Published in "Sedimentary Geology", Volume 431, 1 April 2022, 106106
https://doi.org/10.1016/j.sedgeo.2022.106106

Resedimented limestones in fault-controlled basins (Zorzino Limestone, Southern Alps, Norian, Italy): facies types and depositional model

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Abstract

The Norian succession of the Southern Alps of Italy stores thick successions of resedimented basinal carbonates (Zorzino Limestone) that were deposited in fault-controlled, anoxic, intraplatform basins developed within a vast inner platform domain (Dolomia Principale). To characterise the basinal facies, to define their distribution within these basins and to identify depositional processes, four stratigraphic logs covering about 2000m of total stratigraphic thickness from proximal to distal basinal settings were described bed by bed. Eight different lithofacies organised in 11 bed types were identified according to sedimentary structures, texture, and composition: each bed (about 4500 beds in total) was measured 18 individually at cm scale and classified in one of the 11 bed types. Distribution of bed types in terms of events (i.e. number of beds) and cumulative thickness (i.e. volume of sediments produced by the different depositional processes) in the four selected logs change from the proximal to the distal parts of the basin, reflecting the existence of diverse dominant depositional processes at different places within the intraplatform basins. Bed by bed analyses of thick stratigraphic logs provide important hints about the distribution of different types of depositional processes, from proximal to distal basin. Frequent slump folds and mass flow deposits, with clasts mostly deriving from the slope facies itself, indicate instability of the slope. Sediment composition and facies types document a major role played by the reworking of primary deposits formed along the slope: basinal facies mostly consist of resedimented slope deposits, produced by sliding of sediments, rich in lime mud, accumulated along the slope and low-angle proximal basin, whose instability (likely enhanced by seismic activity related to the Norian extensional tectonics) produced most of the recognised facies types. The two-step depositional processes as well as the facies associations and bed types clearly indicate a different behaviour (in terms of prevailing depositional processes and facies associations) of the studied resedimented limestone with respect to siliciclastic deposits. The distribution of facies and the detailed analyses of bed types, recording the distribution of depositional processes at basinal scale, provide a tool for the interpretation of basin morphology, from the study of stratigraphic logs, that can be applied both to outcrop and to subsurface successions.

Keywords

Carbonate platform, intraplatform basin, resedimented carbonates, carbonate slope, Triassic

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https://doi.org/10.1016/j.sedgeo.2022.106106

1. Introduction

Flow types and sediment texture of gravity-driven deposits (Middleton and Hampton, 1976; Lowe, 1982) are diverse and reflect different sedimentation processes, such as submarine rockfall, slides, slumps, debris flows, turbidity currents. These diverse depositional processes produce different types of deposits, that are characterised by different facies associations from the basinal area close to the slope, where coarse deposits generally prevail, to the distal basin, where fine grained facies dominate (for an overview, see Tinterri et al., 2020).

Beside processes, also the nature of the resedimented sediments (siliciclastic vs. carbonate) may play a role in the type of deposits produced. Gravity driven deposits have been mostly studied in siliciclastic systems (e.g., Mulder and Alexander, 2001 and references therein), allowing for the identification of diverse deposits reflecting different types of density flows. For several aspects the processes that drive deposition of resedimented siliciclastic and carbonates successions are similar (they share the same depositional profiles although with different slope angle), but major differences exist in the facies types produced (Moore, 1989; Adams and Kenter, 2013). Despite the abundance of resedimented carbonates, detailed studies about the processes and type of deposits preserved in these successions are less common.

Carbonate gravity-driven sediments, frequently stored as thick successions of bedded to massive basinal limestones, have been the subject of detailed descriptive works, mostly in the geological record from outcropping successions (e.g., Reijmer et al., 1991; Reijmer and Evraars, 1991; Watts,
1992; Spence and Tucker, 1997), but also from present-day settings (e.g., Eberli et al., 2002). These studies provide details on the sediment composition, sedimentation rates, and controlling factors. Resedimented carbonate deposits can be analysed not only in terms of facies types but also in terms of abundance of different facies types, that may reflect the occurrence of different depositional processes. The relative ratio of different facies types (reflecting different processes) is expected to vary from the proximal to the distal part of the basin. In order to verify this hypothesis, the occurrence of different deposits and related processes across a basin must be identified and evaluated by the detailed analysis of the distribution of bed types, whose sedimentological features reflect depositional events. To achieve this result, a detailed definition of facies types (interpreted as the product of different depositional processes) and bed-to-bed measurement and classification of thick carbonate basinal succession have been performed in a favourable geological setting, represented by the Norian succession of the Lombardy Southern Alps (Italy). The studied

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succession (Zorzino Limestone) consists of a thick basinal, dark, bedded limestone unit that was deposited in fault-controlled intraplatform troughs, that were formed in the vast inner carbonate platform of the Dolomia Principale due to extensional tectonics (Jadoul et al., 1992). Thanks to these favourable conditions, detailed facies and microfacies investigations on the Zorzino Limestone have been performed in order to i) characterise the types of carbonate components and the sedimentological associations, ii) identify the source of sediments and the depositional processes and iii) propose a depositional model. The well-known depositional context and the detailed palaeogeography available for the study area (Fig. 1) allowed to quantify and compare the facies association of these resedimented limestones in different parts of the basin (proximal to distal) and to propose a depositional model that could be tested also on other basins, different in age and geodynamic setting.

2. Geological setting

For most of the Norian, sedimentation on the Tethys shelf was characterised by a wide, earlydolomitised, attached carbonate platform (Dolomia Principale/Hauptdolomit, DP/HD) which is presently preserved in different structural and palaeogeographic domains (e.g., Marcoux et al., 1993): Southern Alps, Central Austroalpine, Northern Calcareous Alps, Transdanubian Range, Western Carpathians and Central and Southern Apennines. This vast carbonate platform was bordered landward by coastal and playa deposits (Keuper in Europe, Grezzoni in the Central Apennine) and toward the Tethys by calcareous backreef and margin facies (Dachstein Lst.) evolving basinward to deep water sediments (Hallstatt Limestone).

During the Middle-Late Norian, the upper part of the Dolomia Principale/Hauptdolomit platform records in the Central Austroalpine and parts of the Southern Alps a major tectonic event which drove the opening of rapidly subsiding fault-controlled, confined, intraplatform basins, (Jadoul, 1985; Bechstadt et al., 1978; Jadoul et al., 1992; Berra, 1995; Berra and Jadoul, 1996, 1999; Cozzi et al., 2002). Syndepositional tectonics was responsible for major thickness changes of the Norian succession, from a few hundreds of meters in low-subsiding domains (e.g., Dolomites) to more than 2 km where fault-controlled intraplatform troughs developed.

Fault-controlled intraplatform troughs are present in the Central and Western Southern Alps (Jadoul, 1985; Jadoul et al., 1992; Berra and Jadoul, 1996, 1999; Berra, 1995; Trombetta and Claps, 1995; Berra et al., 2010) (Fig. 1A), in the Eastern Southern Alps (Carnia; Cozzi, 2002), in the Central Austroalpine (Ortles and Quattervals Nappes; Berra,

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1995; Berra and Jadoul, 1999), in the Northern Calcareous Alps (Seefeld Basin; Fruth and Scherreiks, 1984) and in the Apennines (Cirilli et al., 1999; Zamparelli et al., 1999). Sedimentation in these intraplatform basins is mainly characterised by dark, bedded resedimented limestones and scarp breccias (i.e., Jadoul, 1985), fed by the Dolomia Principale highs. The fault-controlled transition from the platform top to the basin is marked by massive clast-supported breccias with lithified angular pebbles from inner platform and reefal facies ("Brecce Sommitali della Dolomia Principale", topmost breccia of the Dolomia Principale of Jadoul, 1985).

In the Southern Alps of Lombardy (Northern Italy) the Norian basins have an average width of less than 20 km (Jadoul et al., 1992; Bertotti, 2001) and are generally asymmetrical (halfgrabens), with a fault-controlled margin on one side and a flexural-type margin on the other side (Picotti and Pini, 1988; Jadoul et al., 1992; Trombetta, 1992; Berra and Jadoul, 1996) (Fig. 1A, B).

Some major basins (from West to East) can be recognised: Val Menaggio, Val Brembilla-Val Taleggio, Val Cavallina-Western Iseo Lake and Val Trompia-Idro Lake (Assereto and Casati, 1965; Jadoul, 1985; Gaetani et al., 1986; Picotti and Pini, 1988; Berra and Jadoul, 1996; Cozzi, 2002). Along the fault-controlled border of the basin, reef facies dominated by serpulids and microbial dolostones (Berra and Jadoul, 1996; Cirilli et al., 1999), associated with sedimentary dykes, are common. The reef facies rapidly evolve to thick breccia/megabreccia wedges ("Brecce sommitali della Dolomia Principale"; Jadoul, 1985) with angular clasts mainly deriving from the reef and platform top, typically supported by dolomitised lime mud. The platform margins are characterised by steep, fault-controlled slopes (Berra and Jadoul, 1996). Progradational margins are present only in the uppermost part of the succession, frequently on the half-graben border opposite to the main bordering fault (Berra and Jadoul, 1996).

Basinward, slope breccias interfinger with sand-sized bedded dark dolomitised deposits (Dolomie Zonate) and, more distally, to muddy dark limestones (Zorzino Limestone). In the depocentral area of large basins, the Zorzino Limestone reaches the thickness of several hundreds of meters, with a maximum of more than 1000 m in the Iseo Basin (Assereto and Casati, 1965).

The Zorzino Limestone is finest in the depocentral area and becomes gradually coarser toward the Dolomie Zonate and the breccia deposits that characterise the slopes of the Dolomia Principale platform. The unit is generally well-bedded (Fig. 1C), with bed thickness that ranges from a few centimetres to, rarely, more than 1 m. Bioturbation is absent, recording anoxic conditions.

3. Methods

The study was performed on four continuous logs (covering a total stratigraphic thickness of about 1100 m), placed in different palaeogeographic position (distal vs. proximal) within the Norian fault-controlled intraplatform basins (Val Taleggio, Val Bracca, Val Cavallina, Iseo Lake) (Fig. 1). Thickness of each bed was measured at cm-scale, each bed was described in terms of facies association, grain size, texture, and sedimentary structures: about 4500 beds were individually analysed, described, and measured. Samples were collected during logging from different bed types in order to characterise at the microfacies scale nature and characteristics of the components: from the collected samples, more than 150 thin sections were prepared and described. According to the macroscopic and microscopic features, each bed type was classified, allowing the definition of a finite set of possible bed types. Each bed was then assigned to one of the identified bed types. Data about thickness and occurrence of the different bed types were stored in a spread sheet, where for each bed the thickness and the bed type were stored. These data were processed to obtain information about the relative abundance of the identified bed types in terms of thickness and occurrence, in the different part of the basin.

In detail, for the four selected logs that have a well-defined palaeogeographic position with respect to the borders of the basin, the percentage of the occurrence of the different beds in terms of number of beds (i.e., events) and thickness (i.e., volume of the different bed types) has been calculated. The collected data about bed thickness and abundance thus provided the constraints for the quantitative analyses of the bed type distribution in the basin.

4. Data: lithofacies and bed types

4.1 Lithofacies types

The Zorzino Limestone, representing the proximal to distal basinal facies of the Norian carbonate system, consists of an association of limestone characterised by diverse grain

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size, sedimentary structures, and bed types. Bed-to-bed description of stratigraphic logs allowed the identification of sets of recurring deposits (in terms of grain size distribution, textures, and structures). The deposits were hierarchically grouped into three dominant grain-size classes: a) Calcirudite, b) Calcarenite, c) Calcilutites. Eight lithofacies (Fig. 2) were identified in this study, according to the association of different grain size classes and texture: (1) Mud-supported rudstone, (2) Packstone supported rudstone, (3) Homogeneous packstone, (4) Graded packstone, (5) Laminated graded packstone, (6) Massive fine-grained packstone and wackestone; (7) Homogeneous mudstone and (8) Laminated mudstone and wackestone (rhythmites).

