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The tectonically-confined Firenzuola turbidite system (Miocene, Marnoso-arenacea Formation, northern Apennines, Italy): an example of facies variations related to the basin morphology

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ABSTRACT

The Firenzuola turbidite system formed during a paroxysmal phase of thrust propagation, involving the upper Serravallian deposits of the Marnoso-arenacea Formation (MAF). During this phase the coeval growth of two major tectonic structures, the M. Castellaccio thrust and the Verghereto high, played a key role, causing a closure of the inner basin and a coeval shift of the depocentre to the outer basin. This work focuses on this phase of fragmentation of the MAF basin; it is based on a new detailed high-resolution stratigraphic framework, which was used to determine the timing of growth of the involved structures and their direct influence on sediment dispersal and on the lateral and vertical turbidite facies distribution. The Firenzuola turbidite system stratigraphy is characterized by the occurrence of mass-transport complexes (MTCs) and thick sandstone accumulation in the depocentral area, which passes to finer drape over the structural highs; the differentiation between these two zones increases over time and ends with the deposition of marly units over the structural highs and the emplacement of the Visignano MTC. According to the stratigraphic pattern and turbidite facies characteristics, the Firenzuola System has been split into two phases, namely Firenzuola I and Firenzuola II: the former is quite similar to the underlying deposits, while the latter shows the main fragmentation phase, testifying the progressive isolation of the inner basin and a coeval shift of the depocentre to the outer basin.

The final stratigraphic and sedimentological dataset has been used to create a quantitative high-resolution 3D facies distribution using the Petrel software platform. This model allows a detailed analysis of lateral and vertical facies variations that can be exported to several reservoirs settings in hydrocarbon exploration and exploitation areas, since facies distributions and geometries of the reservoir bodies of many sub-surface turbidite basins show a significant relationship to the syndepositional structural activity, but are beyond seismic resolution.

RIASSUNTO

Il sistema torbiditico di Firenzuola si è depositato durante un'importante fase di crescita sin sedimentaria delle strutture tettoniche che ha coinvolto il bacino della Formazione Marnoso-arenacea nel Serravalliano Superiore. Questa fase tettonica è stata indotta dalla crescita coeva delle strutture del thrust del Monte Castellaccio e dell'Alto di Verghereto, il cui avanzamento e sollevamento hanno causato la chiusura del bacino interno e il concomitante spostamento del depocentro principale nel bacino esterno. Questo studio è focalizzato su questa fase cruciale di compartimentazione del bacino di avanfossa della Formazione Marnoso-arenacea, sulla base di una stratigrafia fisica ad alta risoluzione ed una dettagliata analisi di facies, grazie alle quali si sono potute ricostruire le fasi evolutive delle principali strutture tettoniche e la loro influenza sulla distribuzione latero-verticale delle facies torbiditiche. Il sistema torbiditico di Firenzuola è caratterizzato dalla messa in posto di complessi caotici (mass-transport complexes o MTCs) e da potenti accumuli di lobi arenacei nelle areee depocentrali che passano, sia lateralmente che sottocorrente, a successioni condensate di depositi fini nelle aree di alto strutturale. La differenziazione in termini di facies tra queste due zone incrementa nel tempo e termina con la deposizione delle Marne di Calstelvecchio e di Verghereto sugli alti strutturali e con la messa in posto del Complesso caotico di Visignano. Sulla base dell'analisi stratigrafica e della variazione delle facies, il sistema torbiditico di Firenzuola è stato diviso in due fasi, denominate Firenzuola I (o sotto-Unità Va) e Firenzuola II (o sotto-Unità Vb): la prima mostra caratteristiche simili ai depositi sottostanti (Unità IV di Muzzi magalhaes e Tinterri, 2010), la seconda è caratterizzata da una maggiore differenziazione che testimonia il progressivo isolamento del bacino interno e il coevo spostamento del depocentro principale dell'avanfossa nel bacino esterno. L'insieme dei dati rilevati è stato infine elaborato tramite il software Petrel da cui si è estrapolato un modello sperimentale ad alta risoluzione basato sui log stratigrafici rilevati in affioramento. Molti bacini sedimentari sepolti che caratterizzano aree di esplorazione di idrocarburi sono caratterizzati da depositi fortemente influenzati dalla tettonica sinsedimentaria, nei quali la conoscenza della distribuzione delle proprietà è spesso limitata alla risoluzione ottenibile dalla stratigrafia sismica; la modellizzazione ottenuta in questo studio può pertanto essere utilizzata per il miglioramento della predizione della distribuzione tridimensionale delle facies torbiditiche e relative proprietà petrofisiche ad alta risoluzione.

CONTENTS

1. INTRODUCTION: MAIN THESIS OBJECTIVES AND STUDY AREA

The Marnoso-arenacea Formation (MAF, Burdigalian-Messinian) is one of the foredeep units representing the autochthonous domain of the northern Apennines. It crops out along a 120 km alignment extended from the northern Sillaro tectonic line to the southern margin beyond the Gubbio Area, splits by the Marecchia allochthon sheet that divides the north-western Romagna sector from the south-eastern Umbro-Marchean one (fig.1). It was deposited in an elongated, NW-stretched foredeep basin formed in front of the growing Northern Apennines orogenic wedge (fig.1B) and consists of a shoaling upward stratigraphic succession whose thickness could exceed 4000m (see fig.2, Tinterri & Muzzi Magalhaes, 2011). The MAF stratigraphic succession records the progressive closure of the foredeep basin due to the propagation of thrust fronts toward north-east, i.e. toward the outer and shallower foreland ramp (fig.2). In such a setting, the growth of the tectonic structures was able to produce a complex foredeep (Ricci Lucchi, 1986), characterized by synsedimentary highs and depocentres, and a separation of the MAF stratigraphic succession into two main phases, named inner basin (or stage) and outer basin (fig.2). Over the years, several works have stressed the importance of the activity of synsedimentary tectonic structures (Ricci Lucchi, 1986; Argnani & Ricci Lucchi, 2001; Mutti *et al.*, 2002 with references). In particular, Muzzi Magalhaes & Tinterri 2010,

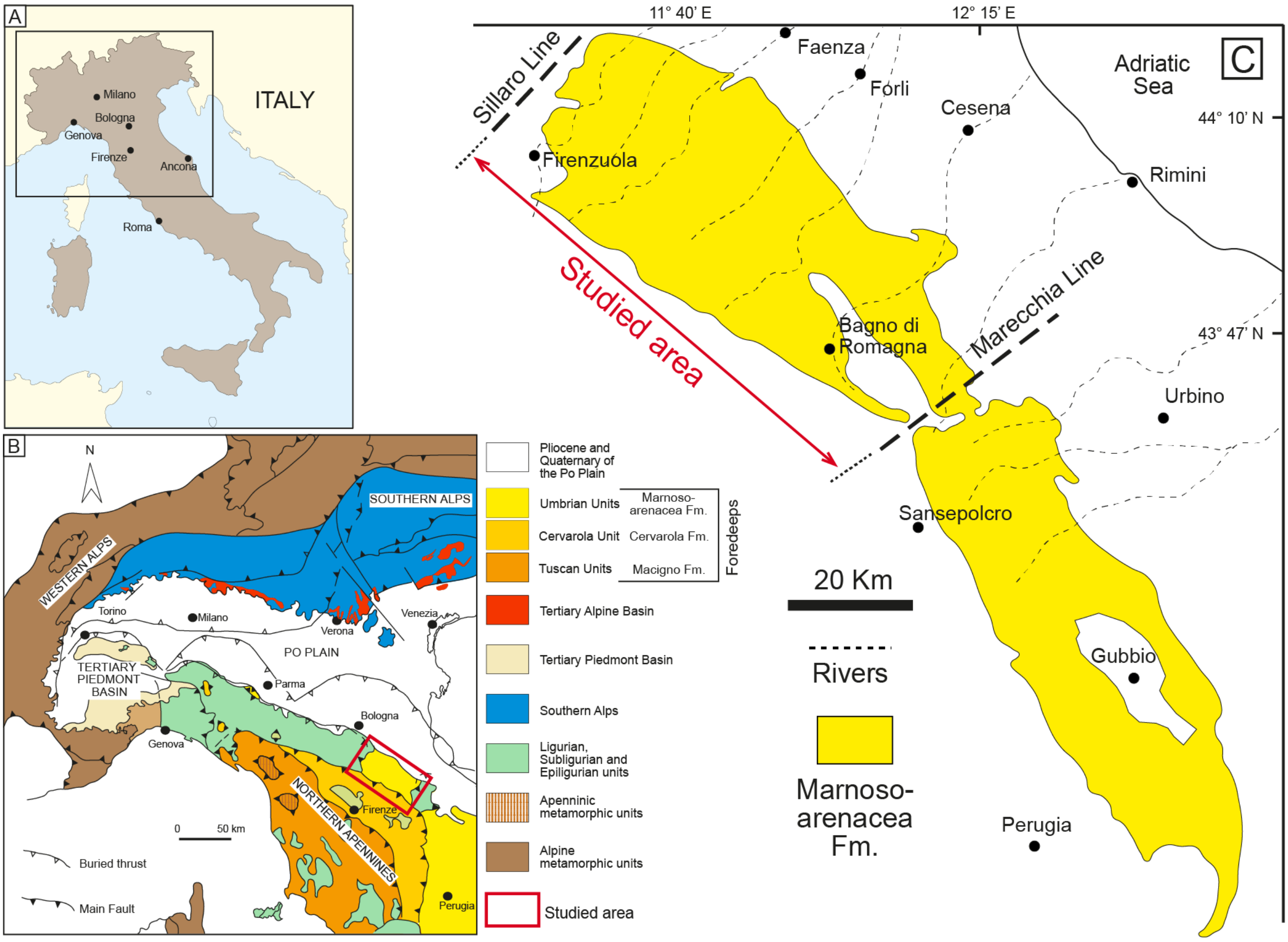


Fig.1 - A) area Shown in B. B) simplified geological map of northern Italy. C) MAF outcropping area (from Muzzi Magalhaes & Tinterri, 2010).

(see also Muzzi Magalhaes, 2009; Tinterri & Muzzi Magalhaes, 2011; Tinterri *et al.*, 2012) presented a new high-resolution stratigraphic framework of the Langhian to Serravallian portion of the Romagna sector, highlighting this strong synsedimentary activity through the introduction of five tectonically controlled stratigraphic units (I, II, II, IV and V). Recently, with the same approach, Tinterri & Tagliaferri (2015) stressed the importance of the growth of the Coniale and Verghereto structures, as well as its influence on the lateral and vertical facies distribution of the entire stratigraphic succession studied. The Coniale antcline is associated with a NW-SE oriented region-wide structural alignment (M. Castellaccio thrust), whose growth produced a progressive segmentation of the foredeep with a mechanism similar to that of figure 2. In this evolution, the Firenzuola turbidite system (Unit V by Muzzi Magalhaes & Tinterri, 2010) that crops out in the Romagna Apennines, between the Sillaro to the Marecchia tectonic lines (fig.1), is very important because it represents the phase of transition between the inner and the outer basin caused by the growth of two major structures, i.e. the M. Castellaccio thrust and the Verghereto high Tinterri & Tagliaferri, 2015, Tagliaferri & Tinterri, in press).

Consequently, the main objective of this work is to propose - for the first time ever - a high-resolution physical stratigraphy and facies analysis of this very important stratigraphic Unit, which records progressive isolation of the inner basin and the coeval shifting of the foredeep main depocentre in the outer basin.

The study has been performed through high-resolution physical stratigraphy (bed-by-bed correlation) and facies analysis of seven stratigraphic logs located in different areas of the Romagna Apennines (fig,1), in order to evaluate stratigraphic and facies changes related to the syn-sedimentary tectonic activity, which deeply affects sediment dispersal pattern and depositional processes. The study of the Firenzuola System is important also because it represents the stratigraphic link between the underlying Langhian to Serravallian deposits (Units I to V) - studied by Muzzi Magalhaes & Tinterri (2010), Tinterri & Muzzi Magalhaes (2011) - and the overlying upper Serravallian Pateraio turbidite system (Unit VI) studied by Tinterri & Tagliaferri (2015).

The final results of the field activity have been used, successively, for performing an experimental high-resolution 3D turbidite facies modeling with the Petrel software platform. The scope of this latter work is to provide a stratigraphic and sedimentologic model exploitable by physicists and statistical experts for developing statistical laws of lateral and vertical facies distribution, improving facies prediction for the hydrocarbon exploration.

The Firenzuola deposits, as highlighted by Tinterri & Tagliaferri (2015), could also represent a good analog of highly-confined turbidite systems, as found in hydrocarbon exploration and production areas (intraslope basins by Prather *et al.*, 1998) where the assessment of properties distribution is limited to seismic interpretations; therefore the final model provides an exploitable tool for the prediction of high-resolution facies and petrophysical properties distribution throughout reservoirs characterized by similar setting.

In conclusion, this PhD Thesis, financed by ENI Spa oil company, falls of a more general scientific project that has been carried out for many years by the sedimentary geology group of the Department of Physics and Earth Sciences of the University of Parma, with the main objective of understanding of the relationship between turbidite systems and tectonically-controlled basin morphology (see Muzzi Magalhaes & Tinterri, 2010; Tinterri & Muzzi Magalhaes, 2011; Tinterri *et al.*, 2012; Tinterri & Tagliaferri, 2015). Part of the results presented in this PhD Thesis has been recently published in the Italian Journal of Geoscience (see Tagliaferri & Tinterri, in press).

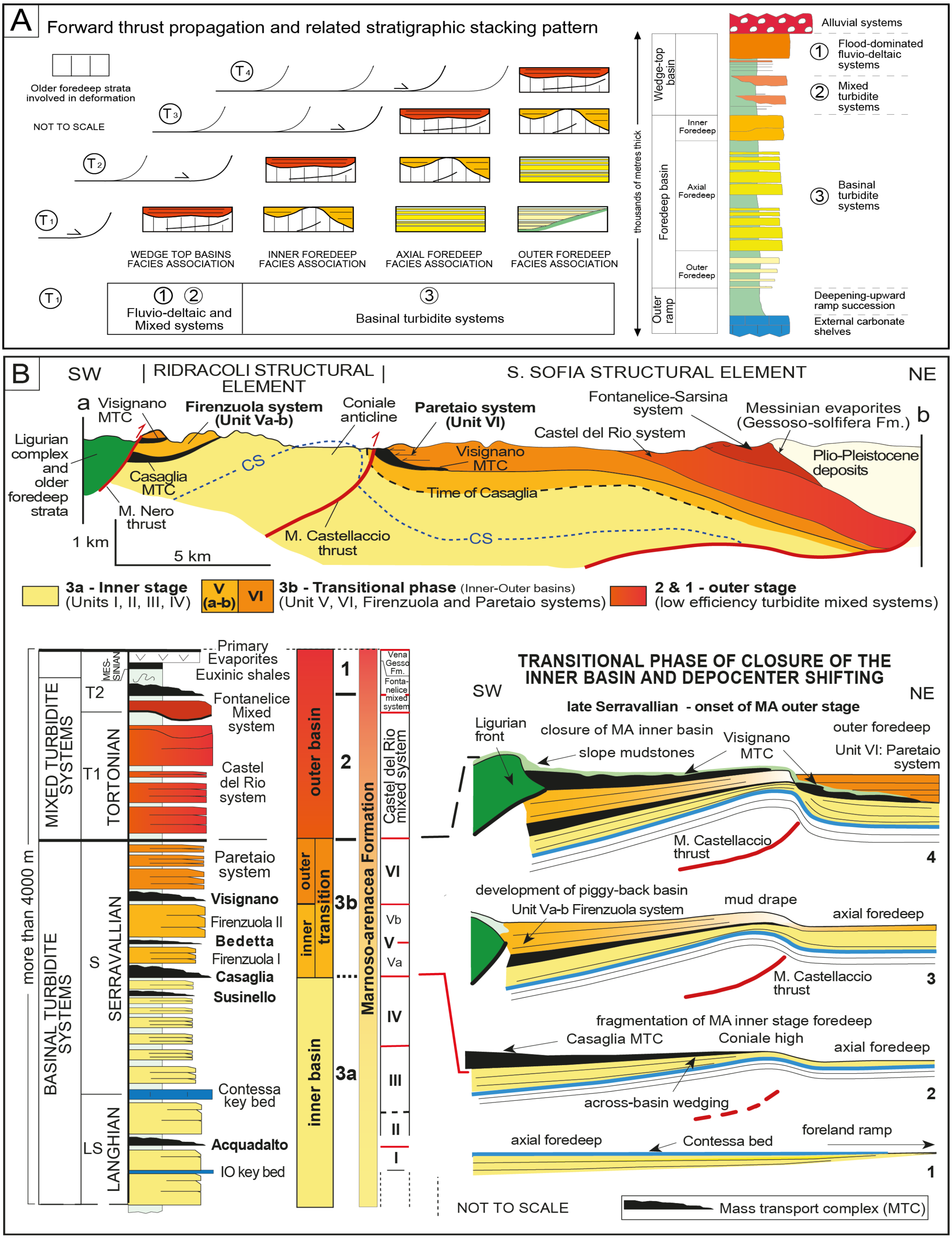


Fig.2 – A) Schematic evolution of foredeep deposits related to thrust propagation (from Mutti *et al.*, 2003 and Artoni *et al.*, 2000). B) Above, the geological cross-section transverse to the basin axis showing the position of major thrust faults subdividing the outcrop into structural elements is shown (modified from Roveri *et al.*, 2002). Below, the schematic stratigraphic log of the MAF. The depositional sequences by Ricci Lucchi and Ori (1985), LS, S, T1, T2 (L 1□4 Langhian, S 1□4 Serravallian and T 1□4 Tortonian), main MTCs (Lucente and Pini, 2002) and the deposits related to inner, transitional and outer stages are also shown. On the right, a diagram showing the stratigraphic and structural evolution of the MAF proximal foredeep from early to late Serravallian recording the passage between inner and outer basins, as meant by Ricci Lucchi (1986) (modified from Roveri *et al.*, 2002; see also de Jager, 1979).

2. APENNINE GEOLOGIC AND STRATIGRAPHIC SETTING

The Apennines form the framework of the entire Italian peninsula, spanning from Liguria to Sicily in a 1500km-long extended alignment that can be divided into two main parts (fig.3): northern and central-southern arches, split by the Anzio-Ancona line, also known as the Olevano-Antrodoco segment (Locardi, 1982; Ricci Lucchi, 1986; Patacca & Scandone, 1989; Vai, 2001). The northern Apennines also borders the Alps chain by the Villavernia-Varzi-Levanto alignment (fig.3); this limits has been essentially deduced from the different timing of the deformation history and sense of transport of the two orogenic belts: westward for the western Alps, eastward for the northern Apennines. The latter can be considered as a thrust and fold belt, derived from the tectonic juxtaposition of two main domains: a structurally lower and younger outer autochthonous domain, consisting of the continental basement of the Adria plate and its relative sedimentary cover, overthrust by an upper and older inner allochthonous domain, derived from obducted slices of the Ligurian – Piedmont oceanic crust overlaid by their relative sedimentary cover. The above domain derived from an E-W stretched branch of the Tethys Ocean, opened during the lower Jurassic

Fig.3 - Main Apennines subdivisions and related tectonic lines: 1) Villavernia-Varzi-Levanto; 2) Olevano-Antrodoco-M.Sibilinni; 3) Sangineto; 4) Taormina.

concomitantly to the central Atlantic Ocean whose subsequent closure was induced by the counter-clockwise rotation of the African plate, in its turn induced by the Cretaceous opening of the southern Atlantic Ocean (fig.4). From a regional point of view the Ligurian-Piedmont basin acted as a separation alignment between the European and Adria plates, whose margins represented the Alpes and Apennines foreland, respectively. Therefore, the allochthonous domain is involved in a complex deformation history, undergoing both Alpine and Apenninic orogenesis (Elter, 1975, 1994; Elter & Marroni, 1991; Castellarin *et al.*, 1992; Vai & Castellarin, 1992; Castellarin, 2001; Vai, 2001)

2.1 Geodynamic evolution

The northern Apennines belt is characterized by a complex evolution history, affecting European and Apula plates from Jurassic up to the present (fig.4). The best way to understand this complex history is is from a wider ranging regional point of view, considering both the Apennine and Alpine orogenic belts. According to Elter & Marroni (1991), the western Alpes, the Corsica-Sardinia Massif and the northern Apennines experienced the same tectonic evolution up to the Paleogene, but from the Oligocene on, the dynamics of these orogenic belts started to be different. This differentiation seems to be related to the beginning of the lower Oligocene Balearic and subsequent Aquitanian Tyrrhenian rifting (fig.4, 5). The latter caused the detachment of the Corsica-Sardinia Massif from the Iberian and European plates through a counter-clockwise rotation that gave rise to the main tectonic phases of the Apennine orogenesis (fig.4, 5). Several models of the geodynamic evolution of the Apennines have been proposed over time; in this work the reference model used is the one by Elter & Marroni's (1991), as modified by di Biase & Mutti (2002). According to this model, starting from the Jurassic, the Apennines geodynamic evolution can be outlined in five main phases (fig.4):

A) Ligurian-Piedmont Ocean opening, through the Jurassic to lower Cretaceous spreading, between the European and Adria plates. On a global scale, the Ligurian-Piedmont basin represents a branch of the Tethys Ocean, whose opening is strictly related to the coeval central Atlantic Ocean spreading. During this time, the inner Ligurian domain was characterized by the formation of oceanic crust, overlaid by deep-water chert and limestone of the Argille a Palombini and Calcari a Calpionelle Formations. Conversely, the outer Tuscan and Umbro-Marchean domain was dominated by thicker carbonate shelfal successions

B) Upper Cretaceous tectonic inversion, called Eo-Alpine phase, related to the beginning of the European plate subduction under the Adria one. This phase was originated by the opening of the southern Atlantic Ocean, which forced the Africa plate to rotate counter-clockwise and its northern part to converge against the southern margin of the European plate. This important tectonic phase is characterized by the depositions of the Helminthoid Flysches

C) European – Adria continental collision, due to the total consumption of the Ligurian-Piedmont oceanic crust in the final stages of the subduction processes. This major late Eocene-Oligocene tectonic stage of the Alpine orogenesis is called Meso-Alpine or Ligurian phase, during which the Ligurian nappes are sealed by Epimesoalpine deposits (as meant by Mutti *et al.*, 1995) that infill piggyback basins such as the Tertiary Piedmont and Epiligurian Basins. This Priabonian-Rupelian succession has not foredeep time-equivalent units yet, since they occured later with the Late Oligocene Macigno deposits (Mutti *et al.*, 1995).

D) Upper Oligocene inversion of the subduction process. The beginning of the Balearic rifting induced a counter-clockwise rotation of the Corsica-Sardinia Massif, which

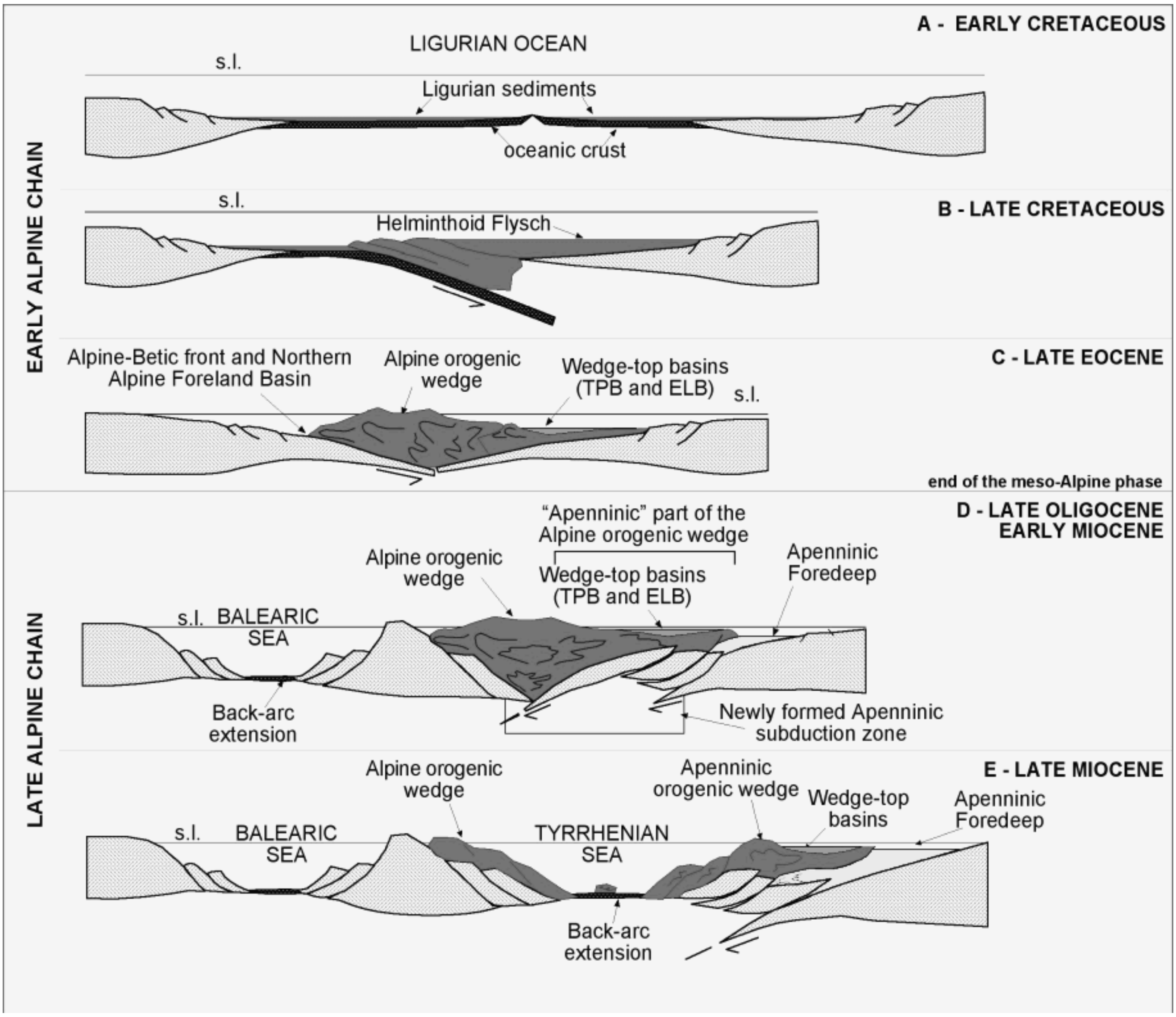


Fig.4 – Main evolutionary phases of the northern Apennines (from Elter & Marroni, 1991; modified by di Biase & Mutti, 2002).

forced a westward subduction of the Adria plate below the European plate. This geodynamic change marks the beginning of the Apennine orogenesis, through the formation of a north-eastern verging orogenic wedge involving the Ligurian units. The weight of the wedge caused a flexure of the Adria plate, from which foreland basins formed on its western margin, in front of the Apennine orogenic wedge. The Apennine wedge-foredeep system was characterized by a continuum space-time NE-migration, caused both by the Balearic spreading, with the related counter-clockwise rotation of the Corsica-Sardinia Massif on its rear and by the Adria slab roll-back (fig.5; see di Biase and Mutti, 2002 with references; Doglioni *et al.,* 1999, 2004). In this geodynamic evolution, starting from the Late Oligocene, several foredeep turbidite systems were deposited: Macigno (Late Oligocene), Cervarola (Lower Miocene), Marnoso-arenacea (Middle Miocene) and Laga (Late Miocene).

E) Opening of the Tyrrhenian basin. The Balearic spreading ends about 16 My BP. However, the Apennine wedge-foredeep system kept on its northe-eastern migration because of the spreading of the Tyrrhenian basin (fig.5). The time-equivalent foreland basin at this time was the Laga foredeep unit and probably the Tortonian upper part of the

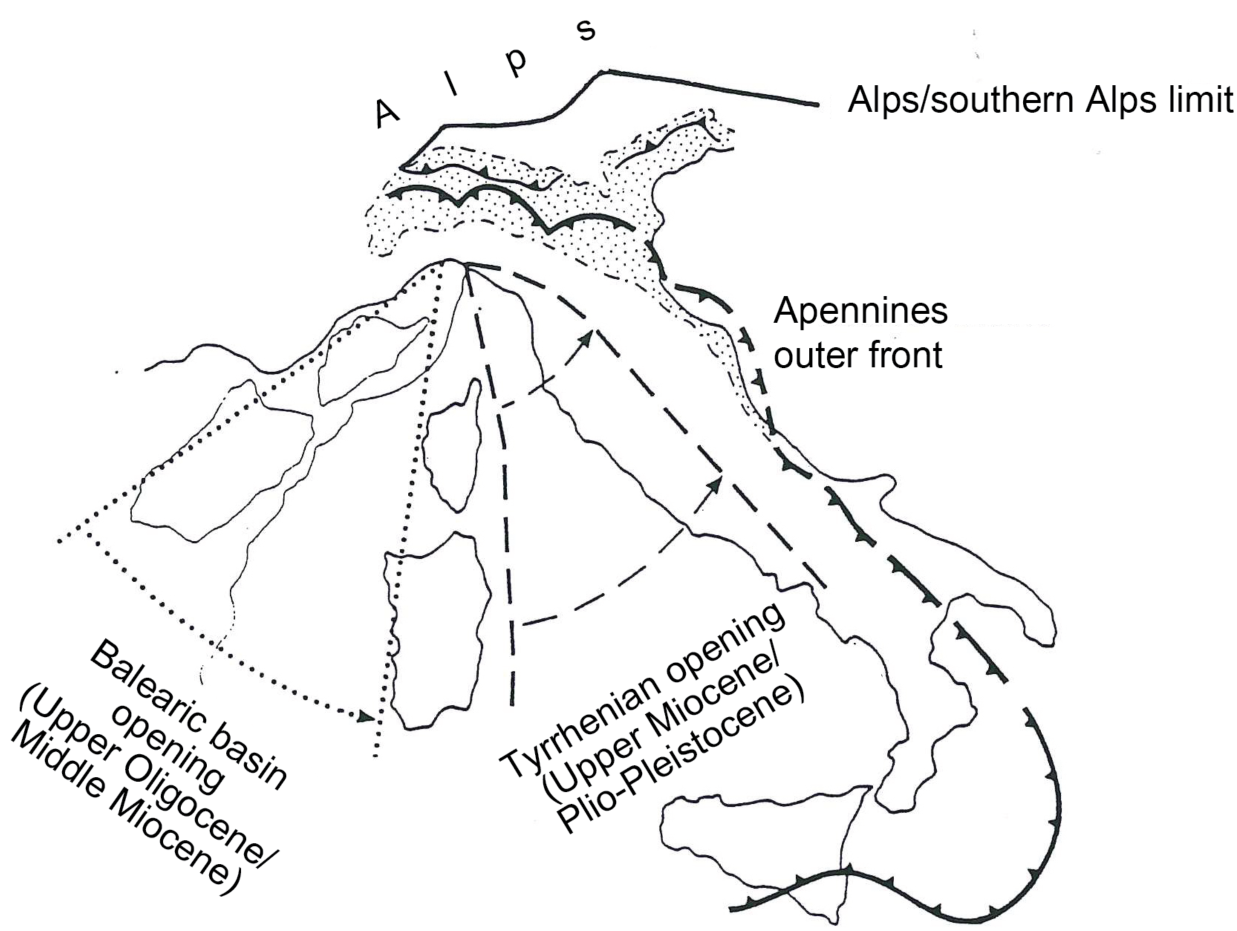


Fig.5 – Main tectonic phases affecting the Apennine orogenesis (modified from Castellarin *et al.*, 1992).

Marnoso arenacea Formation.

At the time foredeep turbidites were deposited, the paleogeographic setting can be outlined by the map of fig.6, where the retrovergent area of the Alps becomes the northern margin of a large basin, named proto-Adriatic by di Biase & Mutti (2002). It can be divided into two main sub-basins: a northern shallower Tertiary Alpine basin and a southern deeper Apennine basin split by the Valle the Salimbene-Bagnolo ridge, which is a sinistral transcurrent tectonic alignment that allowed the westward motion of the southern Alps concomitantly with the eastward one of the Apennines. According to di Biase & Mutti (2002), the Salimbene-Bagnolo fault-system acted throughout the Oligocene and Miocene times and was inherited from an older Liassic fault-system, related to the rifting phases and corresponding to the Emilian fault (Bosellini, 1981; Vescovi, 1993). Because of its particular location, this structure deeply affected the sediment dispersal and depositional systems distribution in the Tertiary Alpine Basin and Apennine one; the former was filled by the shallow flood-dominated, fluvio-deltaic systems of the Gonfolite Formation, whereas the latter was characterized by deeper turbidite systems fed by the most catastrophic floods able to bypass the Salimbene-Bagnolo ridge or by remobilization of delta-front sediments of the Tertiary Alpine Basin triggered by seismic events (fig.6).

2.2 Paleogeographic domains

Hystorically, the Apennine chain is divided into two main tectonic units: an outer and younger, structurally lower autochthonous domain, consisting of the continental basement of the Adria plate, overlaid by a Mesozoic carbonate succession and Late Oligocene to upper Miocene foredeep units, overthrust by an older and inner allochthonous domain, made of obducted oceanic crust slabs of the Liguri-Piedmont ocean and their related sedimentary cover (fig.7; Elter, 1975; Elter & Marroni, 1991; Vai & Castellarin, 1992; Elter, 1994; Bernini *et al.*, 1994; Castellarin, 1994, 2001; Vai, 2001). These two main tectonic units can be further divided into five main domains, which will be briefly described from the western innermost to the eastern outermost part of the Apennine belt.

2.2.1 Ligurian domain

The oldest and structurally uppermost part of the Apennines can be further split into Internal and External domains by the Ottone-Levanto tectonic line, along which the former partly moved over the latter, whereas in the remaining part, the Ligurian units directly overlie the Tuscan nappe with the interposition of the Canetolo sub-Ligurian Unit (Elter, 1994). Both Internal and External Ligurian domains involve ophiolitic

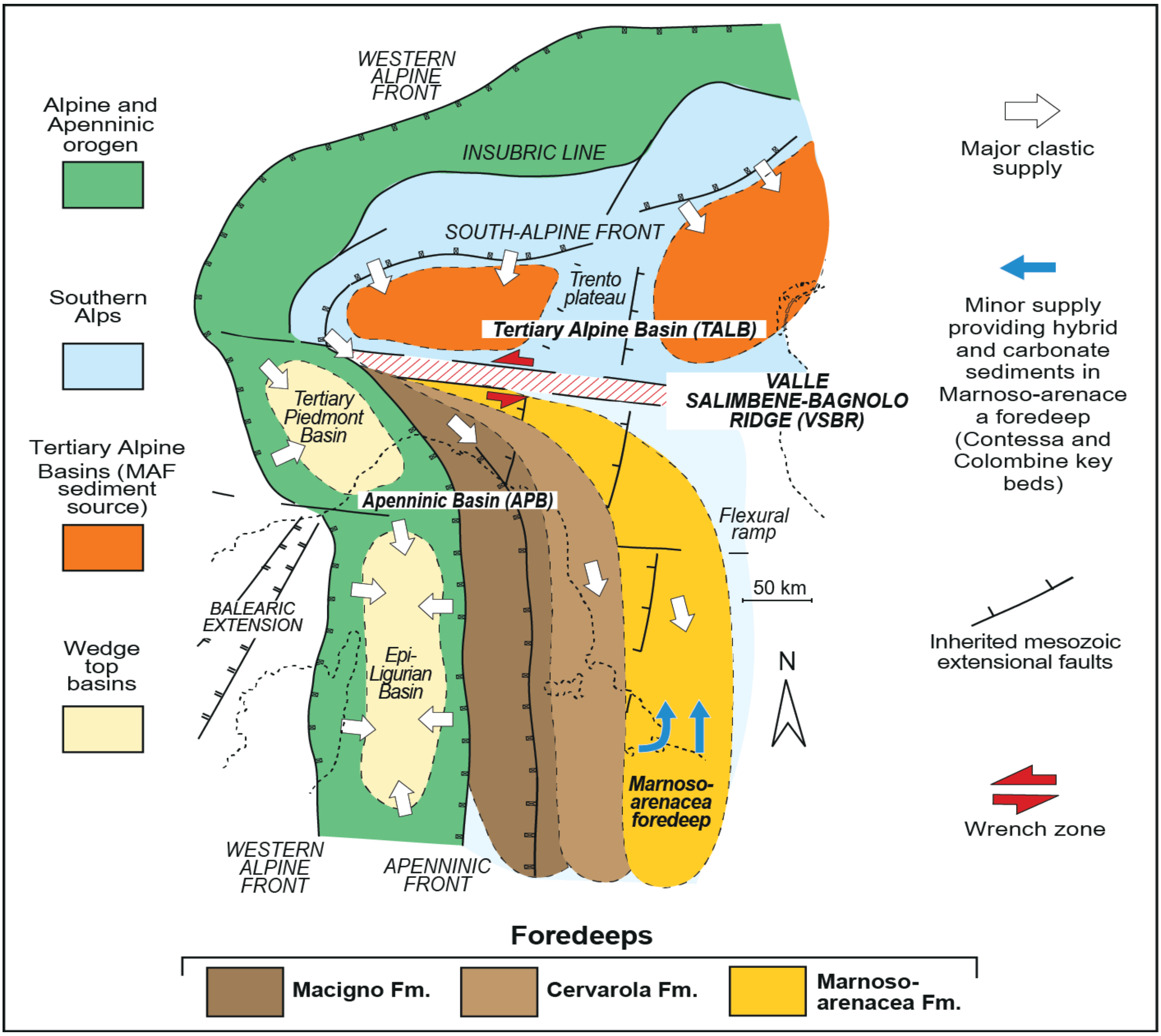


Fig. 6 - Simplified paleogeographic maps of the proto-Adriatic basin from Upper Oligocene to Middle Miocene (modified from di Biase & Mutti, 2002).

rocks, but in different ways. The former (Elter & Pertusati, 1973) consists of the juxtaposition of three tectonic units (Colli/Tavarone, Bracco/Val Graveglia, M.Gottero units, Elter & Marroni, 1991), which are stacked in their original stratigraphic position, hence overlaid by their original oceanic sedimentary stratigraphic succession (late Jurassic radiolarian cherts overlaid by lower Cretaceous Calpionelle limestones and middle to upper Cretaceous Palombini shales). In the External Ligurian domain they are totally detached from their underlying stratigraphic succession, since they are involved in tectonic melanges at the base of the succession named "Complessi di Base" Unit, which is essentially a chaotic complex made of ophiolitic and sedimentary elements. The External Ligurian domain can be characterized by two paleogeographic zones, showing different features: an innermost zone directly overthrust by the Internal Ligurian units and an outermost "Emilian" zone, in which the ophiolitic component within the "Complessi di Base" Unit is sporadic or missing (fig.7).

2.2.2 Sub-Ligurian Domain

Tectonically interposed between the overlying Ligurian and underlying autochthonous units, the Sub-Ligurian domain shows intermediate features in-between the western Ligurian-Piedmont oceanic units and the eastern Tuscan and Umbro-Marchean continental ones. Both the origin and the unit types of the substrate characterizing the Sub-Ligurian domain are still being debated. Some authors argue that the Canetolo Unit only belongs to it (Eocene, Roccaferrara Supergroup) (Barbieri & Zanzucchi, 1963, Elter et al, 1964, Plesi, 1975), while others argue that also the Caldana Supergroup falls within the Sub-Ligurian domain (Vai & Castellarin, 1992). Overall, this nappe can be split into two main groups of formations standing apart because of an important unconformity: 1) a basal group, encompassing the Canetolo (limestones and shales) and the Eocene Groppo del Vescovo formations, resembling allochthonous features; 2) an upper Eocene – Oligocene group, made of thick sandstone formations (Ponte Bratica and Petrignacola Sandstones), which shows

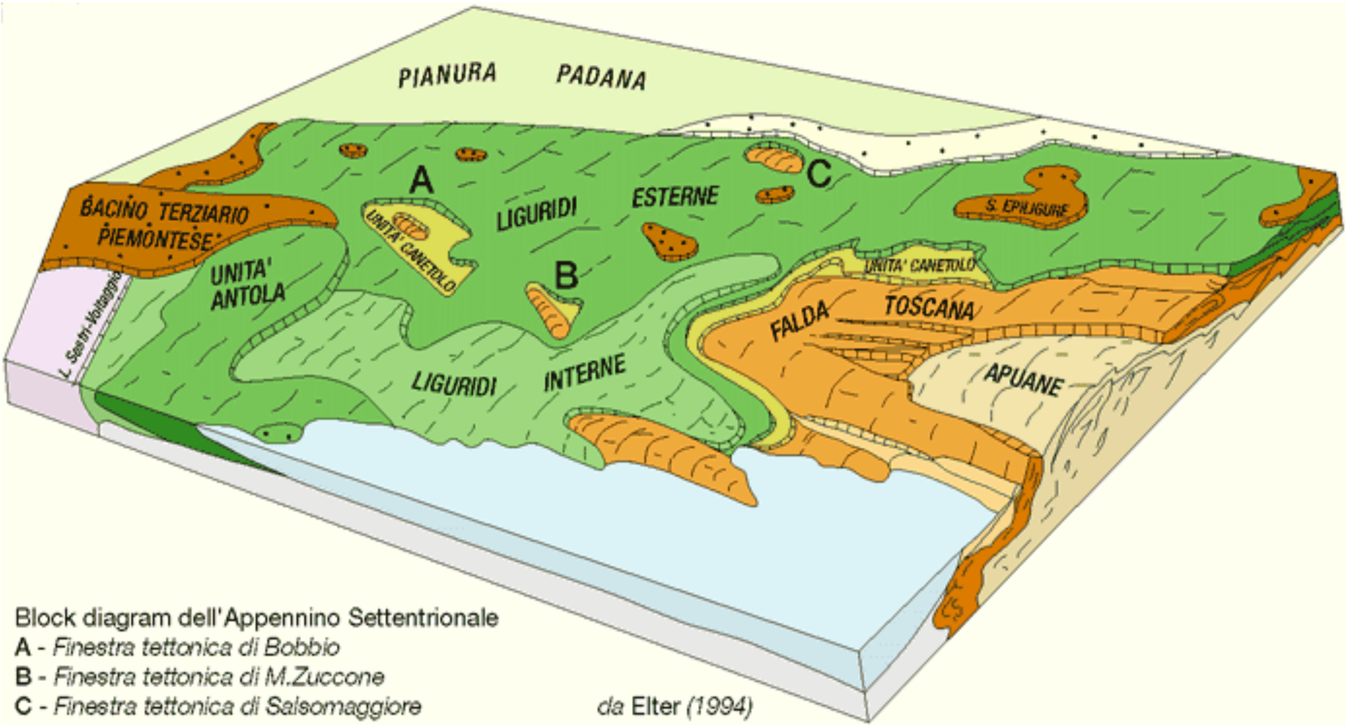


Fig.7 - Structural sketch of the Ligurian-Emilian northern Apennines (from Elter, 1994).

autochthonous foredeep-like characteristics. According to some authors, while the Ponte Bratica Sandstone was depositing above the unconformity, the basal group would have overthrust an incipient Macigno foredeep basin; in that way the Ponte Bratica Formation could be considered as an Epi-Sub-Ligurian Unit (Elter, 1994; Mutti *et al.*, 1995).

