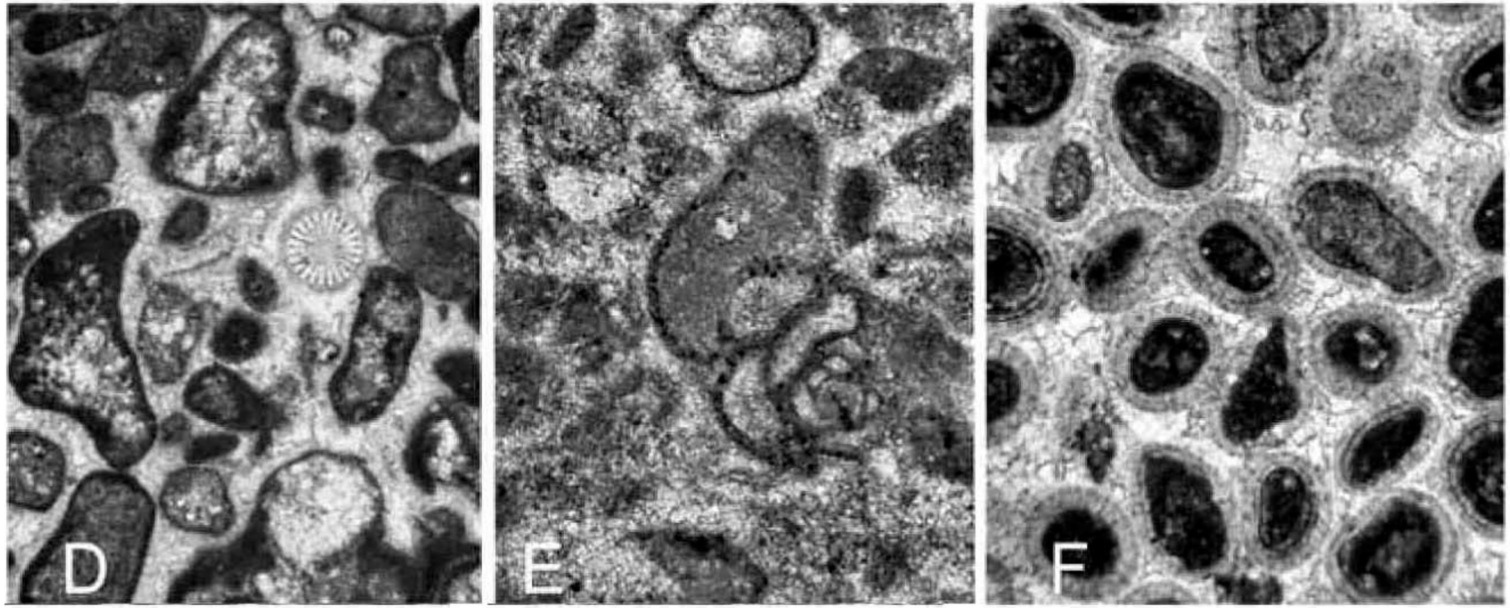


Fig. 15 - **A)** Bioclastic packstone with oncoids and foraminifers (*Glomospirella* sp., *Gandinella* sp.) (Fig. 12, J140, top of Zu3; ×70). **B)** Bioclastic packstone with micritized foraminifers (*Triasina hantkeni*) and small coated grains (J140; ×24). **C)** Bioclastic wackestone with fragments of bivalves and sessile foraminifers (*Planinvoluta* sp.). Inset shows *Agathammina* sp. (last Rhaetian microfacies in a lenticular bed at the boundary with the Malanotte fm. (Fig. 21, Italcementi active quarry, ×120).



D) Grainstone with micritized, recrystallized bioclasts, aggregate grains (J245, upper Malanotte fm., Italcementi quarry section, Fig. 12, ×20). **E)** Recrystallized grainstone with peloids, intraclasts and benthic foraminifer (*Calcitornella* sp.). (J248, upper Malanotte fm., ×70). **F)** Oolitic grainstone with micritized grain nucleus. (J251, basal Albenza fm., Fig. 12, ×24). From Galli et al., 2007, modified.

