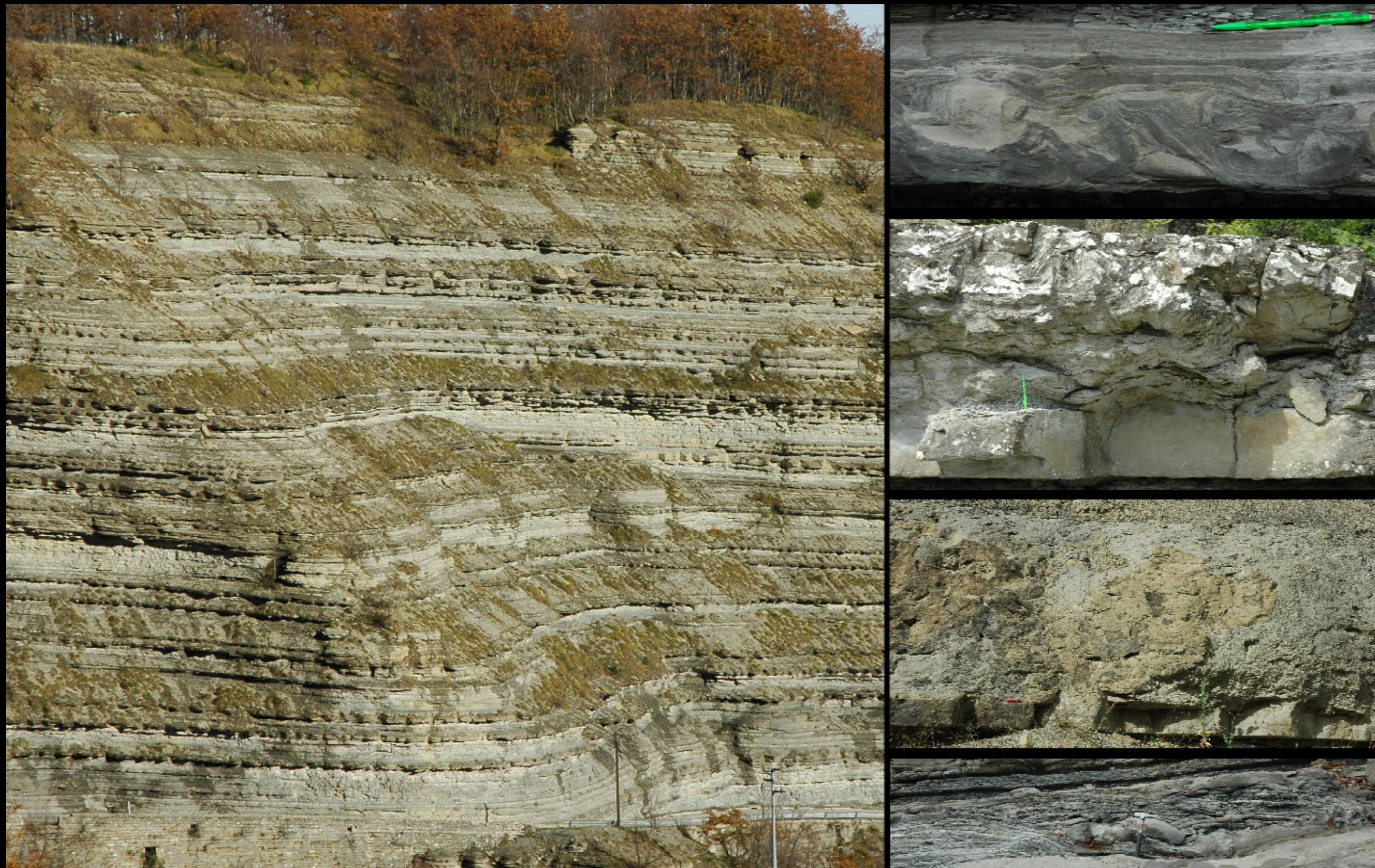
Geological Field Trips



Società Geologica Italiana

ISPRA
Istituto Superiore per la Protezione e la Ricerca Ambientale

SERVIZIO GEOLOGICO D'ITALIA
Organo Cartografico dello Stato (legge N°68 del 2-2-1960)
Dipartimento Difesa del Suolo

2012
Vol. 4 (2.1)

ISSN: 2038-4947

Foredeep turbidites of the Miocene Marnoso-arenacea Formation (Northern Apennines)

AAPG International Conference & Exhibition - Milan, 2011

DOI: 10.3301/GFT.2012.03

GFT - *Geological Field Trips*

Periodico semestrale del Servizio Geologico d'Italia - ISPRA e della Società Geologica Italiana
Geol.F.Trips, Vol.**4** No.2.1 (2012), 133 pp., 65 figs. (DOI 10.3301/GFT.2012.03)

Foredeep turbidites of the Miocene Marnoso-arenacea Formation (Northern Apennines)

AAPG International Conference & Exhibition - Milan, 2011

Roberto Tinterri(1), Pierre Muzzi Magalhaes(1)(2), Alessio Tagliaferri(1)

(1) Department of Earth Sciences, University of Parma, Italy
(2) Petrobras S.A., Rio de Janeiro, Brazil

Corresponding Authors Ph. 0039 0521905363, Fax 0039 0521905305; e-mail address: roberto.tinterri@unipr.it - piermuzzi@petrobras.com.br

ISSN: 2038-4947 [online]

http://www.isprambiente.it/site/it-IT/Pubblicazioni/Periodici_tecnici/Geological_Field_Trips

INDEX

Information

Excursion notes

Itinerary

DOI: 10.3301/GFT.2012.03

Abstract

The Marnoso-arenacea Formation (MAF, Langhian-Tortonian) was deposited in an elongate, NW-stretched foredeep basin formed in front of the growing Northern Apennines orogenic wedge (Figs. 2, 3A). These types of deposits have always had a fundamental role in the hystory of turbidites, because a great part of the models and facies schemes proposed in the literature have often been developed on these types of deposits. Among foredeep turbidites, the MAF is probably the most famous, the best exposed and less structurally deformed, due to its relatively external position within the Apenninic orogen. These characteristics have often favoured detailed physical stratigraphy studies, such as the pioneering ones by Ricci Lucchi and his co-workers (see for example Ricci Lucchi & Valmori, 1980).
As indicated in figure 3, an idealized transect oriented perpendicularly to the main structural axes shows that sedimentation of a foreland region takes place in three distinct and coeval basins including: a) wedge-top basins, characterized by alluvial, deltaic and mixed depositional systems; b) a foredeep basin, characteristically in-filled with deep-water basinal turbidites; c) an outer and shallower ramp developed on the passive foreland plate. The progressive thrust propagation toward the outer margin of the basin produces a vertical superimposition of three depositional systems that, from base to top, are: (1) highly efficient basinal turbidite systems and associated hemipelagic deposits; (2) mixed depositional systems, in which turbidite-like bodies are deposited by poorly efficient gravity flows in a structurally confined basin. They can be associated to prodeltaic sediments, both vertically and laterally; (3) flood-dominated deltaic systems (see Mutti et al., 2003).

The vertical stacking pattern of the MAF, illustrated in figures 4 and 33, is characterized by same vertical stratigraphic evolution in which at least three main depositional systems can be recognized and are represented by Langhian to Serravallian high-efficiency basinal turbidites, Tortonian low-efficiency mixed turbidites and shallow water Messinian euxinic shales and evaporites (Ricci Lucchi, 1978, 1981, 1986; Mutti et al., 2002a; Roveri et al., 2003; Tinterri & Muzzi Magalhaes, 2011). The MAF, therefore, consists of a shoaling-up stratigraphic succession, which results from the progressive closure of the foredeep due to the north-eastward propagation of the main thrust front of the MAF. Consequently, this eastward thrust propagation has produced a progressive uplift of the inner portions of the foredeep and a subsequent shifting in the same direction of the

DOI: 10.3301/GFT.2012.03

main depocentres. For this reason, Ricci Lucchi (1986) introduced the concepts of inner stage or basin (Langhian-Serravallian in age) and outer stage or basin (Tortonian in age). The first one is characterized by deep water high efficiency basinal turbidites, while the second one consists of low-efficient mixed turbidites in a shallower and more confined basin. The passage between inner and outer stages is recorded by an important tectonic phase (upper Serravallian in age) characterising the basal part of Unit V by Muzzi Magalhaes & Tinterri (2010), which is time equivalent to the Firenzuola and Paretaio systems (Figs. 4 and 33).
The MAF stratigraphic succession, therefore, can be described in three stages: 1) a Langhian-Serravallian inner basin; 2) an Upper Serravallian phase that records the transition between inner and outer basins and 3) a Tortonian outer basin (see Fig. 33). These three stages or basins are characterized by three different facies associations related to the progressive increase, over time, of the structural control and the associated morphologic confinement. This fact, influencing especially the erosive degree and the deceleration rate of the turbidity currents, induces the formation of different bed types. The MAF foredeep can be considered as a complex foredeep (as meant by Ricci Lucchi, 1986) characterized by sin-sedimentary structural highs and depocenters related to the main thrust fronts within the MAF foredeep, which significantly control the lateral and vertical distribution of turbidite facies (see Muzzi Magalhaes & Tinterri, 2010; Tinterri & Muzzi Magalhaes, 2011).

Therefore, after a short and general introduction to the geology and stratigraphy of the northern Apennines, the main targets of this field trip will be the stratigraphy, facies and processes of foredeep turbidites of the MAF outcropping in the north-eastern Apennines, focusing especially on two specific aspects of the MAF sedimentation: 1) the synsedimentary structural control affecting the MAF turbidites deposited in an elongate, NW-stretched complex foredeep basin formed in front of the growing Northern Apennines orogenic wedge and 2) the vertical facies changes of the MAF stratigraphic succession (more than 4000m thick) in relation to the progressive closure, uplift and consequent fragmentation of the foredeep due to the north-eastward propagation of the Apennine orogenic wedge (Fig. 33).

Key words: Marnoso-arenacea Formation (MAF); Foredeep turbidites, Facies analysis, Syntectonic sedimentation.

Riassunto

Le torbiditi di avanfossa dell'Appennino settentrionale (Macigno, Cervarola, Marnoso-arenacea) si depongono in un bacino allungato in direzione NW-SE posizionato al fronte del cuneo orogenico appenninico che si propaga verso N e NE. Questi tipi di depositi hanno sempre rivestito un ruolo fondamentale nella storia delle torbiditi perchè gran parte dei modelli e degli schemi di facies proposti nel corso degli anni, a partire dagli stessi concetti di risedimentazione di Migliorini, sono stati sviluppati proprio in depositi di questo tipo. Tra le unità torbiditiche di avanfossa dell'Appennino, la Formazione Marnoso-arenacea (FMA) di età Langhiano-Tortoniana è sicuramente una delle più famose, meglio esposte e tettonicamente meno deformate a causa della sua posizione relativamente più esterna. Queste caratteristiche hanno spesso favorito gli studi di stratigrafia fisica di dettaglio a partire dai lavori pioneristici di Ricci Lucchi e dei suoi collaboratori (vedasi ad esempio Ricci Lucchi & Valmori, 1980).
In particolare, un transetto orientato perpendicolarmente agli assi strutturali di un bacino di avanfossa mostra che la sedimentazione al suo interno può essere suddivisa in tre distinti domini tempo equivalenti: a) bacini di *wedge-top*, caratterizzati dalla presenza di sistemi alluvionali, deltizi e torbiditici misti nel senso di Mutti et al. (2003); b) bacino di avanfossa, dominato da torbiditi bacinali ad alta efficienza; c) rampa esterna caratterizzata da una graduale diminuzione batimetrica (Fig. 3). La progressiva propagazione dei fronti di accavallamento verso il margine esterno del bacino produce la sovrapposizione verticale dei sistemi deposizionali che caratterizzano questi tre domini e che, dal basso verso l'alto, sono: 1) sistemi torbiditici bacinali ad alta efficienza, con associati depositi emipelagici; 2) sistemi torbiditici misti depositati ad opera di flussi gravitativi a bassa efficienza che possono essere associati, sia verticalmente che lateralmente, a sedimenti di prodelta; 3) sistemi deltizi (Mutti et al., 2003).

La successione sedimentaria della FMA, come illustrato nelle figure 4 e 33, è caratterizzata dalla stessa evoluzione verticale; essa infatti è costituita da torbiditi bacinali nella porzione langhiano - serravalliana, che passano verso l'alto a torbiditi a bassa efficienza tortoniane e ad argille eusiniche ed evaporiti messiniane (Ricci Lucchi, 1978, 1981, 1986; Mutti et al., 2002a; Roveri et al., 2003; Tinterri & Muzzi Magalhaes, 2011). La FMA mostra quindi un'evoluzione di tipo *shoaling-upward*, come conseguenza della progressiva chiusura del bacino di avanfossa, causata dalla progressiva propagazione verso NE dei principali *thrusts* del sistema catena-avanfossa. Tale avanzamento tettonico produce un graduale sollevamento e una progressiva riduzione

6

DOI: 10.3301/GFT.2012.03

batimetrica della porzione interna del bacino di avanfossa, con un conseguente spostamento verso NE del depocentro del bacino stesso. Per questa ragione Ricci Lucchi (1986) introduce il concetto di stadio o bacino interno (per la porzione langhiano – serravalliana) e stadio o bacino esterno (per la porzione tortoniana). Il primo è caratterizzato dalla presenza di torbiditi bacinali ad alta efficienza, il secondo da torbiditi a bassa efficienza legate a sistemi misti depositati all'interno di un bacino maggiormente confinato e meno profondo. Il passaggio bacino interno – bacino esterno avviene a causa di un'importante fase tettonica (nel Serravalliano superiore), che caratterizza la parte basale dell'unità V di Muzzi Magalhaes & Tinterri (2010), la quale è tempo equivalente ai sistemi di Firenzuola e Paretaio nella valle del Santerno (vedi figure 4 e 33).
La successione sedimentaria della FMA, quindi, può essere suddivisa in tre fasi: a) un bacino interno langhiano – serravalliano; 2) una fase di passaggio bacino interno – bacino esterno tardo serravalliana; 3) un bacino esterno tortoniano (vedi Fig. 33). Questi tre bacini sono caratterizzati da tre diverse associazioni di facies la cui origine dipende essenzialmente dal controllo strutturale e dal confinamento tettonico che aumenta progressivamente nel tempo. Il grado di confinamento del bacino, infatti, può controllare il grado di erosione e di decelerazione dei flussi i quali tenderanno a produrre facies differenti a seconda di quanto il bacino è confinato (vedasi Fig. 33). L'avanfossa della FMA, inoltre, può essere vista come avanfossa complessa nel senso di Ricci Lucchi (1986) caratterizata da alti strutturali e depocentri sinsedimentari legati ai principali allineamenti strutturali interni all'avanfossa che controllano in modo preponderante la distribuzione latero-verticale delle facies torbiditiche (vedasi Muzzi Magalhaes & Tinterri, 2010 e Tinterri & Muzzi Magalhaes, 2011).

Da questo punto di vista, i principali obiettivi di questa escursione geologica, dopo una breve e generale introduzione alla geologia e alla stratigrafia dell'Appennino settentrionale, saranno la stratigrafia, le facies e i processi delle torbiditi di avanfossa della FMA, focalizzandosi soprattutto su due aspetti specifici della sedimentazione: 1) il controllo strutturale sin-sedimentario e la sua influenza sulle torbiditi della FMA, depositate all'interno di una avanfossa complessa, e 2) il cambiamento di facies verticale che si registra nella successione stratigrafica della FMA (più di 4000 m di spessore) in relazione alla progressiva chiusura, sollevamento e frammentazione dell'avanfossa come conseguenza della progressiva propagazione verso nord est del cuneo orogenetico appenninico (Fig. 33).

Parole chiave: Formazione Marnoso-arenacea (MAF); Torbiditi di avanfossa, Analisi di facies, Sedimentazione sintettonica.

DOI: 10.3301/GFT.2012.03

Program Schedule

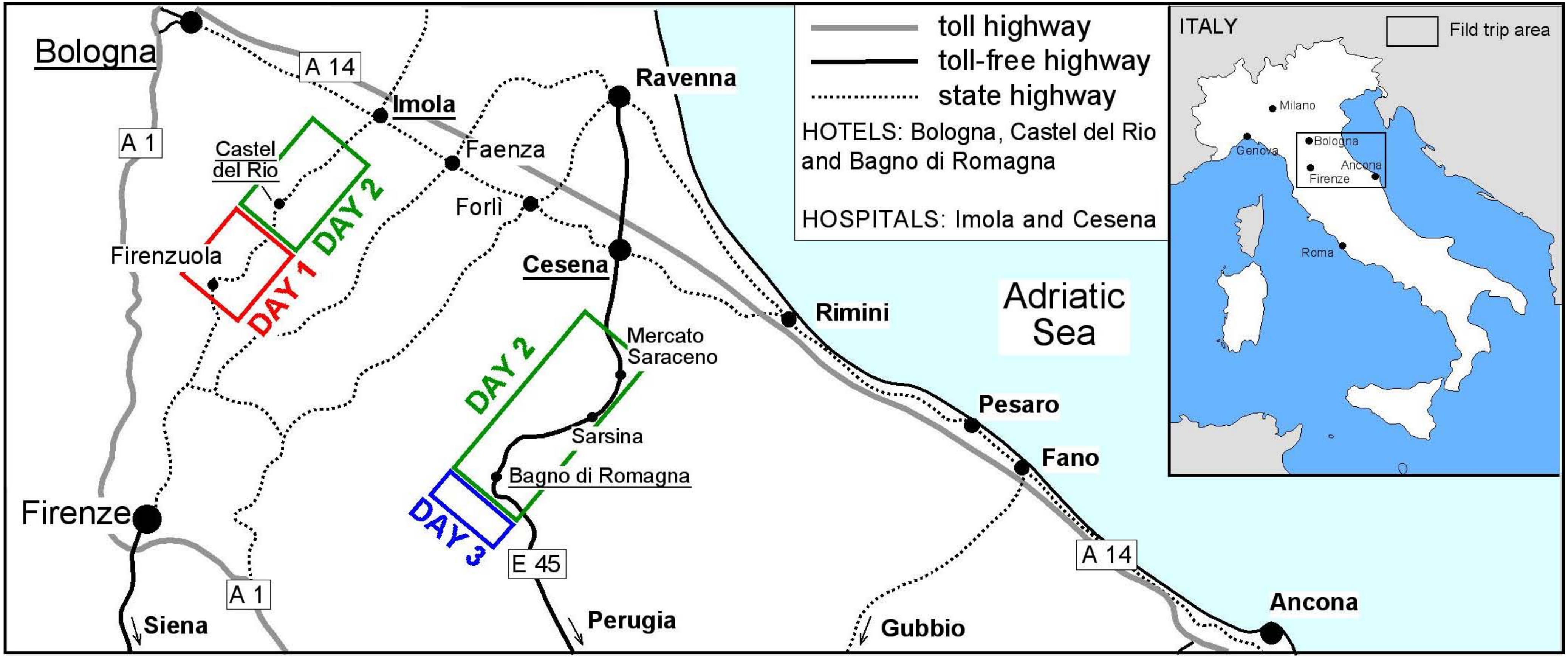


Fig. 1A - Field trip itinerary, showing the main roads, hotels and hospitals locations.

Day 1

A brief introduction to the geological setting of the northern Apennines and the Marnoso-arenacea Formation (MAF, Langhian-Tortonian) will be given on the field. The day will focus on the lower and middle part of the stratigraphic succession (Langhian and Serravallian basin plain turbidites) and on the structural control on the facies distribution pattern associated to the progressive closure of the foredeep. Climbing difficulty: overall low to nil, except Stop 1.6 (low to medium).

DOI: 10.3301/GFT.2012.03

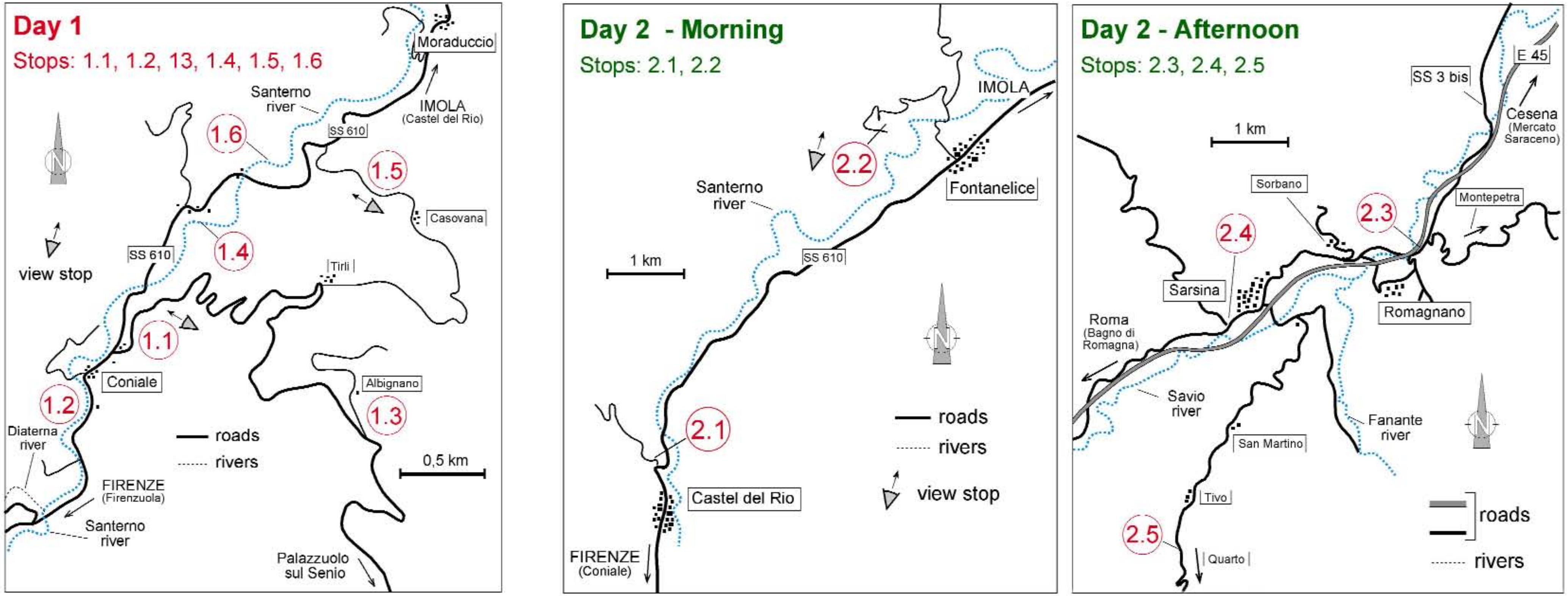


Fig. 1B - Field trip itineraries of the first and second day.

Departure from Bologna to the Santerno Valley, 8.00.

Stop 1 at Coniale, for a spectacular view of sheet sandstones containing the Contessa key bed.

Stop 2 at Acquadalto mass transport complexes (MTC) - lower part of the MAF stratigraphic succession (Langhian) outcropping in the Santerno Valley. Facies characteristics of turbidites influenced by structurally controlled topography and MTC deposition.

Stop 3 Tirli/Albignano - lower part of the MAF stratigraphic succession (Langhian). Facies characteristics of turbidites related to controlled topography.

13.00 lunch on the field

DOI: 10.3301/GFT.2012.03

Stop 4 Contessa Stop - facies analysis of the Contessa bed (a typical example of a contained-reflected bed). Outcrop on the Santerno River.

Stop 5 and 6 Paretaio Stop - MAF, middle part of the stratigraphic succession (Serravallian). Facies characteristics of turbidites influenced by structurally controlled topography and MTC deposition. At this location, two outcrops will be analysed:

A) a view of the Paretaio turbidite systems and the Visignano mass transport deposits.

B) the contact between Visignano MTC and Paretaio turbidite systems along the Santerno river.

18.30 return to the hotel (Imola)

Day 2

The day will be devoted to the analysis of the upper part of the stratigraphic succession (Tortonian) in the Santerno and Savio valleys. Due to a phase of basin narrowing, these deposits show facies characteristics that are quite different from the underlying Langhian and Serravallian turbidites. The structurally-controlled Langhian and Serravallian turbidites of the Savio Valley will be observed in the late afternoon.

Overall very low climbing difficulty – hikes along roads

Departure from Imola, 8.30.

Stop 1 at Castel del Rio - MAF, upper part of the stratigraphic succession (Tortonian). Thick-bedded and coarse-grained turbidites interpreted as mixed turbidite systems (*sensu* Mutti et al., 2003).

Stop 2 at Fontanelice - MAF, overview on the upper part of the stratigraphic succession (Tortonian-Messinian). Thick-bedded and coarse-grained turbidites interpreted as mixed turbidite systems. Discussion on the closure of the MAF foredeep in the Santerno Valley.

Transfer to the Savio Valley (Cesena and Bagno di Romagna)

13.00 lunch on the field

Stop 3 at Romagnano – upper part of MAF, (Tortonian). Thick-bedded and coarse-grained turbidites interpreted as mixed turbidite systems. Comparison with Castel del Rio and Fontanelice facies in Santerno Valley (distance: 60km).

Stop 4 at Sarsina - upper part of MAF (Tortonian). Thick-bedded and coarse-grained turbidites; comparison with Castel del Rio and Fontanelice facies in the Santerno Valley.

DOI: 10.3301/GFT.2012.03

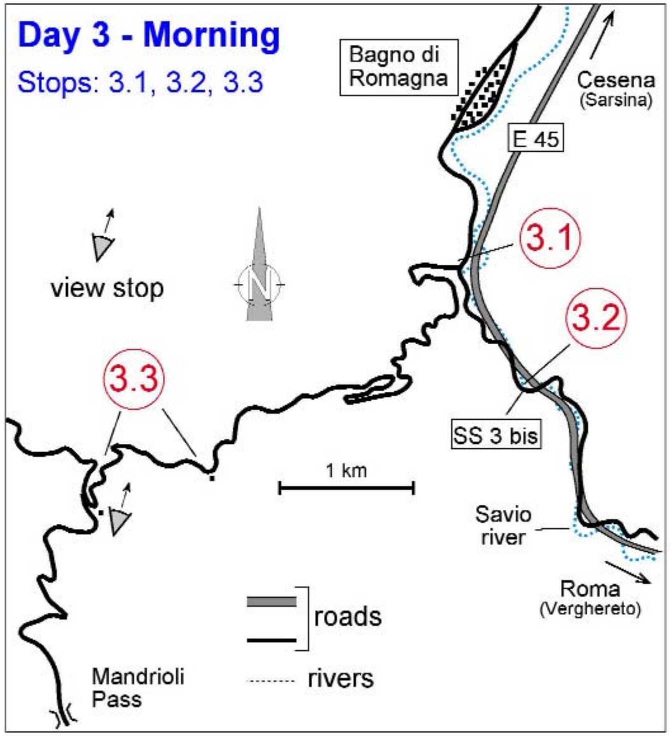
Stop 5 at San Martino - middle part of MAF (Serravallian). Spectacular outcrop showing fine-grained basinal turbidites (contained-reflected beds); the relationship between paleocurrents variations and mass transport complexes will be discussed.
18.30 return to the hotel (Bagno di Romagna)

Day 3

The day will be devoted to the analysis of the Serravallian middle part of the stratigraphic succession in the Savio valley, where spectacular examples of tectonically confined basin plain deposits are exposed. Overall very low climbing difficulty – hikes along roads.

Departure from Bagno di Romagna, 8.30
Stops 1 and 2 at the base of Mandrioli pass - lower part of MAF (Serravallian). Io key bed and bed 66 (base of Unit II). The latter is a bed type indicating structural uplift; its lateral relationship with MTC will be discussed.
Stop 3 at Mandrioli pass - middle part of MAF, (Serravallian). Spectacular outcrop showing fine-grained basinal turbidites (contained-reflected beds).
13.00 lunch on the field

Stop 4 at Verghereto - middle part of MAF (Serravallian). Spectacular outcrop showing mass transport complexes and fine–grained marly turbidites deposited above the Verghereto structural high.
15.30-16.00 transfer to the Bologna railway station and/or airport (expected arrival time: 18.00).



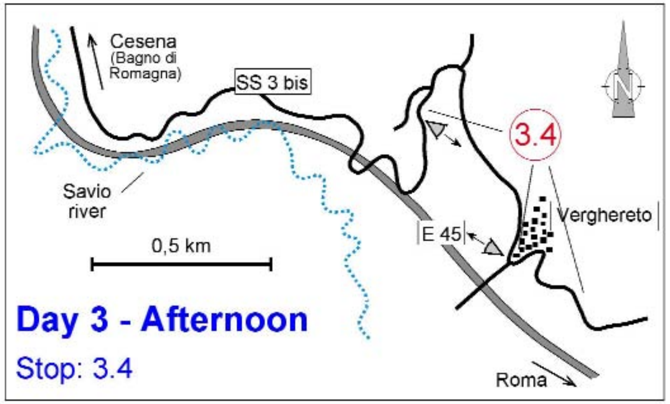


Fig. 1C - Field trip itinerary of the third day.

DOI: 10.3301/GFT.2012.03

Logistics and safety

Safety in the field is closely related to awareness of potential difficulties, fitness and use of appropriate equipment. Safety is a personal responsability and all partecipants should be aware of the following issues: **Climate and temperature (October)**: 8 -18°C, possible showers of rain. **Altitude range (meters)**: 100 -1200m. **Physical difficulty**: low, some walking along moderately steep slopes. Maximum walking distance about 1km (in approximately 30min). **Recommended field equipment**: trekking boots, sun-protection and hats or headscarves. A sweater, a wind jacket, a foldable umbrella and a backpack can be very useful. **Meals and drinks**: all provided, an extra personal bottle of water may be an option.
Participants should inform the excursion leaders (in confidence) of any physical or mental conditions which may affect performance on the field.

Emergency Contact Numbers

Important: to call the U.S. dial the International code first (001). Country Code for Italy is 0039.

Police	113
Carabinieri (a police corp)	112
First aid	118
Firefighters	115

IMOLA – "Azienda Unità Sanitaria Locale di Imola" Hospital, Via Montericco, 4 - 40026 Imola (BO) - Ph. 0039 0542 662111
CESENA – "M. BUFALINI" Hospital, Viale Ghirotti, 286 - 47023 Cesena (FO) - Ph. 0039 0547 352111

DOI: 10.3301/GFT.2012.03

1. Introduction

The outcropping area of the structurally-controlled turbidites of the Marnoso-arenacea Formation (MAF) (Langhian to Tortonian in age) can be divided into two sectors by the Marecchia line (Fig. 2A, B); the northern sector representing the Romagna Apennines and the southern sector representing the Umbrian Apennines. This field trip focuses on the north-eastern Romagna Apennines extending from the Sillaro line to the west and as far as the Marecchia line to the east (red square in Fig. 2A).

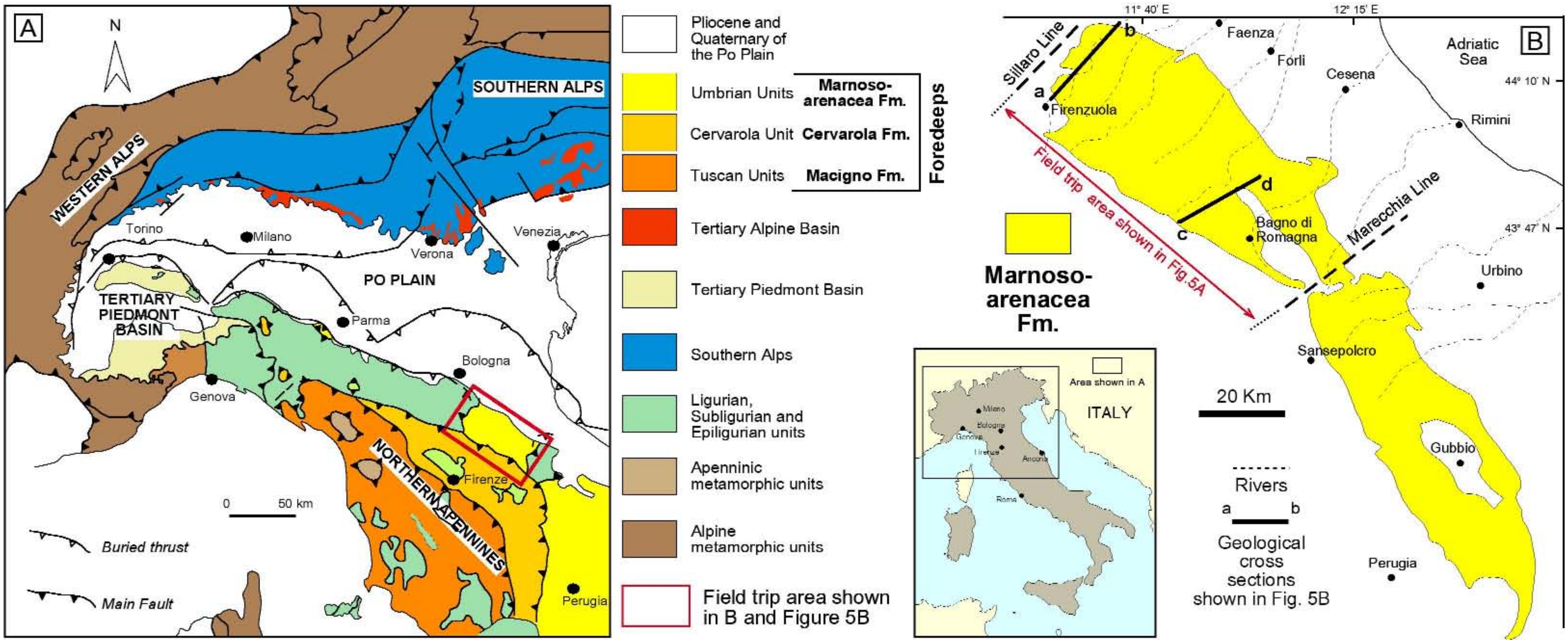


Fig. 2 - A) Simplified geological map of northern Italy; B) MAF crops out in the northern Apennines (from Muzzi Magalhaes & Tinterri, 2010).

DOI: 10.3301/GFT.2012.03

The MAF was deposited in an elongate, NW-stretched foredeep basin formed in front of the growing Northern Apennines orogenic wedge (Ricci Lucchi, 1978, 1981, 1986). The stratigraphic succession of MAF is most likely over 4000m thick and records the progressive closure of the foredeep basin due to the NE propagation of thrust fronts. In this setting, Langhian to Serravallian turbidites are progressively replaced by Tortonian sand-rich mixed turbidites (Mutti et al., 2002a; 2003), late Tortonian-early Messinian euxinic shales and evaporites of the Messinian Gessoso-Solfifera Formation marking the definitive uplift and closure of the MAF foredeep (Roveri et al., 2003).
Various studies have shown that the MAF stratigraphy and depositional setting are complicated by a structural deformation that exerted control over basin geometry, facies distribution patterns and emplacement of mass-transport complexes (MTCs) (Ricci Lucchi, 1986; Argnani & Ricci Lucchi, 2001; Conti, 2001; Mutti et al., 2002a; Roveri et al., 2002; Lucente, 2004; Muzzi Magalhaes & Tinterri, 2010; Tinterri & Muzzi Magalhaes, 2009; 2011). In particular, Muzzi Magalhaes & Tinterri (2010, see also Muzzi Magalhaes, 2009; Tinterri & Muzzi Magalhaes, 2011) presented a new high-resolution stratigraphic framework of the Langhian to Serravallian basin plain deposits of the MAF in the area to the north of Val Marecchia alignment, identifying, in addition to the MTCs, at least five bed types and relative facies tracts (Types 1, 2, 3, 4, 5), which have proven to be important to understand the relationships between flow efficiency and structurally-controlled basin physiography.

By contrast, the upper part of the MAF succession (Tortonian in age) was formed by relatively smaller and sand-richer mixed systems; i.e. immature and poorly-efficient turbidite-like systems formed seaward of, but adjacent to, feeder delta complexes (Mutti et al., 2002b; 2003); their origin also depends upon flow decelerations associated to topographic confinement related to the basin fragmentation due to the progressive closure of the foredeep (Tinterri and Muzzi Magalhaes, 2009; 2011). In particular, the vertical passage between Langhian to Serravallian basinal turbidites and Tortonian sand-rich mixed turbidite systems is marked by the diffuse presence of large volume mass transport complexes (MTCs) and thick sandstone beds with intermediate sedimentary characteristics heralding the upper mixed deposits (Tinterri, Tagliaferri et al., in prep.).
This field trip, therefore, will be focused on two specific aspects of the MAF sedimentation: **1)** the synsedimentary structural control affecting MAF turbidites and **2)** the vertical facies changes of the MAF stratigraphic succession in relation to the progressive closure, uplift and consequent fragmentation of the foredeep due to the north-eastward propagation of the Apennine orogenic wedge.

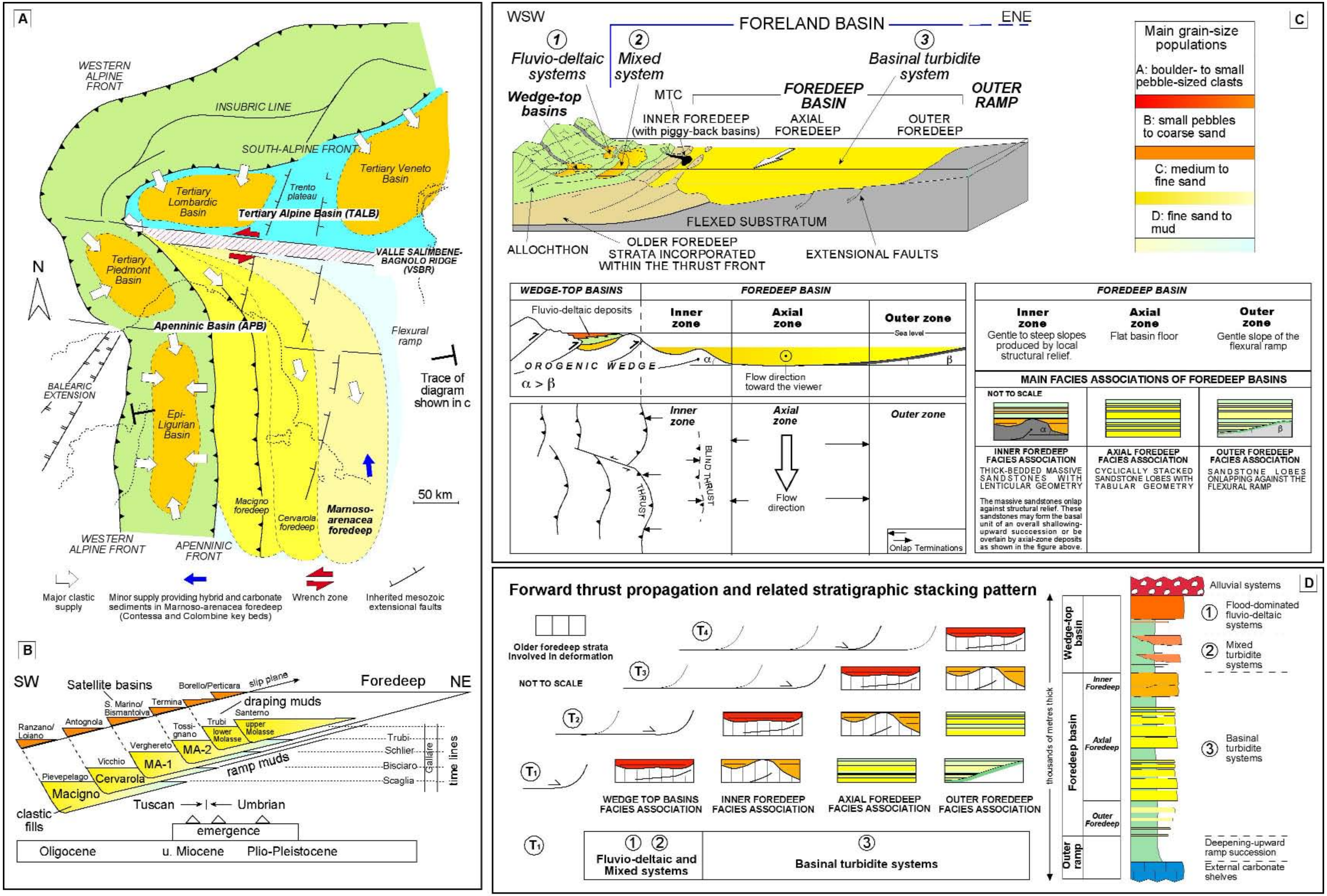
DOI: 10.3301/GFT.2012.03

2. MAF Geologic and Stratigraphic Setting

In foreland basins, the deep and narrow trough which forms adjacent to the thrust front is commonly termed foredeep, and, until the orogenic wedge is not significantly uplifted and emerged, the trough is characteristically filled in with axial turbidites sourced from fluvio-deltaic systems located in emerged areas of adjacent orogens, where substantial tectonic uplift has already occurred (Fig. 3A; see also Allen and Homewood, 1986; Artoni et al., 2000). In such basins, turbidites form huge sedimentary prisms exposed for hundreds of kilometres parallel to local structural axes as, for example, in the Apennines, the western Alps and the Pyrenees. The concept of turbidites (Kuenen & Migliorini, 1950), the Bouma sequence (Bouma, 1962) and early facies and fan models (Mutti & Ricci Lucchi, 1972) were born in basin-fills of this kind.
The Apennines foredeep basin, therefore, is one of the most classic examples of deep-water turbidite basins associated to the development of an orogenic wedge (e.g., Ricci Lucchi, 1986 with references). The sediment fill of this basin mainly consists of deep-water sandy turbidites of the Macigno, Cervarola, Marnoso-arenacea and Laga Formations, which, due to the progressive eastward thrust propagation and ensuing depocentre migration in the same direction, pass into and overlap the fine-grained and progressively younger strata of a receding flexural ramp to the east (Fig. 3B and C). These turbidites were progressively incorporated into the frontal part of the orogen during its NE propagation.

The Langhian to Tortonian MAF, whose proximal deposits are presently buried in the western Apennines under the Ligurian thrust sheet (see Fig. 2A and Zattin et al., 2000; 2002), represents one of the clastic wedges marking the main evolutionary stages of the Apennines foredeep basin. The basin, in which the MAF deposition occurred, is well represented in figure 3A, which shows the simplified paleogeographic map of the Proto-Adriatic basin (PAB) introduced by di Biase & Mutti (2002).
The MAF turbidites were mainly fed by Alpine fluvio-deltaic systems to the north (see also Gandolfi et al., 1983, 2007; Ricci Lucchi, 1978, 1981, 1986; Zattin & Zuffa, 2004) able to produce turbidity currents flowing toward the south-east, which deposited a great part of their sediment load in an elongate, southern NW-SE-stretched foredeep formed in front of the growing Apennine orogenic wedge. The main sediment dispersal pattern of the MAF, therefore, was longitudinal and the NW-to-SE flowing turbidity currents had a siliciclastic composition. However, MAF sedimentation was also characterized by minor sources located in the southern and

DOI: 10.3301/GFT.2012.03



DOI: 10.3301/GFT.2012.03

Fig. 3 - **A)** Physiographic map depicting the inferred configuration and main features of the Proto-Adriatic Basin during the late Oligocene to middle Miocene (slightly modified from di Biase & Mutti, 2002). MAF paleocurrent data are taken from Gandolfi et al (1983); **B)** Model showing the inferred stratigraphic correlations between satellite, or piggy-back, basins and the classic foredeep sandy turbidite systems of the northern Apennines (from Ricci Lucchi, 1986); **C)** Scheme showing the main elements of a foreland basin and the relationships between a growing orogenic wedge and the outer flexed board (from Mutti et al., 2003). The main facies associations of inner, axial and outer foredeep are also illustrated (from Artoni et al., 2000); **D)** Progressive thrust propagation toward the outer zone and related vertical stacking pattern of foredeep turbidites (modified from Mutti et al., 2003).

southeastern margins of the basin which were able to produce carbonate (“Colombine”) and hybrid (“Contessa-like”) turbidity currents flowing in the opposite direction, i.e. towards the NW (Fig. 3A). These southern sources were very important because they produced the main MAF key beds, which are now fundamental for high-resolution stratigraphic correlations.
As stressed by Mutti et al. (2003) (see also Artoni et al., 2000), the fill of a foredeep basin is characterized by three broad facies associations in a cross-section perpendicular to the structural axis of the basin and, thus, to the overall paleocurrent direction.

The <u>inner facies association</u> occurs in the thrust front region and is characterized by thick-bedded and massive sandstone facies, commonly amalgamated or containing thin mudstone partings. These sandstone bodies are generally characterized by lenticular geometry, due to their deposition in structural depressions or in broad channels, and are associated to slope mudstones, chaotic deposits and thin-bedded and fine-grained turbidites. The <u>axial facies association,</u> which represents the volumetrically predominant type of sediment in the fill of the foredeep, is characterized by cyclically stacked sandstone lobes with remarkable tabular geometry. The <u>outer facies association</u> is expressed by the onlap of the axial sandstone lobes against the flexural ramp. Mutti et al. (2003) interpret these facies associations as primarily related to the asymmetric cross-sectional geometry of the basin and, therefore, to the control exerted by the local topography on turbidite sedimentation. The foredeep sedimentation came to an end when the uplifted orogenic wedge was sufficiently emerged to provide a source for the development of laterally-derived turbidites and associated fluvio-deltaic systems. Laterally-derived turbidites are usually deposited at shallower depth than that of the former foredeep.
All foreland basins, therefore, notwithstanding the different geodynamic setting and general basin configuration, show an overall similar evolution characterized by three main stages (Mutti et al., 2003; see

DOI: 10.3301/GFT.2012.03

also Covey, 1986; Ricci Lucchi, 1986, Fig. 3C, D). The first one records the inception of thrusting and flexural subsidence. By contrast, the second one is recorded by turbidite sand deposition in the foredeep and the migration of the foredeep axis and sand depocentres toward the outer flexural ramp, due to forward thrust propagation; while in the third and final stage, basinal turbidite sedimentation has progressively been replaced by fluvio-deltaic and eventually alluvial sedimentation (Fig. 3D).

The sedimentary evolution of the MAF is essentially the same. It has been described as having two main evolutionary stages or basins - an older inner stage (Langhian to Serravallian) and a younger outer stage (Tortonian), recording the progressive closure of the MAF foredeep (Ricci Lucchi, 1986) (Fig. 4). More precisely, the Marnoso-arenacea deposits have been subdivided into four depositional sequences by Ricci Lucchi (1986), i.e. LS and S characterizing the inner stage, and T1 and T2 characterizing the outer stage, each recording the shift towards the foreland (E-NE) of the main depocentre (Figs. 4 and 5).

The basal and middle part of the older inner stage consists mainly of basin-plain turbidites deposited by large-volume and highly-efficient turbidity currents that were able to reach the distal and ponded part of the foredeep. By

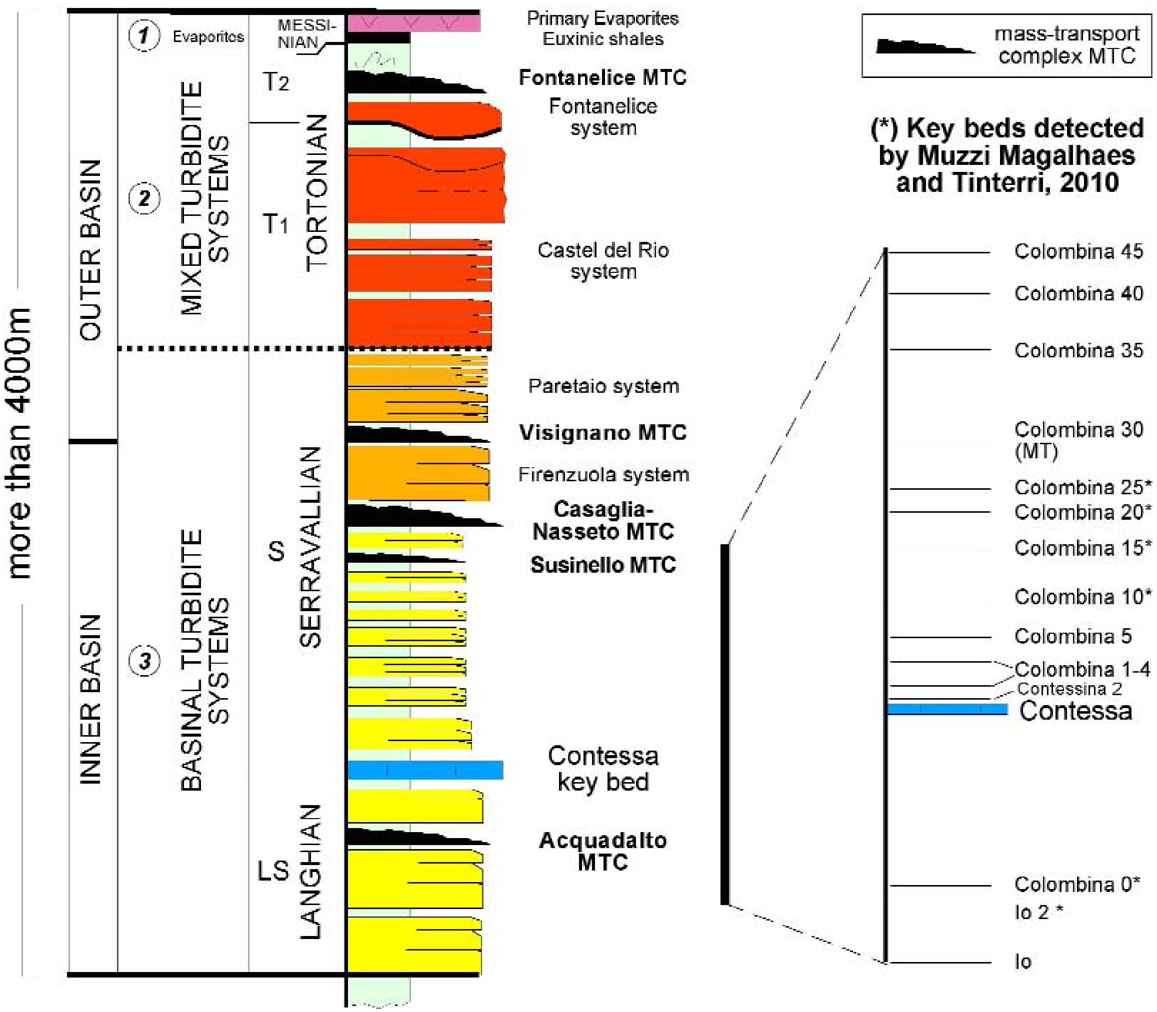


Fig. 4 - Schematic stratigraphic log of the Marnoso-arenacea Formation (in Muzzi Magalhaes & Tinterri, 2010 and modified from Mutti et al., 2002a). The depositional sequences (LS, S, T1 T2, by Ricci Lucchi, 1986), main mass-transport complexes (see also Lucente & Pini, 2002) and key beds by Muzzi Magalhaes & Tinterri, 2010 (see also Martelli et al., 1994) are also shown. Compare to figures 3C and D.