2.2.3 Tuscan Domain

The Tuscan and Umbro-Marchean domains form the outer autochthonous part of the Apennine chain. Their stratigraphic successions are similar and form the sedimentary cover of the Adria contineltal margin, which records the entire geodynamic history of the Apennine chain, from the Jurassic rifting to the convergent and

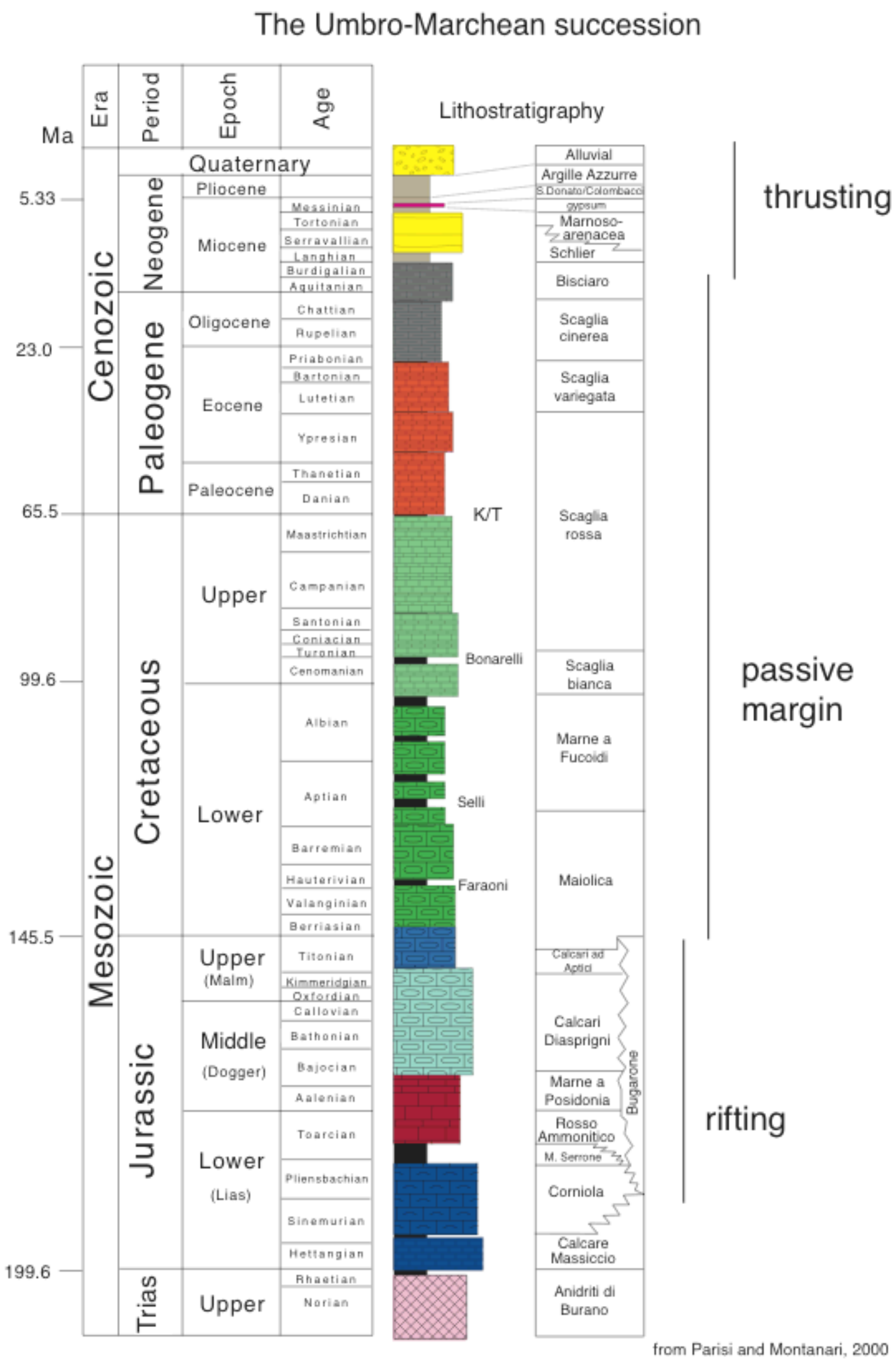


Fig.8 - Schematic stratigraphic log of the Umbro-Marchean domain stratigraphic succession (from Parisi & Montanari, 2000).

collisional phases related to the Apennine orogenesis. From a structural point of view, the Tuscan domain can be split into two main tectonic units: 1) a basal metamorphic Apuan complex, cropping out in the Apuan tectonic window overthrust by 2) an inner and upper non-metamorphic unit, consisting of the Tuscan and Cervarola nappes that are characterized by the Macigno and Cervarola foredeep units, respectively (fig.7). Essentially, the Tuscan succession is characterized by a sedimentary cover that spans from the Triassic continental and shallow marine clastic units up to Late Oligicene-Early Miocene siliciclastic foredeep turbidites (fig.8). The latter, fed by sediments coming from the erosion of the emerged Alpine chain, took place from the beginning of the Apennine orogenesis and are represented by the late Oligocene Macigno and early Miocene Cervarola units. As well as the MAF, the evolution history of these older foredeep units is characterised by an evident syn-sedimentary tectonic control that strongly affect depositional systems and sediment dispersal (Cornamusini, 2004a-b; Tinterri & Piazza, 2015).

2.2.4 Umbro-Marchean domain

It represents the outermost part of both the northern Apennine and the Apula continental margin and it features a stratigraphic succession quite similar to that of the Tuscan domain. However, some differentiations between them began from the Jurassic rifting phases, due to the later shelf drowning that fostered shallow water conditions in the Umbro – Marchean domain compared with the Tuscan one. Carbonate sedimentation of the Maiolica Formation continued until the early Cretaceous, followed by the Pelagic shaly - carbonate sediment of the Scaglia Formation, which continued throughout the Paleogene. The overlying stratigraphic succession is related to the Apennine orogenesis and started with the early Miocene Bisciaro Formation, whose volcanoclastic composition seems to be related to the Baleric basin opening (Cibin *et al.*, 2001). From the early Miocene, the sediment dispersal pattern was mainly affected by the foredeep diachronism related to the progressive NE-migration of the Apennine wedge-foredeep system. According to Vai & Castellarin (1992) the Umbro-Marchean domain can be divided into two sub-domains, namely the Romagna-Umbro and Adriatic-Marchean ones, which are characterized by the Burdigallian to Messinian Manoso-arenacea and Messinnian to Pliocene Laga Formations, respectively (fig.6).

2.2.5 Epimesoalpine and Epiligurian domains

After the Ligurian-Piedmont oceanic closure, the northeastwardly migration of the allochthonous Apennine wedge was characterized by the deposition of thick sedimentary successions, in piggyback basins named Epiligurian basins (fig.4; Ricci Lucchi, 1986; Cibin *et al.*, 2001). Their stratigraphic succession is extends from the Monte Piano to the Termina Marls and shows evident syn-sedimentary tectonic control, due to the highly dynamic nature of the Apennine orogen. Each Epiligurian unit is characterized by time-equivalent deposits in the foreland basin, apart from the basal late Eocene - early Oligocene Monte Piano and Ranzano Formations (Ricci Lucchi, 1986; Mutti *et al.*, 1995). The latter took place during a particular stage of the Apennine evolution, during which a more extended depression, i.e. epimesoalpine basin, linked the Epiligurian basins to the Tertiary Piedmont and Annot ones (Mutti *et al.*, 1995). The Subligurian Ponte Bratica and Petrignacola Sandstones are time-equivalent to these units and, as stated above, can be considered as incipient Rupelian foredeep Units. The Antognola Marls represent the first Epiligurian time-equivalent of the first foredeep deposits of the Macigno Formation (Elter, 1994; Mutti *et al.*, 1995).

3. THE MARNOSO-ARENACEA FORMATION

3.1 Geologic setting and statigraphic evolution

Among the foredeep units of the Apennines, the late Burdigallian to Tortonian Marnoso-arenacea Formation is the best exposed and less structurally deformed, due to its relatively external position within the Apennine orogenic wedge (fig.1). It has played a fundamental role in the history of turbidites, because many models and facies schemes proposed in the literature have been developed on these types of deposits. The MAF stratigraphic succession is more than 4,000m thick in the proximal area and its bulk is estimated as 28,000 km^3, reached thanks to about 12 MA of equilibrium between subsidence and sedimentation rate (Ricci Lucchi & Ori, 1985; Tinterri & Muzzi Magalhaes, 2011). Its basin was a NW-stretched, wedge-shaped, asymmetrical depression, characterized by an inner deep depocenter delimited to SW by a steep slope involving the NE-migrating Apennine orogenic wedge, passing eastward to an outer and shallower foreland ramp (fig.9). Turbidite currents flowed longitudinally, mainly toward SE, fed by siliciclastic Alpine fluvio-deltaic systems; sporadic flows, coming from southern Carbonatic shelves, flowed in opposite direction (fig.10). The latter form the main key beds of the MAF stratigraphic succession and represent important constraints for long-distance correlations; based on their composition, they can be classified as carbonate ("Colombine") or hybrid beds ("Contessa-like") among which the "Contessa" is the most famous of the entire stratigraphic succession (fig.10, 11; see Ricci Lucchi, 1986; Gandolfi *et al.*, 1983; Muzzi Magalhaes & Tinterri, 2010).

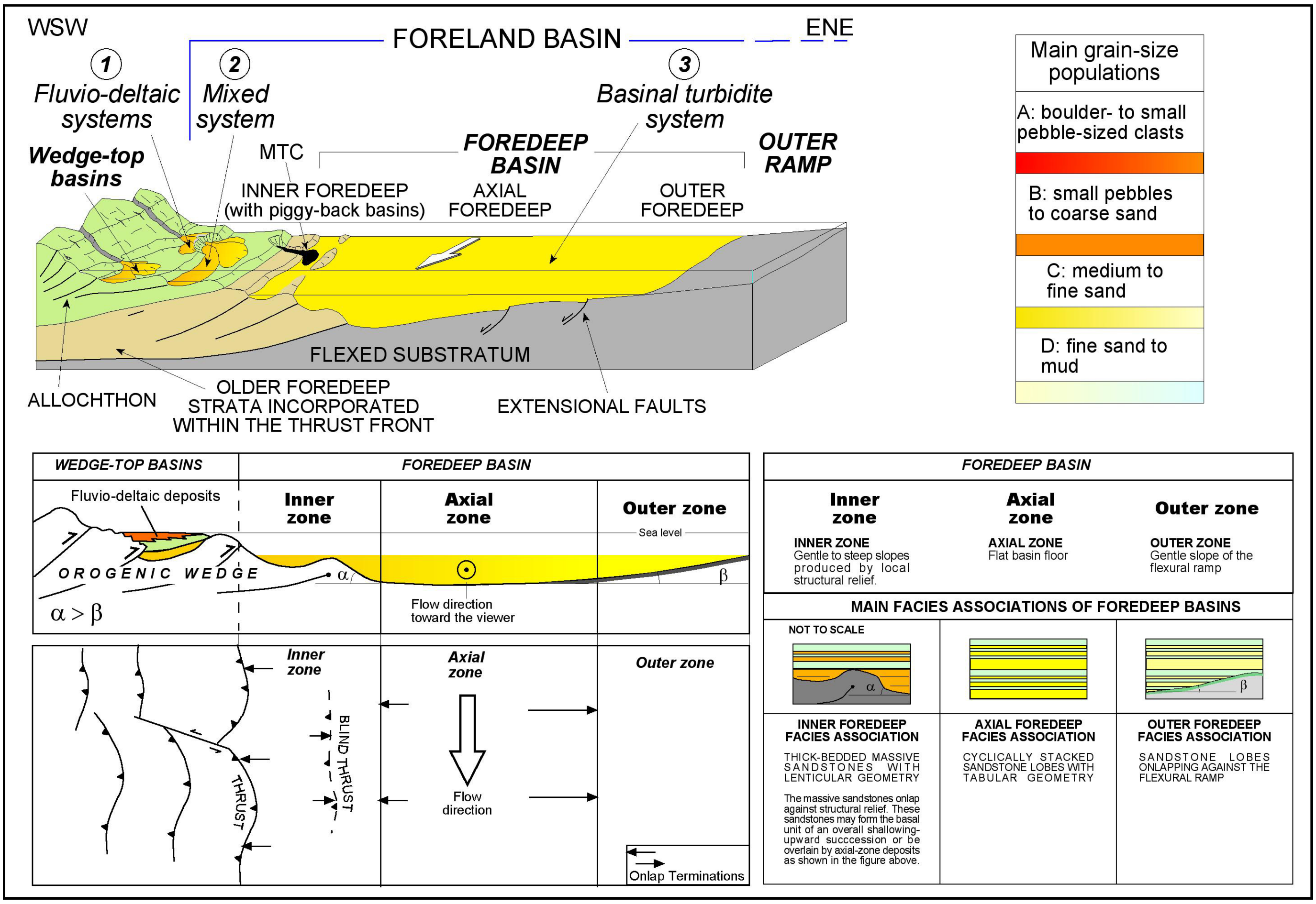


Fig.9 - Schematic section view of foredeep basins and related main facies distribution in the several sub-basins (from Artoni *et al.*, 2000; Mutti *et al.*, 2003).

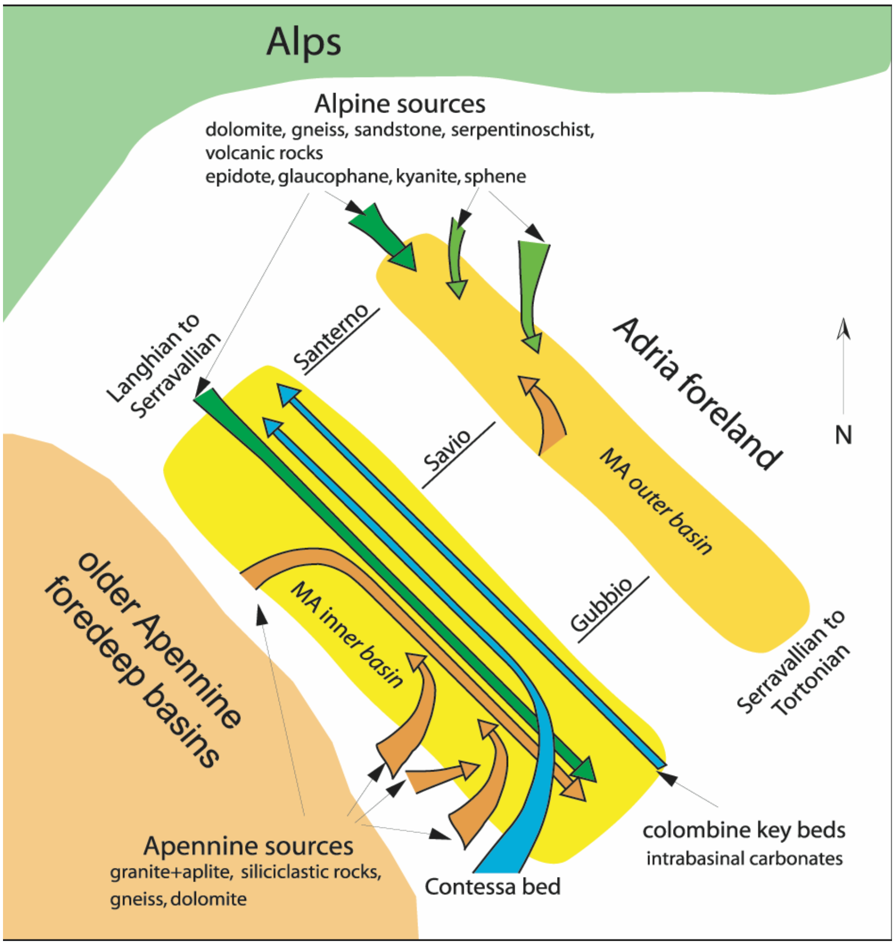


Fig.10 - Source and direction of the turbidite currents within the MAF foredeep (from Gandolfi *et al.*, 1983; Roveri *et al.*, 2002).

Overall, the MAF foredeep was oversupplied, as testified by very thick beds that are able to spread throughout the basin and thicken in distal area because of ponding process (e.g. Contessa key bed). The outcropping MAF deposits can be divided in two parts by the Marecchia Ligurian sheet: the north-western Romagna and the south-eastern Umbro-Marchean sectors (fig.1). In its north-western part the former is delimited by the Ligurian sheet, emplaced by the Sillaro tectonic alignment; the latter is delimited by the southern termination of the foredeep basin beyond the Gubbio area (fig.1).

Northeastwardly the MAF is overlaid by younger Pliocene deposits, whereas, toward southwest, it is overthrust by the older foredeep units (e.g. Falterona Unit). From a tectonic point of view, the MAF deposits are cut by several thrusts that run roughly parallel to its basin axis and form several structural elements involved in fault-propagation fold structures (Capozzi *et al.,* 1991; de Donatis & Mazzoli, 1994; Lucente, 2004). Conversely, from a lithostratigraphic point of view, the MAF consists of several different members, mainly distinguished on the basis of net to gross values and stratigraphic stacking pattern characteristics (Martelli et al. 1994, Cerina Feroni et al. 2002) The entire MAF stratigraphic succession has been divided by Ricci Lucchi (1986) in four depositional sequences, mainly based on different depositional characteristics, namely: LS and S (Langhian-Serravallian and Serravallian) sequences characterizing the inner "stage" or "basin" and T1 and T2 sequences (Tortonian in age) characterizing the outer "stage" or "basin" (fig.11). The former are made of high-efficiency basinal turbidite systems, whereas the latter are mainly composed of low-efficiency "mixed" turbidite deposits (see also Roveri *et al.*, 2002; Mutti *et al.*, 2002; Tinterri & Muzzi Magalhaes, 2011). The latter are overlaid by shallow water euxinic shales and evaporites belonging to the Gessoso-Solfifera Formation, marking the final filling stage of the MAF foredeep (fig.2).

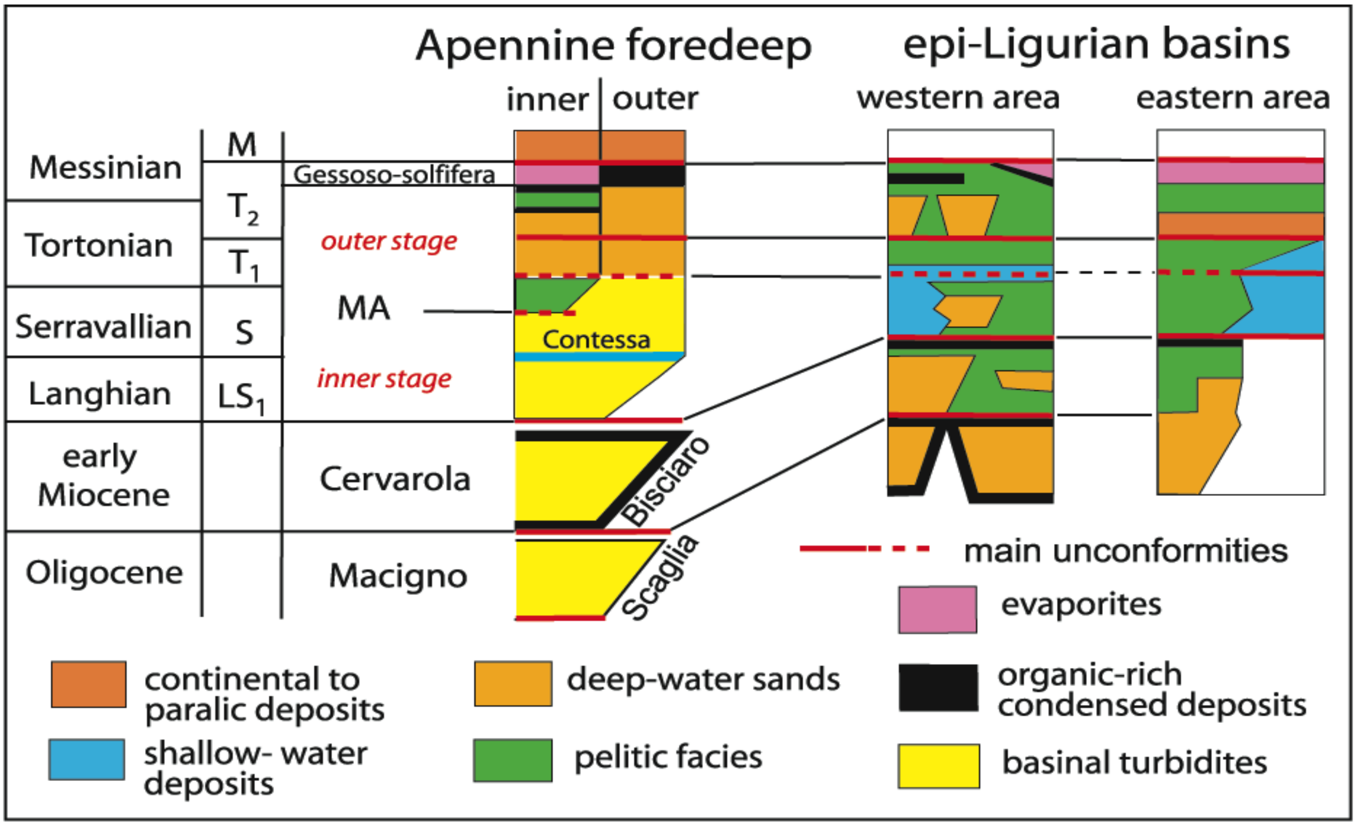


Fig.11 - Main stratigraphic units of the Apennine foredeep and related correlation with the epi-Ligurian basins (from Ricci Lucchi, 1986; Roveri *et al.*, 2002).

3.2 Syn-sedimentary tectonic control on MAF turbidites

The MAF consists of a shoaling upward stratigraphic succession (more than 4000m thick, according to Muzzi Magalhaes & Tinterri, 2010) recording the progressive closure of the Apennine foredeep basin due to the propagation of thrust fronts toward north-east, i.e. toward the outer and shallower foreland ramp (fig.2, 9). This space-time evolution is that typical of a foreland basin, which, notwithstanding different geodynamic settings and general basin configurations, can be divided into three main stages (Mutti *et al.,* 2003; Covey, 1986; Ricci Lucchi, 1986): 1) inception of thrusting and flexural subsidence, 2) foredeep sandy turbidite deposition, affected by syn-sedimentary thrust activity and 3) progressive migration of the depocenters toward the outer flexural ramp, 3) final phase of filling, during which turbidite sedimentation is progressively being replaced by fluvio-deltaic and eventually alluvial depositional systems (fig.2). The same evolution can be seen in a transect orthogonal to the main structural axes, across which three coeval basins can be detected and, from the inner to the outer zone, they are: a) inner wedge-top basins characterized by alluvial, deltaic and low efficiency turbidite systems; b) a foredeep basin consisting of high-efficiency turbidite systems; c) an outer and shallower ramp (Mutti *et al.*, 2003). The progressive thrust propagation toward the outer margin of the basin produced a vertical superimposition of these three basin types, as in the MAF, where Langhian to Serravallian high-efficiency basinal turbidites are replaced by Tortonian – Lower Messinian (Castel del Rio and Borgo Tossignano Member, Cerrina Feroni *et al.*, 2002; Cornamusini *et al.,* 2009*)* “mixed” low-efficiency turbidites overlaid by shallow water Messinian euxinic shales and evaporites (fig.2, 11). Historically, the syn-sedimentary tectonic control affecting MAF sedimentation has been discussed by several authors (de Jager, 1979; Ricci Lucchi & Ori, 1985; Ricci Lucchi, 1975, 1981, 1986, 1987; Martelli *et al.*, 1994; De Donatis & Mazzoli, 1994; Roveri *et al.*, 2002; Lucente & Pini, 2002; Mutti *et al.*, 2002, 2003; Lucente, 2004), all of who agree in defining the MAF basin as a detailed timing of the syn-sedimentary growth of the structures as well as their influence on turbidite facies evolution and distribution (fig.12, 13).

According to these Authors, the overall stratigraphic evolution of the MAF consists in three main stages: 1) an older and inner Langhian-Serravallian basin consisting of basinal turbidites controlled by subtle structural reliefs; 2) an intermediate Upper-Serravallian

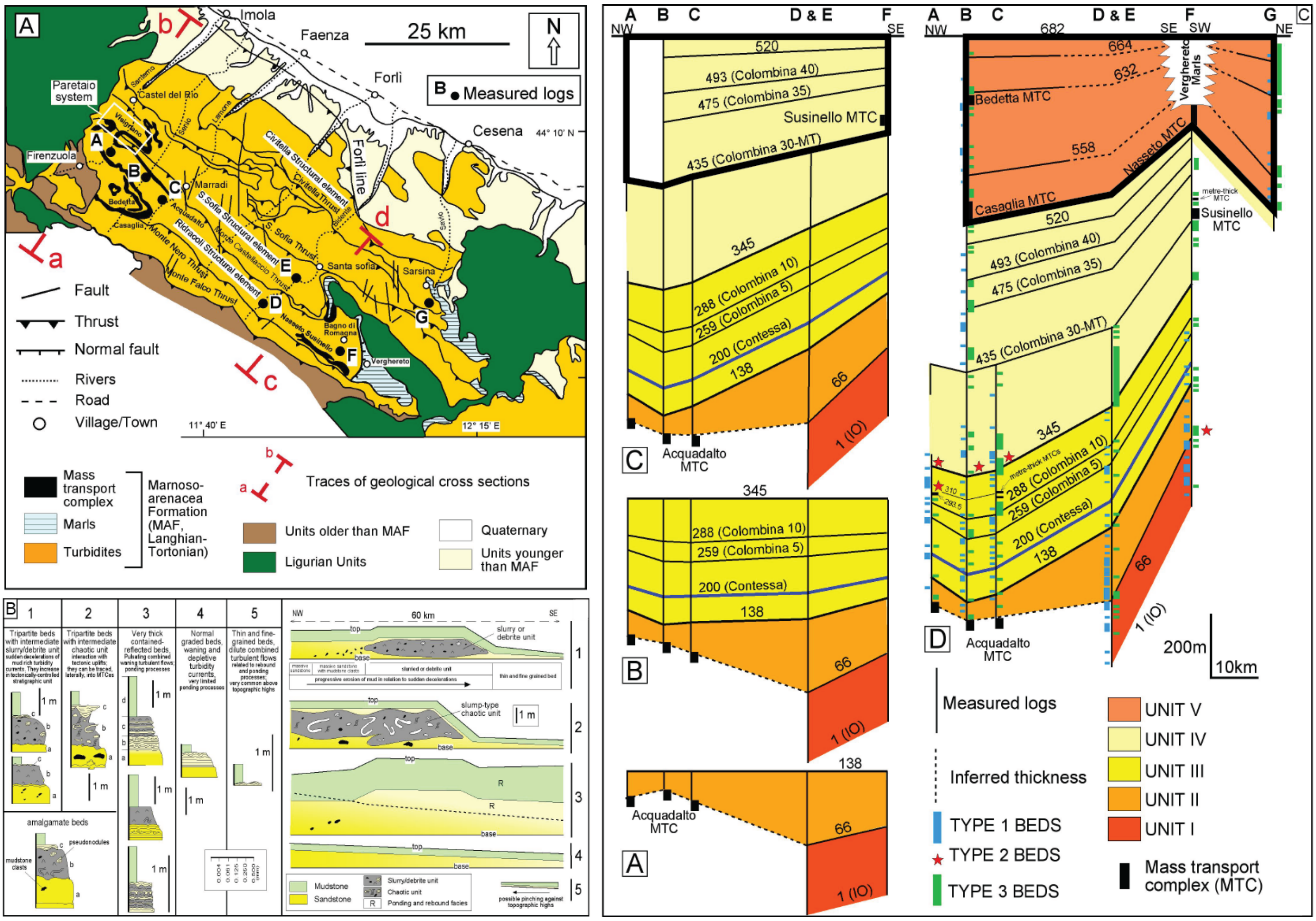


Fig.12 - Langhian to Serravallian stratigraphic framework by Muzzi Magalhaes & Tinterri (2010) and Tinterri & Muzzi Magalhaes (2011). A) Location of the logs. B) Facies scheme. C) Cross-section and related progressive flattenings, black lines to indicate the stratigraphic location of this study (Unit V and upper part of Unit IV).

"complex foredeep" (*sensu* Ricci Lucchi, 1986), characterized by several sub-depocenters separated by topographic highs, whose isolation increases over time. More recently, Muzzi Magalhaes & Tinterri (2010) and Tinterri & Tagliaferri (2015), thanks to high-resolution physical stratigraphy studies of the Langhian to upper Serravallian deposits, have stressed the phase that records the transition between inner and outer basins characterized by mass-transport complexes and thick accumulations of sandstone lobes that filled in thrust-related structural depressions and 3) a younger and outer Tortonian basin characterized by relatively sand-rich turbidite systems deposited by turbidity currents with a low degree of efficiency, due to

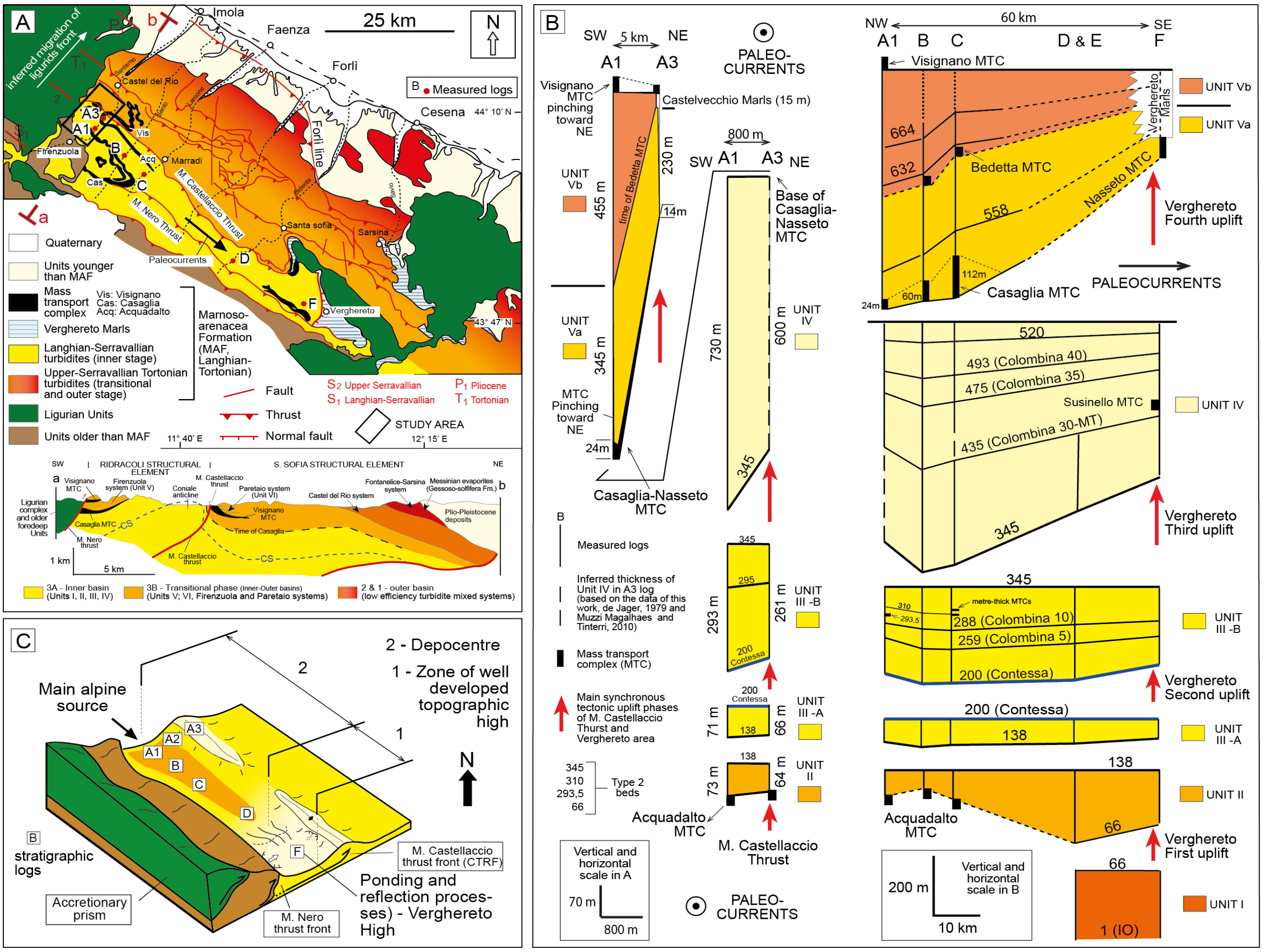


Fig.13 – A) Schematic geological map of the MAF. Capital letters (From A1 to F) indicate the location of the stratigraphic logs in a transect parallel to the main tectonic features (modified from Muzzi Magalhaes & Tinterri, 2010). Below: the geological cross-section transverse to the basin axis showing the position of the major thrust faults subdividing the outcrop into structural elements (modified from Roveri *et al.,* 2002). The deposits related to inner, transitional and outer stages can also be observed. B) Simplified stratigraphic cross-sections oriented perpendicular (left) and parallel (right) to the CTRF and paleocurrents showing the progressive closure of the inner basin through the coeval growth phases (red arrows) of the CTRF and Verghereto area (from Tinterri & Tagliaferri, 2015; see also Muzzi Magalhaes & Tinterri, 2010). C) Simplified paleogeography of the inner basin during the deposition of Units IV and V (from Muzzi Magalhaes & Tinterri, 2010).

flow decelerations induced by basin narrowing (fig.2, 14). In this stage, a fluvio-deltaic influence cannot be ruled out. More precisely, Muzzi Magalhaes & Tinterri (2010) and Tinterri & Muzzi Magalhaes (2011), thanks to their high-resolution stratigraphic framework, divided the Langhian to Serravallian portion into five units (I, II, III, IV, V), on the basis of MTCs occurrence and distribution of five kinds of turbidite beds indicating structurally-induced physiography (fig.12). With the same approach, Tinterri & Tagliaferri (2015, see also Tinterri *et al.,* 2012) stressed the importance of the synsedimentary growth of Coniale thrust-related fold (CTRF), going from unit II to unit V and defining the first deposits of the outer basin (i.e. the Paretaio turbidite System above the Visignano MTC as unit VI (see fig.13).

Consequently, the structural control and associated morphologic confinement increase over time, thus significantly controlling the lateral and vertical distribution of turbidite facies and causing a progressive decrease of the efficiency of the turbidite systems. In this evolution the Firenzuola System (or Unit V in the papers by Muzzi Magalhaes & Tinterri, 2010; Tinterri & Muzzi Magalhaes, 2011) represents a fundamental stage in the Marnoso-arenacea history, since it marks the transition between inner and outer stages produced by the coeval syn-sedimentary growth of the Monte Castellaccio Thrust and the Verghereto High (fig.13, 14). According to the facies changes and the sediment dispersal pattern found with this work, the Firenzuola System has been divided in two sub-Units (Tinterri & Tagliaferri, 2015; Tagliaferri & Tinterri, in press):

- **sub-Unit Va** or **Firenzuola I**, stratigraphically included between Casaglia and Bedetta MTCs, showing sedimentary and sedimentological characteristics similar to the underlying Unit IV, regardless of the progressive increasing of tectonic confinement of the inner basin
- **sub-Unit Vb** or **Firenzuola II**, included between Bedetta and Visignano MTCs, during which the paroxysmal growing of the CTRF and the Verghereto high produced important stratigraphic and facies differentiation between depocenters and topographic highs, together with a overall decrease in in the turbidite system flow efficiency (fig.14).

The overlying Unit VI or Paretaio System, which has been studied in detail by Tinterri & Tagliaferri, 2015, marks the upper part of the transitional phase and is overlaid by the Tortonian, poorly efficient Castel del Rio mixed systems. In that way, this work, along with the ones by Muzzi Magalhaes & Tinterri (2010), Tinterri & Muzzi Magalhaes (2011) and Tinterri & Tagliaferri (2015), provides a complete Langhian to upper Serravallian evolution history based on about 15km of high-resolution physical stratigraphy and facies analysis.

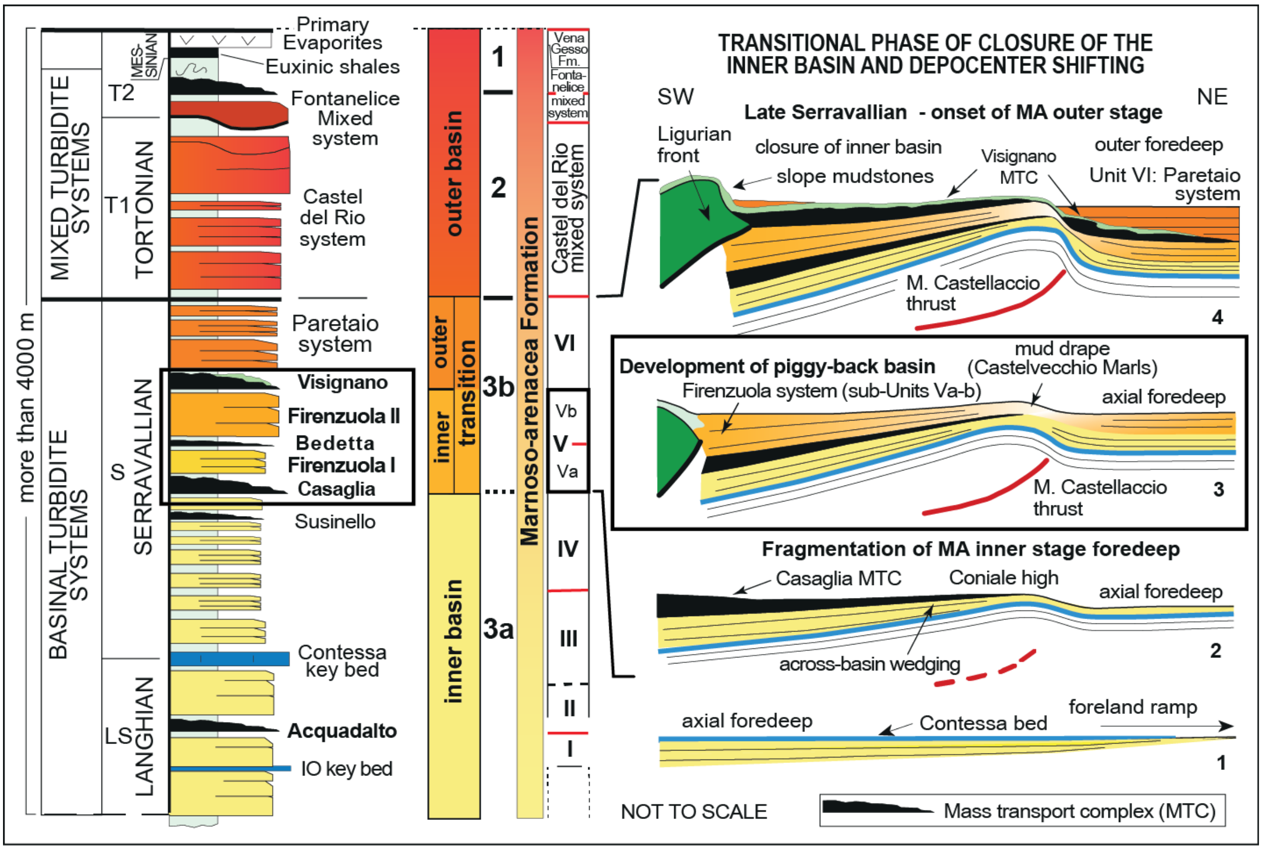


Fig.14 – On the left schematic stratigraphic log of the MAF deposits. The Firenzuola System represent Unit V (according to Muzzi Magalhaes & Tinterri, 2010 stratigraphy) and has been split into Firenzuola I and Firenzuola II (Unit Va and Vb) according to stratigraphy and facies analysis carried out in this work (modified from Tinterri & Tagliaferri, 2015; see also Mutti *et al.*, 2002). On the right main phase of syn-sedimentary growth of the CTRF. Black squares identifying the stratigraphic location and phase of deposition of Unit V related to the growth of the M.Castellaccio thrust.

4. TURBIDITES

4.1 Historical perspectives

The terms "turbidite" was coined by Kuenen (1957) to describe sharp-based, graded beds interpreted by Migliorini (1943) and Kuenen & Migliorini (1950) as deep-water deposits related to turbidite currents, deduced from laboratory and field studies carried out in the northern Apennine Macigno Formation. Therefore, the concept of turbidite was born in collisional Alpine-type orogenic belts and, since then, a numers works dealing with facies, processes and depositional environments were carried out. The first and most famous turbidite depositional model is the Bouma sequence (fig.15), based on the famous studies by the same Author on the Annot Sandstone (western Alps), (Bouma, 1962). His "Ta-e" sequence, whose spatial distribution is expressed by the depositional cone (fig.15), represents the time-space evolution of an ideal wining and depletive turbidite current. Following the Bouma's model, Parea (1965) and Walker (1967) developed proximal and distal concepts related to turbidite deposits. Hydrodynamic processes were neglected by Bouma and were later dealt with by Walker (1967), who using the experimental results of Harms & Fahnestock (1965) and Simons *et al.* (1965), re-interprets the Bouma sequence as the result of deposition via a basal upper flow regime ("a" and "b" divisions) followed by a lower flow regime ("c" to "e" divisions). Since the sixties, several scientists began to be aware that not only could graded beds be deposited turbulent flows (e.g. the fluxoturbidite concept, Dzulynski *et al.,* 1959). The first pioneering insight comes from Sanders (1965), who

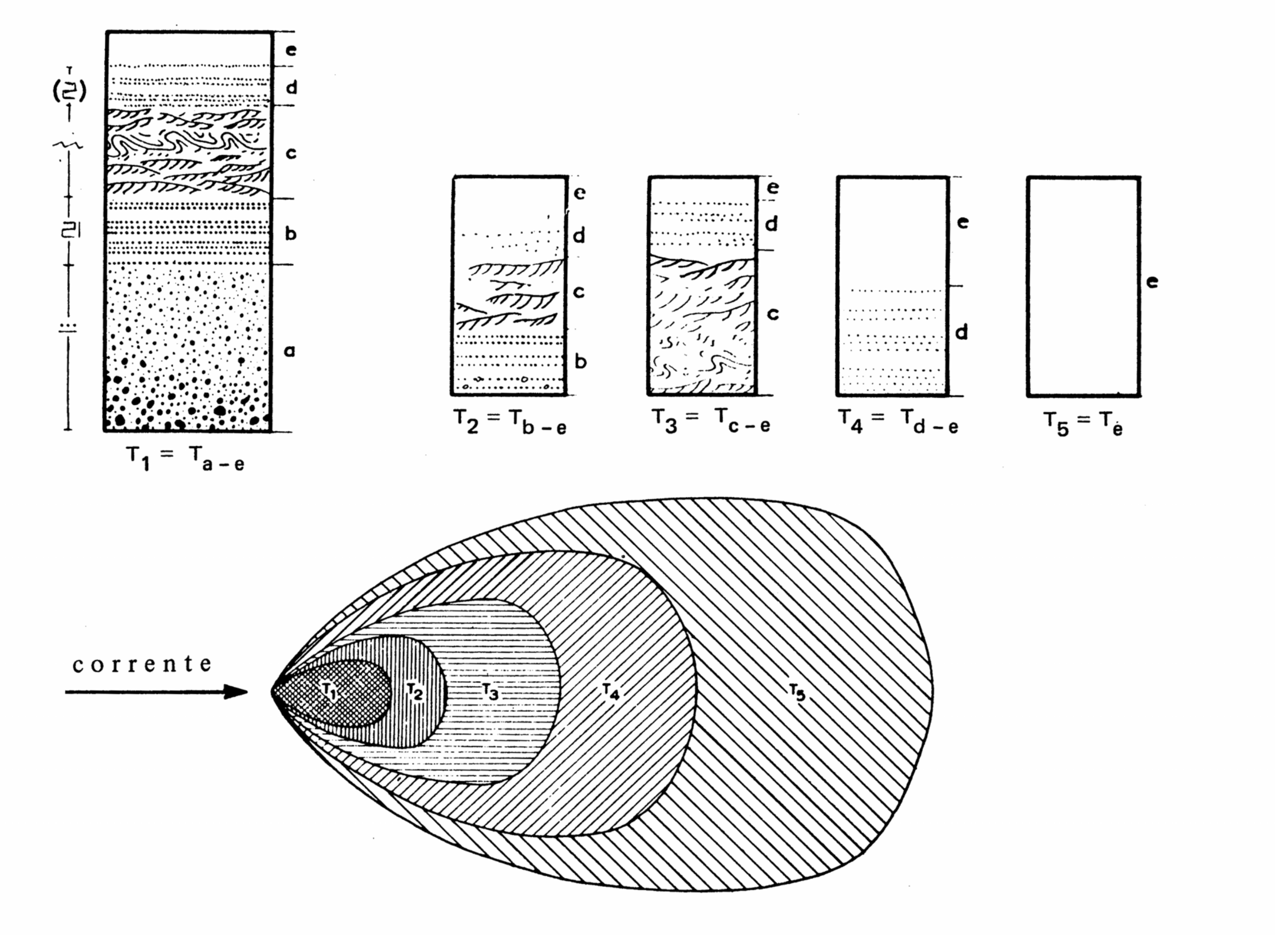


Fig.15 - Bouma sequence and the relative downcurrent evolution expressed by the depositional cone (from Bouma, 1962).

proposed, for the first time, a bipartite turbidite current model; this model provides for an inertial laminar basal flow depositing the lower massive Ta interval and overlaid by an upper turbulent flow depositing the upper Tb-e divisions through traction plus fallout processes (fig.16). According to this model, only the upper Tb-e division is deposited by a turbidite current (*sensu strictu*). These concepts have been recently discussed by Shanmugam *et al.* (1994) and Shanmugam (2000), who explain the massive basal part of turbidite as being deposited by a *sandy debris flow* (see also the discussion in Mutti *et al.*, 1999, 2009). Insights about the origin of turbidite currents came from the laboratory experiments by Hampton (1972), who proved that they can originate from head transformation of debris flows; the same concepts have been recently dealt with by Mohrig *et al.* (1998) and Marr *et al.* (2001). The work by Middleton and Hampton (1973) gave another fundamental examination of the processes, according to whom the particles within a turbidite current can be sustained by four main mechanisms (fig.17): 1) turbulence, 2) dispersive pressure, 3) over pressure and 4) matrix strength, each of which is related to a specific kind of flow: 1) turbidite current, 2)