4.1.1 Calcirudites

This class groups deposits consists of floatstone with clasts from 0.2 to 20-30 cm (cobbles), supported by lime mud or packstone/wackestone. Two different lithofacies can be identified.

Mud-supported rudstone (**1**): lime mud or very fine to fine wackestone with dispersed clasts (0.5 to 15 cm). Clasts represent less than about 20% of the rock volume. The clasts mostly consist of dark grey to black intraclastic wackestone and packstone (frequently laminated) showing softsediment deformation structures documenting they were unlithified at the time of deposition.
Rare, light-coloured clasts derived from the upper slope-platform top may be present (Fig. 2).

Packstone-supported rudstone (**2**): poorly sorted intra-bioclastic packstone, less frequently wackestone, with floating larger clasts, generally consisting of unlithified lime mud: clasts are generally rounded and range from 0.5 cm to about 20 cm in size: they consist of lime mud, laminated and massive packstone, often of lithofacies 4 to 7 (see 4.1.2). Skeletal grains are mainly represented by bivalves, crinoids, gastropods, ostracods, fragments of dasycladacean algae, rare benthic and encrusting foraminifera. Intraclasts are mostly represented by laminated, dark, fine grained packstone and mudstone (Fig. 2).

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4.1.2 Calcarenites

This grain-size class groups all the sediments mostly consisting of packstone and packstone/wackestone with clasts mostly smaller than 2 mm. Four different lithofacies types have been identified in this grain-size class according to their texture and grain types (Fig. 3)

Homogeneous packstone (**3**): homogeneous or poorly graded, medium to coarse, dark grey packstone and, less frequently, wackestone with dispersed lime mud chips from less than 1 cm to a few cm in size. Microfacies consist of bio-intraclastic packstone, with skeletal grains (bivalves, foraminifera, serpulids, and rare bryozoans), intraclasts and peloids. Iso-orientation of intraclasts and skeletal grains is commonly observed.

Graded packstone (**4**): coarse to fine-grained, normally-graded, moderately to well-sorted dark grey packstone, rarely containing clasts up to 1.5 cm in size at the base. Microfacies are commonly represented by intraclastic/bioclastic packstone to wackestone. Intraclasts consist of dark fragments of organic-rich deposits and light grey micrites (locally recrystallised as microsparite). Skeletal grains are represented by bivalve shells, dasycladacean algae, gastropods, serpulids and foraminifera. Intraclasts are locally enveloped by encrusting organisms.

Laminated graded packstone (**5**): medium to fine/very fine, dark grey, plane parallel laminated packstone/wackestone. Locally, current ripple-cross laminations develop in fine or very fine packstone/wackestone. Microfacies typically consist of intraclastic peloidal packstone/wackestone, with rare small skeletal grains (generally iso-oriented bivalves). Intraclasts are mostly represented by fragment of laminated limestone and mudstone.

Massive fine-grained wackestone and packstone (**6**): this lithofacies is generally massive and homogeneous, only locally a poorly defined normal grading can be present, as well as faint laminations. Often, small mm size clasts are present. Microfacies is generally represented by recrystallised wackestone. Intraclasts (dark laminated mudstone) and rare skeletal grains (mostly ostracods and benthic foraminifera) are dispersed in a micritic groundmass.

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4.1.3 Calcilutites

Homogeneous mudstones ***(7)*****:** massive lime mud (only rarely faint laminations are present), mostly consisting of recrystallised mudstone (microsparite) and, less frequently, wackestone with dispersed small intraclasts.

Laminated mudstone and wackestone (rhythmites) ***(8)****:* cm-thick parallel alternation of millimetric light grey micritic levels alternating with dark levels, enriched in organic matter. Bioturbations are absent, allowing the perfect preservation of the laminae. Beds have typically an external tabular geometry and are 2 to 10 cm thick on average. Laminations are frequently deformed by slump overfolds at mm to dm scale.

4.2 Facies organisations and depositional events

Detailed bed-by-bed description of the Zorzino Limestone permitted to identify beds (each considered as a single depositional event, *sensu* Campbell, 1967) represented by one lithofacies or, alternatively, beds characterised by defined associations of more lithofacies. Sedimentological observations document the occurrence of 11 bed-types (Fig. 4), each defined by the combination of one or more lithofacies (Fig. 2). Bed types are here described and for each of them the average thickness, the type of bounding surfaces (Fig. 4) and the possible sedimentary processes are presented. After deposition, some of the bed types record plastic deformations that modify, slightly to completely, the original bedding: this type of conditions is not considered a bed type, but rather a process that acts on one or more of the described 11 bed types.
11 bed types were identified (Fig. 4). Lithofacies numbers mentioned in the text and figures refer to Fig. 2 (as described in section 4.1).

4.2.1 Bed type 1: Matrix-supported rudstone (Br1)

This bed type (Fig. 5) coincides with lithofacies 1. Bed thickness ranges on average from a few to more than 50 cm. This bed type characterises the areas close to the margins of the basin. Beds are tabular (Fig. 5C) to lenticular, sometimes with a slightly erosive base (Fig. 5F); the top is generally regular or gently wavy.

The nature of the clasts (generally lime mud) and their common soft deformation (Fig. 5B, C, E) suggest that clasts derive from the dismantling of cohesive mudstone beds: beds are interpreted as the product from the cohesive freezing of lime mud-rich debris flows. The “matrix strength” (*sensu* Middleton and Hampton, 1973) is the dominant particle-support mechanism that can be considerably supplemented by buoyancy inducing dispersive pressure (Johnson, 1970, Nemec and Steel, 1984). Deposition takes place as shear stress becomes less than the cohesive strength (Middleton and Hampton, 1973, Lowe 1979). The nature of the clasts indicates that this bed type forms from the dismantling of existing cohesive basinal beds deposited on low-angle slopes.

4.2.2 Bed type 2: Packstone-supported rudstone (Br2)

This bed type is entirely represented by lithofacies 2 (Fig. 5C, D). Beds show an irregular geometry, lenticular at the outcrop scale, with a sharp (rarely slightly erosive) (Fig. 5F) base and a wavy upper surface. Commonly, beds thin out laterally, showing a gradual decrease both in the size and in the amount of the clasts. The thickness of each bed usually ranges from 0.5 to 1 meter. However, in some cases, beds may be thin (several centimetres) forming scarcely extended lenses. This bed type is interpreted as the product of freezing of high-concentrated cohesive laminar flows and can be considered to correspond to the sandy debris flows of Shanmugam (1996, 2001), produced by the reworking, on low-angle slope in the proximal basin, of packstone beds.

4.2.3 Bed type 3: Homogenous packstone (Hp):

It is mainly represented by lithofacies 3, occurring as beds with irregular geometry, generally from 10 to 40 cm thick. The basal surface is sharp and tabular, only rarely slightly erosional. This bed type is interpreted as the product of freezing of a high-concentrated cohesive laminar flow and can be referred to the sandy debris flows of Shanmugam (1996, 2001). These flows are characterised by high grain concentration (grain supported) with interparticle space filled by lime mud.

4.2.4 Bed type 4: Rudstone to fine, graded packstone (Cl1):

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It occurs in tabular beds, from 10 cm to 50 cm thick Fig. 6A), characterised by the vertical association of the lithofacies 2, 4, 5 and 7 (Fig. 6A, B, C). Different association of lithofacies, with varying thickness, can be present: associations of lithofacies 2-4-5-7, 2-4-7 and 2-5-7. This bed type is interpreted as the product of the sedimentation of high-density turbidity currents (Middleton and Hampton, 1973 and Lowe, 1982) with abundant lime mud, able also to erode the underlying bed as documented by the presence of rip-up lime clast at the base (Fig. 6B, C). The nature of the grains suggests that the source area for these sediments was mostly represented by the proximal slope facies.

4.2.5 Bed type 5: Coarse to fine sand-sized, graded packstone (Cl2):

It consists of tabular graded beds, from 10 to 70-80 cm thick, represented by diverse associations of lithofacies 4-5-6 and 7, with different thickness and components (Fig. 4). Three main different types of lithofacies associations occur: associations of lithofacies 4-5, 4-5-6 and 4-5-7, (Fig. 6D, E). The base of the beds is generally sharp, locally scours are present. Erosion of the underlying facies is occasionally documented by rip-up lime mud clasts in the basal part of the beds. Bed type 5 can be considered as representing parts of the Bouma sequence. The basal massive part (lithofacies 4) can be related to the Ta division of Bouma, the overlying laminated part (lithofacies 5) corresponds to Tb and Tc and lithofacies 7, when present, represents Te. The lithofacies association in bed type 5 records the associations Tabcd, Tabcde and Tabe of the classical Bouma sequence. The basal part is attributed to the suppression of a near-bed turbulence by excess of sediment concentration (Lowe, 1982, 1988). This process causes a nontractional deposition due to a rapid direct dumping from turbulent suspensions (Allen, 1982; Lowe 1988; Kneller and Branney, 1995). Plane parallel lamination indicates tractional deposition of supercritical flow regimes (Harms, 1975), whereas the ripple-cross lamination, when present, represents tractional deposition from subcritical flow regimes (Harms, 1975; Allen, 1982). The equivalent of the Td division of the Bouma sequence is relatively thin or absent in Bed type 5, where the uppermost homogeneous calcilutitic layer is interpreted to represent the Te division, due to non-tractional movement of lime mud and fallout in lower flow regime (Middleton and Hampton; 1973) or turbiditic mud suspension deposited by post flow fallout (Lowe; 1982). In the studied sections, lithofacies 7 may represent the muddy component of the sedimentary flow, whereas the post-flow fallout are likely represented by finely laminated mudstone and wackestone (bed type LS, see 4.2.11).

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Bed type 5 is interpreted as the deposition from a turbidity current evolving from upper to lower flow regime.

4.2.6 Bed type 6: Laminated medium to fine-grained packstone/wackestone (Cl3):

Bed type 6 consists of a vertical sequence of lithofacies (5) and (7), in tabular beds from 10 to 30 cm thick on average (Fig. 6F). Normal grading is common. The grain size ranges from medium (rarely coarse) to very fine-grained sand. Typically, bed type 6 shows a basal plane parallel laminated part passing up into ripples lamination or, when ripples are absent, to massive
calcilutites.

The basal plane parallel lamination is referred to the Tb of the Bouma sequence and the ripples cross lamination to the Tc (not always present), covered by Td or Te. Bed type 6 is interpreted as being deposited by a low-density turbidity current (Lowe 1982) or representing the distal part of bed type 5.

4.2.7 Bed type 7: Laminated fine to very fine, graded packstone/wackestone (Cl4):

Bed type 7 is similar to bed type 6, but finer and characterised by the common occurrence of ripple cross lamination at different scales in the upper part of the bed, partly or completely smoothed by lime mud.
Bed type 7 is referred to the Tb-c-e of Bouma sequence deposited by a low-density turbidity current (Lowe 1982).

4.2.8 Bed type 8: Thin bedded, graded packstone/wackestone (Cl5):

Bed type 8 consists of sets of tabular beds thinly laminated consisting of the association of lithofacies 4, 5 and 7, ranging in thickness, on average, from 10 to 50 cm (Fig. 7). It consists of thin laminae of mudstone alternating with fine-grained bio-intraclastic wackestone, frequently characterised by normal grading, both at centimetric and millimetric scale. Intraclasts are mostly represented by dark mudstone.
Bed type 8 is interpreted as the deposition of small-volume turbidity currents or from decantation of small volume of lime mud reworked from the slope.

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4.2.9 Bed type 9: Massive fine-grained wackestone and packstone (M1):

Bed type 9 characterises beds, from a few centimetres to 1 meter thick, mostly consisting of lithofacies 6. Bedding can be irregular (showing lateral changes in thickness) or tabular. The base of the beds is commonly sharp. These deposits, massive or faintly graded, frequently contain scattered small clasts of lime mud.