DOI: 10.3301/GFT.2012.03

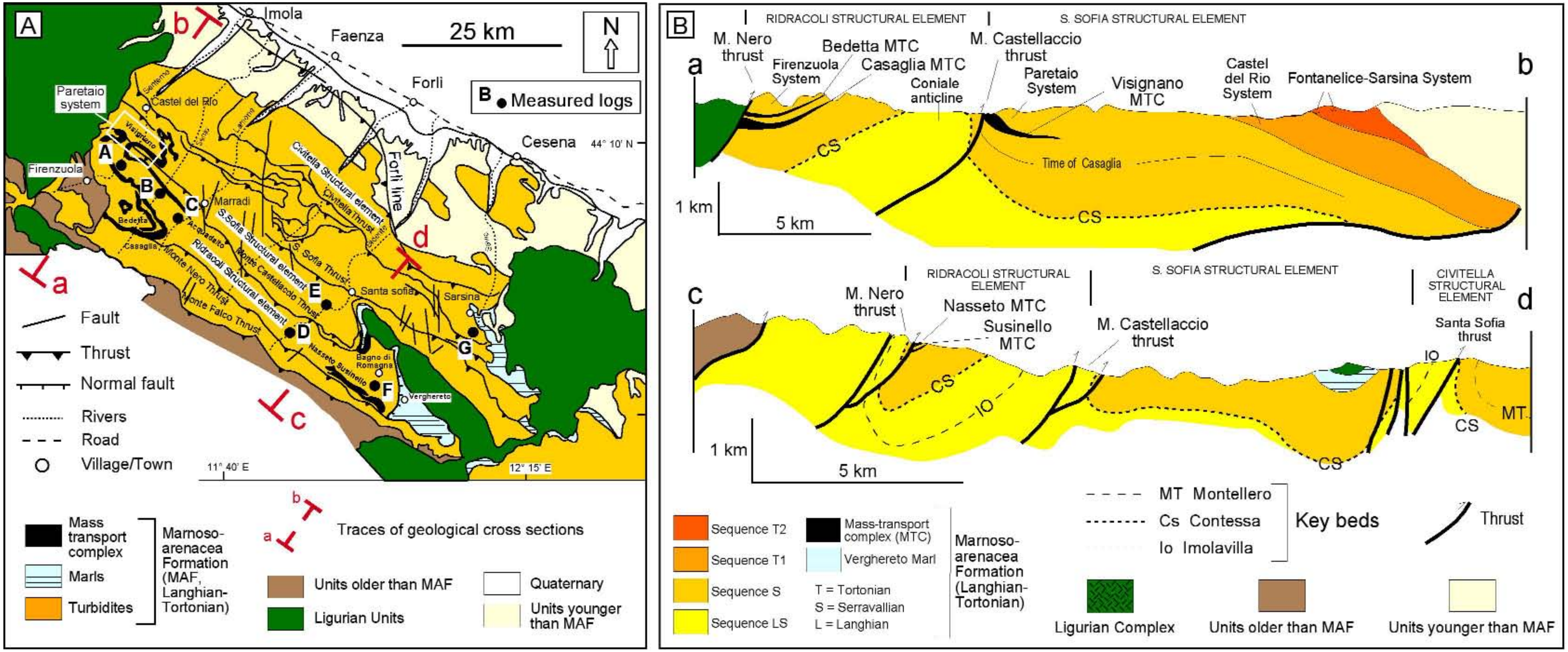


Fig. 5 - **A)** Schematic geological map of the MAF between the Santerno and Savio Valleys showing the main thrust fronts and key beds (modified from Cerrina Feroni et al., 2002). Figures 2A and B show the location of this area. Capital letters (A, B, C, D, E, F, G and H) indicate the location of the stratigraphic logs (see below); **B)** Geological cross-sections transverse to the basin axis in the proximity of the Santerno (a-b, taken from Roveri et al., 2002), and Bidente valleys (c-d, taken from Martelli et al., 1994) showing the position of major thrust faults subdividing the outcrop into structural elements. The depositional sequences LS, S, T1 and T2 are taken from Ricci Lucchi (1986); (L = Langhian, S = Serravallian and T = Tortonian).

contrast, the upper part of this stage is characterized by the appearance of large-volume MTCs and thick massive sandstone lobes which filled thrust-related depressions (Firenzuola and Paretaio turbidite systems by Mutti et al., 2002a and Roveri et al., 2002). These deposits, which are characterized by an evident vertical facies change in comparison with the underlying deposits, herald the Tortonian outer stage (T1 and T2, Ricci Lucchi, 1986) consisting of sand-rich mixed turbidite systems (*sensu* Mutti et al., 2003). Consequently, even if usually placed at the

DOI: 10.3301/GFT.2012.03

Serravallian-Tortonian boundary, the phase of strong basin narrowing that occurs at the boundary between inner and outer stage is here considered to be better represented by slightly older and more evident structural events, as highlighted by the Casaglia and Visignano MTCs (see also Roveri et al., 2002 and Tinterri & Muzzi Magalhaes, 2011). Thus, the vertical passage into mixed turbidite deposits would very likely occur in a more transitional way (Tinterri & Muzzi Magalhaes, 2011). Finally, the mixed turbidites are replaced upward by late Tortonian to early Messinian euxinic shales and by the evaporites of the Messinian Gessoso-Solfifera Fm. marking the definitive closure of the MAF foredeep (Roveri et al., 2002; 2003).
The progressive shifting towards the foreland (E-NE) of the main depocentres occurs along with foredeep basin fragmentation, due to phases of propagation and tectonic uplift of the MAF major thrust-faults, i.e. the Monte Nero, the Monte Castellaccio and Santa Sofia faults (Fig. 5A, B). They are synsedimentary northeast-verging thrusts associated to fault-propagation folds and run roughly parallel to the main NW–SE trend of the Apennine thrust belt. The occurrence of large mass-transport complexes (MTCs) emplaced at the front of thrust sheets, as well as the presence of fine grained sediments on top of intrabasinal, growing anticlines (blind fault-fold drape) (de Jager, 1979; Ricci Lucchi, 1986; Conti, 2001; Roveri et al., 2002; Lucente, 2004; Muzzi Magalhaes & Tinterri, 2010) allow the MAF foredeep to be divided into structural units consisting of broad, asymmetric synclines separated by intrabasinal highs related to blind thrust faults, whose growth rate was not exceeded by sedimentation rate (De Donatis & Mazzoli, 1994; Lucente, 2004). These observations allow the MAF foredeep to be interpreted as a complex foredeep basin, as indicated by Ricci Lucchi (1986), in which a series of sub-basins results from synsedimentary, thrust fault propagation, that is progressively younger towards the foreland.

In conclusion, as mentioned above, the stratigraphic succession of the MAF consists mainly of three types of turbidite deposits, which record the progressive uplift, closure and fragmentation of the foredeep basin. These strata, from base to top, are: 1) Langhian to Serravallian basinal turbidites characterized by a facies association indicating an axial foredeep; 2) Upper Serravallian massive sandstone lobes filling thrust-related depressions (Firenzuola and Paretaio turbidite systems) and 3) Tortonian sand-rich low efficiency “mixed” turbidite systems (Castel del Rio and Fontanelice systems) (see Figs. 3C, D and 4). The first type of turbidites records the inner stage or basin by Ricci Lucchi (1986), while the second one represents a transition phase recording the shift of the depocenter to an outer basin or stage, in which the deposition of the mixed turbidite deposits occurs.
Following this scheme of vertical evolution, these three types of turbidite deposits will be described in succession in the next sections.

DOI: 10.3301/GFT.2012.03

3. Langhian and Serravallian basinal turbidites (Inner stage)

This paragraph presents a stratigraphy and facies analysis of an interval of about 2500 metres in the Langhian and Serravallian MAF turbidite succession in the area shown in figure 5A (Muzzi Magalhaes, 2009; Muzzi Magalhaes & Tinterri, 2010; Tinterri & Muzzi Magalhaes, 2009; 2011). This high-resolution stratigraphic analysis covers an interval included between the Io key bed and time equivalent deposits of the Firenzuola and Paretaio turbidite systems (see Fig. 4) and was performed by measuring 7 stratigraphic logs between the Sillaro and Marecchia lines for a total thickness of about 7000 metres (Fig. 5A). The stratigraphic cross sections with detailed bed by bed correlations are both parallel and perpendicular to the paleocurrents and can be found in the Stop descriptions (Stops 1.1, 1.2 and 2.5). The main paleocurrents evolve toward south east and are parallel to the main structural alignments (see Figs. 3A and 5A).

The correlation of these logs was possible thanks to the presence of a number of key beds characterized by hybrid (Contessa and Io key beds) and carbonate compositions (Colombina key beds) sourced by southern carbonate platforms (Gandolfi et al., 1983; Ricci Lucchi & Valmori, 1980 and Muzzi Magalhaes & Tinterri, 2010) (see Fig. 4). This detailed stratigraphic correlation was achieved using a hierarchical approach similar to that utilized by Remacha & Fernandez (2003) in the Hecho Group (south central Pyrenees): first correlating all main key beds, represented by megaturbidites (Contessa and Colombina key beds) and MTCs, then the thick beds that can be traced over the entire study area, and, finally, thin beds. The main beds traced in all stratigraphic logs have been numbered starting from the Io key bed representing Bed 1, while Colombina beds have been numbered from 0 to 45, with an interval of 5 starting from Colombina 5, thus maintaining the numbering introduced by Ricci Lucchi & Valmori (1980).

3.1 Types of beds and facies tracts indicating synsedimentary structural control

The MAF high-resolution correlations were used to identify five bed types and relative facies tracts interpreted as related to the interaction between flow efficiency and basin physiography (see Muzzi Magalhaes & Tinterri, 2010 and Tinterri & Muzzi Magalhaes, 2011, for more details). A facies tract here means all facies observed within the same bed traced through detailed stratigraphic correlations and paleocurrent directions. In practice,

DOI: 10.3301/GFT.2012.03

it represents the deposits of the same flow undergoing transformations along its down-slope motion (Lowe, 1982; Mutti, 1992; see also Mutti et al., 1999; Tinterri et al., 2003). The general turbidite facies scheme used in this guide book is that of Mutti (1992) modified by Mutti et al. (1999; 2003), see Fig. 6A and B.

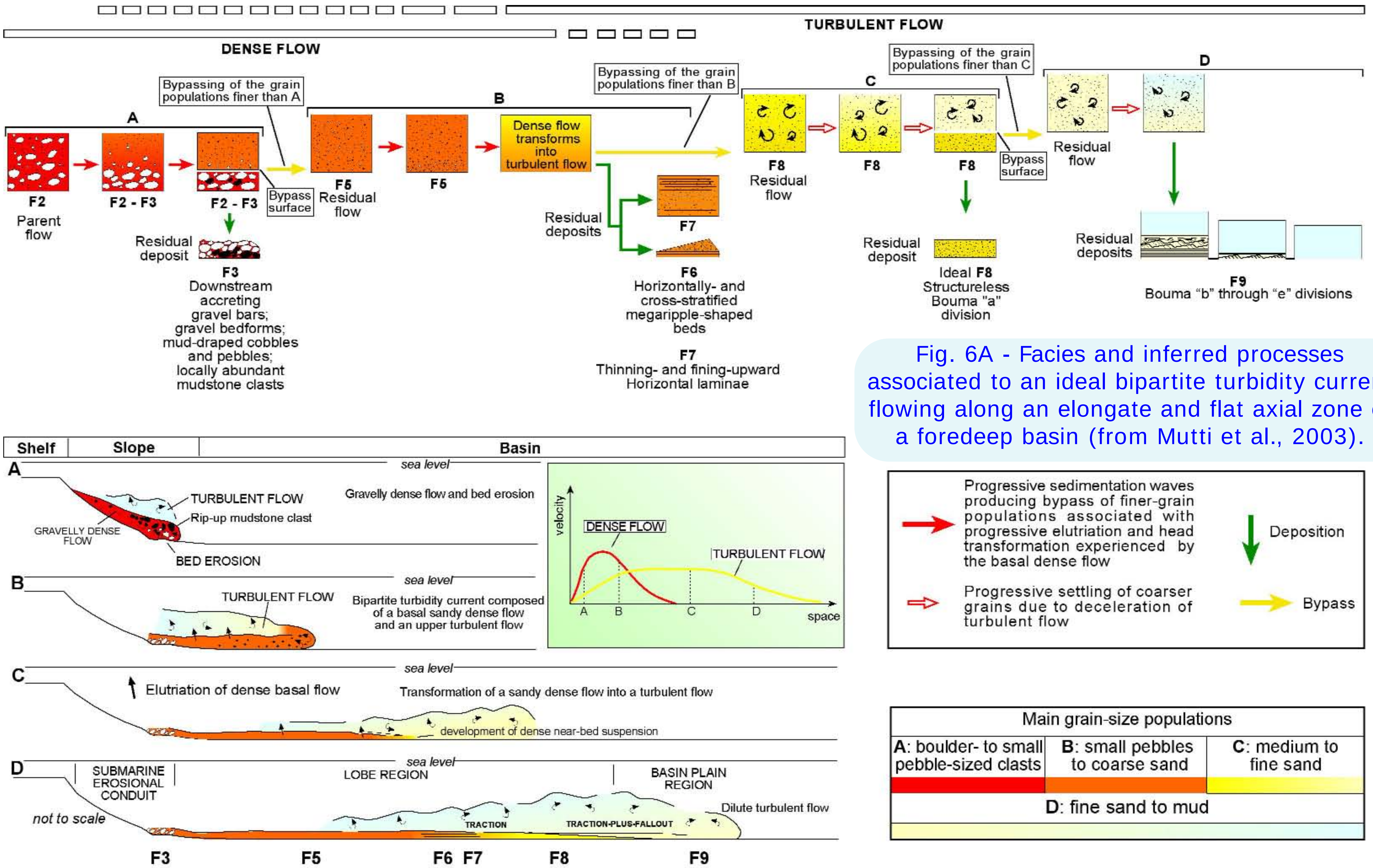
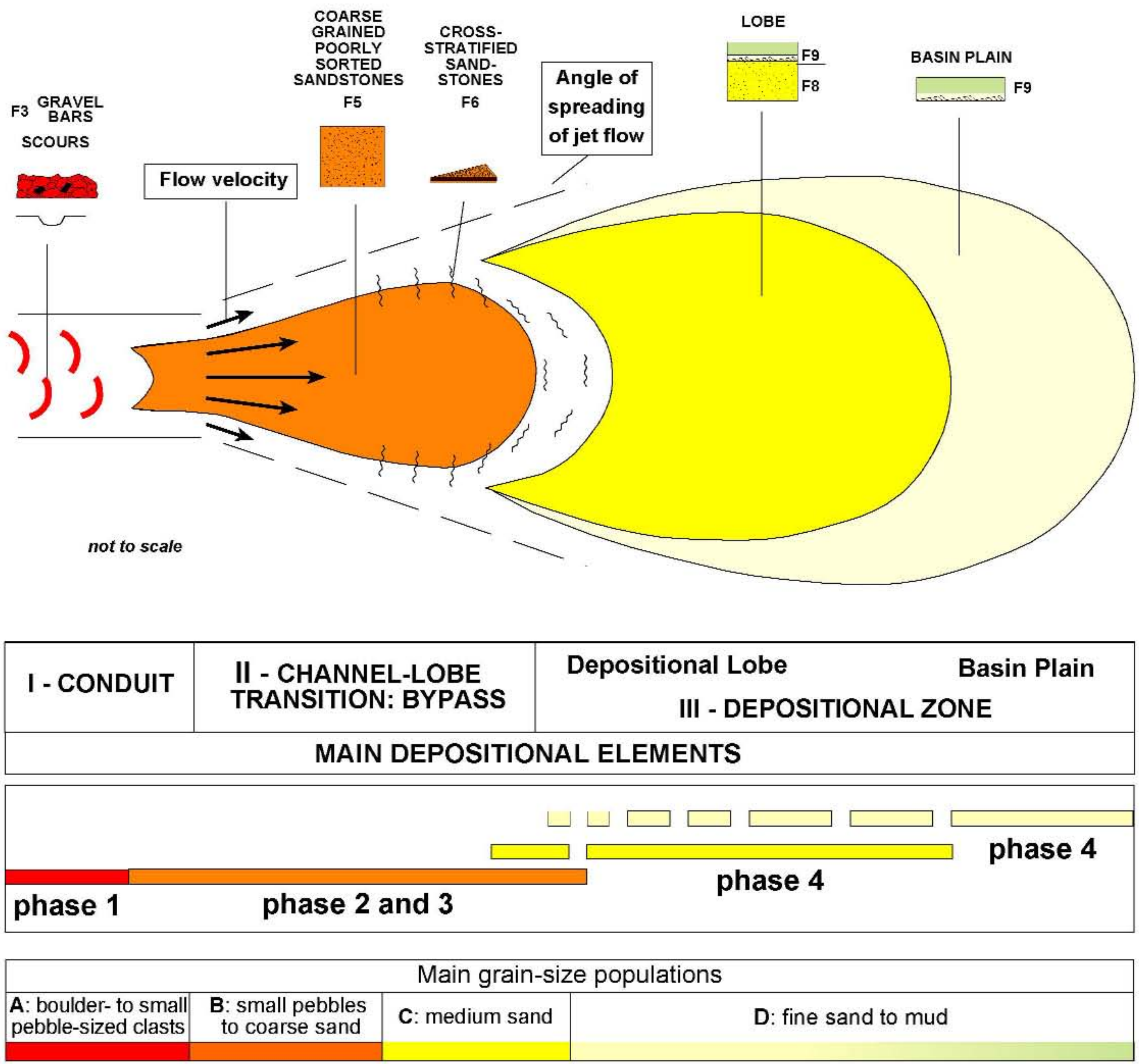


Fig. 6A - Facies and inferred processes associated to an ideal bipartite turbidity current flowing along an elongate and flat axial zone of a foredeep basin (from Mutti et al., 2003).

DOI: 10.3301/GFT.2012.03



phase 1(transfer zone): Gravity flows dominated by dense flows (F2 and F3)

phases 2 and 3 (channel lobe transition): Gravity flows dominated by bipartite flows characterized by a basal dense flow and an upper turbulent flow characterized by a near bed suspension (F5 F6 and mud draped scours)

phase 4 (depositional lobes): Gravity flows dominated by turbulent flows characterized by a basal near bed suspension (F7, F8 and F9)

phase 4 (basin plain): Gravity flows dominated by turbulent flows (F9)

Fig. 6B - Ideal depositional pattern of a highly-efficient turbidity current, in which the characteristics of the main depositional elements are shown (compare to Fig. 6A; modified from Mutti et al., 1999).

DOI: 10.3301/GFT.2012.03

These beds are as follows (see Fig. 7):

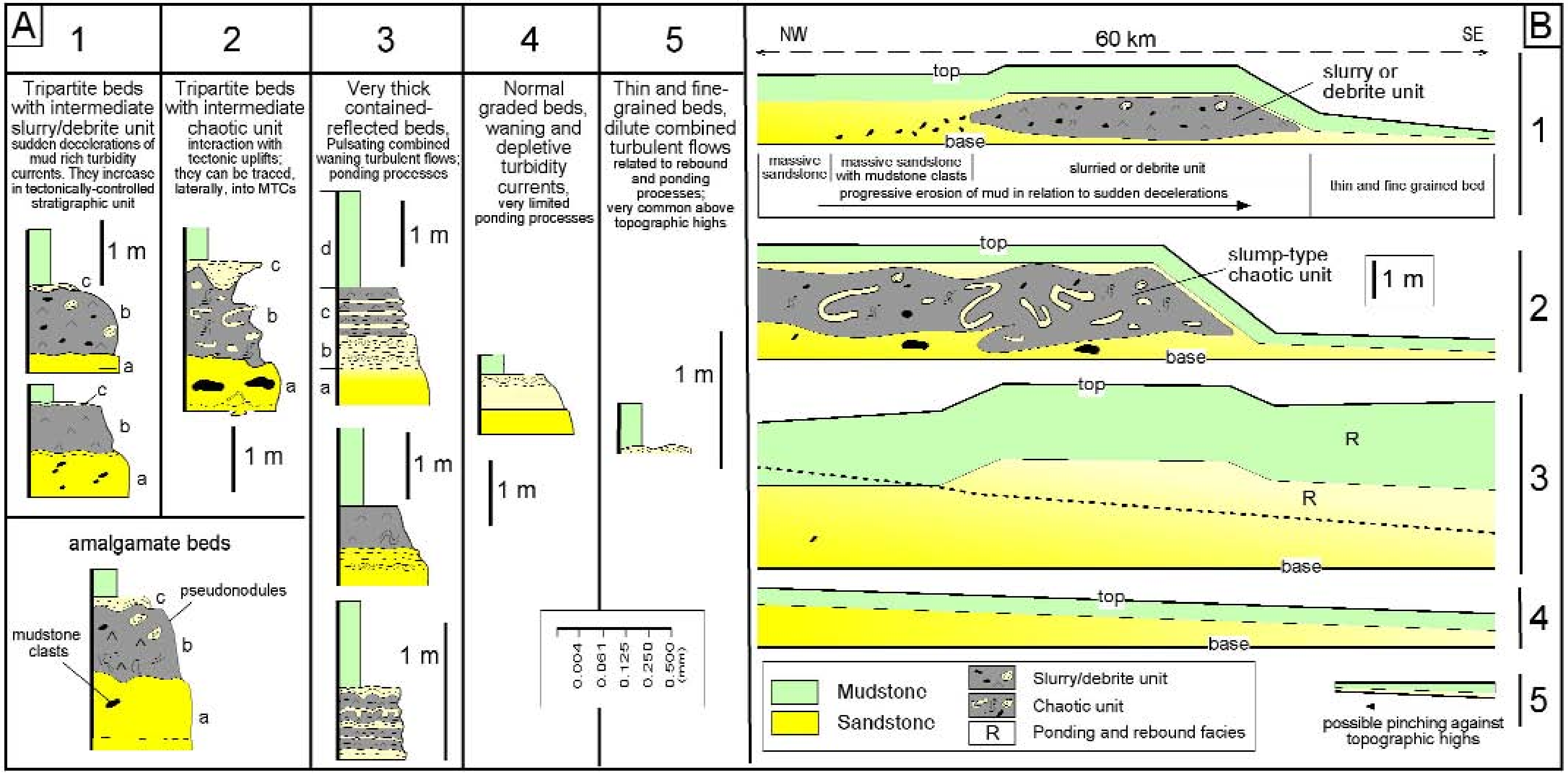


Fig. 7 - Diagram summarising the different types of bed identified in the stratigraphic succession studied. A) Scheme illustrating the five types of bed and relative interpretations; B) Diagram showing the simplified lateral geometry of the facies tracts of the five bed types described in A (from Muzzi Magahlaes & Tinterri, 2010; see also Tinterri & Muzzi Magahlaes, 2011).

Type-1 beds: thick (30cm < H-bed thickness < 100cm) to very thick (H > 100cm) beds with a thin upper mudstone division, which pass down-current into thin and fine-grained beds (Fig. 8). The basal sandstone unit consists, in the most proximal zones, of three subdivisions, which, from base to top, are: a) a massive to crude laminated, coarse to medium-grained sandstone, which sometimes passes upward into unit b through a transitional banded sandstone, as described by Haughton et al. (2009), b) a slurry or debrite unit, i.e. a poorly-sorted muddy sandstone with liquefaction structures and mudstone clasts, which is often rich in plant fragments and carbonaceous matter, c) thin- to very thin (< 10cm) laminated very-fine sandstone. In the literature, these beds have long been described and interpreted as related to flow decelerations of turbidity

DOI: 10.3301/GFT.2012.03

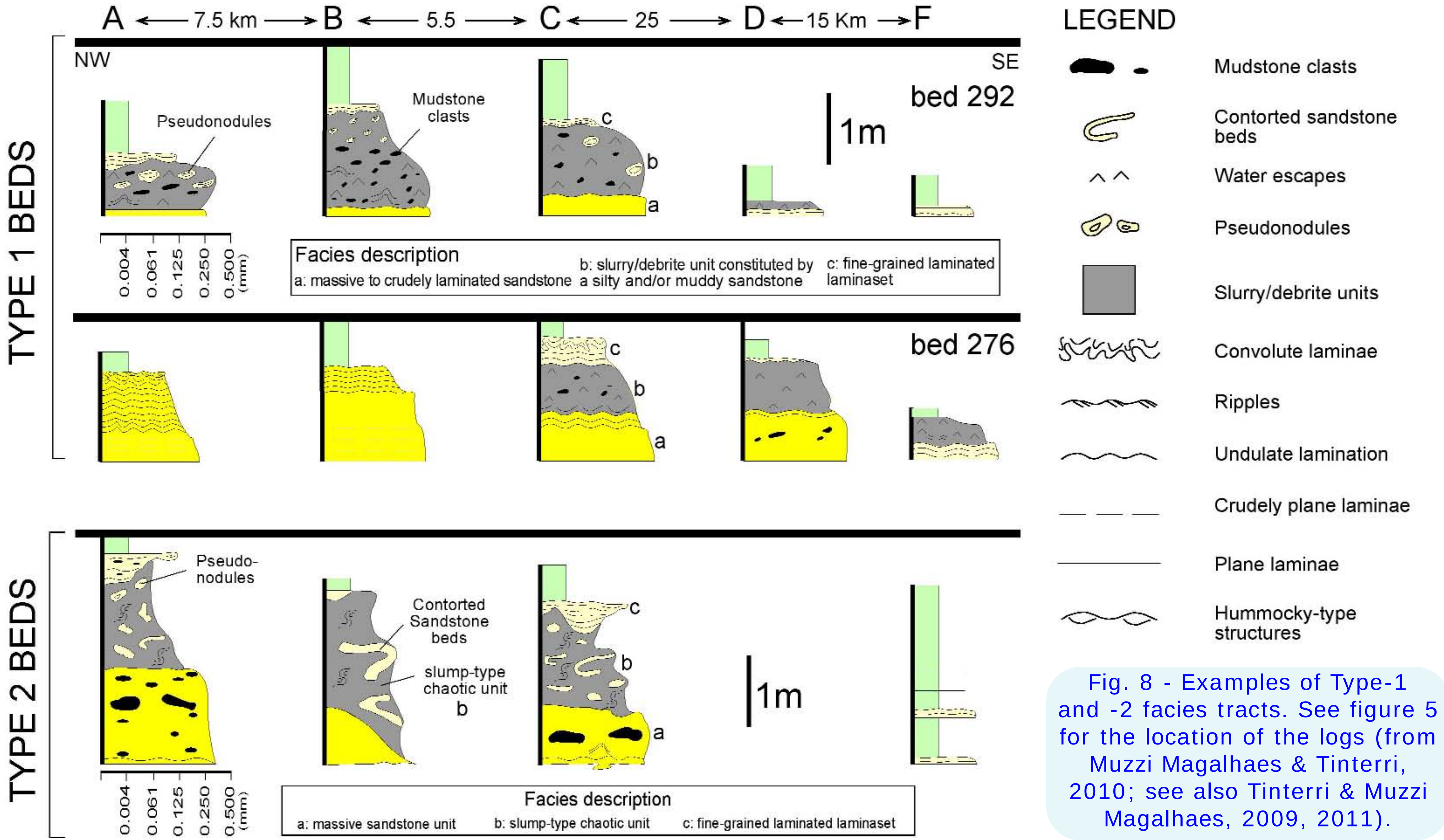


Fig. 8 - Examples of Type-1 and -2 facies tracts. See figure 5 for the location of the logs (from Muzzi Magalhaes & Tinterri, 2010; see also Tinterri & Muzzi Magalhaes, 2009, 2011).

currents, previously enriched in mud through erosive processes (see for example Van Vliet et al., 1978; Mutti et al., 1978 and Ricci Lucchi & Valmori, 1980). Nevertheless, these bed types have been further investigated in recent years (see Haughton et al., 2003, 2009; Sylvester & Lowe, 2004; Talling et al., 2004; Amy et al.,

DOI: 10.3301/GFT.2012.03

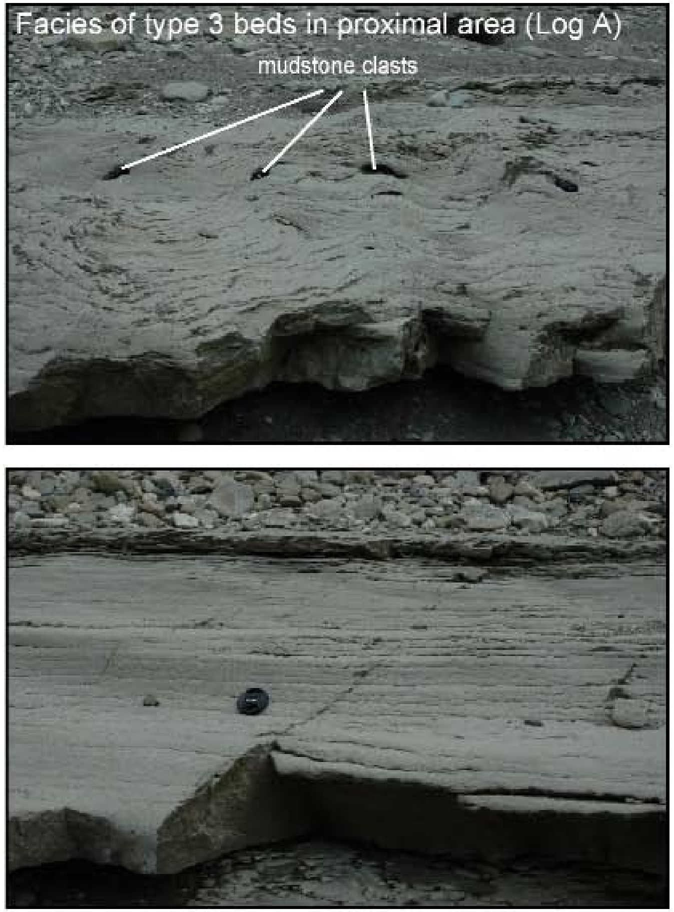
2005; 2006; Amy & Talling, 2006 and Muzzi Magalhaes & Tinterri 2010). However, the origin of these bed types, which are often observed in basin plain distal zones, can be related to two main processes: a) generation of a co-genetic debris flow from up-slope, triggered synchronously with a forerunning turbidity current (Ricci Lucchi & Valmori, 1980; Talling et al., 2004), b) an increase in fallout rate and turbulence decay favoured by rapid decelerations of mud-rich turbidity currents, as shown in experiments by Amy et al. (2006), Baas et al. (2009; 2011), Sumner et al. (2009) and field evidences by Muzzi Magalhaes & Tinterri, 2010 (see also Tinterri & Muzzi Magalhaes, 2009 and Muzzi Magalhaes et al., 2008). The processes reproduced in these experiments can generate transitional flows between turbulent and debris flows, able to create tripartite beds, very similar to Type-1 beds. Consequently, the latter can reflect the deposition from a longitudinally-fractioned ‘hybrid’ flow with a turbulent front followed by a turbulence-suppressed or transitional section (producing the banded facies in unit a) and then a ‘linked’ debris flow.

These beds, therefore, can be interpreted as being associated to out-of-grade depositional profiles that favour up-current mud erosion and the ignition phase (*sensu* Parker, 1982) of the turbidity currents. The data by Muzzi Magalhaes & Tinterri (2010) and Tinterri & Muzzi Magalhaes (2009, 2011), clearly show that the percentage of Type-1 debrite beds tends to increase, mostly in the basal part of structurally-controlled stratigraphic units, where intrabasinal topographic highs and depocentres, characterized by evident slope changes, can favour both decelerations and impact of turbidity currents previously mud-enriched. Consequently, these structurally-induced decelerations of mud-rich turbidity currents in distal basin plain are at the base of Type 1 bed formation. The latter are indeed very common in the Langhian-Serravallian inner basin, while they tend to progressively disappear upward in the Upper Serravallian transitional stage and in the Tortonian deposits of the outer stage, as the progressive closure of the foredeep humpered the flows’ ability to travel and erode large amounts of mud especially in the proximal areas.

Type-2 beds**:** very thick (H > 100cm) tripartite beds with a thin upper mudstone division, which pass down-current into thin and fine-grained beds. These beds, from base to top, consist of: a) a massive sandstone unit with very irregular top and lenticular geometry, b) an intermediate slump-type chaotic unit, generally with limited lateral extent, c) thin- to very thin (H < 10cm) laminated very fine-grained sandstone (Fig. 8). The intermediate unit “b” can be interpreted as a mass-transport deposit resulting from mass-failures produced by earthquakes related to tectonic uplift or flow impact against structurally-controlled topographic highs.

DOI: 10.3301/GFT.2012.03

In these cases, lateral micro-sliding along the beds could produce deformed and liquefied zones, especially along mudstone intervals comprised between sandstone beds. In the formation of Type-2 beds, however, the role of amalgamation processes related to impact phenomena or highly erosive flows should also be considered (Fig. 7; see also Muzzi Magalhaes & Tinterri, 2010, their Fig. 9 and Ricci Lucchi, 1980). These beds are



Facies B and C: In proximal areas these facies are represented by very thick convolute laminae (10 cm >H > 1cm) generally consisting of medium-grained sandstone with mudstone clasts

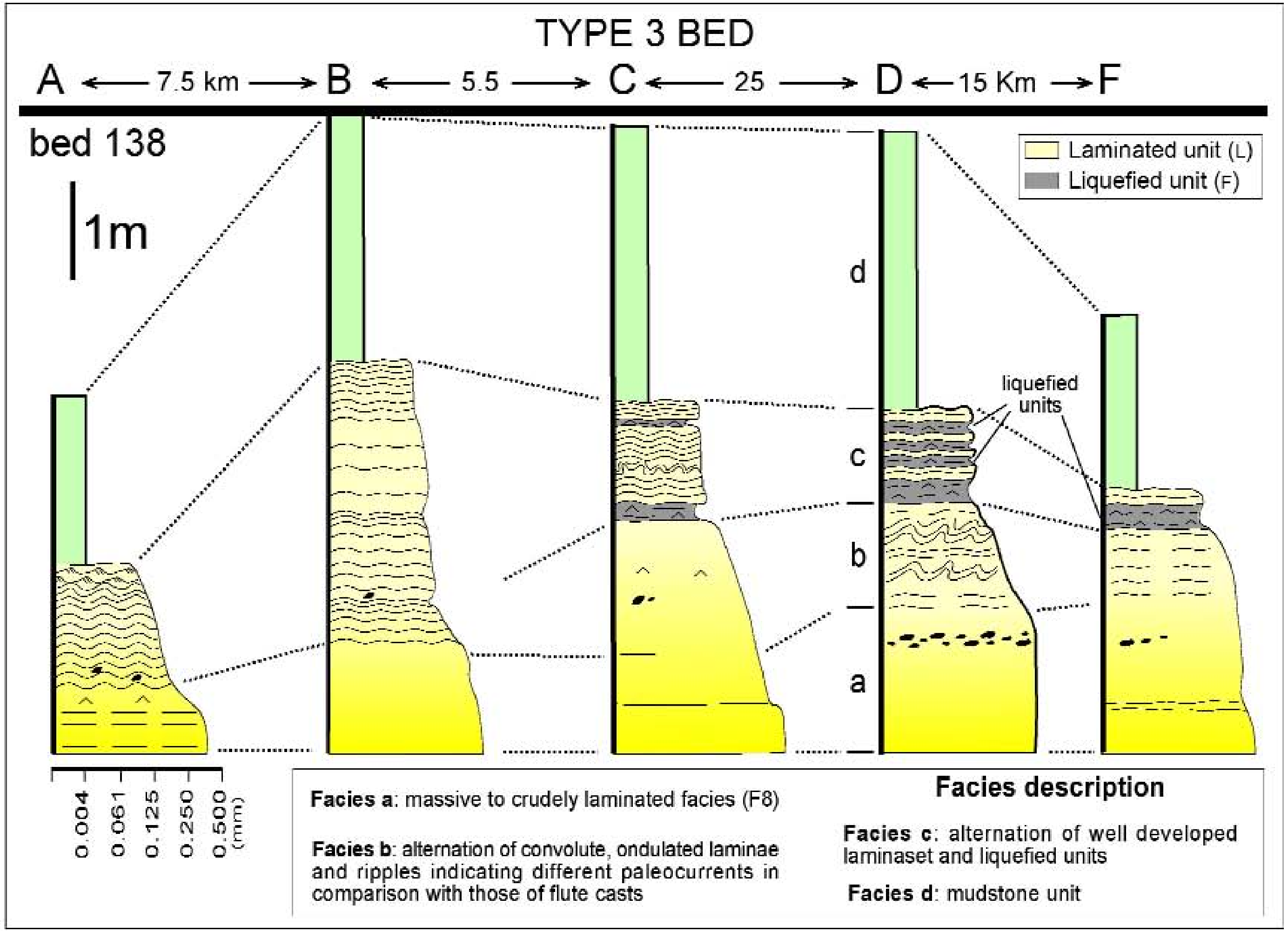


Fig. 9 - Examples of Type-3 beds related to reflections and ponding processes. The photos illustrate the proximal facies which can be interpreted as F8 Facies.

DOI: 10.3301/GFT.2012.03

relatively uncommon in comparison with Type-1 beds and are found at the basal boundaries of structurally-controlled stratigraphic units. They are associated to increases in Type-1 and -3 beds percentages (in Unit II and IV respectively, see Fig. 10) and usually can be traced laterally in well-developed MTCs of different volumes (see Fig. 10D). Type-2 beds, therefore, are interpreted as elements indicating tectonic uplift.
In particular, this work shows that the presence of Type-2 beds associated to an increase in Type-1 debrite/slurry beds can be related to structurally-controlled physiographic relieves within the basin (Muzzi Magalhaes & Tinterri, 2010).

***Type-3 beds*:** thick (30cm < H < 100cm) to very thick (H > 100cm) fine-grained sandstone beds capped by a thick mudstone unit. They are generally characterized by a down-current increase in thickness (Figs. 7, 9). Type-3 beds show great variability but, in general, they are composed of four facies as follows (Figs. 7, 9): a) a basal massive to crude laminated division with rip-up mudstone clasts made of medium-grained sandstone; b) a laminaset of fine-grained sandstone often characterized by an alternation of undulated, convoluted laminae and ripples; c) an alternation of thin to very thin laminated and liquefied units, and d) a very thick upper mudstone unit. Ripples, megaripples, small-scale anisotropic hummocky-type structures and the vergence of convolute laminae, often characterizing facies “b” and “c”, have quite different palaeocurrents from those indicated by sole casts, with variations as large as 180° between each other. However, various beds having moderate paleocurrent changes, in comparison with those of flute casts directed toward the south-east, were also found. This suggests that a continuum between strongly ponded beds and normal graded beds related to waning and depletive flows, indicated here as Type-4 beds (see below), would exist.
The facies “a” can be interpreted as a Bouma Ta or F8 of Mutti et al. (1999) related to high fallout rates able to suppress the turbulence at the boundary layer, whereas the upper fine-grained laminasets and mudstone units (facies b, c, d) can be interpreted as a Bouma Tbe or F9 facies deposited by traction plus fallout processes associated to turbulent flows. Facies b and c, however, pass up-current, in proximal areas, into very thick undulated or convolute laminae (10 cm >H > 1cm), generally consisting of medium-grained sandstone, in which mudstone clasts can be observed (see photographs and Log A in Fig. 9). This facies is a typical characteristic of Type-3 beds in proximal zones and can be interpreted as a Bouma Ta or F8, in which the sedimentation waves able to suppress the turbulence at the boundary layer are perturbated by the propagation of internal waves or bores related to the reflections processes (see also Tinterri, 2011 and Tinterri & Muzzi Magalhaes, 2011).

DOI: 10.3301/GFT.2012.03

In conclusion, these bed types, which show facies sequences very similar to those of the contained-reflected beds by Pickering & Hiscott (1985) and Remacha et al. (2005), are interpreted as being deposited by combined turbulent flows modified by rebound and ponding processes, i.e. turbidity currents characterized by an oscillatory component resulting from internal waves or bores produced by reflection and ponding processes, as shown by laboratory experiments of Edwards et al. (1994), Kneller (1995), see also Tinterri (2011). These bed types indicate different degrees of basin confinement due to a structural control.

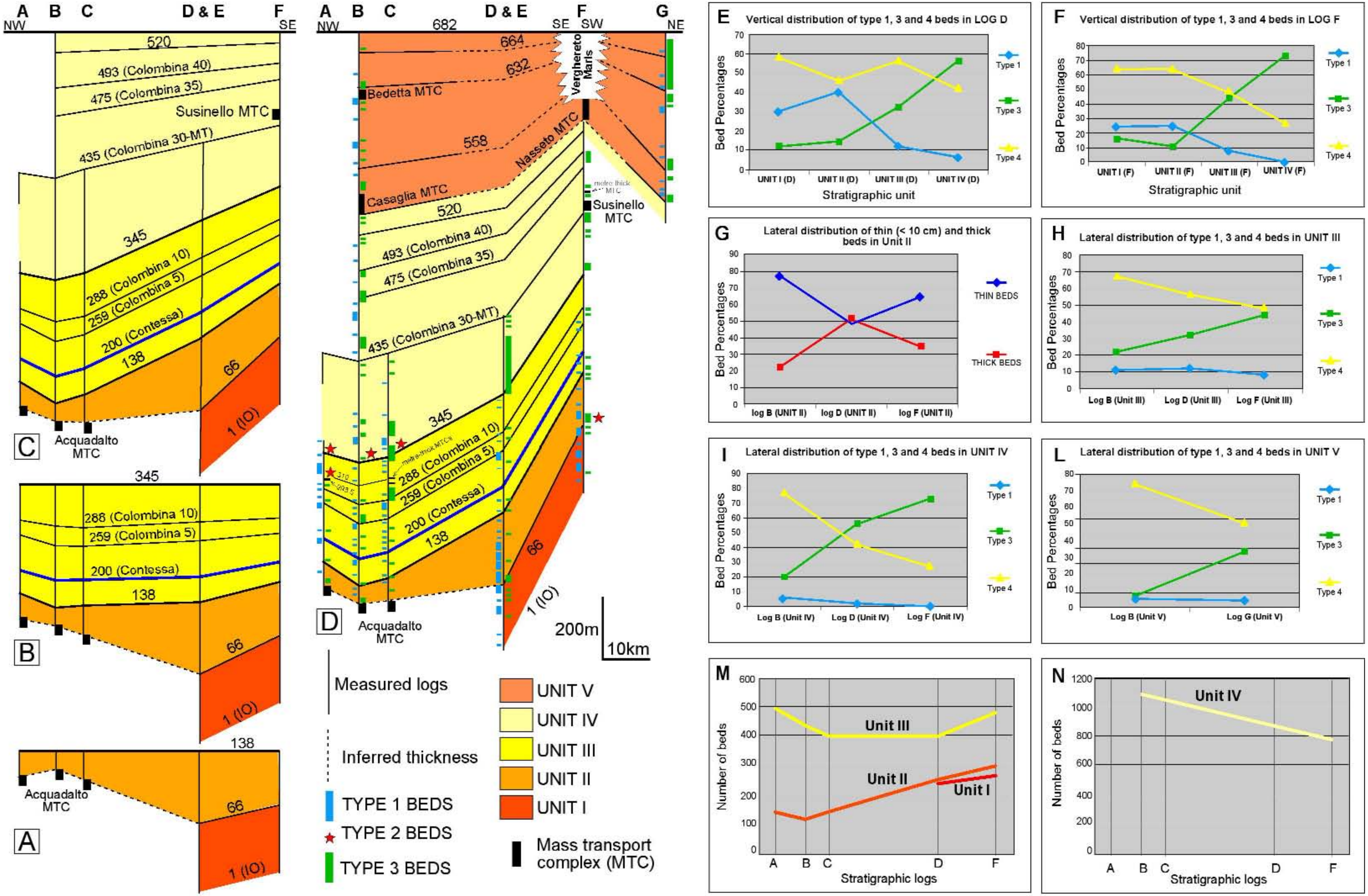
***Type-4 beds*:** medium (10cm < H < 30cm) to thick (30cm < H < 100cm) normally graded beds composed of basal medium-grained crude laminated sandstone (Bouma Ta or F8) and upper laminated fine-grained sandstone (Bouma Tbe or F9), which become progressively finer and thinner down-current. These bed types are interpreted as being deposited by traction plus fallout processes related to depletive and waning turbidity currents, in which fallout rates progressively decrease downcurrent.

***Type-5 beds*:** thin to very thin (H < 10cm) fine-grained beds sometimes characterized by biconvex ripples with sigmoidal-cross laminae and small-scale hummocky-type structures that can be interpreted as being deposited by combined flows. They are found near and above topographic highs, such as MTCs, or tectonically uplifted zones and are interpreted as F9 facies (as described by Mutti et al., 1999) or Bouma Tbe, Tce deposited by dilute turbulent flows capable of raising these morphologic highs. However, the presence of combined flow structures indicates that the turbidity currents ascending the morphologic high can assume an oscillatory component and transform themselves into combined turbidity currents (see Type-3 beds section and Tinterri, 2006; Muzzi Magalhaes & Tinterri, 2010; Tinterri, 2011).
Type-5 beds, furthermore, can also be found in the upper part of Type-3 beds (in facies “c” or even in facies “d”, Fig. 9). In this case, they can be interpeted as related to delayed ponded turbulent flows or bores associated to ponding processes (see also Tinterri & Muzzi Magalhaes, 2011 and the discussion in Mutti et al., 2002b, p. VI-11).

3.2 Stratigraphy of the Langhian-Serravallian basinal turbidites

This MAF stratigraphic interval was subdivided by Muzzi Magalhaes & Tinterri (2010) into five informal stratigraphic Units (I, II, III, IV, V; Fig. 10). These units have been separated mainly on the basis of the structural control highlighted by: 1) the presence of topographic highs and relative depocentres detected

DOI: 10.3301/GFT.2012.03



DOI: 10.3301/GFT.2012.03

Fig. 10 - **A to D)** Diagrams showing the evolution of the stratigraphic succession studied through the progressive flattening approach. The vertical distributions of Type-1, -2 and -3 beds are also indicated in the stratigraphic logs of sketches D. **E** and **F)** Diagrams showing the vertical distribution of Type-1, -3 and -4 beds in Logs D and F respectively; **G)** Down-current distribution, in Unit II, of thin beds (H-sandstone thickness < 10cm) and thick beds with sandstone thickness (H) > 10cm; **H, I, L)** Down-current distribution of Type-1, -3 and -4 beds in Units III, IV and V, respectively. **M** and **N)** Diagrams showing the number of beds in Units I, II, II and IV (from Muzzi Magalhaes & Tinterri, 2010; see also Tinterri & Muzzi Magalhaes, 2011).

through a progressive flattening approach (Fig. 10A-D) and 2) the presence of thrust-related MTCs and the progressive appearance and disappearance of the five bed types described above (Fig. 10E-F).