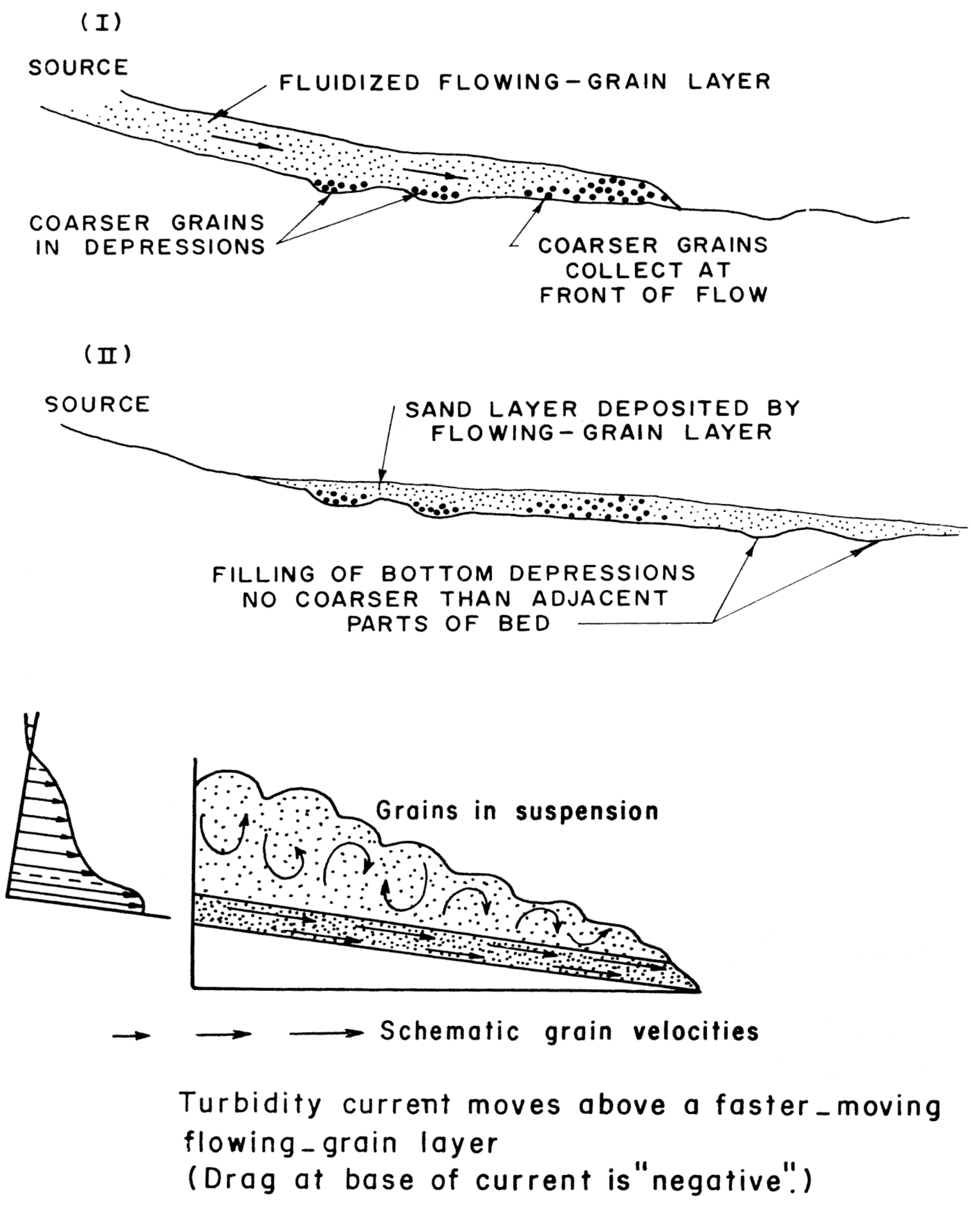


Fig.16 - Deposits and velocity profile of a bipartite turbidite current characterized by a basal inertial flow and an upper turbulent flow (from Sanders, 1965).

grain flow, 3) fluidized flow and 4) cohesive debris flow. Following these concepts, Lowe (1979) dealt with rheology and mechanisms of transport relationships, distinguishing flows with fluidal and plastic behaviours and adding liquefied flows to the Middleton and Hampton's classification (fig.18). At the turn of the sixties and seventies, other important works focused on the same gravity flow that, in turn, can be seen as the downcurrent evolution of the flow itself. The facies tract concept was formulated by Aalto (1976) and was later developed by Lowe (1982), who based his scheme on three dynamic grain populations, each of which is deposited by a specific dynamic process (fig.18): 1) pebble to coarse sand, 2) coarse to medium sand, 3) fine

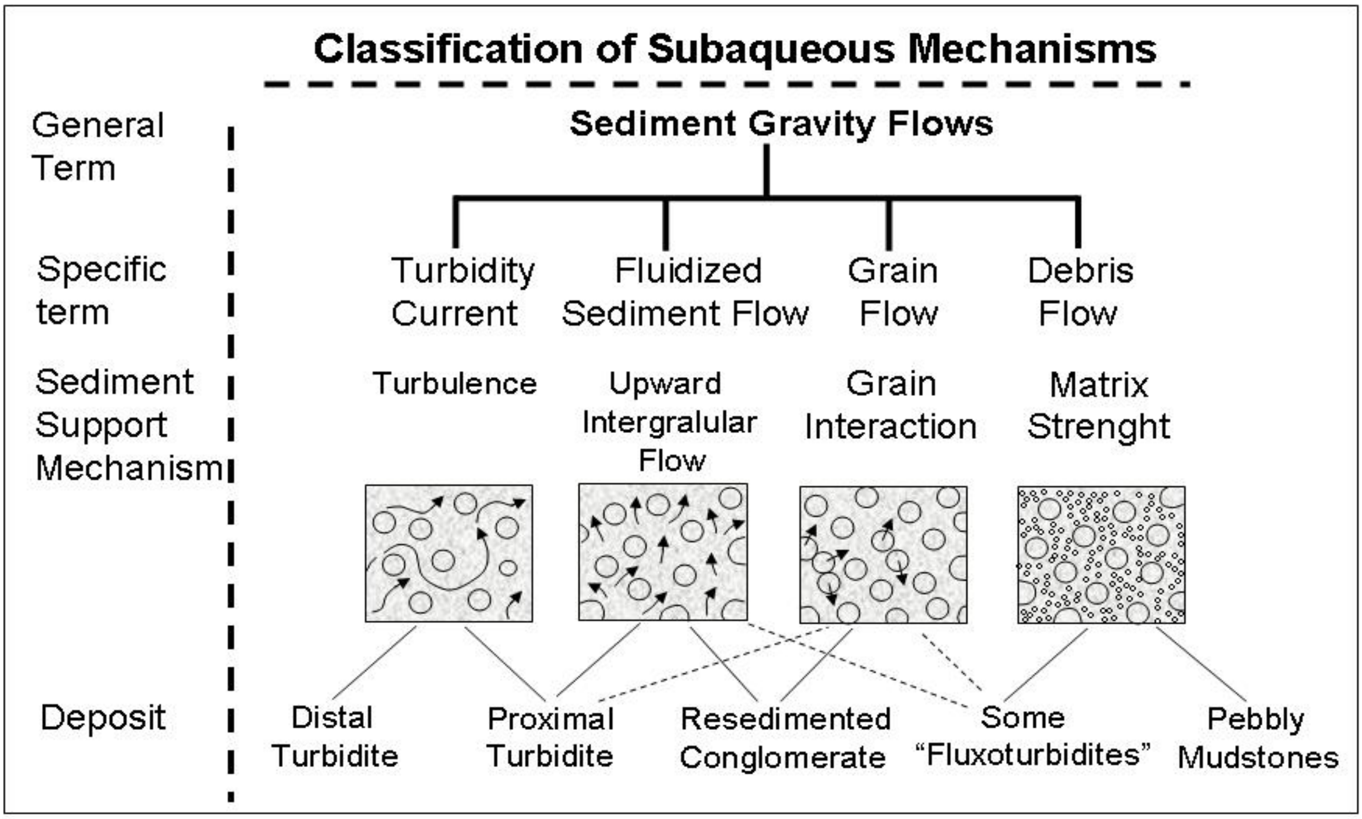


Fig.17 - Classification of sediment gravity flows based on the support mechanisms of the particles (from Middleton & Hampton, 1973).

developing deep-sea fan models (Mutti & Ricci Lucchi, 1972, 1975; Walker & Mutti, 1973; Walker, 1978). From the seventies onwards, turbidite facies schemes developed following two parallel ways: a descriptive one based on the geometric features of the structures and a genetic one, which linked structures to processes. The former caused a proliferation of facies schemes (see for instance Pickering *et al.,* 1986; Ghibaudo, 1992), whereas the latter has always focuses on the genetic link between the several facies deposited by the same turbidite current. This concept is expressed by the *facies tract*, which represents the suit of facies deposited by sand to mud. The first one would be deposited by cohesive debris flow and gravelly-high density turbidite currents, the second one by sandy-high density turbidite currents, the third by low-density turbidite currents. Lowe also explains the three main depositional phases caused by the progressive flow deceleration and related increase in fallout rate: 1) traction (S1), 2) traction carpets (S2) and 3) suspension sedimentation (S3). All these concepts are encompassed in a facies tract and represent the downcurrent evolution gravity flows that, from a cohesive state, progressively transform into high-density and low-density turbidite currents

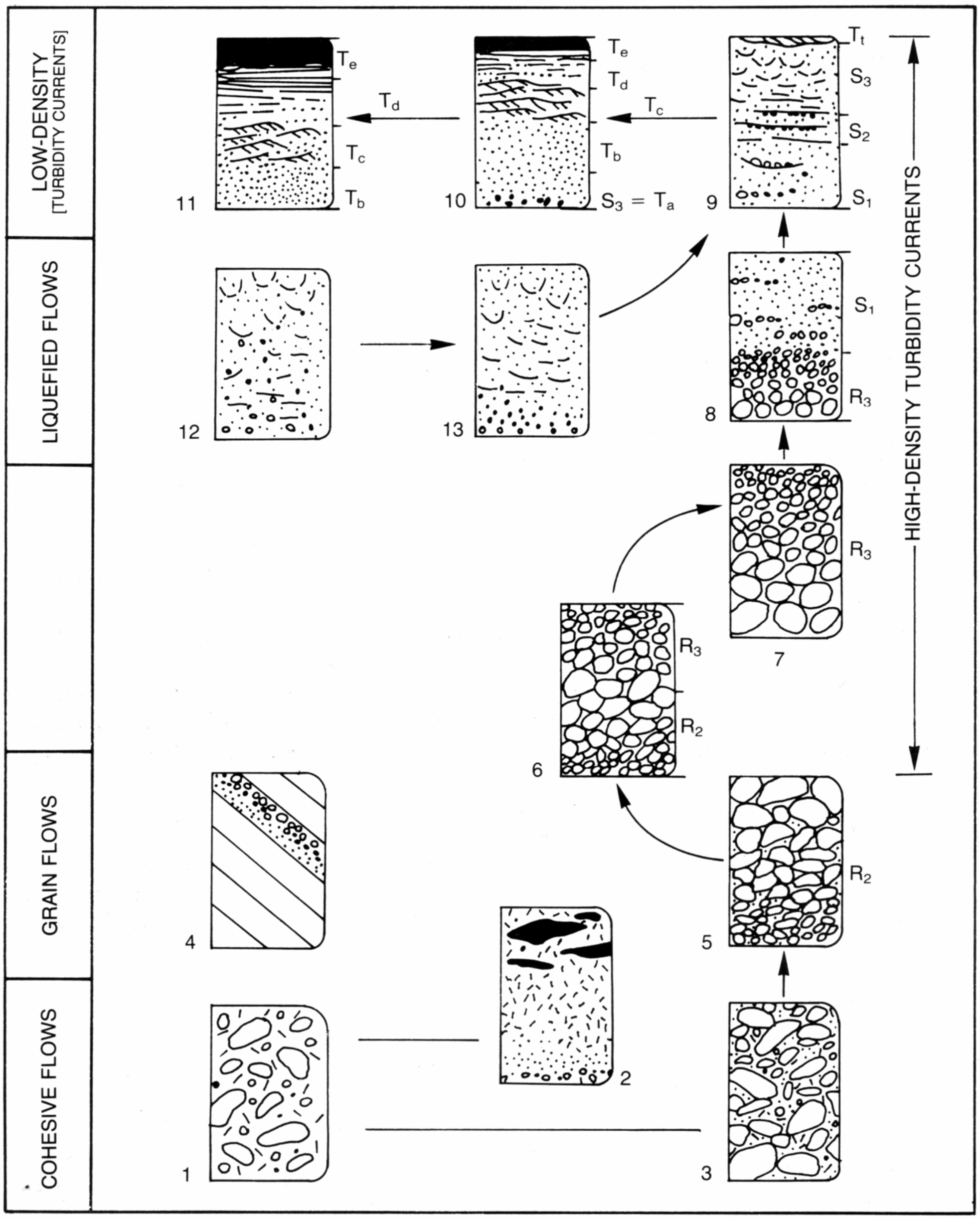


Fig.18 - Lowe's facies scheme, based on three grain size dynamic populations and related kind of gravity flows (from Lowe, 1982).

(fig.18). Following Lowe's model, Mutti (1992) created a scheme based on four dynamic grain populations and introduced the concept of hyper-concentrated flows (facies F2), which represent an intermediate state between cohesive debris flow (facies F1) and more diluted turbidite currents. The latter can be divided in gravelly (facies F4 and F5) and sandy high-density turbidite current (F6, F7, F8) followed by low-density ones (facies F9a, b). Mutti's scheme also stresses bypass facies, expressed by residual orthoconglomerate (facies F3) and sandy megaripple (facies F6). The schemes by Mutti *et al.* (1999, 2003) are an evolution of the scheme published in 1992.

4.2 Turbidite depositional systems and depositional elements

Since the sixties, together with turbidite facies models, several authors began to develop schemes related to turbidite depositional environments. The main purpose of these studies was to create a reference depositional model encompassing turbidite deposits of several geologic settings. The first ones were based on deep-sea fan models, whose concept was developed on modern California borderland (Normark, 1970), as well as on ancient collisional margins of Alpine and Pyrenean orogenic belts (Mutti & Ricci Lucchi, 1972; Mutti & Ghibaudo, 1972). In particular, Mutti & Ghibaudo (1972) introduced facies associations of three main depositional elements (slope, fan and basin plain) and suggested similarities between deep-sea fan and fluvio-deltaic systems, by comparing channels and lobes of the former to channel and mouth-bars of the latter. Furthermore, they explained the different trend of channels, which is characterized by thinning and fining-upward filling (channel fill sequence) vs. the one of lobes that conversely shows a thickening and coarsening-upward stacking pattern. Another important deep-sea fan model was proposed by Walker (1978), who tried to integrate the previous ones. In the following years ahead, scientists realized that deep-sea fan models could not be applied to all turbidite deposits, due to the wide range of geologic settings and evolution of the turbidite systems. Therefore, after two major meetings named COMFAN 1 (1982) and COMFAN 2 (1988), the scientific community decided to base the reference model on the turbidite system concept, which is suitable for both modern and ancient systems; it can be considered as being a framework of several depositional environments, each of which is defined by specific facies associations (fig.19, 20). In that way, depositional elements (Mutti & Normark, 1987, 1991; Mutti *et al.,* 1999, 2003, 2009; Normark *et al.*, 1993; Piper & Normark, 2001) can be considered as the building blocks of the turbidite systems (see fig.19). These systems are similar to fluvial systems (as meant by Shumm, 1981), since they consist of drainage, transfer and depositional zones (fig.20). Mutti *et al.* (2009) suggested that also chaotic deposits and megaturbidite can be considered depositional elements of turbidite systems, because they are important parts of their bulk. The reader is referred to the above articles to find a detailed description of facies and facies associations characterizing each depositional element.

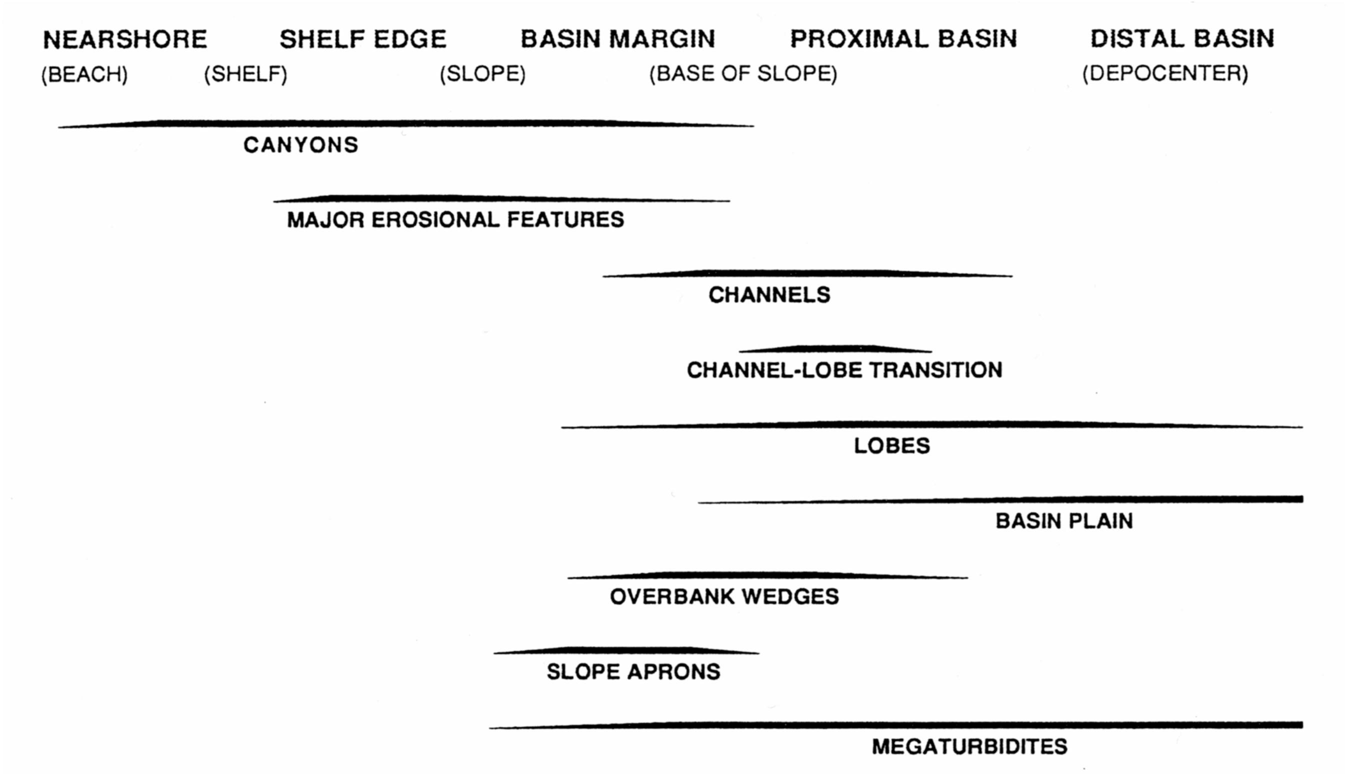


Fig.19 - Depositional elements of a turbidite system (from Mutti & Normark, 1991 and Mutti *et al.*, 2009).

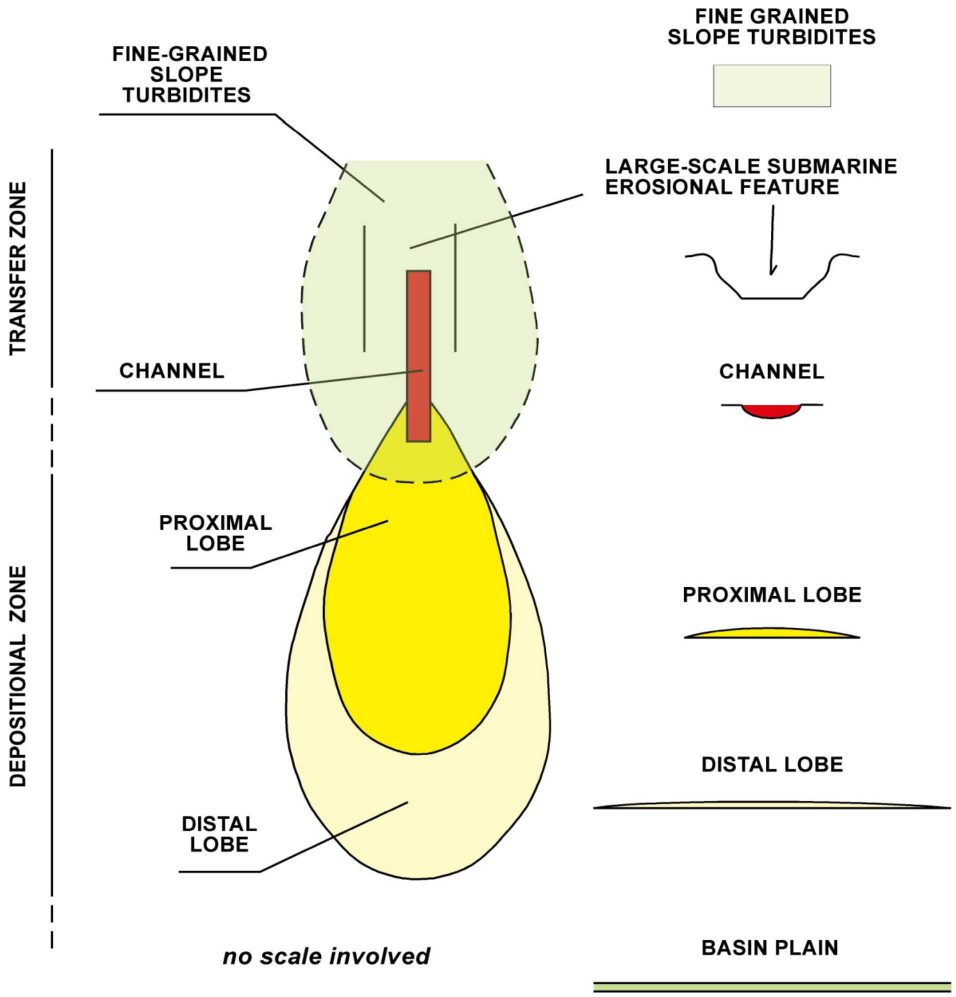


Fig.20 - Plane view of the main depositional elements in a turbidite system (from Mutti *et al.*, 1999).

4.3 Efficiency degree

The efficiency degree can be considered as one of the key factors for the control of turbidite facies distribution and turbidite system arrangement. It is defined as the ability of the flow to spread its sedimentary load over long distances, as well as to develop different turbidite facies (fig.21). This topic has been discussed by several authors, namely Mutti & Johns (1978), Mutti (1979, 1985, 1992) Pickering *et al.* (1989), Mutti *et al.* (1994b, 1999, 2003) and Tinterri *et al.* (2003). It depends upon several physical behaviours and composition characteristics, such as the bulk of fine-grained sediments carried by the flow, which can enhance the basal dense flow in maintaining overpressure; another important factor is the way the head of the basal dense flow can transform itself and pass its sedimentary load into the overlying diluted turbulent flow, mainly depending upon the relationship between shear stress (imposed by the moving flow and fluid environment) and shear resistance of the basal dense flow itself. For more details about this topic, please see Mutti Mutti *et al.* (1999, 2003), Tinterri *et al.* (2003) and Mohrig & Marr (2003). According to Mutti *et al.*, (1999), turbidite flows can be classified on three different degrees of efficiency, each of which gives rise to a different facies tract: very highly-efficient turbidite currents, highly-efficient turbidite currents, very poorly-efficient turbidite currents (fig.21). The formers can segregate their sedimentary load mainly in distal facies (F7, F8, F9), due to the great amount of fine-grained sediments that enhance buoyancy, as well as the ability of turbulent flows to evolve over long distances. Part of fine-grained sediments can be involved in

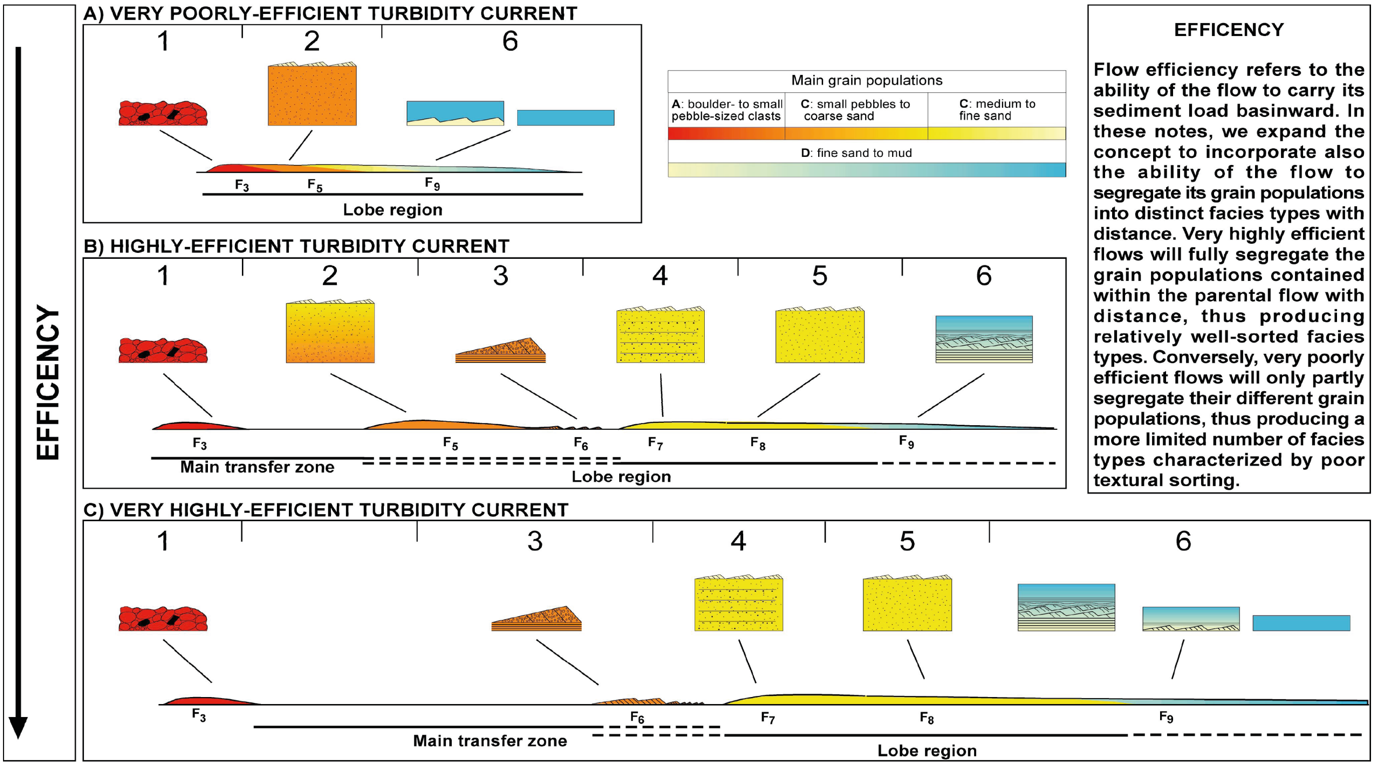


Fig.21 – Different types of facies tracts related to different efficiency degree of the turbidite systems (from Mutti *et al.*, 1999).

the turbulent flow by bulking phenomena, promoted by bed erosion. This kind of flows occur in highly-efficient turbidite system (Mutti, 1979), or type I systems (Mutti, 1985) and possibly they are triggered by long-lived, flood-generated hyperpycnal flows. Conversely, very poorly-efficient turbidite currents are not able to spread their sedimentary load over long distances and can generate facies tract dominated by coarse-grained proximal facies (F2, F3, F5), whereas fine-grained facies (F9) are poorly developed or lacking (fig.21). In fact, the low degree of efficiency of these turbidite currents prevents basal dense flow transformation by hindering upper turbulent flow formation, as well as bulking and bed erosion processes. Facies tracts generated by this kind of turbidite currents occur in low-efficiency systems by Mutti (1979) or type II systems by Mutti (1985). From this point of view, the evolution of the MAF deposits is characterized by a progressive decrease in efficiency degree due to the increase of the tectonically-induced topographic confinement (Tinterri & Muzzi Magalhaes, 2011). More precisely, Langhian to Serravallian deposits of the inner stage (Unit I to IV) can be considered as very highly efficient turbidite systems and pass upward into Tortonian poorly-efficient "mixed" systems of the outer stage (Castel del Rio system, Mutti *et al.*, 2003) through the transitional phase, marked by the Firenzuola and Paretaio turbidite systems (Unit V and VI, Tinterri & Tagliaferri, 2015) that are characterized by turbidite facies association showing intermediate features (fig.14).

4.4 Turbidite facies reference scheme

In the past several authors proposed reference schemes for turbidite facies, following either descriptive or genetic approaches: Mutti & Ricci Lucchi (1972, 1975), Walker & Mutti (1973), Mutti (1979, 1992), Nardin *et al.* (1979), Lowe (1979, 1982), Ghibaudo (1992), Pickering *et al.* (1986, 1989) and Mutti *et al.* (1999, 2003). The reference scheme chosen for this thesis is the one by (1992), modified by Mutti *et al.* (1999, 2003), based on the *facies tract* concept, which represents an ideal genetically-linked suite of facies (fig.22), deposited by the donwcurrent evolution of a unidirectional waning and depletive sediment gravity flow (as meant by Kneller, 1995; see fig.23). As for the scheme by Lowe (1982), Mutti (1992) and Mutti *et al.* (1999, 2003) gathered turbidite facies in several grain-size populations (fig.22), deposited by a basal dense flow and its overlying low-density turbulent flow, according to the bipartite turbidite current concept by Sanders (1965). These grain size populations are:

A) boulders to small pebbles

B) small pebbles to coarse sand

C) medium sand

D) fine sand.

The coarser A and B populations are mainly transported by the basal overpressured dense flow, medium sand of the C population can be carried by both basal dense and upper low-density turbulent flow, whereas the finest D population is essentially transported as a suspended load within the overlying turbulent flow. In that way, each population is deposited by a well-defined process affecting a well-determined part of the turbidite current. The vertical stacking of facies within the same bed in a specific location is named *facies sequence* and represents the time-evolution of the turbidite current at a given point.

A short overview of each facies will be described below.

Facies F2 is made of an immature, very poorly sorted paraconglomerate, in which larger clasts are dispersed throughout a finer matrix made of gravel, sand and mud. It's deposited by an hyperconcentrated flow (as meant by Mutti, 1992) or an overpressured dense flow (as meant by Mutti *et al.*, 1999) that results from the downslope transformation of a cohesive debris flow through progressive mixing with ambient fluid.

Facies F3 consists of a relatively well-sorted, sometimes inverse-graded orthoconglomerate, mainly made of the grain-sized population "A". It represents a residual lag, whose lens-shaped deposits tend to pinch over short distances. Usually it is overlaid by a sharp-based finer facies, testifying bypass processes.

Both facies F2 and F3 can be interpreted as being the head and body deposits of a gravelly dense flow, whose erosive capacity can cause erosion of a great amount of mud clasts during its downcurrent motion; the progressive disintegration of these mud clasts can contribute to the increase fine-grained sediments in the overlying turbulent flow.

Facies F4 represents the first deposit of the gravelly high-density turbidite current; in terms of sedimentary structure, it is made of pebbly traction carpets that can be considered as the

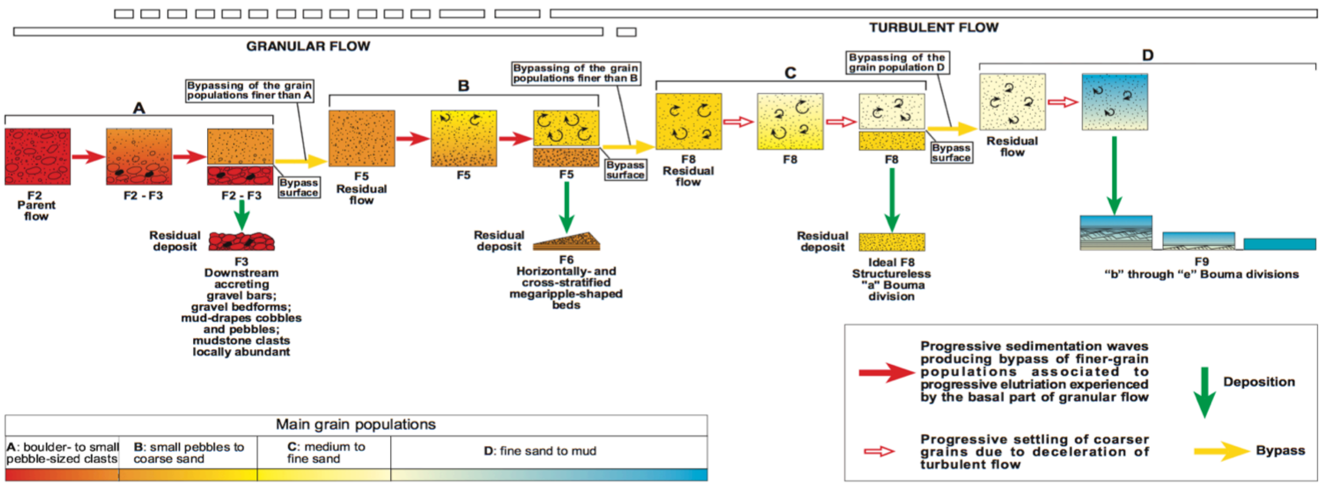


Fig.22 - Mutti's facies scheme (from Mutti *et al.*, 1999).

equivalent of the S2 division of Lowe (1982).

Facies F5 consists of coarse to very coarse, poorly sorted massive to poorly graded sandstones. It represents the deposit of high-density turbidite currents able to bypass more proximal areas characterized by F2 and F3 conglomerate deposition. The sediment in this phase is mainly sustained by overpressure, as testified by common water escape structures (see Mutti *et al.*, 1999). The erosive power of the head of the flow is testified by erosive and impact structures associated with rip-up of mudstone clasts. The lateral and downcurrent extension of this facies is quite variable, according to the efficiency degree of the systems.

Facies F6 and F7 facies represent bypass facies between dense and turbulent flows. The former is made of well-sorted, coarse-grained sandstone showing megaripples structures, sharply overlaid by a thin level of fine grained sandstone (named F9b) deposited by the tail of bypassed low-density turbulent flows. In that way, the megaripples within F6 represent the reworking structure of the distal part of the F5 coarse-sandstone, whereas the overlying sharp passage to the fine F9b facies represents the bypass surface. Facies F7 represents the deposition by the near bed suspension, namely the basal part of the turbulent flow in which the high rate of fallout is able to supress the turbulence and cause the formation of coarse to medium-grained sandstone with traction carpets. In terms of depositional processes, F6 and F7 can be seen as facies representing different deceleration degrees of the turbulent flow (see Mutti *et al.*, 2003; Tinterri *et al.*, 2003): higher in the former, lower in the latter, which can be overlaid by F8 facies made of massive, well-sorted, medium-grained sandstone, testifying the sedimentation rate increase (suspension phase, according to Lowe, 1982) and representing the Ta of the Bouma sequence. Finally, facies F9 is the most evolved and finest one in Mutti's scheme and is deposited by the low-density tail of the turbulent flow, able to reach the most distal zones of the depositional basin. It is made of traction plus fallout structures (Tb-e in the Bouma sequence), testifying the depletive and wining nature of the flow in the final part of its path.

4.5 Topographic control on turbidity currents

Mutti's facies scheme represents the suite of facies deposited by an ideal waning and

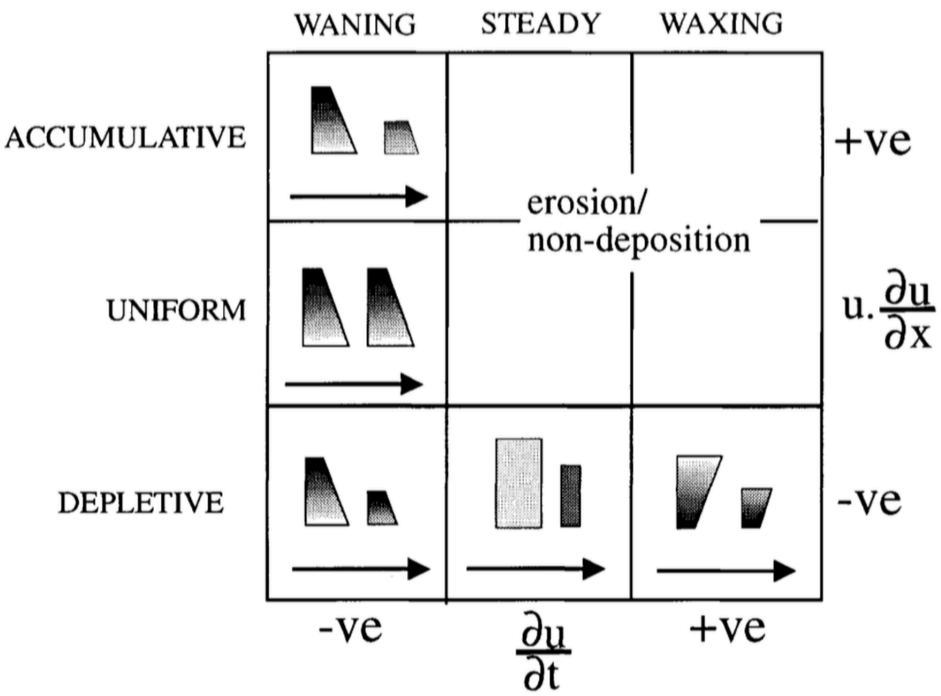


Fig.23 - Acceleration matrix, showing bed sequences with vertical and downcurrent grain size changes (from Kneller, 1995).

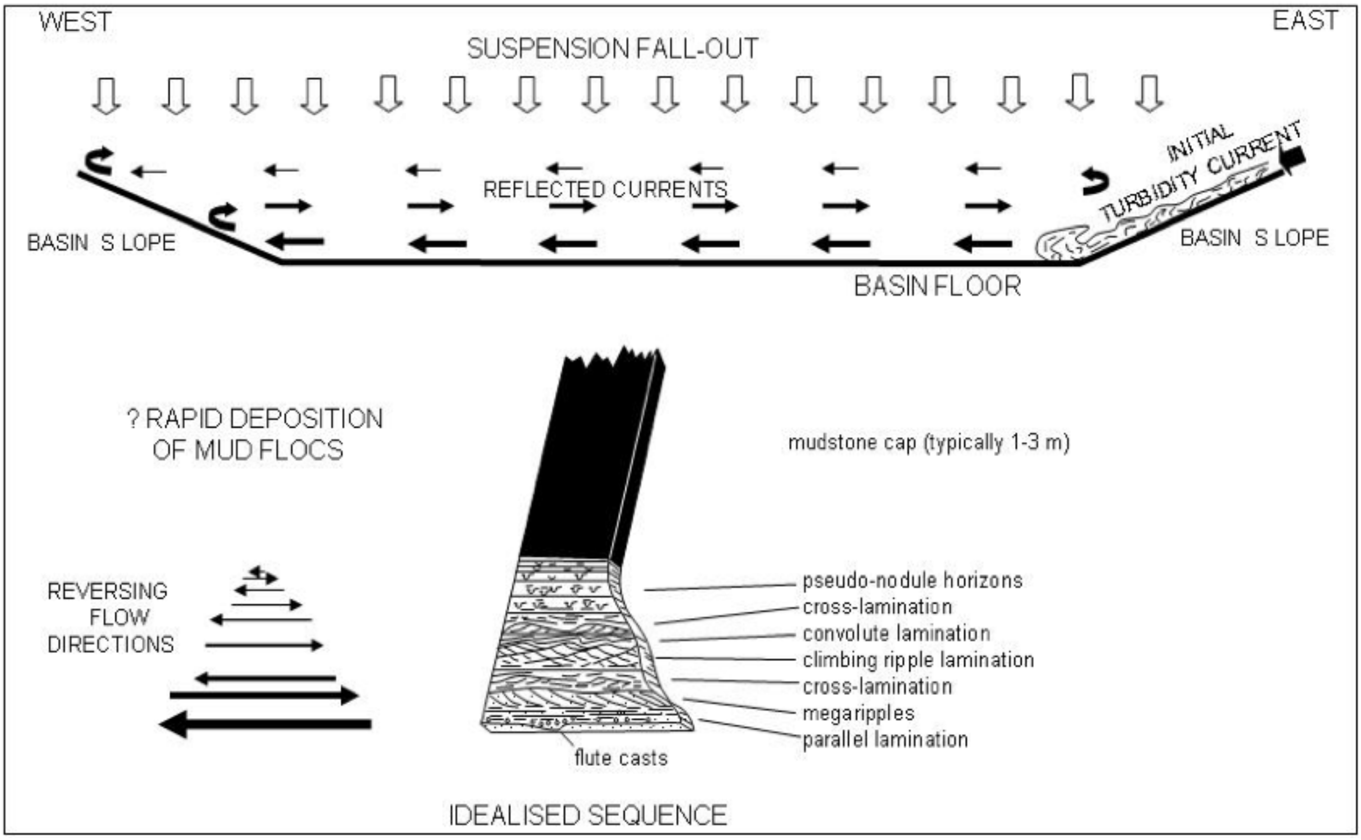
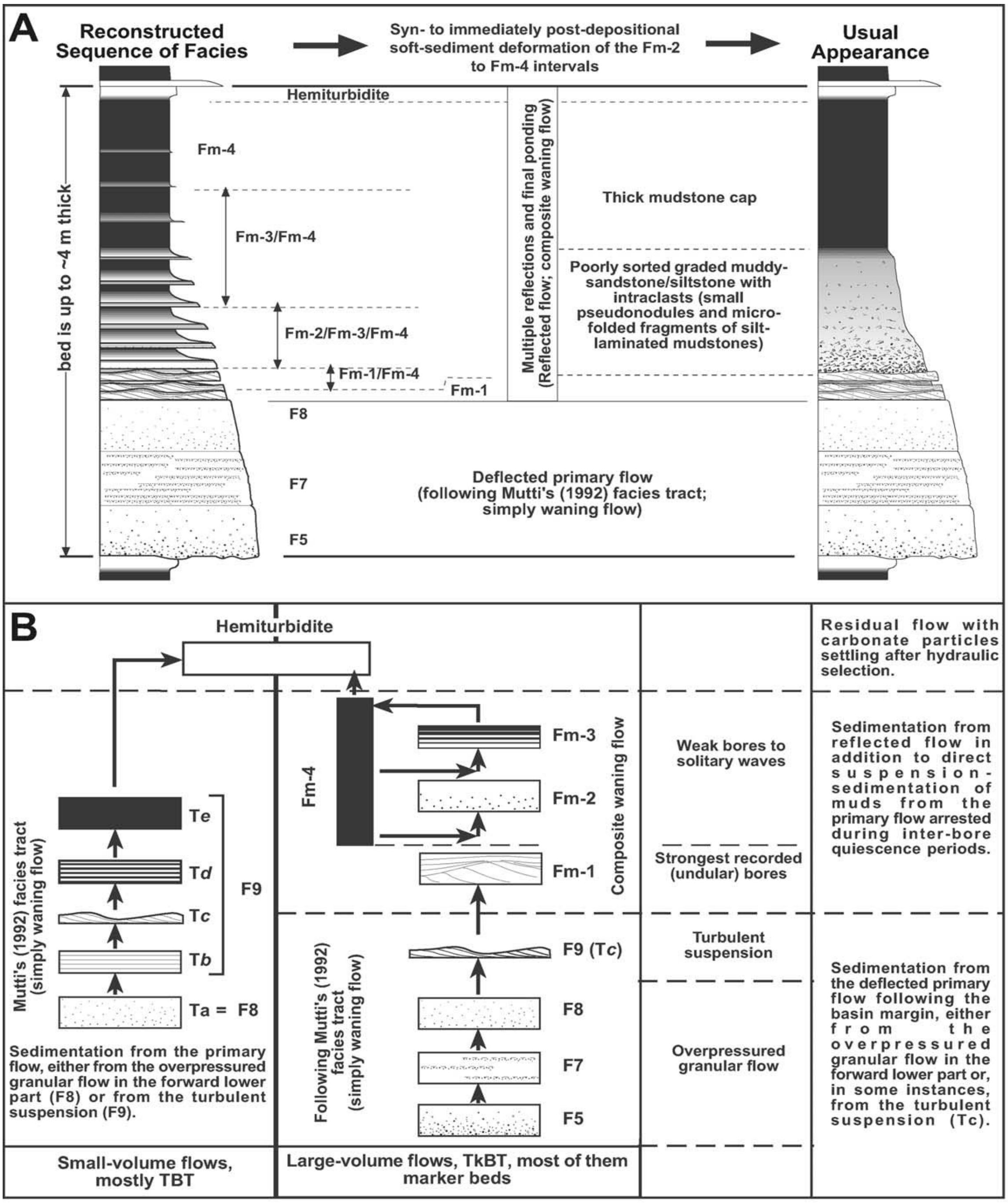


Fig.24 - Processes involved in the formation of contained-reflected beds (from Pickering & Hiscott, 1985).

depletive turbidity current (as meant by Kneller, 1995; fig.23), whose space-time evolution is not affected by topographic control. Most of the turbidite basins are strongly involved in syn-tectonic deformations able to produce topographic "constraints" that can influence turbidite currents dynamics and, as a consequence, the nature and distribution of turbidite facies. Several works have dealt with this topic, both through laboratory experiments (Pantin & Leeder, 1987; Simpson, 1987; Kneller *et al.*, 1991; Edwards *et al.*, 1994; Kneller *et al.*, 1997) and field studies (Van Andel & Komar 1969; Rupke 1976; de Jager 1979; Ricci Lucchi & Valmori 1980; Ellis 1981; Ricci Lucchi, 1986; Marjanac 1990; Pickering & Hiscott 1985; Remacha & Fernandez 2003; Kneller 1995; Edwards *et al.*, 1994; Haughton, 1994; Kneller & McCaffrey, 1999; Mutti *et al.*, 2002, 2003; Lucente 2004). According to Kneller & Bradley (1995) and Kneller (1995), turbidity currents can experience changes in velocity through time and space (fig.23). In the former case, velocity variations can be essentially related to the triggering mechanism, and are described by the "stationary" concept, according to which the flows can be classified as: a) steady, characterized by no variations, b) waxing characterized by increasing velocity and c) waning characterized by decreasing velocity. Conversely, changes in velocity through space can be induced by topography and are stressed by the "uniformity" concept, according to which the flows can be classified as a) uniform, with no space variation, b) accumulative and c) depletive, characterized by acceleration and deceleration respectively. The spectrum of combinations of these kinds of flow provides a matrix with nine fields, each one of which is able to produce a different facies sequence (fig.23). The syn-tectonic influence on sediment yield and turbidite dispersal pattern, especially related to foreland basins, was stressed by Mutti *et al.* (1999, 2003), according to whom the main phases in tectonic growth play a key role in controlling the vertical stacking pattern of depositional systems progressively more and more influenced by fluvio-deltaic sedimentation. In these tectonic settings, however, as recently highlighted by Tinterri & Muzzi Magalhaes (2011) in the MAF foredeep, the tectonically-induced confinement can have an important role causing a decrease efficiency degree of the turbidite systems, by forcing basal dense flows to decelerate and deposit the most part of their sedimentary load in proximal areas in poorly sorted, coarse-grained facies, often rich in mudstone clasts and characterized by amalgamation structures; the resulting facies tracts are basically lacking in more evolved and distal finer facies. Despite the high number of works discussing the influence of the basin morphology on turbidity currents dynamics, only recently the papers by Muzzi Magalhaes & Tinterri (2010), Tinterri & Muzzi Magalhaes (2011) and Tinterri & Tagliaferri (2015) proposed a facies scheme based on a high resolution physical stratigraphy that has led to significantly better understandings about facies evolution of sedimentary basins in accordance with the degree of basin confinement and basin morphology (fig.12, 13). In particular, these works emphatize to two bed types that are considered as the main indicator of topographic confinement, namely *slurry beds* and *contained-reflected beds* (fig.12B). Slurry beds have long been described in the literature (Wood & Smith, 1958; Marshalko, 1970; Carter, 1975; Ricci Lucchi, 1975, 1978; Ricci Lucchi & Valmori, 1980; Van Vliet, 1978; Haughton *et al.*, 2003, 2009; Talling *et al.*, 2004; Zeng & Lowe, 2004; Amy & Talling, 2006; Talling *et al.*, 2007a, b), whereas contained-reflected beds have been introduced by Pickering & Hiscott (1985), after careful studies carried out in the Ordovician Canadian Cloridorme Formation (fig.24). These bed types show anomalous thickening of the upper mudstone unit together with an alternations of laminasets in the fine-grained basal sandstone unit, that from base to top show the following sequence: even parallel laminae, megaripples, cross-laminae, climbing ripples, convolute laminae overlaid by several pseudo-nodules levels. This sequence, along with the anomalous thickening of the mudstone unit, were attributed to the ponding phenomena, able to produce a waning reversing flow forced to settle the sedimentary load in a restricted area because of repeated reflections of the diluted turbulent flow against the basin margins (fig.24). This topic was also dealt with by Remacha & Fernandez (2003) and Remacha *et al.* (2005) for the Hecho Group (central-southern Pyrenees, Spain), who observed an increasing in the thickest beds from the lobes to the basin plain regions (fig.25). In particular, Remacha *et al.* (2005) proposed a facies scheme for basin plain beds, dividing ideal from observed sequences. The latter are characterized by intermediate-upper poorly sorted fine grained muddy sandstone or siltstone units, rich in pseudonodules and micro-folded fragments of silt-laminated mudstone (fig.25), whose formation was attributed to cycling-wave loading phenomena produced by ponding processes in a similar way assumed by Pickering & Hiscott (1985). Finally, as mentioned above, Muzzi Magalhaes & Tinterri (2010) and Tinterri & Muzzi Magalhaes (2011), thanks to a high-resolution physical stratigraphy and facies analysis of the Langhian to Serravallian deposits of the Marnoso-arenacea Formation, stressed the direct link between the syn-sedimentary thrust activity and the occurrence of five bed types (Type 1 to Type 5) and Mass Transport Complexes (fig.12). With the same approach, Tagliaferri & Tinterri (2015) showed the progressive change of turbidite facies affecting the “transitional” phase of the upper Serravallian, Marnoso-arenacea Formation deposits because of the syn-sedimentary growth of the Coniale structure (fig.13).