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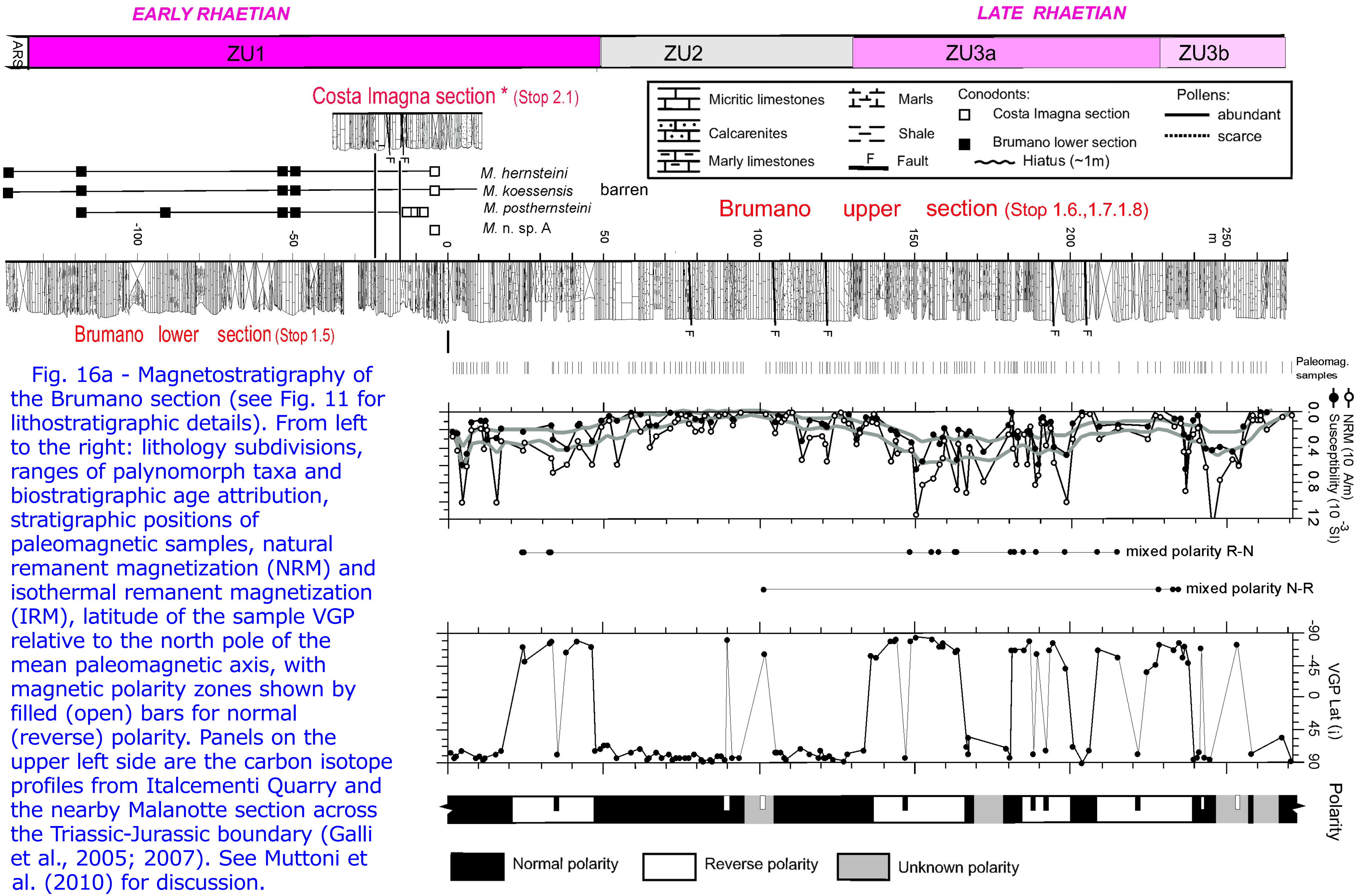

Fig. 16a - Magnetostratigraphy of the Brumano section (see Fig. 11 for lithostratigraphic details). From left to the right: lithology subdivisions, ranges of palynomorph taxa and biostratigraphic age attribution, stratigraphic positions of paleomagnetic samples, natural remanent magnetization (NRM) and isothermal remanent magnetization (IRM), latitude of the sample VGP relative to the north pole of the mean paleomagnetic axis, with magnetic polarity zones shown by filled (open) bars for normal (reverse) polarity. Panels on the upper left side are the carbon isotope profiles from Italcementi Quarry and the nearby Malanotte section across the Triassic-Jurassic boundary (Galli et al., 2005; 2007). See Muttoni et al. (2010) for discussion.