These units indicate different degrees of structural control characterizing the history of the Langhian to Serravallian portion of the MAF. Their bases, except Unit III, are characterized by the presence of MTCs and Type-2 beds. Unit I, even though it shows many similarities to Unit II, will not be discussed in detail because only its south/eastern part has been studied. On the contrary, stratigraphic Unit II is included between Acquadalto MTC, which is correlated with bed 66 (a Type-2-bed) and bed 138 (Fig. 10A; see also Stop 3.2). During this period, the basin structure was associated to a tectonic uplift responsible for the creation of the Acquadalto MTC to the north, and a depocenter in the south characterized by a Type-2 bed (bed 66) (Fig. 10D). This Unit, therefore, is characterized by the presence of a depositional high in northern proximal zones (Logs A, B, C; Fig. 10A), which favoured the presence of Type-5 beds and a depocentre in southern distal zones (Log D) which favoured the formation of Type-1 beds (Fig. 10A, D). The highest percentage of Type-1 beds (nearly 40%) in all the stratigraphic succession studied is in Log B of Unit II above bed 66 (see Stop 3.2) (Fig. 10D, E). This interpretation is also supported by the number of beds, as in Fig. 10M, which shows that in log B, Unit II consists of 124 beds, while in log D there are 243 beds. This means that only 51% of the beds, and, consequently, of turbidity currents, were able to ascend the topographic high represented by Acquadalto MTC. It can also be noted that the number of beds in Unit I has the same trend.

By contrast, Unit III corresponds to a period of relatively quiescent tectonic activity, which coincided with the maximum expansion of the basin, where the beds can be also traced up to southern areas of the MAF for about 120x30km (Ricci Lucchi & Valmori, 1980; Amy & Talling, 2006). In this stratigraphic interval, Type-4 and -3 beds chiefly exemplify the thicker events, whereas the percentage of Type-1 beds falls drastically (Fig. 10D, E, F). In particular, Type-3 beds tend to increase in a down-current direction (Log F), which can be interpreted

DOI: 10.3301/GFT.2012.03

as related to the beginning of the southern zone uplift (Verghereto area, see Fig. 10D, H) and which however, mainly influences the overlying Unit IV. The latter is characterized, like Unit II, by a more evident tectonic control, but, unlike in the latter, the depocentre is located to the north (Log B in Fig. 10C), due to the uplift of the southern areas (Log F in Fig. 10C). The base of Unit IV is characterized by the presence of a Type-2 bed (bed 345, Stops 3.2 and 3.3) and by a progressive bed thinning occurring in its upper part, due to the uplift of the southern Verghereto zone (Log F). Unlike Unit II, Unit IV is characterized by a progressive increase in the occurrence of Type-3 beds and by a further decrease in Type-1 beds, which are essentially absent (see Stop 3.3 and Fig. 10D, E, F). Moreover, Unit IV, in a downcurrent direction, is characterized by an evident increase in Type-3 beds (Fig. 10I), together with a progressive decrease in the number of beds (Fig. 10N), further confirming the uplift of the southern Verghereto area (Figs. 5A and 10).

Units II and IV, in comparison with Unit III, are characterized by a more evident tectonic control, but, in the former, Type-1 beds tend to predominate, whereas, in the latter, Type-3 beds do. Not only could this difference be explained by a progressive decrease in the flows' efficiency and, consequently, in their erosive capacity, as testified by the beds' tendency to become, upward in Unit IV, thinner and thinner, but also by the location of the topographic high in these units (see Stop 3.3). In Unit II, the structural high is located in proximal northern zones and this could favour both up-current mud erosion and decelerations that are fundamental processes for the formation of Type-1 beds. Conversely, in Unit IV, a well-developed topographic high is located in more distal southern zones (Verghereto area). This could not favour up-current mud erosion by turbidity currents, which would arrive as turbulent flows directly against the Verghereto high allowing rebound and reflection processes.

The Nasseto and Casaglia MTCs (Fig. 10) mark the passage into overlying Unit V (Stops 2.5, 3.4), which is characterized by a further deformation phase, as well as by basin segmentation. This phase is highlighted by the presence, in the most proximal zone (Log B, Fig. 5A), of Type-4 beds. These consist of relatively thick massive sandstone facies with a high Sandstone/Mudstone ratio, indicating flow decelerations controlled by topography (Fig. 10D, L). Along the structural element between M. Nero and M. Castellaccio thrusts (Fig. 5), these beds pass down-current into Verghereto marls (Log F, see Fig. 10D and Stop 3.4). On the other hand, in more external zones (Log G), the turbidity currents, able to bypass, are deviated, preferentially toward the east and characterised by diffuse reflection processes (Type-3 beds, see Fig. 10D, L and Stop 2.5). Unit V can be correlated with the Firenzuola turbidite system described by Mutti et al. (2002a) and probably with the

DOI: 10.3301/GFT.2012.03

time-equivalent Paretaio turbidite system (see below; Fig. 4). The basin segmentation at the time of Unit V is also shown by the complete lack of key beds with hybrid and carbonate composition coming from the south, very likely due to the progressive closure of the foredeep (Fig. 4). This basin narrowing heralds the vertical passage into the Tortonian mixed turbidite systems characterizing the outer basin of MAF (as meant by Ricci Lucchi, 1986).

In conclusion, although the syndepositional structural deformation within the MAF has been discussed in various papers (de Jager, 1979; Ricci Lucchi, 1978, 1986; Argnani & Ricci Lucchi, 2001; Mutti et al., 2002a; Roveri et al., 2002; Lucente, 2004; Bonini, 2006) the data prensented by Muzzi Magalhaes & Tinterri (2010) and in this field trip clearly show, for the first time on the basis of a high-resolution stratigraphic framework, that a structural control on sedimentation was active, with different degrees of intensity, during all the stratigraphic interval studied. In particular, this work shows that basin geometry and facies distribution patterns of the MAF were influenced by a subtle syndepositional structural control at different time and physical scales. In the MAF, the latter is represented by subtle topographic highs and depocenters created by thrust-propagation folds and emplacements of large mass transport complexes. In other words, thrust fronts moving toward the north-east, today represented by M. Nero, M. Castellaccio, S. Sofia and Civitella thrusts (Fig. 5), were able, during the Langhian and Serravallian, to produce structural highs, which occasionally could become topographic highs and, consequently, influence the turbidity current deposition. This interpretation is also supported by various papers on the relationship between thrust propagation and emplacements of MTCs, especially in Serravallian and Tortonian stratigraphic succession (Lucente & Pini, 2002; 2003; Lucente 2004; Roveri et al., 2002; see also Fig. 4). As a result, the vertical stacking pattern of the MAF records a close interaction between thrust propagation towards the NE and deposition from turbidity currents flowing towards the SE, i.e. parallel to the thrust front. The five stratigraphic Units and related bed distributions, shown in figure 10 record the syntectonic deposition associated to the progressive closure of the foredeep due to the north-eastward propagation of the thrust sheets.

DOI: 10.3301/GFT.2012.03

4. The Upper Serravallian turbidite deposits: Firenzuola and Paretaio systems (transition between Inner and Outer stages)

This section focuses on the Upper Serravallian structurally controlled turbidites known in the literature as Firenzuola and Paretaio turbidite systems (see Figs. 5 and 11; Mutti et al., 2002a, Roveri et al., 2002). Not only are these systems particularly important because they represent a typical example of a syntectonic deposit controlled by a fault-propagation fold (de Jager, 1979; Roveri et al., 2002), but also because they record the transition between Langhian to Serravallian turbidites and the Tortonian mixed turbidites (Tinterri & Muzzi Magalhaes, 2011). Therefore, the main objectives of this section are: 1) to describe and discuss the vertical and lateral facies evolution of the Paretaio turbidites in relation to the structural control, and 2) to discuss the significance of the vertical facies change in relation to the progressive closure of the foredeep.
In the geologic cross-section of the Santerno River that is perpendicular to the main paleocurrents and parallel to the main direction of tectonic transport (see Fig. 5A, B), it can be seen that the M. Castellaccio thrust front is characterized by a large asymmetric anticline with a northern vertical limb and a southern, gentler SW dipping flank. This structure plunging to the NW is a linear tectonic feature parallel to the Apenninic trend, which can be traced southeastward up to the Savio valley (Fig. 5).

As mentioned above, the synsedimentary nature of this structure has been set forth for the first time by de Jager (1979), on the basis of detailed field mapping data. This author observed that two key horizons, the Contessa bed and the Casaglia MTC, converge from the southern flank to the crest, resulting in a wedge-like geometry of early Serravallian deposits across the basin axis. Moreover, basin plain deposits above the Contessa bed (Coniale member by de Jager, 1979), show a sharp decrease in the sand/shale ratio at the Coniale section (see also Muzzi Magalhaes & Tinterri, 2010, their Unit III). South of this point, a sand-rich turbiditic unit, informally named Firenzuola system by Mutti et al., 2002 (M. Coloreto member by de Jager, 1979), is found above the Casaglia MTC in a narrow syncline south of Coniale. The areal distribution of the MTC and Firenzuola system, together with its bed thickness, grain-size lateral variations and paleocurrent data suggest deposition in a narrow, elongated depocenter confined between the M. Castellaccio or Coniale anticline and the inner Ligurian thrust front (see also Roveri et al., 2002). Furthermore, the frontal NE limb of the M. Castellaccio anticline is characterized by the occurrence of a MTC, mainly consisting of

DOI: 10.3301/GFT.2012.03

intraformational intensely bioturbated marls with interbedded thin-bedded turbiditic siltstones and mudstones. This suggests that their original deposition was a mud drape above the growing Coniale topographic high (Castelvecchio marls by de Jager, 1979).

All these evidences and interpretations have been resumed by Roveri et al., 2002 (see also Mutti et al., 2002). Also on the basis of strong similarities with some seismic examples of Plio-Pleistocene structures buried below the Po Plain and Adriatic Sea (Ori et al., 1986), these Authors proposed a geologic model summarizing the different phases of the synsedimentary growth of the M. Castellaccio structural high during the late Serravallian and the consequent closure of the MAF inner basin (Fig. 11). According to Roveri et al. (2002), the early stages of fold growth were recorded by wedge-like geometry of post-Contessa strata (Fig. 11-2), while a more pronounced topographic relief formed later, concomitantly with the deposition of confined sand-rich turbidites of the Firenzuola system, which pass laterally above the fold into fine-grained turbidites and hemipelagic marls (M. Castellaccio marls) (Fig. 11-3). This blind thrust mud drape was then displaced and deposited as a MTC in front of the structural high, after a paroxistic uplift phase during the middle to upper Serravallian. The Firenzuola system, therefore, would record the transition from an inner foredeep zone to a piggyback basin, formed on the advancing M. Castellaccio thrust sheet and bounded to the NE by the growing M. Castellaccio structural high. The mud drape deposits formed above the Coniale structural high were pushed downslope, resulting in the emplacement of Visignano MTC along the thrust front (Fig. 11-4). On the basis of this model, during the late Serravallian the inner front of the Apennine orogenic wedge moved to the M. Castellaccio thrust front (see also de Jager, 1979).
As a consequence, the Paretaio turbidite system and the underlying Visignano MTC were deposited in the inner zone of the new basin depocentre, represented by the outer basin (de Jager, 1979; Ricci Lucchi, 1986). The Paretaio turbidite system, therefore, played a fundamental role in the geologic and stratigraphic evolution of the MAF, because it represents a link between Langhian-Serravallian basinal turbidites of the inner basin and Tortonian delta-fed “mixed” turbidites of the outer basin.

DOI: 10.3301/GFT.2012.03

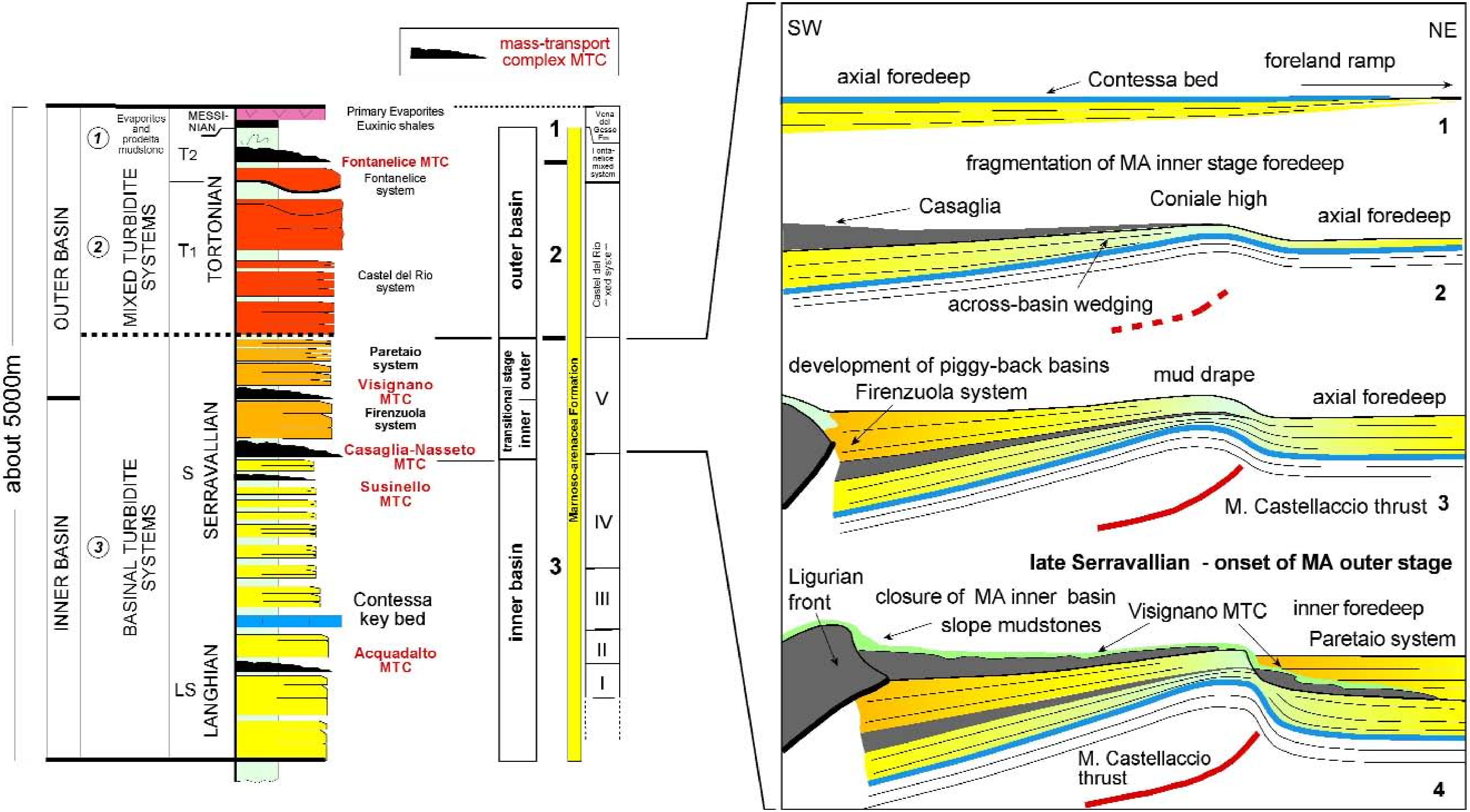


Fig. 11 - Diagram showing the stratigraphic and structural evolution of the MAF foredeep during early to late Serravallian recording the passage between inner and outer basins or stages, as meant by Ricci Lucchi (1986) (modified from Roveri et al., 2002; see also de Jager, 1979). The schematic stratigraphic log of Marnoso-arenacea Formation is also shown (see also Fig. 4). Unit I, II, III, IV and V are those introduced by Muzzi Magalhaes & Tinterri (2010), (see Fig. 10) while numbers 1, 2, and 3 refer to the sedimentary environments in figure 3C.

DOI: 10.3301/GFT.2012.03

4.1 Stratigraphy and sedimentology of the Paretaio turbidite unit

Although this system was already studied by Cattaneo and Ricci Lucchi (1995), up to now a high-resolution physical stratigraphy with bed-by-bed correlations and detailed facies analysis has never been performed. The study presented in this section is based on a new data set by Tinterri, Tagliaferri et al., (in prep.) performed through a detailed measurement of six stratigraphic logs for an overall thickness of about 1800m (see Fig. 12 for the location of the logs).

The studied stratigraphic succession is mainly shown in two stratigraphic-cross sections: 1) the first one shows a stratigraphic interval included between the top of Visignano MTC and the Montecchio key bed, a very thick, massive to crudely laminated bed, found by Cattaneo & Ricci Lucchi, (1995), which can be traced in all the area studied. This cross section covers a stratigraphic thickness of about 280 metres and a lateral extension of about 2.5km, roughly parallel to the M. Castellaccio thrust front (see Fig. 13); 2) the second one (Fig. 14) is essentially represented by log 1, a composite log consisting of six logs (1A to 1F in Fig. 12). This cross section covers a stratigraphic interval of about 600m from the top of the Visignano MTC to bed 179. The stratigraphic cross section in figure 13 shows the vertical and lateral facies variation, mainly due to the M. Castellaccio thrust activity, while the cross section of figure 14 allows the vertical facies changes to be observed and some important considerations to be made about the vertical passage into the Tortonian mixed turbidite deposits. To highlight the vertical variations of the beds' sedimentary characteristics, the stratigrahic succession has been subdivided into three parts, as indicated in figure 14. Furthermore, in addition to these two cross sections, other three stratigraphic cross sections perpendicular to the M. Castellaccio thrust front show the thickness and facies variations perpendicular to the thrust front (see Stops 1.5 and 1.6).

The main beds can be traced in all stratigraphic logs and are numbered starting from Bed 1 directly above the Visignano MTC up to bed 179. The general paleocurrents are directed toward SE, i.e. roughly parallel to the main thrust fronts (see Fig. 12).

In addition to the basal Visignano MTC, the facies analysis carried out on the stratigraphic cross-sections shown in figures 13 and 14 allows six bed types to be identified (Type A, B, C, D, E and F, see Fig. 15).

Their lateral and vertical distribution is interpreted as related to the physiographic confinements produced by M. Castellaccio thrust front propagation and, thus, by the progressive closure of the foredeep. This facies scheme is slightly more articulated than that in Fig. 7, especially regarding Type-4 beds. More precisely, Type-A beds

DOI: 10.3301/GFT.2012.03

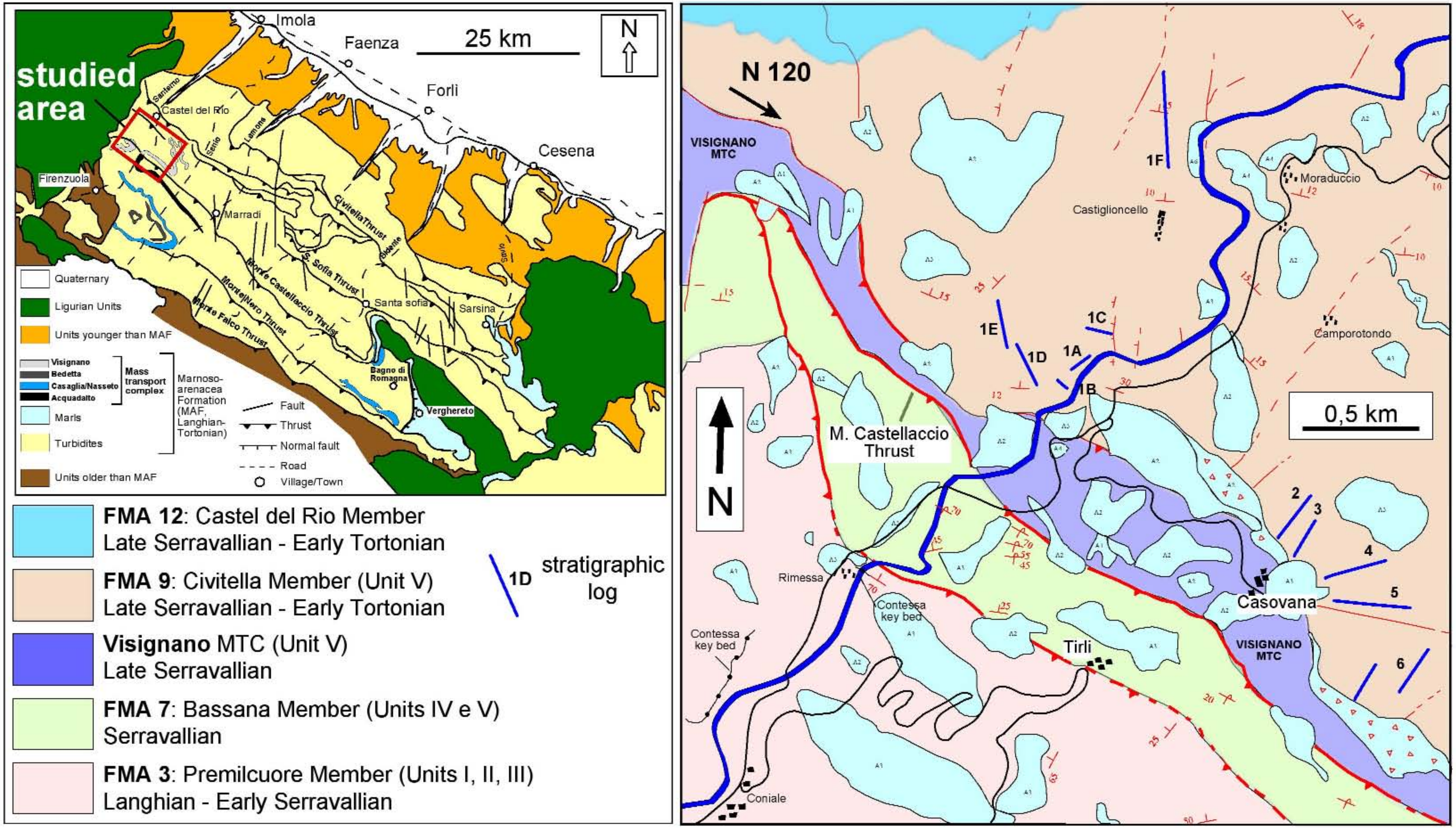


Fig. 12 - On the left, a schematic geological map of the MAF is given with the location of the studied area presented in this section. On the right, a geological map of the M.Castellaccio thrust fronts along the Santerno Valley showing the main stratigraphic units outcropping in this area (modified from Benini et al., 2006). The location of the stratigraphic logs of the Paretaio turbidite systems above the Visignano MTC are also shown (from Tinterri, Tagliaferri et al., in prep.).

DOI: 10.3301/GFT.2012.03

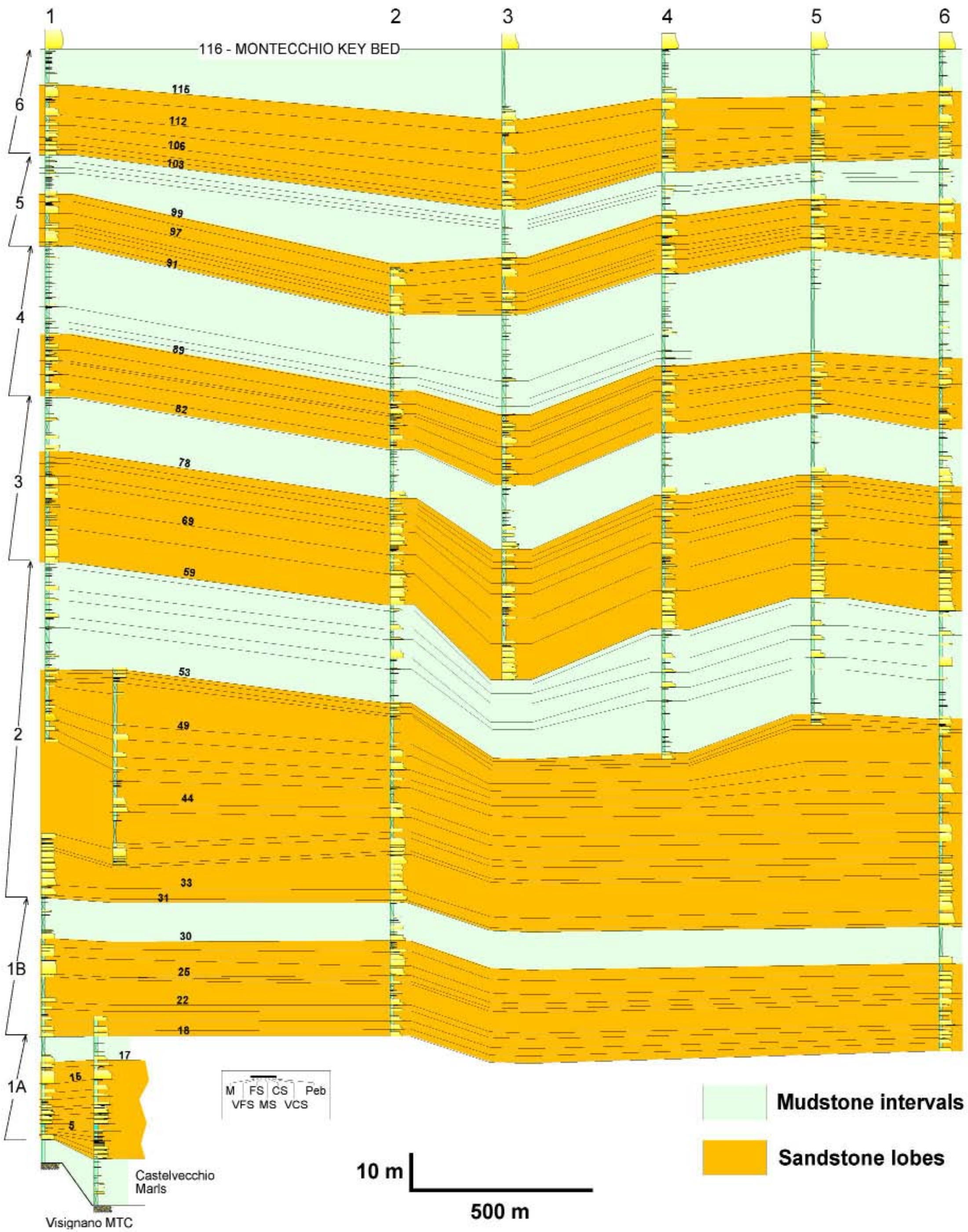


Fig. 13 - Detailed stratigraphic cross section of the Paretaio turbidite system included between the Visignano MTC and the Montecchio key bed. The location of the logs can be seen in figure 12, which shows that the trace of the cross section is parallel to the M. Castellaccio thrust front and, thus, to the main paleocurrents directed toward south-east (see Fig. 12). The bed by bed correlation highlights well-developed ciclicity, which tends to increase upward. This well developed ciclicity allows the stratigraphic succession to be subdivided into 6 units (see the numbers on the left). The numbers of the main beds are also indicated (from Tinterri, Tagliaferri et al., in prep.).

coincide with Type-1 beds; Types B, C and D represent three different categories of Type-4 beds; Type E beds coincide with Type-3 ones related to reflections processes and, finally, Type F beds are thin to very thin beds characterizing the fine grained intervals which separates the thick sandstone lobes (Fig. 15).

In particular, Type A beds are characterized by two main facies sequences: the first one is characterized by thick (30cm < H-bed thickness < 100cm) to very thick (H > 100cm) beds with a thin upper mudstone division, where the basal sandstone unit usually consists of three subdivisions, which, from base to top, are: a) a massive to crude laminated coarse-grained sandstone which sometimes passes upward into unit b through a transitional

DOI: 10.3301/GFT.2012.03

banded sandstone, as described by Haughton et al. (2009), b) a slurry/debrite unit, i.e. a poorly-sorted muddy sandstone with liquefaction structures and mudstone clasts, often rich in plant fragments and carbonaceous matter, c) thin- to very thin (< 10cm) laminated very-fine sandstone (see Fig. 16A).
Conversely, the second one consists of medium–thick (10cm < H < 30cm) to thin (H < 10cm) beds, entirely characterized by a slurry unit b, in which a high content of plant fragments and carbonaceous matter, as well as a diffuse bioturbation, can be found. These relatively thin slurry beds probably represent a lateral facies of

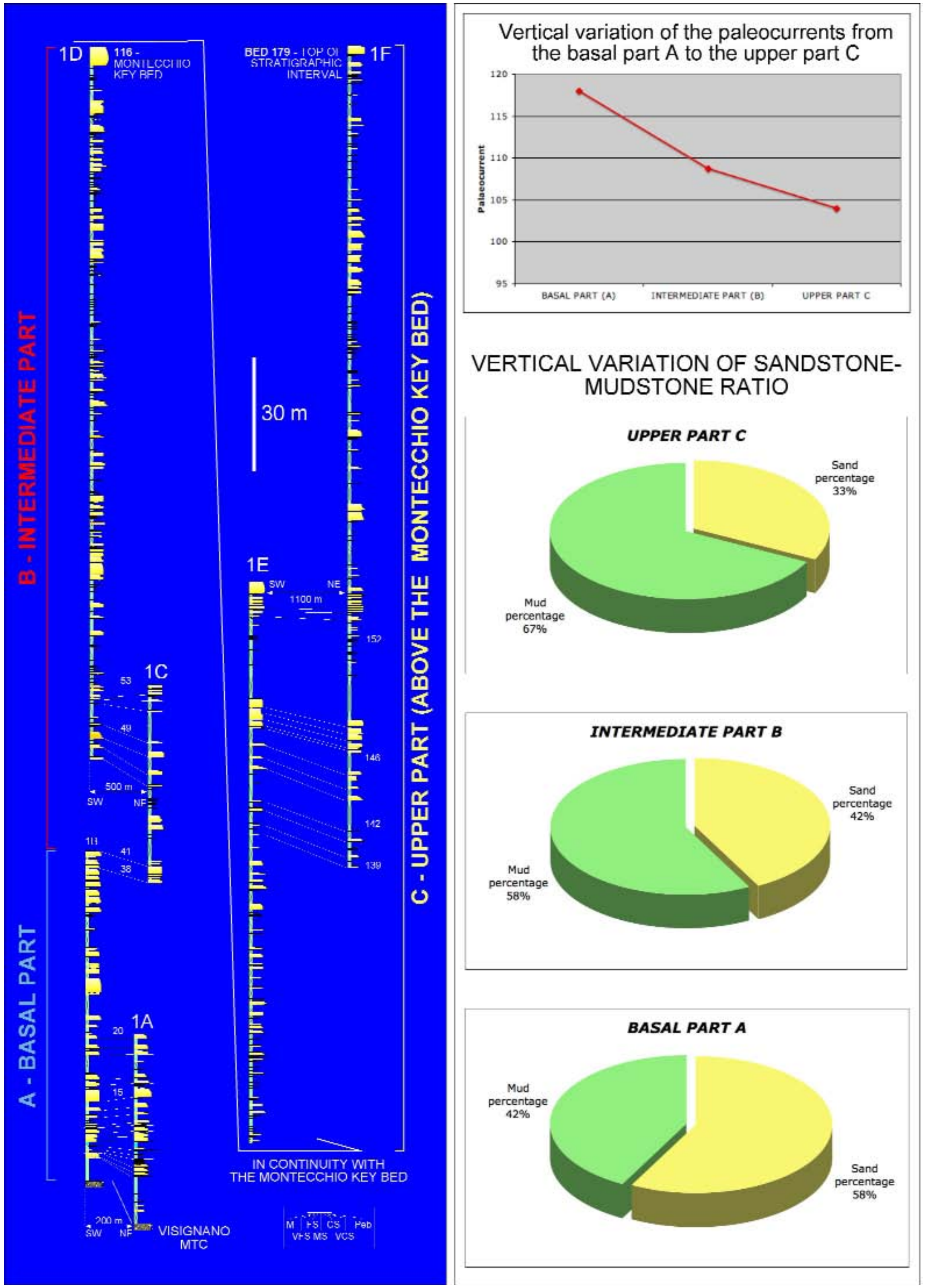


Fig. 14 - This cross section is represented by composite log 1, consisting of six logs (1A to 1F in Fig. 12). It covers a stratigraphic interval of about 600m from the top of Visignano MTC up to bed 179 and shows vertical facies variations, mainly due to the M. Castellaccio thrust activity. Consequently, it allows some important considerations to be made about the vertical passage into the Tortonian mixed turbidite deposits (see text for more details).
With regard to this, the stratigraphic succession has been subdivided into three main intervals, namely: **1)** basal part "A" included between the top of the Visignano MTC and bed 41; **2)** intermediate part "B" included between beds 41 and 116 (Montecchio key bed); **3)** upper part "C" above the Montecchio key bed 116.
On the right, the vertical variation of the paleocurrents and the sandstone/mudstone ratio of these three intervals are also shown (see text for more details, from Tinterri, Tagliaferri et al., in prep.).

DOI: 10.3301/GFT.2012.03

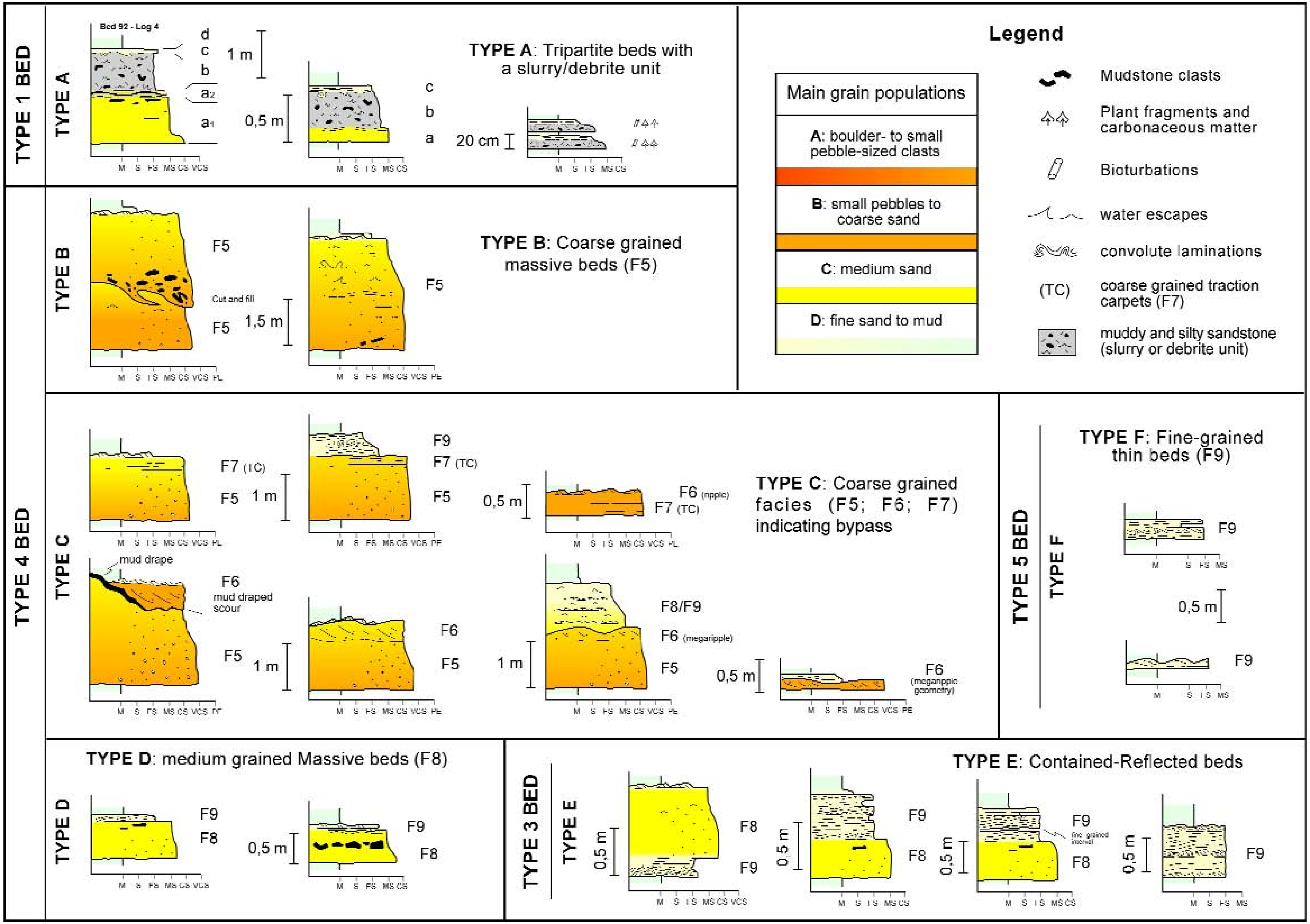


Fig. 15 - The main bed types of the Paretaio turbidite system, important to understand the structural control due to the activity of M. Castellaccio thrust (from Tinterri & Tagliaferri et al., in prep.). The terminology "Type 1, 3, 4 and 5 beds" is taken from Muzzi Magalhaes & Tinterri (2010), see also Fig. 7.

thick Type A beds, characterized by an abrupt pinching due to the morphologic high produced by M. Castellaccio thrust (see Stop 1.6). As mentioned in section 3.1, these bed types can be interpreted as related to flow decelerations of turbidity currents previously enriched in mud through erosive processes. The basal

DOI: 10.3301/GFT.2012.03

part “a” of Type A beds sometimes consists of a F7 facies (*sensu* Mutti et al., 1999), i.e. a typical bypass facies (see Fig. 6), which usually records the deceleration of sandy dense flows able to deposit coarse grained massive sandstone (F5 facies), as well as the bypass of turbulent flows, characterized by grain size populations C and D (see Fig. 16B, C). The percentage of type A beds, however, tends to increase mostly in the basal part of the Paretaio system (see part A in Fig. 14), where the morphology created by the M. Castellaccio thrust propagation can favour both decelerations and impacts, as well as erosive processes.

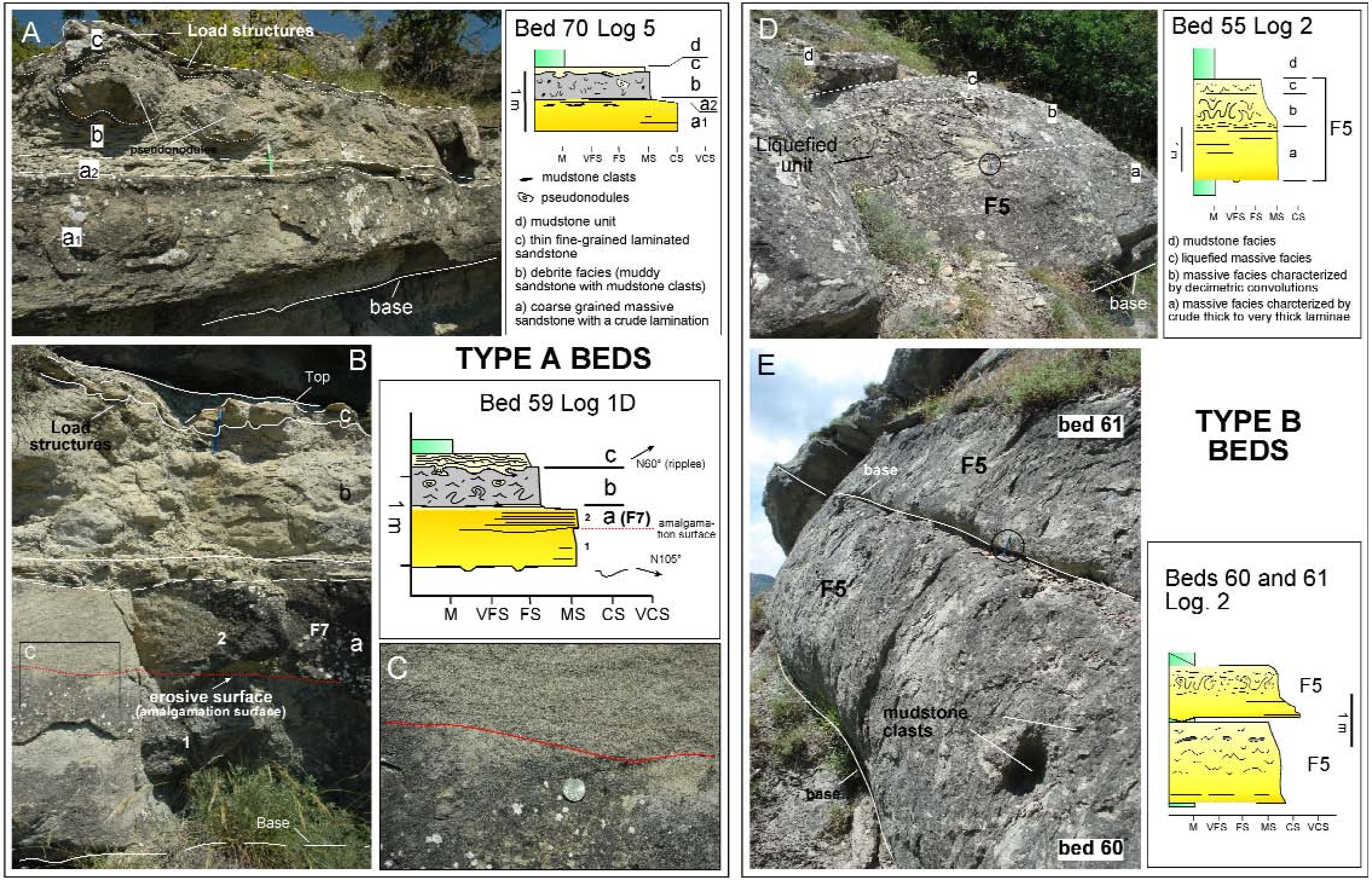


Fig. 16 - **A, B)** Examples of Type A beds characterized by slurry or debrite units (b). In both cases (A and B), a transitional facies between "a" and "b" units can be observed (see section 3.1 for more details). In B, a basal unit "a", characterized by a bypass facies F7, can be recognized (see text for more details). The latter is also characterized by an evident amalgamation surface which can be observed in **C**. **D and E)**: examples of Type B beds consisting of coarse grained massive sandstones (F5).

DOI: 10.3301/GFT.2012.03

Type B, C and D beds are three different categories of Type-4 beds, as in Fig. 7, which are very important to understand the structural control on facies distribution. More precisely, Type B ones are very thick (H > 100cm) massive to normally graded beds made of coarse-grained sandstones that are usually characterized, in their upper parts, by liquefied units with water escape structures (Fig. 16 D, E).

These beds, in which well-developed impact structures with mudstone clasts and amalgamation surfaces are relatively common, can be seen as F5 facies (Fig. 6, Mutti et al., 1999) and interpreted as deposited by high-density flows decelerated by the morphologic confinement associated to the structural uplift of the M. Castellaccio thrust. Furthermore, Type B beds are always devoid of the fine-grained F9 division (Bouma Tbe sequence) indicating that the study area records the deposition of coarse and very coarse-grained sand and the bypass of medium to fine grained sand and mud. This interpretation is also supported by Type C beds, belonging to two main bed categories, namely: 1) coarse-grained thin- to medium thick beds characterized by horizontal traction carpet (F7) or megaripples (F6) (Fig. 17 D, E); and 2) thick to very thick coarse grained sandstone beds, in which the massive facies F5 pass upward into F7 and F6 facies (Fig. 17 A, B, C and Fig. 18). Sometimes these facies pass upward into not well-developed F9 facies, often consisting of undulated and convolute laminae. However, the great majority of these beds are completely devoid of fine-grained F9 division. Mud draped scours (as meant by Mutti & Normark, 1987, 1991) are also present (Fig. 17 F, G).

Type C beds can be interpreted as recording the deceleration of high-density turbidity currents able to deposit massive F5 facies (sometimes characterized by mud draped scours), as well as the bypass of more diluted turbulent flows, able to transport farther down-current grain-size populations C (medium-grained sand) and D (fine grained sand and mud) (Fig. 15). This bypass process produces F7 and F6 deposits that, in the scheme of figure 6, represent the typical bypass facies. In particular, the F6 and F7 deposits above the massive F5 facies mean that the bypassing turbidity current is able to rework the top of F5 in traction carpets (F7) or megaripple (F6) (see Fig. 18), according to the degree of decelerations (Mutti et al., 2003; Tinterri & Muzzi Magalhaes, 2011). In general, the presence of F6 facies indicates a higher degree of deceleration with the possibility, in the same cases, to produce hydraulic jumps and related mud-draped scours.
Type C beds, therefore, record flow decelerations induced by the morphology created by the north-eastward propagation of the M. Castellaccio thrust. These bed types appear for the first time in the Upper Serravallian Paretaio system and can be interpreted as being related to the drastic basin narrowing characterizing this interval.

DOI: 10.3301/GFT.2012.03

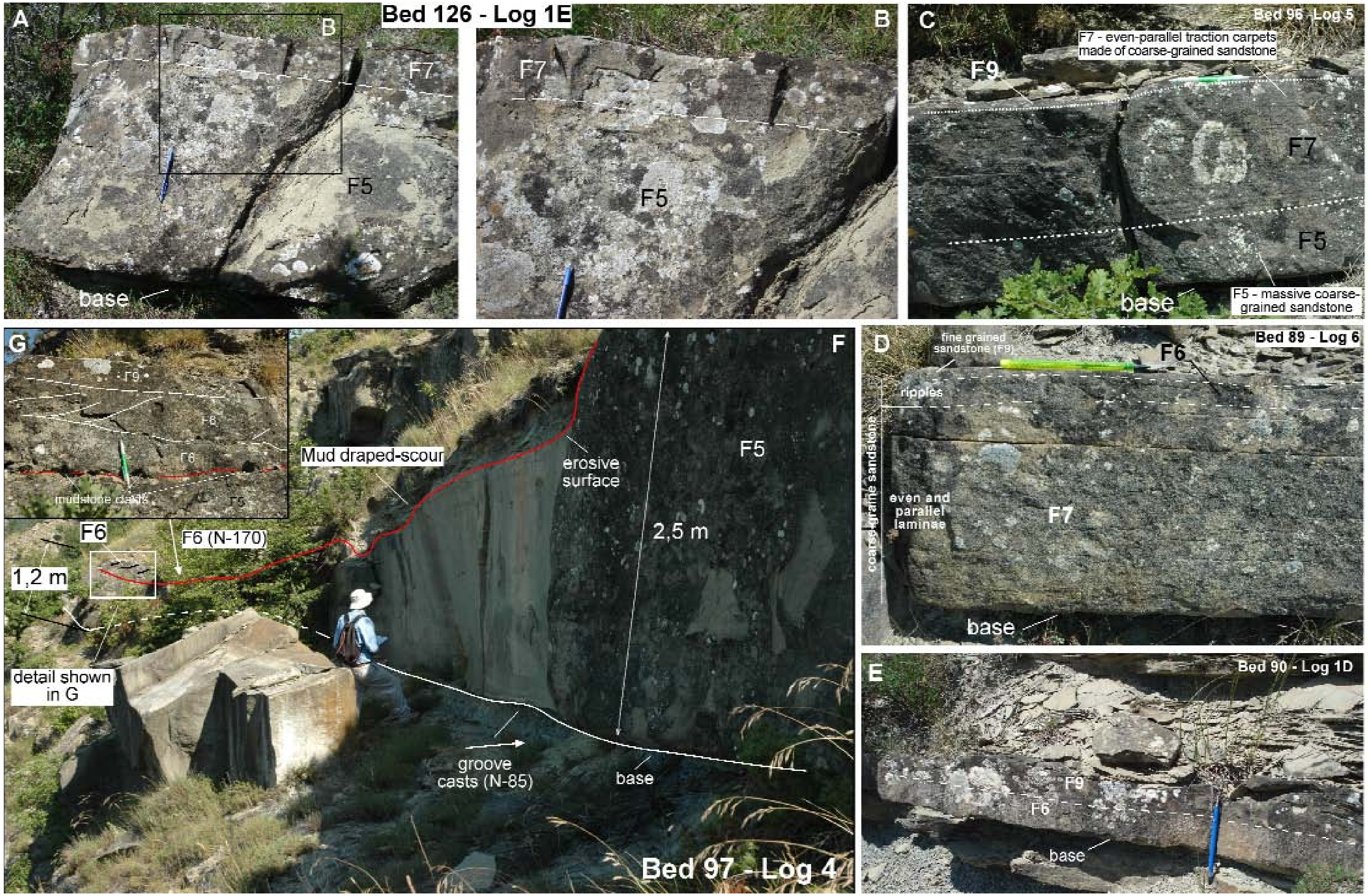


Fig. 17 - Examples of Type C facies. In **A, B** and **C**, F5 overlain by F7 facies can be observed. In **D**, a very clear example of F7 overlain by a coarse-grained sandstone reworked in ripples (F6) can be observed. In **E**, a thin massive coarse grained sandstone with lenticular geometry is shown; this facies can be interpreted as an F6. In **F**, a spectacular example of mud draped scour is illustrated; it is important to note that the facies directly above the scour surface are represented by F6 facies with a well-developed cross bedding. These facies derive from hydraulic jumps associated to sudden flow decelerations induced by morphologic confinement.