F5, F7, F8 and F9 are following Mutti's (1992) nomenclature. Tc comprises small (wavelenght<10 cm) 2D to 3D (linguoid), asymmetrical ripples (current ripples).
Reflected-flow facies (modified-flow facies or Fm):
Fm-1 = Long-wavelength (<2 m) sinuous to rounded, isolated ripples, slightly asymmetrical to symmetrical (combined-flow ripples), with palaeocurrents diverging from sole marks (see Fig. 3).
Fm-2 = Graded (distribution grading) very fine sand to coarse silt.
Fm-3 = Very thin parallel laminated silts and clays.
Fm-4 = Poorly sorted silty muds to clays.

Fig.25 – A) Example of contained-reflected beds; on the left ideal facies sequence, on the right outcrop appearance. B) Facies tracts of both primary flows (facies from Mutti's, 1992 scheme) and reflected flows (from Remacha & Fernandez, 2003).

5. METHODOLOGY

The purpose of this study was achieved by measuring and correlating seven stratigraphic logs, located in the Romagna Apennines, from the Santerno to the Bidente Valleys.

The data were collected and managed as follow:

- bed-by-bed measurement of the logs by using Jacob's staff and measuring tape; estimate of the grain size of each bed with the aid of a grain-size comparator and a hand lens (20x)
- analysis of sedimentary structures in relation to grain-size populations
- paleocurrent measurement of the sole casts and traction plus fallout structures
- correlation of the logs using the hierarchical approach set forth below
- facies tract definitions, based on long-distance correlations.

The studied stratigraphic interval is Unit V by Muzzi Magalhaes & Tinterri (2010), even though, in some logs, the study has been extended to the underlying deposits of Unit IV. Unit V, upper Serravallian in age, is included between the Casaglia and Visignano MTCs (fig.14).

Each log has been named with a letter and a number: the latter to identify the longitudinal relative position (i.e. parallel to the paleocurrents, basin axis and main structural alignments), whereas the number to specifies the relative position orthogonal to the paleocurrents.

The correlation of the logs was possible thanks to the presence of MTCs and several key beds (see below), well-known in the literature (Lucente & Pini, 1999, 2003; Lucente, 2002, 2004; Muzzi Magalhaes & Tinterri, 2010), some of which are also traced in the geological maps of the Emilia-Romagna Region (Martelli *et al.*, 1994, 2005). The regional bed-by-bed correlation was achieved through a hierarchical approach, following the scheme by Remacha & Fernandes (2003) and Remacha *at al.* (2005) in the Echo Group (south-central Pyrenees) and by Ricci Lucchi & Valmori (1980) and Muzzi Magalhaes & Tinterri (2010) in the MAF: first correlating the MTCs and the main key beds, representing the megaturbidites, then the beds, traceable over the entire studied area, and finally the thinnest ones. At the end, each correlated bed has been identified with a number following the numbering introduced by Muzzi Magalhaes & Tinterri (2010).

This approach has allowed a high-resolution stratigraphic framework to be obtained, that has proven fundamental for the description of facies tract as defined by Lowe, (1982) and Mutti, (1992), (see also Mutti *et al.*, 1999, Tinterri *et al.*, 2003). Specifically, the general referential facies scheme is that by Mutti *et al.* (2003, see above, fig.22). Conversely, to describe the facies variations related to the structurally-controlled basin morphology, the facies schemes by Muzzi Magalhaes & Tinterri (2010; see their figure 21) and Tinterri & Tagliaferri (2015; see their figure 5, or see Tinterri *et al.,* 2012 their figure 15) were used, which include a series of bed types, whose lateral and vertical distribution allows the basin morphology variation to be understood as mainly related to the MTCs emplacement and tectonic uplift.

5.1 KEY BEDS

The examined stratigraphic interval shows several key beds, which represent the main constraints for log correlations. They have been divided into three main groups: Mass Transport Complexes (MTCs), Carbonate key beds and Siliciclastic key beds. In each group they are described following the stratigraphic order.

5.1.1 MTCs

Mass Transport Complexes (MTSs) are both important key beds for basin scale correlations and markers of tectonic activity phases. They can be found throughout the Marnoso-arenacea stratigraphic succession (fig.12, 14), but their occurrence increases during the upper Serravallian (see Lucente & Pini, 2002, 2003; Lucente, 2004). Their composition is mainly intrabasinal, even though an extrabasinal component appears and seems to increase starting from the Casaglia-Monte della Colonna MTC. This aspect can be related to the progressive NE-migration of the Apennine wedge and its allochthonous sheet front, which could be progressively involved during phases of inner margin collapses.

Casaglia Monte della Colonna (CMC) MTC

Stratigraphically located at the limit between Unit IV and Unit V (as meant by Muzzi Magalhaes & Tinterri, 2010), this MTC is one of the thickest and most extended in the MAF stratigraphic succession (fig.26). Its source area is located in the inner margin of the Lamone Valley and seems to have been triggered by a phase of tectonic advancement of the Monte Nero thrust. It is characterized by important thickness variations, especially near the source area where it reach a maximum thickness of about 500 m (fig.26). It is made of both extrabasinal (or olistostrome) and intrabasinal deposits, named Casaglia and Monte della Colonna (CMC), respectively, by Lucente (1998). These MTC components show a

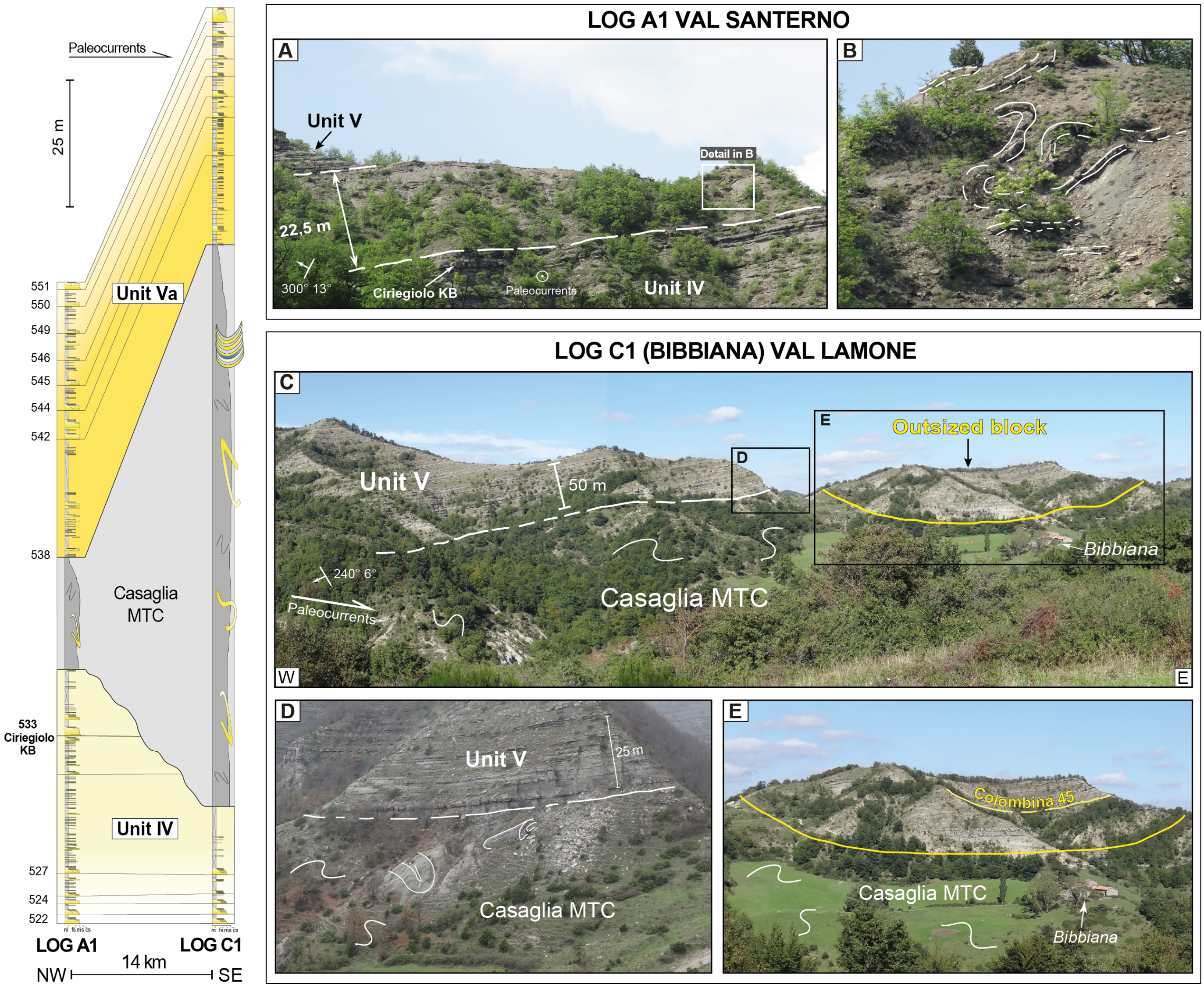


Fig.26 – Stratigraphic cross-section of the Casaglia MTC between Logs A1 and C1 Bibbiana. A) Panoramic view in Log A1. B) Detail of folded beds involved in the MTC emplacement. C) Panoramic view in Log C1 Bibbiana. D) Detail of the MTC top and the overlying basal part of Unit V. E) Detail of the outsized block made of the upper part of Unit IV eroded in more proximal areas (see also Lucente & Pini, 2003).

different distribution: the former mainly fill the inner part, the latter show a wider distribution toward more distal areas. This different distribution seems to be related to the emplacement mechanism, originated by a collapse of both fine-grained inner autochthonous deposits and allochthonous deposits belonging to the orogen advancing from SE.

The CMC has been the object of several structural studies (Lucente, 1998, 2002; Lucente & Pini, 2003) which mainly deal with emplacement mechanisms on the basis of deformation styles, axis fold orientation and distribution, as well as the characteristics of boundary surfaces and the stratigraphic thickness of the MTC related to some key beds in the underlying stratigraphic succession.

These studies showed an irregular basal surface characterized by ramps and flats, featuring progressively deeper erosion toward the south-western source area. The new data collected in this work provide further important details of the CMC MTC and its implications on the Unit VI and Unit V stratigraphic succession and turbidite facies distribution.

NASSETO MTC

Considered as time equivalent of the Casaglia MTC (Ricci Lucchi, 1986; Muzzi Magalhaes & Tinterri, 2010), the Nasseto MTC can be followed for more than 10km in NW direction, thanks to the good outcropping condition in the area of the Verghereto high and Savio Valley. It reaches a maximum thickness of about 100m and, similarly to the Casaglia MTC, it involves both extrabasinal and fine intrabasinal sediments (Farabegoli *et al.*, 1994), probably due to a displacement of fine sediment deposited on the inner slope, triggered by a seismic event related to the inner Monte Nero Thrust activity. According to Muzzi Magalhaes & Tinterri (2009) and Tinterri & Muzzi Magalhaes (2010) and their Log F (fig.12, 13), the Nasseto MTC is directly overlaid by the Verghereto Marls, testifying the sin-sedimentary growth of the Verghereto high.

BEDETTA MTC

According to the new data by Tinterri & Tagliaferri, (2015), Tagliaferri & Tinterri (in press) and the work for this thesis, this MTC marks the major changing phase in the sediment dispersal pattern and turbidite facies distribution characterizing Unit V; for that reason it was conventionally placed as the limit between sub-Unit Va and Vb (i.e. Firenzuola I and Firenzuola II, fig.14, 27). It consists of intrabasinal sediment, made of highly bioturbated marlstone, mudstone and fine-grained sandstone beds (fig.27B, C), showing folds vergence directed toward NE. Similarly to the CMC MTC in the Lamone Valley, it thicken toward SW and shows an erosive base that cuts about 20 meters of sub-Unit Va beds (see fig.27). Its thickness spans from 55m in Log C1 Casaglia to 32m in Log C1 Bibbiana and 20m in Log B1 (fig.27), while it has not been detected in others logs. In Log A1 it has been correlated with a bedset made of massive sandstones rich in mudstone clasts. According to these characteristics, the Bedetta MTC can be thought as being made of fine-grained highly bioturbated sediments deposited by diluted turbulent flows on the SW inner margin of the foredeep and displaced during a phase of growth of the Monte Nero thrust; the triggering mechanism was probably not able to involve the innermost allochthonous margin, due to its reduced bulk compared with of CMC MTC.

VISIGNANO MTC

The uppermost MTC of the studied stratigraphic succession presents an impressive bulk near the source area, located in the proximal zone represented by the Santerno Valley.

From a stratigraphic point of view, it represents the top of Unit V and the base of Unit VI, i.e. the Paretaio turbidite system (fig.14, Tinterri & Tagliaferri, 2015). According to the geologic

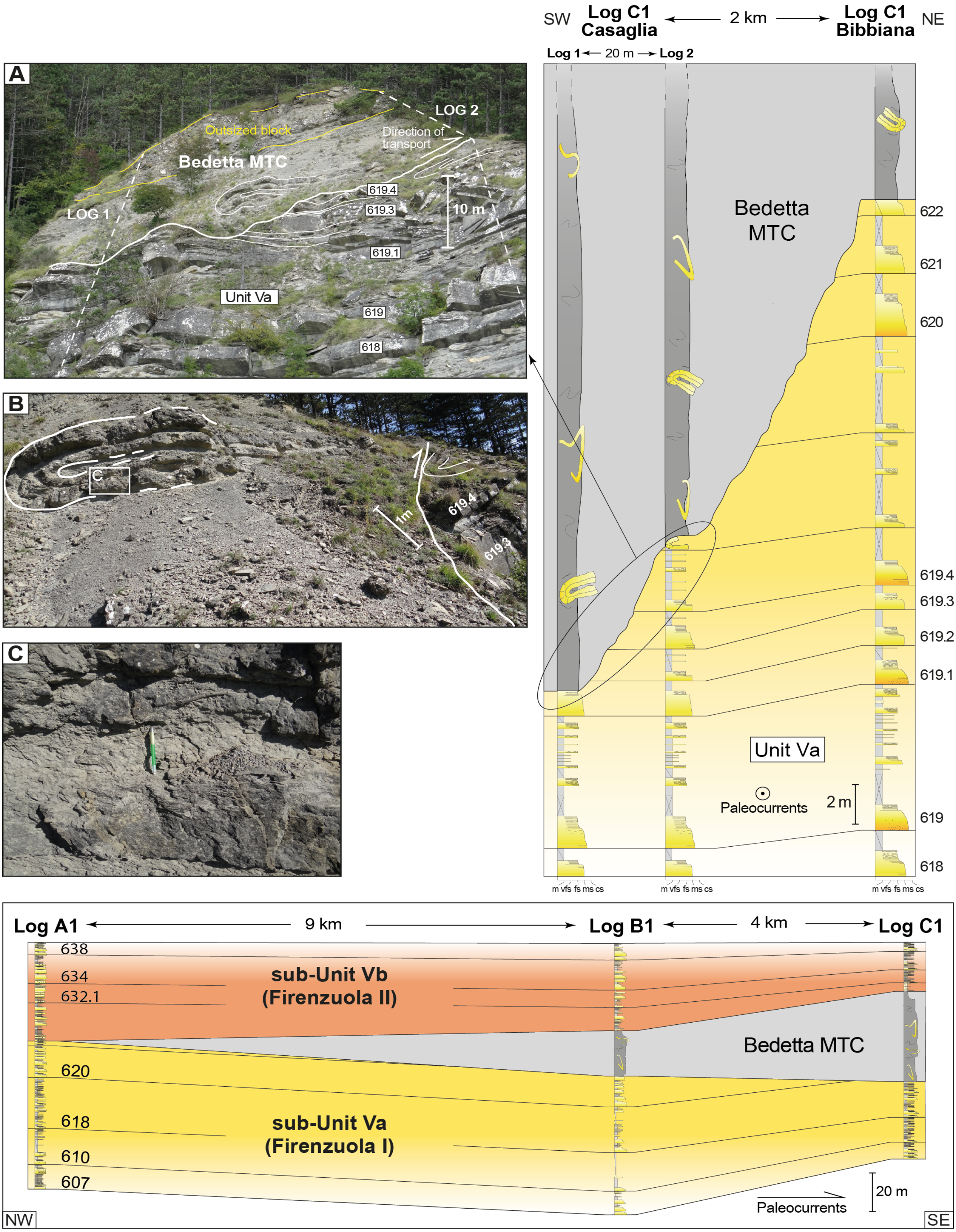


Fig.27 - Bedetta MTC. In the upper cross-section detail of the basal erosion between Log C1 Casaglia and Log C1 Bibbiana, in the lower one detail of the correlation between Log A1, Log B1 (from Muzzi Magalhaes & Tinterri, 2010) and Log C1 Casaglia. A) Panoramic view in Log C1 Casaglia. B) Erosional base and folded bioturbated bed involved in the MTC emplacement. C) Detail of the highly bioturbated bed shown in B.

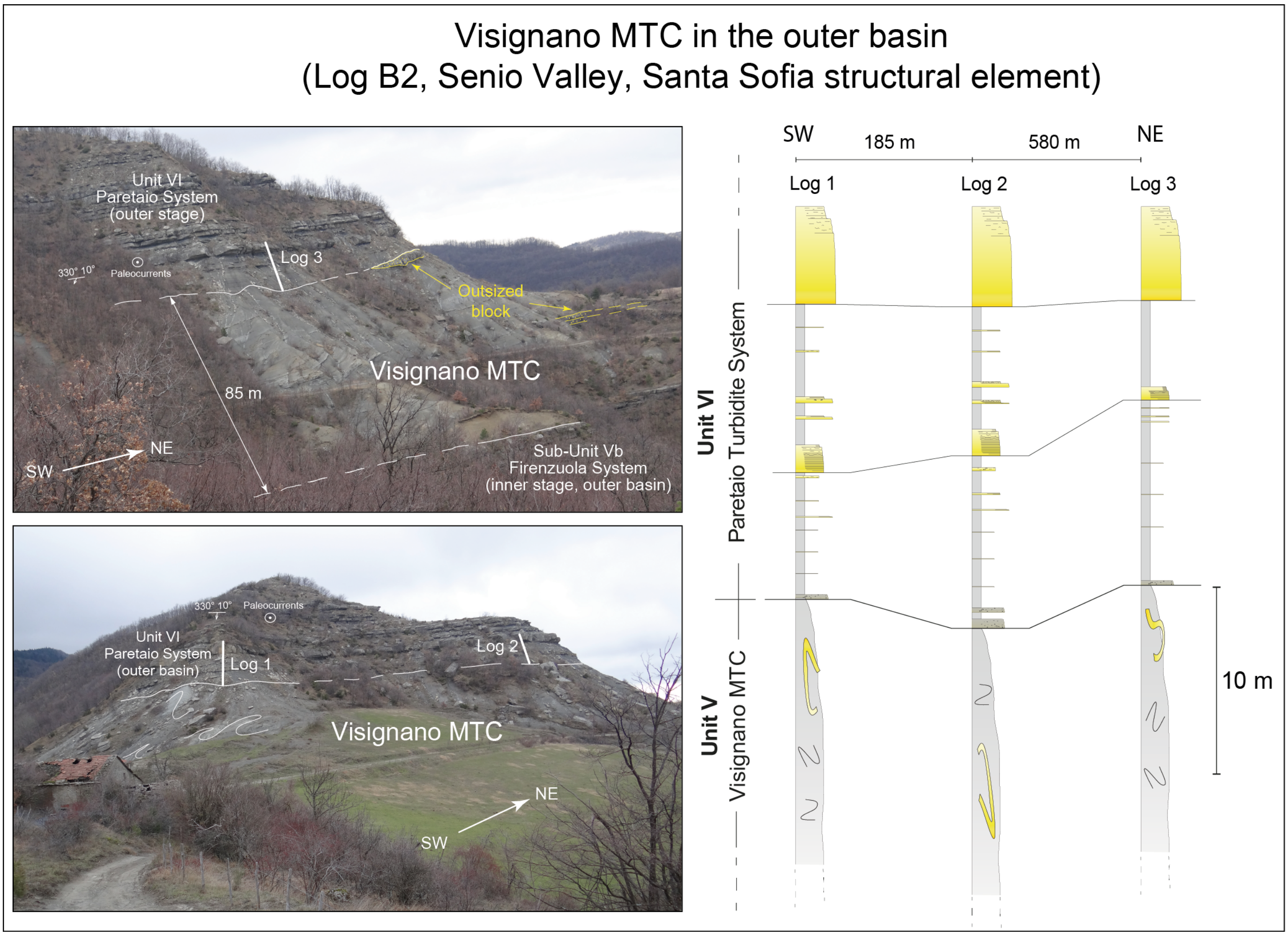


Fig.28 - Visignano MTC in the outer basin (top of Log B2). In the pictures panoramic views and location of the logs shown in the cross-section on the right. In this area the Visignano MTC is made only of intrabasinal sandy beds, outsized blocks and very fine grained marly beds of the Castelvecchio Unit deposited above the syn-sedimentary topographic high created by the growth of the CTRF and involved in the emplacement (see text for more details). The correlation of the three detailed logs shows the irregular top of the MTC affecting the first deposits of Unit VI (Paretaio System, Tinterri & Tagliaferri, 2015).

map (Martelli *et al.*, 2005), the maximum thickness of the Visignano MTC is estimated in the order of several hundreds of meters, even though the exact value is quite difficult to detect due to the intense deformation caused by Sillaro tectonic line in the proximal area. The Visignano MTC crops out extensively between the Santerno and Senio valleys in both inner and outer basins and is made of intrabasinal and extrabasinal sediments (Lucente, 2004), which show an opposite trend distribution: the former thicken toward the source area and are replaced by the latter toward distal areas. The extrabasinal components crop out extensively near the villages of Peglio and Visignano and border the Sillaro Line to the west. The intrabasinal components are made of highly bioturbated marlstone-mudstone and very thin to thin fine-grained sandstone beds, deposited above the syn-sedimentary structural high related to the growth of the CTRF and displaced during the emplacement of the Visignano MTC (Roveri *et al.*, 2002; Tinterri & Tagliaferri, 2015). These autochthonous contorted beds, involving some less deformed outsized block (fig.28), can be observed in the forelimb of the CTRF along the (Imolese main road SS610) between the villeges of Coniale and Moraduccio and near the village of Casovana. The Visignano MTC also crops out in the Senio Valley where its good exposure consented details about thickness and first draping deposits to be collected (fig.28).

5.1.2 Carbonate key beds

As stated above, carbonate beds were sourced by central Italy carbonate platforms and flowed in opposite direction compared to the siliciclastic beds of the MAF (fig.10; Ricci Lucchi & Valmori, 1980; Gandolfi *et al.*, 1983; Muzzi Magalhaes & Tinterri, 2010). Thanks to their sporadic occurrence, peculiar composition and opposite paleocurrent direction, they are very important key beds and the main constraints for long-distance correlation throughout the Langhian to Serravallian deposits of the MAF basin (fig.29). They can be found in the most part of the MAF stratigraphic succession, from Unit I to Unit IV (fig.12C, 13B), but they disappear from Unit V on, because the relief created by the growth of the Verghereto high at the time of upper Serravallian time (Unit V) prevents them from flowing toward their distal area of the Romagna Apennines. The numbers of the Colombina key beds are those introduced by Muzzi Magalhaes & Tinterri (2010) (fig.12), and the names as per the geologic maps of the Emilia Romagna Region Geological Service are also indicated.

COLOMBINA 30 MT (COLOMBINA MONTERELLO)

It represents one of the thickest and more extended Colombina in the MAF deposits as well as the lowermost carbonate bed of the studied stratigraphic succession (upper part of Unit IV). Measured only in Log A1 (Val Santerno), it crops out near the village of San Pellegrino, along the "Imolese main road SS610". It shows a 45cm thick basal fine-grained, laminated calcarenitic division overlying by a 250cm thick calcilutite unit (fig.29A).

COLOMBINA 35 (COLOMBINA CRESPINO OR TIRAVENTO)

As well as the Colombina 30 MT it was measured only in the lower part of Log A1, near San Pellegrino Village. Its base is characterized by a 25cm-thick, fine grained calcarenitic division, with undulated laminae that pass upward into a 135cm-thick calcilutite unit (fig.29B).

COLOMBINA 40 (COLOMBINA MAESTÀ DELLE VALLI OR M.MIRABELLO)

Stratigraphically located some tens of metres above the key bed 486 (fig.12C, 13C), it was found and measured in Logs A1, B2, C1 Bibbiana, and E2. Thinner than Colombina 30 and 35 it is made of a basal part, a few cm thick, composed of fine to very fine-grained calcarenite, overlaid by a 50-60cm-thick calcilutite unit (fig.29C, E).

COLOMBINA 45 (COLOMBINA AVALCELLI OR DELLA FRATTA)

It is the uppermost Colombina key bed in the stratigraphic succession of the MAF and lies some tens of metres above Colombina 40. As the latter, it crops out in several logs (A1, B2, C1 Bibbiana, E2) and shows a base that is few centimetres thick and is overlaid by a 50-60cm-thick calcilutite unit (fig.29D, F).

5.1.3 Siliciclastic key beds

Among the thousands of siliciclastic turbidite beds of the MAF, some of them represent very important key beds, both thanks to their particular stratigraphic location and their sedimentological characteristics.

BED 486, BADIA SUSINANA OR POGGIO SERRA HORIZON

This key bed named 486 by Muzzi Magalhaes and Tinterri (2010) lies between Colombina 35 and Colombina 40 and, thanks to its thickness, can be traced throughout the MAF basin. Its name (Badia Susinana) comes from a little village located in Senio valley, just near the base

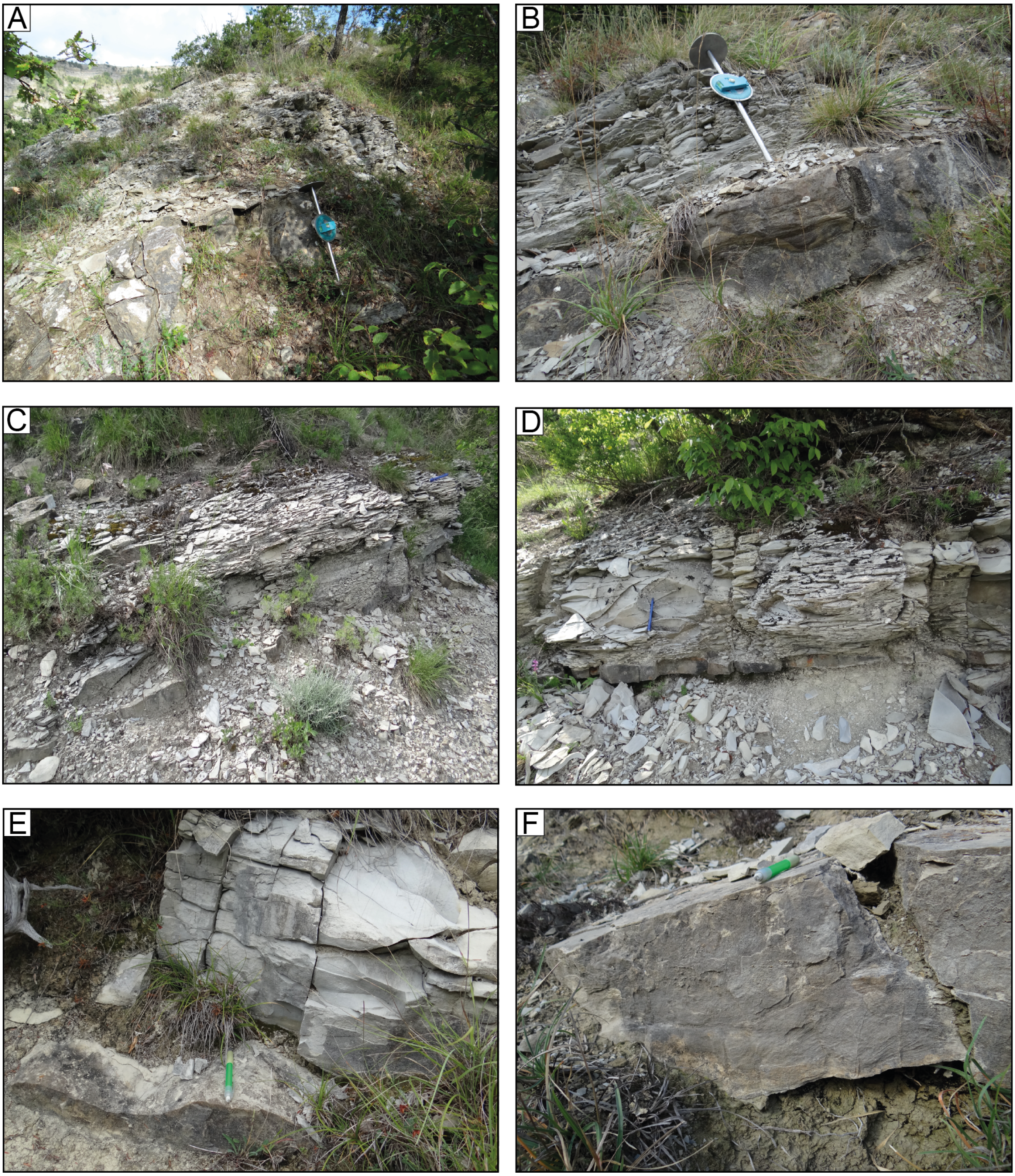


Fig.29 - A) Colombina 30 or Monterello (MT) from Log A1. B) Colombina 35 or Tiravento or Crespino from Log A1. C) Colombina 40 or M.Mirabello or Maestà delle Valli from Log A1. D) Colombina 45 or della Fratta or Avalcelli from Log A1. E) Colombina 40 from Log E2, whose basal fine sandstone laminated unit (F9) is characterized by boxy ripples, probably because of the interaction of the diluted turbulent flow with the Verghereto high, able to add internal waves to the unidirectional flow (pencil is N-S oriented). F) Basal fine grained, laminated sandstone unit (F9) of Colombina 45 in Log E2, characterized by ripples indicating paleocurrent toward NW (pencil is N-S oriented).

of Log B2 (Italian Geologic chart 1:50.000, sheet 253-Marradi, Martelli *et al.*, 2005). In this work, it was measured in Logs A1, B2, C1 Casaglia, C1 Bibbiana and E2. Its base is characterized by sandstone toward the other logs. Conversely, the first bed above 486 shows a sandwich structure in Log A1 and passes to a slurry facies containing clasts of allochthonous composition

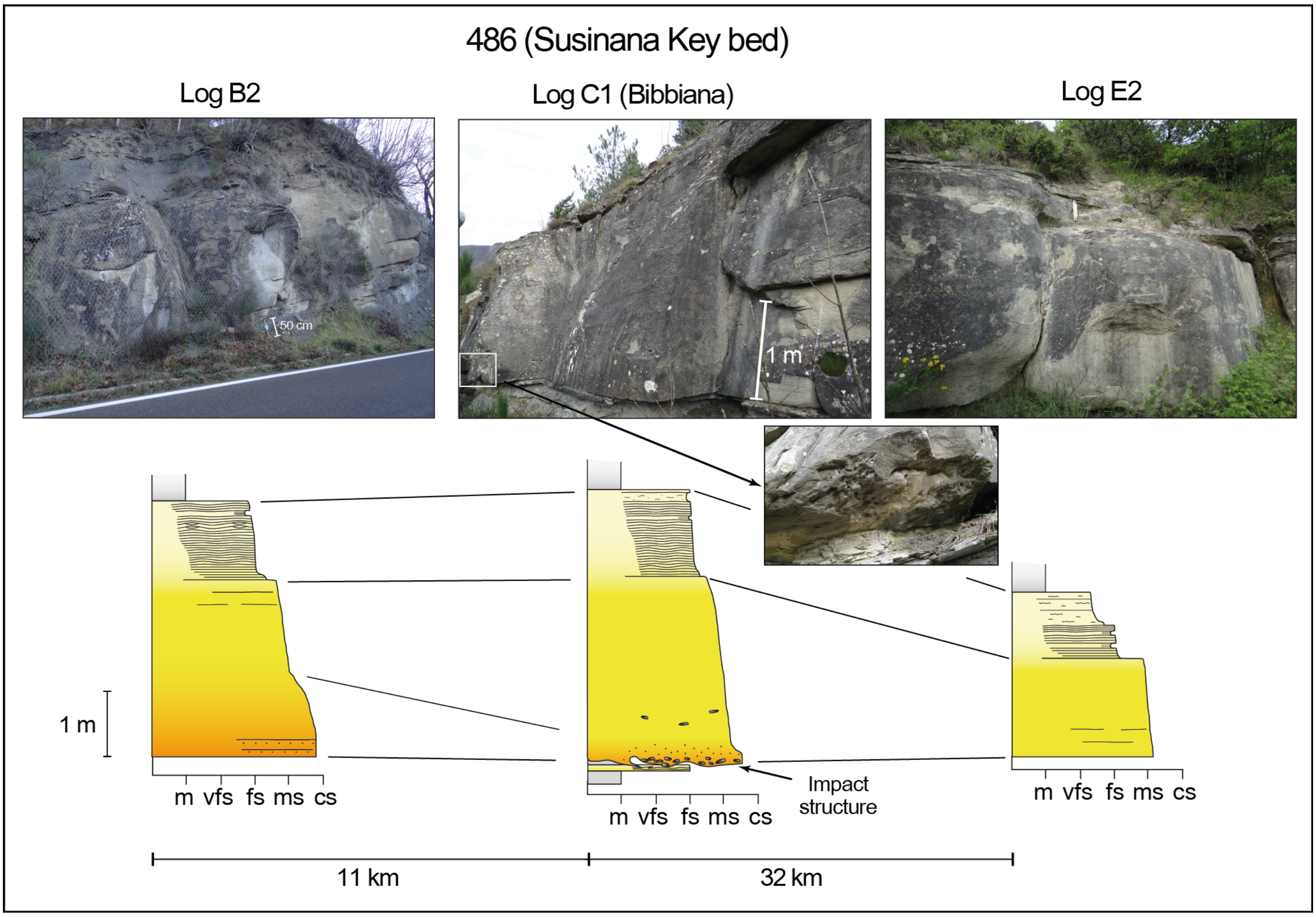


Fig.30 - Susinana or Poggio Serra Key Bed, 486 bed by Muzzi Magalhaes & Tinterri (2010) and Tinterri & Muzzi Magalhaes, (2011). It is worth noting the basal impact structure in log C1 Bibbiana and the liquefaction structures in the upper fine grained sandstone facies (F9), probably caused by reflection processes of the diluted turbulent flow against the Verghereto high (see text for detailed explanation).

a thick to very thick coarse to medium-grained graded sandstone (fig.30), showing massive to crudely laminated structures (Facies F8) often rich in mudstone clasts and sometimes showing impact structures (e.g. Log C1 Bibbiana, fig.30). This massive basal part is overlaid by a medium to thick fine-grained and laminated sandstone, often characterized by ponding structures (contained-reflected bed). The basal sandstone interval is, in turn, overlaid by a 2-3 m thick mudstone interval. Just below key bed 486, a couple of slurry beds were found in Log A1, which pass to thin, fine-grained laminated in Log C1.

CIRIEGIOLO KEY BED

Up to now it has been found only in the proximal area between the Senio and Lamone Valleys, but thanks to the high-resolution physical stratigraphy of this work, it was discovered for the first time also in the distal area of the Bidente and Valley (Log E2, fig.31). It is stratigraphically located near the basal contact between Casaglia MTC and Unit IV (fig.26) and it represents an important tool to evaluate the amount of the Casaglia MTC's erosion occurred during its emplacement (fig.26). In Log A1 it is located about 11m below the Casaglia MTC (fig.26); in Log B1 it is just at the basal contact with the Casaglia MTC, whereas toward the Lamone Valley it is eroded and involved in the chaotic body (fig.26). Its stratigraphic location is also an important constraint for the correlation of the logs where the Casaglia MTC does not crop out (Log B2, Log E2). It is characterized by a basal very thick, massive to crudely laminated medium sandstone grained facies (F8) overlaid by a poorly developed laminated fine grained sandstone and mudstone facies in the proximal area (fig.31, Type D bed in Log A1 and Log B2, see paragraph 6.2 for detailed explanation of bed types); toward the distal area of Log E2 the upper fine grained facies tend to thicken and shows laminations of contained-reflected bed, because of ponding processes against the Verghereto high in the distal area (fig.31, Type E beds, see paragraph 6.2 for detailed explanation of bed types).

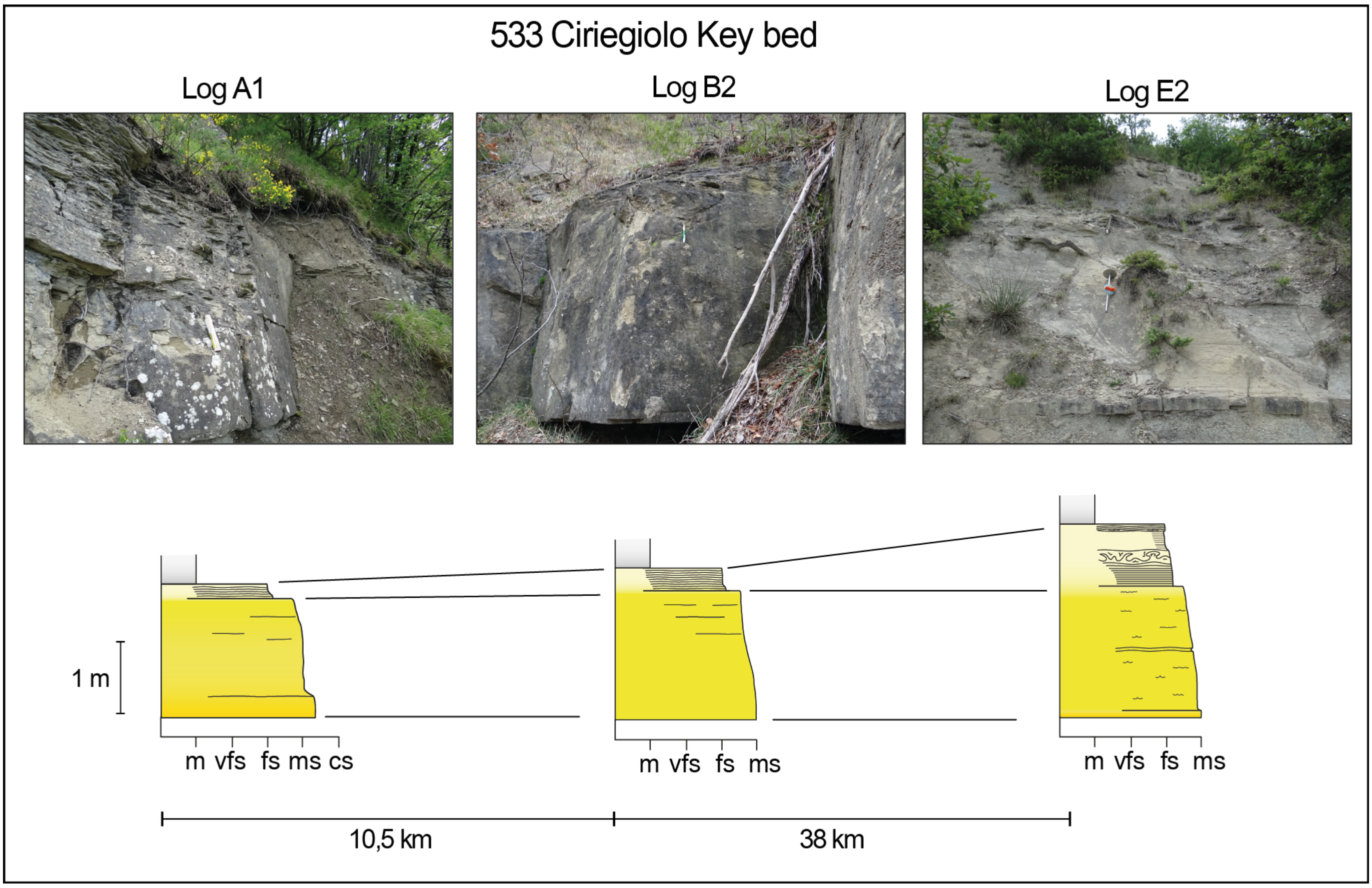


Fig.31 - Ciriegiolo Key Bed, bed 533 by Muzzi Magalhaes & Tinterri (2010) and Tinterri & Muzzi Magalhaes (2011). It is worth noting the thickening of the upper fine grained sandstone facies (F9) in Log E2, which shows convolute laminae and liquefaction structures because of reflection processes of the diluted turbulent flow against the Verghereto high.

6. STRATIGRAPHY AND FACIES ANALYSIS OF THE STUDY AREA: UNIT V

6.1 Description

This study is based on the measurement of seven stratigraphic logs with a total thickness of about 5.500m collected in the Romagna Apennines, between the Santerno and the Bidente valleys (fig.32). More precisely, they have been measured in the Ridracoli structural element, included between M. Nero and M. Castellaccio thrusts and in the Santa Sofia structural element, between M. Castellaccio and Santa Sofia thrusts (fig.32). As stated above, based on a high-resolution physical stratigraphy and facies analysis, Unit V can be divided into two sub-units (i.e., Unit Va-Firenzuola I and Unit Vb-Firenzuola II) thanks to the occurrence - within the studied stratigraphic unit - of a small MTC that indicates an important tectonic phase (i.e., the Bedetta MTC, fig.14, 27). Consequently, Firenzuola I (Unit Va) is included between the Casaglia and Bedetta MTCs, whereas Firenzuola II (Unit Vb) is included between the Bedetta and Visignano MTCs (fig.14).

Unit V stratigraphy is described through four stratigraphic cross-sections, characterized by different orientations with respect to the paleocurrents and the main tectonic structures, in order to stress the stratigraphic and facies variations of this important stratigraphic unit during which the closure of the inner basin and the displacement of the deposition in the outer basin occurred (see Tinterri & Tagliaferri, 2015).