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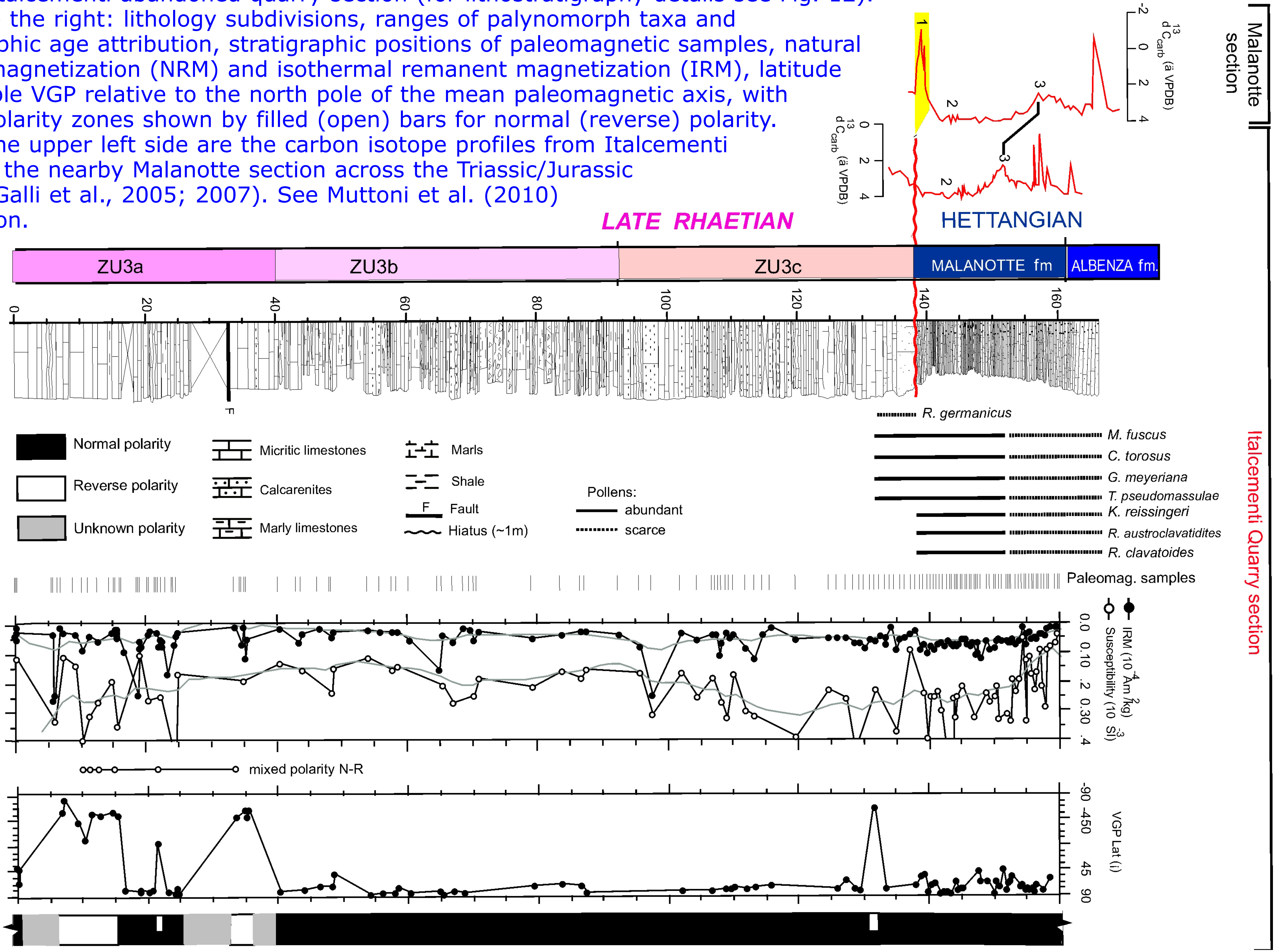
Fig. 16b - Italcementi abandoned quarry section (for lithostratigraphy details see Fig. 12). From left to the right: lithology subdivisions, ranges of palynomorph taxa and biostratigraphic age attribution, stratigraphic positions of paleomagnetic samples, natural remanent magnetization (NRM) and isothermal remanent magnetization (IRM), latitude of the sample VGP relative to the north pole of the mean paleomagnetic axis, with magnetic polarity zones shown by filled (open) bars for normal (reverse) polarity. Panels on the upper left side are the carbon isotope profiles from Italcementi Quarry and the nearby Malanotte section across the Triassic/Jurassic boundary (Galli et al., 2005; 2007). See Muttoni et al. (2010) for discussion.



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Stop 2.4

This stop is focused on the T/J boundary in the inactive Italcementi quarry (see the guide photo cover) and on the transgressive micritic limestones of the Malanotte formation (Fig. 12).
In the western Albenza area, the sharp Zu3/Malanotte stratigraphic boundary (Fig. 17A and Fig. 14C) corresponds to a paraconformity marked by a Fe-rich hardground that may represent a sedimentation gap at the base of the Malanotte fm. in the western Albenza area. It may be correlated with a marly horizon present in the lowermost section in the active Italcementi quarry (Malanotte section Fig.17B; Stop 2.6). This state might indicate the presence of a more complete stratigraphic succession in the eastern Bergamasc area then to the western Albenza.

The Malanotte fm. differs from the Zu Fm. in lacking any evidence of cyclicity. It represents a stratigraphic marker horizon, up to 30 m thick, separating the upper Rhaetian from the lower Hettangian shallow-water carbonates.
It consists of thinly bedded (centimeter to decimeter scale) grey-dark grey micritic limestones, with marly intercalations decreasing upward (Fig. 12).
The Malanotte fm. may be subdivided in two different lithofacies associations:
1) The lower part consists of prevalent mudstone-wackestone, with rare thin-shelled bivalves and crinoids. Bed surfaces are often bioturbated (Fig. 14E) with thin intercalations of intraclastic-peloidal packstone. Slumping phenomena are frequently present (Fig. 14D, Fig. 17A and Fig. 17B).
2) The upper part differs from the underlying in the progressive upward increase of calcarenites consisting of bioclastic wackestone-packstone with thin-shelled bivalves, crinoids, ostracods and gastropods, intercalated to mudstone passing to grainstones, containing reworked ooids, peloids, intraclasts and bioclasts mostly represented by bivalves, brachiopods, gastropods, Dasycladales, crinoids and rare bryozoans.
Macrofacies and microfacies analysis from Malanotte fm. did not reveal any fossil useful for biostratigraphic correlation. The rich micro- and macrofaunal assemblages, characterizing the underlying strata abruptly disappear at the top of Zu3 member. Based on the palynological composition from the Zu3 member to the Malanotte fm. (Galli, 2002; Galli et al., 2007) propose to locate the palynological T/J boundary in the lowermost Malanotte formation (Fig. 18).