Bed type 9 is produced by high-concentrated gravity flow mostly consisting of lime mud. The massive fabric, the external geometry of the beds, both irregular and tabular, and the sharp or erosive basal contact suggest deposition from silt-sized debris flow to high density silty/mud dominated turbidity current (Piper, 1978, Piper and Stow, 1991, Stanley and Maldonado, 1981). The texture and the grain size of similar sediment gravity flows are interpreted by Middleton and Hampton (1973) as en-masse displacement of mud-rich slumps.

4.2.10 Bed type 10: Laminated fine-grained, packstone, wackestone and mudstone (M2):

This bed type (Fig. 8A), consisting mostly of lithofacies 6 and 7, is represented, on average, by 5 to 25 cm thick beds consisting of thin (usually less than 5mm), very fine-grained dark-grey peloidal packstone/wackestone and mudstone alternating with discontinuous, thin (less than 1 cm thick) darker wackestone/mudstone layers. These layers, as well as those belonging to bed type LS are enriched in organic matter (Fig. 8) of marine origin (Scotti, 2005). The rare skeletal grains are mainly ostracods.

Bed type 10 may be produced by dilute-and mud-dominated turbidity currents, possibly representing the distal evolution of a turbidity current alternating with hemipelagic sedimentation, mostly provided by settling of fine-grained lime mud.

4.2.11 Bed type 11: Laminated mudstone and wackestone (rhythmites) (LS):

Bed type 11 (Fig. 8) consists of lithofacies 8, represented by tabular 2 to 10 cm thick beds characterised by high-frequency alternation (higher than in bed type 10) of submillimetric light grey and black layers, the latter enriched in organic matter (Fig. 8A, D). The top of this bed type is planar when not eroded by successive depositional events, whereas the base mantles existing irregularities of the sea-bottom. This bed type is frequently affected by soft sediment deformations, typically by slump overfolds.

Bed type 11 is produced by grain-by-grain or aggregate settling from lime mud suspension during periods of low sedimentation rate, associated with microbial mats able to stabilise these sediments. The absence of burrowing and the abundance of organic matter indicates anaerobic-dysaerobic conditions, with a relatively slow sedimentation. The alternation of lighter and darker laminae can represent high-frequency variation of the bottom condition or variation in the input of organic matter and sediments in the water column.

The abundance of slumpings (Fig. 8B, C, E), indicates deposition on a low-angle but not perfectly flat basin floor, according to the fine-grained texture of the sediments.

4.2.12 Post-depositional deformations: chaotic deposits and slumps (Ch)

Bed types may be affected by post-depositional deformations predating lithification, common in the proximal part of the basin and clearly recorded by laminated facies. These processes are responsible for the plastic deformation of primary sedimentary structures (e.g., bedding and laminations). The degree of deformation changes significantly, from slightly to heavily deformed laminations and beds: beds from few centimetres to several decimetres thick are locally deformed by slump overfolds. Slumps are abundant especially in stratigraphic successions characterised by bed types Cl2, Cl5, M2 and LS. Field observations, texture and microfacies associations indicate that bed types Br1 and Br2 originate from the resedimentation, due to slope instability, of bed type Cl2 sediments, originally deposited on unstable low-angle slopes (Figs. 5, 8). Sliding of bed type CL2 deposits occurred when sediment shear strength was exceeded (Pickering et al., 1986): this process produced the 0.5 to about 3 meters thick beds (bed types Br1 and Br2) of clast-supported, subangular, partly lithified rudstone with intraformational clasts.

4.3 Facies distribution and abundance

Each bed of the four stratigraphic logs (Fig. 1) was assigned to one of the bed types, according to sedimentary structures and type of sediments involved. Data elaboration was performed both considering the number of beds (i.e., the depositional events) and the cumulative thickness of the different bed types (i.e., proxy of the volume of the different events), in order to define the relative abundance of the different facies in each of the studied sections (Fig. 9). The elaboration of the data from the different logs documents diverse occurrence, distribution and association of the identified bed types, varying in abundance according to the position within the sedimentary basin, recording the prevalence of different depositional processes from the proximal to the distal part of the

Published in “Sedimentary Geology”, Volume 431, 1 April 2022, 106106
https://doi.org/10.1016/j.sedgeo.2022.106106

basin. In the proximal part of the basin (log A, Val Taleggio, 475 beds and log B, Val Bracca, 402 beds), the highest variability of bed types is present. The prevailing bed types are represented by laminated limestone (LS) and packstone (Br2, Hp, Cl1, Cl2, Cl3, Cl4 and Cl5), whereas wackestone and mudstone are subordinate. Dark grey rhythmites (bed type LS), frequently affected by slumps and microslumps, can constitute thin layers between the packstone or can be associated with the wackestone facies. The distribution of the packstone beds (mostly Cl2, Cl3 and Cl4) is constant throughout the logs, but bed thickness is extremely variable. Bed type Cl2 ranges from 10 to 50 cm, bed type Cl3 ranges from 7 to 35 cm and bed type Cl4 ranges from 5 to 30 cm. Bed type Br1 and Cl1 are present but rare (12 and 11 beds, respectively). Beds referred to facies Cl5 (24 beds) are up to several decimetres thick, often affected by slumping.

Resedimented packstone (mainly bed types Cl3 and Cl4) is more abundant in Val Bracca than in Val Taleggio and is present all across the log. Packstone facies are mainly represented by bed type Cl2, in beds from 4 to 42 cm thick. Bed type LS is present all along the log, bed type M1 is also common (82 beds, from 3 to 22 cm thick). Despite the relative low number of events producing bed types Br1 and Br2, their cumulative thickness is high, especially in the Val Bracca log, where bed types Br1 and Br2, although representing less than 5% of the events, represent about 30% of the total thickness. The opposite is observed for bed type LS, abundant in terms of number of beds but with reduced thickness.

Bed type abundance and ratio dramatically differ in distal basinal settings (Val Cavallina and Iseo Lake logs). The Val Cavallina log (1112 beds) consists of two parts (Armati Quarry, 676 beds, and

Cantamessa Quarry 436 beds) separated by a non-outcropping area corresponding to about 150 m of stratigraphic thickness. The most common bed type (596 beds) is M1, representing about the 50% of the total beds, equally distributed in the two logs. Bed thickness ranges from 5 centimetres to more than one metre. Bed type Cl2, mainly consisting of packstone and wackestone, represents about 20% of the sediments (222 beds: 16% in the Armati quarry, 27% in the Cantamessa quarry) (Fig 9). Bed thickness ranges from 10 cm to 1 metre. Bed types Cl3 and Cl4 are scarcely represented (6% in the Armati quarry and 4% in Cantamessa quarry). Bed type LS (sometimes deformed by slumps) is also scarcely represented, occurring in thin layers often associated with bed type M2, which represents the 13% of the succession.

The Iseo Lake composite log (resulting from the integration of three logs: Bögn di Zorzino, Old House and Riva di Solto, for a total of 2516 beds) consists of a monotonous sequence of wackestone and mudstone (bed type M1, 80%) (Fig. 9). A limited increase in the

Published in "Sedimentary Geology", Volume 431, 1 April 2022, 106106
https://doi.org/10.1016/j.sedgeo.2022.106106

abundance of packstone is observed in the Old House log, whereas an increase in the relative abundance of bed type M2 is observed in the Riva di Solto log (Fig. 9).

As a general rule, the coarsest deposits (bed types Br1, Br2, Cl1 and Hp) characterise the proximal area, moving basinward bed types Cl2, Cl3 and Cl4 prevail on the mudstone and wackestone of bed types M1 and M2; the opposite is observed in the distal basinal setting (Val Cavallina log and
Iseo Lake log), where the packstone and the rhythmites (LS) deposits are less common (less than 10% in the Iseo Lake log) (Fig. 9) with respect to the fine grained packstone and wackestone deposits. Packstone bed types (Cl2, Cl3 and Cl4) represent the 26% in the Val Cavallina log and the 6% in the Iseo Lake log, respectively. The bed types M1 and M2 represent the 67% in the Val
Cavallina log and the 87% in the Iseo Lake log; bed type LS ranges from 7% (Val Cavallina log) to 6% (Iseo Lake log). Chaotic bodies and slump deposits are more common in proximal settings (5% of the events in Val Taleggio and 4% in Val Bracca).

Both bed types M1 and M2 are dominant in terms of number of beds and thickness in the depocentral area of the basin (Val Cavallina and Iseo Lake logs): comparing the relative abundance of different depositional events and the corresponding thickness, in the basinal domain the differences are less marked than in the proximal logs, with the exception of the facies LS, whose thickness is reduced, as these events generally produce deposits thinner if compared with the others. The correspondence between number of events and cumulative bed thickness reflects a comparable range of thickness for the dominant bed types (a few centimetres, with the exception of LS), although produced by different processes in the distal part of the basin. Post depositional deformations are more abundant in the logs at the border of the basin: slump overfolds in fine-grained sediments record a significant instability of the deposited sediments in the proximal slope. The presence of scars suggests the local evolution of slump overfolds to slope failures, giving rise to a significative reworking of already deposited sediments, producing secondary deposits, clearly documented in the proximal part of the basin (Val Taleggio and Val Bracca logs).

Published in “Sedimentary Geology”, Volume 431, 1 April 2022, 106106
https://doi.org/10.1016/j.sedgeo.2022.106106

5. Discussion

5.1 Facies distribution

The studied logs, crossing the upper part of the basinal Zorzino Limestone, were deposited in different positions within fault-controlled intraplatform basins (Jadoul et al., 1992; Berra and Jadoul, 1996; Berra et al., 2010). The detailed bed-by-bed analyses document that the distribution of bed types strongly reflects the palaeogeographic position of the logs. All the studied successions, independently from the position with respect to the basin borders, are characterised by the preservation of laminations and the absence of any burrowing, reflecting that the sea-bottom (from the slope and in the basin floor) was characterised by anaerobic conditions (Czurda, 1973; Hopf et al., 2001), favouring the complete preservation of sedimentary structures.

The analyses of the distribution of bed types indicate differences both in terms of the occurrence of each bed type and their cumulative thickness, according to their position within the basin (Fig. 1). In the proximal settings (Val Taleggio and Val Bracca) the Zorzino Limestone mainly consists of bio-intraclastic packstone and wackestone (bed types Cl2, Cl3, Cl4) that prevail on the intraclastic wackestone and mudstone (bed types M1 and M2). Br1 and Br2 bed types are reduced in number (around 5% of the beds are represented by these facies) but reach up to about 30% of the total thickness. In distal settings, the situation is different, both in terms of number of beds and thickness: bed types M1 and M2 dominate (around 85% in the Iseo Lake log, 60% in the Val Cavallina log) (Fig. 9).

The presence of bed-type Ls is more common in the proximal area (34 to 37% of the events in Val Taleggio and Val Bracca) with respect to the distal part of the basin (where they represent 5 to 15% of the total number of beds). This distribution likely reflects a more discontinuous sedimentation in the proximal areas, where this bed type represents intervals of reduced sedimentation between events of resedimentation. In distal settings the number of beds and the thickness of the bed-types show similar percentages, documenting a roughly constant thickness of the beds, independently from the depositional processes. Skeletal grains (foraminifera, bivalves, gastropods, serpulids and encrusting organisms) indicate a provenance of the biointraclastic packstone-wackestone from the platform top (as documented in other carbonate systems, e.g., Reijmer et al., 1991; Nakashima and Sano, 2007), whereas intraclasts, mostly consisting of facies of bed type LS, record reworking of proximal basin facies (Fig. 10).

This distribution of platform-derived grains and facies types suggests a bypass of the fault-controlled slope (steeper that the critical angle of repose of the basinal facies) by platform-

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https://doi.org/10.1016/j.sedgeo.2022.106106

derived sediments (Fig. 10), rich in skeletal grains, occurring in the proximal part of the basin (Jadoul, 1986). Texture and composition of the basinal deposits indicate that they originate from either deposition of sediments derived from the platform top or from resedimentation of slope sediments due to instability along the distal slope. Proximal slope deposits (derived from lime mud decantation and platform-derived grains) are characterised by slump overfolds that can evolve in slope failures, producing therefore secondary resedimented limestone, mostly represented by basinal intraclastic wackestone and mudstone with clasts of the facies present in the proximal basin. The degree of cohesion of the distal slope sediments and the basin morphology strongly controlled the facies produced by resedimentation processes: evolution from cohesive to non-cohesive flows was probably prevented by the dominance of lime mud and by the low angle slope that did not allow the re-organisation of the failed sediments.