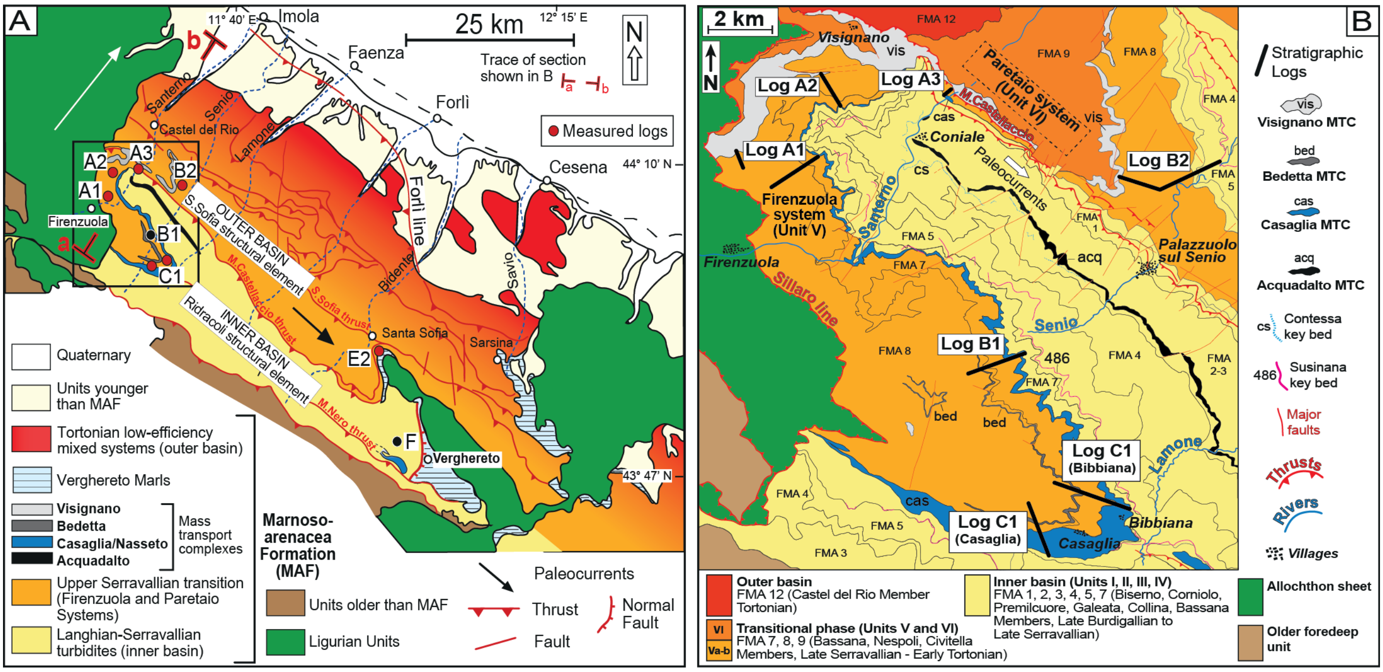


Fig.32 - A) Location of the seven stratigraphic logs. B) Square in A, showing the location of the logs in the proximal area of the Santerno, Senio and Lamone valleys.

Related facies scheme, as well as location and characteristic of the logs, will be described in the next paragraphs, in order to better understand the cross-sections obtained by their correlation.

6.1.2 Log A1

Located in the proximal area of the Santerno Valley, this stratigraphic log represents the deposits of the inner depocenter (fig.32, 33, 34). It is a composite log, whose different intervals were measured in several localities of the Firenzuola town area (see fig.33A); the stratigraphic continuity was achieved thanks to the presence of key beds or by correlating the

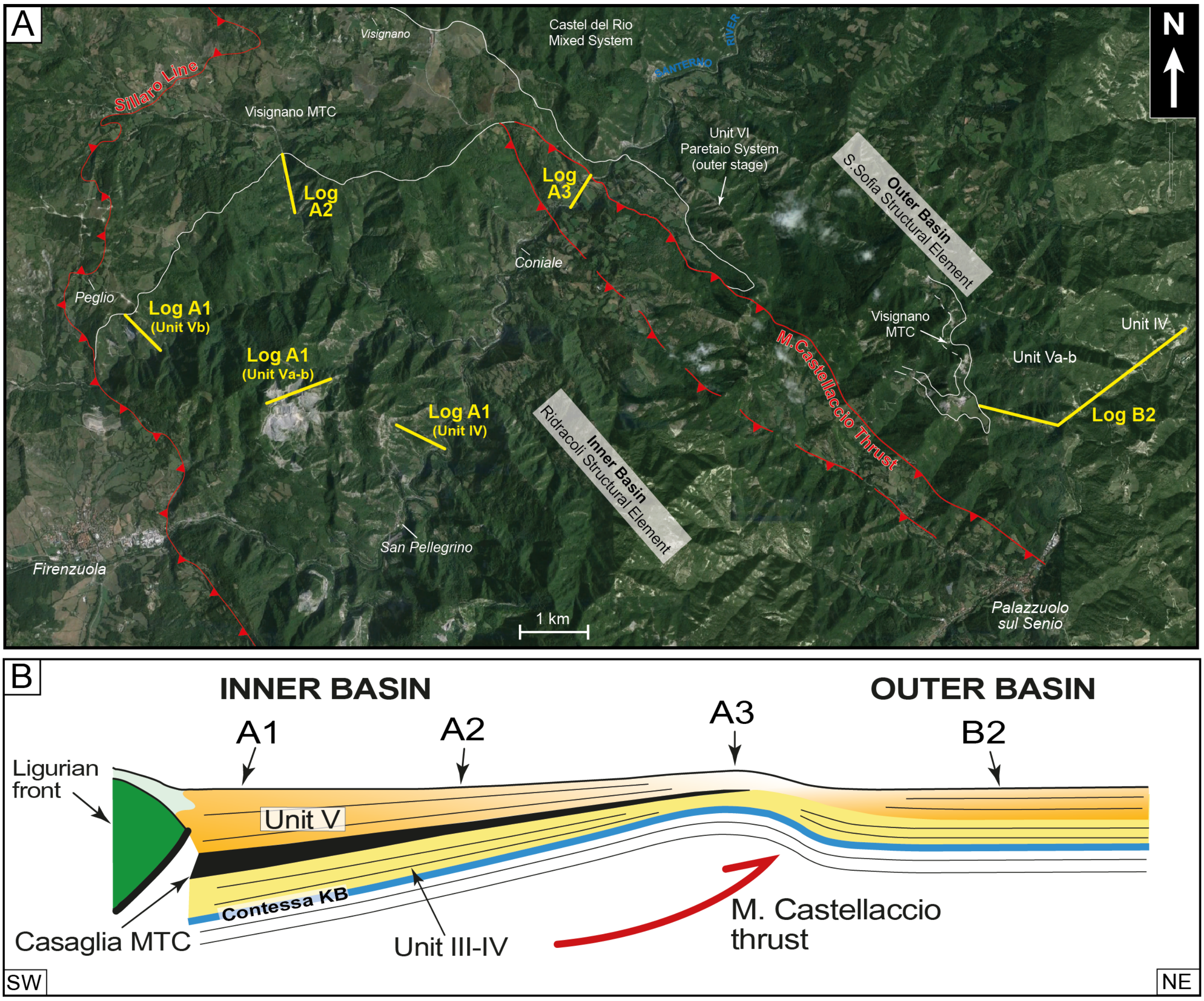


Fig.33 - A) Location of Logs A1, A2, A3 and B2 (from Google Earth). Red lines: trace of the main tectonic structures; white lines: main stratigraphic contacts; yellow lines: location of the logs. B) Location of Logs A1, A2, A3, B2 across a simplified geological section of the CTRF (modifief from Roveri *et al.,* 2002), reproducing syn-depositional conditions. See text for detailed description.

overlapping parts of the several single logs. From a stratigraphic point of view, Log A1 encompasses part of Unit IV and the entire Unit V. The basal interval (Unit IV) was measured near the village of San Pellegrino (fig.33A), starting from Colombina 30 (MT) up to key bed 486 (Susinana horizon), whereas the upper part of Unit IV, Unit Va and the basal part of Unit Vb were measured near the village of “le Piagnole” and the Brento Alto quarry (fig.33A, 34B). The Casaglia MTC was measured at the base of the latter, pinpointed also thanks to the aid of the geologic chart of the area (Italian Geologic chart 1:50,000, sheet n.253 - Marradi). Finally, the upper part of Unit Vb was measured from the Diaterna River to the top of the Roncacci di Carpine quarry, located near the village of Peglio (fig.33A), where the stratigraphic contact between the top of sub-Unit Vb and the Visignano MTC crops out (fig.33A, 34A). The high tectonic deformation of the area, due both to thrusting and Sillaro tectonic line, does not allow the thickness of the Visignano MTC to be measured, but according to the geologic chart (Italian Geologic chart 1:50,000, sheet n.253-Marradi) it is estimated to be in some hundreds of meters. In addition to the purposes of this study, Log A1 has been also useful to create a

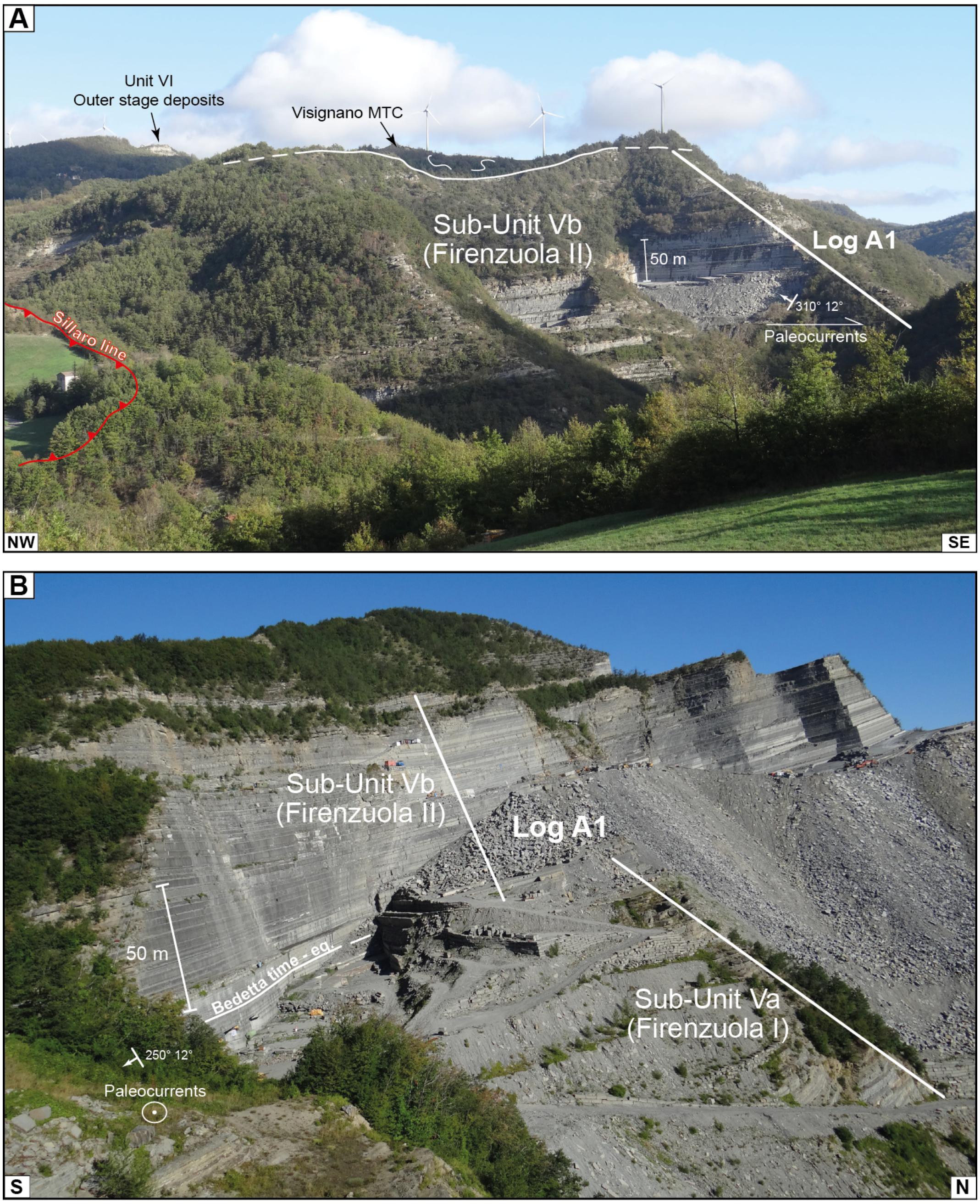


Fig.34 - Log A1 panoramic views (see fig.32, 33 for the location). A) Upper part measured in the Roncacci di Carpine quarry, near the village of Peglio. B) intermediate part measured in the Brento Alto quarry, near the town of Firenzuola.

stratigraphic link between Log A measured by Muzzi Magalhaes & Tinterri (2010) and the outer basin deposits of the Paretaio System measured by Tinterri & Tagliaferri (2015). In that way, the resulting 3,000m-thick log, that spans from the basal part of Unit II to Unit VI, has allowed detailed understanding of the stratigraphic evolution of the inner Langhian to the inner and outer upper Serravallian transitional deposits in this proximal location of the MAF basin.

6.1.3 Log A2

This log was measured along one of the branches of the Diaterna River, near the Calcinaia village (fig.33A, 35); it is 437m-thick and covers the entire unit V, from Casaglia to Visignano MTCs. In a SW-NE oriented transect (i.e. orthogonal to the paleocurrents and CTRF) Log A2 represents an intermediate position between Log A1 and Log A3, which is between the inner depocenter and the area of the structural high culmination created by the CTRF (fig.33B). The beds in Log A2 are characterized by a 300° in strike and by a

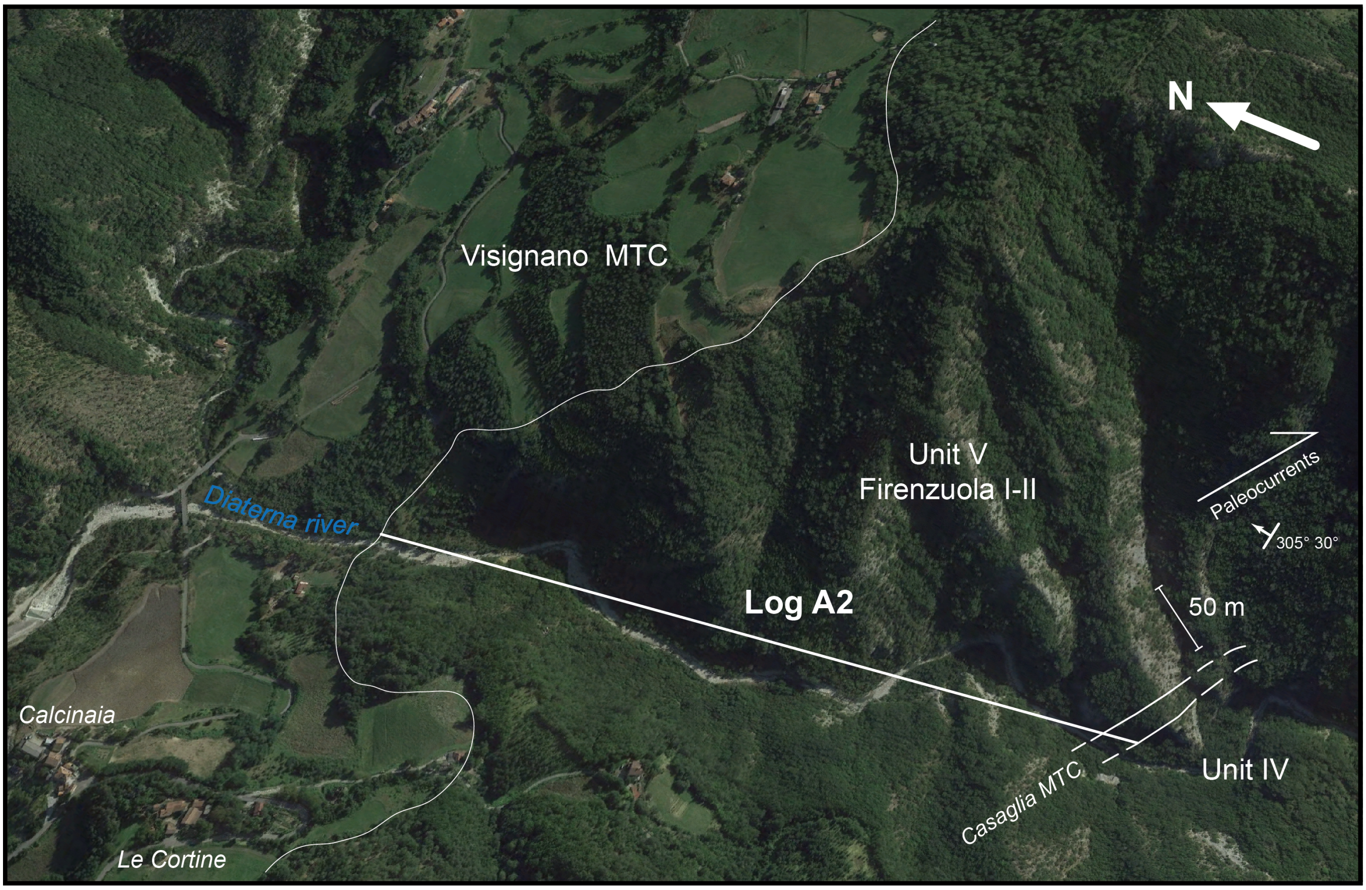


Fig.35 - Panoramic view of Log A2 (from Google Earth). See fig.32, 33 for the location.

35° in angle of dip, because the stratigraphic succession is involved in the fault propagation fold structure of the Monte Castellaccio thrust and this value increases from SW to NE in the hanging wall. The Casaglia MTC is 16m-thick, whereas the Bedetta MTC was not detected. The thicknesses of both the entire Unit V and of the singular beds are significantly lower compared with Log A1 (see paragraph 6.3).

6.1.4 Log A3

Log A3 is located along the Santerno River, near the village of Coniale (fig.33A). It was measured along the vertical limb of the CTRF hanging wall, whose location is very important since it represents the stratigraphic succession in the culmination area of this syn-sedimentary structure (fig.33B). It extends from the Casaglia to the Visignano MTCs, thus encompassing the entire Unit V, whose thickness (248m) is extremely lower than in Log A1 and Log A2, as are the overall grain size and thickness of the singular beds (see paragraph 6.3). In the upper part, just below the Visignano MTC, the succession shows a sharp transition to the Castelvecchio Marls, i.e. the marly unit coeval with the Verghereto Marls (see Tinterri & Tagliaferri, 2015, and below for detailed description and interpretation). Despite the location in a maximum deformation zone related to the CTRF, the small-scale tectonic structures limited to parasitic folds and faults with metric displacement have allowed Unit V to be completely measured, by following the stratigraphic succession along both banks of the Santerno River.

6.1.5 Log B2

Measured along the Senio Valley, Log B2 represents the deposits of the outer basin (Santa Sofia Structural element) in the proximal area (fig.33A, B). It provides important understandings about the relationship between the inner and outer basins at the time of the

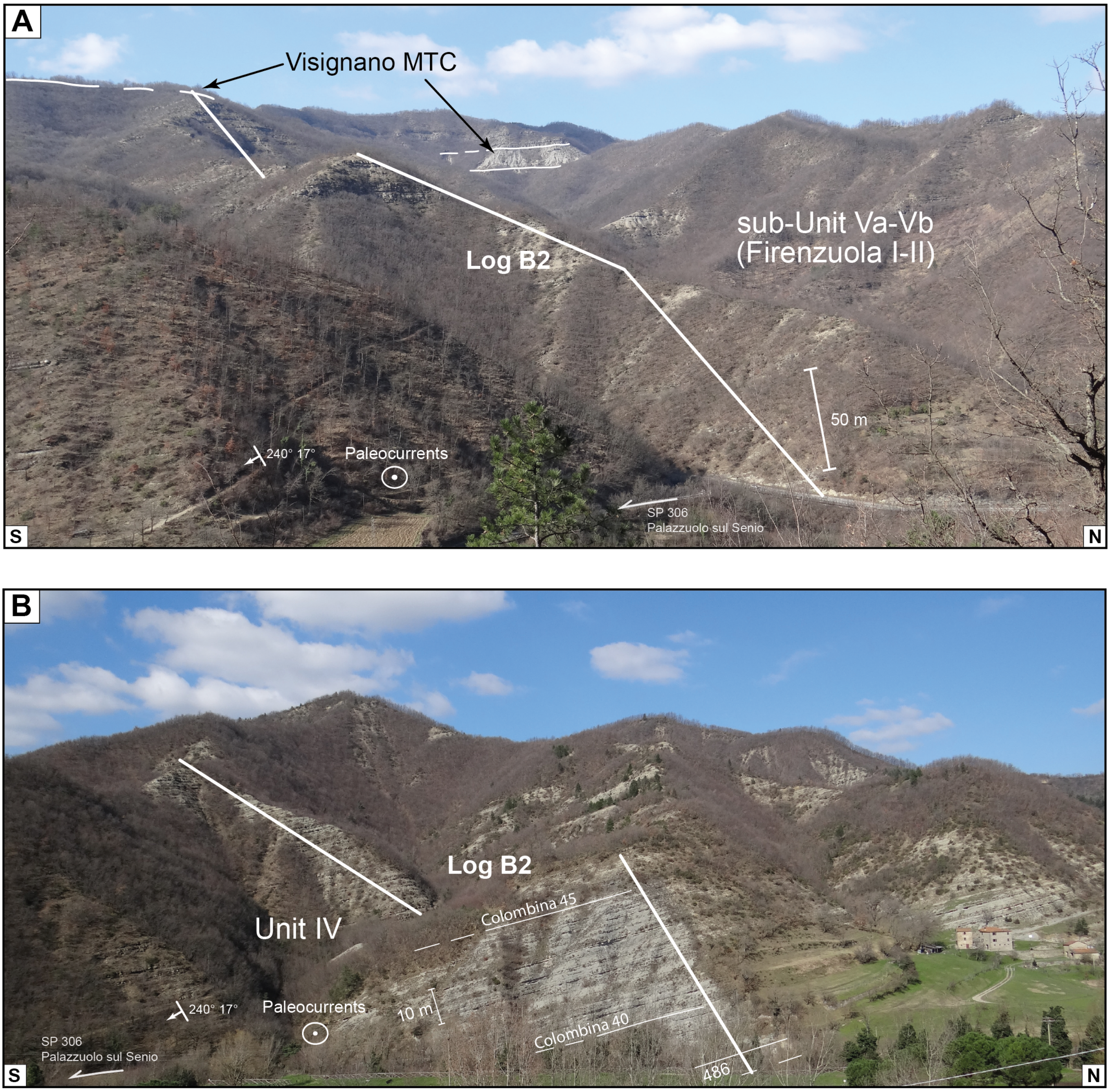


Fig.36 - Panoramic view of Log B2. A) Lower part measured near the Village of Badia di Susinana. B) Upper part measured near the town of Palazzuolo Sul Senio. See fig.32 and 33 for the location and the text for detailed description.

transition between these two depocenters, occurring at the time of the Unit V. It encompasses the upper part of Unit IV and the entire Unit V, from 486 key bed (Susinana Horizon) cropping out along the SP306 road near the village of Badia Susinana (fig.36B), to the Visignano MTC (fig.36A). The latter shows a very good exposure in the uppermost part of the outcrop, allowing its thickness to be measured and some details of its top to be collected (fig.28). The underlying MTCs (Casaglia and Bedetta) do not crop out in this area, probably due to their closure against the CTRF, which represented an obstacle at the time of their emplacement.

Log B2 is some 1,400m-thick, 150m of which belonging to unit IV and 1250m belonging to Unit V. The limit between the Units was found both thanks to both the correlation and the presence of the Ciriegiolo key bed (fig.31).

6.1.6 Log C1 (Casaglia and Bibbiana)

Details of the source area of the Casaglia and Bedetta MTCs at the time of Unit IV and V were added thanks to the measurements of these two logs. They are 2 km apart and are located in the Lamone Valley, near the villages of Crespino del Lamone and Casaglia (fig.32A, B, 37). The former log encompasses Unit V (sub-Unit Va and part of sub-Unit Vb), is 835m thick and shows the maximum thicknesses in both the Casaglia and Bedetta MTCs, which are of 480m and 55m, respectively.

Log C1 Bibbiana is 760m thick and both MTCs (Casaglia and Bedetta) show a significant decrease in thickness vs. Log C1 Casaglia (112m and 35m, respectively). It was measured from 486 key bed in order to add details of the upper part of Unit IV. Further details of the erosive

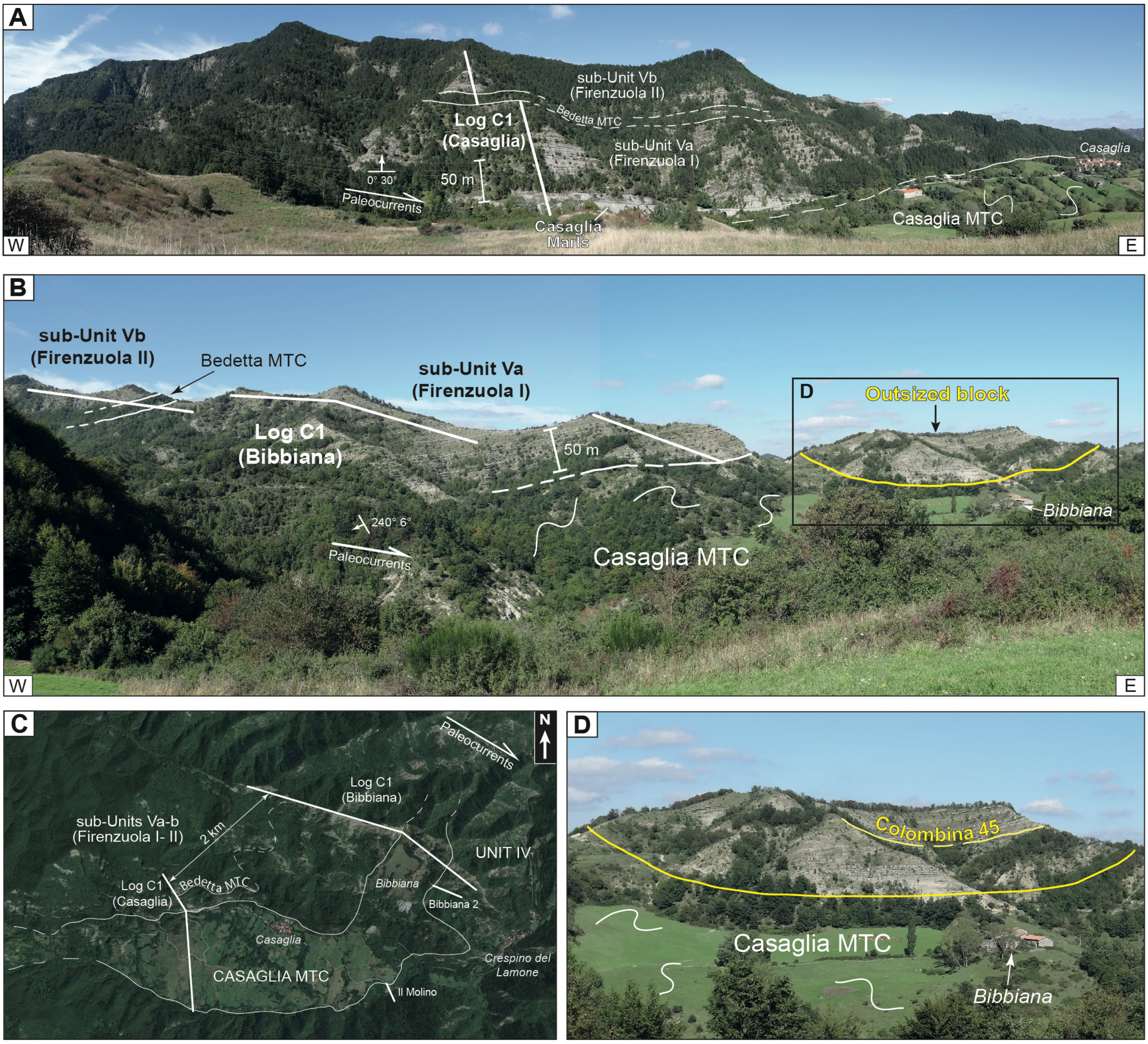


Fig.37 - A, B) Panoramic view of Log C1 Casaglia and Log C1 Bibbiana. C) Satellite view of the study area where the location of Log C1 Casaglia, Log C1 Bibbiana, Casaglia and Bedetta MTCs can be observed (from Google Earth). D) Panoramic view of the outsized block involved in the Casaglia MTC near the village of Bibbiana (see also Lucente & Pini, 2003), to be noted the Colombina 45 key bed that allows this outsized block to be interpreted as eroded from the upper part of the underlying Unit IV.

contact between the base of the Casaglia MTC and the underlying unit IV were collected by measuring and correlating several detailed logs of this stratigraphic boundary (fig.37C, see paragraph 6.5 for detailed explanations).

6.1.7 Log E2

Located in the Bidente Valley, this log provides important constraints about the upper part of the Unit IV and V in the distal part of the outer basin (i.e. Verghereto high area). It was measured in front of the village of Poggio Lastra (fig.32A, 38), from key bed 486 up to the Verghereto marls for a total thickness of 380m. The limit between the two units was found thanks to the presence of the Ciriegiolo key bed.

6.2 Facies analysis

Unit V deposits represent the beginning of the transitional phase involving the upper Serravallian MAF foredeep, due to the syn-sedimentary growth of the Coniale and Verghereto structures (see Tinterri & Tagliaferri, 2015, and below for detailed explanations). The progressive increase in tectonically-induced confinement deeply affects depositional processes by causing an important decrease in the efficiency degree of turbidite currents (fig.21). As a consequence, facies tracts are characterized by sharp across and downcurrent facies changes and turbidite beds show completely different facies expression compared with the higher efficient underlying Langhian to

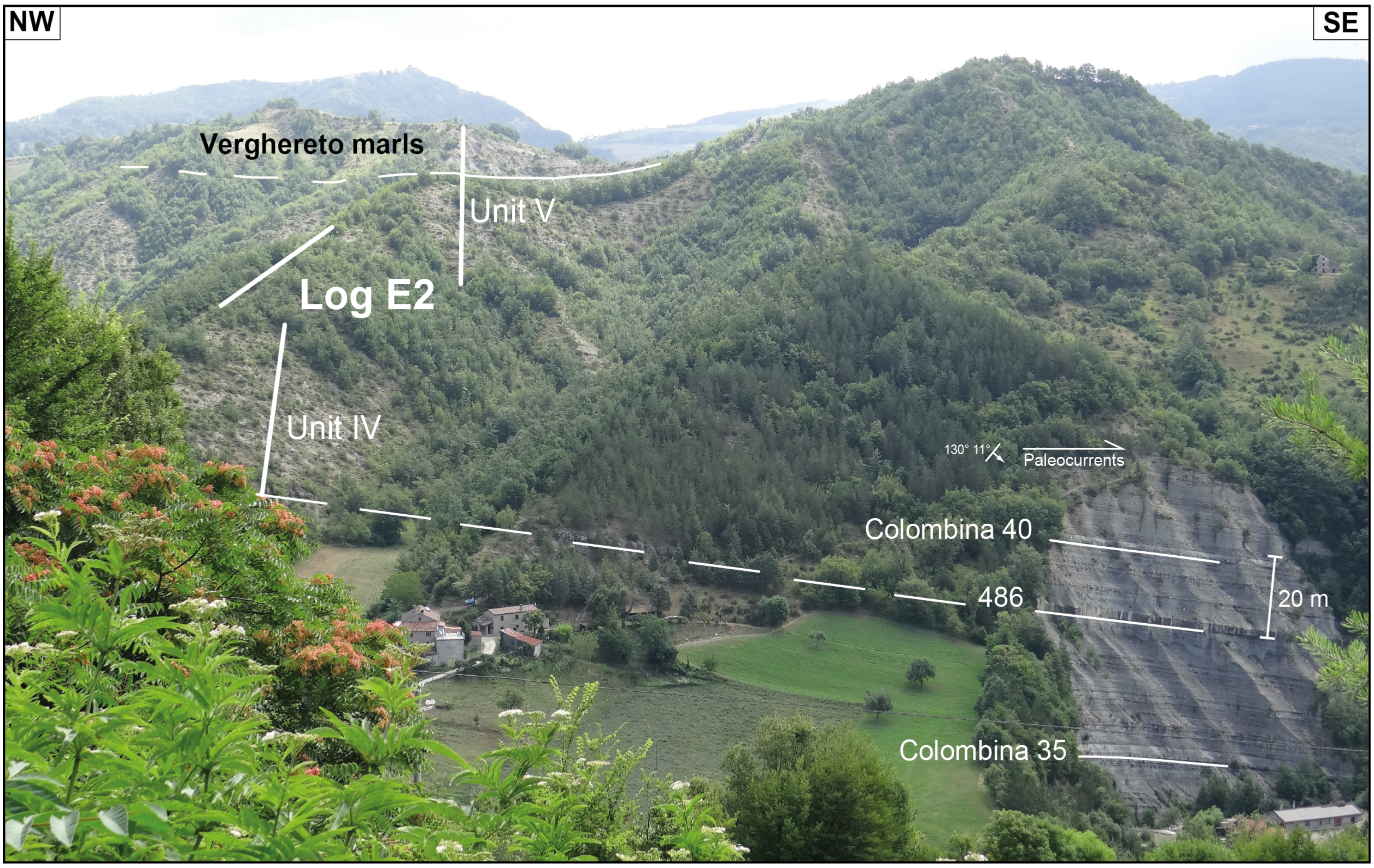


Fig.38 - Panoramic view of Log E2 (see fig.32 for the location).

The upper part of the log shows a clear and relatively sharp transition to the marly unit of the Verghereto Formation (see paragraph 6.6; see also Amorosi, 1996; Lucente, 2004).

Serravallian turbidite systems. They can be classified following the scheme by Tinterri & Tagliaferri (2015) (see also Tagliaferri & Tinterri, in press), which is an evolution of a previous one by Tinterri & Muzzi Magalhaes (2011), created specifically for turbidite beds of

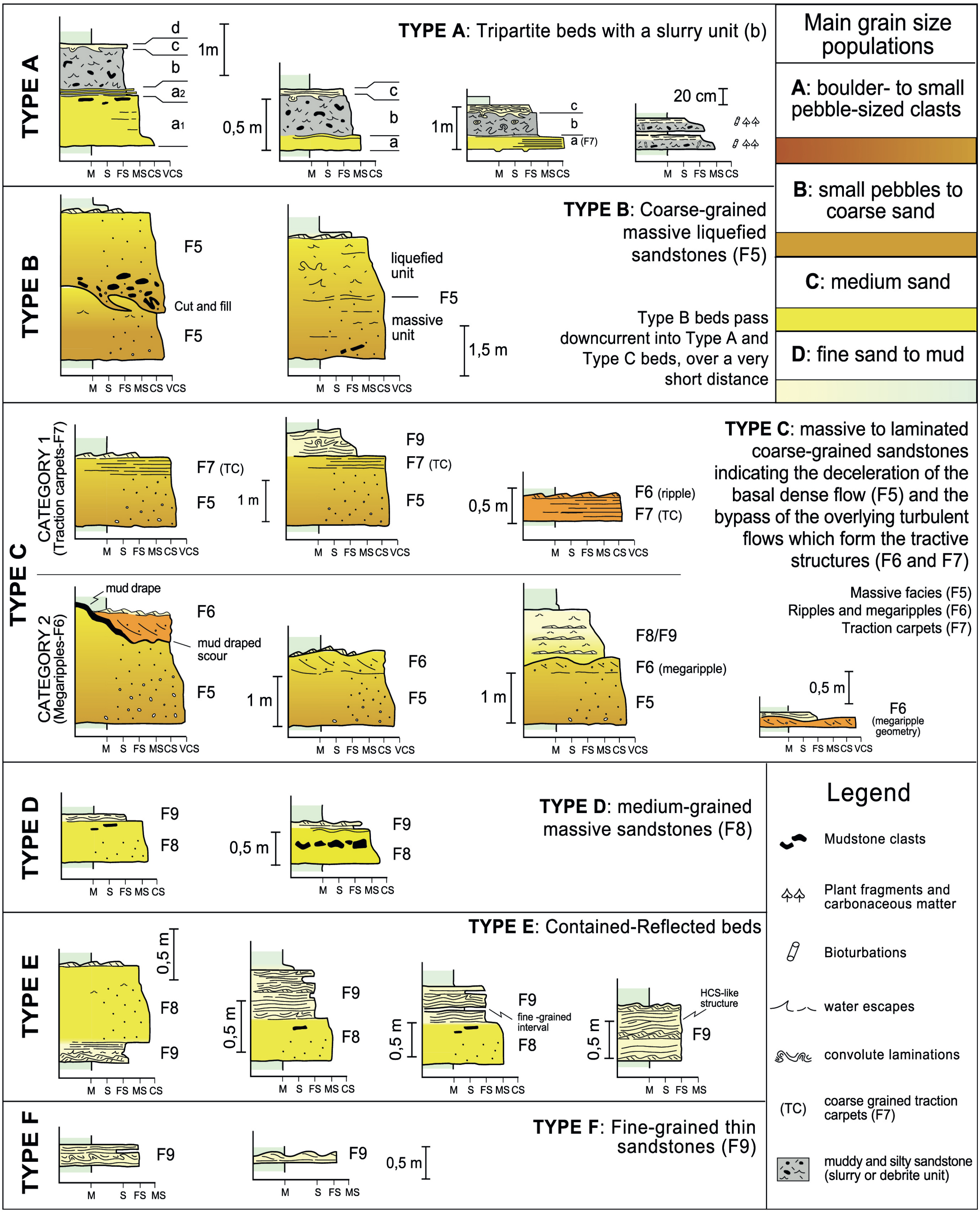


Fig.39 - Bed types characterizing the transitional phase of the MAF deposits, (i.e Unit V and Unit VI, Firenzuola and Paretaio System) (from Tinterri *et al.*, 2012; Tinterri & Tagliaferri, 2015)

the transitional phase (fig.39). In this scheme turbidite beds are classified into the following six types.

6.2.1 Type A beds

DESCRIPTION

Type A beds (Tinterri & Tagliaferri, 2015; Type 1 bed in Muzzi Magalhaes & Tinterri, 2010) are thick to very thick beds, usually characterized by a tripartition, shown especially in proximal areas (fig.39, 40). The three units of the tripartition can be summarized as follow:

a) A basal coarse to very coarse well sorted grained sandstone unit, usually massive, sometimes showing a crude lamination and rip-up of mudstone clast; the latter are often located at the limit with the intermediate part "b". Sole casts can be found especially in proximal part, mostly as groove casts
b) An intermediate poorly-sorted, muddy sandstone unit, often showing liquefied structures, pseudonodules and ball and pillow and involving mudstone clasts spread throughout the unit. The latter can be from millimetre to metre-sized as well as they can be absent
c) An uppermost layer, characterized by a thin to medium-thick, fine-grained laminated sandstone to siltstone unit. The laminasets show plane, ripple and convolute laminae, sometimes with combined-flows characteristics, as biconvex ripples or

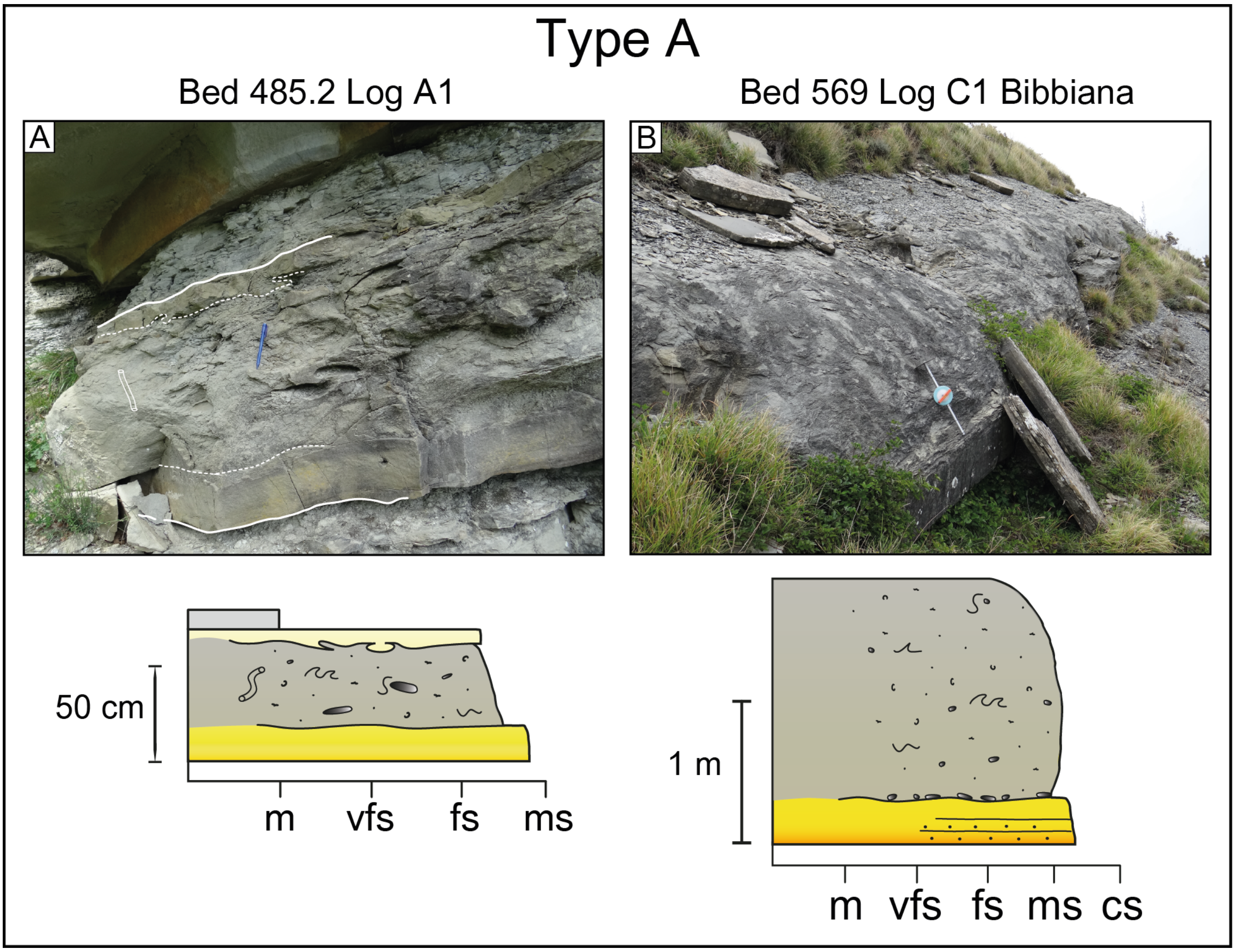


Fig.40 - Examples of Type A beds.

hummocky-type structures. The limit between the underlying unit b can be flat or deformed by load structures that can evolve into pseudonodules.

Two main facies tracts have been found within Unit V (see also Muzzi Magalhaes & Tinterri, 2010; Tinterri & Tagliaferri, 2015):

1) Some of them show a more or less wide lateral and down-current extension and evolve into thinner, fine to very fine – grained sandstone bed (facies F9) toward more distal area or zone of topographic high

2) Some of them occur near topographic relief areas, as down-current evolution or lateral facies change from thick to very thick, massive, medium-grained sandstone beds (facies F8).

The distribution of Type A vertical facies shows a significant differentiation trend from the inner to the outer basin (Logs A1 and B2, respectively); in the former, they tend to disappear, mostly in the upper sub-Unit Vb, whereas they tend to increase in the latter.

INTERPRETATION

As shown by several recent works (Muzzi Magalhaes & Tinterri, 2010; Tinterri & Tagliaferri, 2015), Type A beds occur and tend to increase in areas of high topographic confinement of highly efficient turbidite systems. In terms of depositional processes, they are related to high-density turbidite currents able to erode a large amount of mud from the substrate, causing abrupt deceleration and deposition of the slurry unit. Thus, their occurrence provides important understanding of the basin setting and its direct influence on depositional processes. Their vertical decrease within sub-Unit Vb in the inner basin and the concomitant increase in the outer basin can be attributed to their different degree of confinement (see discussion in Tinterri *et al.*, 2012; Tinterri & Tagliaferri, 2015); it is higher in the former due to the significant growth phase of the Monte Castellaccio thrust, which isolated it almost completely from the new outer main depocentre; it is lower in the latter, where the high density turbidite flow had enough space and time to erode mud and generate slurry facies. The slurry facies, however, disappear even in the outer basin during the deposition of the uppermost Tortonian deposits, i.e. when also the outer basin undergoes drastic narrowing. All things being equal, this fact would confirm that the degree of basin confinement could control the formation of slurry beds (see discussion in Tinterri & Muzzi Magalhaes, 2011; Tinterri *et al.*, 2012; Tinterri & Tagliaferri, 2015). Type A distribution also increase in sub-Unit Va above the Casaglia MTC in Log C1 Casaglia; their occurrence, together with the underlying Casaglia Marls in this specific location, represents an onlap sequence, characterizing several other facies sequences above MTCs of the MAF deposits (Tinterri & Tagliaferri, 2015).

The transformation into thin, fine grained sandstone beds shown in the facies tracts by Type A beds over structural highs or down-current, can be caused by the bypass of a low-density upper turbulent flow able to reach more distal area or ascend topographic high after the "freezing" of the lower basal dense flows in more proximal or depocentral zones.