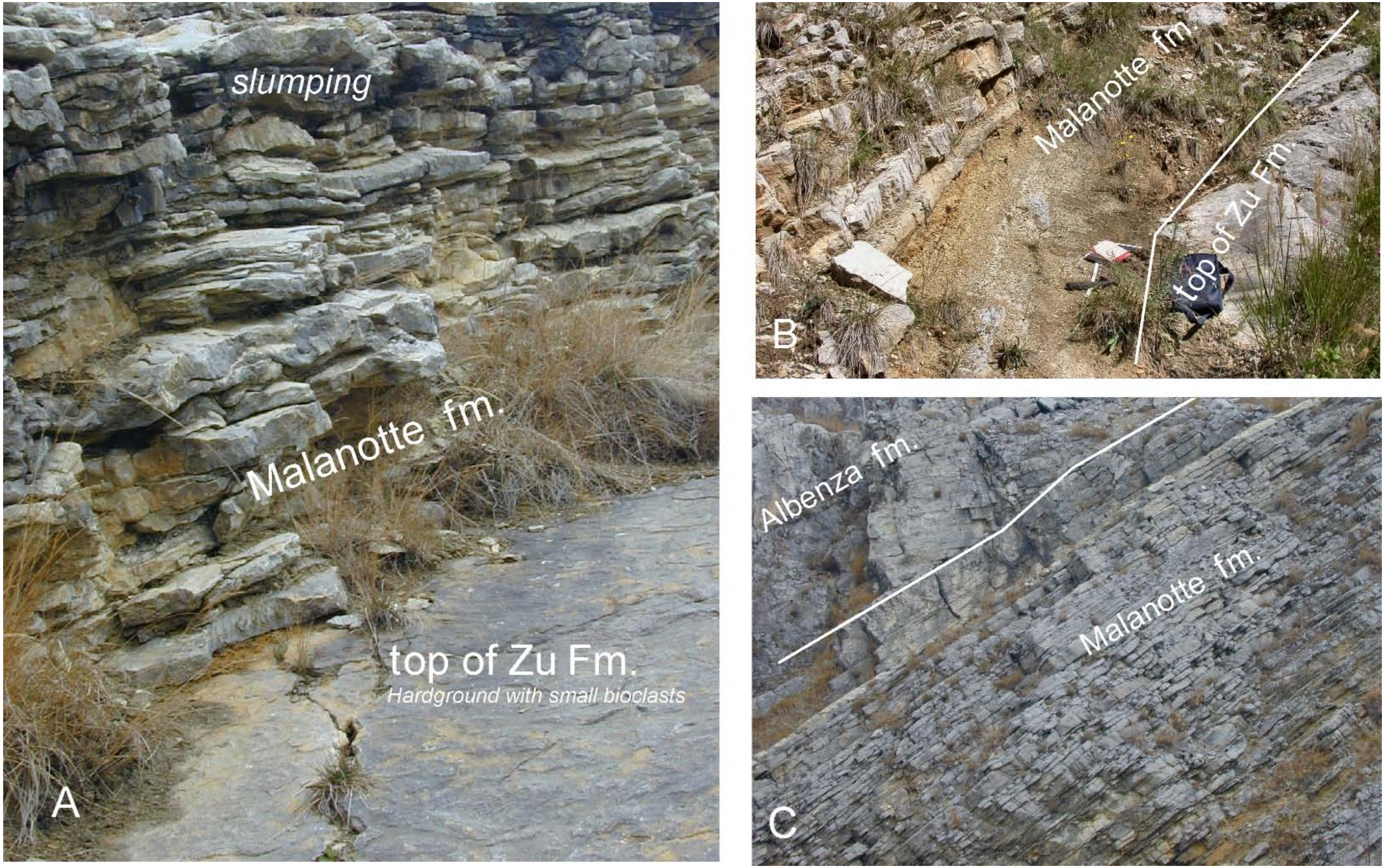

Fig. 17 - The Zu Limestone - Malanotte formation boundaries (T/J boundary) in two abandoned Italcementi quarries: **A)** see Fig. 12 and 13D. **B)** see Fig. 20. **C)** The progradation of the basal Albenza oolitic grainstone (downlap geometry) above the Malanotte more basinal limestones (see Fig. 12). After Galli et al., (2007), modified.