Bed type distribution and abundance reflect thus two main depositional settings: i) a distal slope-proximal basin setting with prevalence of sand-sized carbonate facies, commonly associated with mass flows (bed types Br1 and Br2) and slumpings, that indicate the existence of a low-angle slope and ii) a basinal setting where mudstone prevails (Fig. 10). Facies associations in the Zorzino Limestone, as well as the abundance of the different bed types, thus reflects the palaeogeographic position within the basin, with changes form the distal slope to the depocentral part of the basin.

The quantitative analyses of the occurrence and thickness of the identified bed types thus represent a tool to identify the relative position of studied sections within a basin, providing hints about their palaeogeographic position within the borders and depocenter of the basin. This approach may represent therefore an important tool, at least at the basin scale, to identify in resedimented carbonates not only the sediment transport direction, but also the distribution of dominating depositional processes within a basin, also from discontinuous observations, such as wells or logs.

5.2 Sediment composition and provenance

The Zorzino Limestone is characterised by the abundance of lime mud. Lime mud occurs as matrix for breccias and packstone, mudstone beds and laminites. As a significant planktonic contribution can be excluded, due to the scarce pelagic production documented in the Triassic (e.g., Suchéra -Marx et al., 2019; Demangel et al., 2020), lime mud has three possible origins: i) distal part of well-selected mass flows from the platform top, ii)

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winnowing of the platform top, directly arriving in the basin or iii) sliding along the slope of fine-grained slope deposits, evolving to mudstone in the depocentral area of the basin.
Sedimentological observations (rarity of classical turbidites and the abundance of cohesive flow deposits) indicate that the last two origins are more likely. The abundance of lime mud-rich facies (especially in distal basinal domain) reflects a high production of lime mud at the platform top: this lime mud reached the basin by winnowing and by resedimentation of lime mud-rich slope facies. The effects of winnowing are recorded by the abundance of bed type LS in the proximal part of the basin: thin laminations support a decantation of lime mud from the platform, settled down in the proximal part of the basin. The common occurrence of slump overfolds, especially in bed type LS where thin laminations perfectly record soft-sediment deformations at different scale (Fig. 8) documents the instability of the slope and the common reworking of fine-grained sediments deposited in the proximal part of the basin, directly deriving from the platform top (bed types Hp and Cl 1 to 5), from mobilisation and resedimentation of slope sediments (bed types Br, but also M1 and M2) or from decantation of suspended carbonates (bed type LS).
Proximal basin packstone facies (Cl2, Cl3, Cl4) from proximal and distal parts of the basin not only differ in terms of abundance, but also for composition: proximal basin packstone are characterised by abundant skeletal grains, whereas intraclasts prevail in distal basinal packstone. The frequency of preserved slumped intervals as well as the occurrence of mass flows containing clasts of slope facies confirm that proximal basinal/distal slope sediments were commonly involved in slope failure events, producing resedimented wackestone, packstone and mudstone deposited as high-density gravity flows, evolved from slope failures.

5.3 Depositional model

The characterisation of the facies associations of the carbonate deposits of the Zorzino Limestone indicates the existence of two major sources of sediments: i) the platform top, providing lime mud and bioclastic grains and ii) the slope itself that provides sediments by sliding and reworking of slope sediments due to local collapses, even on low angle slopes. The role of direct resedimentation of slope carbonates from the platform top represents an important contribution of the basinal sedimentation is different depositional systems (King, 1986; Reijmer et al., 1991; Reijmer and Evraars, 1991; Watts, 1992; Sano and Rui, 2001; Nakashima and Sano, 2007) but, in the Zorzino Limestone, an important source of sediment is also represented by the slope itself. Actually, facies analysis of the studied logs indicates that slope failures represent the source of a significant part of the intraplatform basin sediments: the proximal basin itself was a major secondary source for sediments, producing both matrix-supported rudstone with pebbles derived from slope facies, as well as intraclastic packstone, wackestone and, distally, mudstone. The pebbles in the calcirudites were not scraped off from the underlying beds during mass flows but were part of the sediment volume that, becoming unstable, was involved in the slope failure.

The limited role of erosion during mass flows is supported by the dominance of tabular bases in the beds, not only in the distal part of the basin, but also in the proximal. Irregular surfaces mantled generally by fine-grained sediments are interpreted as scour surfaces, marking the starting places of mass flows.

In detail, it is possible to identify the following elements that control the depositional processes and facies associations in the basinal carbonate deposits of the Zorzino Limestone:

1) the grain size of the sediments coming from the platform top is dominated by lime mud, which represents most of the volume of the basinal sediments, both as mudstone and as matrix for intraclastic and bioclastic wackestone and packstone;

2) the abundance of lime mud increases viscosity and cohesion of the sediments favouring the development of slump overfolds in muddy sediments sliding along low angle distal slope/proximal basin, evolving in packstone to mudstone-supported rudstone with clasts mostly represented by slope facies itself (dark, bedded limestone), especially abundant in proximal settings;

3) decantation of lime mud (likely from winnowing of the platform top) in the time intervals between resedimentation events produced, on anoxic bottoms, dark grey laminites, enriched in organic matter, commonly affected by slumps (bed type LS), in the distal slope/proximal basin. The high instability of this bed type is recorded by the abundance of slumps and by the presence of wackestone with clasts almost exclusively represented by fragments of LS, documenting collapses along low-angle slopes;

4) cohesion and viscosity of the sediments prevent the development of classical turbidites and produce, due to slope instability, poorly-selected bed type Br1 and Br2, with clasts consisting mostly of facies from bed types Hp, Cl (1 to 5), M2 and also LS, interpreted as poorly evolved mass flow along low-angle slopes;

5) primary resedimented deposits sourced by the platform top (bioclastic packstone of bed type Hp and some events of bed types Cl1 to 5, and Br2) are limited to the borders of the basins and can be recognised by the presence of skeletal grains of shallow-water organisms and by the presence of light-grey lime mud clasts with affinity with the upper slope-margin of the platform. The studied logs indicate that a significant volume of the

basinal sediments is originated from the reworking of distal slope/proximal basin belt deposits, documenting an efficient process of resedimentation (Fig. 10). The geodynamic setting existing at the time of deposition of the Zorzino Limestone probably favoured instability of sediments deposited on low-angle carbonate slopes: the documented extensional tectonics (e.g., Jadoul et al., 1992) was surely associated with seismic shocks responsible for triggering frequent collapses (and likely liquefaction, as suggested by the presence of soft-sediment deformation structures; Shanmugam, 2017) along the slope.

A contribution to the basinal sedimentation is provided by the fall-out from suspension of platform derived lime mud clouds, able to produce fine laminations (rhythmites) marking quiet periods between redepositional events. Preservation of rhythmites is partial, as they are frequently reworked by sliding along the slope, as documented by the common presence of slumpings frequently evolving to mass flows producing wackestone beds with plastically deformed clasts of bed type LS.

The resedimented facies of the Zorzino Limestone are thus the expression of four main depositional processes (Fig. 10), in order of abundance: 1) reworking of slope sediments in distal slope/proximal basin setting producing high-density turbidity currents, 2) cohesive flows (lime mud and sand-sized debris flow in different ratio) derived from the remobilisation of slope sediments, 3) turbulent flows originated from the platform top (low-density turbidity currents, producing deposits rich in skeletal grains) and 4) settling from lime mud suspension.

The sliding of basinal sediments produces not only lime mud-rich flows (when the original sediment was totally reworked) but also lime mud and grain-supported rudstone with clasts of slope facies, evolving from slumped beds (when parts of the beds involved in the slope failure maintained their integrity, producing the clasts in the paraconglomerate).

5.4 Carbonate and siliciclastic gravity driven deposits: considerations from the case study

The depositional model of the resedimented carbonates of the Zorzino Limestone highlights major differences with respect to resedimented siliciclastic deposits.

The first difference is related to the facies types. The resedimented siliciclastic deposits in deep water setting are mostly characterised by turbidites (dominating), debris flow and hybrid beds (Middleton and Hampton, 1976; Lowe, 1982; Haughton et al., 2003; Talling et al., 2004; Haughton et al., 2009; Mutti et al., 2009; Talling et al., 2012; Fonnesu et al., 2016; Tinterri et al., 2020). Turbidites are rare in the Zorzino Limestone, whereas bed types Br1 and Br2 of the Zorzino Limestone may recall, for texture and structures, hybrid beds, characterised by enrichment in clay pebbles when sand-bearing turbidity currents erode sufficient substrate. Despite the cohesive nature of the beds, the facies of the Zorzino Limestone differ from the typical hybrid beds, as they do not generate from an enrichment of lime mud within a turbulent flow by erosion of the substrate (as observed in hybrid flows; e.g., Fonnesu et al., 2016) but, as indicated by their composition, from the sliding and resedimentation of unstable slope deposits.

Some considerations are possible also about the types of initiation processes. In siliciclastic deposits, three major types of initiation process have been identified (Piper and Normark, 2009): transformation of failed sediment, resuspension of sediment near the shelf edge by oceanographic processes, and hyperpycnal flow from rivers or ice margins. Of these processes, the latter can be excluded for carbonate sediments of the Zorzino Limestone (carbonate sediments are directly produced in the basin), whereas the second may be limited (resuspension of large amount of sediment near the shelf edge by oceanographic processes is unlikely in intraplatform basins, far away from the open oceans with a steep depositional profile affected by early cementation; Adams and Kenter, 2013). Therefore, transformation of failed sediment is the dominant process.

The sedimentological analyses of the facies types and distribution indicate general elements that differentiate the resedimented carbonates of the Zorzino Limestone from siliciclastic deposits. The range of grain-size and texture of siliciclastic sediments involved in gravity-driven sediment flows is controlled by the transport processes that delivered the clastic grains to the coastal setting, whereas carbonate systems are mostly controlled by the carbonate-producing processes

(e.g., Schlager, 2003, Pomar and Kendall, 2008), tectonics (e.g., Bosence, 2005; Randazzo et al., 2020) and the efficiency of early-marine cementation (e.g., Grammer et al., 1999). Early cementation plays a major role in the carbonate depositional systems, strongly controlling the geometry of the depositional profile and the efficiency of gravitational processes. As a consequence, slope angle in carbonate systems can reach a steepness that has no counterparts in siliciclastic deposits (Kenter, 1990) due to the sediment fabric, biological processes, early cementation but also submarine collapses (Adams and Kenter, 2013): the existence of steep slopes is responsible for a general bypass of the finer sediments that are thus deposited at the toe of the slope and in the basinal area, producing wedge-shaped carbonate aprons (Mullins ad

Cook, 1986), rather than submarine fans, characteristics of siliciclastic deposits. In the case of the Zorzino Limestone, bypass of the upper slope was favoured, beside early cementation, also by the presence of syndepositional normal faults, able to create steep slopes with coarse intraformational breccias (“Brecce sommitali della Dolomia Principale”; Jadoul, 1986) deposited at the toe.

In the Zorzino Limestone no evidence of channels is observed, both in distal and proximal settings. This element further differentiates the studied resedimented carbonate deposits with respect to siliciclastic (Mullins ad Cook, 1986): whereas in siliciclastic systems the input of sediments is generally fixed (e.g., river mouth) and incised submarine canyons commonly control the sediment trajectory, the conditions are different for the carbonate sediments of the Zorzino Limestone, characterised by diverse and changing source points from the platform top and from different parts of the slopes. The sedimentological processes recorded in the Zorzino Limestone create a higher variability of sediment types, reflecting the absence of fixed sediment routes.