Tipe C beds are very important because they are very similar to the facies sequences characterizing the overlying Tortonian mixed turbidite deposits (see below and Tinterri & Muzzi Magalhaes, 2011).

Type D beds are thick beds (30cm < H < 100cm) consisting of basal massive medium-grained sandstone (F8 facies in Fig. 6), often characterized by rip-up mudstone clasts that pass upward into very thin laminaset of fine-grained sandstone (F9) consisting of even or slightly undulated laminae (Bouma Tb) and ripples (Bouma Tc) (Fig. 19A, B). This facies sequence records the deposition of grain size population C and the bypass of grain size population D characterizing F9 facies. Type D beds, therefore, are interpreted as deposited by decelerating turbidity currents,

DOI: 10.3301/GFT.2012.03

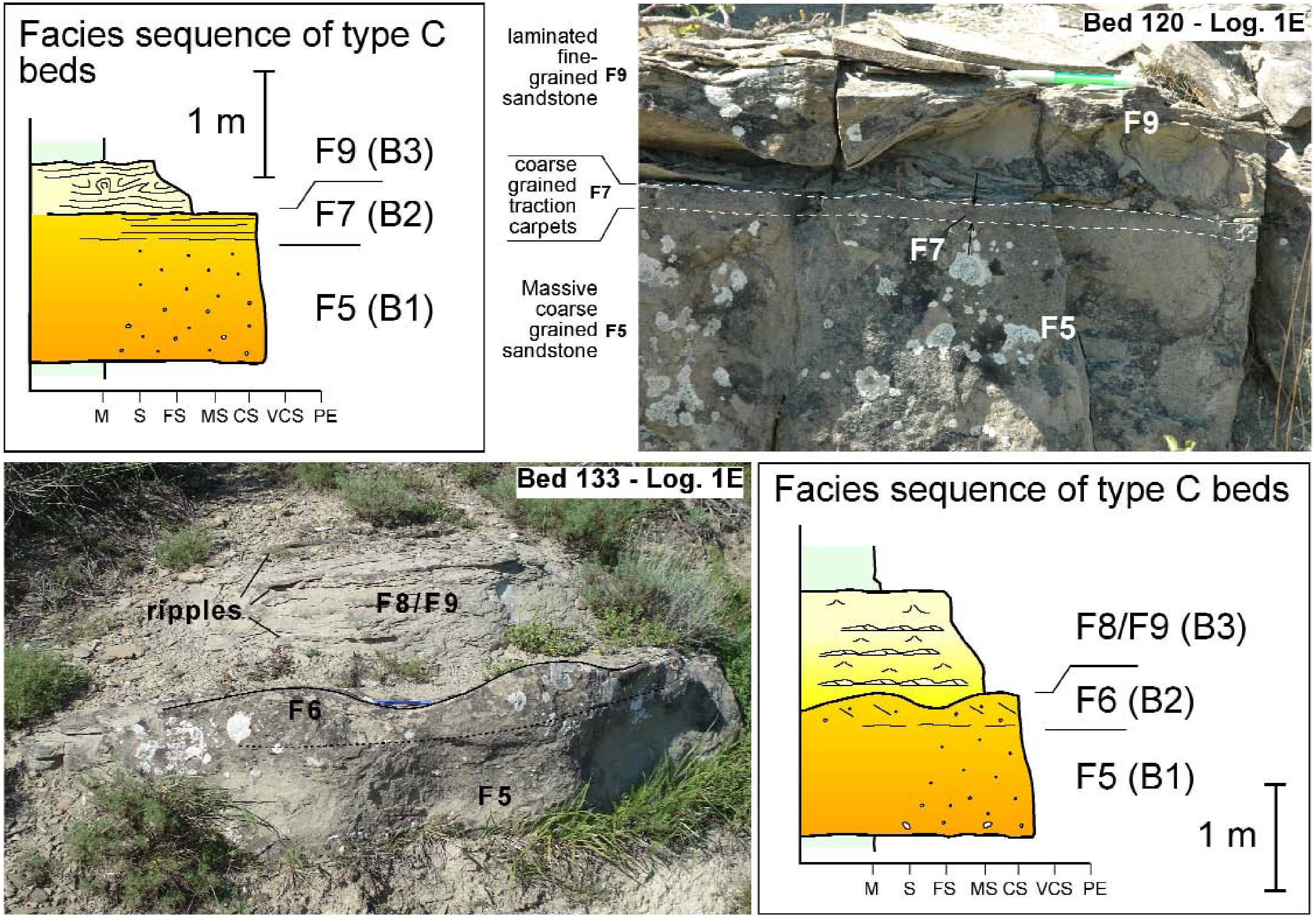


Fig. 18 - Facies sequences of Type C beds resembling those of Tortonian mixed turbidite deposits (see below). In these bed types, F5 was reworked by a bypassing turbulent flow in plane-parallel traction carpets (F7) or in megaripples (F6), (see beds 120 and 133, respectively). These two facies sequences are interpreted as being related to two different degrees of flow deceleration, due to the morphologic confinement produced by the M. Castellaccio thrust front (see below and Tinterri & Muzzi Magalhaes, 2011). The analogy between basinal turbidite (F5, F7 and F9) and mixed facies (B1, B2 and B3 as introduced by Mutti et al., 2003, see below) is also shown.

where F8 facies is deposited by high fallout rates able to suppress the turbulence at the boundary layer. On the other hand, the very thin F9 facies is deposited by traction plus fallout processes related to the tail of bypassing low density turbulent flows able to transport farther downcurrent a great part of the fine grained sand and mud (i.e., grain size population D). Although they represent a more evoluted facies than bed types A, B and C, Type D beds also indicate a morphologic confinement of the flows associated to the M. Castellaccio thrust uplift.

DOI: 10.3301/GFT.2012.03

This interpretation is further confirmed by the presence of Type E beds that are contained, reflected beds (Type 3 beds in figure 7). These types of beds show laminasets of fine-grained sandstone (F9), often characterized by an alternation of undulated, convoluted laminae and ripples that can have different paleocurrent from those indicated by the sole casts (Fig. 19C, D, E). These alternations are interpreted as related to flow velocity variations associated to reflection processes induced by the structural confinement.

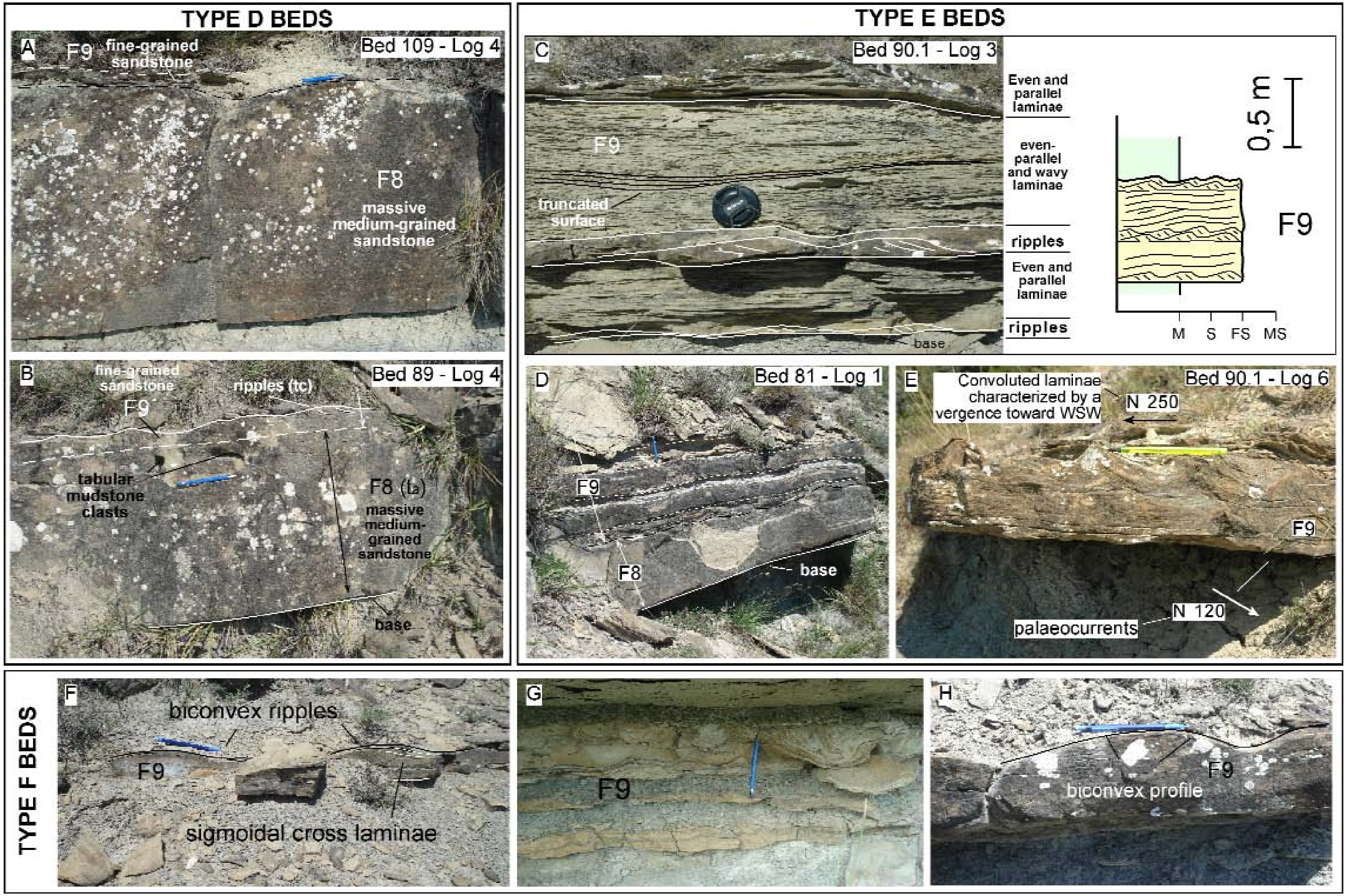


Fig. 19 - **A**, **B)**: examples of Type D beds characterized by F8 facies and devoid of well-developed F9 facies; **C**, **D** and **E**) examples of Type E beds. These bed types, corresponding to Type III beds by Muzzi Magalhaes & Tinterri (2010), consist of an alternation of different types of sedimentary structures related to flow velocity variations associated to rebound and reflection processes. **F**, **G** and **H**): examples of type F beds characterized by biconvex and rounded ripples.

DOI: 10.3301/GFT.2012.03

Finally, Type F beds are thin to very thin fine-grained sandstone beds, in which ondulated and convolute laminae, as well as biconvex rounded ripples, can be recognized. In any case, there are two types of these beds: 1) the first type characterizes the top of the Visignano MTC and, consequently, can be interpreted as Type-5 beds, as meant by Muzzi Magalhaes & Tinterri (2010) (see Fig. 7); 2) the second type (Fig. 19F, G, H) can be found in the decametric-thick mudstone dominated intervals characterizing the stratigraphic succession of the Paretaio turbidite systems (see Fig. 13).

4.2 Lateral and vertical facies variations

As indicated in figure 14, the stratigraphic succession of the Paretaio turbidite system can be subdivided into three main intervals to highlight vertical and lateral facies variations. These three intervals are characterized by a progressive change, not only in bed types, but also in the bioturbation degree, sandstone/mudstone ratio and bed's angle of dip, indicating an evident growth structure represented by M. Castellaccio thrust. Below, these stratigraphic intervals will be discussed following their stratigraphic order.

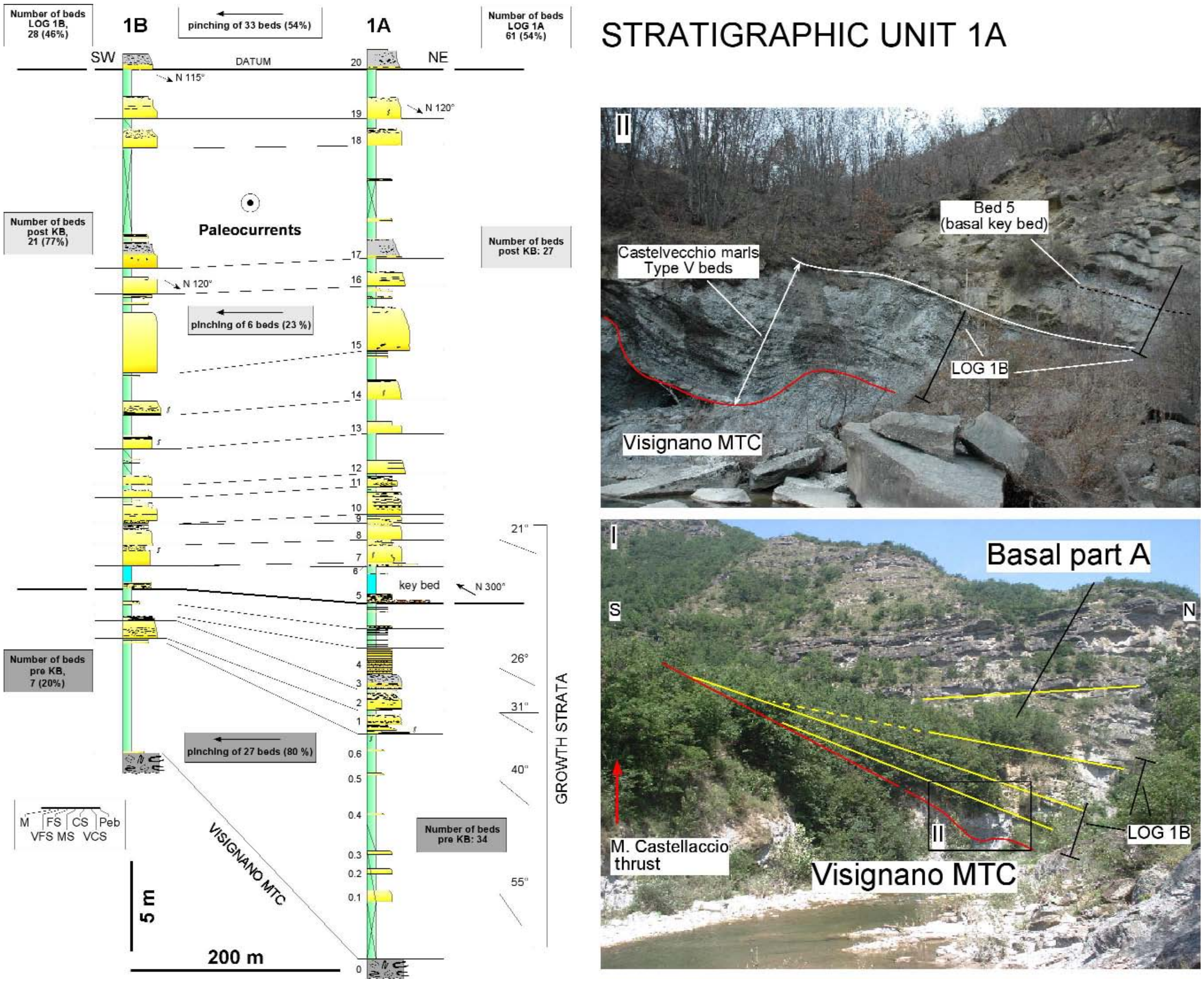
4.2.1 Basal interval "A"

This interval is included between the top of Visignano MTC and bed 41. The contact between Visignano MTC and the studied stratigraphic succession is entirely covered and the only area where this contact can be observed is along the Santerno river, where logs 1A and B were measured (Figs. 12 and 13). The cross section between these two logs is perpendicular to the M. Castellaccio thrust front; the stratigraphic expansion toward NE and a progressive decreasing in the angle of dip (i.e. growth strata) can be observed, showing an evident growth structure represented by the M. Castellaccio thrust (Fig. 20).

This interpretation is also supported by other important evidence, such as the highest sandstone-mudstone ratio in the entire stratigraphic succession (Figs. 14 and 21), which is very similar to that of the inner Firenzuola turbidite system (see Figs. 5B and 11). This high ratio is due to a high percentage of thick to very thick massive Type B and D beds (F5 and F8 respectively), as well as to a high percentage (about 30%) of slurry-debrite Type A beds (see Fig. 21), many of which are characterized by a clear bed pinching toward the structural alignment of M.Castellaccio thrust (see also Stop 1.6).

DOI: 10.3301/GFT.2012.03

Fig. 20 - Stratigraphic cross section perpendicular to M. Castellaccio thrust front and included between the top of Visignano MTC and bed 20 (basal part A in Fig. 14). In this cross section the following evidences can be observed: 1) the evident beds' pinching toward SW, i.e. against the M. Castellaccio thrust front, 2) the progressive decrease in angle of dip indicating a growth structure (see also photo I), 3) the mud drape directly above the Visignano MTC, mainly consisting of type 5 beds (see also photo II), (from Tinterri, Tagliaferri et al., in prep.).



DOI: 10.3301/GFT.2012.03

Moreover, observing the lateral facies change shown in Fig. 22, it can be noted that there is an increase in the number of type A beds and a concomitant decrease in that of type B beds, suggesting a downcurrent transformation of massive Type B beds into slurry Type A beds, as also indicated by bed correlations (see for example bed 22 shown in Fig. 22).

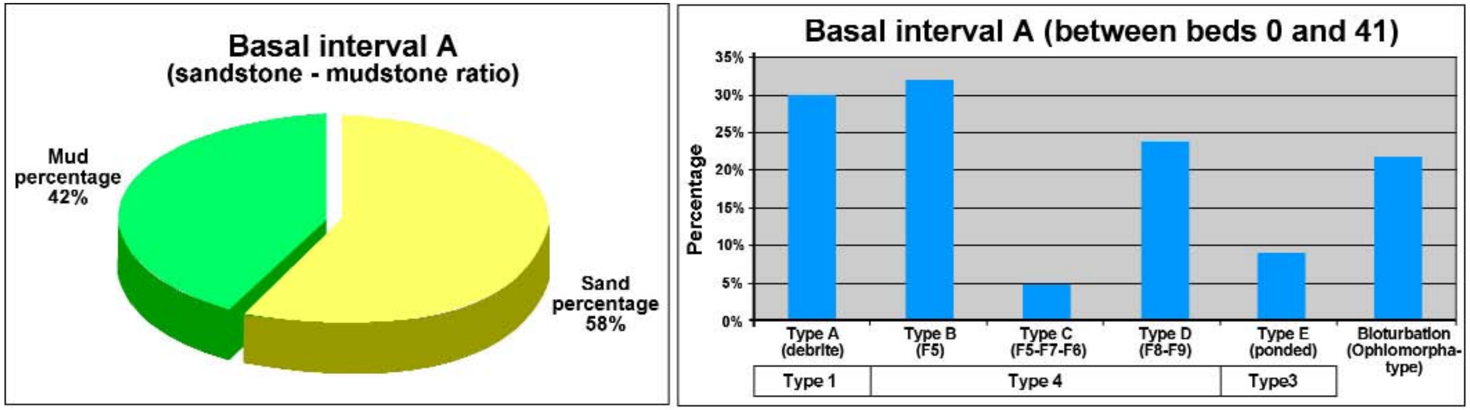


Fig. 21 - Sandstone-mudstone ratio and bed types percentages in basal part A, see also Fig. 14.

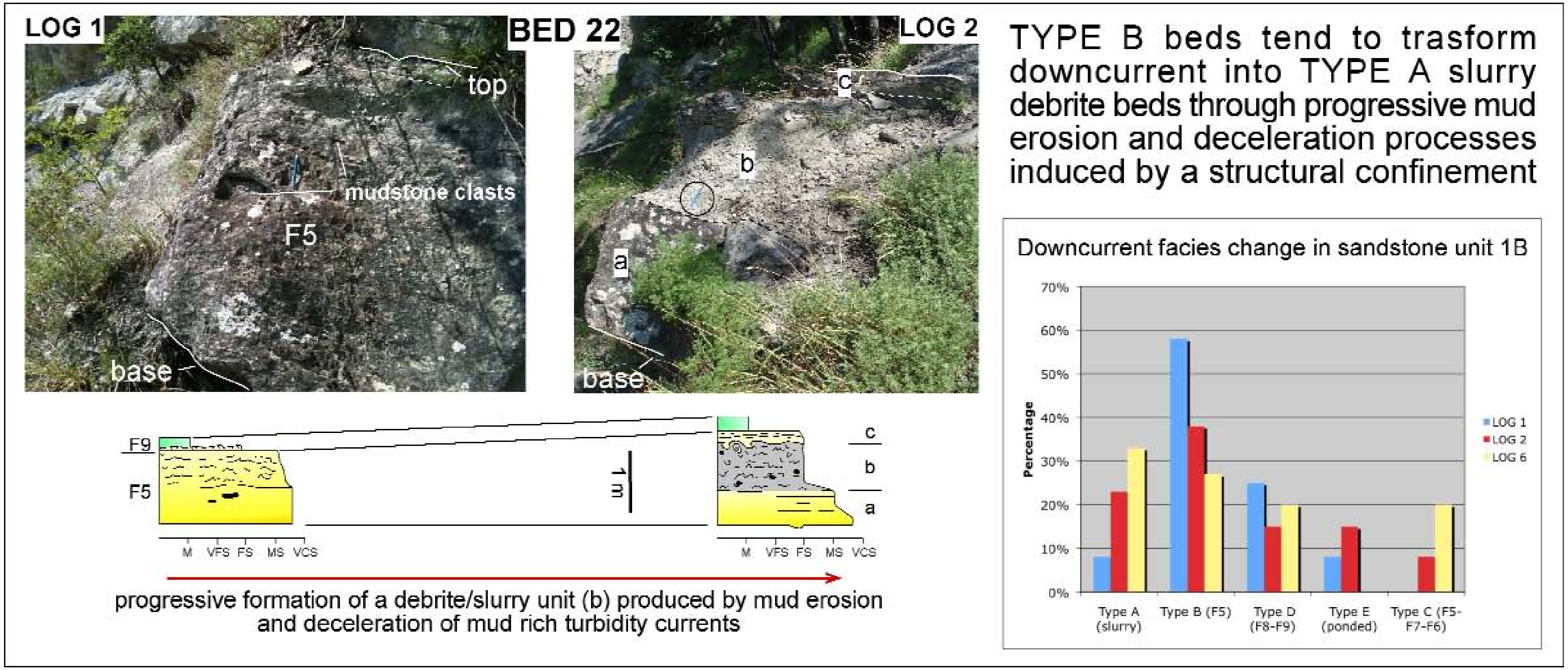


Fig. 22 - On the right, lateral facies change in Unit 1B (see Figs. 13 and 14). On the left, the physical bed correlation of bed 22 can be observed. It should be noted the down-current transformation from a massive type B bed into slurry type A bed.

DOI: 10.3301/GFT.2012.03

These sedimentary characteristics are interpreted as being related to the deceleration of high density turbidity currents induced by a morphologic confinement produced by the growth of the M. Castellaccio thrust front. The latter is also testified by a decametric-thick mud drape above the Visignano MTC represented by the Castelvecchio marls (see Fig. 20 I and II) which are composed of fine-grained Type E beds; i.e. Type-5 beds by Muzzi Magalhaes & Tinterri, 2010. This interval, therefore, was deposited by diluted muddy turbidity currents able to ascend and to mantle the morphologic high produced by M. Castellaccio thrust uplift and the Visignano MTC.

4.2.2 Intermediate interval "B"

This interval, included between bed 41 and the Montecchio key bed 116, is well represented in figure 13 (see also Fig. 14), where the Paretaio system can be observed in its entire lateral extension (about 2.5km). In this interval, the synsedimentary action of the M. Castellaccio thrust is still evident thanks to: 1) the progressive flattenings that highlight the depocentres and morphologic highs produced by thrust movement (Fig. 23A); 2) an evident stratigraphic pinching in a perpendicular direction to the M. Castellaccio thrust front (Fig. 23B); and 3) a progressive upward decrease in the beds' angle of dip, which testifies a growth structure (Fig. 23C).
Furthermore, this interval is important because the down-current facies variation of the bed types of figure 15 shows a decrease in the percentage of F5 (Type B beds) and a concomitant increase in Type A slurry beds and F5-F6-F7 Type C beds (Fig. 24). This suggests a genetic link between these bed types, confirmed by many physical bed correlations, in which Type B beds evolve down-current in Type A and C beds (see also Fig. 46A in Stop 1.5). These facies tracts indicate different degrees of flow decelerations, as discussed in section 4.1, due to the structural confinement produced by the M.Castellaccio thrust propagation.
In particular, Type C facies are important because they are very similar to the facies sequences characterizing the overlying Tortonian low-efficiency mixed turbidite deposits (see below and Tinterri & Muzzi Magalhaes, 2011). The progressive increase in this bed type number, therefore, heralds the Tortonian turbidites, which are deposited in a more confined and uplifted outer basin characterized by shallower depths than Langhian and Serravallian turbidite deposits. In this regard, it is important to note the first appearance in the Paretaio turbidite system of Ophiomorpha-type bioturbations, generally typical of delta-front environments and completely absent in lower Langhian and Serravallian turbidites (see Stop 1.5).

DOI: 10.3301/GFT.2012.03

A

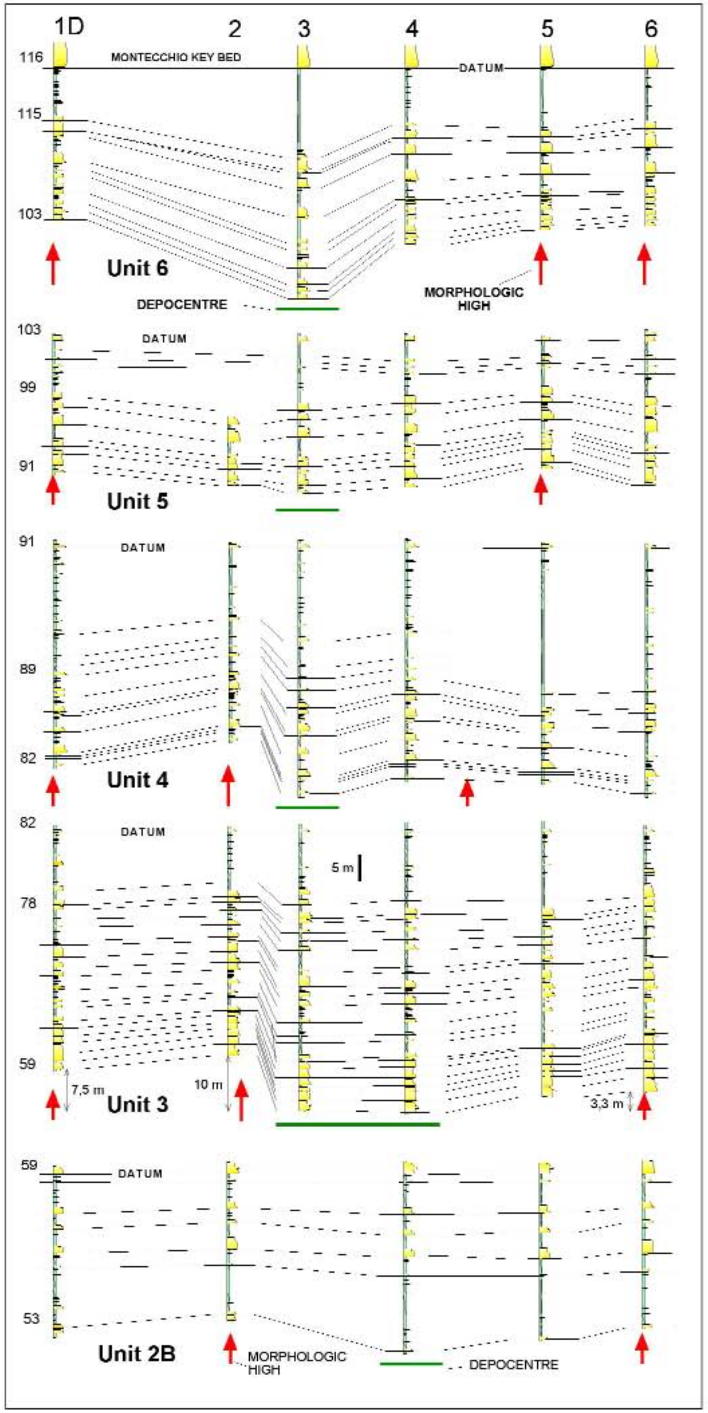
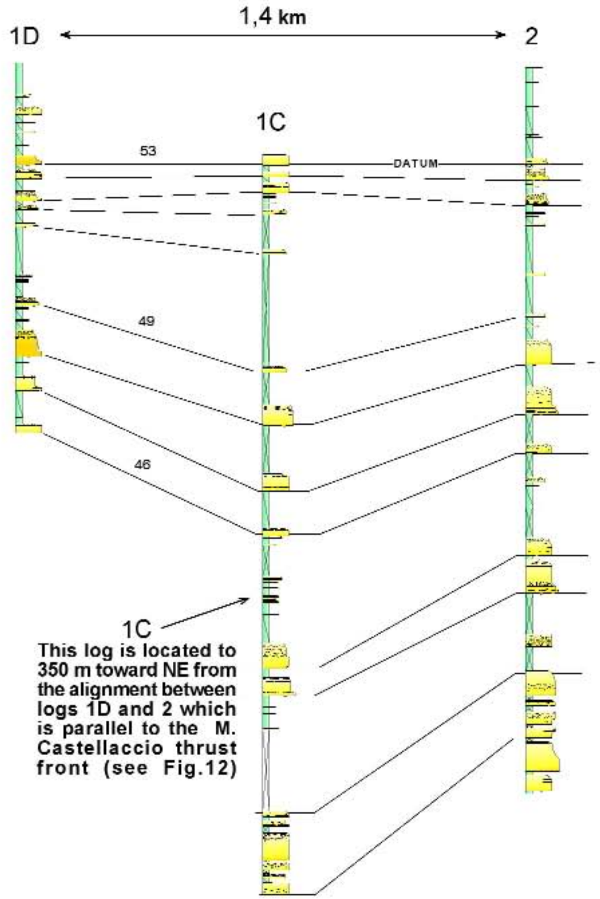
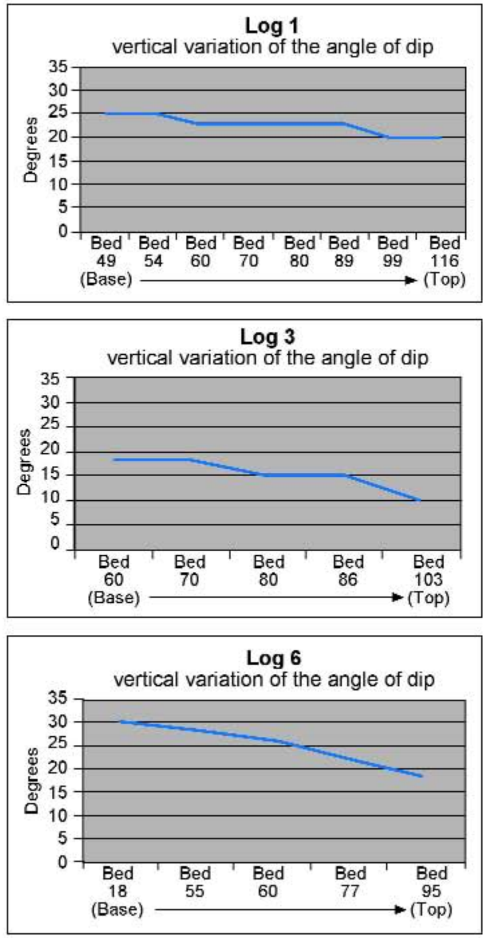


Fig. 23 - **A)** Stratigraphic cross section showing the progressive flattenings of the intermediate part B (see also Figs 13 and 14) where subtle morphologic highs and depocentres associated with thrust activity can be observed;
B) Detail of the basal part of Unit 2 (Fig. 13 for the location of the logs) showing a stratigraphic cross section in which a stratigraphic pinching against the M. Castellaccio thrust front can be observed;
C) Diagrams showing the progressive vertical decrease of the angle of dip in logs 1, 3 and 6.

B



C



DOI: 10.3301/GFT.2012.03

Figure 24, moreover, shows a very interesting lateral distribution of Type E beds associated to flow reflections and rebounds. Indeed, their percentage tends to increse in proximal and distal logs (logs 1, 2 and logs 5, 6 respectively), exactly where the progressive flattening approach highlights the presence of two morphologic highs produced by thrust propagation (Fig. 23A).

4.2.3 Upper interval "C" and vertical facies evolution: a discussion

This interval is included between the Montecchio key bed 116 and the uppermost bed 179 (Fig. 14). The synsedimentary action of the M. Castellaccio thrust is still acting, especially thanks to a still evident stratigraphic pinching in a perpendicular direction to the M. Castellaccio thrust front (see Stops 1.5 and 1.6). This uppermost stratigraphic interval is characterized by further increasing in the percentage of Type C beds (F5-F7-F6) and in the degree of bioturbation (Ophiomorpha-type) in comparison with the lower interval B.

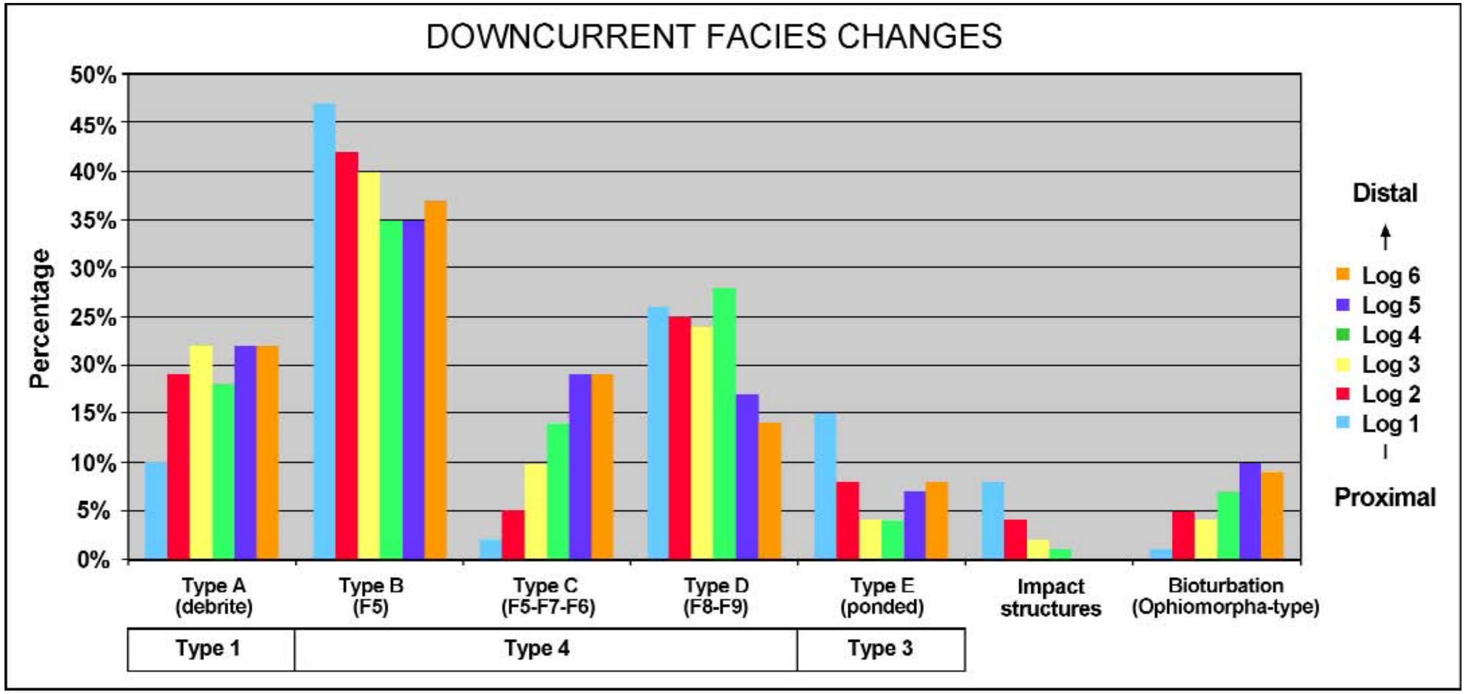


Fig. 24 - Diagram showing lateral facies variations in the intermediate part B, see Figs. 13 and 14.

This allows some important consideration to be made about the vertical facies changes in the Paretaio turbidite system. More precisely, the composite log 1, illustrated in figure 14, shows a stratigraphic interval about 600 meters thick above the Visignano MTC, where a progressive increase in Type D and C beds, as well as in the bioturbation degree (Ophiomorpha-type) can be observed (see Fig. 24).

As mentioned above, Type C beds are very similar to

DOI: 10.3301/GFT.2012.03

the facies sequences characterizing the overlying Tortonian low-efficiency mixed turbidite deposits (Tinterri & Muzzi Magalhaes, 2011). In particular, F5 overlaid by F6 or F7 records the deceleration of bipartite high density flows, which are consequently forced to deposit coarse grained massive F5 facies, and the bypass of upper turbulent flows, which are able to rework the F5 top in megaripples (F6) and traction carpets (F7). The presence of F6 or F7 on the top of F5, depends mainly upon flow deceleration degree, as suggested by Mutti et al. (2003) in figure 26. In particular, in the Paretaio turbidite system, F7 facies above F5 ones tend to predominate in comparison with F6 facies. The latter, on the contrary, seem to be more common in the inner Firenzuola system, which is characterized by more confined conditions, as shown in Fig. 11. Consequently, the progressive increase in the number of beds of this type and such a drastic increase in Ophiomorpha-type bioturbations testify that the turbidites of the Paretaio system are deposited in a more confined and less deep basin than that of Langhian and Serravallian turbidite deposits, due to the progressive closure, segmentation and uplift of the foredeep associated to the north-eastward propagation of the main thrust fronts.

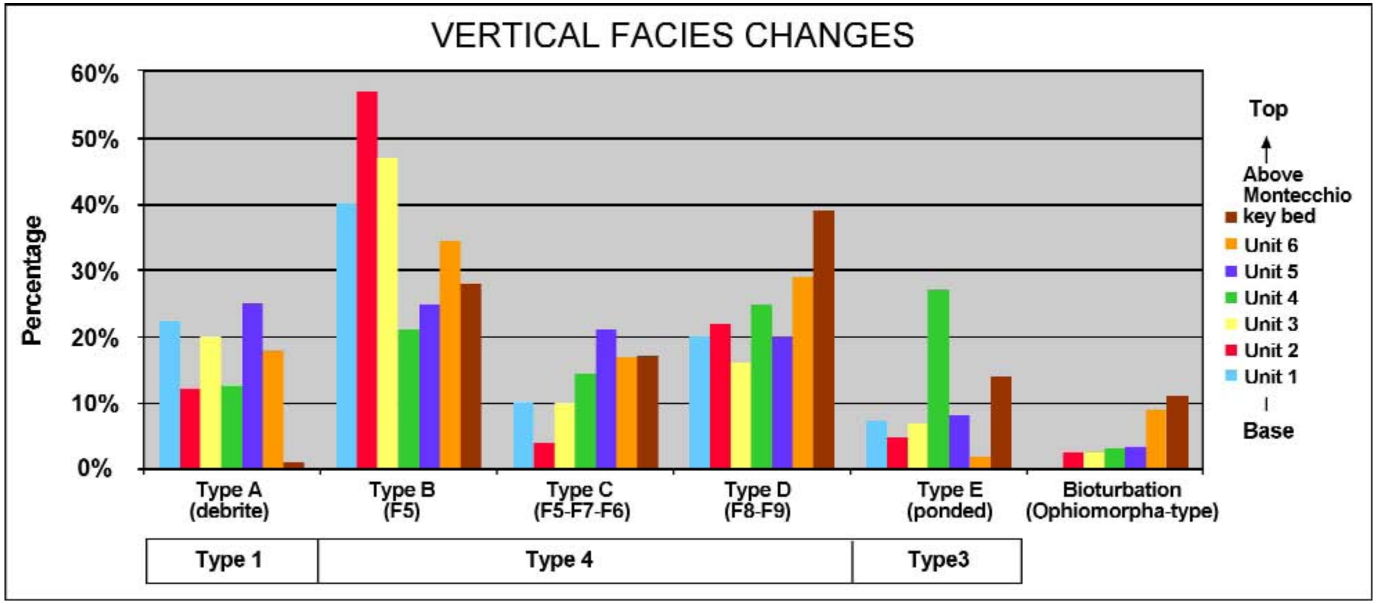


Fig. 25 - Diagram showing vertical facies variations of the basal, intermediate and upper parts A, B and C above the Montecchio key bed (see Figs. 13 and 14).

In conclusion, the turbidite deposits of the Paretaio system herald the upper low-efficiency Tortonian turbidites. More precisely, the Paretaio turbidite system, which is time equivalent to Unit V by Muzzi Magalhaes & Tinterri (2010) (see Fig. 10), records, with the slightly older inner Firenzuola system, an important tectonic phase that caused strong segmentation of the MAF foredeep with the uplift of the inner Langhian-Serravallian basin and the consequent

DOI: 10.3301/GFT.2012.03

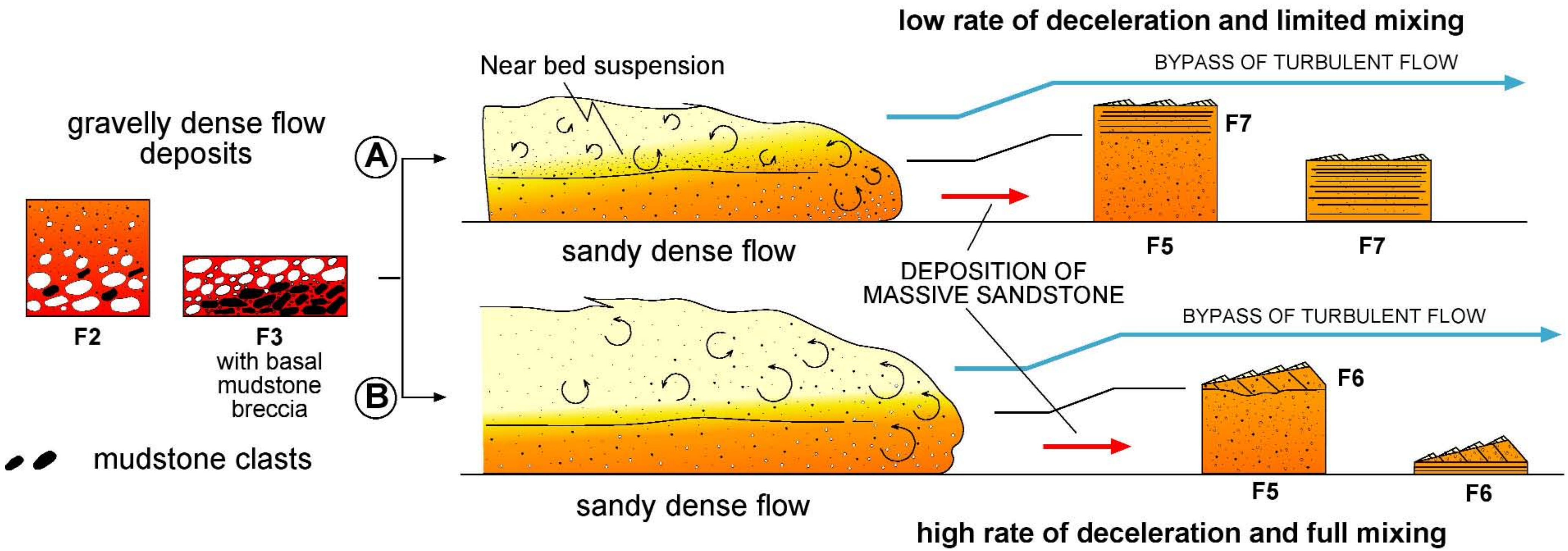


Fig. 26 - Facies types observed upon transformation of a dense sandy flow into a turbulent flow (from Mutti et al., 2003).

shifting of the main depocentre to a more outer basin characterized by Tortonian sedimentation. In this regional framework, the Visignano MTC and the Paretaio turbidites represent the first deposits of the outer basin as meant by Ricci Lucchi (1986) and, based on the facies associations shown in Figs. 13 and 15, these deposits can be interpreted as representing the inner foredeep (see Fig. 3C, D) of the outer basin. The vertical passage into Tortonian low-efficiency mixed turbidite deposits would occur in a more transitional way, as suggested by the progressive facies variations highlighted in figure 25.

Consequently, the boundary between inner and outer stage, although usually placed at the Serravallian-Tortonian boundary (Ricci Lucchi, 1986), could be better represented by a slightly older and more evident structural event, highlighted by Visignano MTC (see also Roveri et al., 2002 and Tinterri & Muzzi Magalhaes, 2011).

DOI: 10.3301/GFT.2012.03

5. Tortonian low-efficiency mixed turbidite systems (Outer stage)

5.1 Introduction

The Upper Serravallian tectonic phase that characterizes Unit V and, consequently, the Visignano MTC and the Paretaio systems, produces a significant basin narrowing and segmentation, as well as a shifting of the main depocentre towards the foreland (E-NE), as shown in figures 27 and 28. Ricci Lucchi (1981; 1986) defined these deposits as “outer basin” or “outer stage”. Since the deposits of the outer stage occurred mainly during the

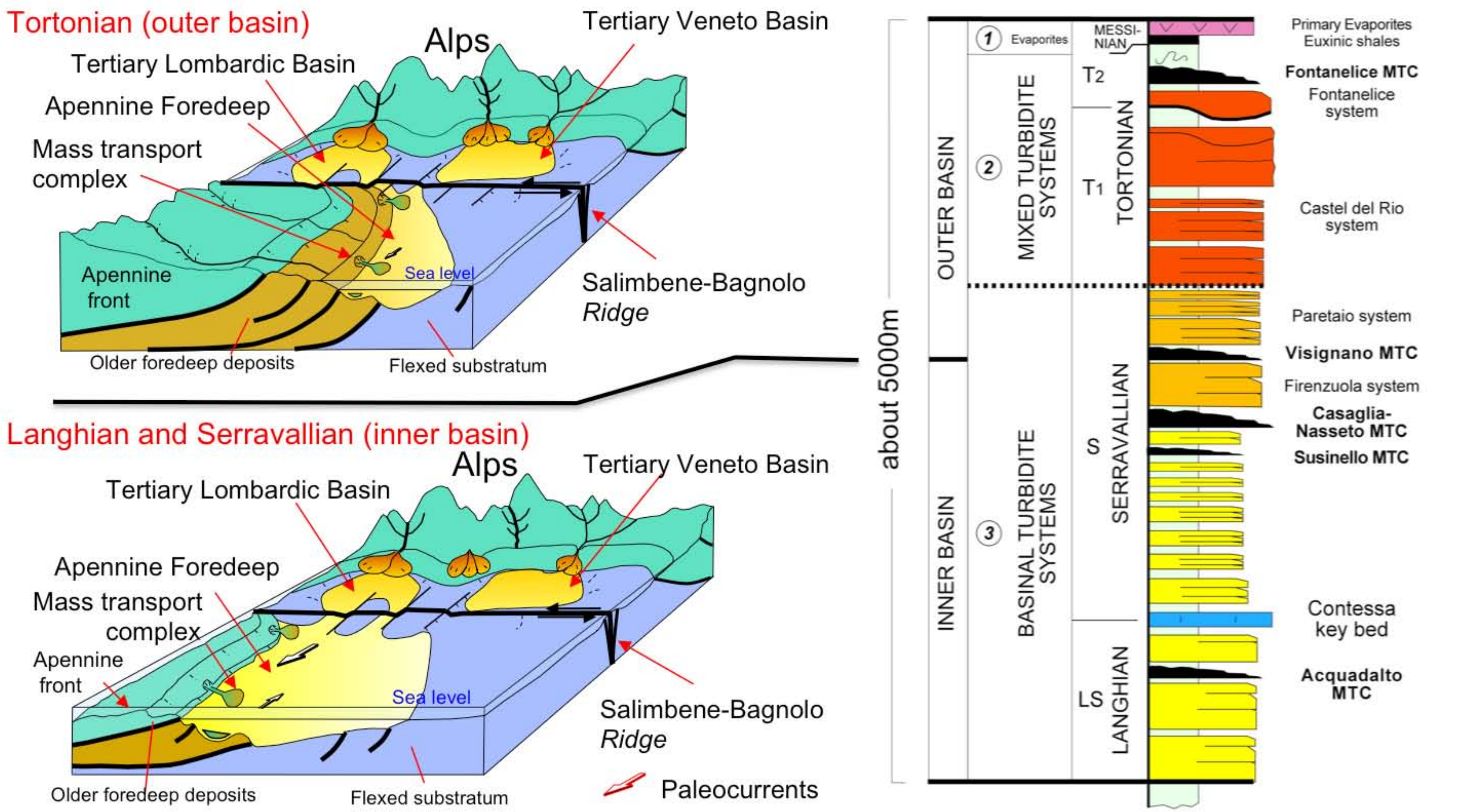


Fig. 27 - Diagrams showing simplified geodynamic models of the setting of the Proto-Adriatic Basin during the middle and late Miocene (inspired by di Biase & Mutti, 2002; in Muzzi Magalhaes, 2009). In particular the inner and outer stages of the MAF foredeep evolution according to Ricci Lucchi (1986) are shown.