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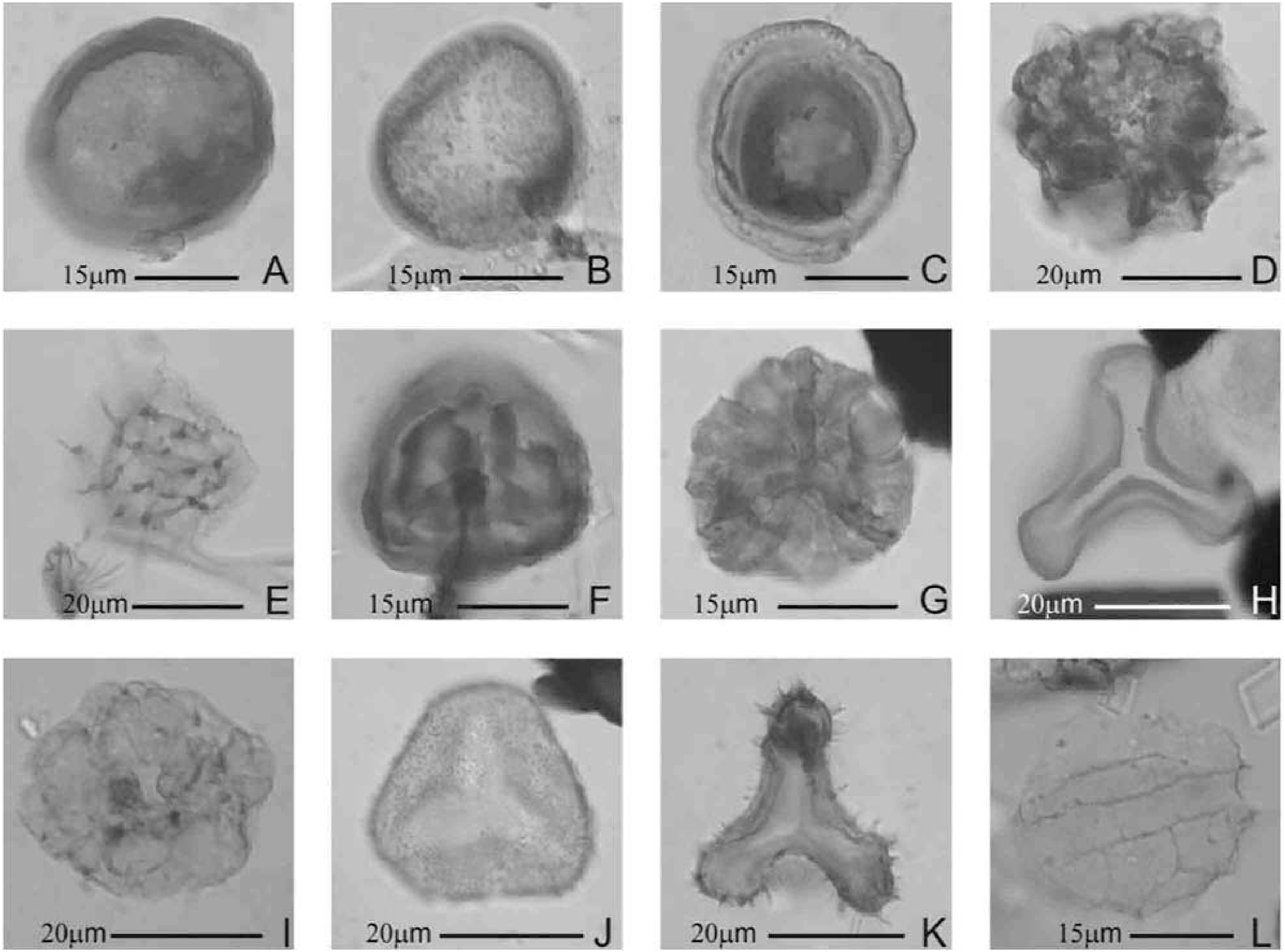

Fig. 18 - The palynological assemblage from the Malanotte formation (from Galli et al., 2007). **A)** *Gliscopollis meyeriana*; **B)** *Classopollis* sp., **C)** *Gliscopollis* sp.; **D)** *Cerebropollenites macroverrucosus*; **E)** *Kraeuselisporites reissingeri*; **F)** *Striatella seebergensis*; **G)** *Callialasporites dampieri*; **H)** *Concavisporites crassexinius*; **I)** *Tsugaepollenites pseudomassulae*; **J)** *Microreticulatisporites fuscus*; **K)** *'Acanthotriletes' varius*; **L)** *Dapcodinium priscum*.

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A detailed stable isotope study of the Malanotte fm. documents that this unit exhibits an excellent preservation of the isotopic signal as testified by the reproducibility of data in several investigated sections (Fig. 19). A marked negative anomaly at the base of a positive excursion has been identified in the eastern sections (Fig. 19). Although the sampling density was very high, in the more proximal area (Albenza) the negative excursion is absent, possibly due to condensation/sedimentary gap and iron mineralization at the top of the drowned carbonate ramp (Lakew, 1990; Jadoul et al., 1994).

The detailed C-isotope records across the marine T/J boundary interval in the Lombardy Basin document (Galli et al. 2005; 2007) that the C-isotope anomaly coincides with the end-Triassic biotic crisis and with a widespread carbonate-platform drowning. Galli et al. (2005; 2007) argue that a sudden increase in atmospheric CO_2 was responsible for the C-cycle perturbation and, consequently, for the marine biotic crisis at the end of the Triassic.

Lithological features and facies analysis of Malanotte fm. underline an important relative sea-level rise that controlled the deposition of micritic limestones all over the inner-outer Rhaetian ramp system, leading to a more uniform outer ramp depositional environment. The transgressive event of the Malanotte fm. may be related to the well-known transgression recognized in the lower Hettangian of the Western Europe (Hallam & Wignall, 1999).

The dominant ooidal facies (Fig. 14F and Fig. 14G) of the lower Albenza fm. present in all the Albenza area seems to represent the proximal high-energy margin of the rimmed carbonate ramp that separates the peloidal lagoon facies from the more open subtidal environment.