6. Conclusions

The bed-by-bed study of composition and facies associations in continuous basinal carbonate successions within fault-controlled Norian intraplatform basins, permits to reconstruct sediment distribution and dominating depositional processes in the different parts (from proximal to distal) of the basin. Evidence of frequent reworking of slope deposits on low-angle slopes indicates the cannibalisation of proximal packstone and wackestone due to common sliding and disruption of sediments, documenting, in the Zorzino Limestone, the abundance of depositional processes that differ, for frequency, from those governing siliciclastic deposits, dominated by classical turbidites, more or less associated with hybrid beds. The rarity of well-expressed turbidites (that are present mostly in bioclastic packstone, directly derived from sediments sourced on the platform top) is related to the abundance of lime mud, able to increase the viscosity and cohesion of the carbonate sediments, preventing the self-organisation of siliciclastic deposits. Also, the coarsest facies are frequently represented by matrix- to packstone-supported breccias with clasts of finegrained dark, basinal limestone.

The basinal facies of the Zorzino Limestone indicate that: 1) an important contribution to the sediment supply was provided by the instability of slope sediments deposited from the carbonate top (mostly bioclastic packstone, but also laminated mudstone-wackestone, likely resulting from decantation of platform-derived lime mud); 2) the source of sediments was diffused along the slope and proximal basin, showing differences with classical siliciclastic systems (where the input point is generally better defined); 3) the grain size range of the sediments was limited, with a dominance of lime mud (coarse-grained facies are intraformational packstone and rudstone); 4) properties and composition of the carbonate sediments (muddy cohesive deposits and early diagenesis) control the physical behaviour of the sediments, showing different facies associations with respect to that of siliciclastic turbidites.

The study demonstrates that in carbonate systems, sliding of deposits on low-angle wedge-shaped carbonate aprons of cohesive fine-grained sediments dominated by mudstone and wackestone may represent a major source for basinal sediments, indicating two-steps depositional processes, differentiating carbonate resedimented deposits from siliciclastic resedimented deposits, in terms of facies association and dominant depositional processes. The bed-by-bed study of basinal carbonate succession can provide an interesting tool for reconstructing, thanks to a detailed classification of the facies types and quantitative distribution, the relative position (marginal vs. depocentral) of studied logs, the vertical evolution of the succession and the type and recurrence of depositional processes. The instability of primary sediments in the case of the Zorzino Limestone was probably amplified by the syndepositional tectonics documented during the Norian in the study area, associated to seismic shocks able to liquify sediments and trigger frequent failures also on low-angle slopes.

Acknowledgements

This research benefitted from the support, experience of Flavio Jadoul, who firstly recognised the complex palaeogeography and syndepositional tectonics of the Norian succession in the Southern Alps of Lombardy: the long and fruitful discussions with Flavio suggested us this research approach. We would like to thank Roberto Tinterri and an anonymous reviewer: their constructive comments helped us to improve an earlier version of the manuscript and to clarify the message of our research. The Editor Catherine Chagué followed with attention and patience all the editorial process: her precious and constructive comments significantly improved the original manuscript.

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Figure captions

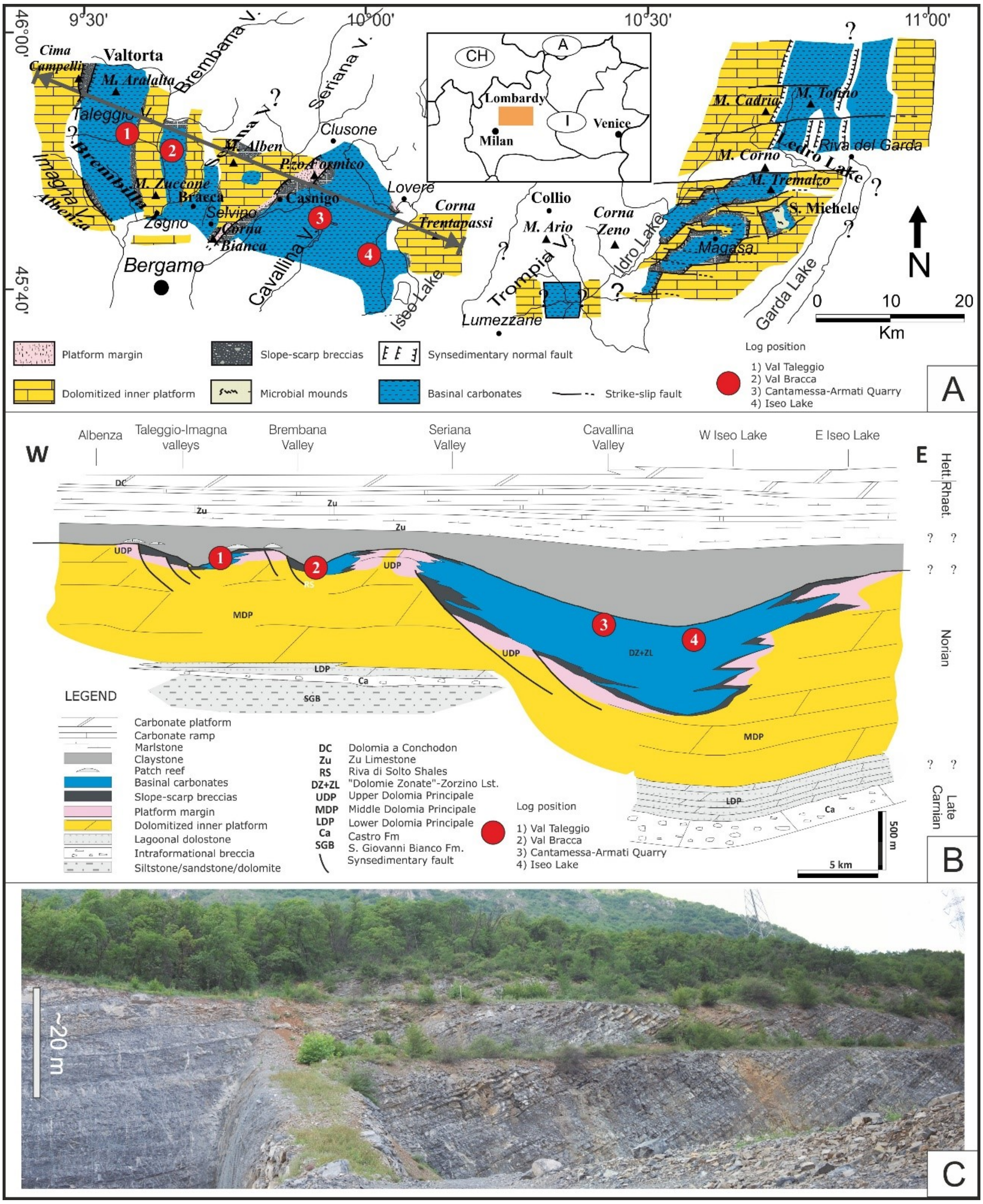

Fig. 1 - Reconstruction of the palaeogeographic setting of the Lombardy basin during the Norian, with the position of the studied logs (marked by the red circles) and examples of outcrops of the basinal succession: A) Palaeogeographic reconstruction of the Lombardy Basin during the Norian (modified from Berra and Jadoul, 1966 and Trombetta and Claps, 1995); B) Stratigraphic sketch of the Norian succession from Val Taleggio to Iseo Lake (grey line in fig. A); C) view of a classical succession of the basinal sediments of the Zorzino Limestone (Cantamessa-Armati Quarry).

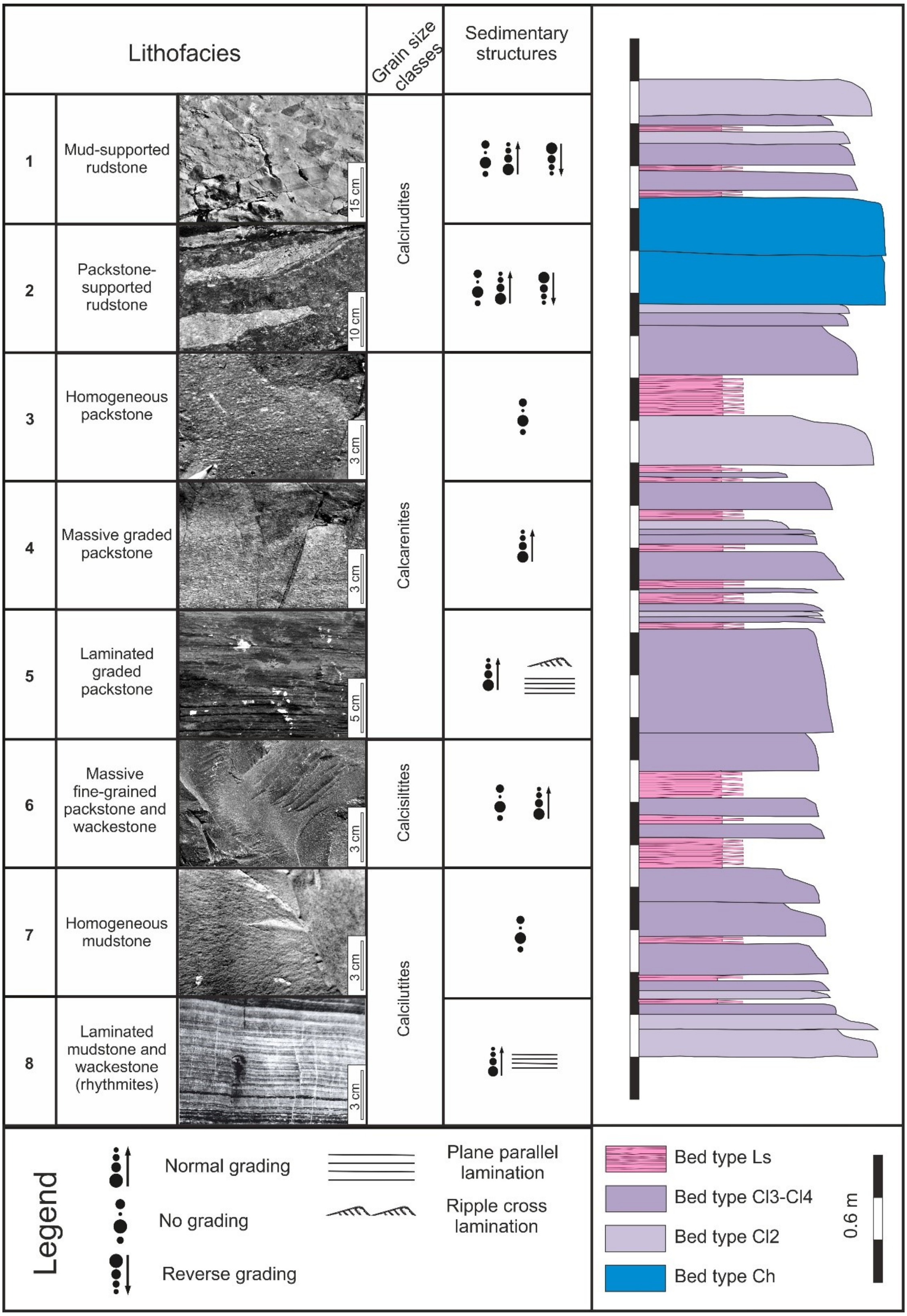

Fig. 2 – Lithofacies types recognised in the Zorzino Limestone, defined according to grain size associations and sedimentary structures, scale bar is indicative (on the left); example of the classification of the bed types (see fig. 4) on a small part, about 4.5 meters, of the Val Taleggio log (on the right).