DOI: 10.3301/GFT.2012.03

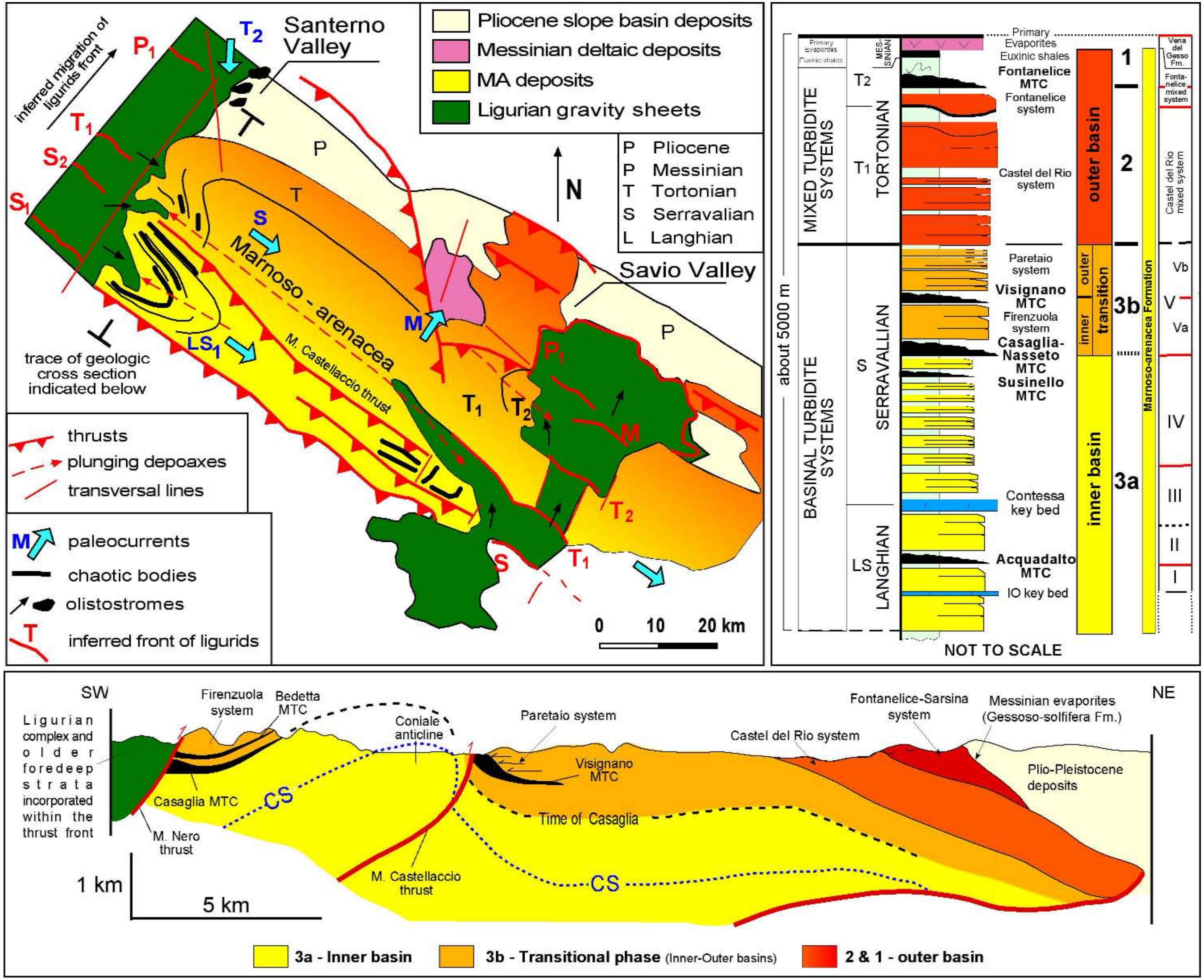


Fig. 28 - On the right a simplified diagram of the study area shown in figure 5A, showing the progressive migration of thrust fronts and main depocenters toward NE (taken from Ricci Lucchi & Ori, 1985; in Roveri et al., 2002). S - Serravallian; T - Tortonian; M - Messinian and P - Pliocene. This migration can be also observed in the schematic stratigraphic log of the MAF and in the geological cross section transverse to the basin axis in the proximity of the Santerno valley indicated below (modified from Roveri et al., 2002).

DOI: 10.3301/GFT.2012.03

Tortonian, Ricci Lucchi (1986) subdivided them into two depositional sequences, T1 (i.e. Tortonian 1), (Castel del Rio system by Mutti et al., 2002) and T2 (i.e., Tortonian 2), (Fontanelice-Sarsina system described by Mutti et al., 2002) (Figs. 4 and 5). In particular, the stratigraphic succession of T2 sequence is important because it records the closure of the Marnoso-arenacea outer basin which culminated with the well-known Messinian salinity crisis of the Mediterranean Sea, recorded by Messinian euxinic shales overlain by the primary and resedimented evaporites (mainly selenitic gypsum) of the Vena del Gesso Formation (Fig. 4; see Roveri et al., 2002; 2003).
The aim of this paragraph, however, is to discuss the Tortonian MAF "mixed" low-efficiency turbidites, as described by Mutti et al. (2003) and Tinterri & Muzzi Magalhaes (2009; 2011).

5.1.1 Description

The MAF Tortonian deposits have long been studied by various Authors (Ricci Lucchi, 1969, 1978, 1981, 1986; Ricci Lucchi & Pignone, 1979; de Jager, 1979; Benini et al., 1991; Mutti et al., 2002a, b, 2003; Roveri et al., 2002; Carubelli, 2005; Tinterri & Muzzi Magalhaes, 2011), nevertheless a detailed regional physical stratigraphy of these deposits is still lacking.
However, they usually consist of thick bedded and coarse-grained sandstone packages alternating with fine-grained deposits, which have sedimentary features quite different from those of the underlying Langhian to Serravallian turbidites. The main differences are:
1) an evident increase in sand content proven by a sandstone-mudstone ratio that can come to about 84% in the T2 sequence, i.e. Fontanelice-Sarsina system (see Fig. 29B in comparison with Fig. 29A that shows the sandstone-mudstone ratio of the underlying basinal turbidite deposits);
2) beds characterized by facies sequences quite different from those of the underlying turbidites with the predominance of coarse grained massive sandstones (see Fig. 29C) and the substantial absence of Type 1 debrite beds.
3) increase in bed amalgamations often highlighted by highly erosive surfaces (Fig. 29E);
4) increase in dewatering structures (Fig. 29D);
5) an increase in the bioturbation degree (Fig. 29F), in which Ophiomorpha-type trace fossils become very common, especially in the upper part of the Tortonian stratigraphic succession (T2 sequence in Figs. 4, 27);
6) the presence of shallow water fossil debris;
7) a cyclicity represented by an alternation of decametre-thick sandstone lobes and fine-grained intervals, much more developed than the underlying Langhian and Serravallian basin plain turbidites.

DOI: 10.3301/GFT.2012.03

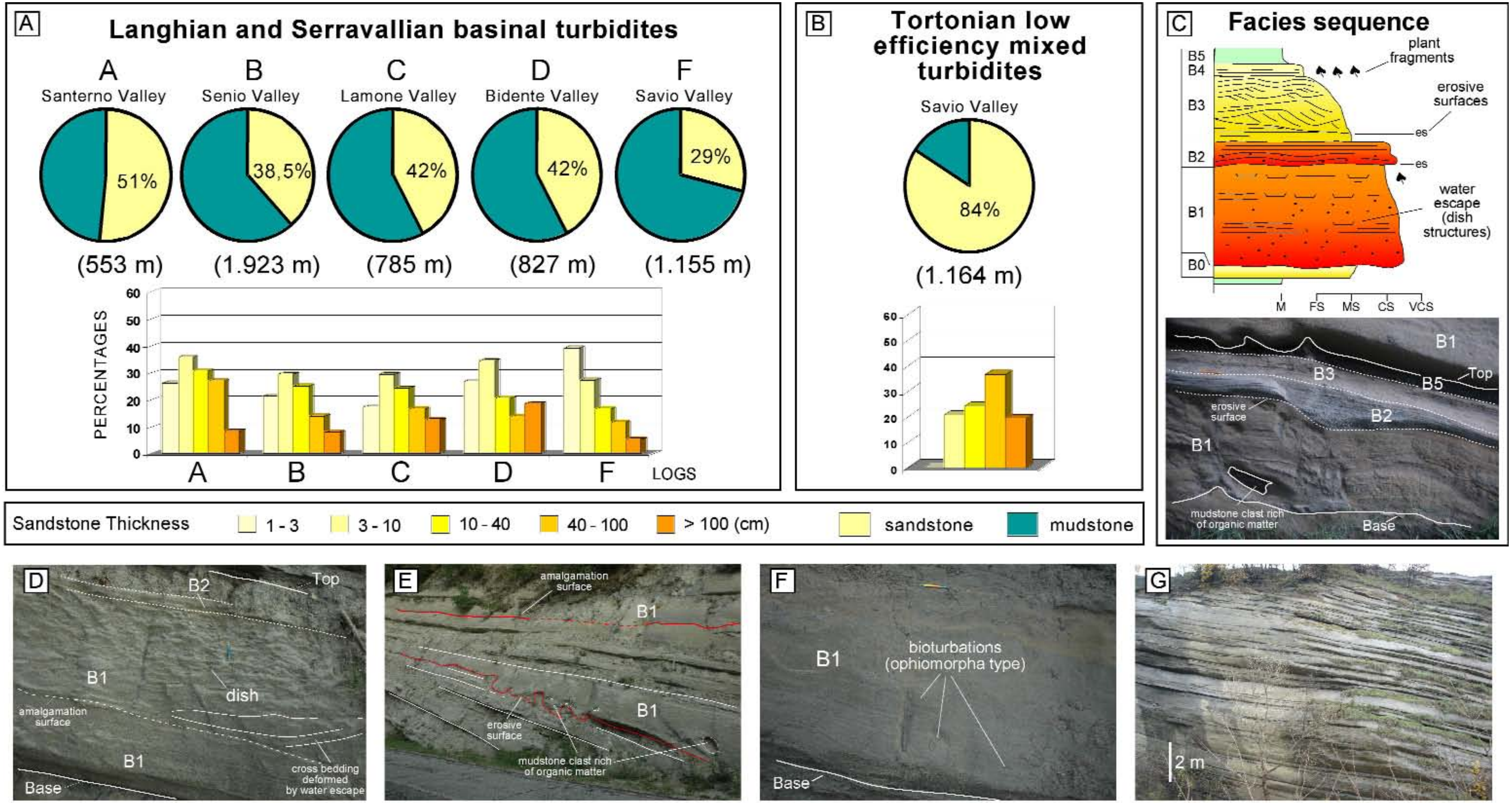


Fig. 29 - **A** and **B)** Net to Gross down-current variation in the Langhian and Serravallian turbidites and in the Tortonian mixed depositional systems in the Savio Valley (see also Fig. 4, taken from Tinterri & Muzzi Magalhaes, 2011). This high value of about 84% is also evident in the panoramic view shown in **G**; **C)** Sedimentary characteristics of sand-rich mixed deposits as described by Mutti et al. (2003, see their Fig. 10B; see also Stops 2.1; 2.3); **D)** crude laminated B1 division characterized by dish structures, **E)** Examples of amalgamations and erosive surfaces, **F)** Ophiomorpha-type burrows characterizing B1 division.

DOI: 10.3301/GFT.2012.03

Although consisting of massive coarse grained facies characterized by a high sandstone-mudstone ratio, the Castel del Rio deposits (sequence T1 by Ricci Lucchi, 1986) show relatively higher tabular geometries and lateral continuity than the overlying sequence T2. In particular, beds with inverse to normal grading, as illustrated in Fig. 29C, D (see also Stops 2.1, 2.3) begin to be more common than in the underlying deposits of Unit V (see Paretaio turbidite system). Conversely, Sequence T2, in proximal zones (around the Santerno Valley, see Figs. 4, 5A, 30), consists of sandstone lobes confined in erosional depressions known in the literature as "Fontanelice channels" (Ricci Lucchi, 1981, 1986), which show massive to crudely laminated coarse–grained sandstones essentially devoid of upper fine-grained laminated divisions and often characterized by erosive bases, amalgamation surfaces and poor lateral continuity (see Stop 2.2). At the base of these erosional depressions metre-thick successions of ortho-conglomerates with alpine composition can also be found (Ricci Lucchi, 1981; 1986, see Stop 2.2). Based on the model introduced by Roveri et al. (2002) the down-current time-equivalent deposits of the Fontanelice system would be the strata of the Sarsina system in the Savio Valley (60km to the SE) as illustrated in Fig. 30. These distal deposits, well described by Mutti et al. (2002b, 2003), mainly consist of metre-thick and coarse-grained graded sandstone beds with abundant dewatering structures and Ophiomorpha burrows, showing a very particular facies sequence sometimes characterized by inverse to normal grading with internal erosive surfaces, as indicated in figure 29C. These deposits are associated to decametre-thick mudstone-dominated units containing thin sandstone beds and very thin sandstone-mudstone couplets.

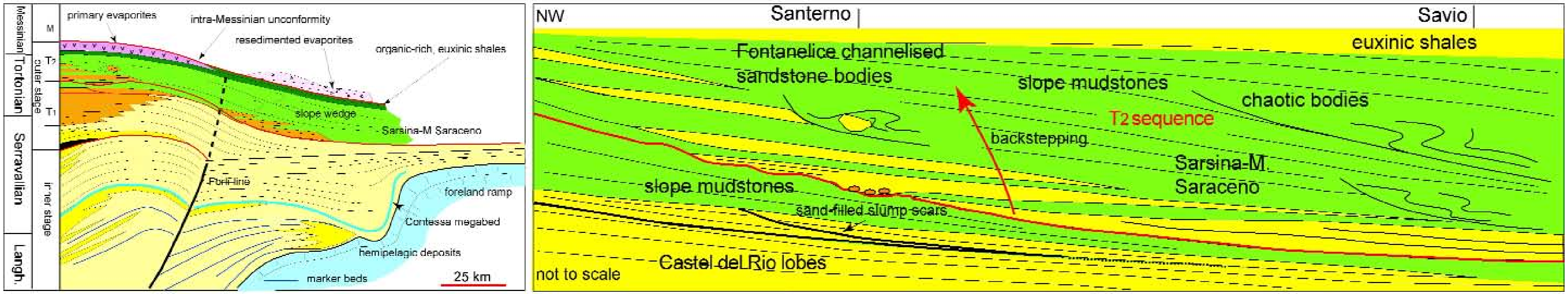


Fig. 30 - On the left, a schematic cross-section showing the evolution of the MAF foredeep basin illustrating the fragmentation of the foredeep basin and formation of shallow piggy-back basins during the late Messinian period (see Fig. 5 for the location of Forlì line). In the diagram on the right, a model showing a correlation between Fontanelice and Sarsina-M. Saraceno systems is given (from Roveri et al., 2002 published upon the Author's permission).

DOI: 10.3301/GFT.2012.03

5.1.2 Interpretation

Several factors, such as: 1) the presence of thick mudstone successions interpreted by Mutti et al. (2002a, b) as prodelta deposits, based also on the similarities with the deposits of the Hecho Group in the south-central Pyrenean foreland basin (Mutti et al., 1999; 2003); 2) the above-listed sedimentary characteristics indicating deposition at a shallower water depth and in a narrower basin than the underlying Langhian to Serravallian turbidites; 3) the general geologic context associated to the uplift and closure of the foredeep prompted Mutti et al (2002b; 2003) to interpret these deposits as mixed turbidite systems, i.e. relatively small and sand-rich depositional systems sharing several characteristics with basinal turbidites, but differing from these by showing a more immature facies development (cf. “poorly-efficient turbidite systems” by Mutti, 1979) and for their close vertical and lateral stratigraphic association with distal fine-grained prodelta deposits. These systems can thus be viewed as immature, marginal and poorly-efficient turbidite-like systems formed seaward of, but adjacent to, feeder delta complexes. Mixed turbidite systems usually consist of thick bedded and coarse-grained sandstone packages deposited by immature turbidity currents triggered by the combined effect of severe flood events and/or ensuing failure of fluvio-deltaic deposits (see Fig. 31, Mutti et al., 2007).

The relative tabularity of the beds belonging to the Castel del Rio system, however, suggests a deposition by still relatively unconfined flows running parallel to the basin axis (i.e., in a northwest/southeast direction), while facies and geometry characteristics of sandstone bodies of the Fontanelice channelled systems imply the lateral confinement of turbiditic flows running from the northwest to the southeast, in a progressively narrowing basin. The geometry of the erosional surfaces and subsurface data suggest the creation of a topographic relief to the northeast, possibly elongated in a direction parallel to the basin axis, which can be seen as the first evidence of the growth of an anticline related to the Forlì Line (Roveri et al., 2003, Fig. 5A). Moreover, the presence of a metre-thick succession of ortho-conglomerates at the base of the upper Fontanelice body (sequence T2, Ricci Lucchi, 1981; 1986; see Stop 2.2) testifies that this feature acted as a bypass zone and, consequently, as a kind of structurally-controlled conduit. The distal deposits related to Fontanelice strata are recorded, 60km down-current, by the Sarsina system (Savio Valley in Fig. 5) where the typical facies sequence illustrated in figure 29C becomes very common (see Fig. 30).
In particular, the facies sequences characterizing Castel del Rio and Fontanelice-Sarsina systems (Fig. 29, see also Stops 2.1, 2.2 and 2.3) can be interpreted as deposited by sediment-gravity flows strongly influenced by accumulative and depletive conditions related to topographic confinements typical of this outer stage (see Fig. 32).

DOI: 10.3301/GFT.2012.03

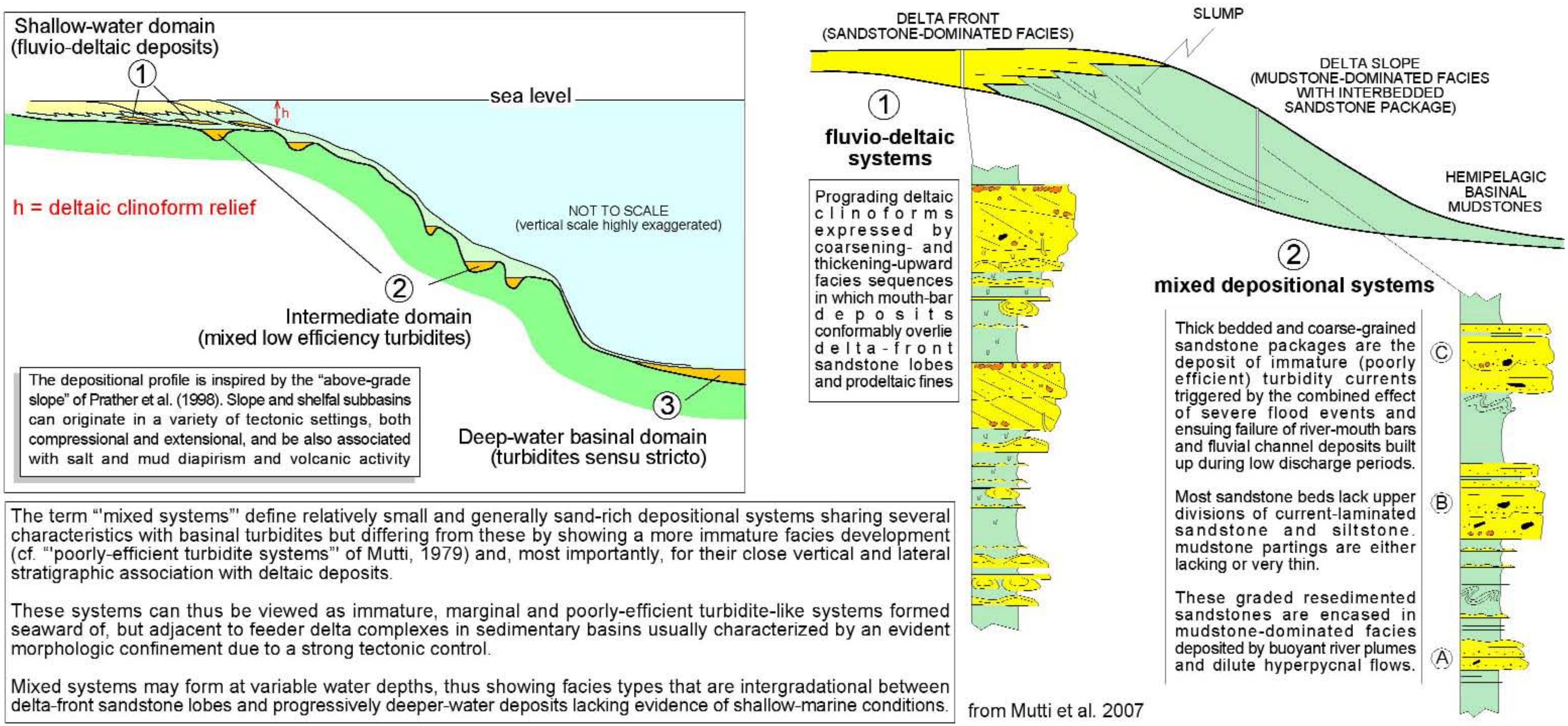


Fig. 31 - On the left a diagram showing the three main types of occurrence of "turbidite-like" facies in marine environments of divergent, convergent, and collisional continental margins. The diagram shows (1) a "shallow-water domain", where graded sandstones are essentially attached to their feeder fluvio-deltaic systems, (2) an "intermediate domain", where graded sandstones are mostly trapped in intra-slope basins (in both compressional and extensional regimes), and (3) a "deep-water, basinal domain", where graded sandstones record the final depositional zone of turbidity currents, whatever their origin (hyperpycnal flows, submarine slides or a combination thereof). On the right, there is another diagram representing the depositional environment and facies sequences of the mixed systems introduced by Mutti et al. (2002; 2003; 2007). The main definitions are also quoted (from Mutti et al., 2003;, 2007).

DOI: 10.3301/GFT.2012.03

More precisely, in the formation of the mixed facies sequences of Fig. 29C, also the role of capacity-driven deposition with concomitant development of turbulent energy induced by flow decelerations associated to morphologic confinements, should be considered (Fig. 32, Tinterri & Muzzi Magalhaes, 2011; see also Hiscott, 1994 and Kneller & McCaffrey, 2003).

In particular, B2 division and its erosive base can be interpreted as related to the deposition and reworking of the top of B1 division associated to a bypassing turbulent flow. The formation of the latter would be favoured by sediment concentration drops and relative increase in turbulent energy produced by the deposition of B1 division induced by decelerations due to morphologic confinements of the basin. It is deemed that strong bypass processes can occur, if the development of turbulent energy is sufficiently high due to strong decelerations related to high degree of structurally-controlled confinement. In this case, the undulated laminae of B2 division could be replaced by megaripples with well developed cross bedding. On this basis, the presence of undulated laminae or megaripples in B2 division could depend on the rate of deceleration associated to the degree of structurally controlled confinement. All things being equal, facies sequences characterized by B2 division consisting of low-angle undulated laminae (Fig. 32A) could be interpreted as associated to basins with a relatively lower degree of confinement. Conversely, facies sequences characterized by B2 division consisting of megaripples could be seen as associated to basins with a higher degree of structurally-controlled confinement (Fig. 32B). From this point of view, a strong analogy is believed to exist with the concepts introduced by Mutti et al. (2003) in which the transformation of a high density turbidity current in a dilute turbulent flow takes place through two different and probably intergradational facies sequences, in which massive to crudely laminated F5 facies (analogous to B1 facies) can be overlain by even, parallel, coarse grained laminae F7 (a B2 analogous with undulated laminae) or by well sorted cross bedding F6 (B2 analogous with megaripple cross bedding) depending on the rate of deceleration induced by the degree of confinement (see Fig. 26, Mutti et al., 2003). As mentioned in section 4, these type of facies are very similar to the underlying structurally-confined Paretaio turbidite system.

In general, the MAF is characterized by beds with facies sequences similar to that illustrated in Fig. 32A, while examples of facies sequences with megaripple B2 division (Fig. 32B), interpreted as delta-fed mixed turbidite systems with a higher structural confinement, are the Late Eocene/Early Oligocene Annot Sandstone in the south of France and the Messinian Laga Formation (see Tinterri & Muzzi Magalhaes, 2011).

DOI: 10.3301/GFT.2012.03

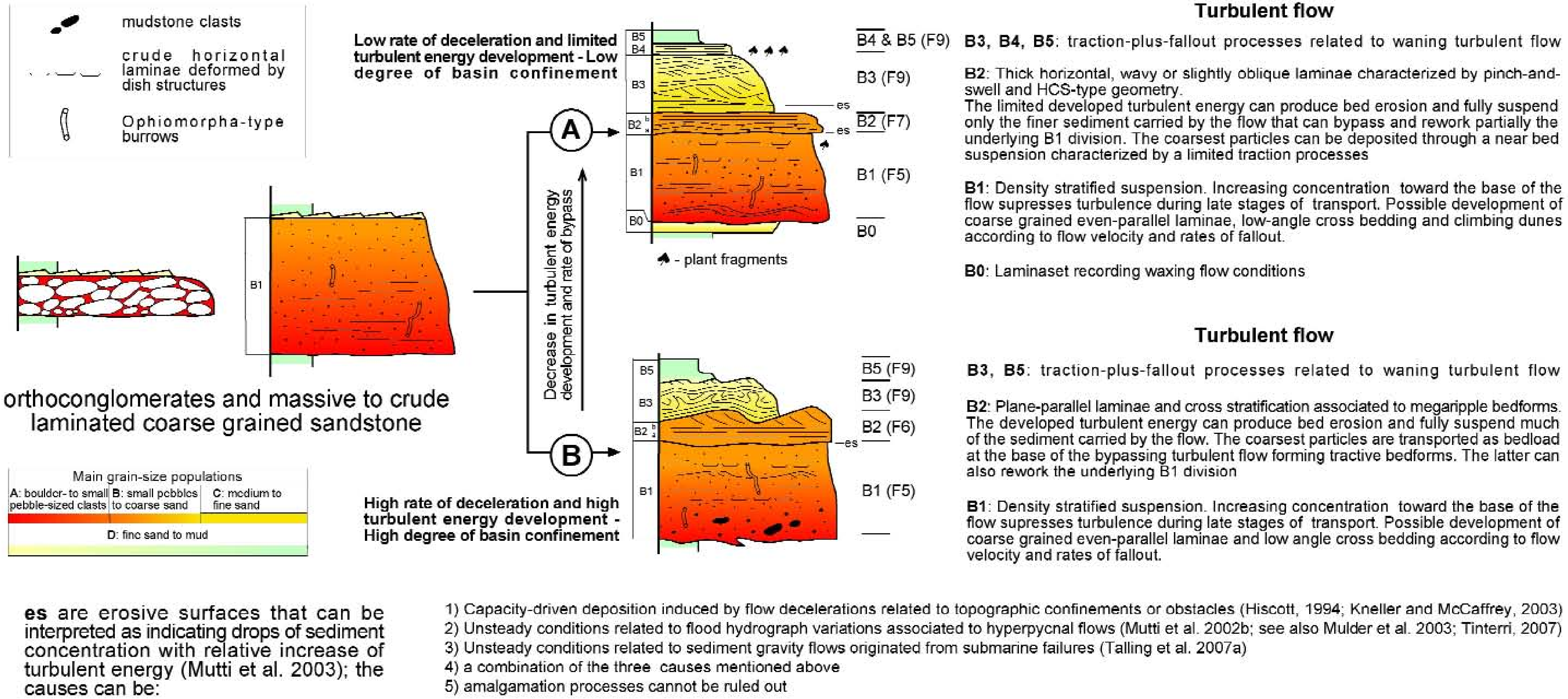


Fig. 32 - Two different mixed turbidites facies sequences in relation to basin confinement degree due to a structural control. **A)** facies sequence characterizing the MAF Tortonian mixed deposits as described by Mutti et al. (2003). It is interpreted as being deposited in a basin with a relatively low degree of confinement; **B)** facies sequence interpreted as deposited in a relatively highly confined basin. Both are inspired by figure 26 in which, on the basis of the degree of deceleration induced by slope changes of topographic obstacles, massive sandstone (F5, analogous to B1) can pass upward into plane parallel coarse grained laminae (F7, analogous to B2 facies with low-angle undulated laminae as shown in A) or into cross bedding associate to megaripple bedforms (F6 analogous to B2 facies with megaripple bedforms illustrated in B) (from Tinterri & Muzzi Magalhaes, 2011).
This facies scheme can be perfect for Fontanelice-Sarsina system; the facies which fill the structurally controlled Fontanelice channels are characterized by ortho-conglomerates and coarse grained massive sandstone, while in the Sarsina (60km down-current) beds are characterized by the typical facies sequence illustrated in A (see also figure 30).

DOI: 10.3301/GFT.2012.03

6. Summary and conclusions

As indicated in figure 3, an idealized transect oriented perpendicularly to the main structural axes shows that sedimentation of a foreland region takes place in three distinct and coeval basins including: a) wedge-top basins, characterized by alluvial, deltaic and mixed depositional systems; b) a foredeep basin, characteristically in-filled with deep-water basinal turbidites; c) an outer and shallower ramp developed on the passive foreland plate. The progressive thrust propagation toward the outer margin of the basin produces a vertical superimposition of three depositional systems that, from base to top, are: (1) highly efficient basinal turbidite systems and associated hemipelagic deposits; (2) mixed depositional systems, in which turbidite-like bodies are deposited by poorly efficient gravity flows in structurally confined basin and can be associated to prodeltaic sediments, both vertically and laterally; (3) flood-dominated deltaic systems (see Mutti et al., 2003).

The vertical stacking pattern of the MAF, illustrated in figures 4 and 33, is characterized by the same vertical stratigraphic evolution, in which at least three main depositional systems can be recognized and are represented by Langhian to Serravallian high-efficiency basinal turbidites, Tortonian low-efficiency mixed turbidites and shallow water Messinian euxinic shales and evaporites (see also Ricci Lucchi, 1978, 1981, 1986; Mutti et al., 2002a; Roveri et al., 2003; Tinterri & Muzzi Magalhaes, 2011). Therefore, the MAF, consists of a shoaling-up stratigraphic succession, which resulted from the progressive closure of the foredeep due to the north-eastward propagation of the MAF main thrust fronts. This eastward thrust propagation produced the progressive uplift of the inner portions of the foredeep and the consequent shifting in the same direction of the main depocentres. For this reasons, Ricci Lucchi (1986) introduced the concepts of inner stage or basin (Langhian and Serravallian in age) and outer stage or basin (Tortonian in age). The first one is characterized by deep water high efficiency basinal turbidites, while the second one consists of low-efficiency mixed turbidites in a shallower and more confined basin. The passage between inner and outer stage is recorded by an important tectonic phase (upper Serravallian in age) characterizing the basal part of Unit V by Muzzi Magalhaes & Tinterri (2010) which is time equivalent to the Firenzuola and Paretaio systems in the Santerno Valley (see Figs. 4 and 5A, B).

DOI: 10.3301/GFT.2012.03

The MAF stratigraphic succession, therefore, can be described in three stages: 1) a Langhian-Serravallian inner basin; 2) an Upper Serravallian phase recording the transition between inner and outer basins and 3) a Tortonian outer basin (see Fig. 33).
The Langhian to Serravallian inner stage (or basin) is well documented by the recent work by Muzzi Magalhaes & Tinterri (2010) (see also Muzzi Magalhaes, 2009; Tinterri & Muzzi Magalhaes, 2009; 2011), which presents

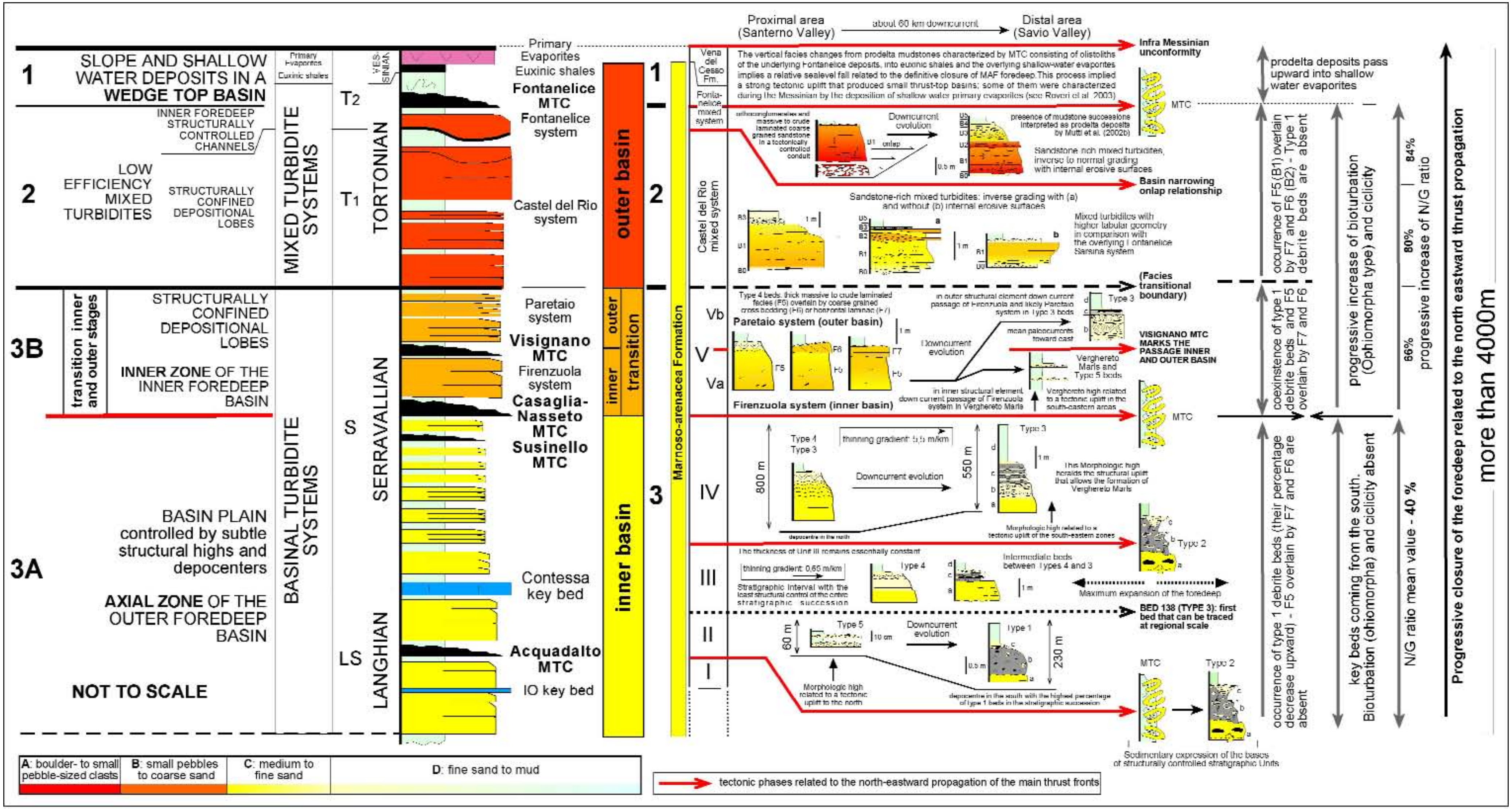


Fig. 33 - The schematic stratigraphic log on the left describes the vertical stacking pattern of the MAF foredeep basin from its inception to its final infill with shallow water deposits represented by Messinian evaporites (modified from Mutti et al., 2002a and Roveri et al., 2002). The depositional sequences (LS, S, T1, T2), the inner and outer basins by Ricci Lucchi (1986) and the main MTCs (see also Lucente & Pini, 2002) are also shown. On the contrary, the diagram on the right tries to summarise the vertical facies changes relating to the physiographic change of the basin primarily produced by thrust propagation toward the outer margin of the foredeep. The main tectonic phases (red arrows) and the sedimentary expression of the bases of the structurally controlled stratigraphic units are also shown. The boundary between inner and outer stages, although usually placed at the Serravallian-Tortonian boundary, is here associated to a slightly older and more evident structural event highlighted by the Visignano MTC (see also Roveri et al., 2002). This MTC and the older Casaglia MTC characterize Unit V, which can be interpreted as representing a transitional stage between inner and outer basin, which is also testified by the evident facies change that characterizes this unit (see text for more details). As a consequence, the hypothesis is here advanced that the vertical passage into mixed turbidite deposits of the Castel del Rio system would occur in a more transitional way, thus suggesting a continuum between the structurally confined turbidites of Unit V and the structurally controlled mixed deposits (see text for more details). Numbers 1, 2 and 3 on the left indicate the three different depositional systems in the diagram of a foreland basin illustrated in Fig. 3C (slightly modified from Tinterri & Muzzi Magalhaes, 2011).

a high-resolution stratigraphy with bed by bed correlations and facies analysis of an interval of about 2500m covering the greater part of the MAF Langhian to Serravallian succession between the Santerno and Savio valleys (Figs. 4, 5 and 10).

In addition to the high-resolution physical stratigraphy of the greater part of the MAF inner basin stratigraphic succession, the main novelty of this study is its subdivision into five informal stratigraphic units (I, II, III, IV, V) on the basis of syndepositional structural control made evident not only through the characterisation of regional-scale structural highs and depocentres, but also on the basis of vertical and lateral variations in beds characteristic. The syndepositional structural deformation within the MAF has been discussed in various papers (de Jager, 1979; Ricci Lucchi, 1978, 1981, 1986; Argnani & Ricci Lucchi, 2001; Mutti et al., 2002a; Roveri et al., 2002; Lucente & Pini, 2002; Lucente, 2004; Bonini, 2006). The facies analysis carried out by Muzzi Magalhaes & Tinterri (2010), however, clearly shows that a structural control on sedimentation was important, with different degrees of intensity, during the entire stratigraphic interval studied. In particular, this work shows that basin geometry and facies distribution patterns of the MAF were influenced by an evident syndepositional structural control at different time and physical scales.

DOI: 10.3301/GFT.2012.03

The great tabularity of MAF turbidites shown by long-distance correlations studies, carried out by Ricci Lucchi & Valmori (1980) and Amy & Talling (2006), has led some workers to consider the MAF foredeep basin as essentially flat. In truth, these works focus on a stratigraphic interval around the Contessa key bed, which is the interval with the least tectonic control in the entire MAF. Conversely, our data show that thrust fronts moving toward the NE, today represented by M. Nero, M. Castellaccio, S. Sofia, Civitella thrusts, were able, during the Langhian and Serravallian, to produce structural highs, which occasionally could become topographic highs and, consequently, influence the turbidity current deposition. This interpretation is also supported by a number of papers on the relationship between thrust propagation and emplacements of MTCs, especially in the Serravallian and Tortonian stratigraphic succession (Conti, 2001; Lucente & Pini, 2002, 2003; Lucente, 2004; Roveri et al., 2002; see also Figs. 4 and 5). As a result, the vertical stacking pattern of the MAF records a close interaction between thrust propagation towards the NE and deposition from turbidity currents flowing towards the SE, i.e. parallel to the thrust fronts.

The synsedimentary structural control on sedimentation is shown by the stratigraphic-cross section in figure 10, where five informal stratigraphic units (I, II, III, IV, V) have been identified through: 1) highlighting regional-scale structural highs and depocentres through a progressive flattening approach and 2) detecting the presence of thrust-related MTCs, as well as the vertical and lateral changes in the percentage of five types of beds and facies tracts (Fig. 7) interpreted as related to the interaction between flow efficiency and basin physiography (Type 1, 2, 3, 4 and 5 in Fig. 7, see also Figs. 8 and 9). The bases of Units II, IV and V are characterized by MTCs with intrabasinal components and Type-2 beds further testifying the tectonic control on these stratigraphic Units and the high diagnostic value of Type-2 beds.
The base of Unit II, for example, is marked by the Acquadalto MTC to the north and a time-equivalent Type-2 bed to the south (bed 66; see Fig. 10). Unit II, therefore, is interpreted as being related to a tectonic uplift able to produce a topographic high in northern proximal zones, where Type-5 beds predominate, and a depocentre in southern distal zones, where there is the highest percentage of Type-1 beds in the entire succession studied (Fig. 10). By contrast, Unit III, containing the Contessa key bed, corresponds to a period of relative tectonic quiescence where, although Type-3 beds are present, Type-4 beds increase and Type-1 beds decrease drastically. Unit IV, in turn, whose base is marked by a Type-2 bed (bed 345, Fig. 10), records an evident uplift of the southern distal areas where Type-3 beds increase. Finally, Unit V, whose base, is marked by the Casaglia-Nasseto MTC, records an important phase of basin narrowing and uplift of the southern Verghereto zone and M. Castellaccio thrust sheet (Figs. 10 and 11).

DOI: 10.3301/GFT.2012.03

More precisely, Unit V, which is time equivalent with the Firenzuola system and the slightly younger Paretaio system, is particularly important because it records a transitional stage between inner and outer basins. Unit V is indeed characterized by an evident facies change compared with the underlying turbidites highlighted by a drastic increase in sandstone-mudstone ratio, due to the presence of massive sandstones (F5) often overlaid by F6 and F7 facies. These bed types are interpreted as related to flow decelerations due to drastic basin narrowing; in these cases, flow decelerations favour the deposition of coarse grained massive F5 facies and the bypass of more diluted turbulent flow able to rework the underlying F5 in megaripples (F6) or even-parallel traction carpets (F7). In particular, the massive sandstone beds of the Firenzuola system fill a thrust-related depression associated to the uplift of the inner basin, due to the propagation of the M.Castellaccio thrust sheet. These thick massive sandstone lobe accumulations pass down-current into Verghereto marls, which mainly consist of graded turbiditic mudstones and thin, very fine grained, laminated sandstones (F9) with pinch out geometry, interpreted as deposited by dilute turbidity currents able to rise the Verghereto high. Conversely, in more outer zones (i.e. to the NE of the M. Castellaccio thrust front; see Log G in Figs. 5 and 10), the turbidity currents, able to bypass, are deviated preferentially toward the east, probably due to the forward thrust propagation and are characterised by diffuse reflection processes (Type-3 beds).

The Firenzuola system, therefore, records the transition from an inner foredeep zone to a piggyback basin, formed above the advancing M. Castellaccio thrust sheet and bounded to the NE by the growing M. Castellaccio structural high and to the SE by the Verghereto high (see Fig. 11 and Stop 3.4). The destabilization of the mud drape deposits formed above the M. Castellaccio (or Coniale) high, associated to a further tectonic phase in the Upper Serravallian, results in the emplacement of the Visignano MTC along the thrust front (Fig. 11-4). During the late Serravallian, therefore, the inner front of the Apennine orogenic wedge moved to the M. Castellaccio thrust front and the depocentre shifted from the inner into the outer basin. Consequently, the Paretaio turbidite system and the underlying Visignano MTC represent the first deposits of the new outer basin depocentre (de Jager, 1979; Roveri et al., 2002) recording the transition into the Tortonian mixed low-efficiency turbidite system of Castel del Rio (T2 sequence, see Fig. 33).
The data presented in sections 4.1 and 4.2 show the syntectonic nature of the Paretaio turbidite system, as well as that the facies types of the Paretaio system herald those of Tortonian mixed deposits as testified by the progressive upward increase in the bioturbation degree (Ophiomorpha-type) and Type C beds (F5 overlain by F7).

DOI: 10.3301/GFT.2012.03

These sedimentary characteristics, very similar to those of overlying mixed turbidites, indicate a progressive decrease in water depth, as well as an increase in flow deceleration phenomena, due to a higher degree of basin confinement related to the progressive closure of the foredeep.

The sedimentary characteristics of the Tortonian low-efficiency mixed turbidites, even if similar to those of the Paretaio turbidites (Unit V in Fig. 10), are, however, completely different from the underlying Langhian to Serravallian high-efficiency basinal turbidites (Units I, II, III and IV in Fig. 10) as testified by quite different bed types (see Fig. 32), as well by an evident increase in: 1) sandstone-mudstone ratio, 2) bed amalgamations, 3) massive facies with dewatering structures, 4) bioturbation degree (Ophiomorpha-type), 5) shallow water fossil debris and 6) a well-developed cyclicity represented by an alternation of decametre-thick sandstone lobes and fine-grained intervals interpreted as distal prodelta deposits (Fig. 29). The Tortonian deposits, therefore, can be interpreted as relatively small and sand-rich depositional systems sharing several characteristics with basinal turbidites, but differing from these by showing a more immature facies development (cf. “poorly-efficient turbidite systems” by Mutti, 1979) and for their close vertical and lateral stratigraphic association with distal fine-grained prodelta deposits (Fig. 31). These systems can thus be viewed as immature, marginal and poorly-efficient turbidite-like systems formed seaward of, but adjacent to feeder delta complexes. However, although they are likely fed by delta systems through the combined effect of catastrophic flood events and/or ensuing failure of fluvio-deltaic deposits (Mutti et al., 2007), their low degree of efficiency is here considered also strongly related to a depositional basin with a higher degree of structurally-controlled confinement respect to that of the underlying Langhian and Serravallian basinal turbidites. The facies sequences illustrated in Fig. 32 are interpreted as being deposited by an interplay between waxing and waning conditions (*sensu* Kneller, 1995) associated to the type of trigger mechanisms, namely floods or slumps on the one hand, and, on the other, capacity-driven deposition with concomitant development of turbulent energy induced by flow decelerations due to the topographic confinements typical of this outer stage (Tinterri and Muzzi Magalhaes, 2009a, b; 2011). More precisely, the development of erosive B2 division above B1 division, consisting of undulated coarse grained laminae (F7-analogous in basinal turbidite Fig. 32A) or well-developed cross stratification associated to megaripple bedforms (F6-analogous in basinal turbidite Fig. 32B), is interpreted as related to different degrees of deceleration rate and turbulent energy development, which control the bypass rate as indicated in figure 32 (see also Fig. 26).

DOI: 10.3301/GFT.2012.03

In particular, the Tortonian mixed turbidite deposits consist of two units represented by the Castel del Rio system (T1 sequence by Ricci Lucchi, 1986) and Fontanelice-Sarsina systems (T2 sequence by Ricci Lucchi, 1986). The relative tabularity of the beds belonging to the Castel del Rio system and their well-developed cyclicity suggest that these beds can represent structurally controlled sandstone lobes deposited by still relatively unconfined flows in comparison with the massive sandstone bodies of the Fontanelice channelled system, which imply a lateral confinement of turbiditic flows running in a progressively narrowing basin. The presence of a metre-thick succession of ortho-conglomerates at the base of the upper Fontanelice body testifies that this feature acted as a bypass zone and, consequently, as a sort of structurally-controlled conduit. Consequently, the shoaling and coarsening up-trend characterizing the vertical stratigraphic succession of the MAF foredeep, which imply a progressive fore-stepping of the depositional environments, due to the progressive uplift and closure of the foredeep caused by the NE thrust propagation, can be also observed in the vertical stacking pattern of the turbidite depositional elements as indicated in figures 3C and D. The Langhian to Serravallian basin plain turbidites are progressively replaced upward by tectonically confined sandstone lobes of the Upper Serravallian Unit V (Firenzuola and Paretaio systems) and of the lower Tortonian mixed deposits of Castel del Rio system, which in turn are overlaid by the structurally-controlled channelled deposits of Fontanelice system. Ultimately, the definitive closure of the Marnoso-arenacea outer basin, associated to the well-known Messinian salinity crisis of the Mediterranean Sea, is recorded by Messinian euxinic shales overlain by the primary and resedimented evaporites (mainly selenitic gypsum) of the Vena del Gesso Formation (Figs. 4 and 33).

In conclusion, these evolutionary phases characterizing the Marnoso-arenacea Formation are well described in figure 33, which well represents the spirit of this guide book, since it is meant to summarize the vertical facies changes in relation to the physiographic change of the basin primarily produced by thrust propagation toward the outer margin of the foredeep. The five bed types described in the Langhian to Serravallian basinal turbidites (Fig. 7), together with the different bed types of the Upper Serravallian Paretaio system (Fig. 15) and Tortonian mixed low efficiency turbidites (Fig. 32) represent different answers to a variable degree of structurally controlled confinements in different tectonic contexts, related to the progressive uplift and closure of the foredeep. In particular, it is very interesting to note how Type 1 beds, characterized by an intermediate debrite unit, are very common in the Langhian-Serravallian inner basin while start to be relatively uncommon in the Upper Serravallian intermediate stage for being completely absent in the Tortonian outer basin (Fig. 33).