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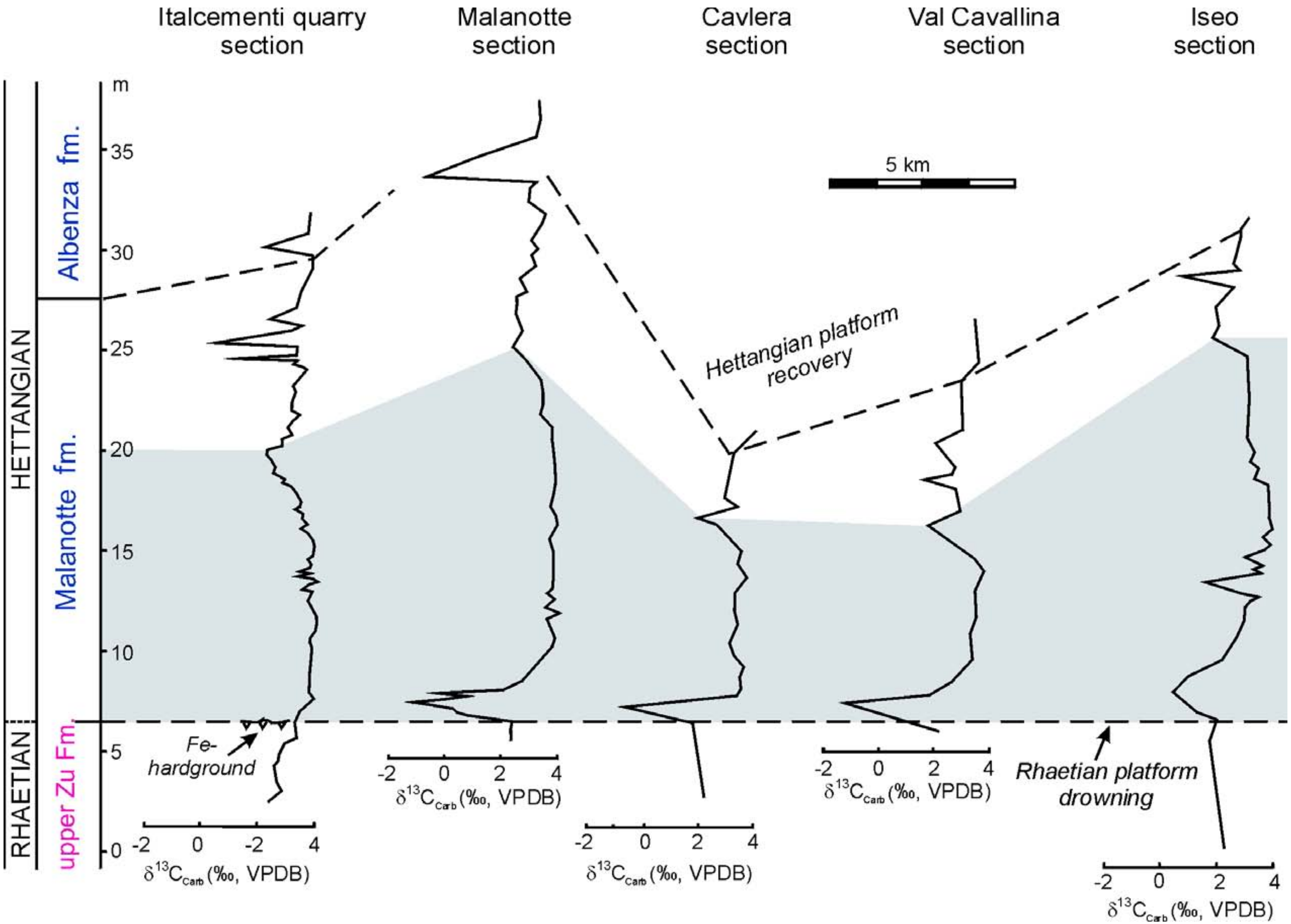

Fig. 19 - C-isotope stratigraphy and correlation of the T/J boundary sections of the Bergamasc Alps (from Galli et al., 2007, modified).

Stop 2.5

The stop is at the inactive Malanotte quarry (1000 m of altitude; Fig. 20). In this quarry the entire Hettangian succession (Malanotte, Albenza and Sedrina limestone fms.) crop out as well as the underlying boundary with the Rhaetian Zu Limestone. This section represent the type section of both the Malanotte fm. (Galli et al., 2007) and the Albenza fm. (Jadoul & Galli, 2008).

At the base of the Hettangian succession the meter thick marly horizon (Fig. 17B) with Jurassic bivalves at the base (Chlamys; McRoberts, personal comm.) represents a regional marker.

Fig. 20 - Stop 2.5. View of the type section of Malanotte formation at Malanotte abandoned quarry (from Galli et al., 2007, modified). Stable isotope results of this section are in Fig. 19.

The Malanotte fm. represents a lithostratigraphic unit (Galli et al., 2007) cropping out in the western Southern Alps of Lombardy for about 60 km from east to west, from Iseo Lake to Como Lake. Mt. Albenza is designated as the type area, with Malanotte as the type section (Gauss Boaga coordinates: 1540268, 5088998). In this region, the Malanotte fm. is well exposed, and its upper and lower boundaries crop out in several localities (Valcava-Torre dei Busi, Italcementi quarry and the type section).
The thickness of the Malanotte fm. is up to 30 m in the Malanotte section. The Zu Limestone-Malanotte formation boundary, between the thick-bedded, coral and megalodontid bearing grey bioclastic limestone (Jadoul et al., 1994, 2004) at the top of the Zu3 member (Fig. 14A) and the thinly bedded, micritic limestone of the Malanotte formation, is sharp and readily identifiable. The lower Malanotte formation consist of a one-meter-thick, marly-silty horizon with thin, parallel laminations.
The transition from the Malanotte to the Albenza fms. is either abrupt (Mt. Albenza sections; Fig. 17C and Fig. 22B) or gradational (Iseo Lake). In the Mt. Albenza area, the basal Albenza fm. is characterized by cross-bedded, well-sorted, grey oolitic grainstone displaying a downlap with an angle of 25–30°. A rapid increase of fine to coarse, cream oolitic grainstones with local lime-mud intraclasts characterizes the transitional boundary in the other sections.