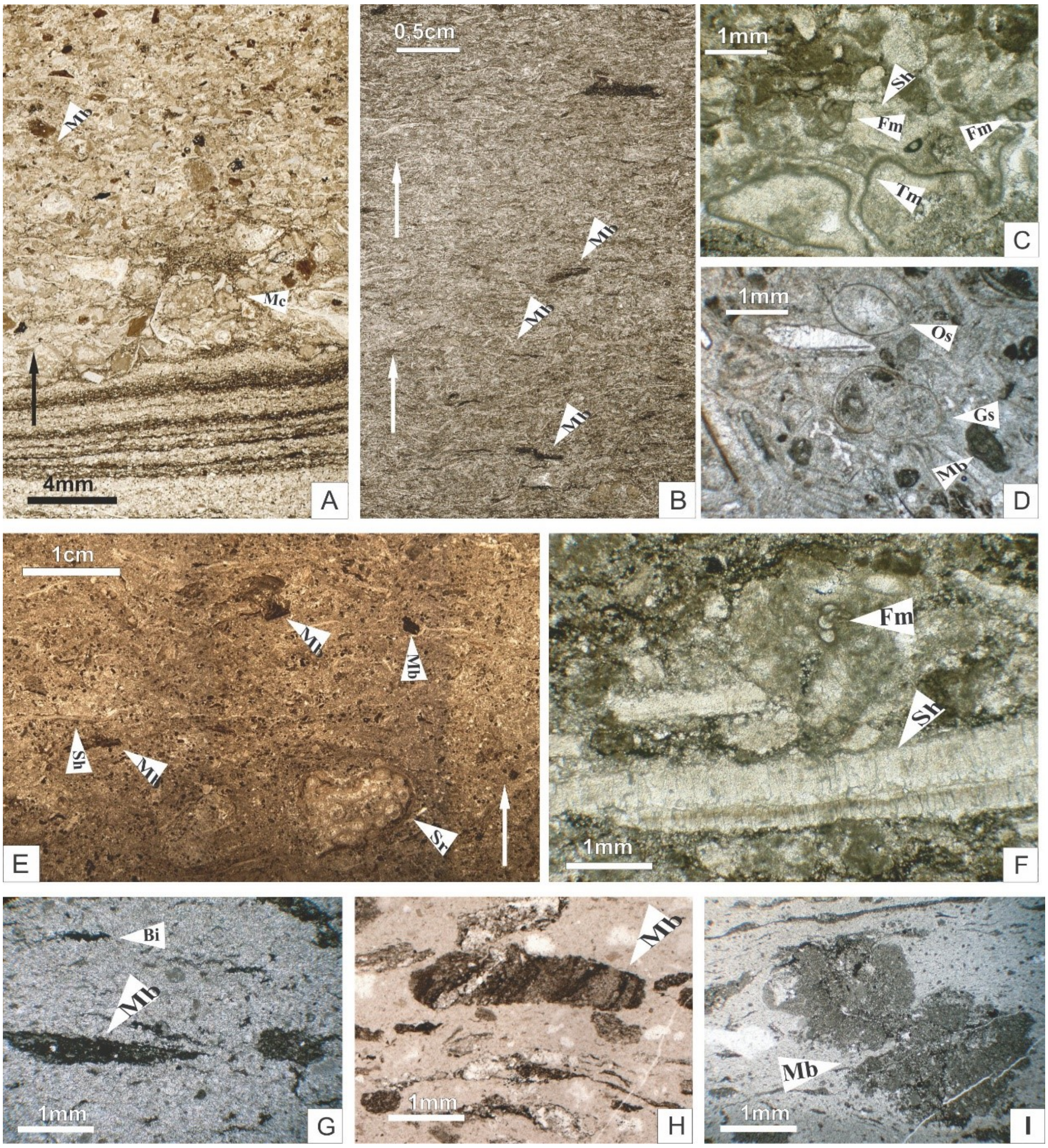

Fig. 3 – Microfacies of different packstone, for texture and components: A) fine grained laminated packstone (below, lithofacies 5), covered along a slightly erosional surface by a normally-graded, intra—bioclastic packstone (above, lithofacies 4); B) fine-grained bioclastic packstone (lithofacies 3) containing iso-oriented bivalve shells and dark intraclasts (Mb), irregular in shape; C) grainstone-packstone (lithofacies 4) with intraclasts, encrusters (*Thaumatoporella;* Tm) and skeletal grains, consisting of foraminifera (Fm), small bivalves shells (Sh); D) bioclastic grainstone (lithofacies 4) with gastropods (Gs), ostracods (Os) and fragments of possibly bivalve shells; dark intraclasts are also present; E) peloidal-intraclastic packstone (lithofacies 3), with dark intraclasts (rich in organic matter; Mb), fragment of bivalve shell (Sh) and serpulids (Sr), the white arrow marks the polarity; F) bioclastic packstone (lithofacies 4), with a large shell fragment (Sh) and foraminifera (Fm); G) intraclastic wackestone (lithofacies 1), with dark intraclasts consisting of fragments of slope facies rich in organic matter; H) intraclastic packstone, the large intraclast (Mb) consists of a fragment of laminites; I) intraclastic packstone, with a partly lithified or cohesive intraclasts, plastically deformed (Mb).

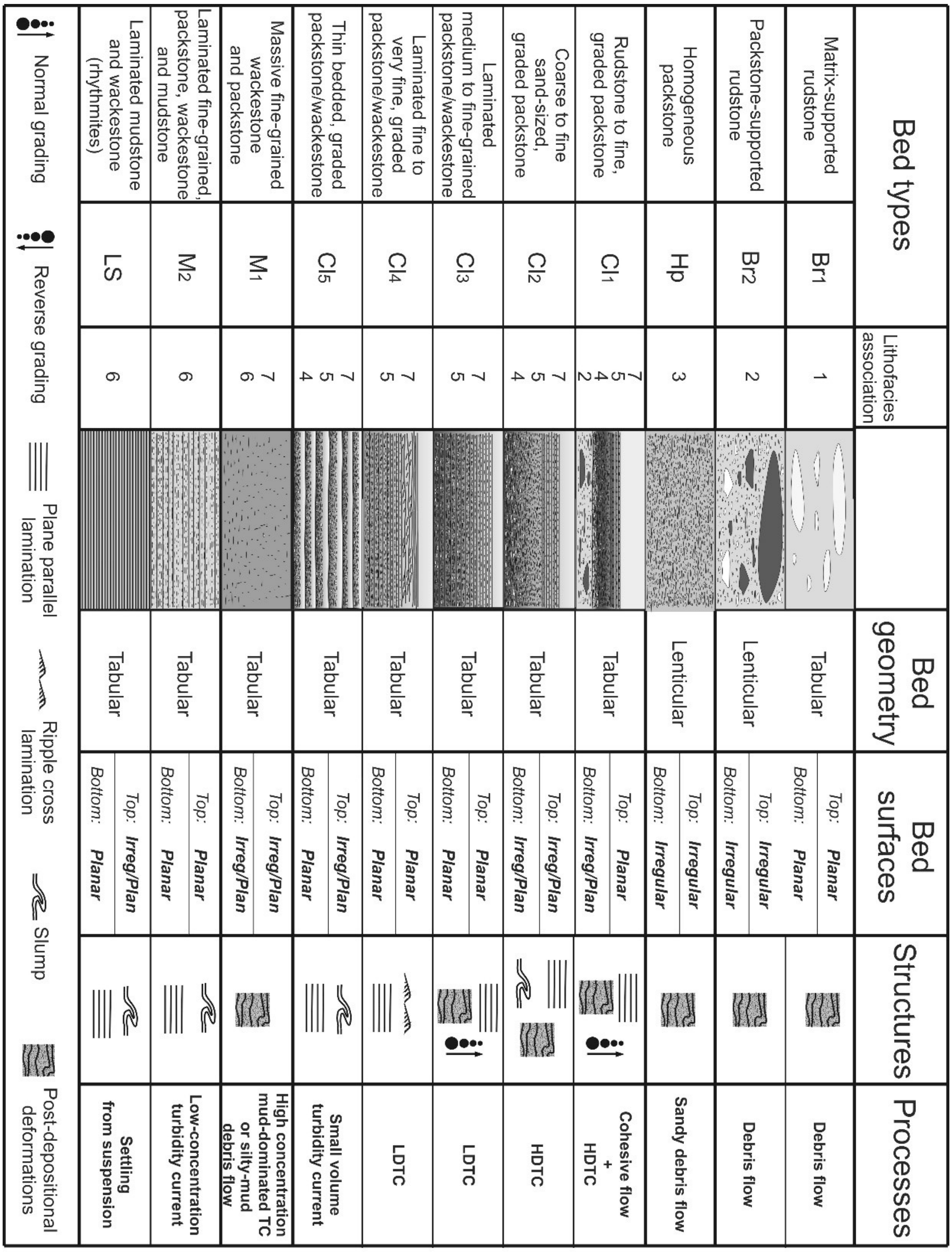

Fig. 4 – Summary of the main characteristics of the different bed types identified in the Zorzino Limestone. Bed types may consist of a single lithofacies or of recurring lithofacies associations (for lithofacies types, refer to Fig. 2). HDTC: high-density turbidity currents; LDTC: low-density turbidity currents.

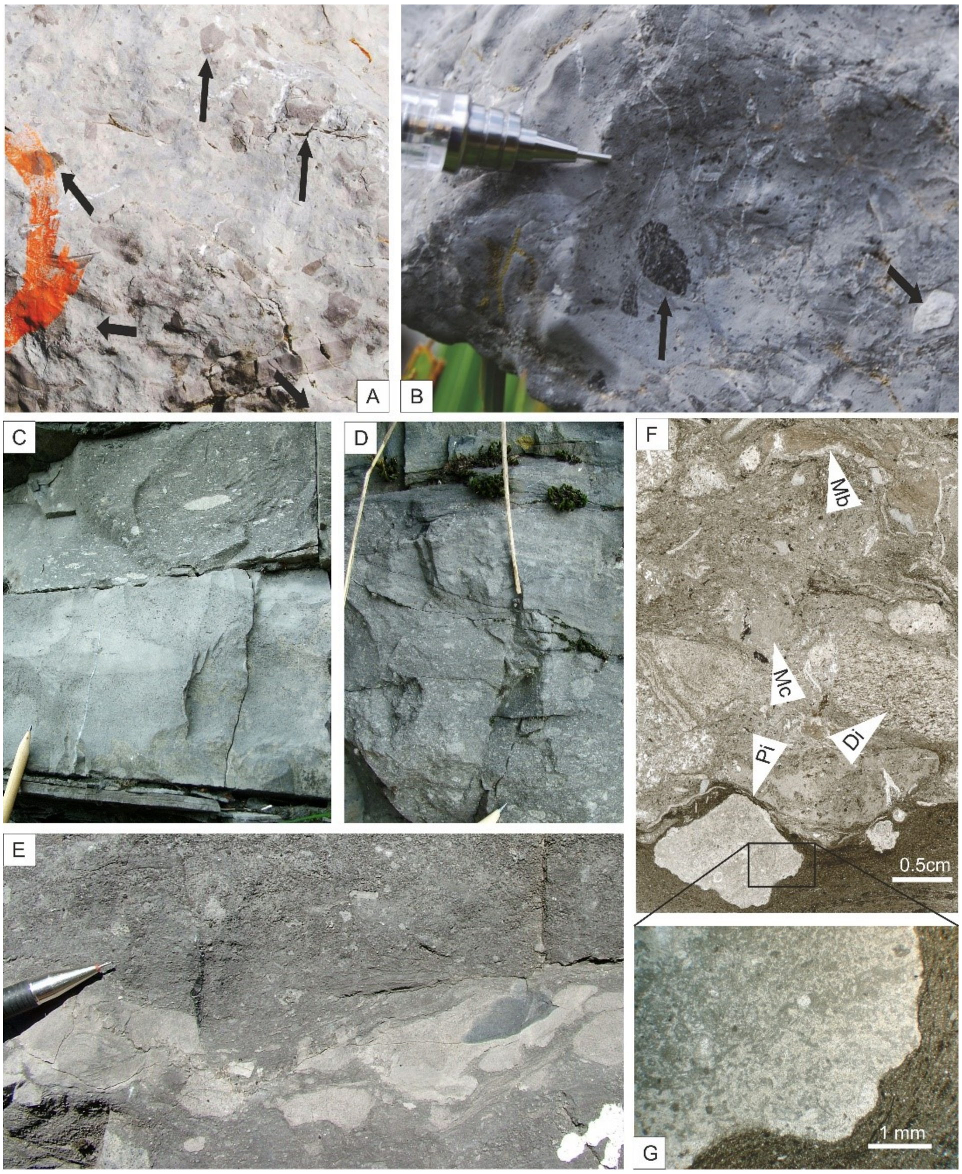

Fig. 5: Examples of bed types Br1 and Br2: A) poorly selected, clast-supported rudstone breccia (bed type Br1), arrows point to dark pebbles; B) lime mud-supported breccia (bed type Br1) with black (reworked slope facies) and white (shallow water facies) pebbles, deposited close to the basin border (Pizzo Formico); C) two rudstone beds, the lower one with lime mud soft (cohesive or partly lithified) clasts dispersed in a packstone with dark small intraclasts (Br1), the upper one with smaller light-grey pebbles dispersed in a dark matrix (Br2); D) unsorted rudstone with monospecific light-grey clasts consisting of packstone, embedded in a dark packstone, faintly laminated in the upper part (Br2); E) lime mud-supported rudstone (Br1), with clasts consisting of light grey soft (cohesive or partly lithified) packstone; F) Bio-intraclastic rudstone (Br2) with clasts of reworked slope sediments: intraclastic wackestone with small, plastically deformed clasts (Di), partially recrystallised fine-grained packstone (Pi), dark (Mb) and light grey mudstone (Mc); the interparticle space is filled by bio-intraclastic packstone, skeletal grains mostly consist of thin-shelled bivalves; note the erosional scours in the underlying fine-grained intraclastic packstone; G) detail of (F) showing a recrystallised intraclastic-pellettiferous packstone with rare ostracods.