DOI: 10.3301/GFT.2012.03

By contrast, the coarse grained massive facies F5 overlain by megaripples (F6) and traction carpets (F7) are completely absent in the Langhian-Serravallian inner basin while start to appear and increase upward in the Upper Serravallian intermediate stage for becoming very common in the Tortonian deposits of the outer basin (Fig. 33). This evidence can support the fact that type 1 beds can form especially in relatively large basins with basin plain characterized by intrabasinal structural highs and depocentres. In basins of this type, high efficiency turbidity currents can accelerate along out of grade proximal slope and erode a great amount of mud for being successively decelerated against intrabasinal topographic highs and depocentres characterized by evident slope changes. Consequently, these topographically-induced decelerations of mud rich turbidity currents in distal basin plains favour the formation of slurry or debrite unit and are at the base of Type 1 bed formation (see also section 3.1). The progressive upward decrease of type 1 beds percentage (see Fig. 33) can mean that the progressive closure of the foredeep humpers the ability of the flows to travel and erode a large amount of mud especially in the proximal areas. For these reasons F5 massive sandstones (B1 facies) reworked by F6 and F7 facies (B2 facies) tend to increase upward (Fig. 33). The deceleration of relatively mud poor high density turbidity currents (i.e. low eficiency turbidity currents as meant by Mutti, 1979) in a narrowed foredeep favour the formation of thick massive facies with dewatering structures rather than type 1 beds. This interpretation is also confirmed by the comparison with many other low efficiency turbidite systems in different type of basins such as for example the Annot Sandstone in southern French foredeep, Laga Formation in the central Apennines foredeep and Ranzano Formation in northern Apennines piggy back basin which are characterized by a diffuse presence of massive sandstones (F5) with megaripples (F6) and traction carpets (F7) and by the substantial absence of type 1 debrite beds (see also Tinterri & Muzzi Magalhaes, 2011).

Type 1 beds, therefore, tend to characterize especially mud-rich high-efficiency turbidites systems deposited in relatively large basin such as for example the Marnoso-arenacea foredeep during the Langhian and Serravallian; the fact that type 1 beds are not always present in these types of basin can depend upon various factors such as: 1) the basin dimension which controls the runout distances and consequently the time for eroding and disgregating the mud within the fluid phase of the flow; 2) the tectonic control which can produce both out of grade profiles and tectonically dissected basin plains which favour respectively mud erosion and flow decelerations and 3) the type of eroded mud in which the presence of active or inactive clay (see Marr et al., 2001) can favour the formation of the intermediate slurry or debrite units characterizing type 1 beds (see Fig. 7).

DOI: 10.3301/GFT.2012.03

In conclusion, the knowledge of the vertical and lateral distribution of the bed types described in this guide (see Figs. 7, 15 and 32) which has been obtained through the bed by bed correlation of about 9 kilometres of stratigraphic logs is considered of fundamental importance to understand basin physiographic variations related to the structural control and the progressive closure of the foredeep (see Fig. 33).

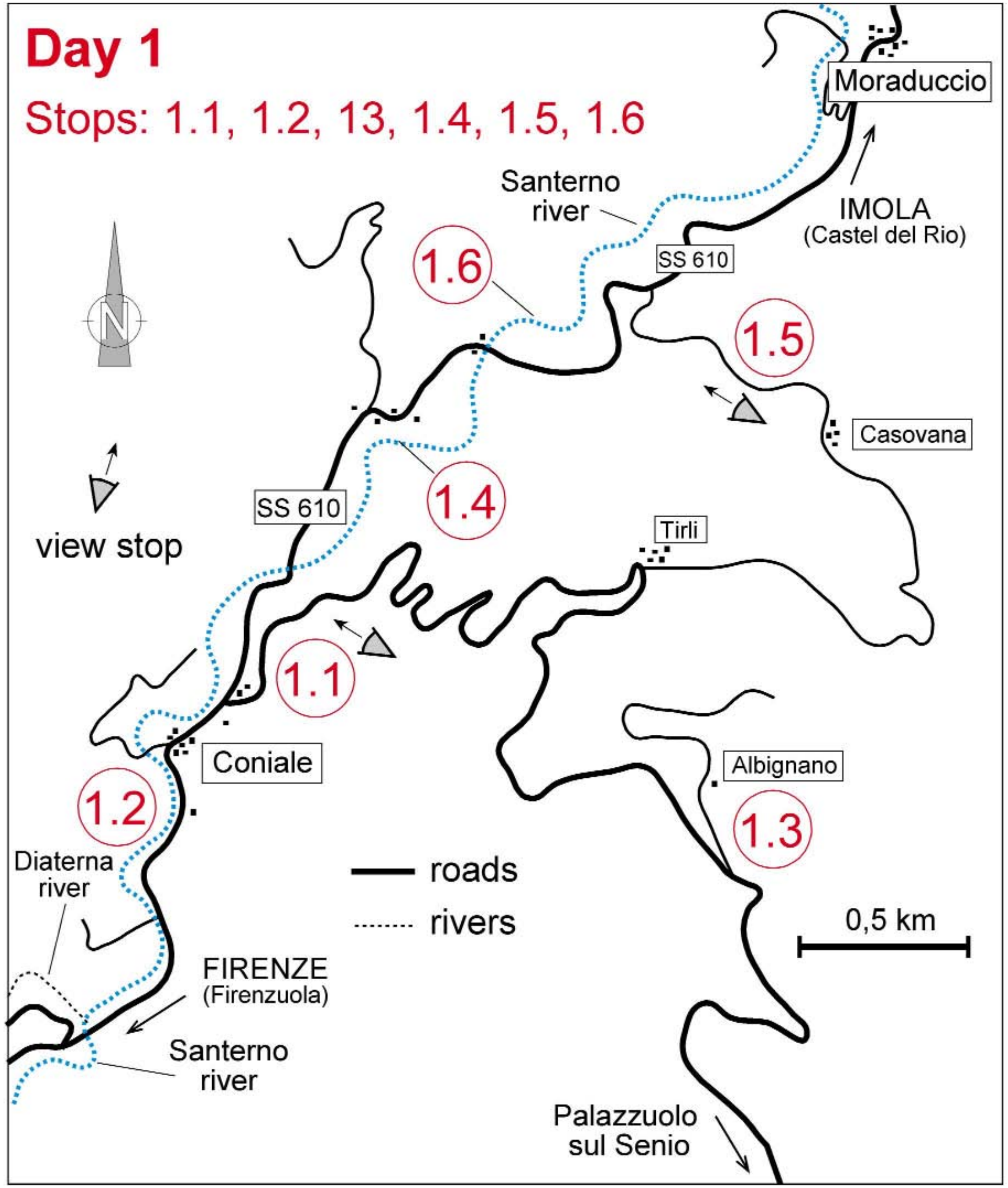
Acknowledgements

The Authors would like to thank Emiliano Mutti for his teachings and constructive discussions over the years on turbidites and the Marnoso-arenacea Formation. The Authors are also grateful to João Guerreiro, José Souto Filho, Gustavo Basta, Rogerio Soares Cunha, Kei Ogata, Paolo Carubelli, Claudemir de Vasconcelos and Alexandre Grassi for their assistance on the field. Rogerio Soares Cunha is also thanked for his valuable help in the final phase of editing. The Authors would also like to thank Franco Ricci Lucchi, Marco Roveri, Salvatore Milli, Andrea Fildani and Andrea Artoni for their useful advices and discussions in the field. Again, the Authors would like to deeply thank Giuseppe Cadel (ENI and AAPG Field Trips Chair), Maria Letizia Pampaloni and Mauro Roma (ISPRA - Servizio Geologico d'Italia) for their precious help and patience. Finally we also wish to thank Petrobras S.A. and in particular Mário Carminatti, Sylvia Couto Anjos, André Romanelli, Almério França. Gian Gaspare Zuffa is deeply thanked for his very helpful review. Much of this research was funded by Petrobras (Petroleo Brasileiro S.A.).

DOI: 10.3301/GFT.2012.03

Itinerary and Stops description

Day 1: Santerno Valley

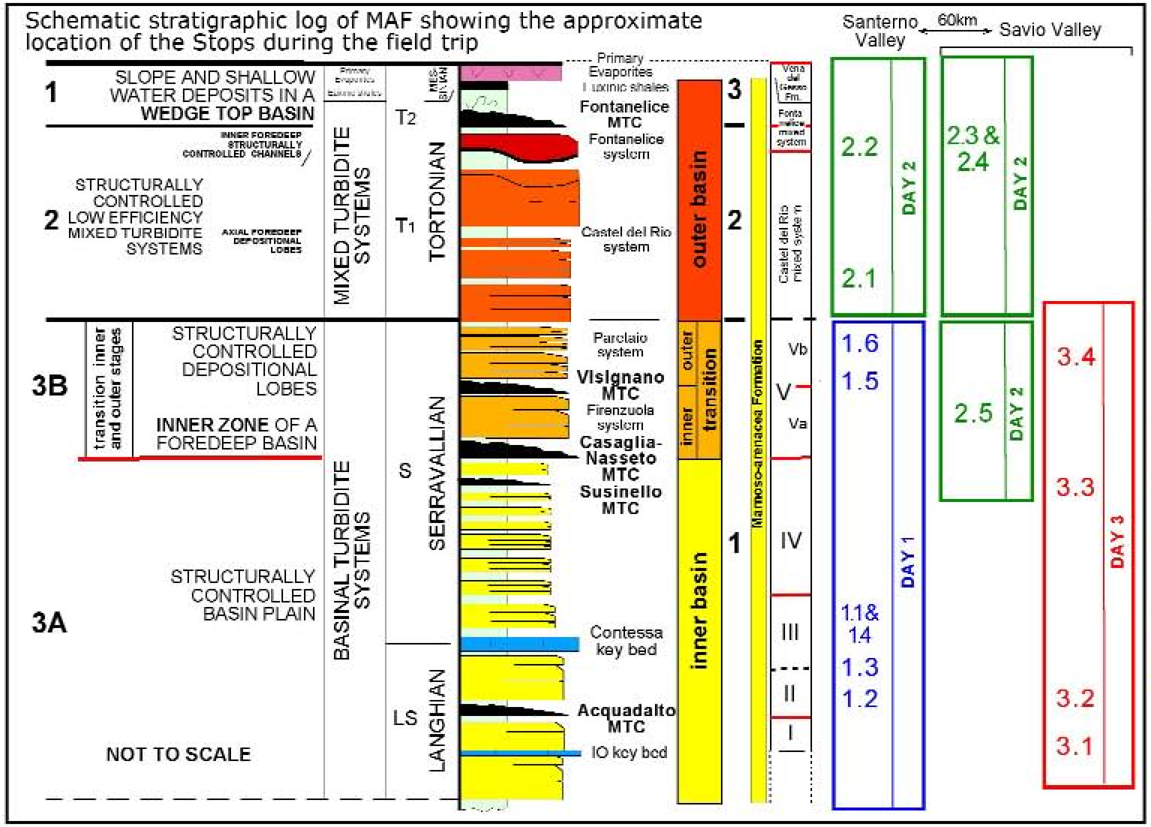


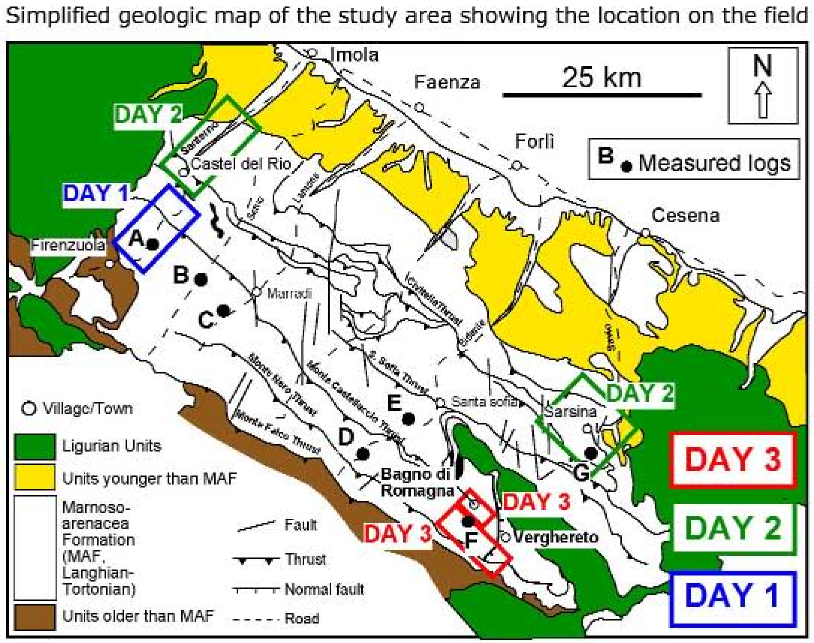
The first day will be spent in Santerno Valley (Fig. 34). Many of the outcrops that will be examined and discussed in this guide book have been described in classic papers by various authors over the years, starting from the works by Ricci Lucchi and his co-workers to the recent guide book by Mutti, Ricci Lucchi & Roveri (2002, with references) who reviewed the Marnoso-Arenacea Formation foredeep turbidites and their basin-margin equivalents. Therefore, even if a great part of the following Stops is inserted and explained based on the facies schemes (Figs. 7 and 15) and the high-resolution stratigraphic framework of Fig. 35 by Muzzi Magalhaes & Tinterri (2010), some specific references relating to the described outcrops will be reported.

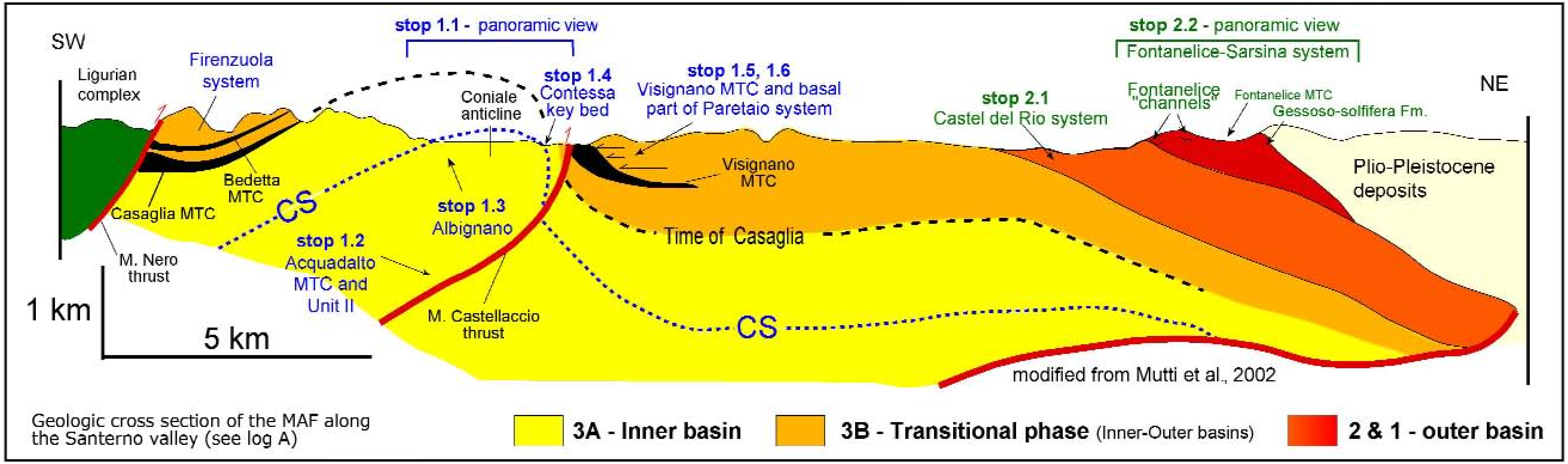
The MAF stratigraphic succession in the Santerno valley is well represented by the simplified log in figure 34 and spans in age from late Langhian-early Serravallian to Messinian. The MAF vertical evolution is related to the progressive closure of the foredeep, due to the north-eastward propagation of the main thurst sheet (see Fig. 35). In general, however, the MAF strata in Santerno Valley form a regular homocline, gently dipping to the north-east (see geologic cross section in Fig. 34 taken from Mutti et al., 2002a, see also Roveri et al., 2002).

DOI: 10.3301/GFT.2012.03

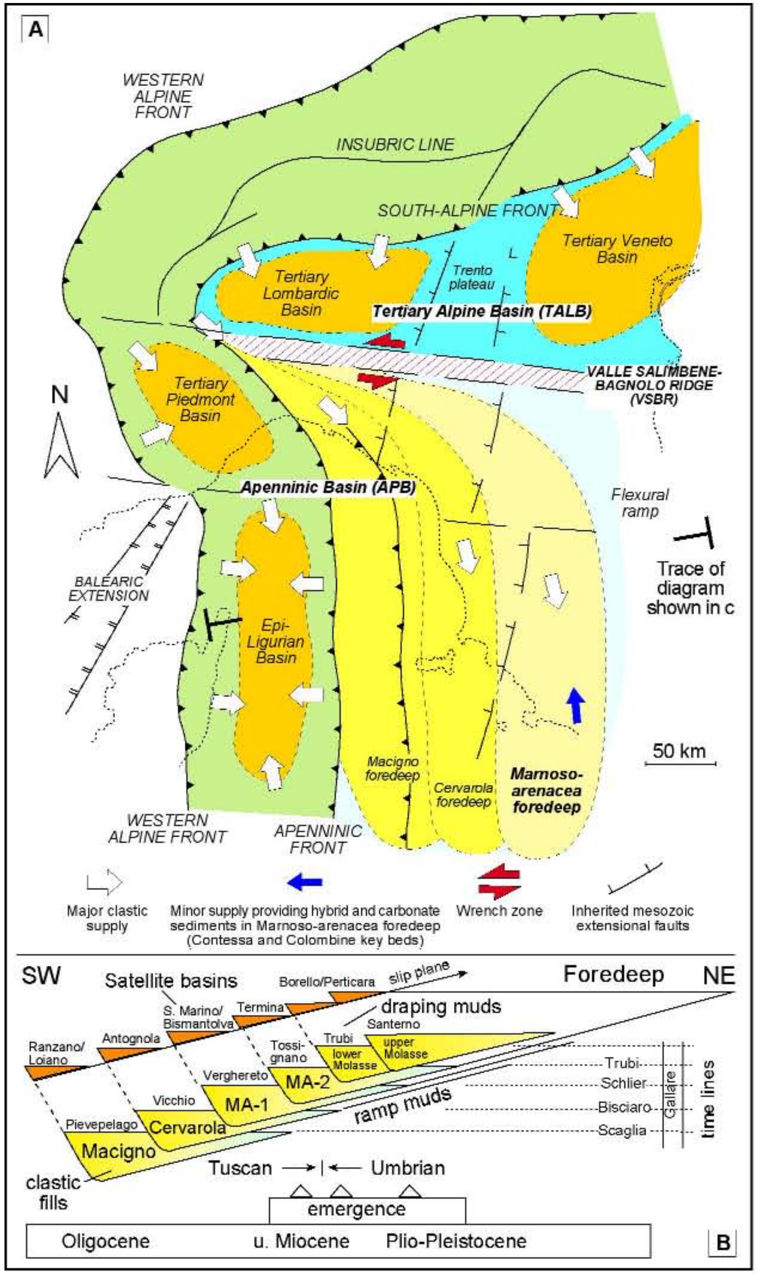
Fig. 34 - Stratigraphic and and geographic location of the field trip Stops.







DOI: 10.3301/GFT.2012.03



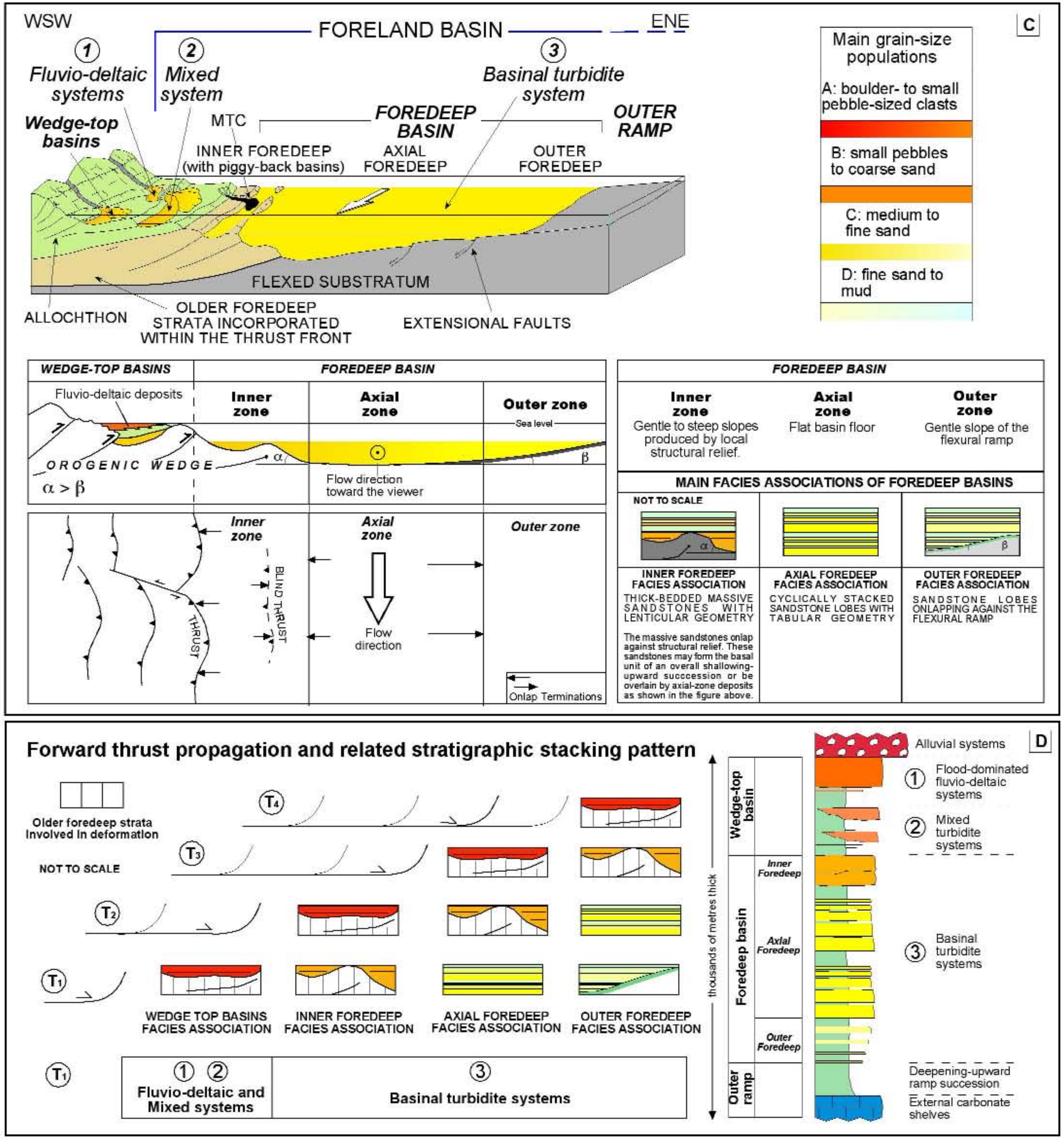


Fig. 35 - Geological setting of the MAF and the main characteristics of a foreland basin (see Fig. 3 for the references).

DOI: 10.3301/GFT.2012.03

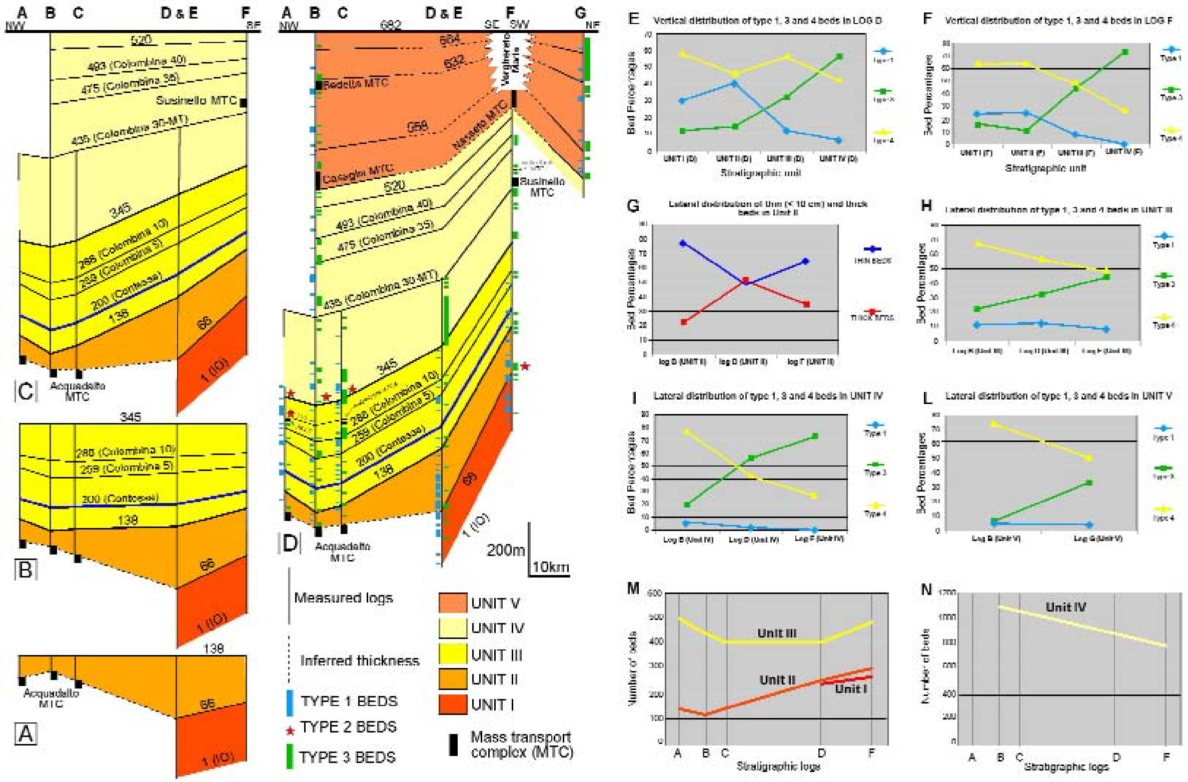


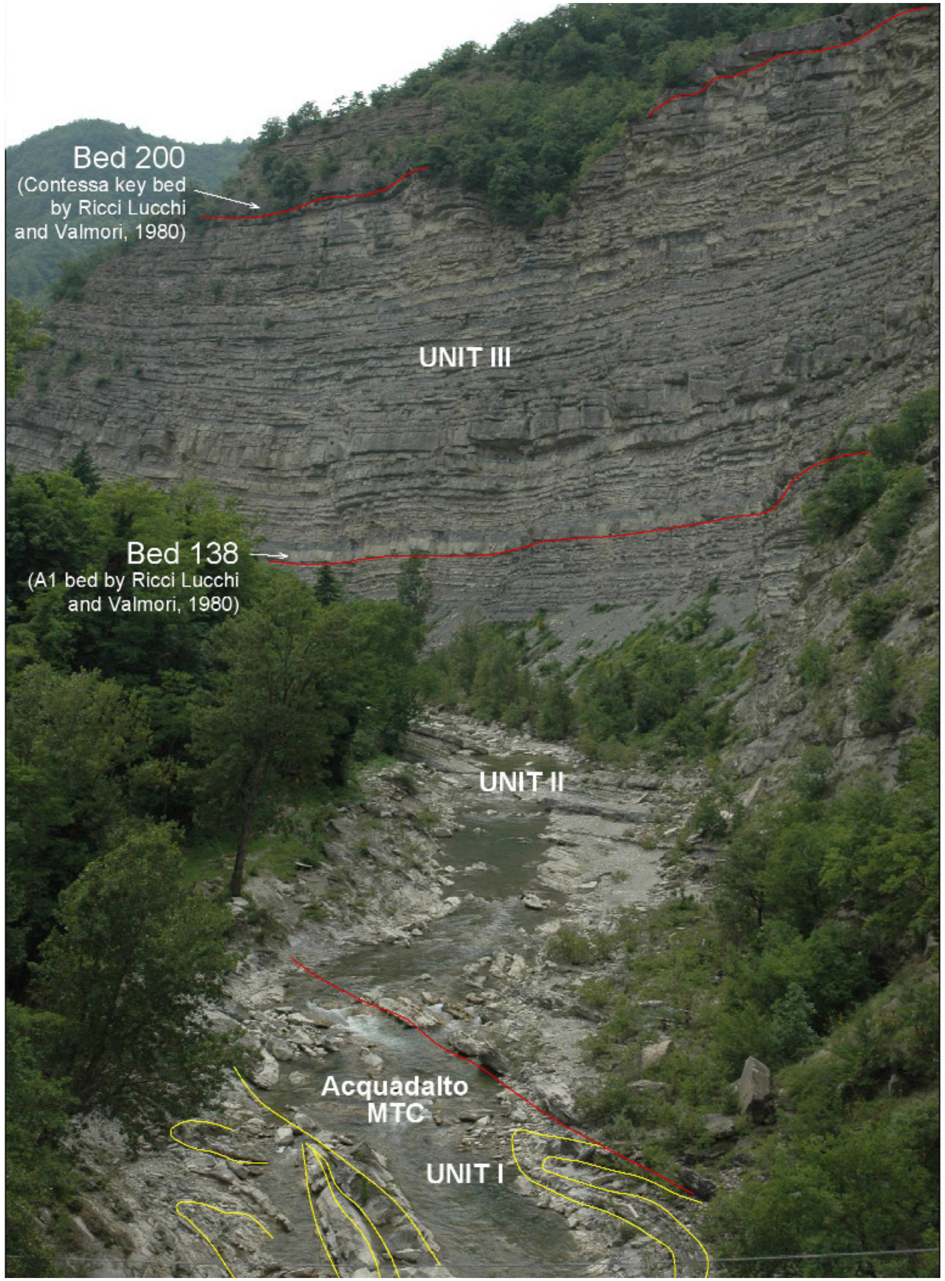
Fig. 36 - Stratigraphic cross section and bed type distributions of the Langhian and Serravallian portion of the MAF (references: see Fig. 10; location of the logs: see Fig. 5).

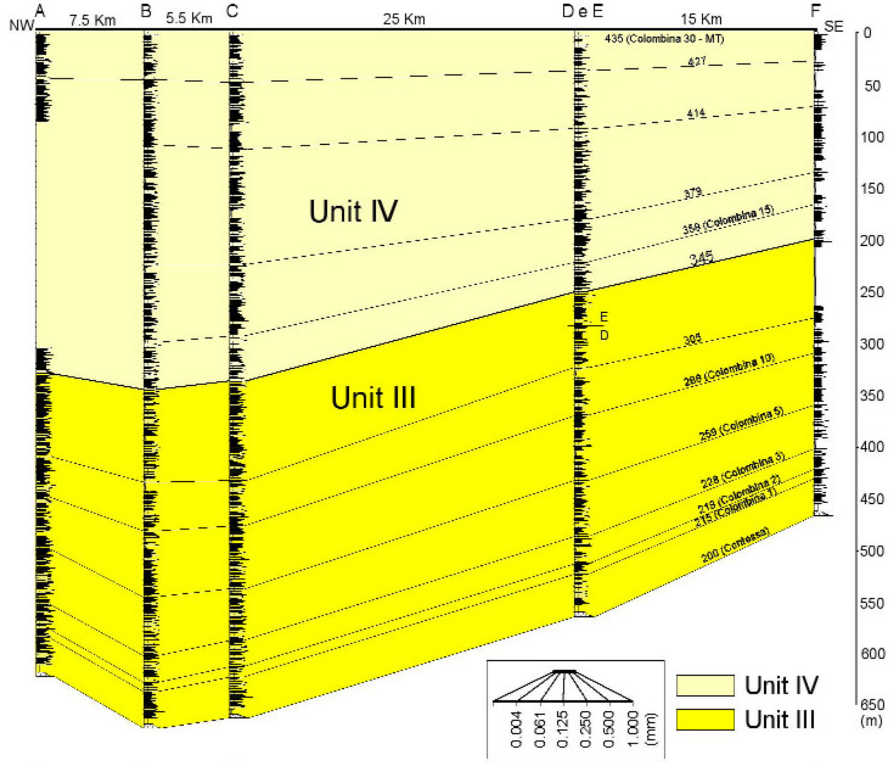
Stop 1.1: Coniale panoramic view

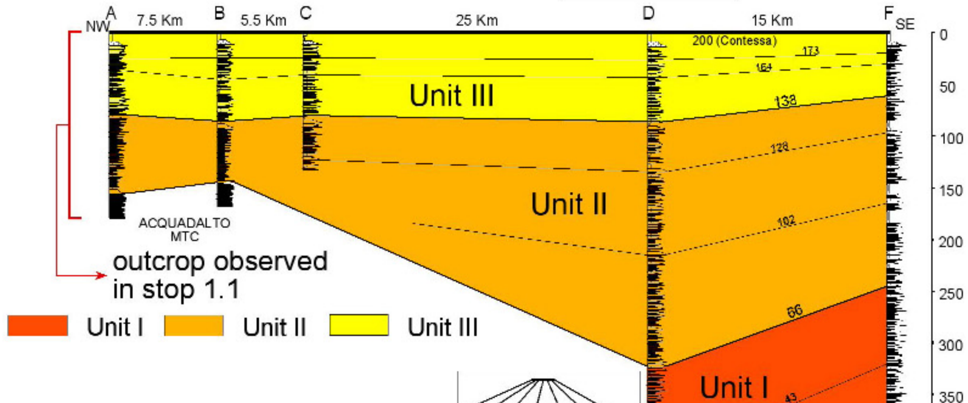
Stratigraphic unit: MAF inner stage, sequence LS (Ricci Lucchi, 1986) and Units II and III (Muzzi Magalhaes & Tinterri, 2010).
Age: late Langhian-early Serravallian.
Main features to observe: panoramic view of the Contessa key bed and associated proximal basin plain deposits.
Main outcrop references: Ricci Lucchi & Pialli (1973); Ricci Lucchi & Valmori (1980); Mutti et al. (2002a); Muzzi Magalhaes & Tinterri (2010); Tinterri & Muzzi Magalhaes (2011).

Description: After a brief introduction on the northern Apennines and MAF geologic setting, together with the main previous works about MAF stratigraphy (e.g., Ricci Lucchi & Valmori, 1980), we will examine, from a distance, the tabular geometry of proximal basin plain deposits of Units II and III (see Figs. 34, 36, 37 and 38). In the panoramic view, we will also be able to observe bed 138 (Bed A1 by Ricci Lucchi & Valmori, 1980), which marks the base of Unit III and the Contessa key bed. The latter is a basin-wide stratigraphic marker that can be traced and mapped over a distance of nearly 120km. The bed is about 12m thick and here contains a thick upper carbonate mud division (see also Stop 1.4). This marker is generally thought to be located near the Langhian-Serravallian boundary (Fig. 4). The Acquadalto MTC is at the base of this outcrop (it cannot be seen from this location, see Fig. 37) and will be observed during Stop 1.2. See section 3.2 for the sedimentary characteristics of proximal basin plain deposits of Units II and III (see also Fig. 36).

DOI: 10.3301/GFT.2012.03







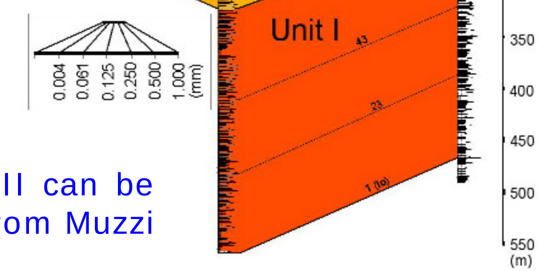


Fig. 37 - On the left a panoramic view of the Coniale outcrop, where the Contessa key bed and associated proximal basin plain deposits of Units II and III can be observed. On the right, the detailed stratigraphic cross sections of Units I, II and III (from Muzzi Magalhaes and Tinterri, 2010). See Fig. 34 for the location of the logs.

DOI: 10.3301/GFT.2012.03

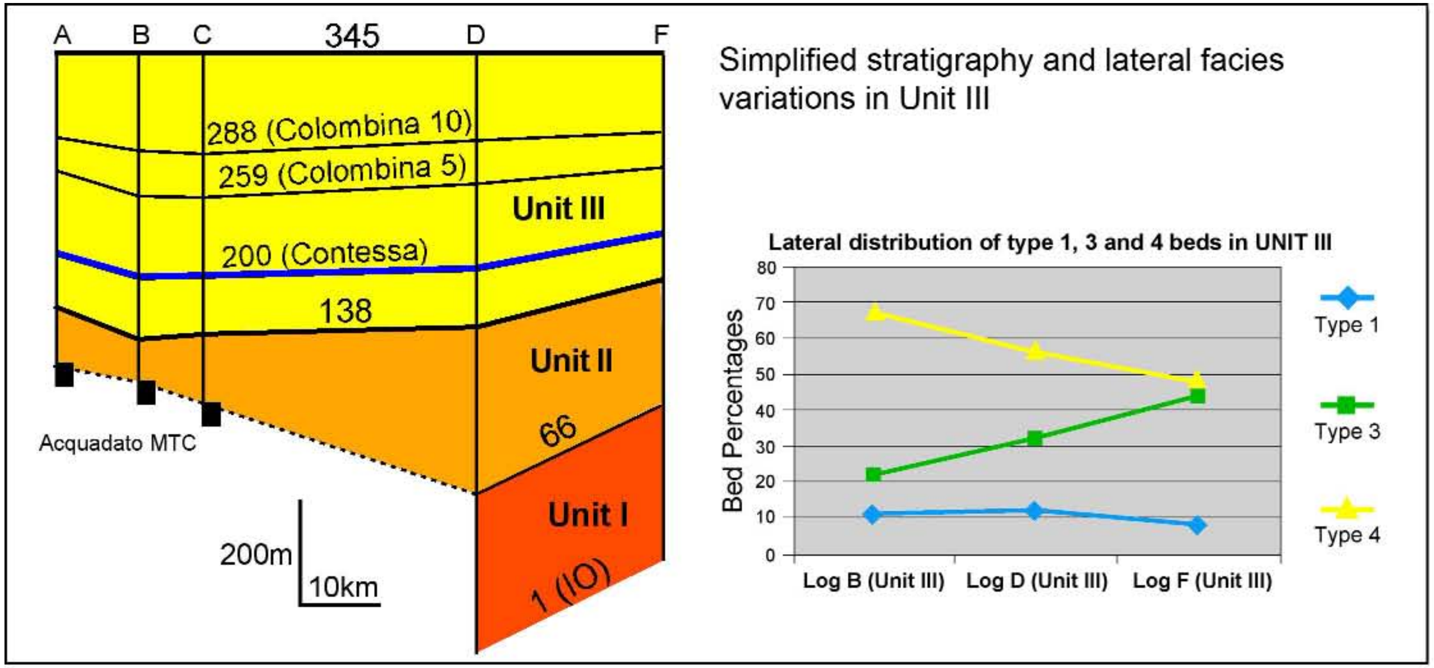
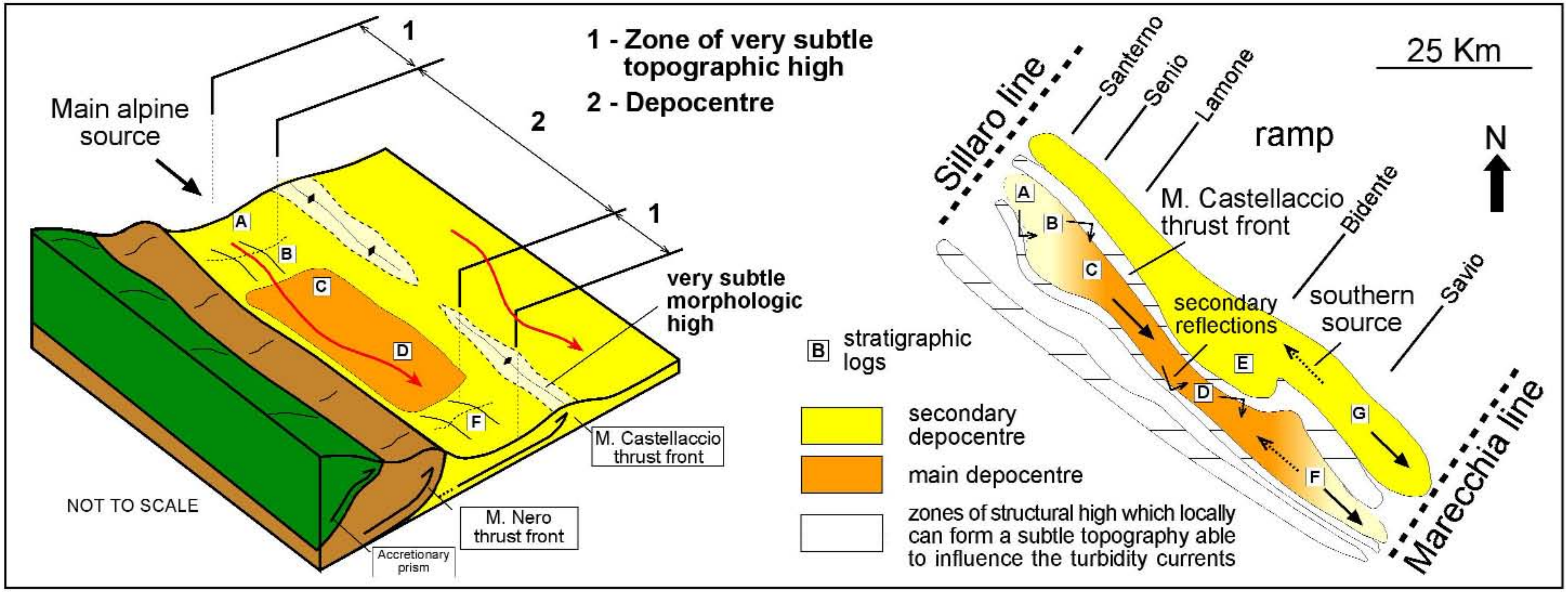
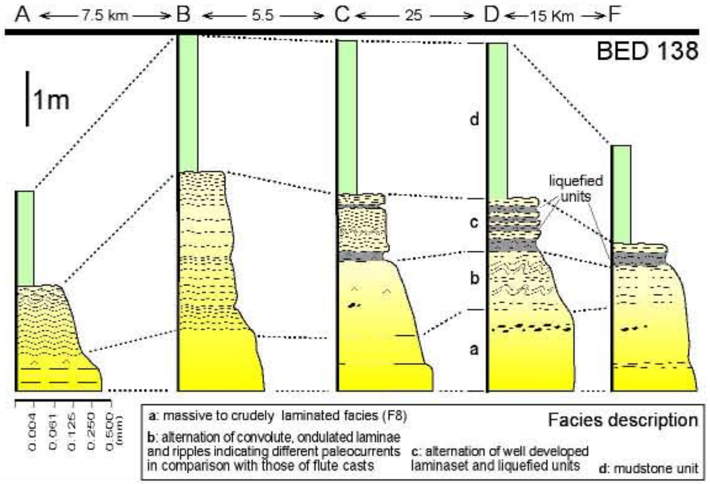


Fig. 38 - Simplified stratigraphic cross section flattened at the top of Unit III (bed 345) where we will be able to observe that Unit III is the stratigraphic Unit with the lowest structural control in the entire MAF stratigraphic succession studied. Nevertheless, the increase in the number of Type-3 beds (see Fig. 39) toward the south can be interpreted as being related to the initial phase of the structural uplift of the southern Verghereto area. The diagrams below show a simplified physiographic setting during Unit III (compare with Unit II described in Stop 1.2).

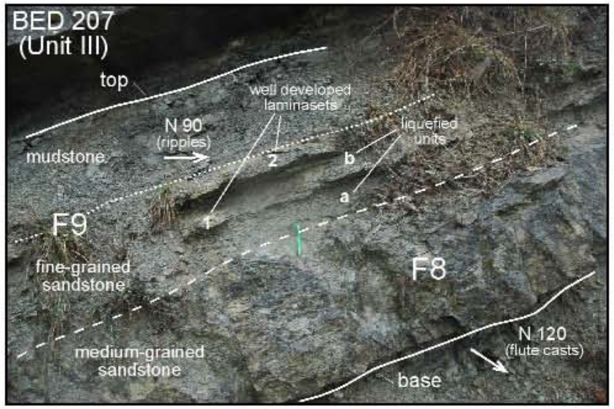


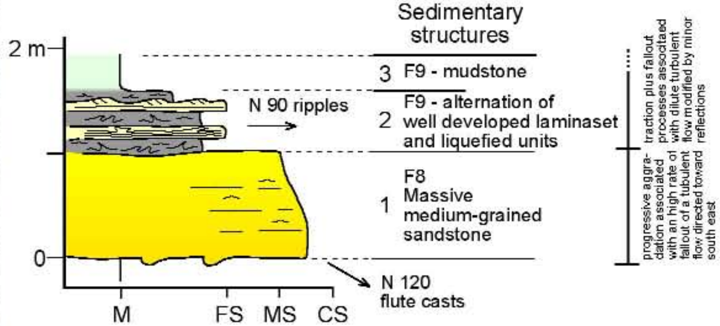
DOI: 10.3301/GFT.2012.03

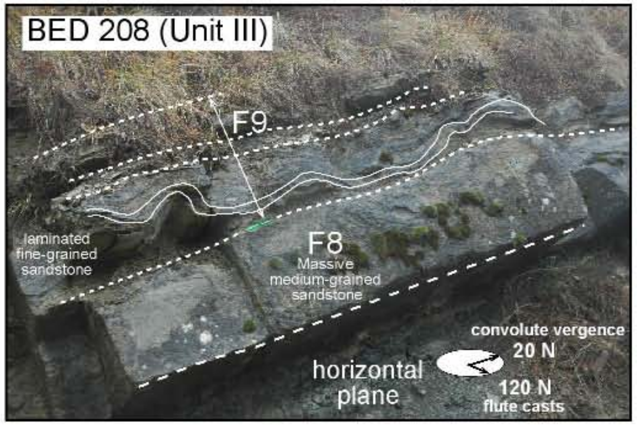
BED 138 (base of Unit III)

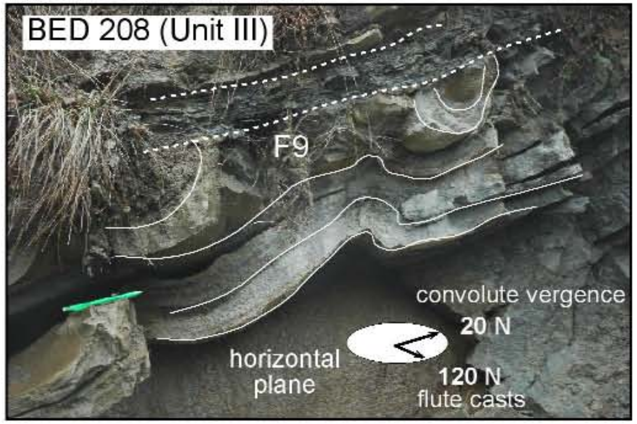


BED 207 (Unit III) - A Type 3 bed with minor reflection processes

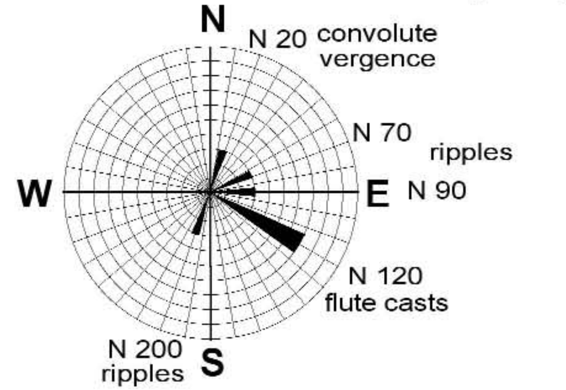




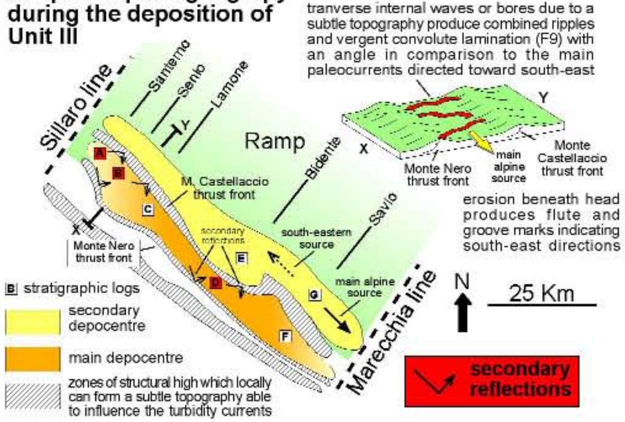


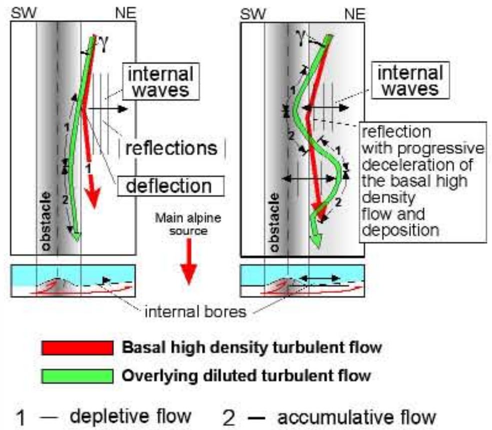


Palaeocurrents related to reflection processes (Unit III - above the Contessa key bed)



Simplified paleogeograpy during the deposition of Unit III





Possible types of minor reflection processes occurring along Ridracoli structural element

DOI: 10.3301/GFT.2012.03

Fig. 39 - Unit III is characterized by an increase in Type-4 beds. Nevertheless, many Type-3 beds, characterized by moderate reflection processes, can be observed. Therefore, although Unit III is characterized by a low degree of structural control, these types of beds show that subtle morphologies created by the thrust front propagation are present.