Stop 2.6

The stop, located in the active Italcementi quarry (1180 m of altitude, Fig. 21), is mainly focused on the T/J boundary and on the carbonates facies of the Albenza fm. with a selective dolomitization (the quarry there is the type section, Jadoul & Galli 2008). The T/J boundary section is close to the previous one, but is more spectacular for the excellent exposition. The base of the Malanotte fm. is characterized by the grey marly horizon (Fig. 21) over a thin black phosphatic rich crust and overlying a centimeter thick intra-bioclastic packstone/fine rudstone with fragments of vertebrates, fishes, rhaetian foraminifers. This T/J boundary lithofacies association confirms the presence, also in the thickest section of the Mt. Albenza, of a condensed sedimentation in correspondence of the T/J boundary and corresponding to the drowning surface on top of the upper Zu fine grained dark grey marl-limestone ramp cycles (in this section the upper Zu facies document more basinal environments).

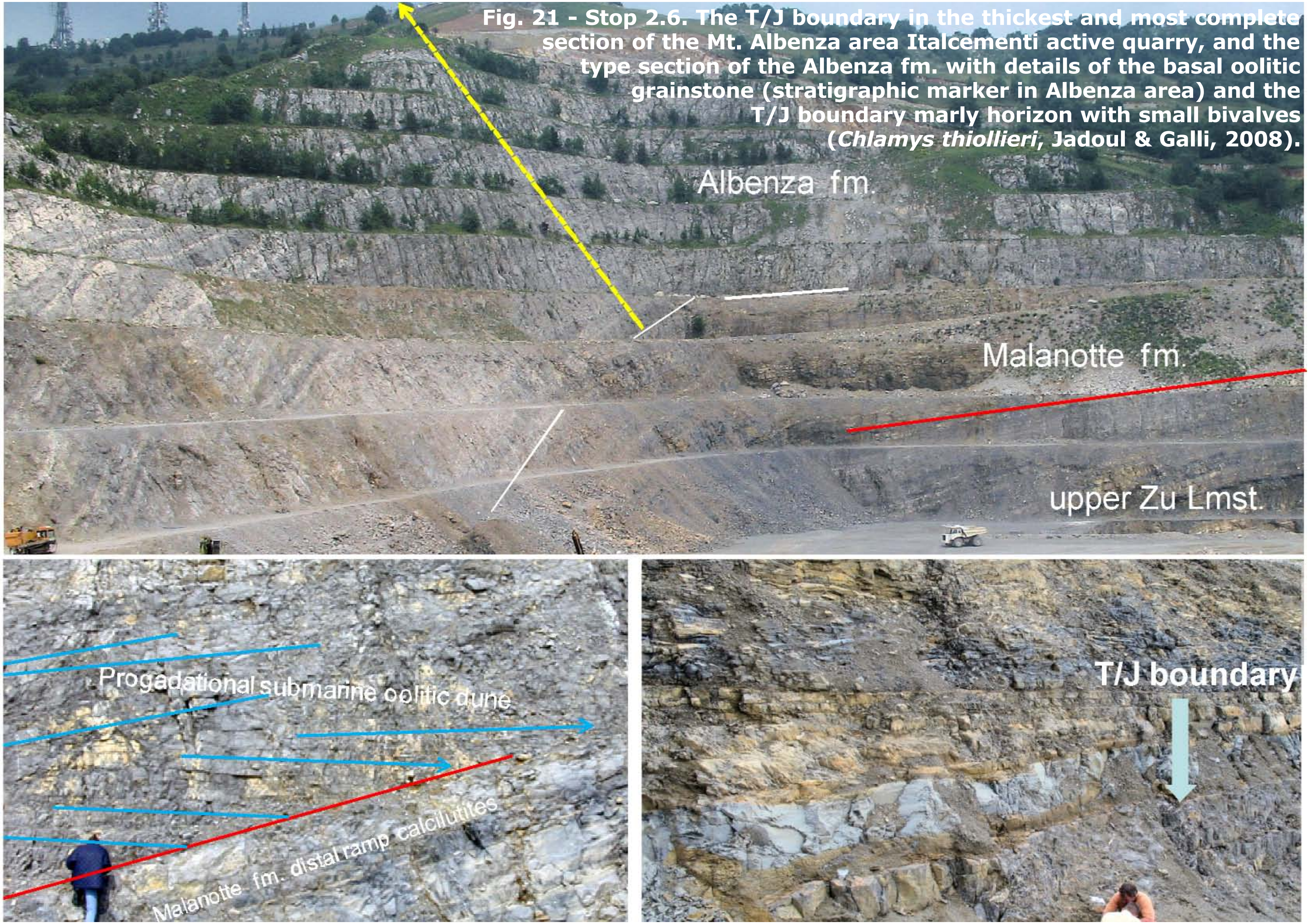

Fig. 21 - Stop 2.6. The T/J boundary in the thickest and most complete section of the Mt. Albenza area Italcementi active quarry, and the type section of the Albenza fm. with details of the basal oolitic grainstone (stratigraphic marker in Albenza area) and the T/J boundary marly horizon with small bivalves (*Chlamys thiollieri*, Jadoul & Galli, 2008).