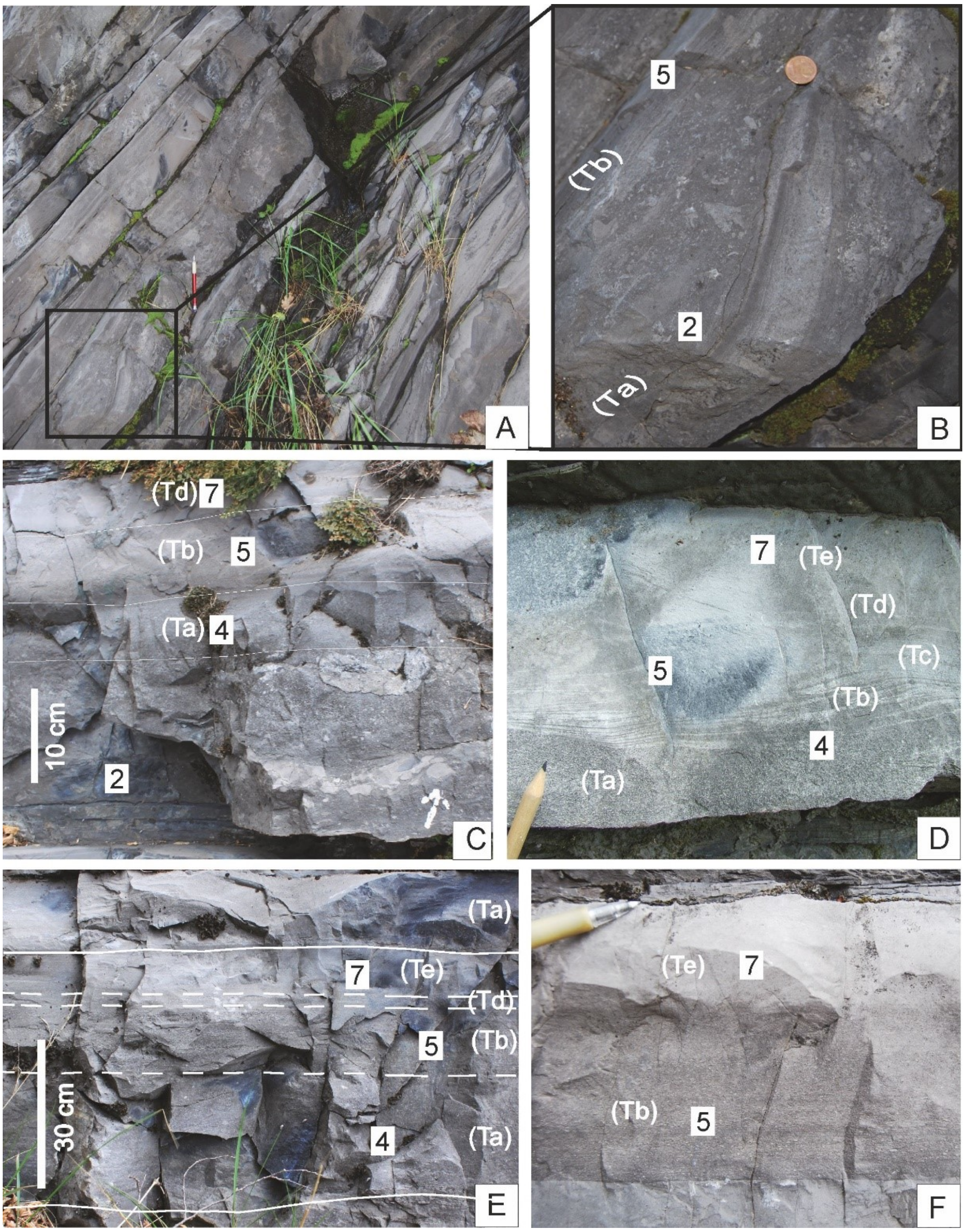

Fig. 6 - Bed types Cl1 and Cl2: A) typical aspect of the bed type associations in the Val Taleggio section; B) detail of a bed type Cl1 (box in "A"), with a lower part consisting of packstonesupported rudstone (lithofacies 2) passing upward, in the same bed, to laminated graded packstone (lithofacies 5); C) detail of another Cl1 bed, with a coarse lower part covered by different lithofacies (4, 5 and 7); D) graded and laminated bed type Cl2, with a complete Bouma sequence, evolving from packstone at the base to mudstone at the top; E) , F) two other example of bed type Cl2, with cross laminations between a lower massive part (interpreted as Ta of the Bouma sequence) and an upper lime mud (interpreted as Te of the Bouma sequence). All images from the Val Taleggio and Val Bracca sections; black numbers in white box indicate the lithofacies, the white letters correspond to the intervals of the Bouma sequence.

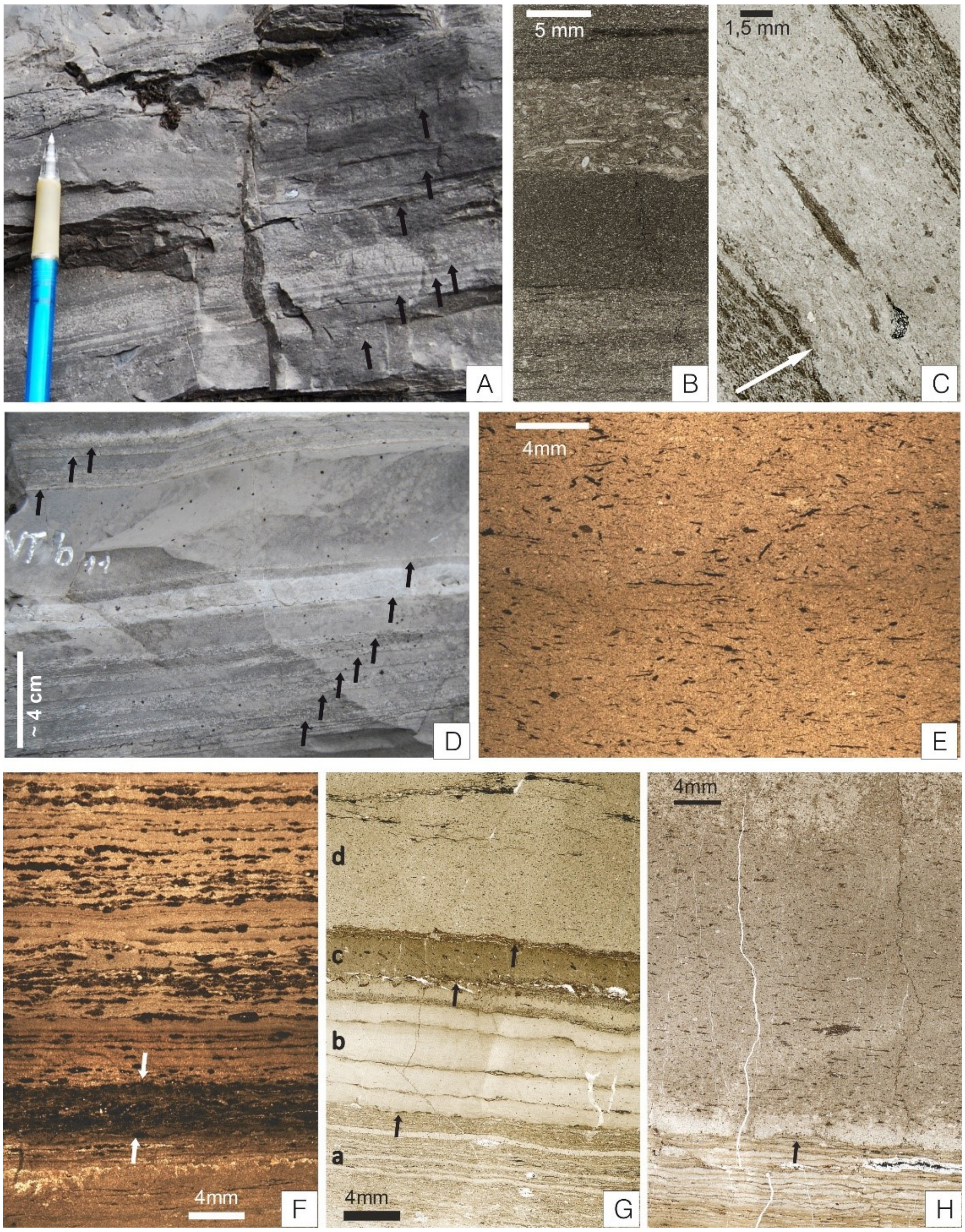

Fig. 7 Facies of bed type Cl5: A) thin alternation of dark fine-grained to very fine-grained packstone and wackestone layers; B) Thin section of the high-frequency alternation of packstone and normally-graded wackestone/mudstone; C) detail of a packstone interval, containing plastic intraclasts derived from bed type LS; D) alternations of packstone and mudstone/wackestone layers; a lighter horizon is present in the middle part of the bed; E) intraclastic wackestone, with intraclasts deriving from the resedimentation of rhythmites from bed type LS; F) laminated mudstone with a dark interval rich in organic matter (between two arrows); G) succession of laminated wackestone and mudstone (a), clear microsparite (b), dark wackestone with dispersed dark intraclasts (c) and a thicker wackestone horizon with dispersed dark soft intraclasts (d); H) thinly laminated mudstone covered by intraclastic wackestone (the arrow points to the base); intraclasts are mostly represented by dark, unlithified intraclasts derived from the reworking of laminated facies of bed type LS.