6.2.2 Type B beds

DESCRIPTION

Type B are thick to very thick beds, made of a basal massive to normally graded coarse to very coarse-grained poorly sorted sandstone, characterized, in their upper parts, by liquefied units with common water escape structures (F5; fig.39, 41). Impact structures with mudstone clasts and amalgamation surfaces are relatively common (fig.39, 41). They are usually devoid of an upper fine-grained F9 division (Bouma Tbe sequence). Their facies tracts often show abrupt facies changes or closures, due to the nature of their depositional processes and their occurrence in highly confined setting. In the MAF stratigraphic succession, they tend to appear especially in the upper Serravallian transitional phase, represented by Unit V and VI (Firenzuola and Pateraio systems).

INTERPRETATION

Type B beds can be interpreted as relatively low-

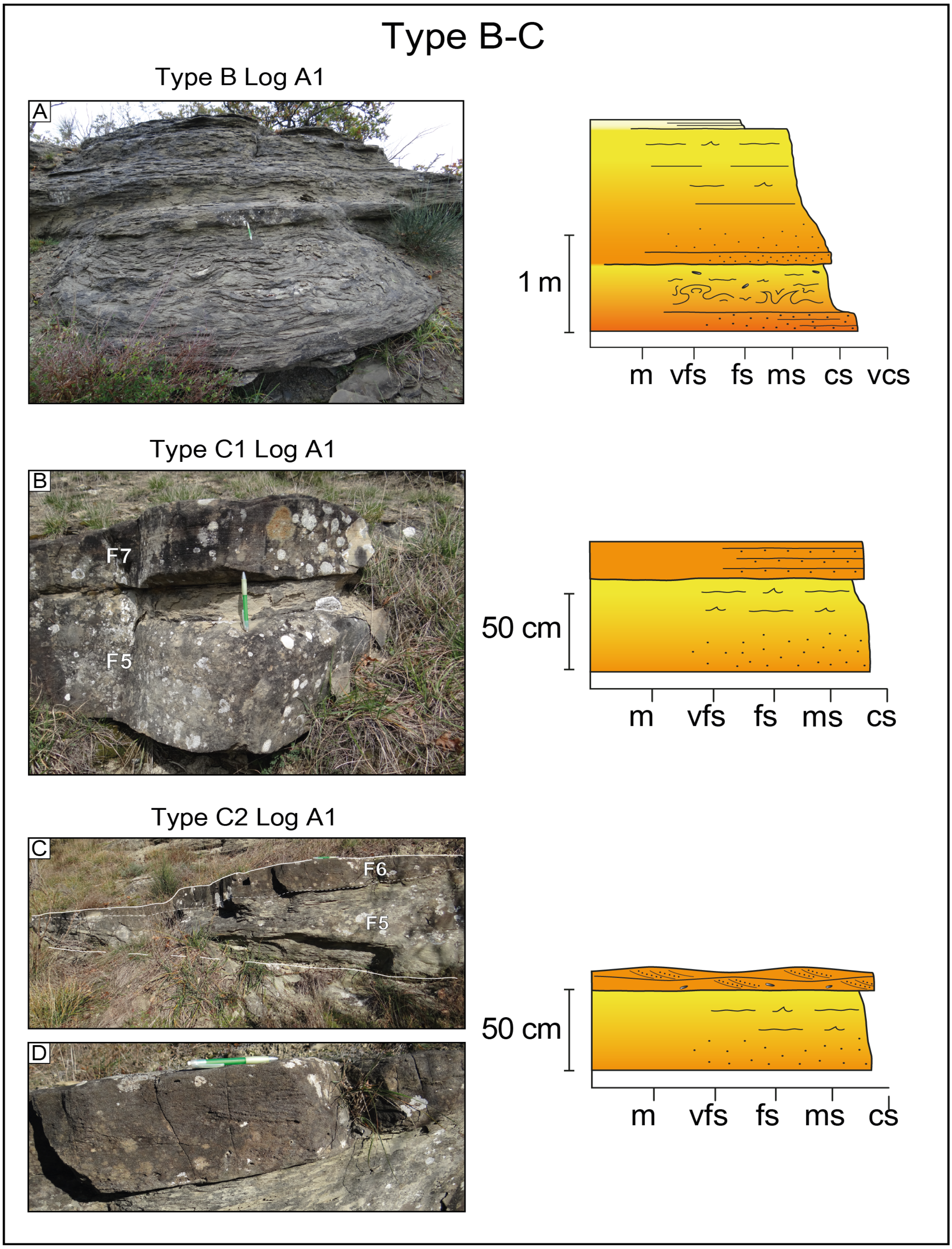


Fig.41 - Examples of Type B and C beds.

efficiency turbidites, whose capacity to evolve downcurrent and to segregate the different grain-size populations in different facies is reduced by the increase of structurally-related basin confinement (Tinterri & Tagliaferri, 2015). They can be interpreted as F5 facies (fig.22), deposited by bipartite turbidity currents and characterized by a basal dense flow, which undergoes sudden decelerations, and by an overlying low density turbulent flow, able to bypass and depose its sedimentary load more downcurrent in topographic high areas. Their appearance and increase in depocentral areas of Unit V, in particular sub-Unit Vb, is enhanced by the tectonically-induced basin narrowing, produced by the growth of the CTRF and Verghereto high. Amalgamation structures and rip-up of mudstone clasts further testify their erosive capability induced by deceleration.

6.2.3 Type C beds

DESCRIPTION

Type C beds are quite similar in terms of structures and depositional processes to Type B beds. They are thick to very thick beds, made of a basal massive to crude-laminated, coarse to very coarse-grained, poorly sorted sandstone unit (F5), overlaid by a coarse-grained, well sorted, sandstone unit, showing 1) traction carpet (F7) or 2) cross-lamination (mega ripples, F6; fig.39, 41B, C, D). The top of massive beds can be characterized by mud-draped scours. Coarse-grained thin beds characterized by lenticular geometry (F6) are also present. Type C beds pass upward into poorly developed Tbe Bouma divisions (F9; fig.39).

INTERPRETATION

As Type B, Type C beds are originated by sudden deceleration of bipartite flows. The deposition of basal dense flows produces massive units (F5), whereas the bypass of the overlying turbulent flows forms different tractive structures according to the deceleration rate (megaripples F6 and traction carpets F7). Sudden decelerations can also produce hydraulic jumps forming mud-draped scours. The decelerations are interpreted as being enhanced by the structurally-controlled morphology. The turbidite facies sequence of Type C bed (F5, overlaid by F6 or F7), is very similar to those of the Castel del Rio low-efficiency, mixed system, characterizing the outer basin Tortonian deposits of the MAF (Tinterri & Muzzi Magalhaes, 2011; Tinterri & Tagliaferri, 2015). Thus they represent a transitional passage between high efficiency Langhian to Serravallian systems to low-efficiency mixed Tortonian systems. In more detail, the two turbidite facies sequences of Type C beds, indicate a different degree of tectonically-induced confinement producing deceleration: higher in the case of F6, lower in the one of F7 on the top of F5 (Tinterri & Tagliaferri, 2015; see also Mutti *et al.*, 2003).

6.8.4 Type D beds

DESCRIPTION

Type D are medium to very thick, normally graded beds, consisting of basal well sorted, massive medium-grained sandstone (F8) often characterized by rip-up mudstone clasts that pass upward into very thin fine-grained sandstone (F9), consisting of even or slightly undulated laminae and ripples (Bouma Tbc; fig.39, 42). They drastically increase within sub-Unit Vb of the inner basin, where they form tens of metres-thick sandstone lobes (fig.34, 42), passing downcurrent and over the structural highs to Type E and Type F beds.

INTERPRETATION

The basal F8 facies is deposited by high-fallout rates able to suppress the turbulence at the boundary layer, whereas the overlying very thin F9 facies are deposited by traction-plus-fallout processes related to the tail of bypassing low-density turbulent flows able to transport a large part of fine-grained sand and mud (i.e., grain-size population D) further downcurrent or above the topographic highs. They represent a more evolved facies than bed Types A, B and C, but they, all the same, indicate deceleration, which can be enhanced by structurally-controlled morphologic confinement, as testified by their drastic increase in sub-Unit Vb of the proximal inner basin (Log A1). In the latter they form thick sandstone lobe accumulation, causing an important increase in the net to gross, which reaches the highest value (70%) in the Unit V (fig.34, 42). As shown by the facies tracts, their finer bypassed sedimentary load is carried downcurrent or over the structural highs by the low-density turbulent tails, where Type E and Type F beds take place (Log A3, Log C1, Log E2). As well as Type B and C beds, their increase in the outer depocentre is not so evident, testifying once more a lower degree of confinement of the latter.

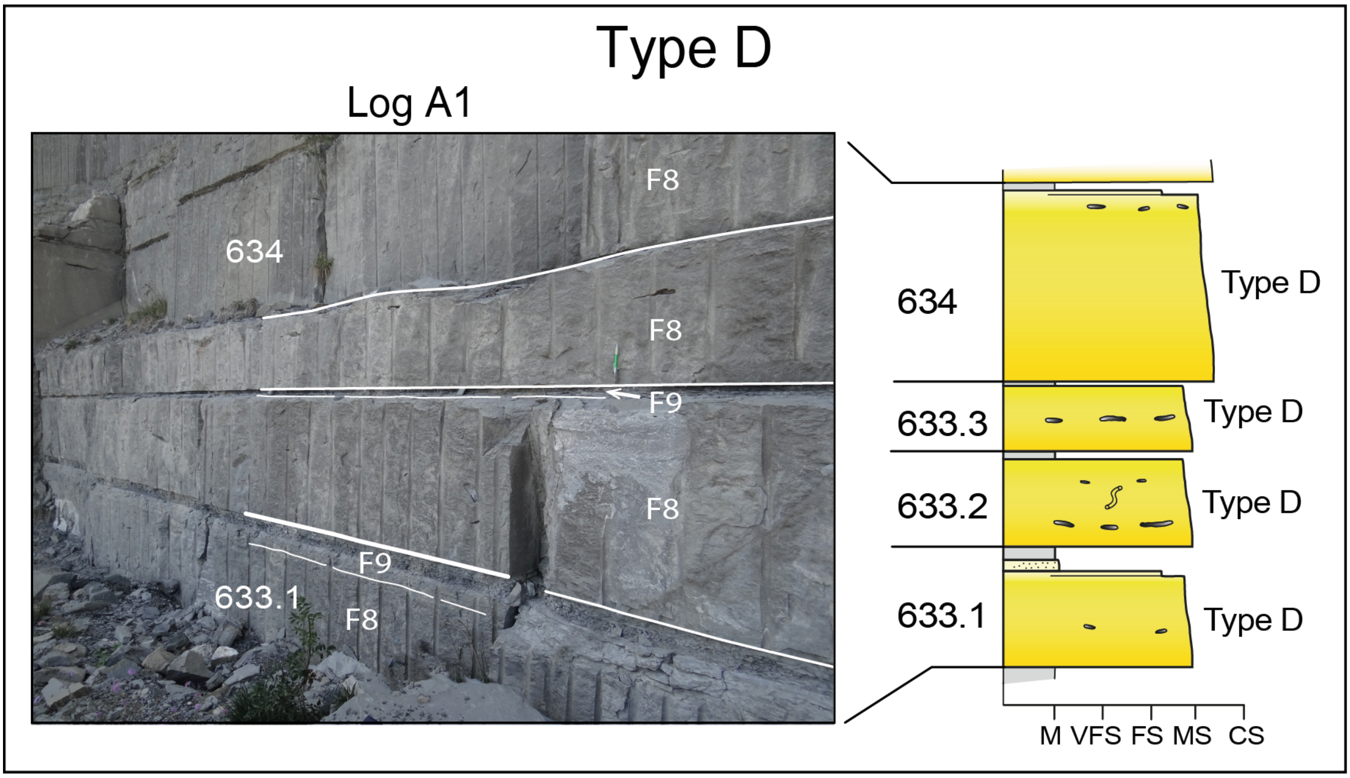


Fig.42 - Examples of a bedset made of Type D beds characterizing the basal part of sub-Unit Vb in Log A1. It is worth noting that fine grained sandstone facies (F9) are almost totally lacking, due to bypass processes (see text for detailed description).

6.2.5 Type E beds

DESCRIPTION

Thick to very thick and normally graded, Type E beds (Tinterri & Tagliaferri, 2015; Type 3 bed in Muzzi Magalhaes & Tinterri, 2010, fig.12B) are made of laminated fine-grained sandstones (F9) where basal massive medium-grained sandstones (F8) are also found (fig.39, 43). Facies F9 is often characterized by an alternation of undulated, convoluted laminae, combined flow structures and ripples that can have paleocurrents different from those indicated by sole casts (fig.43). The combined structures are represented by biconvex ripples and megaripples and small-scale hummocky-type bedforms (wavelength of about 30-50cm) characterized by various degree of anisotropy (Tinterri, 2011). Soft sediment deformations are very common (convolute laminae, load casts; Tinterri *et al.*, in press). Within Unit V they tend to increase approaching syn-sedimentary topographic highs and distal

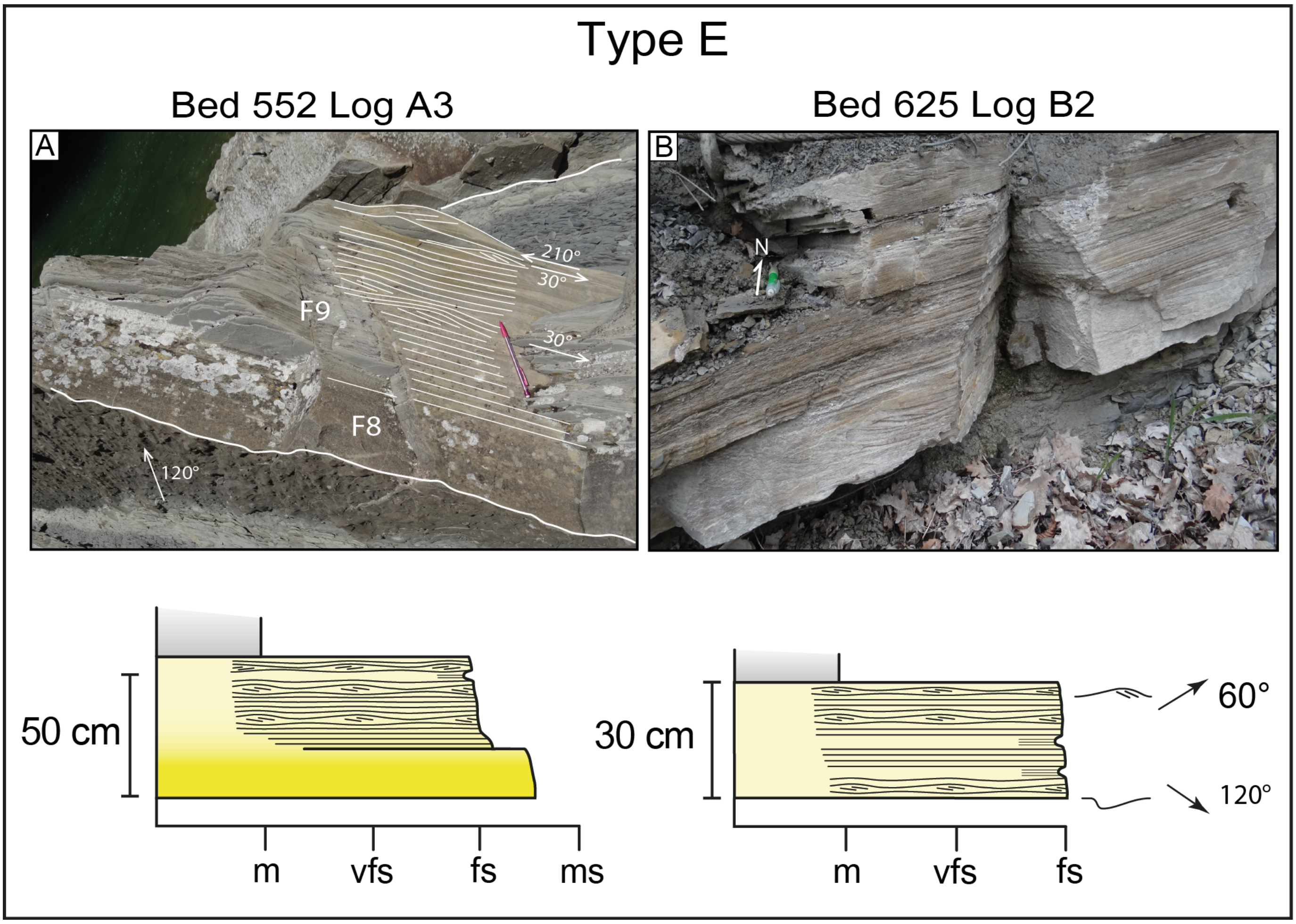


Fig.43 - Examples of Type E beds.

areas (Log A3, Log E2), often as lateral or downcurrent facies transition from Type D beds deposited in more proximal depocentral areas (Log A1, Log B2).

INTERPRETATION

These beds are interpreted as contained-reflected beds related to lateral and downcurrent reflections against the NW-SE oriented high produced by the CTRF and the SW-NE oriented Verghereto high, which can produce reflected bores and internal waves roughly perpendicular to this structural alignment (Tinterri & Tagliaferri, 2015; Tinterri *et al.*, in press). The alternations of different laminasets with combined flow structures can be interpreted as related to flow velocity variations, associated to reflection processes, as well as to flow type variations related to the interference between unidirectional flows and oscillatory components derived from reflection processes against structural highs (Tinterri, 2011). Their facies tracts show upcurrent and lateral transitions toward depocentral areas to Type D beds, proving them as deposited by low-density turbidite flows able to ascend topographic highs or reach distal area after decoupling from their related basal dense flows.

6.2.6 Type F beds

DESCRIPTION

They are thin to very thin, fine grained-sandstone beds, consisting of undulated and convolute laminae, as well as biconvex rounded ripples (fig.29E, 44; Tinterri & Tagliaferri, 2015; Type 5 bed in the paper by Muzzi Magalhaes &

Tinterri, 2010). There are two types of these beds: 1) the first-type ones characterize the morphologic highs produced by the CTRF and Tagliaferri, 2015) and the Castel del Rio mixed system.

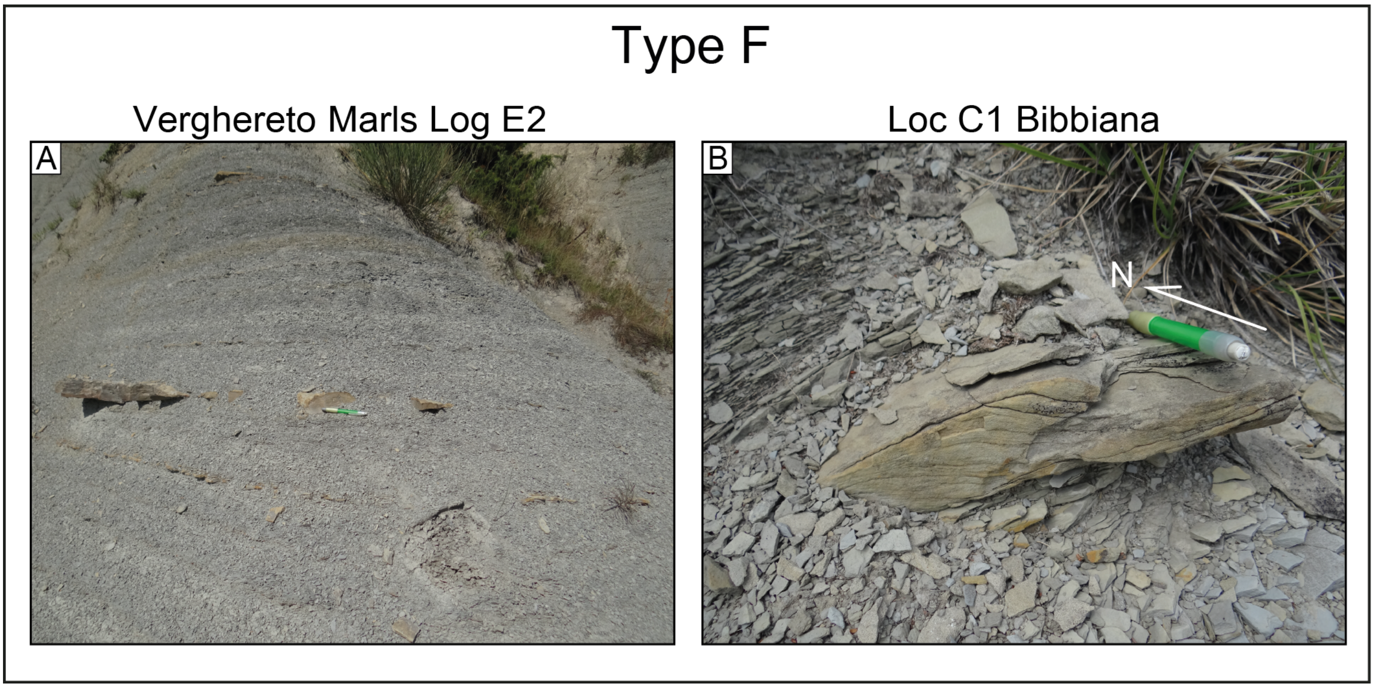


Fig.44 - A) Pinch out closure of a Type F bed within the Verghereto Marls in Log E2. B) Biconvex ripples with sigmoidal-cross laminae shown by a Type F bed at the base of Sub-Unit Vb in Log C1 Bibbiana.

Verghereto high (fig.29E, 44), 2) the second type ones are found especially in the decametric-thick mudstone dominated intervals characterizing the stratigraphic succession of Unit V in the outer basin depocenter (Log B2).

INTERPRETATION

The first bed type is interpreted as deposited by diluted turbulent flows that are able to ascend the morphologic high that sometimes can collapse to form a Te sandy siltstone showing a facies with pseudonodules. In this case, homogenization processes due to bioturbation cannot be ruled out. In the second case, the alternation of these fine-grained intervals with decametric thick sandstone lobes produces a cyclic stacking-pattern that appears for the first time in the MAF succession, within sub-Unit Vb in the outer depocenter and becomes more evident within the upper Unit VI (Paretaio system, Tinterri &

6.3 Stratigraphic succession perpendicular to the paleocurrents and to the CTRF (Logs A1-A2-A3-B2)

DESCRIPTION

Located in the proximal area between the Santerno and the Senio Valleys, this cross section is SW-NE oriented and is perpendicular to the CTRF and the paleocurrents (fig.32, 33, 45, 46, 47). It has been used to evaluate the activity of the CTRF at the time of Unit V. In detail, Logs A1, A2, A3 are located in the inner basin (i.e., the Ridracoli structural element); Log A1 in the inner depocentral area, Log A3 close to the M. Castellaccio thrust, whereas Log B2 is located in the outer basin (i.e., the Santa Sofia structural element), (fig.33).

The stratigraphic cross-section of figure 45 has the following characteristics:

- drastic stratigraphic pinching of Unit V from Log A1 to Log A3, most evident in Firenzuola II and highlighted by a drastic decrease in the number of beds

- evident stratigraphic expansion of Firenzuola II in Log B2, highlighted by a drastic increase in the number of beds in comparison with Logs A1, A2, A3 in the inner basin (fig.45B)

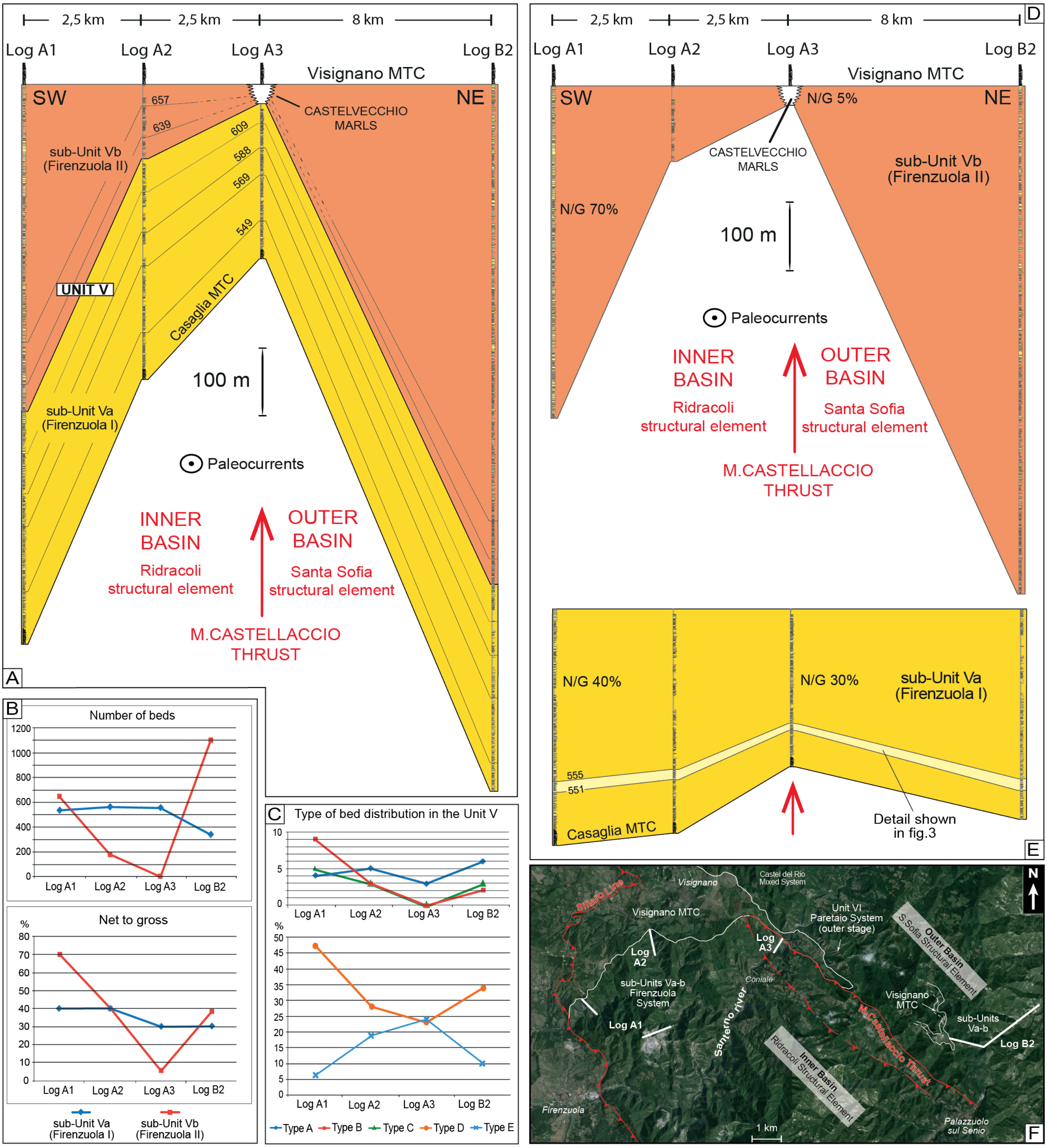


Fig.45 - A) Cross-section SW-NE oriented, perpendicular to the M. Castellaccio thrust and paleocurrents, located in the proximal area between the Santerno (Logs A1, A2, A3) and the Senio (Log B2) Valleys. B) Number of beds and sandstone/mudstone ratio variation in sub-Units Va and Vb. C) Type of bed lateral distribution in the entire Unit V. D-E) Progressive flattening at the top of sub-Units Vb and Va (Firenzuola II and Firenzuola I, respectively), F) Satellite view of the study area where the location of the logs can be observed (from Google Earth, see also fig.32, 33).

- vertical increase, in the depocentral area (Log A1), in the sandstone/mudstone ratio that passes from 40% in Firenzuola I to 70% in Firenzuola II (fig.45B, 47)
- vertical decrease in Log A3 (i.e., the zone near the CTRF) in the sandstone/mudstone ratio, which passes from 30% in Firenzuola I to 5% in Firenzuola II (i.e., marly Castelvecchio unit), (fig.45B, 47)
- lateral decrease in the sandstone/mudstone ratio, from Log A1 to Log A3, especially evident in Firenzuola II, which passes from 70% in Log A1 (fig.47 A, B, C) to 5% in Log A3 (fig.45D). This very low value characterizes the marly developed, laminated fine-grained sandstone facies (F9). The paleocurrent directions derived from traction plus fallout structures (F9) often show evident deflections in comparison with those of the sole casts that indicate paleocurrents parallel to the basin axis directed towards SE. It is also interesting to observe that these paleocurrent variations are perpendicular to the main structural alignments (fig.47, rose diagrams). These beds can be classified as Type D and E beds (see paragraph 6.2). Conversely, Firenzuola II is dominated by three kinds of beds: a) thick (30cm< H-thickness <1m) to very thick (H > 1m) beds with massive, well-sorted

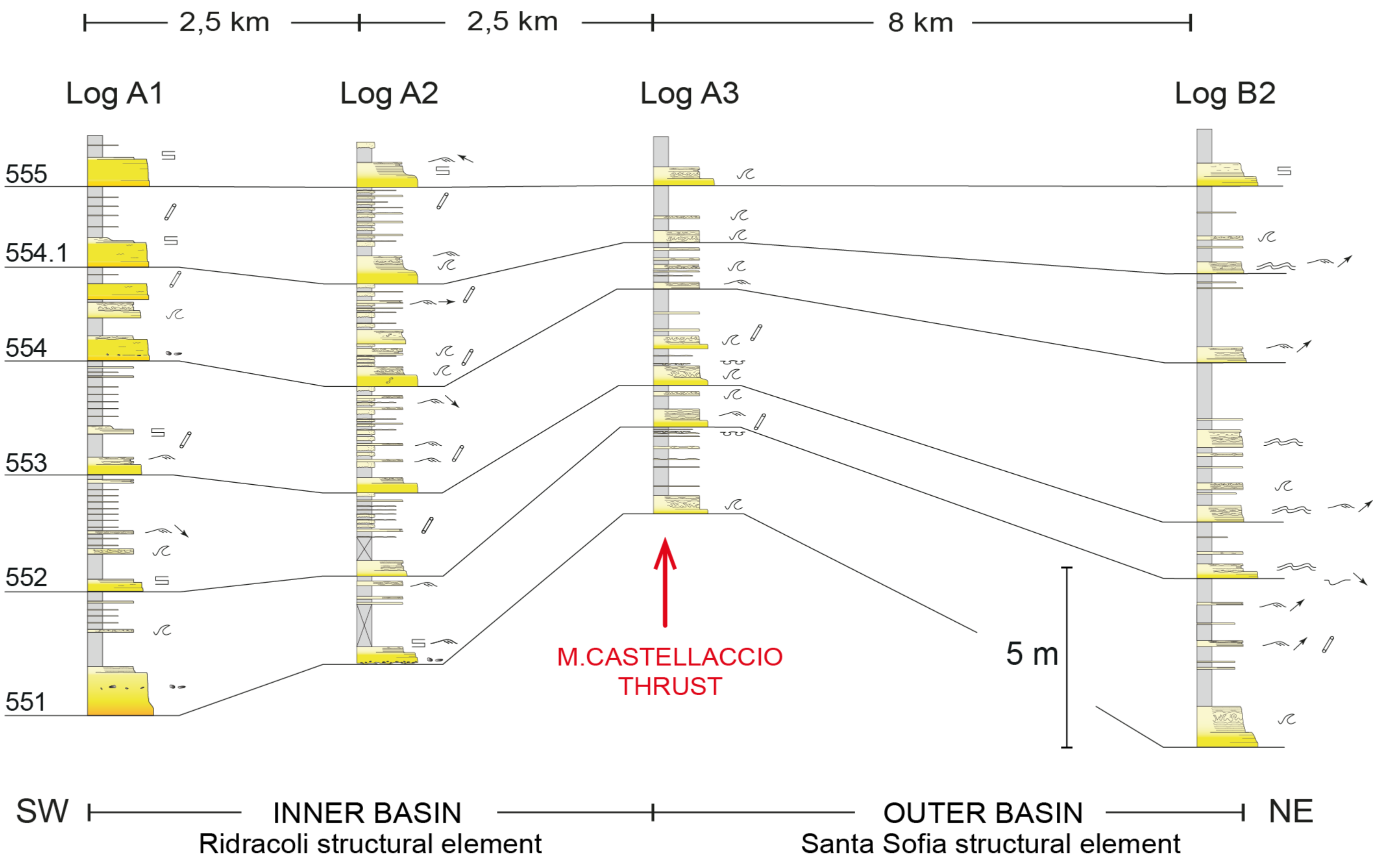


Fig. 46 - Example of a detailed stratigraphic cross-section in sub-Unit Va, where the lateral facies change across the CTRF can be observed.

deposits of the Castelvecchio Unit (fig.47D)
- vertical facies change in Log A1. In this log, Firenzuola I is dominated by medium (10cm < H-thickness < 30cm) to very thick (H > 1m) beds, having a basal massive medium-grained sandstone facies (F8) overlaid by a well-medium-grained sandstone facies (F8) passing upward into poorly-developed laminated, fine-grained sandstones (F9); sometimes these units are completely lacking (Type D beds, fig.39, 42, 46); b) thick to very thick beds made of coarse-grained, poorly-sorted sandstone facies, often

rich in mudstone clasts and liquefaction structures, showing amalgamation or mud-draped scour structures (F5, Type B beds; fig39, 41A, 47A, B, C); c) medium to thick, poorly sorted, coarse-grained sandstone facies (F5), overlaid by well-sorted, coarse-grained sandstone facies showing traction carpets (F7 facies) or cross-laminated structures (ripples, megaripples; facies F6), (Type C beds; fig.39, 41B, C, 47B). The paleocurrents, derived from F9 facies, show highly dispersed data with an evident component toward NW (rose diagram, fig.47).

Finally, it is also important to note the overall decrease in slurry Type A beds in unit V, especially in Firenzuola II (fig.45C)

- vertical facies change in Log A3. In this Log, Firenzuola I is dominated by very thin (H < 10cm) to thick beds, characterized by poorly-developed, basal massive, medium-grained sandstone (F8) overlaid by thicker laminated, fine-grained sandstone facies (F9), often showing the typical characteristics of Type E beds (see paragraph 6.2; fig.43A, 46, 47E). On the other hand, Firenzuola II shows a sharp transition into the Castelvecchio unit (fig.47D), dominated by marlstone and mudstone beds characterized by very thin (H < 3cm) laminated fine-grained sandstones (Type F beds)
- lateral facies change perpendicular to the paleocurrents and structural alignments (fig.46, 45C). From Log A1 to Log A3 a drastic decrease in Type D, B and C beds and a concomitant increase in Type E beds characterized by deflected paleocurrents can be observed (fig.45C). This lateral facies change is much more drastic in Firenzuola II, where the sandstone deposits of Type, B, C and D beds of Log A1 pass, in Log A3, into the marly deposits of the Castelvecchio Unit, mainly composed of Type F beds. Conversely, in Log B2, located in the outer basin, there is a lateral increase in Type B, C and D beds and a concomitant decrease in Type E beds (fig.45C). It is also important to stress that these lateral facies change are associated to a drastic decrease in the sandstone/mudstone ratio and the number of beds toward NE, i.e. toward Log A3 near the CTRF (fig.45B).

INTERPRETATION

All the above-listed evidences demonstrate the synsedimentary growth of the CTRF during the deposition of Unit V. Thanks to the perpendicular orientation to the CTRF, this cross-section provides a detailed evaluation of the growth timing and its direct influence on stratigraphy and facies distribution.

In particular, the moderate stratigraphic pinching toward NE (i.e. toward Log A3) of Firenzuola I associated with a moderate decrease in the sandstone/mudstone ratio testifies a subtle uplift of the CTRF (fig.45D, 46). The latter is also confirmed by the gradual lateral facies change, where Type D beds in Log A1 tend to pass - toward Log A3- into Type E contained-reflected beds characterized by F9 facies with ripples and vergent-convolute laminae indicating paleocurrents perpendicular to the CTRF and inner M. Nero thrust (fig.46). This evidence can be interpreted as related to an interaction of the diluted-turbulent flows with the subtle topographic high induced by the growth of the M. Castellaccio thrust that, through a lateral rebound, can produce internal waves and bores able to propagate perpendicularly to the main structural alignments (see Kneller, 1995; Tinterri, 2011; Tinterri *et al.*, in press). On the contrary, the drastic lateral changes in Firenzuola II in terms of stratigraphic pinching, sandstone/mudstone ratio and number of beds, all testify the strong tectonic uplift of the CTRF occurring during the deposition of this unit that heralds the definite closure of the inner basin occurring concomitantly with Unit VI above the Visignano MTC (see Tinterri & Tagliaferri, 2015). Consequently, it is evident that, during Unit V, the isolation of the inner basin begins

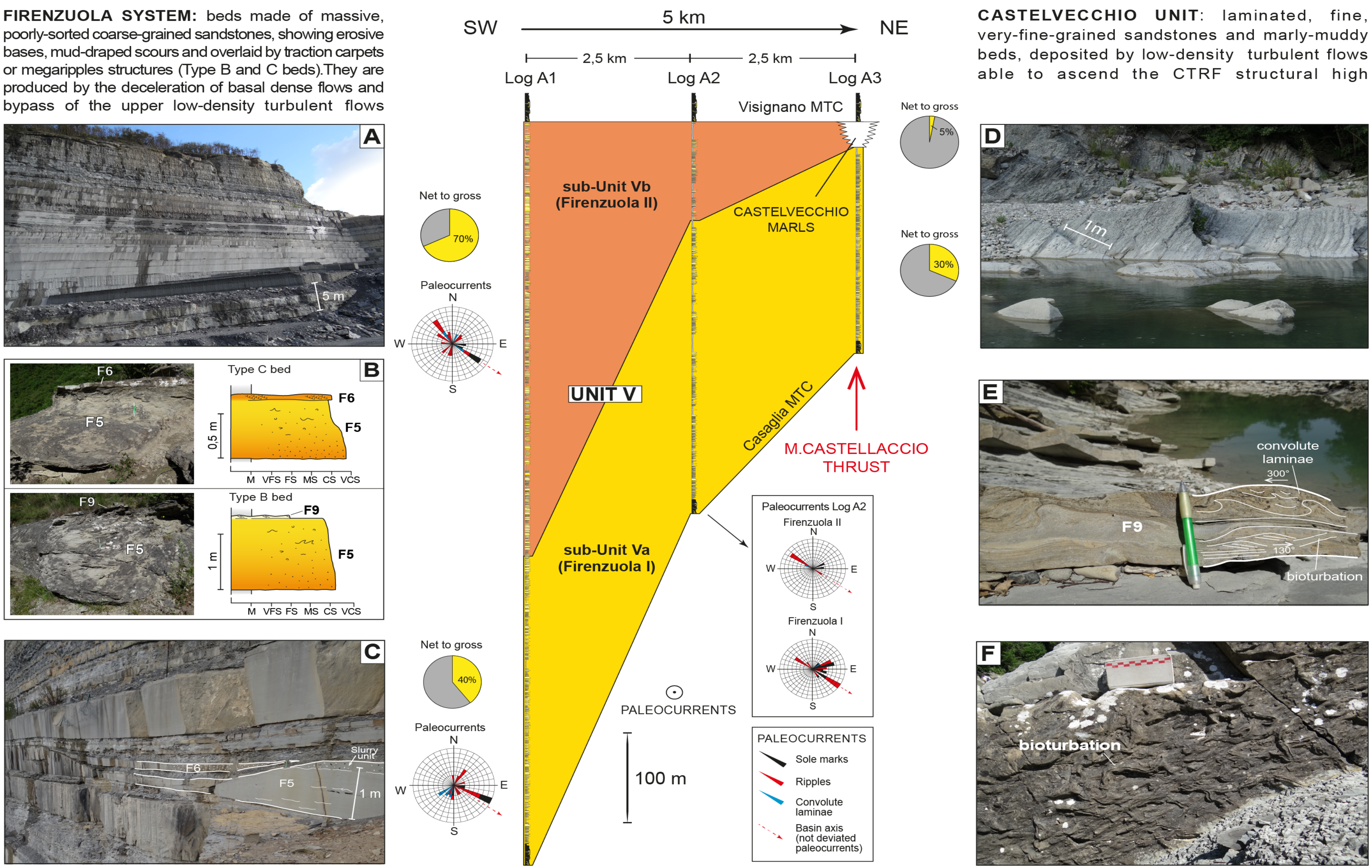


Fig.47 - Detailed stratigraphic cross section and lateral facies change in sub-Units Va and b, from the inner depocentral area represented by Log A1 to the structural high represented by Log A3. To be noted the data relative to the sandstone/mudstone ratio and paleocurrents variations. A) Massive sandstone lobes made of Type B, C and D beds characterizing Firenzuola II (sub-Unit Vb) in Log A1. B) Examples of Type B and C beds measured in the upper part of sub-Unit Vb in Log A1. C) Mud-draped scours related to hydraulic jumps (see Mutti & Normark, 1987, 1991). D) Castelvecchio Unit made of marly and muddy Type F beds, occurring in the upper part of Log A3 (Firenzuola II, sub-Unit Vb). E) Type F bed detected in the sub-Unit Va (Firenzuola I) deposits of Log A3, where deflected paleocurrents can be observed. F) Intense bioturbation shown by most of the beds of Firenzuola I in Log A3 deposited above the structural high.

and causes sandstone-rich lobes to accumulate in the depocentral area (in the Log A1), passing to a finer siltstone/mudstone drape over the structural high, represented by the Castelvecchio Marls at the top of Log A3. These characteristics substantiate the hypothesis that, during Firenzuola II, the inner basin tends to become a piggyback-type basin (see also Roveri *et al.*, 2002; Tinterri & Tagliaferri, 2015). The facies associations characterizing the inner depocenter (Log A1) and the structural high (Log A3) further testify the creation of a highly-confined basin. In particular, Type B (F5) and Type C beds (F5 overlaid by F7-F6) observed in Logs A1 and B2, are interpreted as being diagnostic of abrupt decelerations of bipartite flows producing a flow decoupling, with the deposition of the basal dense flows and with the bypass of the upper low-density turbulent flows. The bypass of these turbulent flows is able to produce the tractive structures (F6 and F7 facies) above F5 and the deposition, above the lateral structural high represented by the CTRF, of the fine grained deposits of the Castelvecchio Marls. The latter, together with the time-equivalent Verghereto marls, represent the closure facies of the inner basin (see Tinterri and Tagliaferri, 2015).

At the same time, the drastic stratigraphic expansion of Firenzuola II in Log B2 shows the concomitant formation of a depocentre in the outer basin testifying that, during the deposition of Unit Vb (Firenzuola II), the main depocenter begins to shift from inner to outer basin.

6.4 Stratigraphic succession parallel to the paleocurrents in the inner basin (Logs A1-B1-C1)

DESCRIPTION

The stratigraphic cross-section in figure 48 is located in the proximal area of the Ridracoli structural element and derives from the correlation of three logs: Log A1 in the Santerno valley, Log B1 in the Senio Valley and Log C1 in the Lamone valley (see fig.32). Since the upper part of Firenzuola II, in the area of Log B1 and C1, does not crop out, bed 670 has been selected as stratigraphic datum, because it is the last bed detected in Log C1 which can be safely correlated upcurrent (fig.48).

This cross section has been created to evaluate the downcurrent evolution of Unit V (Firenzuola System) in the depocentral area of the inner basin; i.e. in a direction parallel to the paleocurrents and to the M. Castellaccio thrust alignment. It also provides important aspects about the emplacement of the Casaglia MTC and its influence on the stratigraphy and facies distribution in Firenzuola I.