Stop 1.2: Acquadalto MTC and Unit II

Stratigraphic unit: MAF inner stage, sequence L (Ricci Lucchi, 1986); Unit II (Muzzi Magalhaes & Tinterri, 2010).
Age: Langhian.
Main features to observe: Acquadalto mass-transport complex (MTC) and facies of the stratigraphic interval above the topographic high represented by the Acquadalto MTC (Unit II).
Main outcrop references: Muzzi Magalhaes & Tinterri (2010) and Tinterri & Muzzi Magalhaes (2011).

Description: In the Santerno Valley (Log A in Fig. 34), stratigraphic Unit II is included between the Acquadalto MTC and bed 138 (i.e., bed A1 by Ricci Lucchi & Valmori, 1980) (Fig. 36). In this north-western area, Unit II is relatively thin, with total thickness of about 60m in Logs A and B, while in the south-eastern zone (Log D) its thickness is about 230m, thus highlighting the formation of an important depocenter (Figs. 36; 40). Directly above the Acquadalto MTC, a very thick bed characterized by a basal impact breccia and a slurry-debrite unit together with a high percentage of bioturbated beds and fine-grained sediments consisting of thin Type-5 beds can be recognized (Figs. 40 and 41); contained-reflected Type-3 beds, even though less common, can also be observed (Fig. 41). Type-5 thin beds, which are often characterized by sedimentary structures indicating reflection and rebound processes, are interpreted as being related to diluted turbulent flows able to ascend the topographic high created by the Acquadalto MTC (see Fig. 41). In particular, Unit II is characterized by 124 beds in Log B and 243 in Log D, which means that only 51% of the beds, and, consequently, of turbidity currents, were able to rise the topographic high represented by the Acquadalto MTC. In conclusion, based on these characteristics, during the deposition of Unit II, the basin can be interpreted as associated to a tectonic uplift, able to generate the Acquadalto MTC to the north (Logs A, B, C), and a depocenter in southern zones, characterized, at the base, by a Type-2 bed (bed 66) and by the highest percentage of Type-1 beds in the

DOI: 10.3301/GFT.2012.03

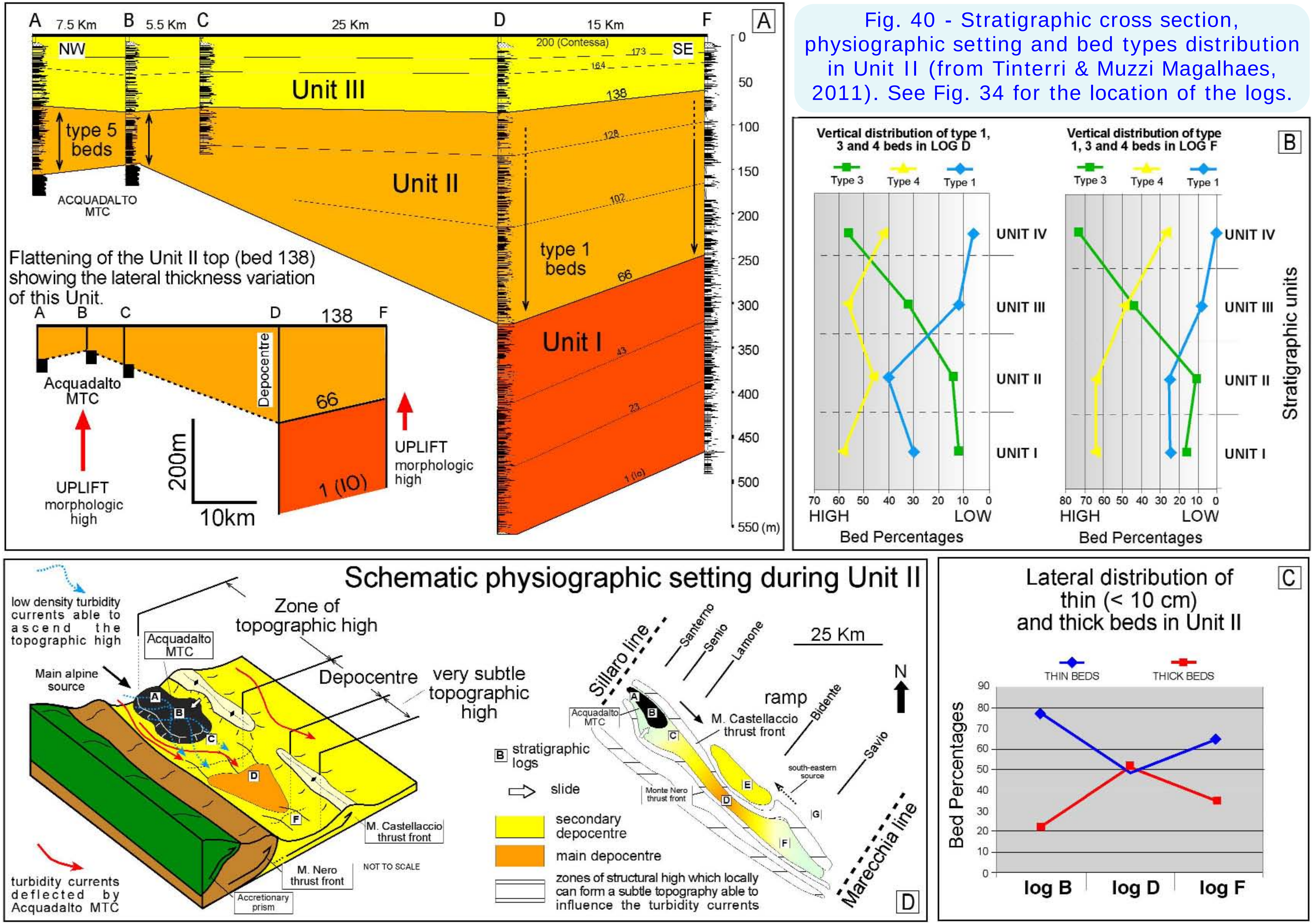
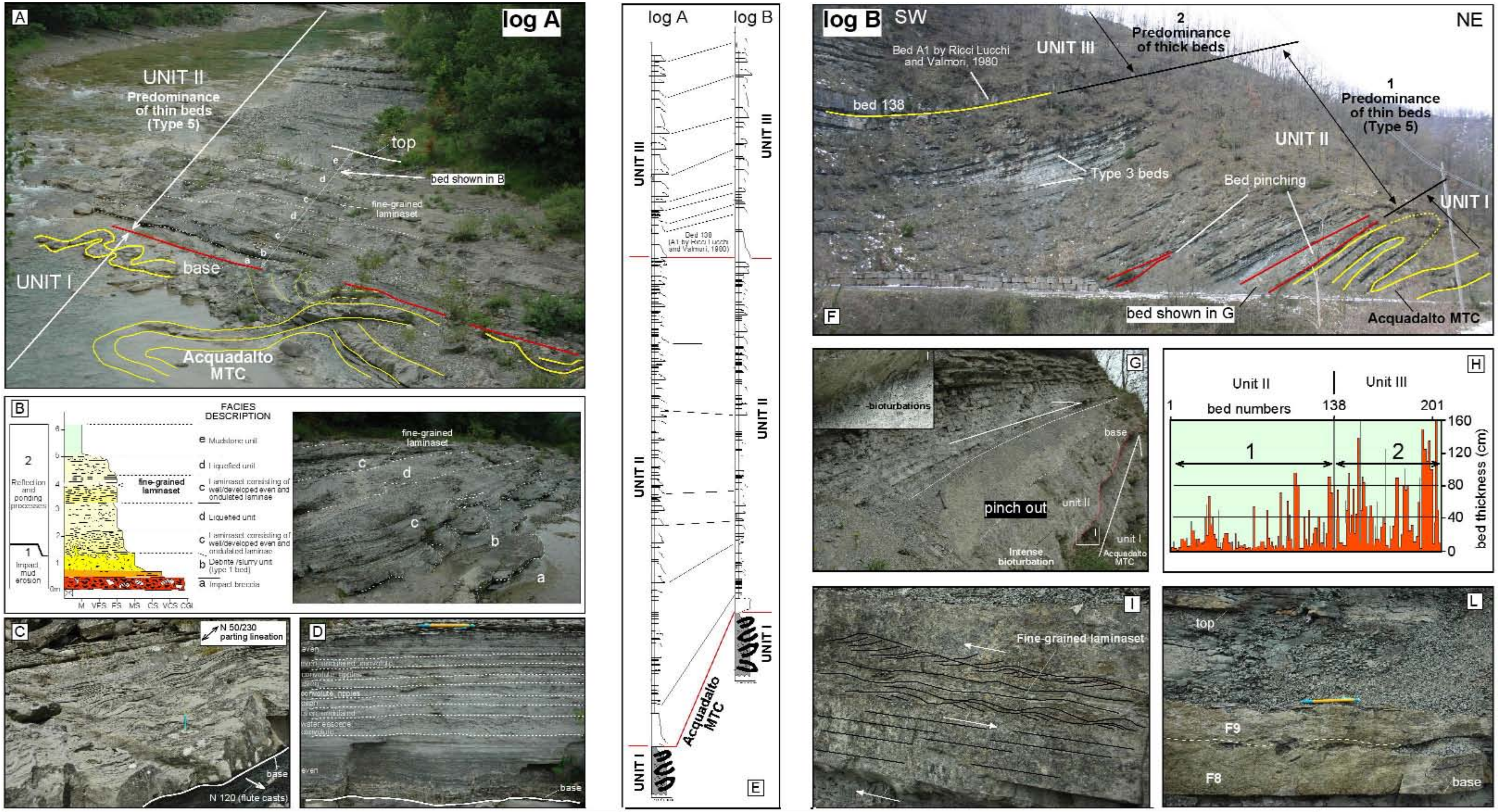


Fig. 40 - Stratigraphic cross section, physiographic setting and bed types distribution in Unit II (from Tinterri & Muzzi Magalhaes, 2011). See Fig. 34 for the location of the logs.

DOI: 10.3301/GFT.2012.03



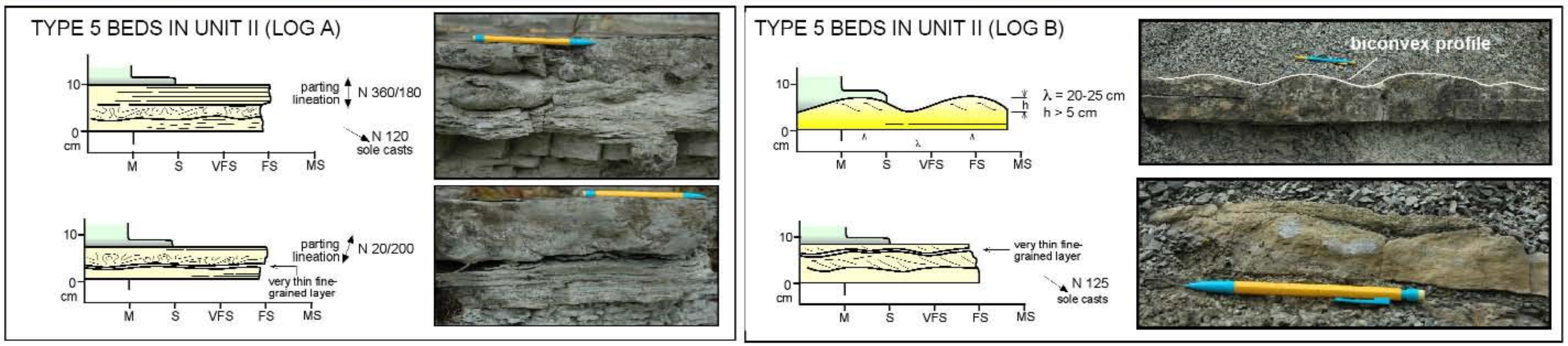


Fig. 41 - Sedimentary characteristics and bed types of Unit II in Log A and Log B (see Fig. 34 for the location of the logs).

DOI: 10.3301/GFT.2012.03

entire stratigraphic succession studied (see Figs. 35B, D, E, F; 40B and Stop 3.2). Therefore, not only was the physiographic setting of Unit II particularly favourable for the paleocurrent changes (see above), but also for the formation of Type-1 beds, by promoting erosive processes of mudstone deposits in the northern part, above and laterally with respect to the Acquadalto topographic high, and decelerations in the southern zones due to the slope change. The analogies with the Visignano MTC and the overlying Serravallian Paretaio turbidite systems will be discussed in Stop 1.6.

Stop 1.3: Albignano

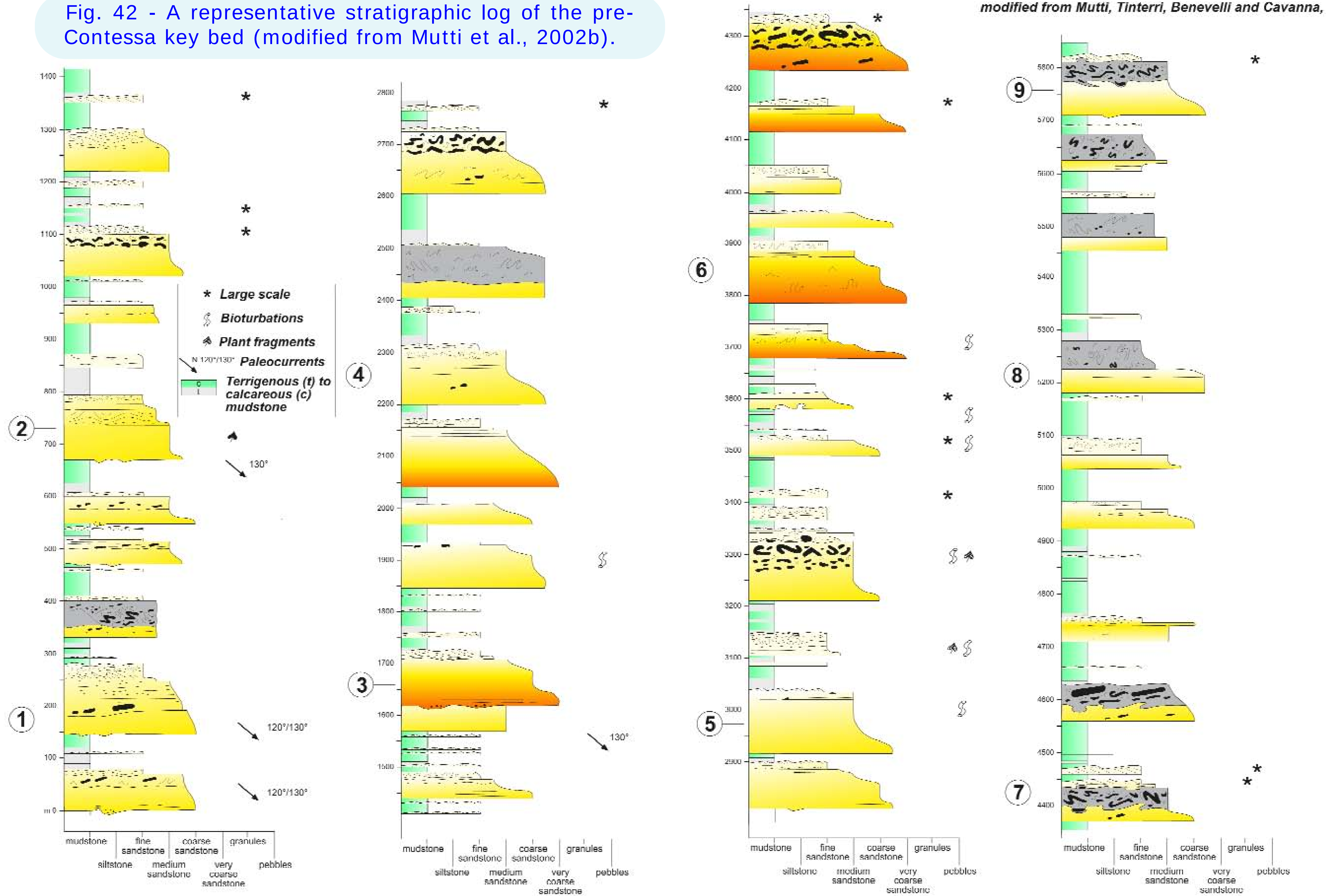
Stratigraphic unit: MAF inner stage, sequence LS (Ricci Lucchi, 1986) and Unit III (Muzzi Magalhaes & Tinterri, 2010).
Age: late Langhian-early Serravallian.
Main features to observe: facies characteristics of proximal basin plain deposits below the Contessa bed.
Main outcrop references: Mutti et al. (2002a, b); Tinterri & Muzzi Magalhaes (2009).

Description: This outcrop consists of a 60m-thick succession of turbidite sandstones and mudstones (Fig. 42). These sediments are below the Contessa bed and their facies characteristics are those of basinal turbidites deposited by turbidity currents, showing paleocurrents from the NW. The succession consists of parallel-sided, thick to very thin, sharp-based and graded sandstone beds alternating with mudstones. The net to gross ratio is about 58%.

These beds show a number of features indicating that structurally-induced subtle submarine topography was affecting deposition. In particular, these features include: 1) Type-1 beds and sandwich-type beds characterized by abundant rip-up mudstone clasts floating within or at the top of massive and coarse-grained sandstone divisions (see Fig. 43 and section 3.1 for more details); 2) massive sandstone divisions with dewatering features and hydroplastic deformations of the overlying finer-grained and current-laminated divisions; 3) the presence of “large-scale ripples” (commonly associated with flow reflections; see Tinterri & Muzzi Magalhaes, 2011 and Remacha et al., 2005); and 5) the presence of calcareous mudstones (light-grey in colour), whose significance will be discussed in the field.

DOI: 10.3301/GFT.2012.03

Fig. 42 - A representative stratigraphic log of the pre-Contessa key bed (modified from Mutti et al., 2002b).



DOI: 10.3301/GFT.2012.03

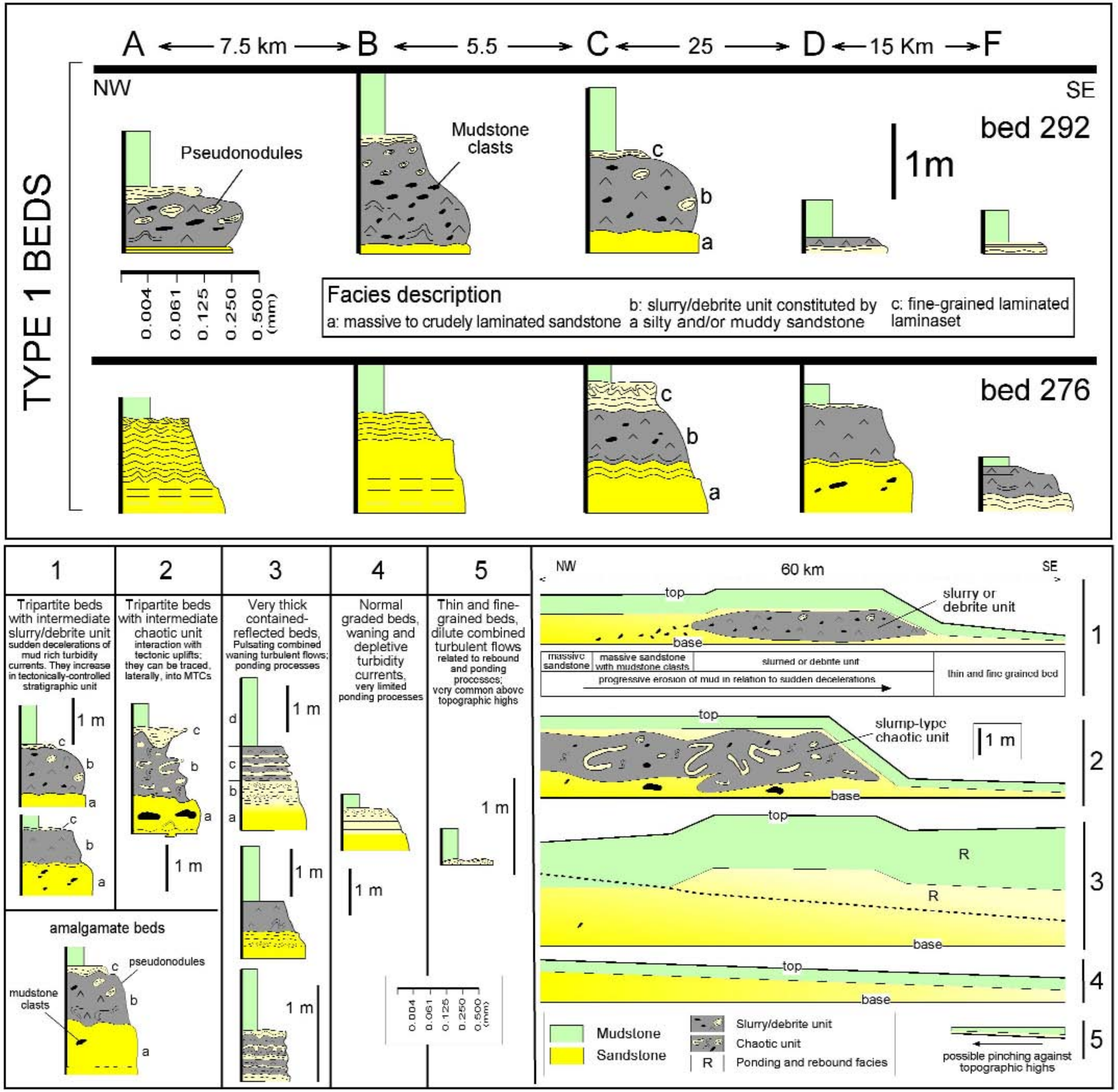


Fig. 43 - Diagram summarising the different bed types identified in the stratigraphic succession studied.
A) Scheme illustrating the five bed types and relating interpretations.
B) Diagram showing the simplified lateral geometry of the facies tracts of the five bed types described in A (from Muzzi Magalhaes & Tinterri, 2010; see also Tinterri & Muzzi Magalhaes, 2011).
Above, examples of Type-1 facies tracts. See figures 5 and 34 for the location of the logs.

DOI: 10.3301/GFT.2012.03

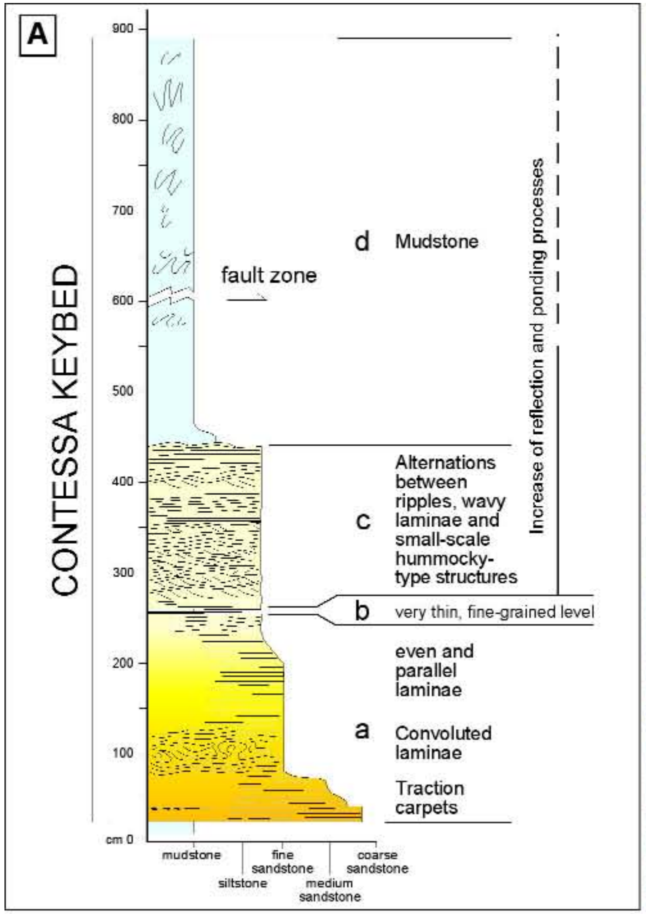
Stop 1.4: The Contessa key bed

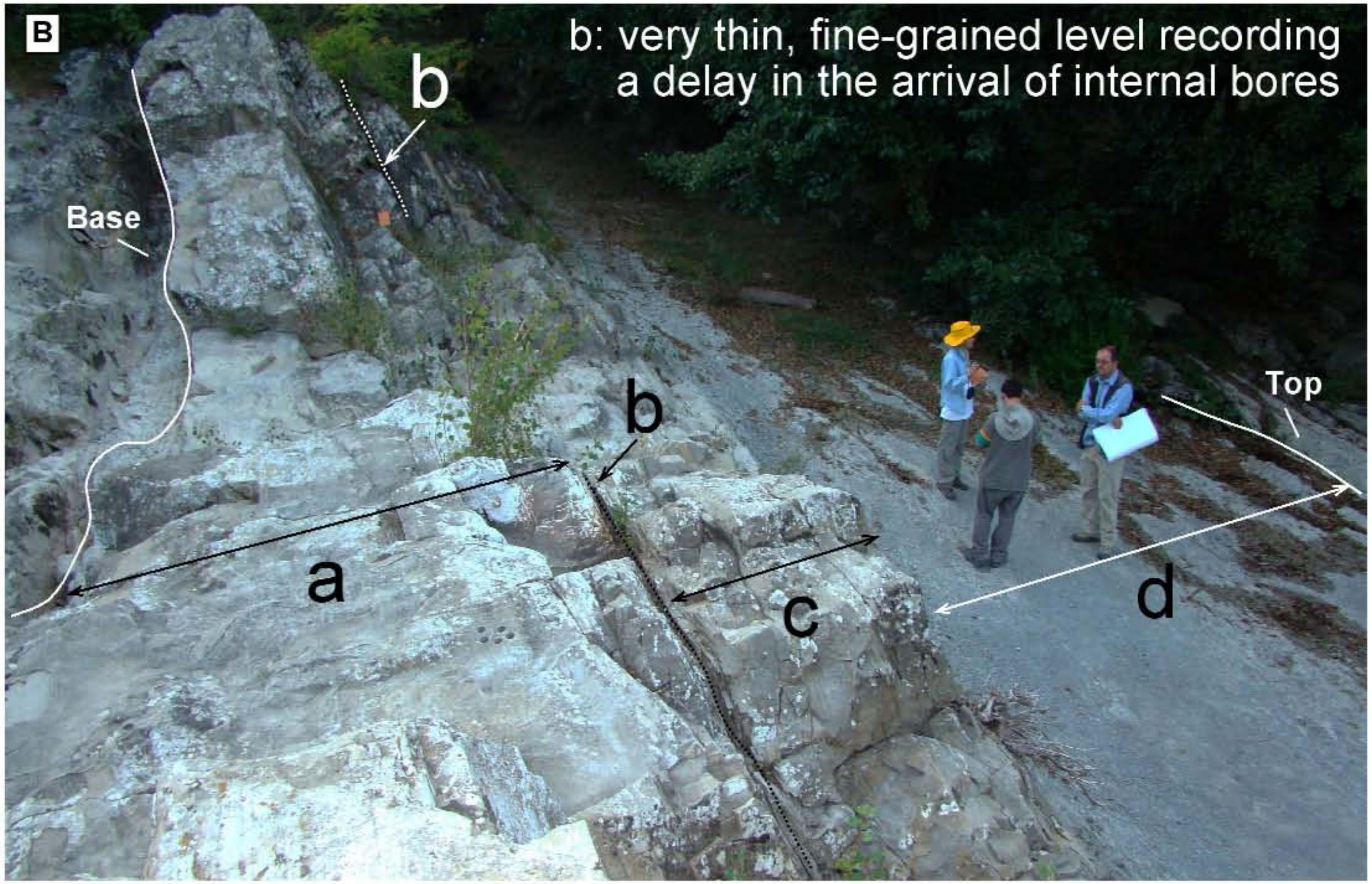
Stratigraphic unit: MAF inner stage, sequence LS (Ricci Lucchi, 1986) and Unit III (Muzzi Magalhaes & Tinterri, 2010).
Age: early Serravallian.
Main features to observe: sedimentary structures related to ponding processes of the Contessa key bed (a typical contained-reflected Type-3 bed).
Main outcrop references: Ricci Lucchi & Valmori (1980); Mutti et al. (2002b); Tinterri & Muzzi Magalhaes (2009).

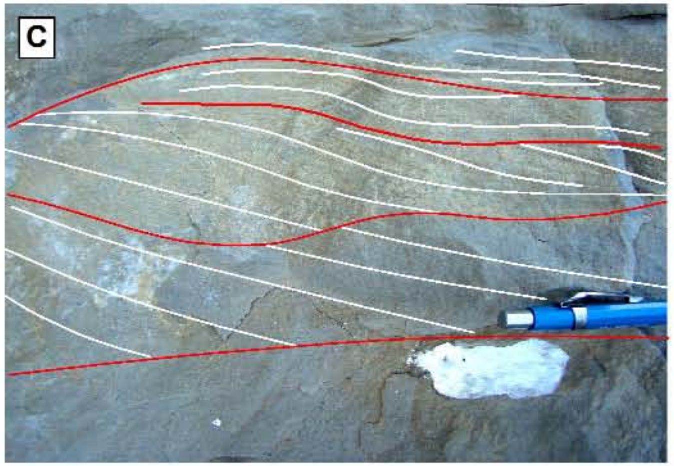
Description: we will examine the Contessa key bed in the northern limb of the Coniale anticline along the Santerno riverbed (see Fig 34 for the location of this outcrop). The Contessa key bed is a basin-wide stratigraphic marker that can be traced and mapped over a distance of nearly 120km. This bed came from the south and is characterized by a hybrid composition with a thick upper carbonate mud division (see also Stop 1.1). The marker is generally thought to be located near the Langhian-Serravallian boundary (Figs. 33, 34). In this Stop, well-developed sedimentary structures related to flow reflections can be observed (Fig. 44). These sedimentary structures consist of symmetric rounded ripples (wavelenght: about 30 cm) and small-scale hummocky type structures that can be well observed in interval “c” above the very thin fine grained level “b” (see Fig. 44). The latter is interpreted to record a delay in the arrival of reflected bores or internal waves (Tinterri & Muzzi Magalhaes, 2009; 2011). The Contessa key bed is included in Unit III, the low degree of structural control of this Unit allows the arrival from the south of many turbidity currents characterized by a hybrid (Contessa-type) or carbonate (Colombina-type) composition producing the main key beds.

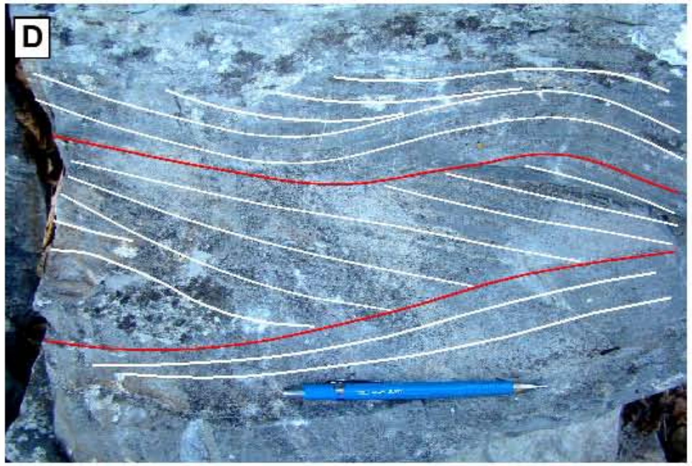
Fig. 44 - **A** and **B)** The Contessa key bed in the Santerno Valley (see Log A in Fig. 5A). **C**, **D** and **E)** Large-scale ripples and hummocky-type structures in the interval c (see Diagram in A). The latter can be interpreted as combined flow sedimentary structures associated to reflections and ponding processes (see Tinterri & Muzzi Magalhaes, 2009; Tinterri, 2011).

DOI: 10.3301/GFT.2012.03

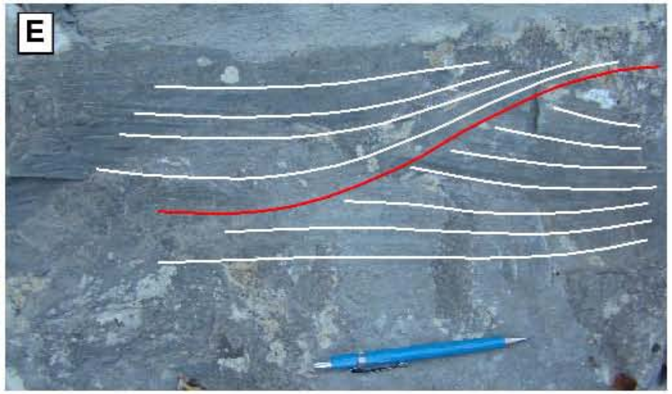








Small-scale symmetric ripples and hummocky type structures in the interval C



DOI: 10.3301/GFT.2012.03

Stop 1.5: Panoramic view of the Paretaio turbidite unit and Visignano MTC

Stratigraphic unit: transition inner-outer stages; sequence S (Ricci Lucchi, 1986); Unit V (Muzzi Magalhaes & Tinterri, 2010).
Age: Upper Serravallian
Main features to observe: panoramic view of the Paretaio system (evidence for synsedimentary growth of M. Castellaccio thrust and on-lap relationships with folded older turbidite deposits); sedimentary characteristics of the Visignano MTC near Casovana.
Main outcrop references: de Jager, 1979; Ricci Lucchi & Ori, 1985; Cattaneo & Ricci Lucchi (1995); Roveri et al. (2002); Mutti et al. (2002a); Tinterri & Muzzi Magalhaes (2011); Tinterri, Tagliaferri et al., in prep.

Description: the Paretaio turbidite system, consisting of tabular sandstone lobes characterized by a well-developed cyclicity, records the synsedimentary growth of the M. Castellaccio thrust (Fig. 45). These deposits, recently studied in detail by Tinterri, Tagliaferri et al., (in prep.) allow some hypothesis to be made about the stratigraphic relationships between the Paretaio turbidite deposits and the underlying Visignano MTC and, consequently, about the tectonic and sedimentary evolution of the Marnoso-Arenacea foredeep basin during the middle to late Serravallian. The detailed data collected by Tinterri, Tagliaferri et al., (in prep.), see also section 4, confirm the syntectonic nature of the Paretaio system and support the model introduced by de Jager (1979) and Roveri et al., (2002), in which the Paretaio turbidite system, developed in front of the M. Castellaccio thrust, is deposited after a phase of thrust propagation that caused the growth of the Coniale anticline (Figs. 11, 45) and the subsequent emplacement of the Visignano MTC (Figs. 45, 46A, B). The latter consists mainly of fine-grained sediments (essentially turbidite mudstones and highly-bioturbated Type-5 beds) deposited by the dilute turbulent flow able to rise the topographic high relating to the first uplift phase of M. Castellaccio thrust (see Fig. 48). Time equivalent of this fine-grained drape would be the Firenzuola system (Fig. 45) deposited in the tectonically-confined innermost part of the foredeep above the Casaglia MTC (see Fig. 45). The Firenzuola and Paretaio turbidite systems are time equivalent to the deposits of Unit V by Muzzi Magalhaes & Tinterri (2010) and record a transitional stage between inner and outer basin (Fig. 33). In particular, the Paretaio turbidite system records the first deposit of the outer stage and is characterised by a vertical facies change that heralds the Tortonian mixed low efficiency deposits (Fig. 47). From base to top, there is a progressive increase in Ophiomorpha-type bioturbation and Type-C beds characterized by F7 overlain by F7 and F6 (Fig. 47), which are very similar to the facies sequences of Tortonian mixed deposits (Fig. 32).

DOI: 10.3301/GFT.2012.03

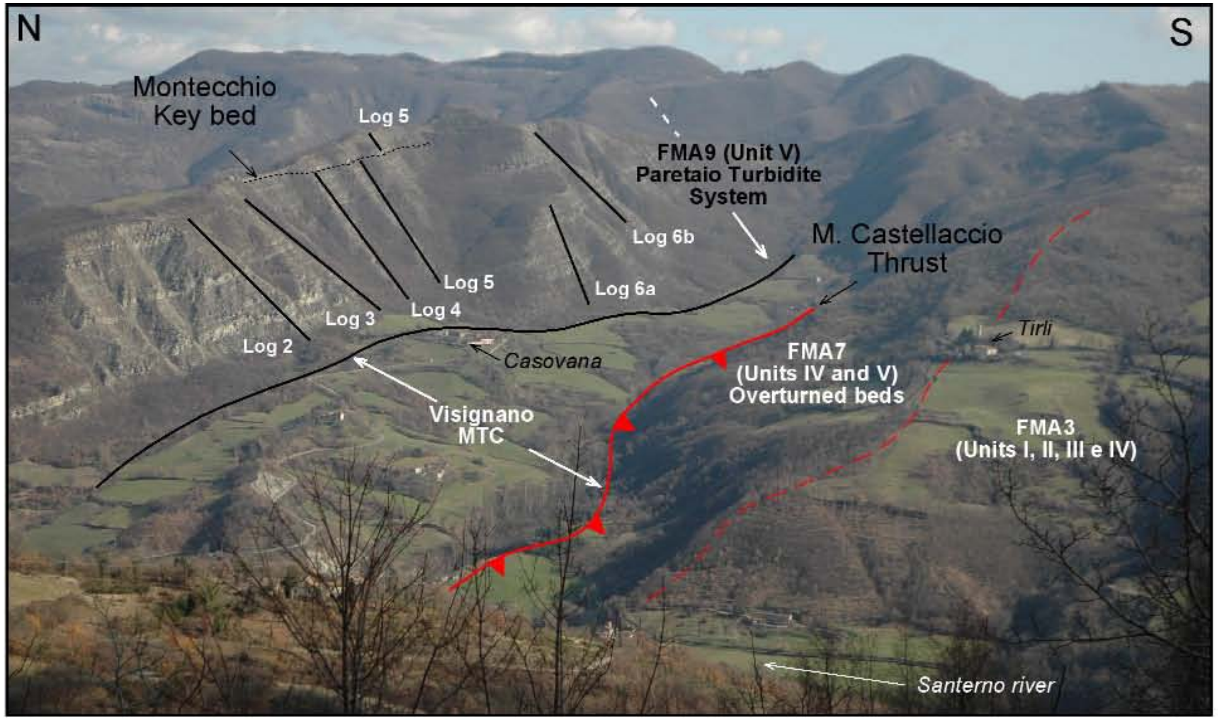
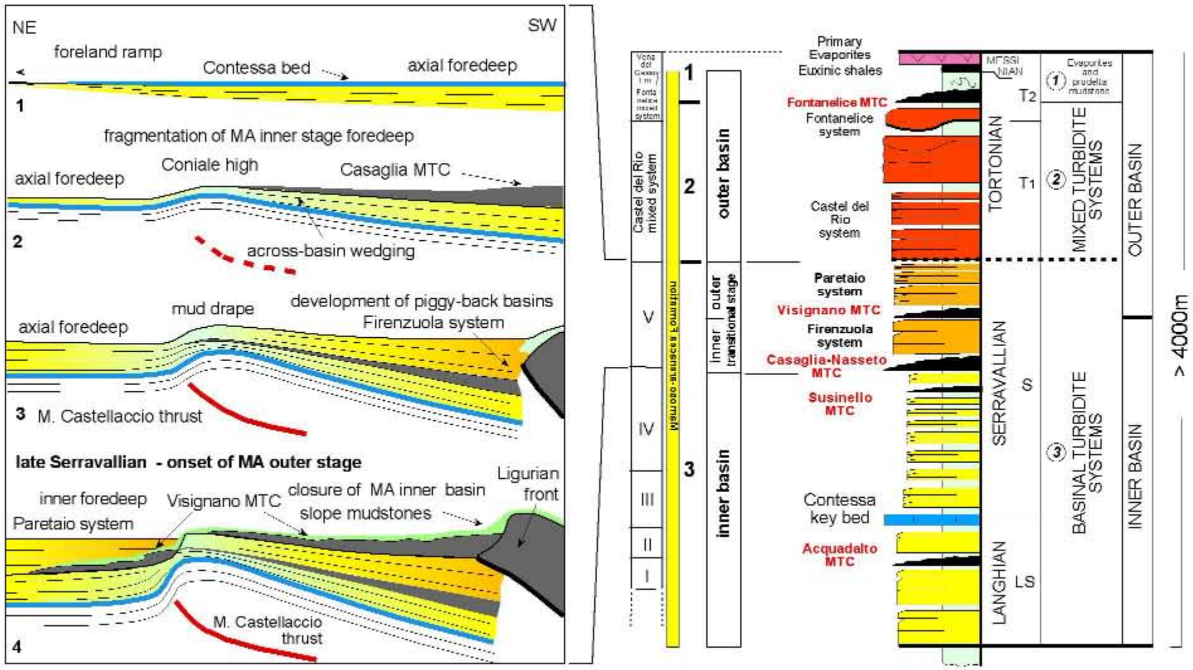
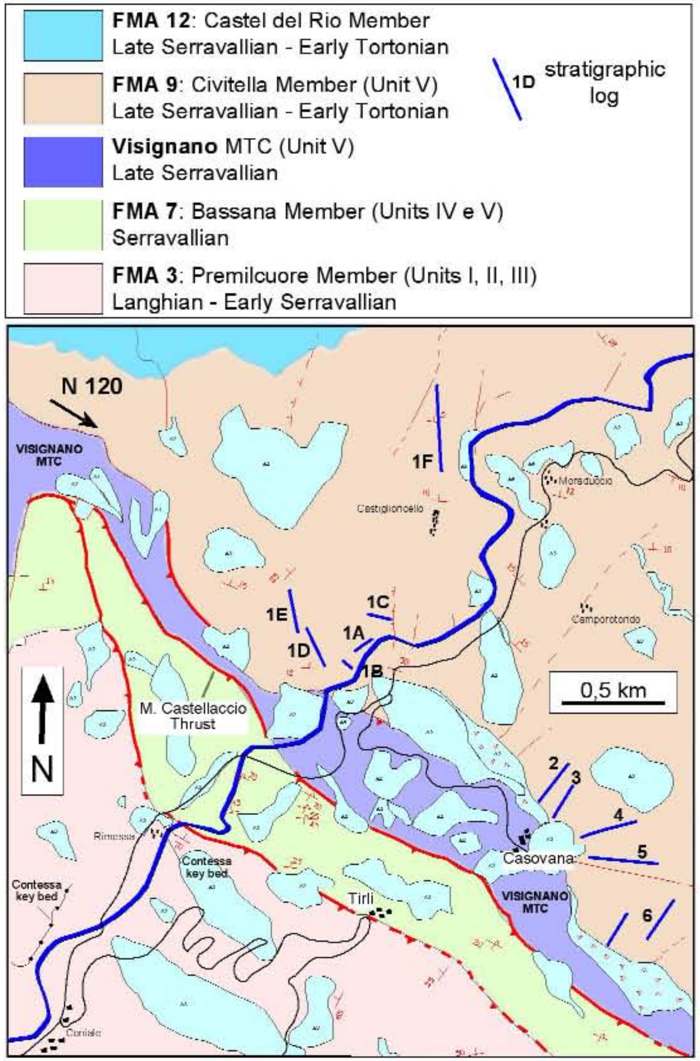
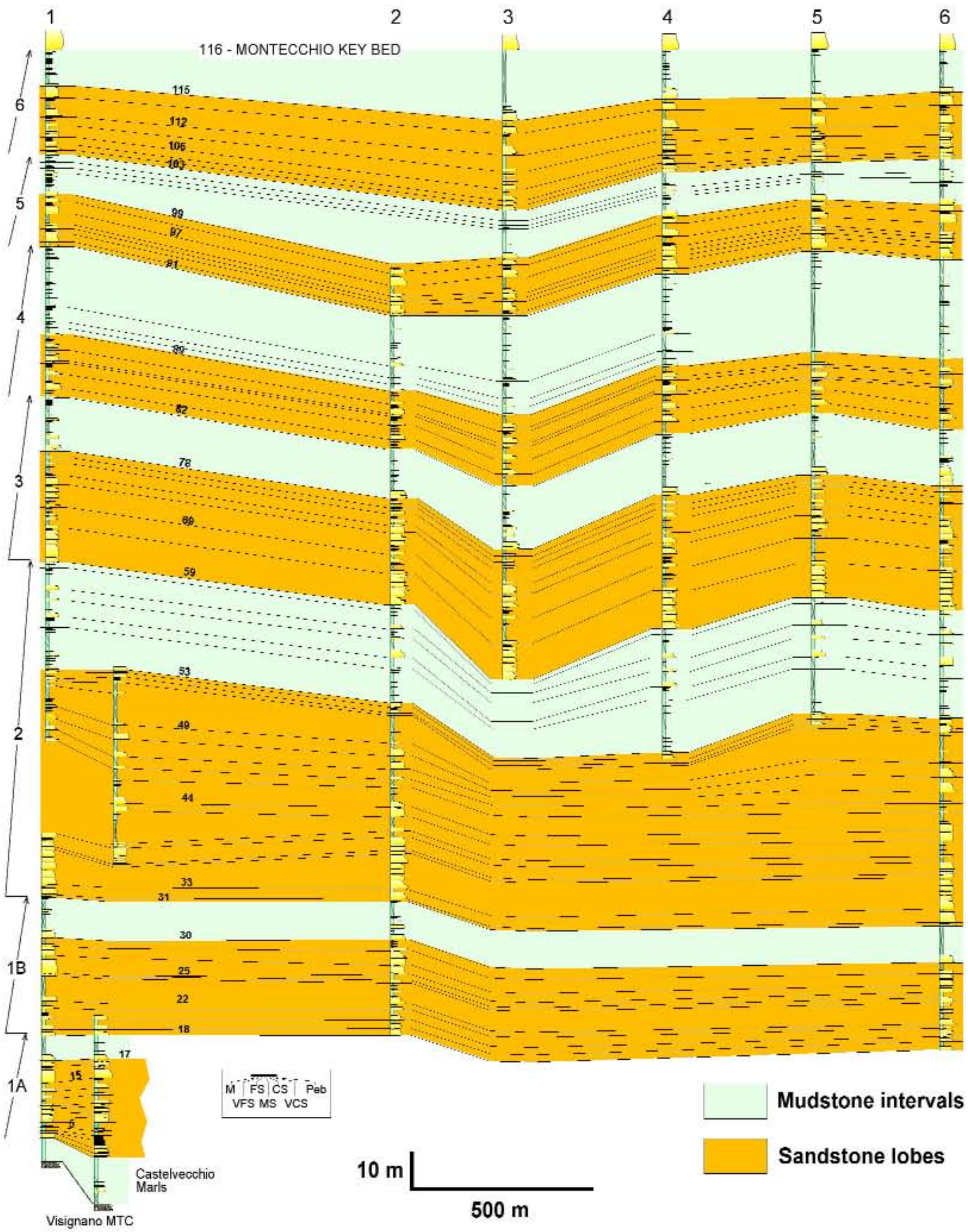
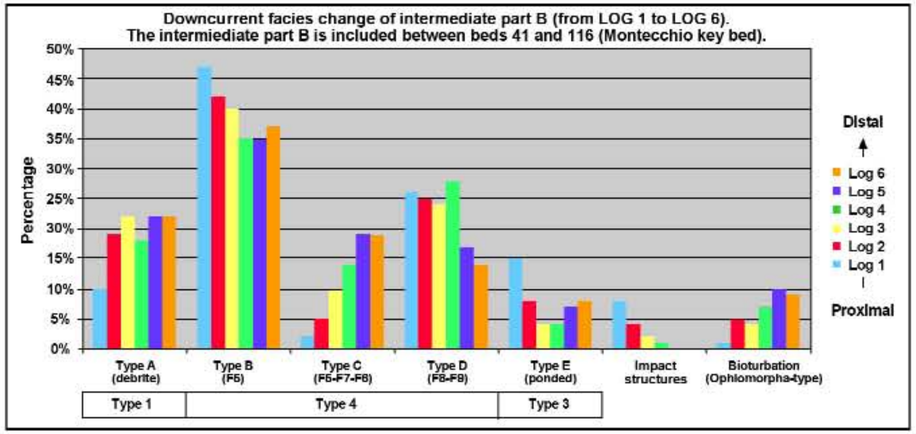


Fig. 45 - Panoramic overview and geologic map of the Paretaio system (see Fig. 12). On the left, a diagram showing the stratigraphic and structural evolution of the MAF foredeep during early to late Serravallian recording the passage between inner and outer basin in the meaning of Ricci Lucchi (1986) (modified from Roveri et al., 2002; see also de Jager, 1979).