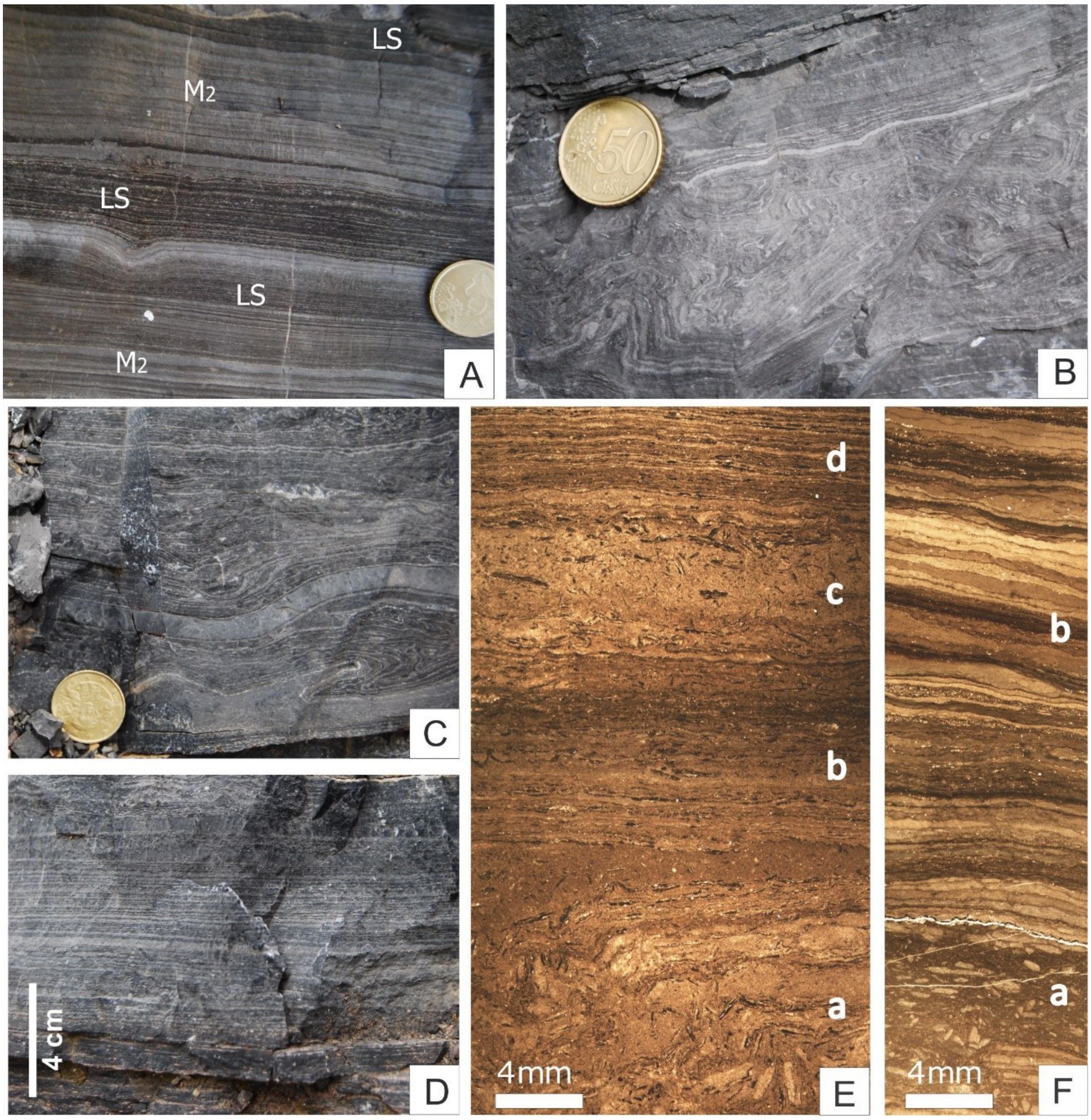

Fig. 8 – Laminites and laminated packstone, bed types LS and M2: A) classical aspects of alternating dark laminites (LS) and laminated packstone (M2); B) slump folds in bed types LS and M2; C) cm thick mudstone horizon embedded in LS bed type, plastically deformed by a slumping; D) plane parallel alternating dark and light laminae; E) microphotograph of bed type LS, with a plastically deformed (slumping) interval (a), well-preserved laminated dark intervals rich in organic matter (b), an intraclastic wackestone produced by the resedimentation of LS bed type (as those underlying, c) and another interval of thinly laminated mudstone (d); F) intraclastic packstone (at the base, a) produced by the reworking of laminated mudstone and wackestone similar to those preserved in the upper part of the microphotograph (b).

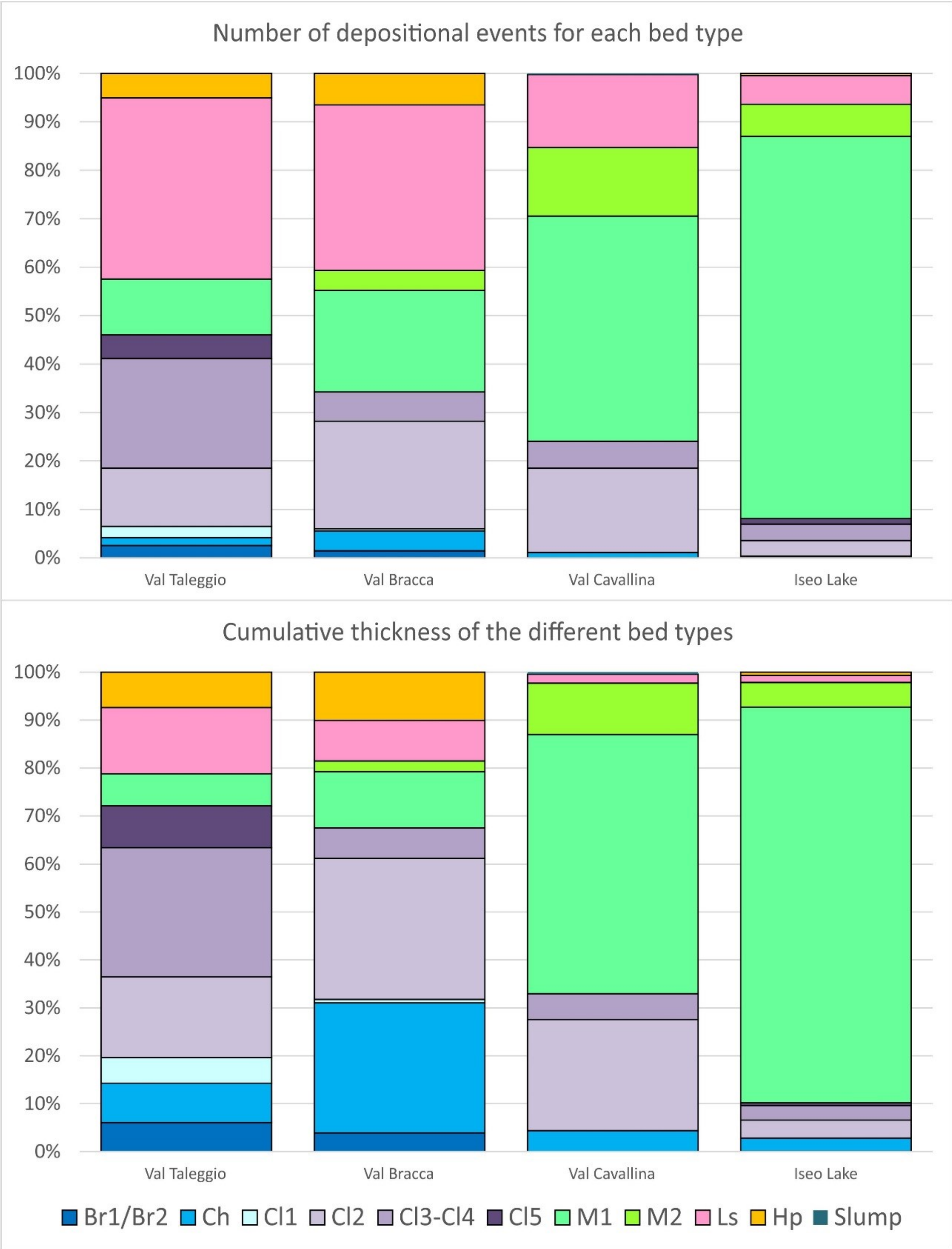

Fig. 9 - Quantitative distribution, in percentage, of the number of beds (above) and of the thickness (below) of each bed type described in the text, for the four different logs, from the border of the basin (left) to the depocentral area (right).

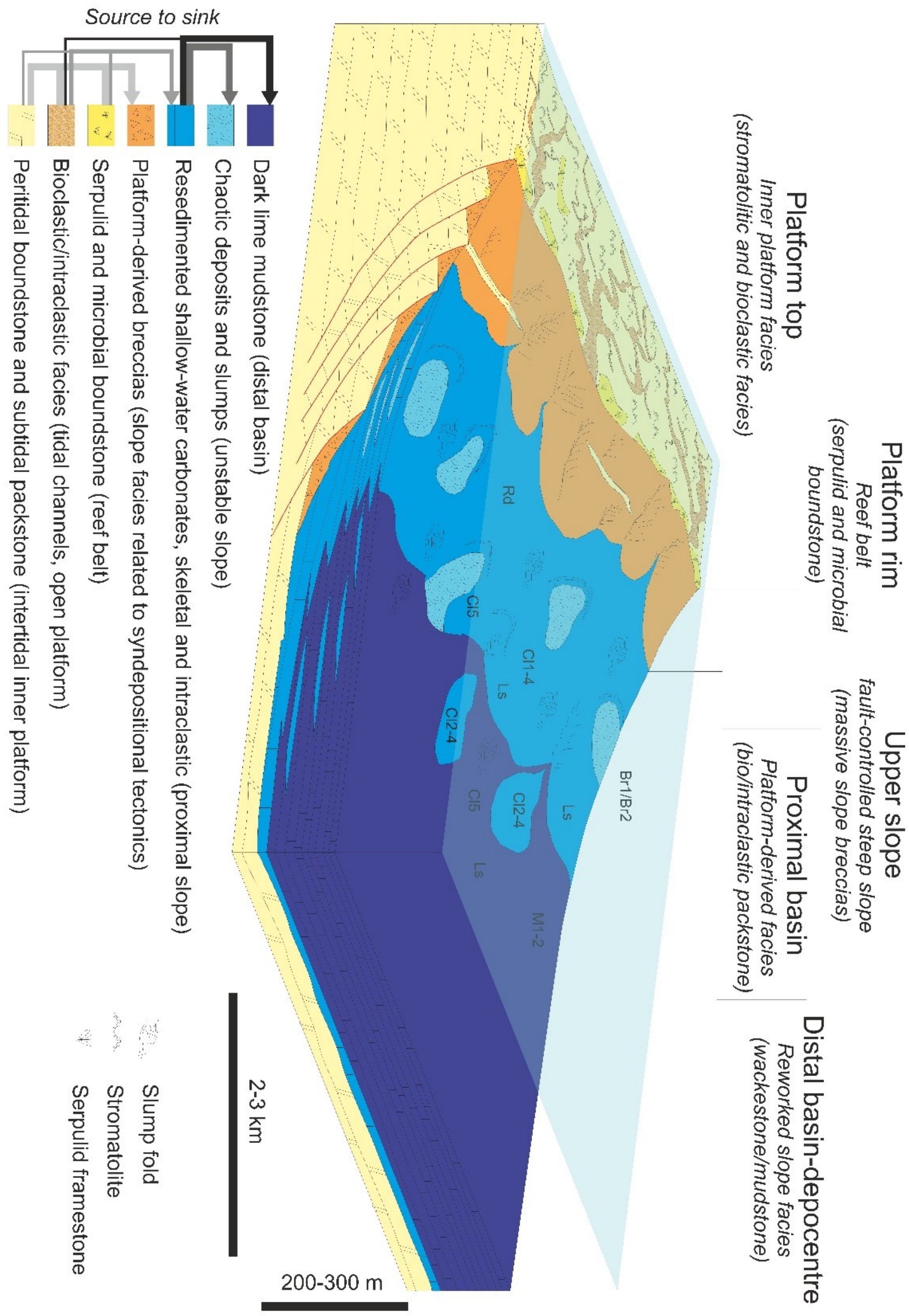

Fig 10 – Depositional model of the different facies identified in the fault-controlled basins developed in the Dolomia Principale. Sediments derived from the platform top, bypassing the steep, fault-controlled scarps, are commonly resedimented due to the instability of the slope, documented by slump scars and slumpings in the proximal part of the basin. The source to sink arrows indicate qualitatively the contribution of the different sub-environments to sediment accumulation (the largest is the line, the more significant is the contribution, from proximal, light-grey lines, to distal settings, black lines).