Correlation and facies analysis highlight the following main aspects (see fig.48):

- impressive thickening of the Casaglia MTC approaching the Lamone valley (Log C1), which can be seen as the source area of this MTC (see also Lucente & Pini, 2002)
- stratigraphic pinching of Firenzuola I above the Casaglia MTC in Log C1
- presence of a marly unit just above the Casaglia MTC in Log C1, (herein called Casaglia Marls)
- overall deflection of the paleocurrents associated with traction plus fallout structures (F9 facies)
- progressive decrease in the sandstone/mudstone ratio and thickness of the beds from Log A1 to Log C1, mainly evident in Firenzuola II
- downcurrent facies change from Log A1 to Log C1, mainly evident in Firenzuola II. In Log A1, Firenzuola II is dominated by Type B, Type C and Type D beds, essentially devoid of a F9 facies (see paragraph 6.2). Conversely, Log C1 is dominated by beds showing well-developed Bouma sequences (Bouma, 1962), with basal massive medium-grained sandstones, overlaid by well-developed laminated fine-grained sandstone (Type E beds). The latter is often characterized by laminasets composed of an alternation of undulated, convoluted laminae and ripples showing paleocurrents with a high degree

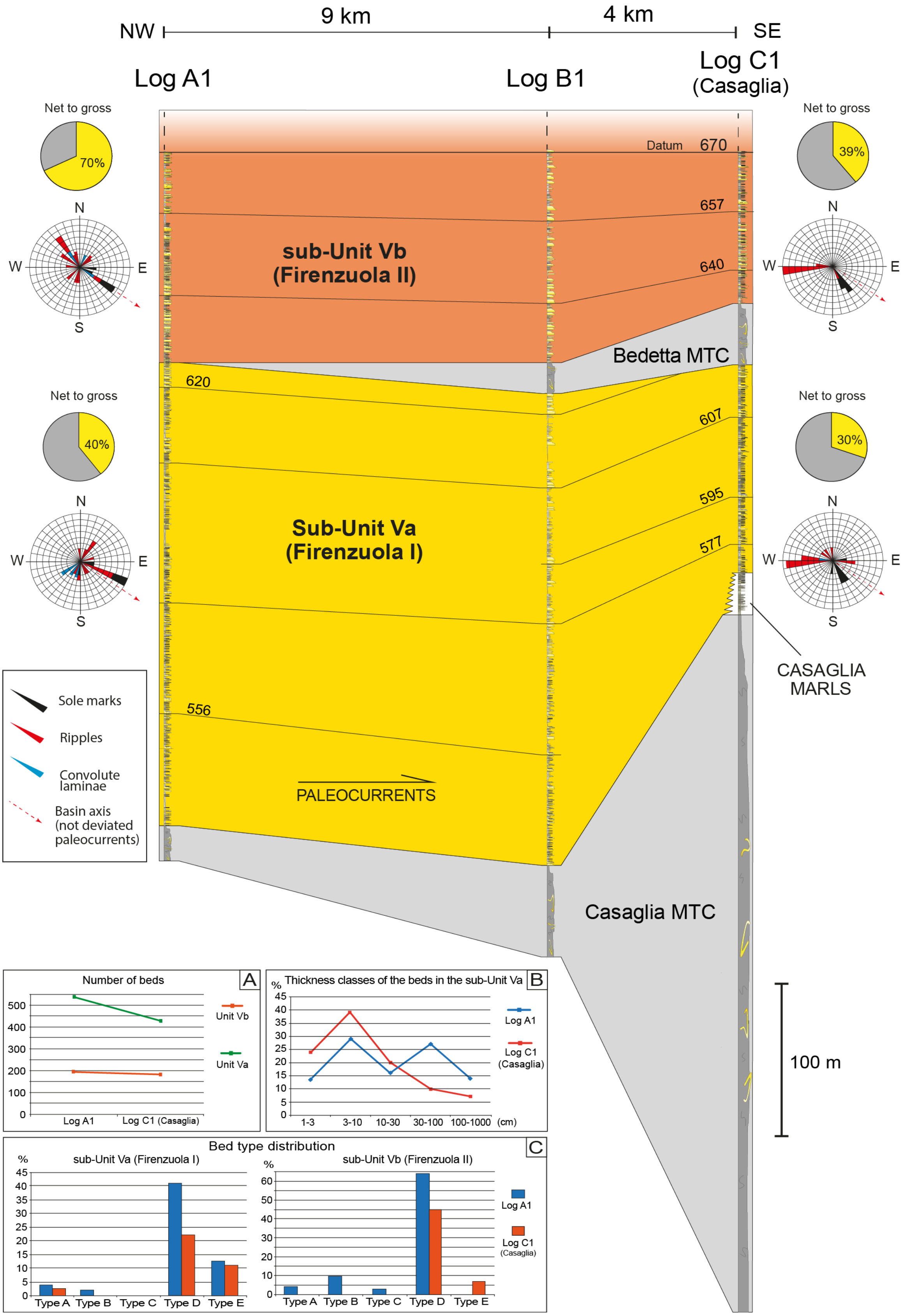


Fig.48 - Longitudinal stratigraphic cross-section parallel to the basin axis and paleocurrents, located in the proximal area from the Santerno Valley (Log A1) to the Lamone Valley (Log C1-Casaglia) (see fig.32 for the location of the logs). A) Number of beds in Logs A1 and C1 Casaglia, within sub-Units Va and Vb. B) Comparison between the different bed-thickness classes from Log A1 to Log C1 Casaglia, within the Firenzuola I deposits (sub-Unit Va). C) Bed type distribution in Logs A1 and C1-Casaglia, within Firenzuola I (on the left) and Firenzuola II (on the right). To be noted the data relative to the sandstone/mudstone ratio and paleocurrents variations.

of dispersion with an evident component toward NW in Log A1 and toward W in Log C1 (rose diagrams, fig. 48).

Firenzuola I characteristics are very similar to those of Firenzuola II, with a predominance of Types B and D in the proximal part (Log A1) and beds with well-developed Bouma sequences (F8 and F9) and Type E beds in the more distal area (Log C1). The main difference with the overlying Firenzuola II is the occurrence of a high percentage of Type E beds, also in the proximal area of Log A1, and Type A slurry beds in the basal part of Log C1 above the Casaglia MTC that, in this area, is characterized by the highest thickness (about 480m; see fig. 48C).

INTERPRETATION

The Location and orientation of the cross-section in figure 48 allows some important considerations about the downcurrent evolution of the flows in the proximal depocenter of the inner basin that, in this area, is strongly influenced by the impressive thickness of the Casaglia MTC (480m in Log C1). Indeed, the area around Log C1 represents the source area of the Casaglia MTC that, according to the data by Lucente (2004) (see also Lucente & Pini, 2002), originates from a phase of tectonic uplift of the inner M. Nero thrust. The emplacement of this important MTC, marking the base of Unit V and the beginning of the closure phase of the inner basin (Muzzi Magalhaes & Tinterri, 2010), especially affected the overlying deposits of Firenzuola I, as shown by the stratigraphic pinching toward Log C1 and the lateral facies changes, where a stratigraphic succession dominated by thick to very thick Type B and D beds in Log A1 passes downcurrent in Log C1 (i.e. above the MTC-related morphologic high), into a stratigraphic succession dominated by thin to very thin Type E and Type F contained-reflected beds. This downcurrent facies variation can be interpreted based on the fact that only the more diluted turbulent flows bypassing the proximal zone of Log A1 can ascend the morphologic high produced by the Casaglia MTC and form the fine-grained deposits characterizing Log C1 (fig. 48A, B, C). This process is particularly evident in the basal part of Firenzuola I in Log C1, where a marly drape (Casaglia Marls) formed (fig.48, 49C). The influence of the Casaglia MTC high is particularly evident in the paleocurrent analysis of the turbidite deposits of Log C1, where a strong westward component can be interpreted as related to a complete reflection of the turbulent flows against the morphologic high produced by the Casaglia MTC. Conversely, the occurrence of Type E beds in Log A1, with paleocurrents oriented perpendicularly to the main structural alignments, testifies that, in this proximal area, rebound processes are much more influenced by the M. Castellaccio and M. Nero thrusts (fig.32, rose diagrams fig.47).

Conversely, in the Firenzuola II, the stratigraphic pinching toward Log C1 is much less developed, due to the progressive flattening of the morphologic high caused by the deposition of underlying Firenzuola I (fig.48). Once again, facies analysis provides important understanding about structurally-induced topographic control on the depositional processes. As discussed above, Firenzuola II deposits of Log A1 are dominated by Types B, C and D, which indicate abrupt decelerations and deposition of basal dense flows (facies F5) and bypass of the low-density turbulent flows, whose basal shear stress can form facies F6 and F7; both processes were induced by the confinement created by the growth of the M. Castellaccio thrust in a more proximal area (see discussion in Tinterri & Muzzi Magalhaes, 2011). The increase in the deceleration and fallout rates, due to the increased structurally-induced confinement, is also confirmed by the remarkable increase in the sandstone/mudstone ratio in Firenzuola II, both in Log A1 and Log C1. Furthermore, the fact that Type E beds are completely absent in the proximal area (Log A1, fig. 45C, 48C) is further evidence of the complete bypass of the dilute turbulent flows responsible of the deposition of facies F9 (i.e. the facies where the reflection processes can be better observed, see Tinterri & Muzzi Magalhaes, 2011; Tinterri, 2011).

On the contrary, Firenzuola II in Log C1 is mainly dominated by thick-to-very-thick beds, with a well-developed Bouma sequence and Type E contained reflected beds (F8 and F9 facies), (fig.48C). In terms of depositional processes, F8 at the base of these beds represents the deposition of high-density turbidite currents able to reach more distal area, whereas overlying F9 indicates deposition by the low-density turbidite flows that are able to bypass the proximal area of Log A1; the overall deflection of the paleocurrent direction detected in the traction plus fallout structures of facies F9, testifies reflection processes of the diluted flows against the structurally-induced topography. In particular, the evident paleocurrent component directed toward the west could be related to complete reflections of the turbidity currents against the morphologic high associated to the concomitant uplift of the CTRF and the Verghereto high; the latter represents an obstacle, located 40km downcurrent (see fig. 32A), oriented perpendicularly to the main paleocurrents that can justify the reflection toward the W of the flows, rather than the morphology created by the Casaglia MTC, since, at the time of Firenzuola II, it was essentially already flattened (see Tinterri & Tagliaferri, 2015).

6.5 Stratigraphic succession perpendicular to the paleocurrents around the casaglia MTC source area

DESCRIPTION

The cross section shown in figure 49 provides details of the Firenzuola turbidite system (Unit V) in the inner basin near the source area of the Casaglia and Bedetta MTCs, i.e. the area where these two MTCs are characterized by the maximum thickness. It is based on the correlation of two stratigraphic logs, 2km apart, oriented perpendicularly to the paleocurrents and between the villages of Casaglia and Bibbiana (see fig.33, 37). The former (fig.37A) is included between the base of the Casaglia MTC and bed 670, the latter (fig.37B, C, 49D) extends between bed 486 (fig.30, Unit IV) and bed 670. In order to highlight the erosional base of the Casaglia MTC, additional details around the stratigraphic boundary between Unit IV and MTC were collected, by measuring and correlating this contact zone near the villages of Bibbiana and Il Molino (fig.37C, 49D). The cross-section has shown the following main aspects (see fig.49):

- maximum thickness of the Casaglia and Bedetta MTC's in Log C1-Casaglia (480m and 52m, respectively)
- drastic stratigraphic pinching of Firenzuola I toward SW, i.e. toward the area where the Casaglia MTC has the maximum thickness. This stratigraphic pinching is also associated with a progressive decrease in the sandstone/mudstone ratio and in the thickness number of beds (fig.49E, F)
- Log C1 Casaglia shows, from base to top, the following transitional vertical facies changes: 1) an intensely bioturbated marly unit at the base, just above the Casaglia MTC, (see Casaglia Marls in fig.49C); 2) an interval characterized by very thin to thin laminated, fine-grained sandstone beds, often characterized by evident pinch-out, 3) an upper interval mainly composed of thick beds, showing well-developed Bouma sequences (facies F8 overlain by F9 facies), often characterized by drastic pinch-out (fig. 49B). Furthermore, in the basal part of this interval, Type A slurry beds are also common
- in Log C1 Bibbiana, Firenzuola I is characterized by a stratigraphic succession that, in comparison with that of Log C1 Casaglia, has a higher percentage of thick to very thick beds

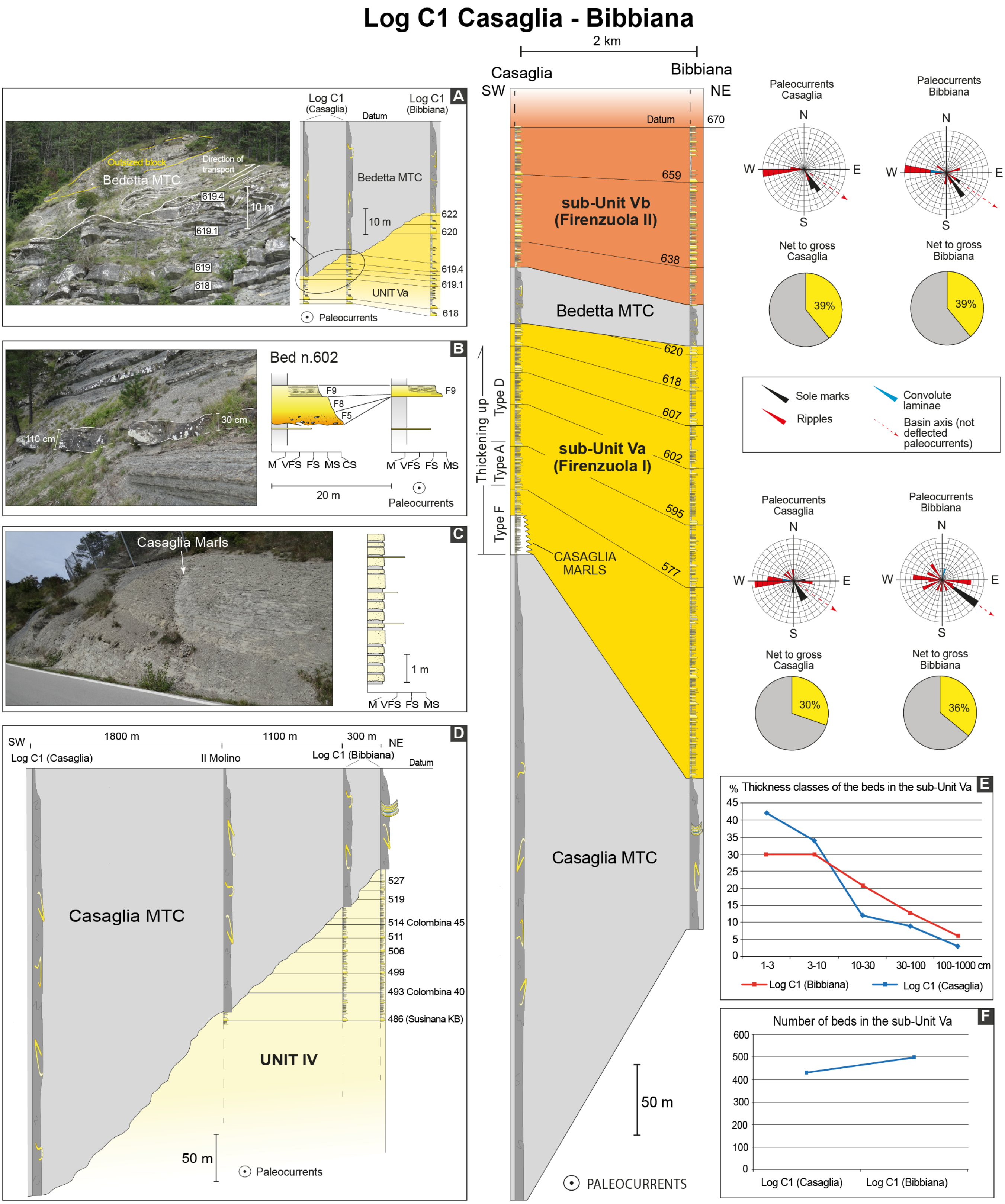


Fig.49 - Stratigraphic cross-section showing the correlation between Log C1 Casaglia and Log C1 Bibbiana in which the lateral and vertical variations of the sandstone/mudstone ratio and paleocurrents can be observed (see fig.32, 37C for the location of the logs). A) Panoramic view and stratigraphic cross-section showing the erosive base of the Bedetta MTC near the village of Casaglia; B) Pinch-out of bed 602 in Log C1-Casaglia. C) Casaglia Marls composed of marly and muddy Type F beds deposited above the Casaglia MTC. D) The Casaglia MTC's erosive base highlighted by measuring and correlating the upper part of Unit IV below the Casaglia MTC (see fig.37C for the location of the logs). E) Distribution of bed-thickness classes in sub-Unit Va (Firenzuola I). F) Number of beds in sub-Unit Va (Firenzuola I).

and a lower percentage of thin to very thin beds (fig.49E, F). The first type of beds are mainly composed of Type D beds; Type E beds are also common

- both in Log C1 Casaglia and Log C1 Bibbiana, the paleocurrents analysis of the sedimentary structures in facies F9 characterizing especially Type E beds, shows a high degree of dispersion with a strong component toward the W (fig.49, rose diagrams)
- The stratigraphic cross section of figure 49D enables to assess the thickness of the underlying stratigraphic succession of Unit IV eroded by the Casaglia MTC. It is very interesting to note that this MTC can erode more than 350m of the underlying Unit IV and that the erosive degree of the MTC base increases toward SW, i.e. toward the Log C1-Casaglia
- in Log C1 Bibbiana, the Casaglia MTC includes an out-sized block, about 100m thick and 300m wide (fig.37B, D; see also Lucente & Pini, 2003). The characteristics of the stratigraphic succession and the occurrence of the Colombina 45 key bed within this out-sized block allow this block to be identified as the upper part of Unit IV.

INTERPRETATION

Thanks to the location near the MTCs source area, stratigraphy and facies analysis of this cross-section provided important insights about the emplacement of the mass-transport deposits and their influence on the underlying and overlying stratigraphic succession. The stratigraphic detail of the contact between the base of the Casaglia MTC and the underlying Unit IV reveals the impressive erosion caused by the MTC emplacement and its deepening toward its source area represented by Log C1 Casaglia (see also Lucente, 2004; Lucente & Pini, 2008). This erosion is also testified by the occurrence of the over-sized block in the Casaglia MTC in Log C1-Bibbiana (fig.37B, D; see also Lucente & Pini, 2003), where the identification of Colombina 45 allows it to be interpreted as belonging to the upper part of Unit IV eroded from more southern area (fig.37B, D)

In the same way, the erosion caused by the emplacement of the Bedetta MTC can be observed (fig.27, 49A), and it is interesting to note that it has the same pattern of the Casaglia MTC one. Once emplaced, the Casaglia MTC produced a topographic relief that deeply affected the Firenzuola I deposits, especially near the source area, where it reaches its maximum thickness. This evidence is shown by the stratigraphic pinching from Log C1 Bibbiana to Log C1 Casaglia and by lateral and vertical facies distribution that can be interpreted as related to an onlap relationship as already described by Tinterri & Tagliaferri (2015).

The basal marly unit (fig.49C) and thin beds at the base of the Firenzuola I can be interpreted as being deposited by the diluted, low-density tails of the turbidity current able to ascend the topographic high created by the MTC.

The progressive flattening of the latter caused by the turbidite deposition, allowed the flows to reach this high, where the erosive and deceleration processes can form Type A slurry beds; once the major relief was flattened, all turbidity currents could reach this area, depositing Type D and Type E beds still influenced by the topography, as shown by pinch-out of some beds and the paleocurrents dispersion. The latter indicate that although the basal high-density parts of the turbidity currents flow parallel to the basin axis, the upper low-density turbulent flows could be modified by continuous lateral rebound against the morphologic highs created by MTC emplacements and structural alignments represented by M. Nero and M. Castellaccio thrusts (fig.32A).

6.6 Stratigraphic succession parallel to the paleocurrents in the outer basin (Logs B2 and E2)

DESCRIPTION

The cross-section shown in figure 50 is NW-SE oriented and is located in the outer Santa Sofia structural element; it displays the downcurrent evolution of the outer basin deposits from proximal to distal areas (38km apart), represented by Log B2 and Log E2, measured in the Senio and Bidente Valleys, respectively (see fig.32A). It also provides important understanding about the timing of growth of the Verghereto high in the outer basin and how it affected the stratigraphic succession and facies distribution of the Firenzuola System (see also Muzzi Magalhaes & Tinterri, 2010; Tinterri & Tagliaferri, 2015).

The cross-section (fig.50) shows the following aspects:

- considerable thickness of Unit V in Log B2, especially of the Unit Vb (Firenzuola II), (as shown in the cross-section of figure 45)
- drastic stratigraphic pinching toward SE, i.e. toward Log E2
- in Log B2, Firenzuola I is characterized by medium to very thick beds, composed of a basal massive well-sorted, medium-grained sandstone facies (F8) and an upper well-developed, laminated fine-grained sandstone facies (F9) (fig.46). Conversely, Firenzuola II is mainly characterized by the presence of two types of bed, namely: a) thick to very thick beds made of coarse-grained, poorly-sorted sandstone facies, often rich in mudstone clasts, in which amalgamation surfaces and liquefaction structures can be common (F5, Type B beds, fig. 50A); b) medium to thick, poorly sorted, coarse-grained sandstone facies (F5), overlain by well-sorted, coarse-grained sandstone facies showing traction carpets (F7 facies, Type C1, fig.41B, 50B) or cross-laminated structures (ripples, megaripples; F6 facies), (Type C2 beds, fig.41C, D). Consequently, Log B2 shows a vertical facies evolution quite similar to Log A1 one in figure 47, except for the some differences regarding the Firenzuola II. These differences are: 1) a decrease of Type D beds (fig.45C); 2) the decrease in Type A slurry beds as found in Log A1 was not detected (fig.45C); 3) in Log B2, the upper part of Firenzuola II shows a cyclicity quite similar to that detected in the overlying Unit VI (Paretaio turbidite system) deposited in the outer basin above the Visignano MTC (see fig.14 and Tinterri and Tagliaferri, 2015).
- in Log E2, Firenzuola I is dominated by very thin to thick beds (fig.50E), characterized by thick laminated, fine-grained sandstone F9 facies, often showing laminaset characterized by alternation of undulated, convoluted laminae and ripples with different paleocurrents in comparison with those indicated by the sole casts (Type E beds). These deposits pass upward through a relatively sharp transition into Verghereto Marls dominated by intensely bioturbated marlstone and mudstone beds. The Verghereto Marls represent Unit Vb (Firenzuola II) (fig.44A, 50C, D).

INTERPRETATION

Stratigraphy and facies analysis of the stratigraphic cross-section shown in figure 50 enable to understand the downcurrent evolution of the turbidity currents in the outer basin at the time of Unit V; it also provide important insights about the timing of growth of the Verghereto high in the outer basin. The latter, together with the CTRF, represents the main tectonic structure that produces the fragmentation of the MAF foredeep during upper Serravallian (see Tinterri & Tagliaferri, 2015). The drastic downcurrent facies changes and stratigraphic pinching of Firenzuola I and II from Log B2 to Log E2, clearly show the structurally-induced topographic relief created by the synsedimentary growth of the Verghereto high. The Firenzuola I deposits are characterized by a subtle

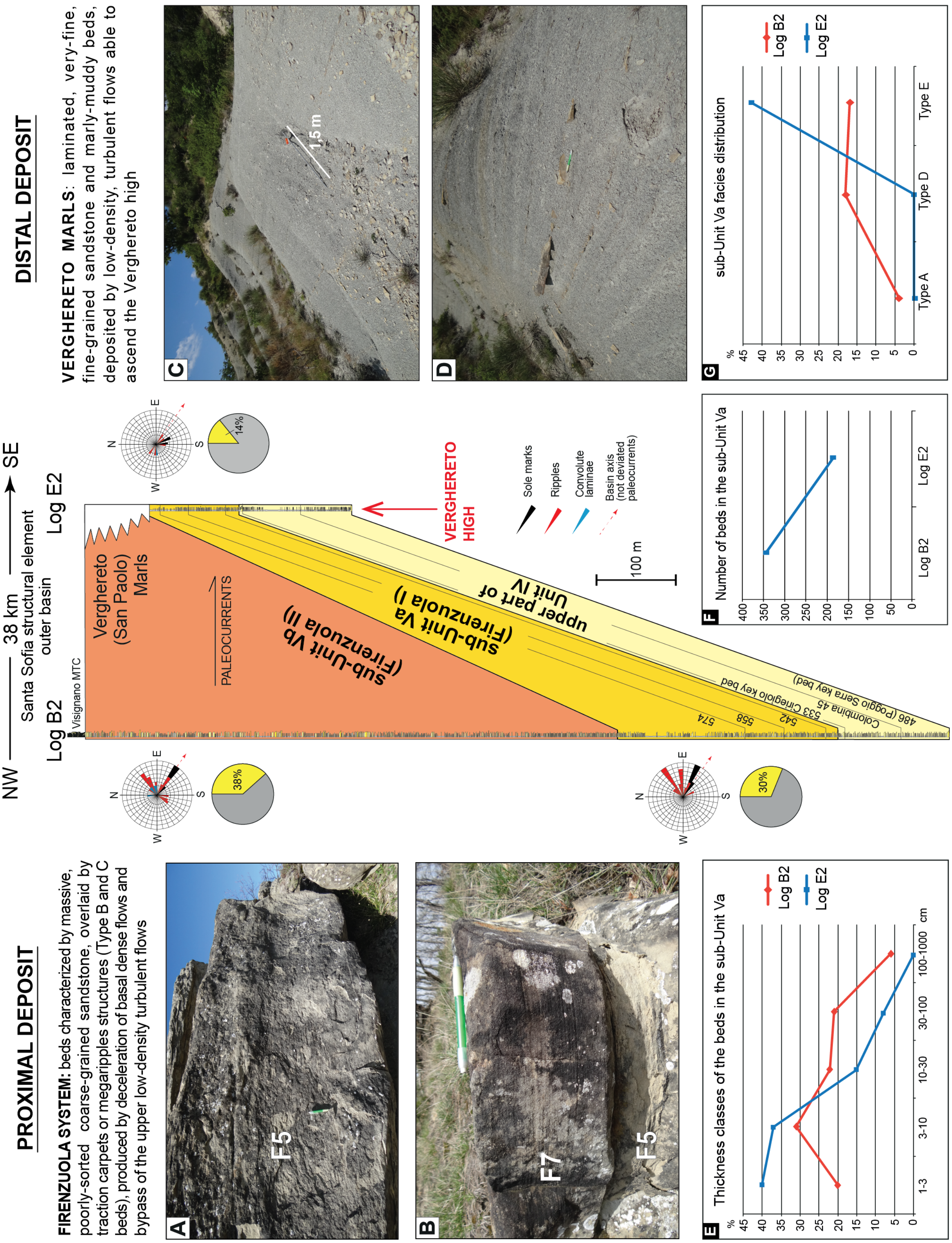


Fig.50 - Longitudinal stratigraphic cross-section and downcurrent facies change in the outer basin, from proximal area (Log B2 in the Senio valley) to distal area (Log E2 in the Bidente Valley), (see fig.32 for the location of the logs). A) Example of a Type B bed. B) Example of a Type C bed. C) Panoramic view of the Verghereto Marls in Log E2. D) Type F bed characterized by an evident pinch-out within the Verghereto Marls. E) Distribution of bed-thickness classes in sub-Unit Va (Firenzuola I). F) Number of beds in Firenzuola I. G) Lateral distribution of the bed types characterizing Firenzuola I (sub-Unit Va).

stratigraphic pinching toward SE (i.e. from Log B2 to Log E2, see fig.50) and in terms of depositional processes, the Type E contained-reflected beds of Log E2 (fig.50G) clearly indicate that only diluted, low-density turbidite flows were able to ascend the topographic high of the Verghereto area, where reflection and rebound processes occurred.

The paleocurrent analysis shows clearly rebound and ponding processes against the inner basin margin represented by the M. Castellaccio thrust (see the component toward the NE in the rose diagram of Log B2) and against the Verghereto high that represents an obstacle perpendicular to the paleocurrents (see the component toward WNW in the rose diagram of Log E2).

Finally, the drastic downcurrent stratigraphic pinching and facies change, as observed in Firenzuola II, show that the paroxysmal growth phase of the Verghereto area occurs at the time of deposition of this Unit, where a stratigraphic succession dominated by Type B and C beds in Log B2 (fig.50A, B) passes downcurrent into the Verghereto Marls mainly composed by Type F beds made of marly Te Bouma divisions (fig.50C), even though a hemipelagic component can also be common. The Verghereto Marls are interpreted as a mudstone-siltstone drape, deposited only by the more diluted fraction of the low-density turbidite flows able to reach the pronounced morphologic high (see also Muzzi Magalhaes & Tinterri, 2010). On the contrary, the dominance of Type B and Type C beds in the proximal areas indicates deceleration and sharp deposition of the basal dense flows associated with bypass of the low-density turbulent flows; both processes were induced by the progressive creation of the outer depocentre in the proximal area induced by the growth of the CTRF as also testify by the analysis of the paleocurrents that indicate deflections of the turbulent flows towards NE, i.e. perpendicularly to the M. Castellaccio thrust front.

7. PETREL FACIES MODELING

The Entire dataset of the Unit V was imported in the Petrel 2014 software, in order to create an experimental high-resolution 3D facies model based on field data. This software is a powerful tool used by oil and gas companies to model subsurface geobodies, both in exploration and production phases. It offers the possibility to integrate data coming from different sources (seismic, well-logs, stratigraphic logs) and to manage them with different approaches, both in the case of thick and poor-data datasets. As suggested by Tinterri & Tagliaferrri, (2015), the Firenzuola deposits represent a good analog of tectonically-controlled turbidite systems found in several exploration and production areas all over the word, such as Gulf of Mexico intraslope basins (Sinclair & Tomasso, 2002; Prather *et al.*, 1998; Prather, 2003) or sin and post-rift basins of passive continental margins (Africa and Brazil offshores), in which turbidite facies distribution are strongly affected by sin-depositional tectonics. 3D models with resolution higher than seismic stratigraphy ones, can thus be useful tools for geostatistical studies, as well as to predict turbidite facies spatial arrangements. The latter are directly related to petrophysical properties, which in exploration and production phases, can be used for bulk volume calculations (storage fluid capacity of the system) and fluid-dynamic behaviour throughout the reservoirs. According to stratigraphy and facies characteristics, the modeling was split into two files, namely Unit Va (Firenzuola I) and Vb (Firenzuola II). Workflow and the facies modeling results will be described in the following paragraphs.

7.1 Data import

7.1.1 Project setting

The project was set by choosing WGS84 as the reference system and meters as the storage unit. Every log was imported assigning the relative coordinates and stratigraphic thickness; the top of the Bedetta MTC and the top of the Visignano MTC were chosen as datum (level 0)

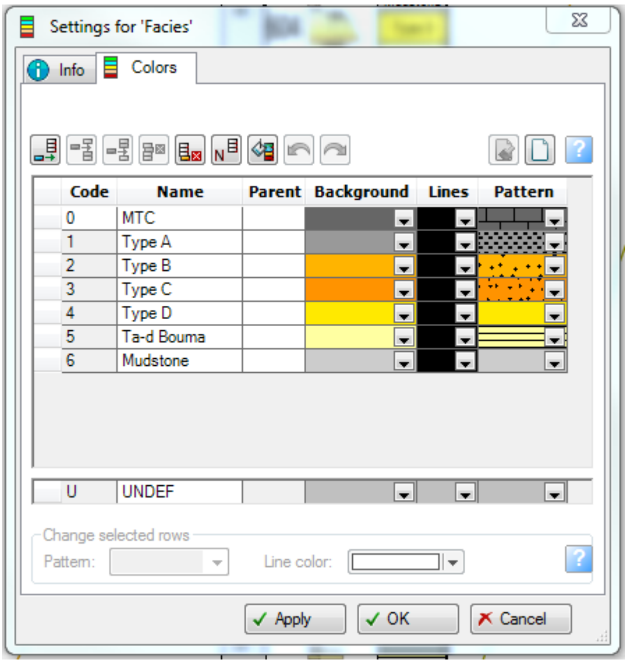


Fig.51 - Facies template.

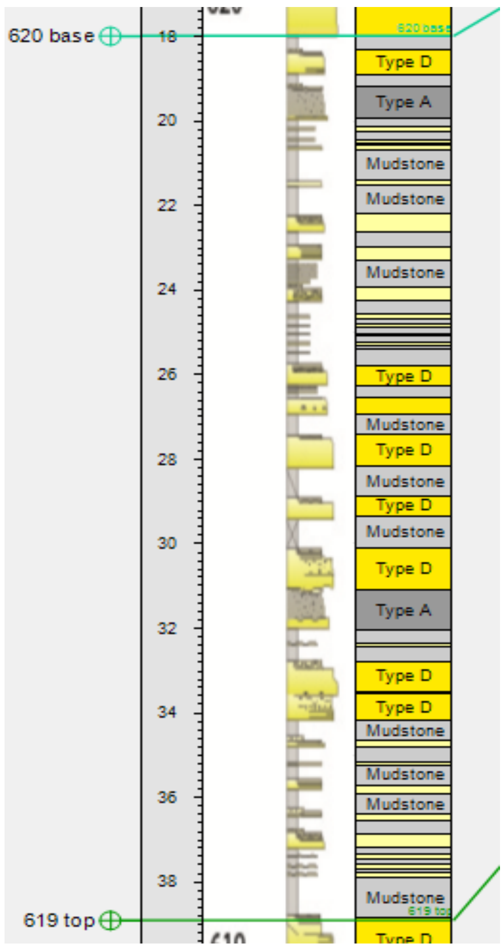


Fig.52 - Trace of the log. On the left the jpeg key trace, on the right the relative traced facies log (from Log A1).

for the Unit Va and Vb files, respectively. Each log, previously drawn in a drawing software and exported in jpeg format, was imported in Petrel by using the import tool (on selection), in order to have a key trace to create the facies log.

7.1.2 Log trace

In order to draw the facies logs, a template with the turbidite facies was created, under the *discrete property template* of the *template pane* (fig.51). Having created the template, every facies log was traced by following the relative imported jpeg as key trace and drawing it by using the painting tool under *new discrete log* in the *stratigraphy* folder (fig.52).

7.2 Well top and surface editing

The further step was the creation of the main well tops, deduced from the correlation. They were vertically spaced at the scale of the bedsets (as meant by Cambpell, 1967), which usually show thickness ranging from ten to some tens of meters (fig.52, 619 top and 620 base).

The created well tops, together with a polygon drawn at the limits of the area defined by the logs themselves, were used as input data for the creation of the surfaces. It that way, every surface delimits the top and bottom of the bedsets that define the stratigraphic framework of Unit Va and Vb (fig.53).

7.3 Gridding and layering

The volume of the area was defined by using the *Make simple grid* under the *Utilities* of the *Processes* pane. The previously created polygon and surfaces were used as boundary and input data, respectively; the x-y geometry of the cells was set at 100 x 100m as grid increment. The vertical resolution, so far defined by the bedset surfaces, was improved by using the Layering process, under the *Corner point gridding* of the *Processes* pane. The number of layers was set in order to reach a vertical resolution between 1m and 50cm for Unit Va and between 1m and 25cm for Unit Vb, which are consistent with the medium thickness of the turbidite beds in the studied units.

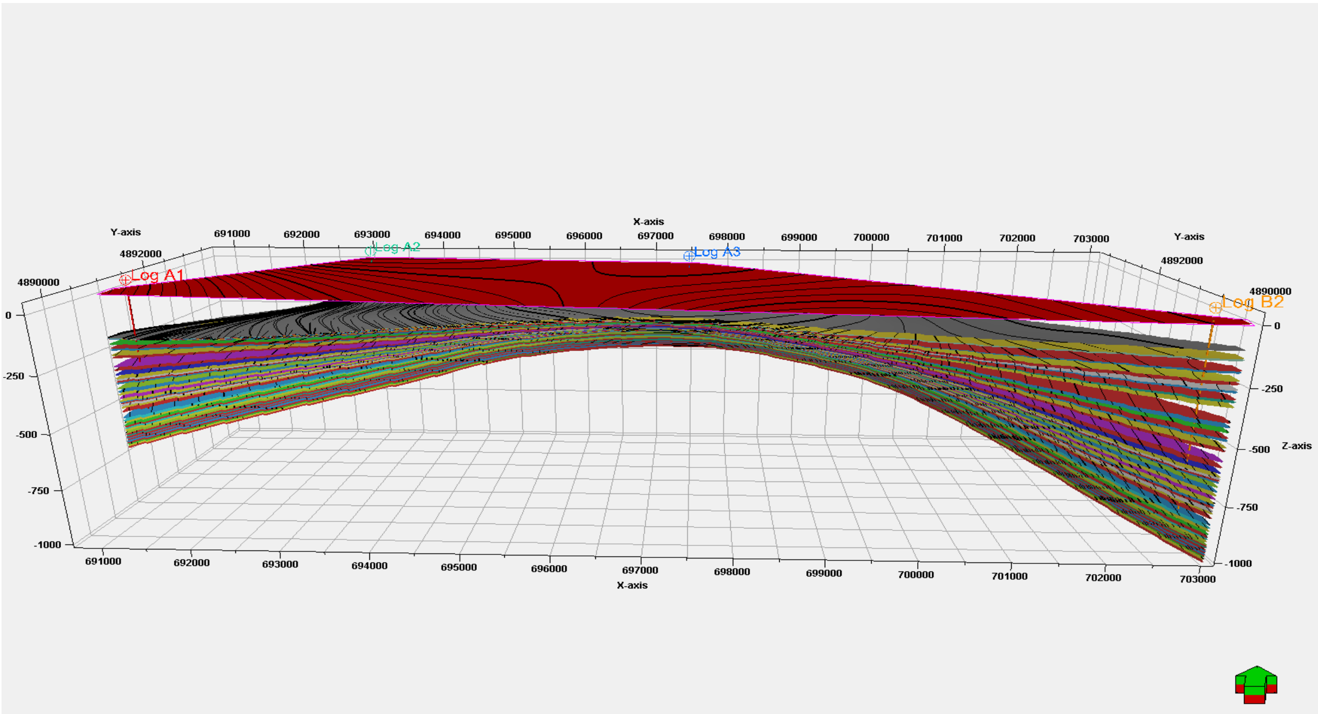


Fig.53 - Resulting surfaces after the surface editing of Unit Vb.

7.4 Well log upscaling

Having defined horizontal and vertical cell resolution in the 3D grid, upscaling of the stratigraphic logs was carried out.

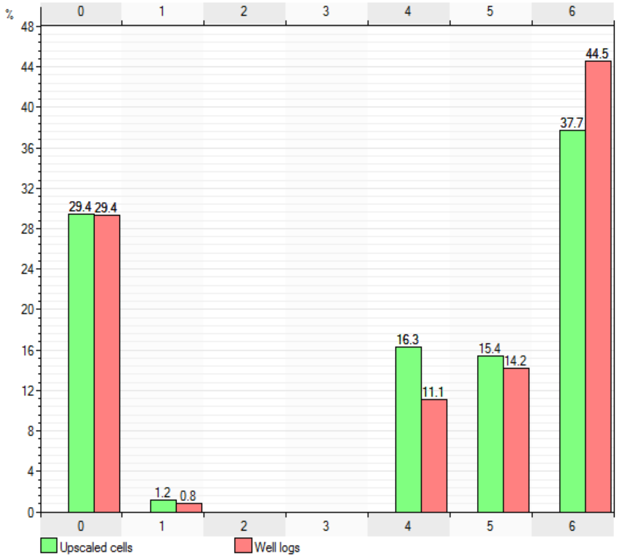


Fig.54 - Histograms showing the result of the well log upscaling operation for Unit Va. Facies are as follow: 0) MTC, 1) Type A, 2) Type B, 3) Type C, 4) Type D, 5) Ta-d, 6) Mudstone.

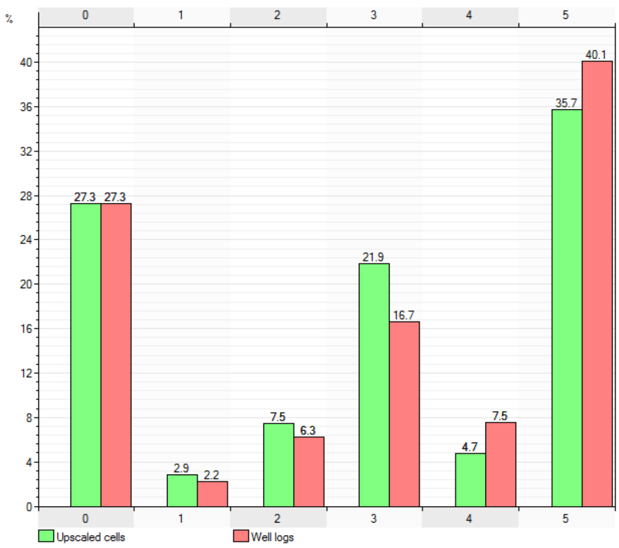


Fig.55 - Histograms showing the result of the well log upscaling operation for Unit Vb. Facies are as follow: 0) MTC, 1) Type A, 2) Type B-C, 3) Type D, 4) Ta-d, 5) Mudstone.

This operation allows the facies to be assigned to the cells around the logs, which are subsequently used by Petrel to model the entire volume.

In order to better stress the sandstone facies of the model, facies weighting was applied in a proportion of 1 to all sandstone facies and MTC and of 0.5 to mudstone facies. The final results for both Va and Vb Units are shown in the histograms below (fig.54, 55).

7.5 Facies modeling preparation

7.5.1 Log location and facies distribution

The measured logs are located in specific areas of the basin, where turbidite beds are affected by facies changes. Logs A1-A2-A3-B2 represent a transect perpendicular to the paleocurrents and to the Monte Castellaccio Thrust (CTRF, Castellaccio Thrust Related Fold) in the proximal area of the Santerno and Senio valleys (fig.33). Specifically Log A1 is located in the depocentre of the inner basin and Log A3 is located above the syn-sedimentary topographic high created by the growth of the examined structure, whereas Log B2 represents the depocentre of the outer basin. Log C1 Casaglia and Log C1 Bibbiana represent an intermediate area of the inner basin, quite important, since it is the source area of the Casaglia and Bedetta MTC's, whose emplacement deeply affect the stratigraphy and facies distribution in Unit Va. Log E2 is located in the distal area of the syn- sedimentary Verghereto high, whose growth - coeval to that of CTRF - caused the segmentation of the MAF basin at Unit V time. Therefore, this specific distribution of the logs is important to stress facies variation across and along the CTRF alignment and the Verghereto high, the two structures involved in the segmentation of the MAF Basin at Unit V time.

7.5.2 Facies

The turbidite facies characterizing Unit Va are Type A, Type D, Ta-d of Bouma sequence, which include Type E and Type F beds (see paragraph 6.2) and interbedded mudstone levels. Unit Vb, representing the major phase of basin segmentation, is characterized by the

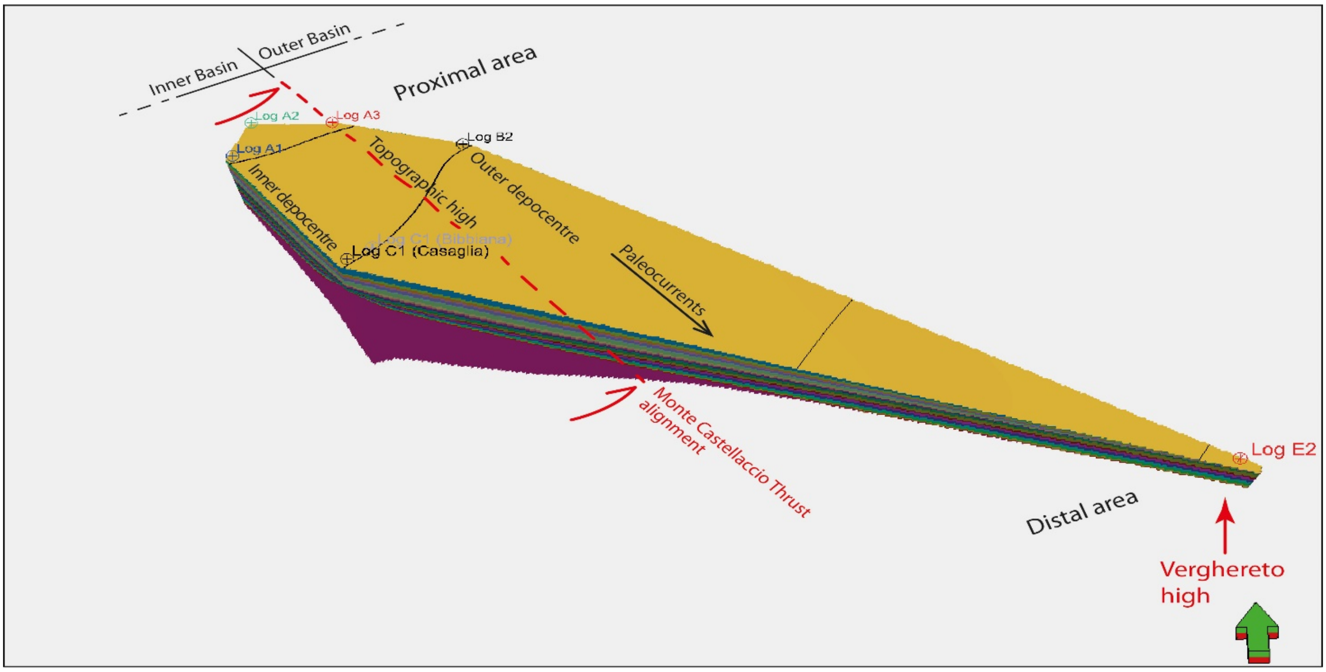


Fig.56 - 3D grid of Unit Va, showing the location of the logs and their relative position compared to paleocurrents and tectonic structures.

appearance also of Type B and Type C beds. MTCs represent the boundaries and key layers at the base and top of the Units and sub-units (Casaglia MTC at the base of Unit Va, Bedetta MTC at the top of Unit Va and base of Unit Vb, Visignano MTC at the top of Unit Vb).

7.5.3 Algorithm

Petrel assigns properties to all the cells of the volume according to input data (in the case of this study represented by the stratigraphic logs) and several kinds of algorithms, each of which carries out different distribution pattern. Algorithms can be divided in two main categories: stochastic and deterministic. The former fit poor-data projects and provide several solutions, whereas the latter carry out one-solution models characterized by higher continuity of the property. Since the MAF is a highly efficient turbidite system in which beds are characterized by significant lateral continuity, as much as several tens of kilometres, the deterministic *Indicator kriging* is the one that best suits the turbidite facies distribution of its deposits (fig.56, 57). The Indicator Kriging distribution depends upon upscaled cells of the logs, the variogram (see below) and the fraction for each individual facies. In the case of the MTCs layers, in which no facies variation occurs, the assign value was adopted (see Casaglia, Bedetta and Visignano MTCs).