Stop 2.7

On the Valcava-Torre dei Busi road (about 1000 m in altitude, Fig. 22) the uppermost Triassic-lowermost Jurassic succession is well cropping out, showing the sharp Zu3 -Malanotte contact, the transgressive early Hettangian micritic limestones and the fast progradation of the Albenza ooidal grainstone bars, this latter characterized by a downlap (angle of about 25°).

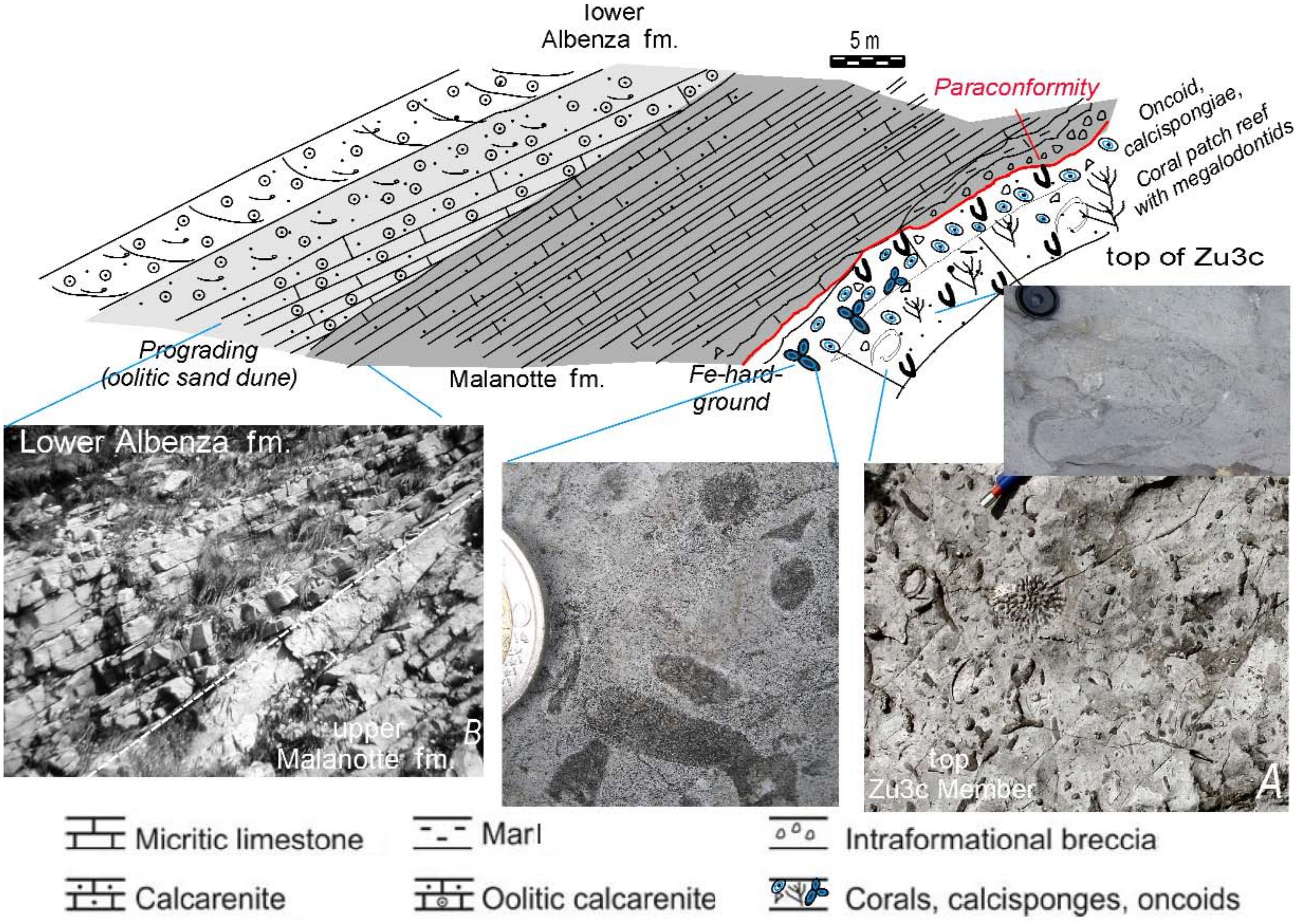

Fig. 22 - **Stop 2.7**, the Valcava-Torre dei Busi road section. **A)** Stratigraphic sketch of the T/J boundary succession of the NW Albenza. At the top of the late rhaetian proximal carbonate ramp facies (Zu3c) the T/J boundary is represented by a paraconformity with thin intraformational breccias and/or a Fe hardground. **B)** The low angle, fast progradation of oolitic grainstones of the Albenza fm. (From Jadoul et al., 1994, 2004, modified).

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memorandum

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