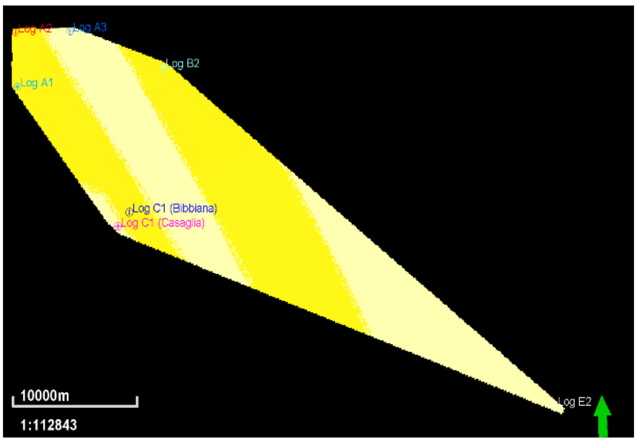


Fig.57 - Example of facies distribution within a layer of Unit Va. Limits between facies are characterized by an area with cell filled with both facies, in order to indicate the transition between them.

VARIOGRAM

Once chosen the algorithm, spatial distribution can be led according to specific patterns by defining orientation and axis dimension of the variogram ellipse. For this study it was oriented at a 130 degree angle, which represents the orientation of the basin axis, paleocurrents direction and Monte Castellaccio Thrust alignment. The anisotropy range (axis dimensions) was set with a major and minor direction comparable to the extension of the studied area and to the turbidite facies continuity, parallel and orthogonal to the basin axis, respectively.

7.6 Facies modeling results

Facies modeling allows some important trends about lateral and vertical distribution of the turbidite facies to be highlighted, as described in the first part of the thesis.

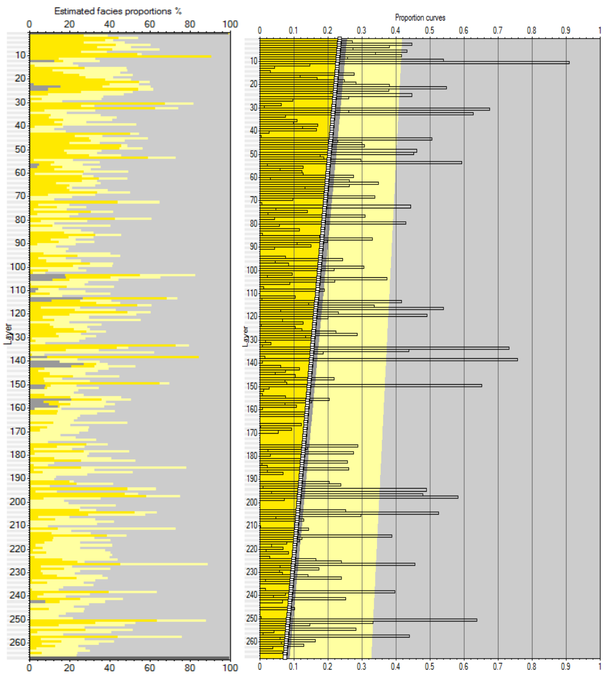


Fig.58 - Facies proportions of Unit Va. The progressive increase in Type D beds can be seen by observing the spikes of the estimated facies proportion (on the left) and by fitting Type D facies to a linear regression in the proportion curves (on the right).

7.6.1 Unit va

The basal Unit Va represents a phase of increasing but relatively low structural control of the tectonic structures; in this setting, turbidite facies are characterized by higher lateral continuity than Unit Vb. Nevertheless, data analysis after facies modeling allowed some vertical and horizontal trends to be stressed. The data analysis shows a vertical increase in Type D facies together with an overall decrease in Ta-d and mudstone facies (fig.58). This trend perfectly matches the increase in structurally-induced topographic confinement experienced by the Unit V deposits, which causes a progressive increase of sand entrapment in the depocentral areas.

Layer-by-layer horizontal distribution can be observed by filtering the K direction with the *property player tool* (fig.57), whereas horizontal trends characterizing the entire Unit Va were pointed out by creating thickness maps for facies. The resulting maps show that Type D beds infill the depocentral areas of the inner and outer basin represented by Logs A1 and B2 (fig.59, 60); conversely, they become progressively thinner toward the syn-sedimentary topographic highs, located in the areas of Log A3 and E2. Type D thickness peak can be seen in the inner depocentre of the Log A1, which represents the area with the highest structurally-induced topographic confinement of the inner basin. The Ta-d thickness map for facies shows an opposite trend, since it thickens toward the structural high of the Monte Castellaccio Thrust (Log A3 area), due to the deposition of the diluted turbulent flows bypassing the depocentral area and able to ascend the structural high after flow decoupling processes. The distribution for both facies shows a NW- SE pattern, induced by the Monte Castellaccio Thrust alignment and paleocurrents direction. The only exception is for Log C1 Casaglia, where Type D beds thickness sharply taper (fig.59, 61); this is due to the topographic high at the base of the unit created by the Casaglia MTC emplacement, against which Type D beds pinches-out. Other important facies trends emerge by observing facies modeling results in the intersection windows. The first one (Logs A1, A2, A3 and B2) has been designed to evaluate horizontal and vertical facies transitions across the CTRF (fig.60). It shows the layer thinning toward Log

A3 and the overall lateral facies transition from Type D to Ta-d beds, from Log A1 to Log A3, as shown by thickness maps as well. Another important trend concerns Type A beds, which can be found especially at the margins of the inner and outer basin (Logs A1, A2, B2), whereas they tend to disappear in the area of Log A3. This transition can be related to the deceleration and erosion processes affecting the turbidite currents against the syn-sedimentary

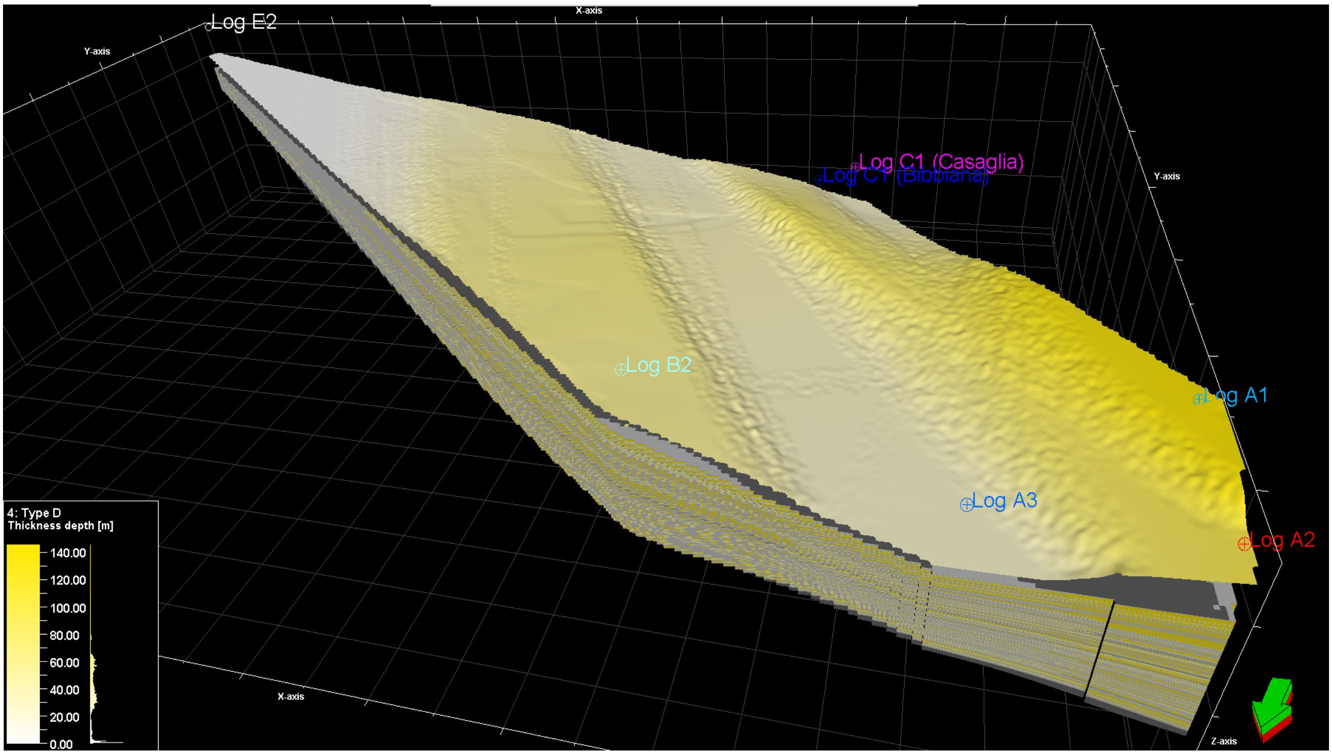


Fig.59 - Thickness map for Type D facies. It is woth noting the drastic thickness increase in the area of the inner depocentre (Log A1), the thinning along the NW-SE alignment of the CTRF (Log A3) and Verghereto high (Log E2) and the local thinning in the area of Log C1 Casaglia (see text for explanation).

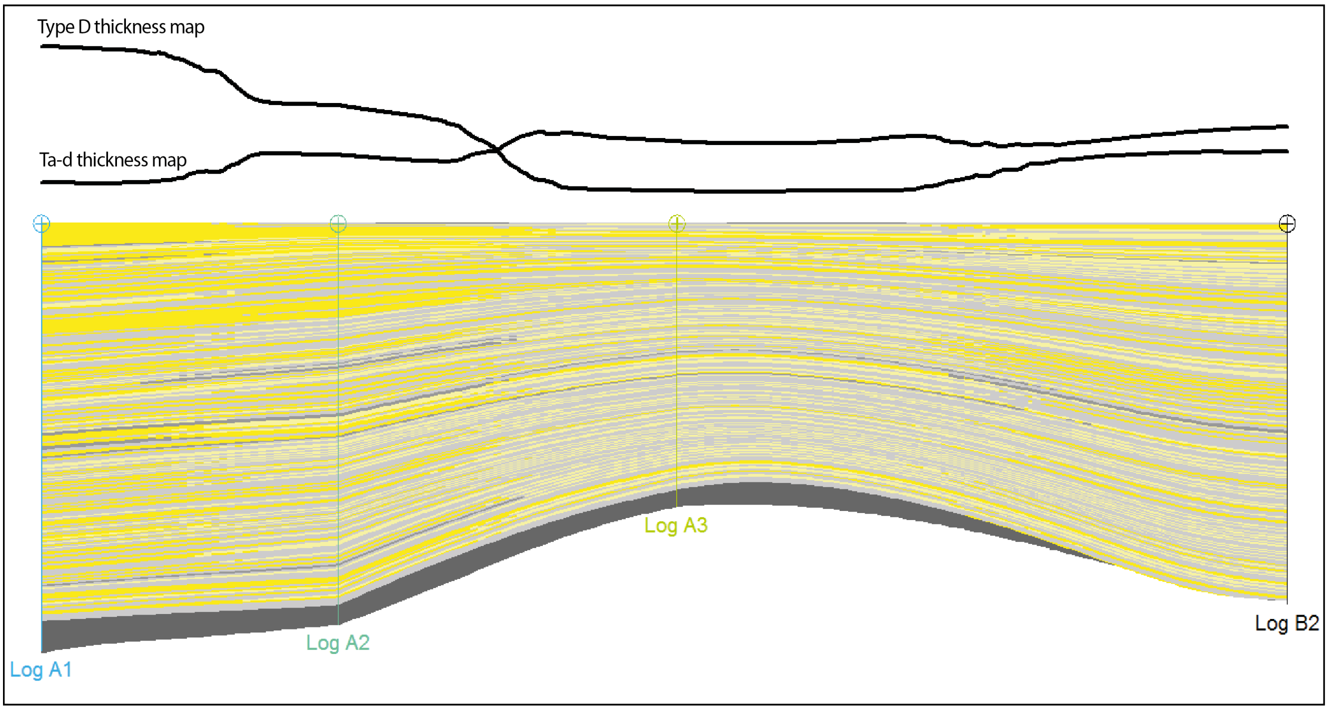


Fig.60 - Intersection window across the CTRF, showing the stratigraphic pinching toward Log A3 associated with a lateral facies change from Type D to Ta-d beds, also testified by thickness maps. Type A beds mainly occur in the marginal areas of the inner and outer basin (see text for further explanation).

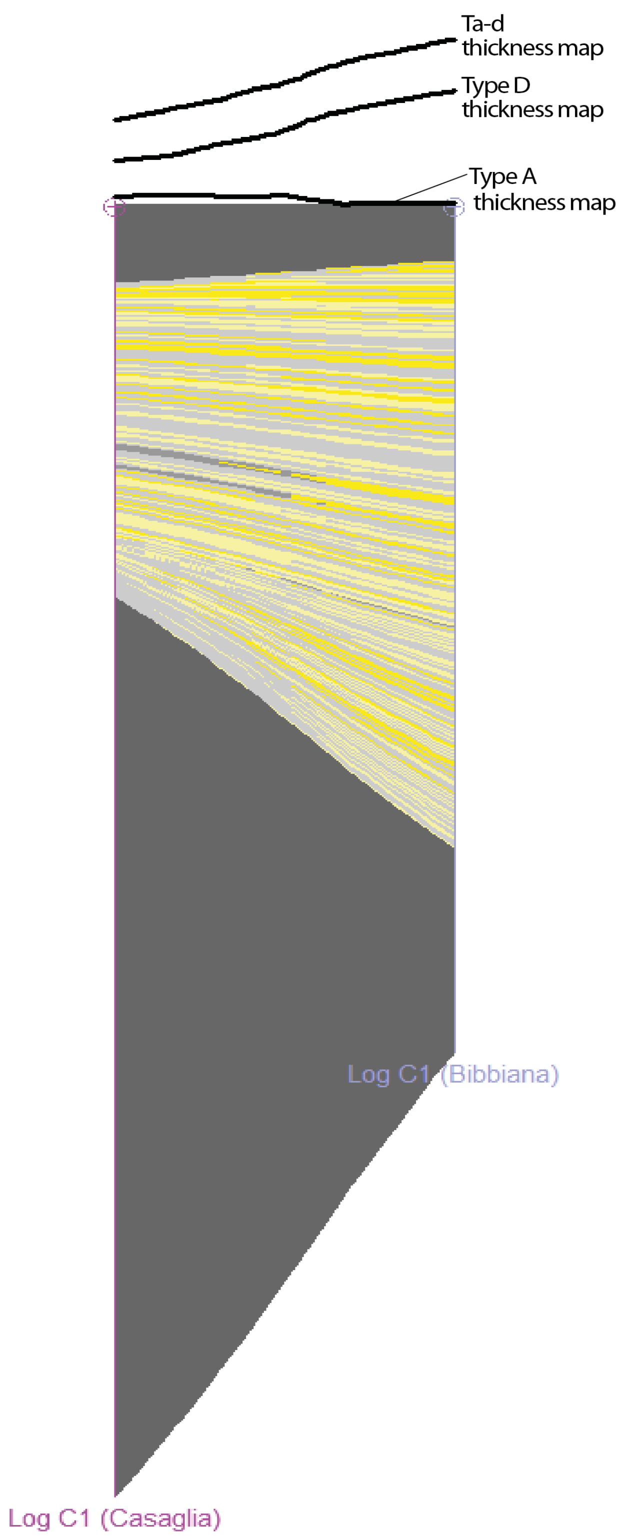


Fig.61 - Intersection window between Log C1 Casaglia and Log C1 Bibbiana. It shows the onlap relationship of the basal part of the Unit Va just above the Calaglia MTC in the Log C1 Casaglia, as well as the related lateral facies transition between the two logs.

morphologic high generated by the growth of the CTRF. The second intersection window (fig.61), located in the inner basin near the source area of the Casaglia and Bedetta MTCs, shows the influence of both MTCs on the stratigraphic succession and lateral facies distribution. The morphologic high, created by the Casaglia MTC emplacement, causes evident onlap relationships in the basal part of the unit Va, toward the area of Log C1 Casaglia, as well as lateral facies change from Type D to Ta-d beds, from Log C1 Bibbiana to Casaglia. Another important lateral and vertical facies transition concerns Type A beds. They appear in the vertical facies succession of Log C1 Casaglia above the finer Ta-d beds, confirming the onlap facies succession that characterizes most deposits above the MTCs in the Marnoso-arenacea formation (Tinterri & Tagliaferri, 2015). Furthermore, they shows a lateral transition to Type D beds toward Log C1 Bibbiana confirming that this kind of facies is strictly related to deceleration and erosion processes occurring against a topographic obstacle, in this case represented by the Casaglia MTC (fig.61). In the upper part of the succession, the unit above Type A beds is characterized by no evident lateral facies transition, probably due to the progressive flattening of the area around the Casaglia MTC caused by the turbidite beds deposition. Finally, the upper part of the unit shows the powerful basal erosion of the Bedetta MTC emplacement, able to erode about 20m of stratigraphic succession toward the source area of Log C1 Casaglia.

7.6.2 Unit vb

The facies modeling for Unit Vb was carried out in the proximal area of the Santerno and Senio valleys, since the upper part of the sub-unit does not crop out in more distal parts of the basin. As introduced in the first part of the thesis, Unit Vb is involved in the critical phase of growth of the CTRF and Verghereto high,

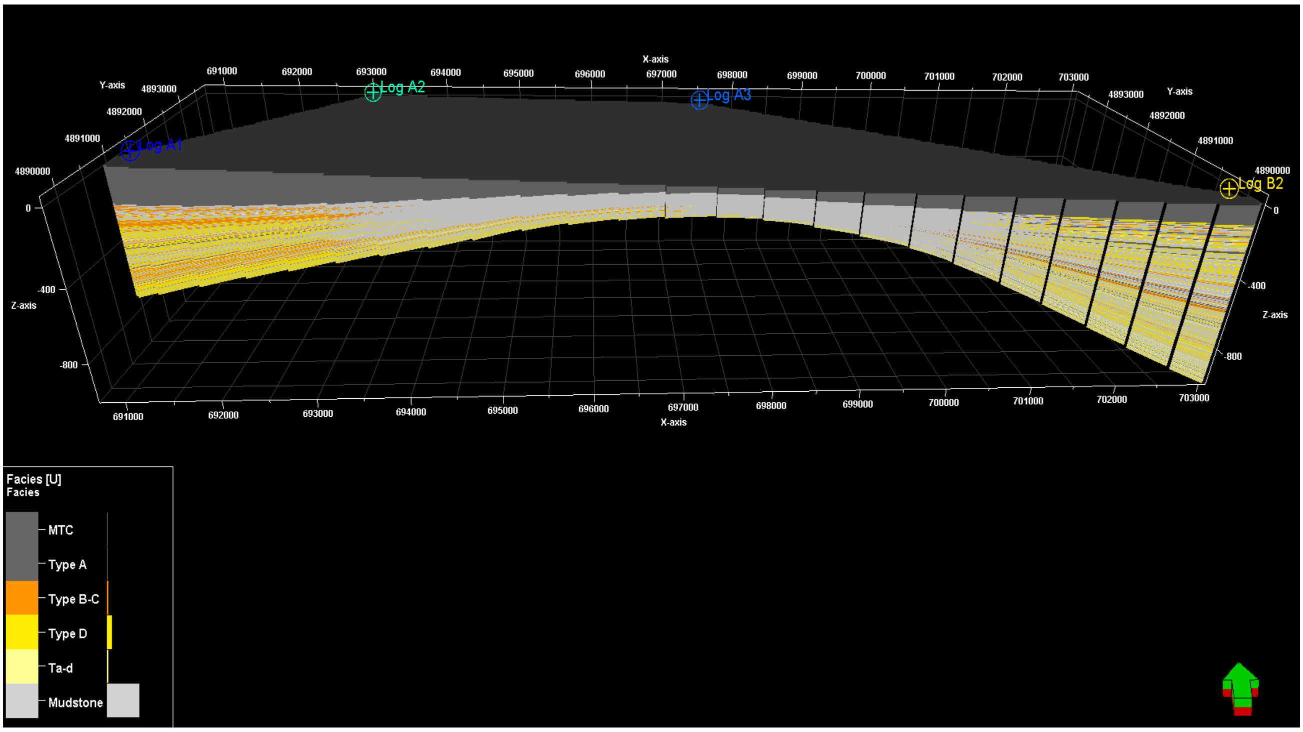


Fig.62 - 3D window of Unit Vb facies modeling results, where the evident progressive facies differentiation between depocentres (Logs A1 and B2) and topographic high (Log A3) can be observed.

which deeply affect depositional processes and facies distribution over short distances.

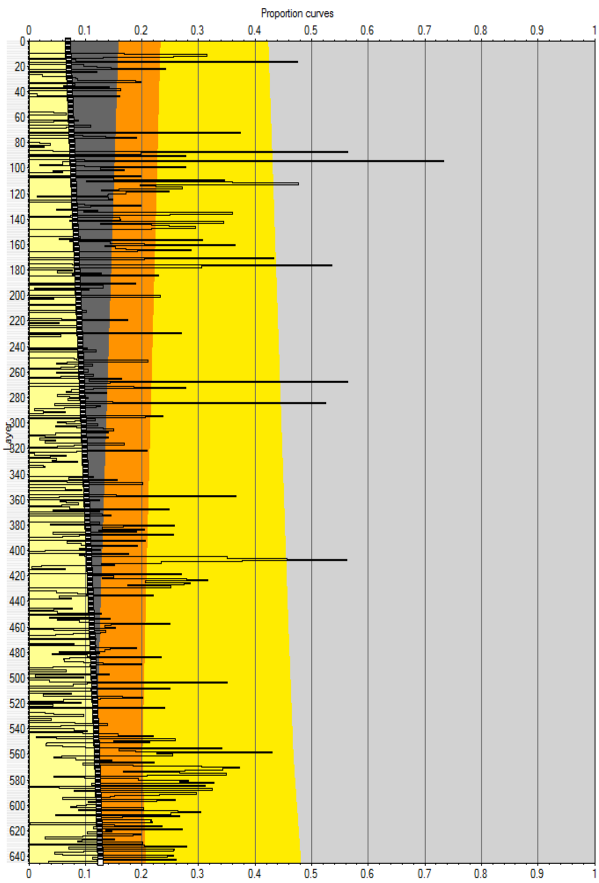


Fig.63 - Facies proportions curves of Unit Vb.

The facies model was developed by correlating Logs A1, A2, A3 and B2, whose disposition runs across the CTRF. By showing the results in a 3D window, the facies differentiation between the depocentral areas of the inner and outer basins represented by Logs A1 and B2 and the area of syn-sedimentary topographic high located in the area of Log A3, can be easily observed (fig.62). The depocentres are characterized by thick sandstone lobe accumulations, whereas the topographic high shows a sharp horizontal and vertical transition to mudstone beds. More detailed trends emerged from the data analysis, which shows a vertical trend of decreasing in Ta-d beds, together with an increase in Type A and mudstone facies over the entire area (fig.63). The former is due to the structurally-induced confinement, causing flow decoupling and bypass processes of upper diluted turbulent flows, which deposit fine grained Ta-d facies in more distal areas The increasing confinement also induces deceleration of the basal dense flows, causing the deposition of Type B-C and Type A facies in the proximal depocentral

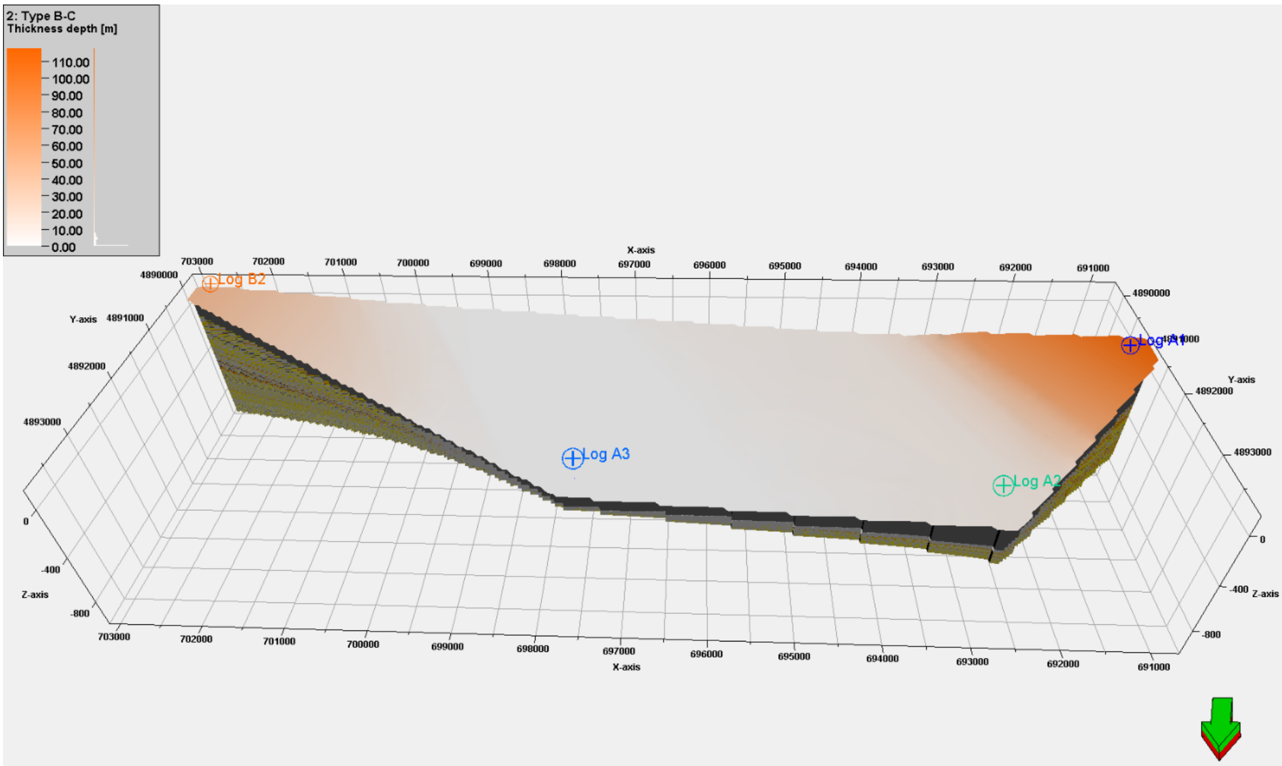


Fig.64 - Thickness map for Type B-C facies.

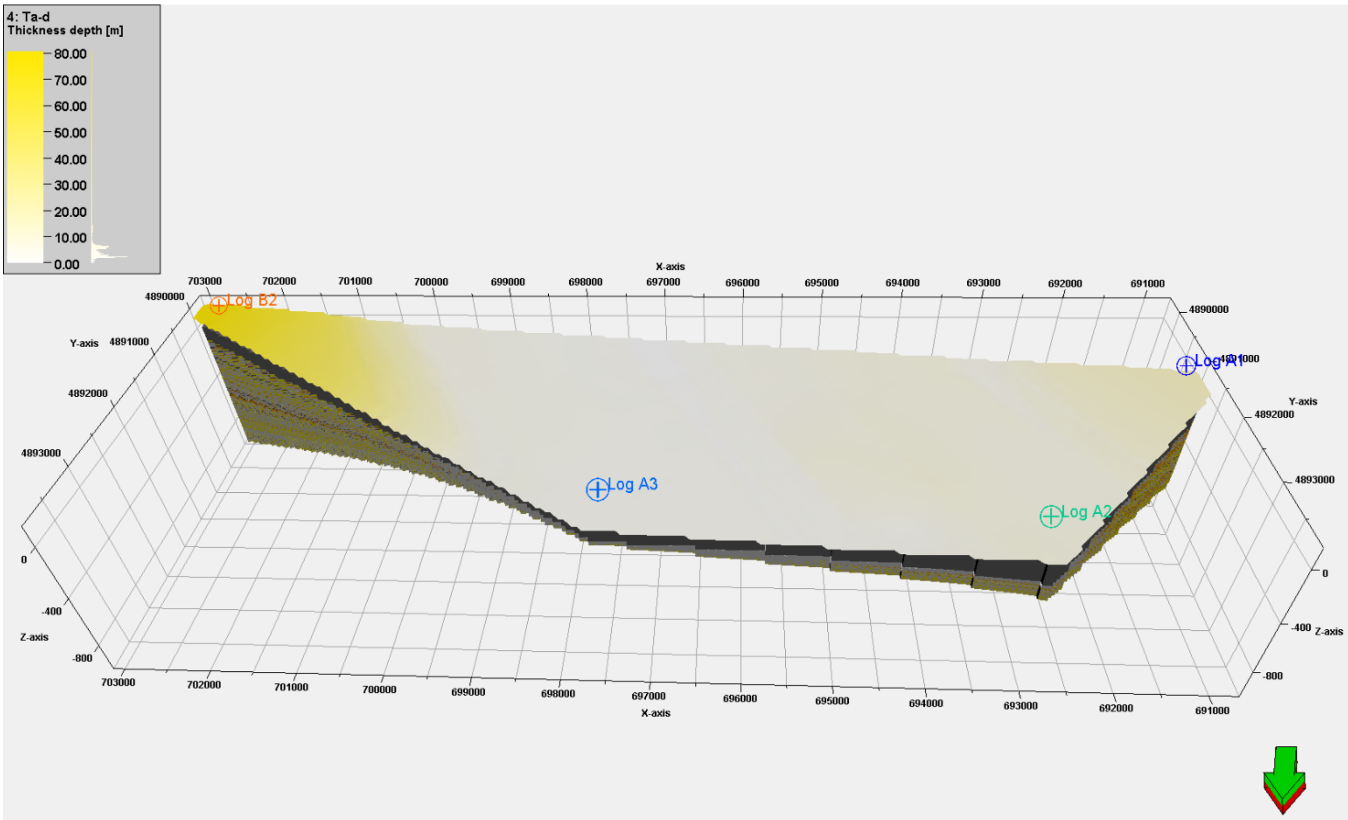


Fig.65 - Thickness map for Ta-d facies.

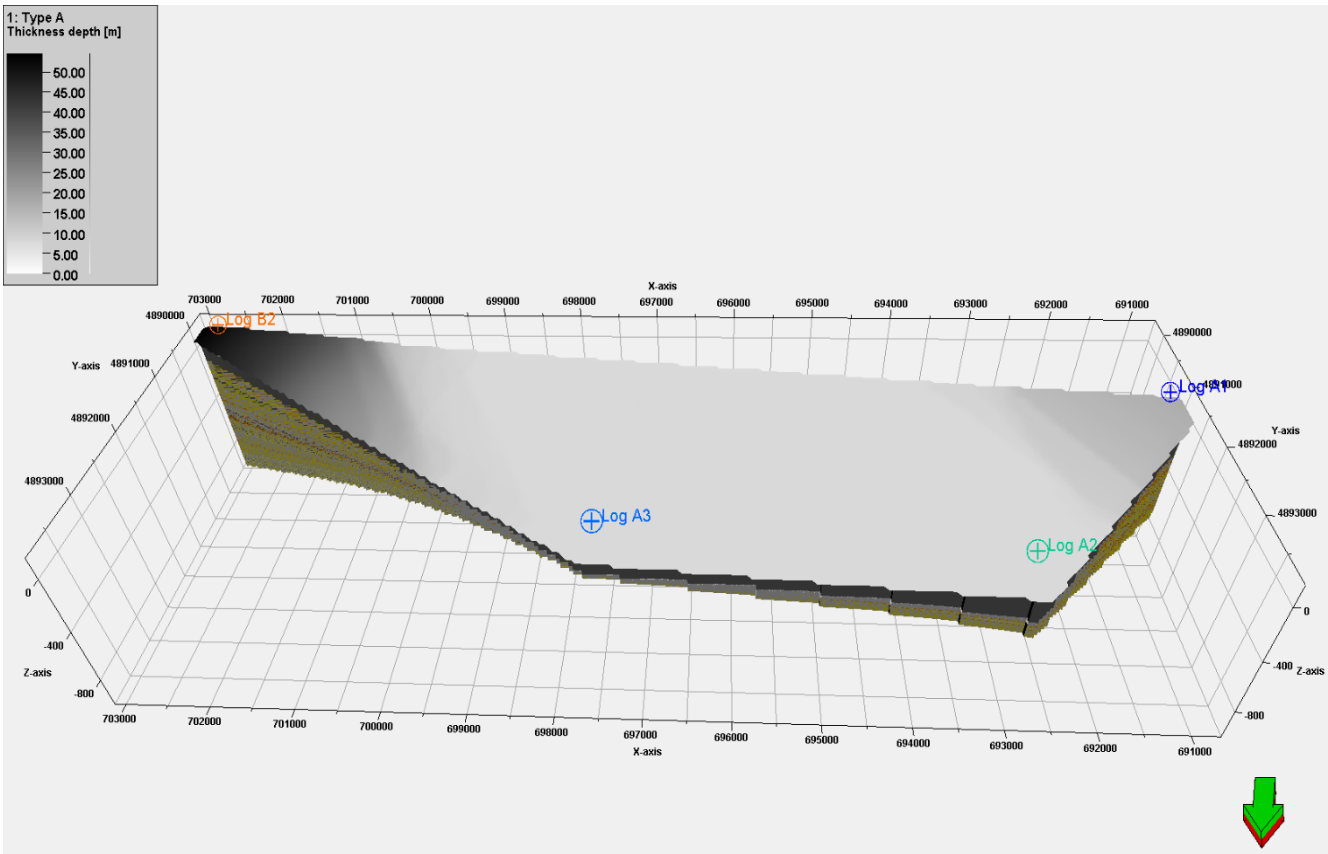


Fig.66 - Thickness map for Type A facies.

areas. The thickness maps for facies (fig.64, 65, 66) allow a better view of the horizontal distribution of these facies over the studied area. Thickess map for Type B-C facies is thicker above the area of the inner basin (fig.64, Log A1); conversely the Type A one is thicker over the outer basin (fig.66, Log B2). This result is quite important because it stresses a different degree of confinement between inner and outer basin and its influence on depositional processes. Type A beds typically occur when turbidite basal dense flows are able to erode mud in a confined but still relatively open basin. Conversely, Type B-C facies typically occur when a higher degree of confinement causes basal dense flows to decelerate but not with enough space and time to erode and produce slurry (Type A beds) facies (see Tinterri & Tagliaferri, 2015). Therefore, the different distribution of these two facies can be related to the different degree of confinement between the inner and outer basin: higher in the former, representing an almost completely isolated piggyback-type basin, lower in the latter, which represents the new main depocentre of the MAF basin. Similarly, thickness map for Ta-d facies is thicker in the area of the outer basin (fig.64). This fine-grained facies is deposited by the upper diluted turbulent flows that can undergo a bypass the more confined inner basin, whereas can partially depose in the wider outer basin.

8. SUMMARY AND CONCLUSIONS

8.1 The importance of Unit V in the MAF basin evolution (tectonics and sedimentation)

This thesis presents the high-resolution stratigraphy and facies analysis of Unit V by Muzzi Magalhaes & Tinterri (2010), known in the literature as the Firenzuola turbidite system (Mutti *et al*., 2002). This Unit, upper Serravallian in age and included between the Casaglia and Visignano MTCs, is quite important in the geologic evolution of the MAF, because it records the closure of the inner basin and the displacement of the deposition in a new outer depocenter. The progressive closure and isolation of the inner basin occur through the concomitant uplift of the M. Castellaccio thrust front and Verghereto area, as recently demonstrated by Tinterri & Tagliaferri (2015).

According to the data analysis, the Firenzuola turbidite system of Unit V can be divided in two sub-units: Unit Va (Firenzuola I), extending from the Casaglia to the Bedetta MTCs and Unit Vb (Firenzuola II) included between the Bedetta and the Visignano MTCs. The former shows sediment dispersal pattern and facies association similar to the underlying deposit of Unit IV (see Muzzi Magalhaes & Tinterri, 2010) even though the occurrence of the Casaglia MTC at the base and lateral facies variations clearly show the beginning of the closure phase of the inner basin (fig.67A). The latter phase heralds the strong coeval tectonic uplift of the M. Castellaccio thrust (CTRF) and Verghereto high, occurring in Firenzuola II. This coeval uplift is clearly demonstrated by the comparison between the stratigraphic-cross sections of figures 47 and 50 (perpendicular and parallel to the CTRF and paleocurrents, respectively) where the time equivalence of the Castelvecchio and Verghereto Marls can be observed (see also Tinterri & Tagliaferri, 2015). These marly units deposited above the structural highs represent the closure facies of the inner basin, which, during the deposition of Unit Vb (Firenzuola II) become an isolated piggyback-type basin (see fig.67B). In the same way, the drastic increase in the stratigraphic thickness of Unit V in Log B2 shows the concomitant creation of a new depocentre in an outer basin to the northeast of CTRF (fig.45). Both depocenters in the proximal parts of inner and outer basins (see Logs A1 and B2 in fig.45, respectively) were filled in with thick-sandstone lobe accumulations, mainly made of Type B, Type C and Type D beds, testifying decelerations and high rates of sedimentation caused by structurally-induced topographic confinement (see also the discussion in Tinterri & Muzzi Magalhaes, 2011; Tinterri & Tagliaferri, 2015). The structurally-induced decelerations and massive sandstone depositions, mainly evident in the inner basin depocentre (Log A1), are further demonstrated by the high value of the sandstone/mudstone ratio and the nearly absolute lack of fine-grained sandstone F9 facies, which testify very efficient decoupling processes of bipartite flows, causing bypass of the most part of low-density turbulent flows that can deposit fine-grained sediments laterally and more downcurrent, above the structural highs. The high degree of bypass is also shown by the occurrence of well-developed tractive structures (F6 and F7) and mud-draped scours that characterize Type C beds in the proximal areas (see fig.47, 50).

Consequently, the structural highs, represented by the M. Castellaccio thrust front (CTRF) and Verghereto area, are characterized by the fine-grained deposits dominated by Type E contained-reflected beds, where evident sedimentary structures related to rebound and reflections processes can be observed. The progressive increase in the tectonic confinement is also testified by the paleocurrent analysis that highlights the directions of deflected and reflected low-density turbulent flows induced by the structural highs. The rose diagrams of figure 47, for example, show that, in the proximal part of Unit V, rebound processes were perpendicular to the M. Nero and M.Castellaccio thrusts,

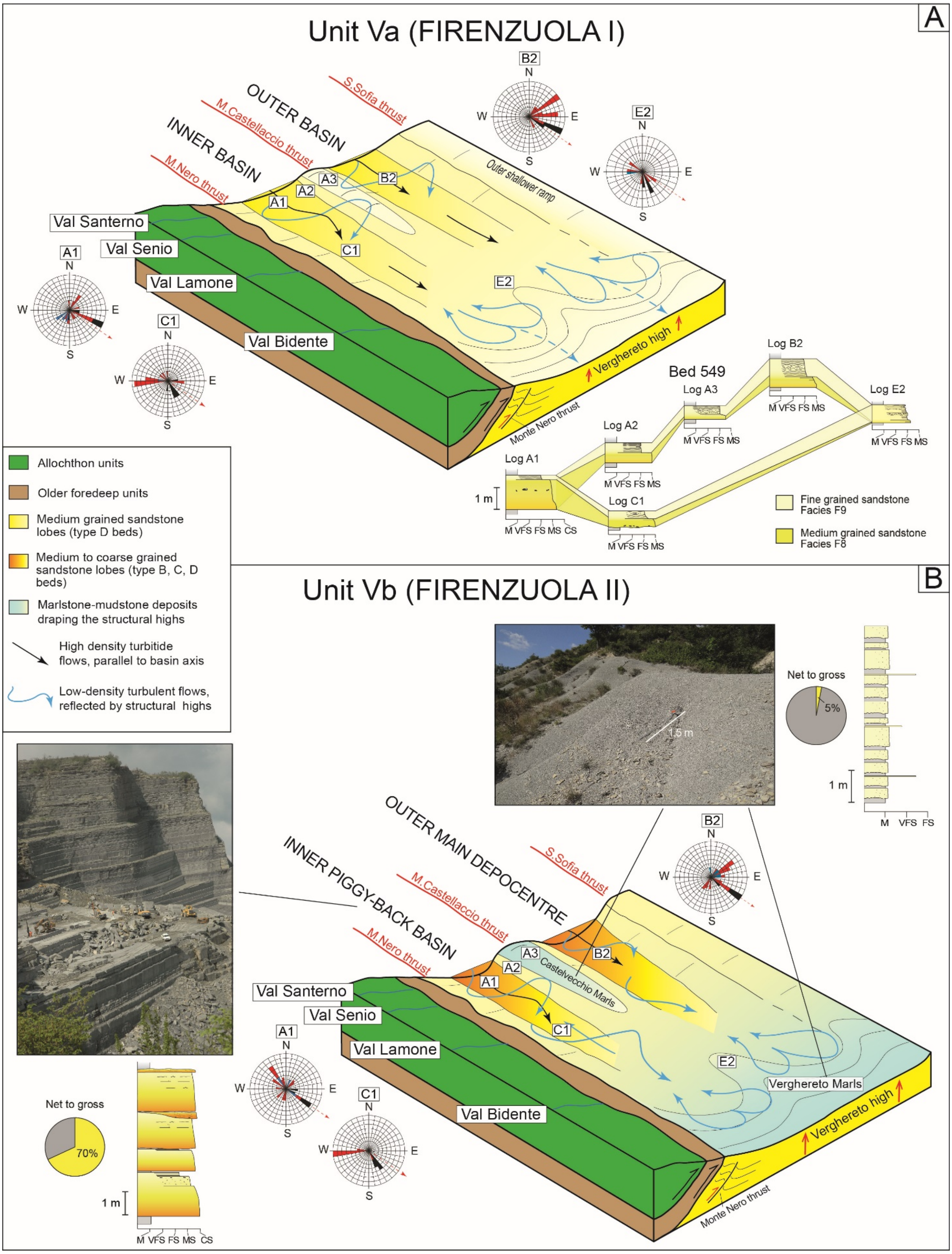


Fig.67 – Simplified schematic diagrams showing the physiographic setting of the MAF foredeep during the deposition of Unit Va (A) and Unit Vb (B), (see text for more details). In A, a fence diagram of bed 549, representing the typical facies tract down- and across-current within the Firenzuola I deposits.

showing that the turbidity currents in this areas were encased within these two structural highs (see also fig.67 and Tinterri *et al*., in press). Conversely, in more distal area of the inner basin (see Log C1) rebound processes were dominated by a components toward the W and NW, indicating that the turbidity currents were strongly influenced by the morphology created by the Casaglia MTC and the structural alignment represented by the M. Castellaccio thrust and Verghereto area (fig.67). In the same way, the analysis of the stratigraphic cross section in the outer basin (figure 50) shows that, in the proximal area (Log B2), the turbidity currents were almost systematically reflected toward NE, due to the strong uplift of the inner margin of the new outer basin represented by the M. Castellaccio thrust front; conversely, in more distal areas, paleocurrents show an evident components toward the W and NW, because of the strong influence of an obstacle oriented perpendicularly to the general paleocurrents and represented by the Verghereto high.

In conclusion, the stratigraphic and sedimentologic data presented in this work can substantiate a detailed paleogeographic scheme of the MAF foredeep during the strong phase of basin segmentation occurring in Unit V (see also Muzzi Magalhaes & Tinterri, 2010; Tinterri & Muzzi Magalhaes, 2011). The paleogeography proposed in figure 67 is also consistent with that proposed by Lucente (2004) (see also Lucente & Pini, 2003, 2008), which was based mainly on the study of the dynamics and emplacements of MTCs related to the growth of thrust propagation folds. The main novelty of this work - in comparison with those by Lucente & Pini (2003, 2008) is the highlighting of the basin physiographic variations controlled by syn-sedimentary tectonics based on high-resolution stratigraphic framework and lateral and vertical variations of the six bed types (Type A to F), which has proven fundamental to understand the location and geometry of the topographic highs and depocenters produced by M. Castellaccio thrust propagation fold, Verghereto high and emplacements of Casaglia and Bedetta MTCs as well as the way they affected depositional processes.

8.2 Exploration perspective

The Firenzuola system represents a perfect analog of a turbidite system in which syn-sedimentary tectonics plays a key role in controlling flow efficiency, sediment dispersal pattern and facies distribution. Similar settings can be found in hydrocarbon exploration and exploitation areas, such as subsurface syn / post-rift basins of passive continental margins and in intraslope basins of the Gulf of Mexico (Prather *et al*., 1998, Prather, 2003, Sinclair & Tomasso, 2002, Tinterri & Tagliaferri, 2015), in which syn-depositional tectonics is mainly driven by salt withdrawal. The evolution of the latter can be summarized in three main phases:

1) Flow ponding, characterized by a tectonic confinement that can favour ponding processes
2) Filling and flow stripping, during which the increasing tectonic confinement causes deposition of massive sandstone in depocentral areas and flow stripping of the finer low density turbulent parts of the flows
3) Bypass and abandonment, characterized by the shifting of the main depocenter toward outer basins.

This evolution resembles the transitional deposits of the MAF (Tinterri & Tagliaferri, 2015), characterized by a first phase of Type E beds deposition near areas of topographic highs (Unit IV and Va) due to tectonic-induced topographic reliefs able to produce ponding processes, a second phase of increasing tectonic confinement and progressive isolation of the inner basin, dominated by Type B and C sandstone-lobe accumulation in depocentral areas associated with bypass of the low density turbulent part of the flows that deposit finer sedimentary load over lateral and downcurrent topographic highs, a final shifting of the main depocenter toward the outer basin Paretaio

system deposits (Unit VI) after the Visignano MTC emplacement.
Therefore, detailed facies analysis together with high-resolution physical-stratigraphy studies like this one, can be useful to predict detailed vertical and lateral facies transitions in subsurface basins characterized by similar evolution history, in which the seismic stratigraphy resolution is not enough to unravel singular beds or facies thickness. Moreover, the 3D facies model carried out with Petrel provides a basis for further future studies, such as bulk volume calculations and prediction of fluid dynamic behaviour throughout the system, since each facies is characterized by specific petrophysical properties (porosity and permeability).

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