THE LATERAL FACIES CHANGE IN THE INTERMEDIATE PART IS CHARACTERIZED BY THE FOLLOWING SEDIMENTARY CHARACTERISTICS INDICATING A STRUCTURAL CONTROL ON FACIES DISTRIBUTION

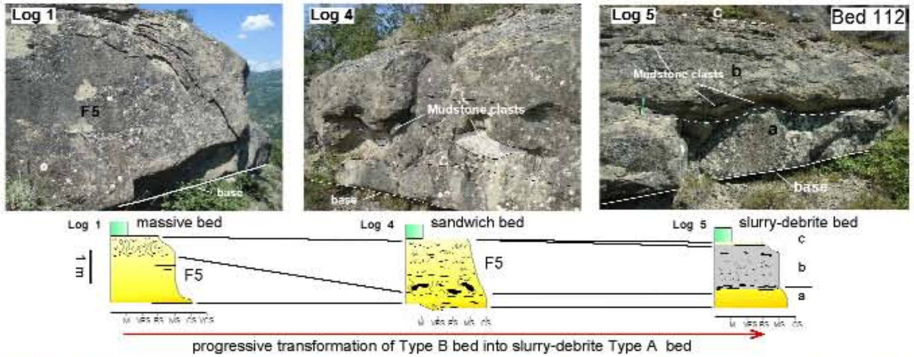
1) THE STRATIGRAPHIC THICKNESS VARIATIONS HIGHLIGHTED BY A PROGRESSIVE FLATTENING APPROACH (DEPOCENTRES AND MORPHOLOGIC HIGHS)

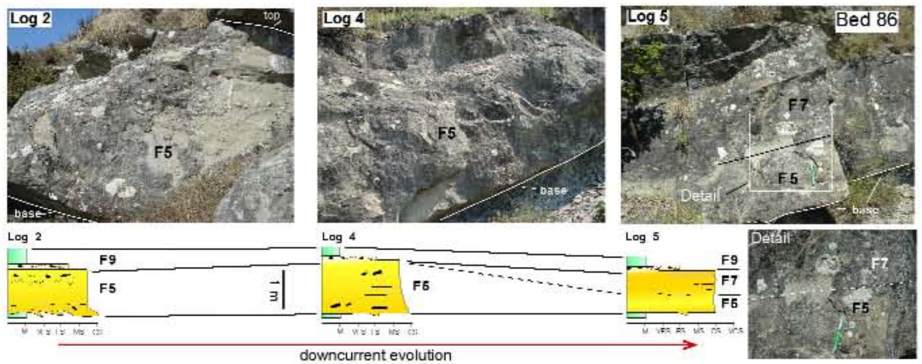
2) A HIGH PERCENTAGE OF MASSIVE TYPE B BEDS (F5) THAT PASS DOWNCURRENT IN SLURRY-DEBRITE TYPE A BEDS AND F5-F7 TYPE C BEDS DUE TO DIFFERENT DEGREES OF STRUCTURALLY INDUCED MORPHOLOGIC CONFINEMENTS. THE SLURRY-DEBRITE BEDS ARE PRODUCED BY DIFFERENT DEGREES OF TURBIDITY CURRENTS DECELERATIONS

3) THE RELATIVE INCREASE OF REFLECTED-CONTAINED TYPE E BEDS (TYPE III BY MUZZI MAGALHAES AND TINTERRI, 2010) IN CONJUNCTION WITH THE MORPHOLOGIC HIGHS

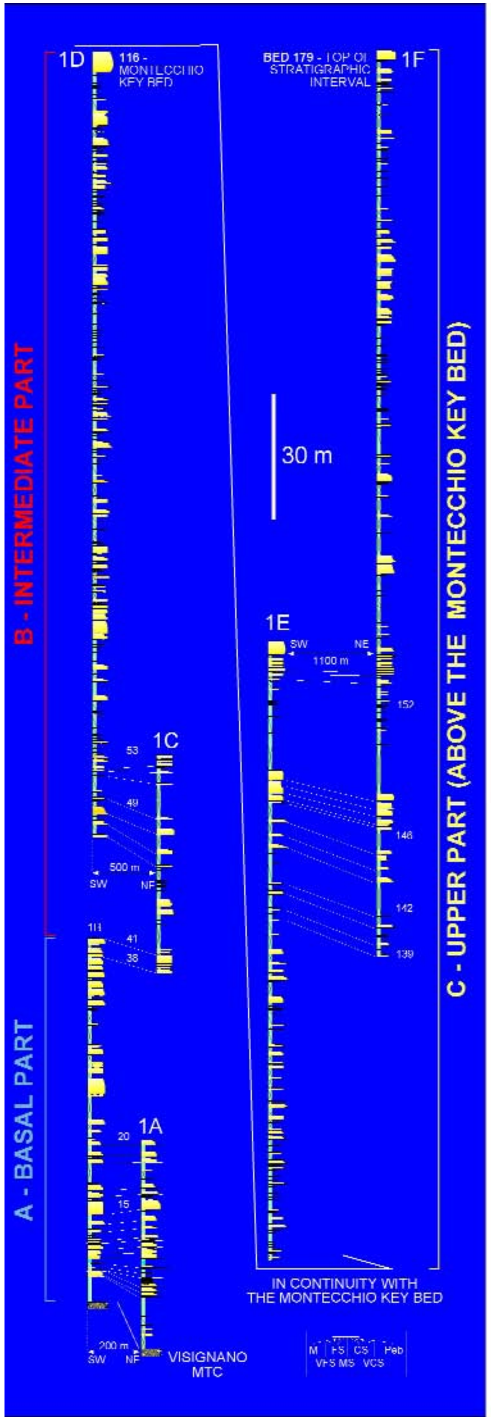
4) THE STRATIGRAPHIC EXPANSION TOWARD NE IN CROSS SECTIONS PERPENDICULAR TO THE M.CASTELLACCIO THRUST FRONT

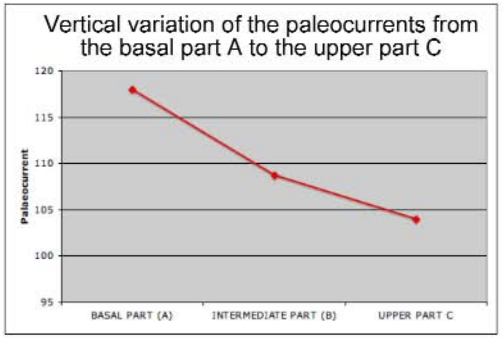
5) A PROGRESSIVE DECREASE OF ANGLE OF DIP OF THE BEDS (I.E. GROWTH STRATA) SHOWING AN EVIDENT GROWTH STRUCTURE REPRESENTED BY THE M. CASTELLACCIO THRUST.





DOI: 10.3301/GFT.2012.03





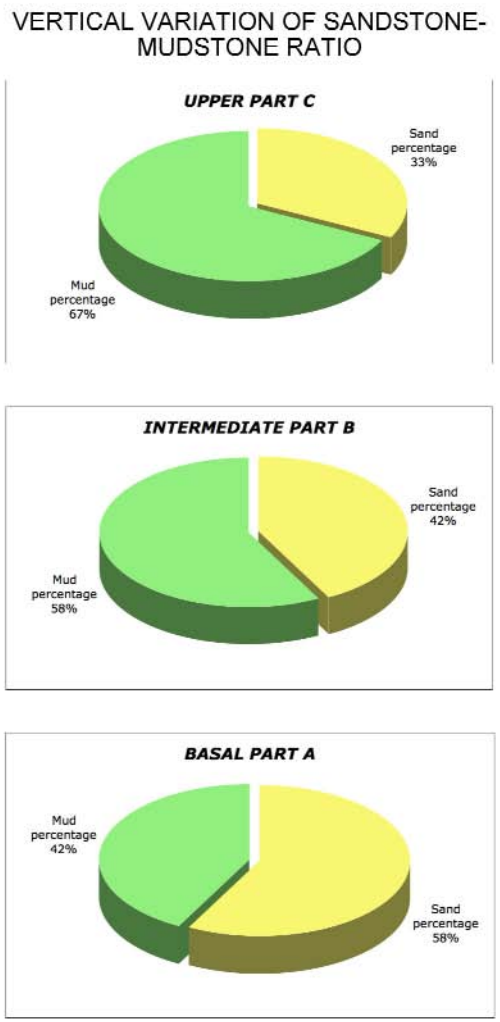


Fig. 46A - Detailed stratigraphic cross section of the Paretaio turbidite system included between the Visignano MTC and the Montecchio key bed. The location of the logs can be seen in figure 45, where we can observe that the trace of the cross section is parallel to the M. Castellaccio thrust front and, thus, to the main paleocurrents directed toward south-east.
The bed by bed correlation shows the well-developed cyclicity, which tends to increase upward. This well developed cyclicity allows the stratigraphic succession to be subdivided into 6 units (see the numbers on the left).
The numbers of the main correlated beds are also indicated (from Tinterri, Tagliaferri et al., in prep.).

Fig. 46B - This cross section is represented by composite log 1 consisting of six logs (1A to 1F in Fig. 45). This cross section covers a stratigraphic interval of about 600m from the top of Visignano MTC up to bed 179 and allows the vertical facies variations to be observed, which are mainly due to the M. Castellaccio thrust activity, and consequently, some important considerations to be made about the vertical passage into the Tortonian mixed turbidite deposits (see text for more details).
With regard to this, the stratigraphic succession has been subdivided into three main intervals, namely: **1)** Basal part "A" from the top of the Visignano MTC and bed 41; **2)** Intermediate part "B" included between beds 41 and 116 (Montecchio key bed); **3)** Upper part "C" above the Montecchio key bed 116.
On the right, the vertical variation of the paleocurrents and the sandstone/mudstone ratio of these three intervals are also shown (see text for more details, from Tinterri, Tagliaferri et al., in prep.).

DOI: 10.3301/GFT.2012.03

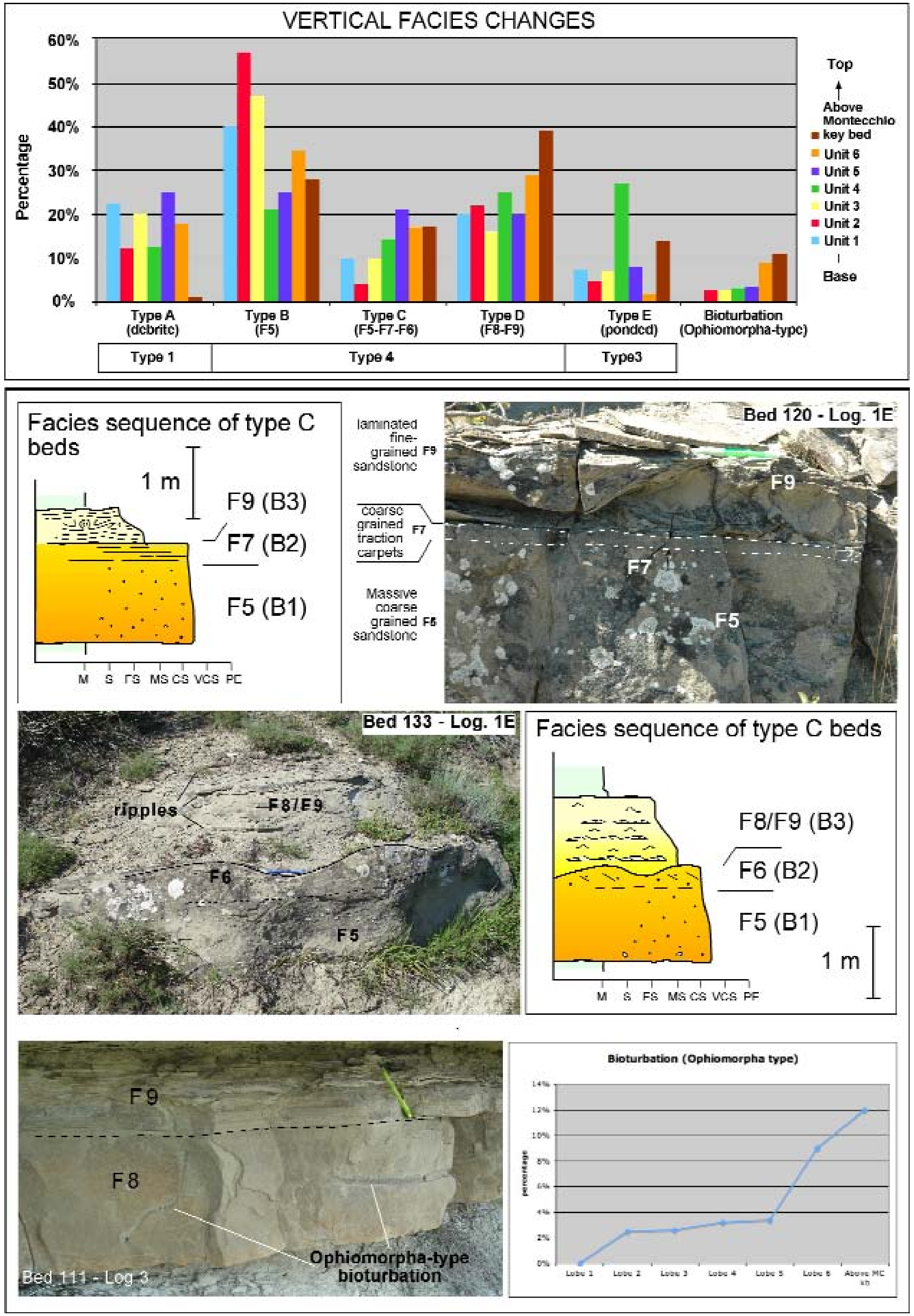


Fig. 47 - The above diagram shows the vertical facies variations of the basal, intermediate and upper parts A, B and C above the Montecchio key bed (see Figs. 13 and 14). The stratigraphic Units 1, 2, 3, 4, 5 and 6 are indicated in figure 46A.
Below the facies sequences of Type C beds resembling those of Tortonian mixed turbidite deposits are illustrated. In this bed type, F5 is reworked by a bypassing turbulent flow in plane-parallel traction carpets (F7) or in megaripples (F6), (see beds 120 and 133, respectively). These two facies sequences are interpreted as being related to two different degree of flow deceleration, due to the morphologic confinement produced by the M. Castellaccio thrust front (see below and Tinterri & Muzzi Magalhaes, 2011). The analogy between basinal turbidite (F5, F7 and F9) and mixed facies (B1, B2 and B3 as introduced by Mutti et al., 2003) is also shown.
In the photo and diagram below, the progressive upward increase of the Ophiomorpha-type burrows is also shown (from Tinterri, Tagliaferri et al., in prep.).

DOI: 10.3301/GFT.2012.03

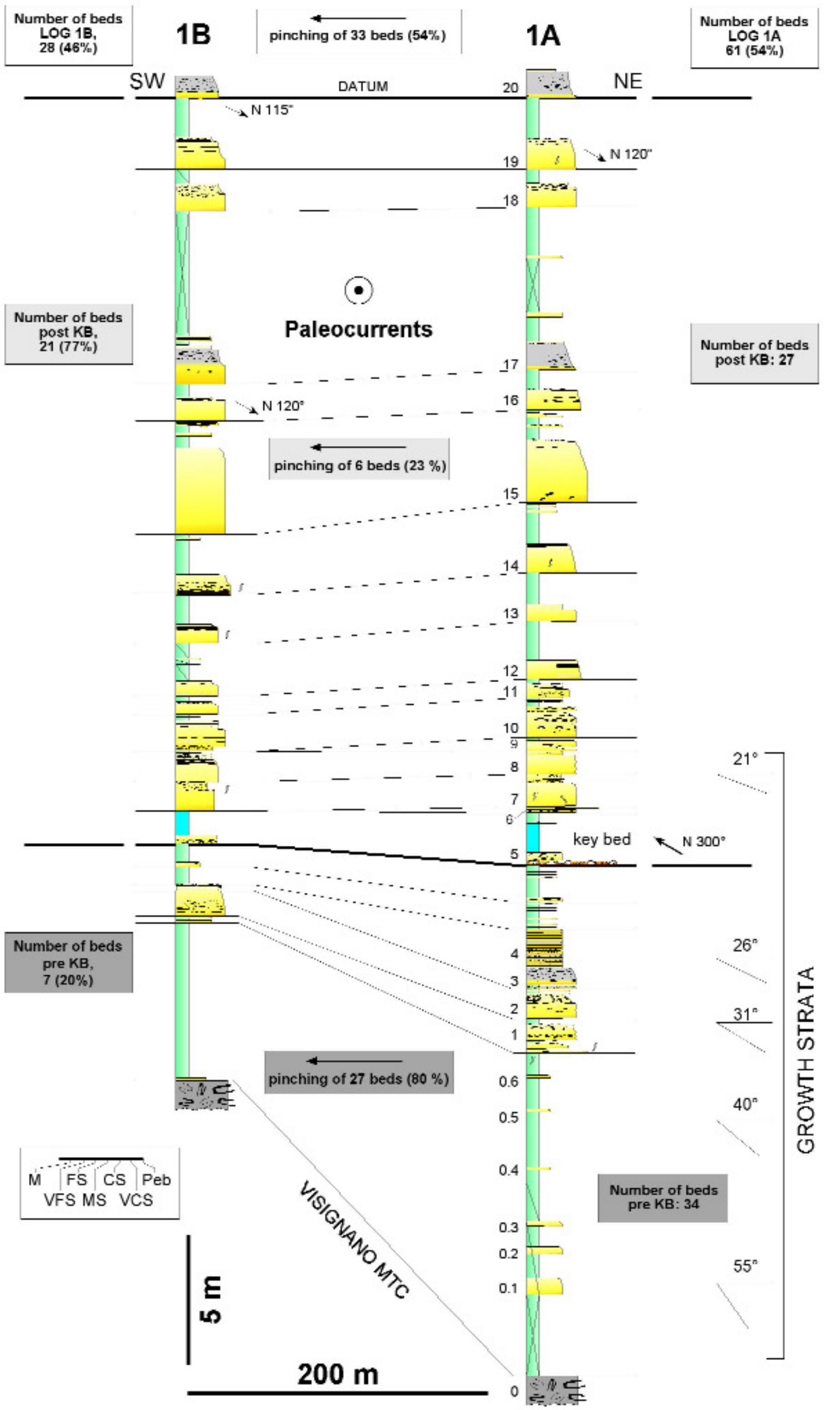
Stop 1.6: Paretaio turbidite unit along the Santerno river

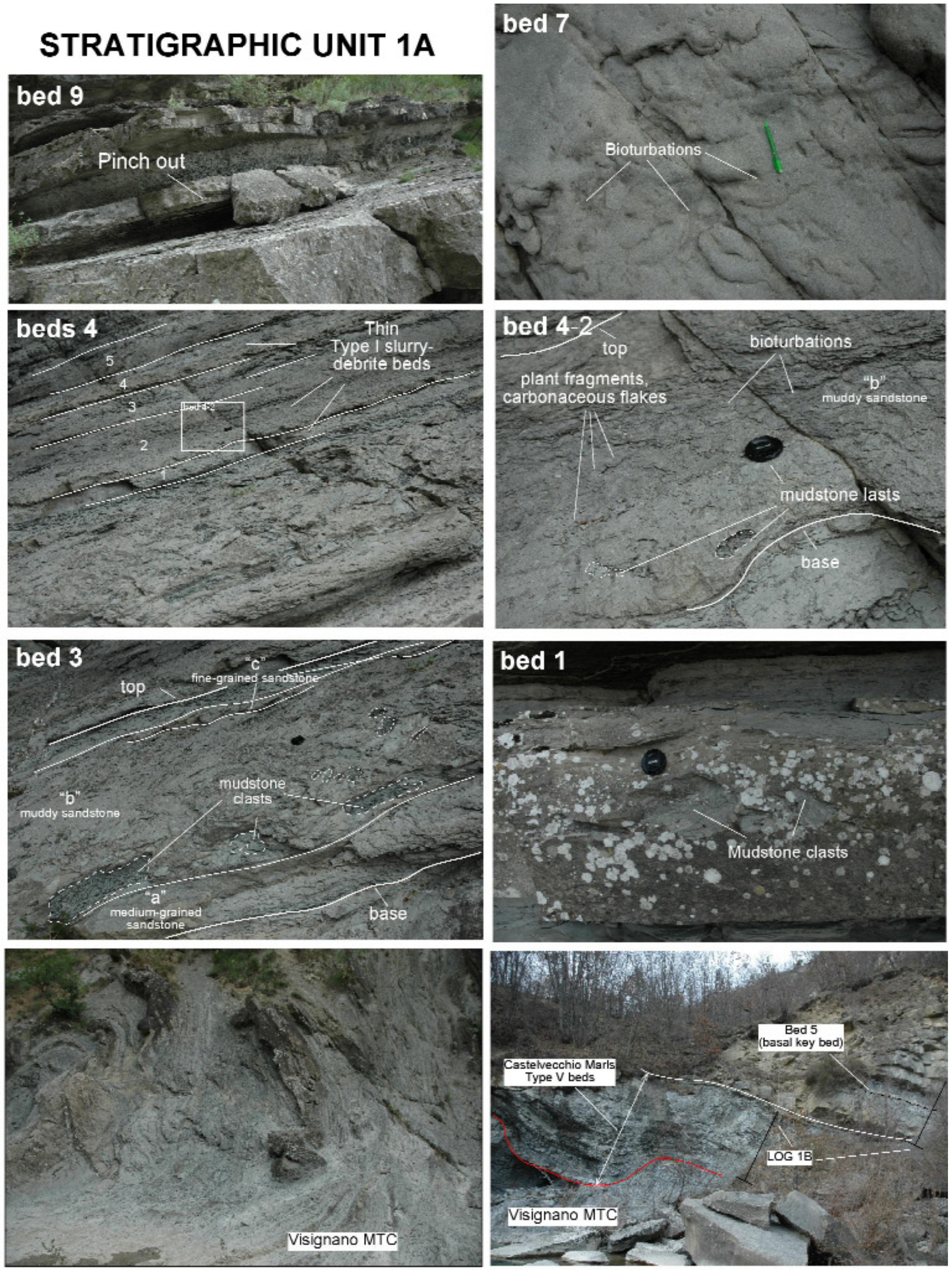
Stratigraphic unit: MAF inner stage, sequence S (Ricci Lucchi, 1986) and Unit V (Muzzi Magalhaes & Tinterri, 2009).
Age: Serravallian
Main features to observe: Visignano MTC; facies characteristics of the beds directly above the Visignano MTC.
Main outcrop references: Mutti et al. (2002a); Tinterri, Tagliaferri et al., in prep.

Description: the relationship between the Paretaio turbidites and the underlying Visignano MTC can be observed in more detail along the Santerno riverbed between Coniale and Moraduccio (Figs. 34, 48). In this Stop, the following elements can be observed and discussed: 1) the frontal (NE) limb of the Coniale anticline related to the M. Castellaccio thrust; 2) the evident stratigraphic pinching in a cross current direction toward SW; i.e. toward the M. Castellaccio thrust front that represents the inner side of the foredeep outer basin (Fig. 48); 3) the progressive decrease in the angle of dip; 4) the Visignano MTC (Fig. 20I, II) and its irregular upper surface draped by fine-grained deposits (Type-5 beds, Fig. 20II); 5) the bed types, directly above the mud drape consisting of slurry-debrite Type-A and bioturbated beds (beds 3, 4 and bed 7 in Fig. 48 respectively); 6) the pinch-out of some beds against the M. Castellaccio thrust front (bed 9 in Fig. 48). The analogies with Acquadalto MTC and the stratigraphic interval above this MTC (Stop 1.2) will be discussed.

Fig. 48 - Stratigraphic cross section perpendicular to the M. Castellaccio thrust front and included between the top of Visignano MTC and bed 20 (basal part A of Figs. 14 and 46A, see map in Fig. 45 for location of the logs). In this cross section we can observe: 1) the evident beds pinching toward SW, i.e. against the M. Castellaccio thrust front, 2) the progressive decrease in the angle of dip indicating a growth structure (see also photo I of Fig. 20). The photos on the right show the different types of beds characterizing this basal part A. From base to top, there are the Visignano MTC, the mud drape directly above the Visignano MTC (Castelvecchio marls), mainly consisting of Type-5 beds, a sandwich bed (Bed 1), slurry Type-A beds, particularly rich in plant fragments (beds 3, 4); Ophiomorpha-type bioturbations (bed 7); bed pinching toward the M. Castellaccio structural high (bed 9), from Tinterri, Tagliaferri et al., in prep.).

DOI: 10.3301/GFT.2012.03

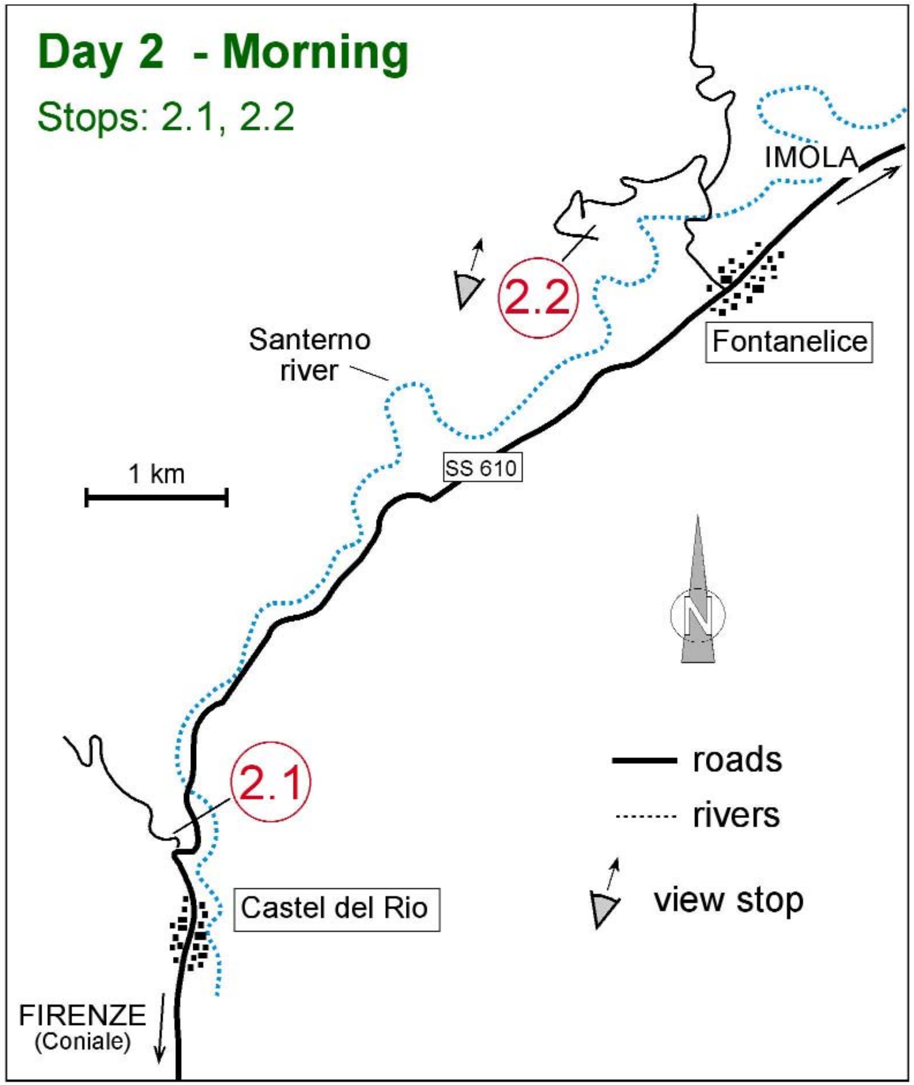




DOI: 10.3301/GFT.2012.03

DAY 2 (morning) – Santerno Valley

The second day will be spent in the Santerno and Savio Valleys in the Tortonian mixed low efficiency turbidites, which characterize the outer basin (Figs. 33, 34). This type of depositional system is related to the basin narrowing produced by the Upper Serravallian tectonic phase (see Fig. 34). In the last Stop of the day (2.5) we will examine the Upper Serravallian Unit V in an outer structural element (Log G; Fig. 34, 36).

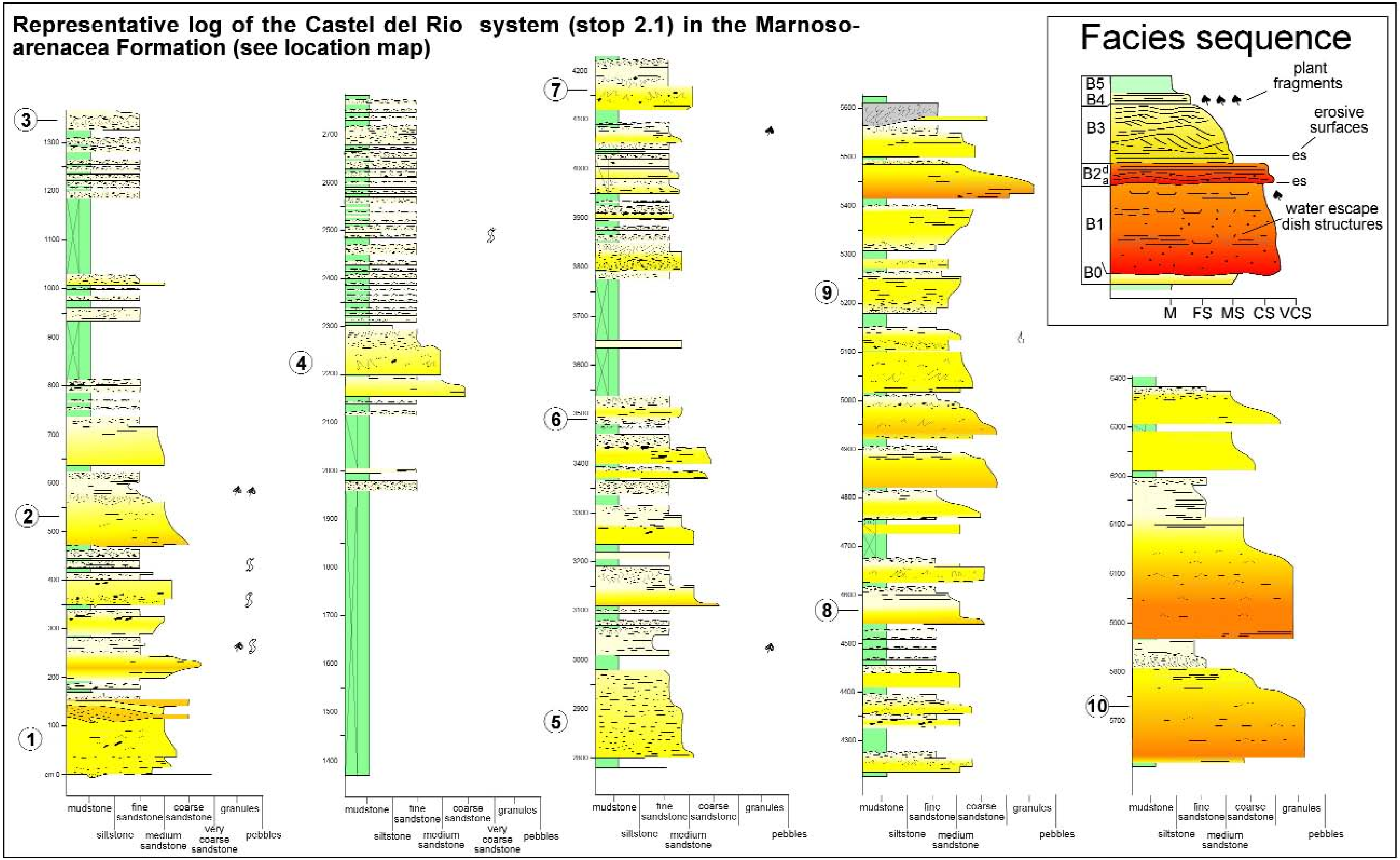


Stop 2.1: Castel del Rio: sand-rich low efficiency turbidites

Stratigraphic unit: MAF outer stage, sequence T1 (Ricci Lucchi, 1986), Castel del Rio system (Mutti et al., 2002a).
Age: Tortonian
Main features to observe: facies characteristics of sandstone lobes of the Castel del Rio mixed system.
Main outcrop references: Ricci Lucchi & Pignone (1979); Ricci Lucchi & Ori (1985); Ricci Lucchi (1981; 1986); Mutti et al. (2002a, b; 2003; 2007); Tinterri & Muzzi Magalhaes (2011).

Description: this system records the first Tortonian deposits of the MAF outer stage heralded by the structurally-confined Upper Serravallian Firenzuola and Paretaio systems (Stops 1.5, 1.6). Due to this physiographic change, the Castel del Rio deposits are characterized by sedimentary features different from those of the underlying Langhian to Serravallian turbidites.

DOI: 10.3301/GFT.2012.03



modified from Mutti, Tinterri, Benevelli and Cavanna, 2002b

Fig. 49A - Castel del Rio system representative log. The typical facies sequence of Type-B mixed low efficiency turbidites is also shown in the square (modified from Mutti et al., 2002b).

DOI: 10.3301/GFT.2012.03

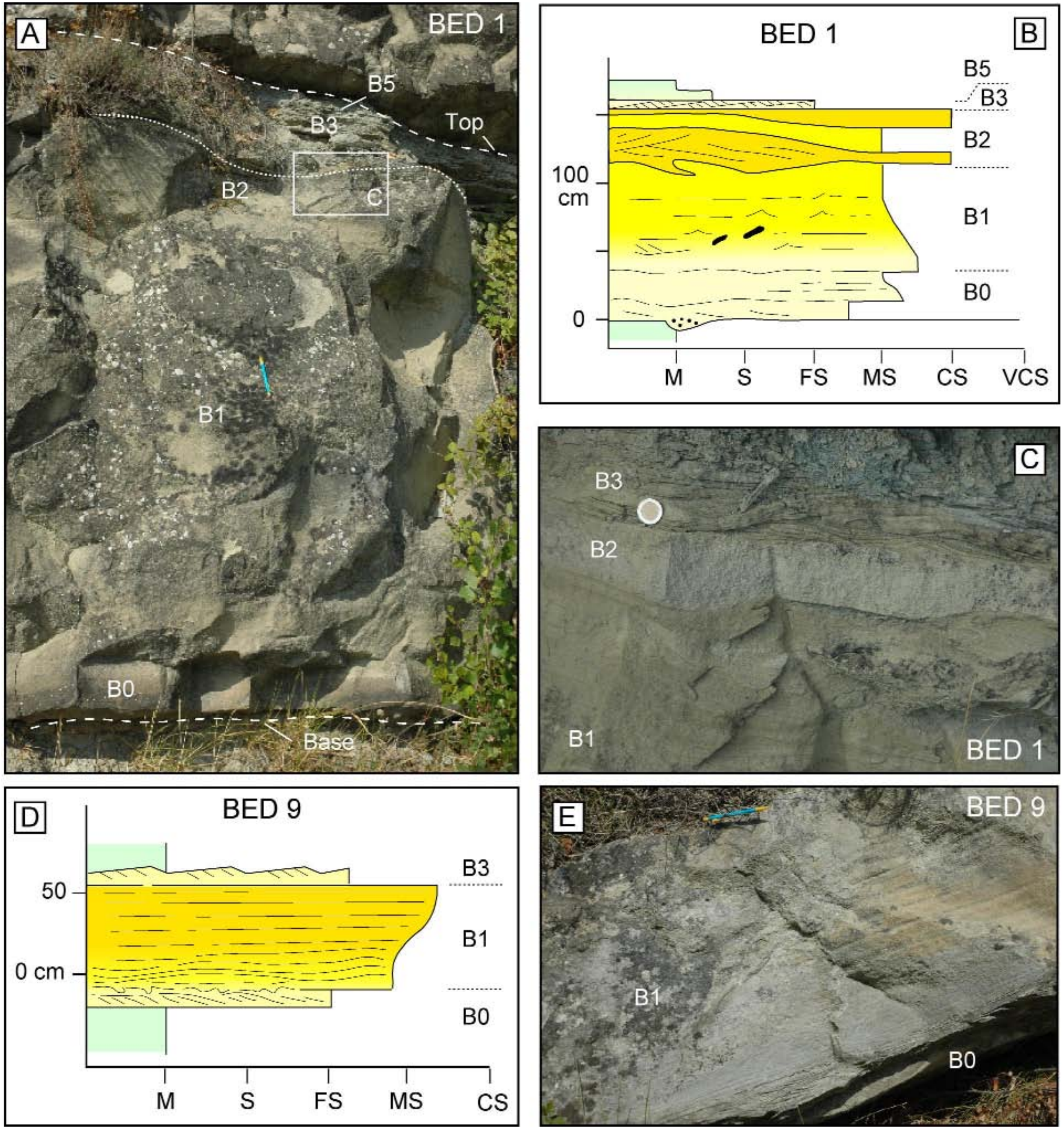


Fig. 49B - Facies sequences characterizing the stratigraphic log of Fig. 49A. In A and B, a thick bed is shown, characterized by inverse to normal grading with internal erosive surfaces, whereas D and E show a bed in which the inverse grading occurs without evident erosive surfaces (from Tinterri & Muzzi Magalhaes, 2011. The facies terminology comes from Mutti et al. (2003); see also Fig. 32.

The main differences are: 1) an evident increase in sand content (N:G is about 80%), especially due to the presence of thick, commonly amalgamated sandstone beds, 2) an increase in the Ophiomorpha-type bioturbation; 3) the presence of fossil debris, 4) the substantial absence of type 1 debrite beds; 5) beds having facies sequences quite different from those of the underlying Langhian to Serravallian turbidites (see Fig. 49A, B) characterized by inverse to normal grading with internal erosive surfaces, which can be related to

DOI: 10.3301/GFT.2012.03

waxing and waning conditions (*sensu* Kneller, 1995) induced both by the type of trigger mechanism and acceleration or deceleration relating to topographic confinements typical of this outer stage (see also Stops 2.2, 2.3 and 2.4). The significance of these facies sequences is explained in section 5.2.2 and they will be discussed in the field; however, the role of flow decelerations induced by topographic confinement in the formation of mixed facies sequences of Fig. 32 should be considered (Tinterri & Muzzi Magalhaes, 2011).

The above-listed sedimentary characteristics indicating deposition at a shallower water depth and in a narrower basin than the underlying Langhian to Serravallian turbidites, together with the general geologic context associated to the uplift and closure of the foredeep, prompted Mutti et al. (2002b; 2003) to interpret these deposits as mixed turbidite systems, i.e. relatively small and sand-rich depositional systems sharing several characteristics with basinal turbidites, but differing from these by showing a more immature facies development (cf. “poorly-efficient turbidite systems” by Mutti, 1979) especially due to the high morphologic confinement (see Tinterri & Muzzi Magalhaes, 2011 and discussion in section 6).

In particular, although consisting of massive coarse grained facies characterized by a high sandstone-mudstone ratio, the Castel del Rio deposits (sequence T1 by Ricci Lucchi, 1986) show relatively higher tabular geometries and lateral continuity than the overlying Fontanelice sequence T2, suggesting a deposition by still relatively unconfined flows running parallel to the basin axis. However, beds with inverse to normal grading, as shown in Fig. 49B, begin to be common compared with the underlying deposits of Unit V (see also the underlying Paretaio turbidite system). These sedimentary characteristics can be interpreted as being related to an enhancement of confinement conditions due to the progressive closure of the foredeep, which, however, becomes particularly evident in the upper Fontanelice system (Stop 2.2).

DOI: 10.3301/GFT.2012.03

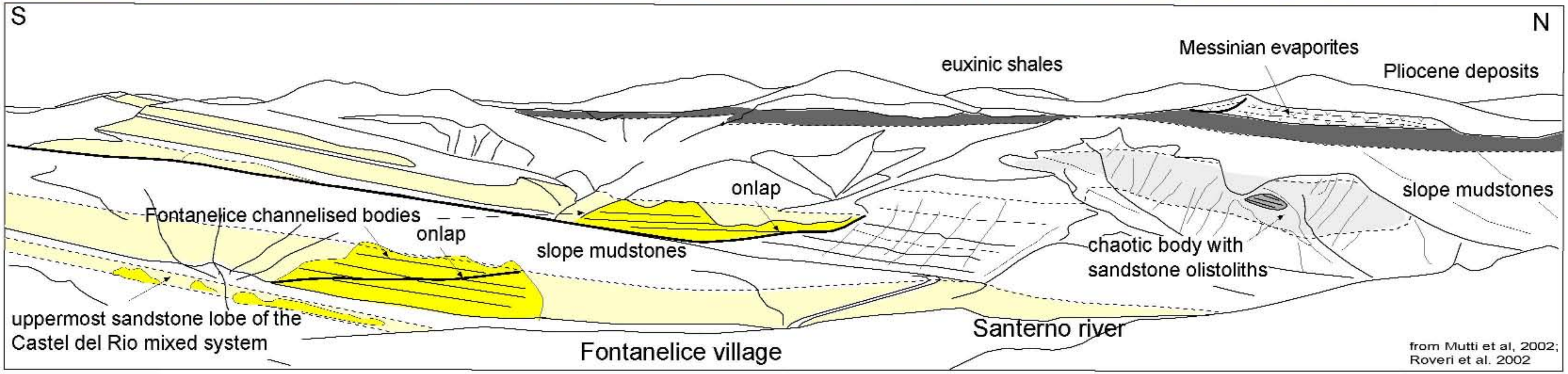
Stop 2.2: Fontanelice: sand-rich low efficiency turbidites

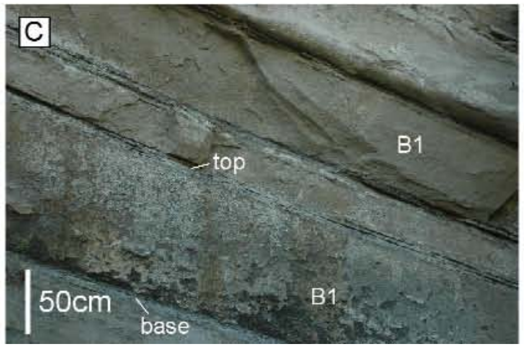
Stratigraphic unit: MAF outer stage, sequences T1 and T2 (Ricci Lucchi, 1986), Fontanelice system (Mutti et al., 2002a).
Age: late Tortonian
Main features to observe: geometry and facies characteristics of mixed turbidite deposits of the Fontanelice system; slope mudstone with MTCs; primary evaporites.
Main outcrop references: Ricci Lucchi (1981; 1986); Ricci Lucchi & Ori (1985); Mutti et al. (2002a) and Roveri et al. (2002; 2003).

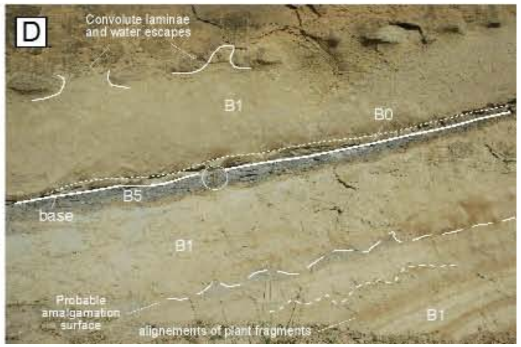
Description: this area is well known in the literature for its spectacular exposures of the MAF outer stage and, particularly, for its sandstone lobes confined in erosional depressions known in the literature as Fontanelice channels (Fig. 50). The beds, mainly consisting of massive to crudely laminated facies (B1 facies of Fig. 50; see Fig. 50C, D) essentially devoid of upper fine-grained divisions, are probably related to the decelerations due to a structurally-induced topographic confinement, as suggested by subsurface data (Roveri et al., 2002; 2003). However, the presence of a metre-thick succession of ortho-conglomerates at the base of the upper Fontanelice body (T2 sequence, Ricci Lucchi, 1981, see Fig. 50B) testify that this feature acted as a bypass zone and, thus, as a structurally-controlled conduit for a certain period of time. Following the model introduced by Roveri et al. (2002) (Fig. 51), the distal time-equivalent deposits of Fontanelice system should be recorded by the strata of Sarsina/M. Saraceno system, which will be examined in Stops 2.3 and 2.4.
In particular, this succession is important because it records the closure of the Marnoso-Arenacea outer basin that culminated in the well-known Messinian salinity crisis of the Mediterranean Sea, here recorded by Messinian euxinic shales overlain by the primary evaporites (mainly selenitic gypsum) of the Vena del Gesso Formation (Figs. 50 and 51).

Fig. 50 - Panoramic view of the upper part of the MAF along the Santerno valley, in which the Fontanelice turbidite system, slope mudstones with chaotic bodies and the primary evaporites of the Vena del Gesso Formation can be observed (from Roveri et al., 2002; 2003 published upon the Author's permission). A) Panoramic view of the structurally confined Fontanelice mixed systems in the Santerno Valley. In B, the orthoconglomerates with alpine provenance (Ricci Lucchi, 1981) located at the base of the deposits illustrated in A, are also shown; C and D) a detail of the sandstone lobes mainly composed of B1 divisions (see Fig. 32) characterizing the Fontanelice system shown in A.

DOI: 10.3301/GFT.2012.03







DOI: 10.3301/GFT.2012.03

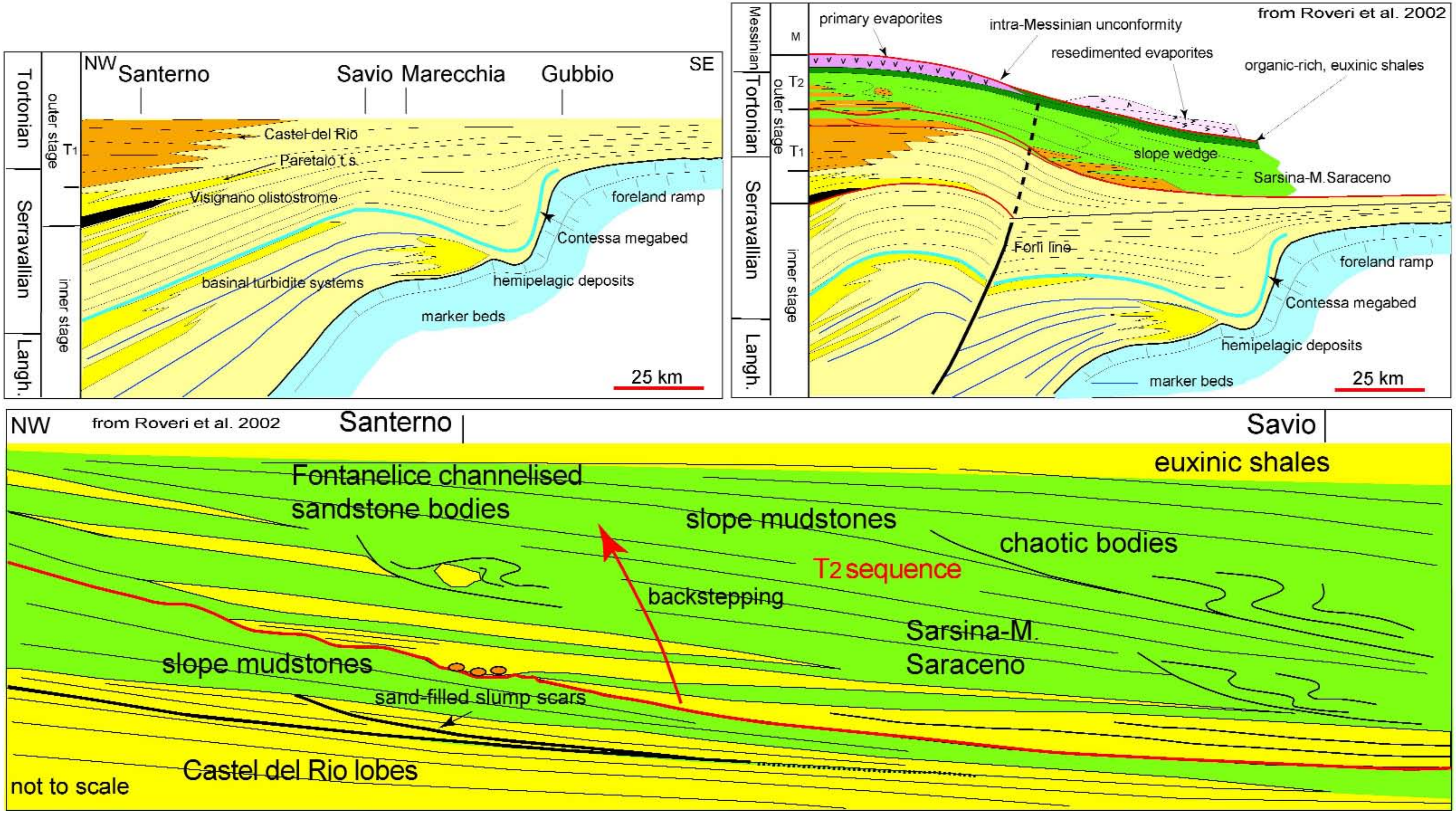
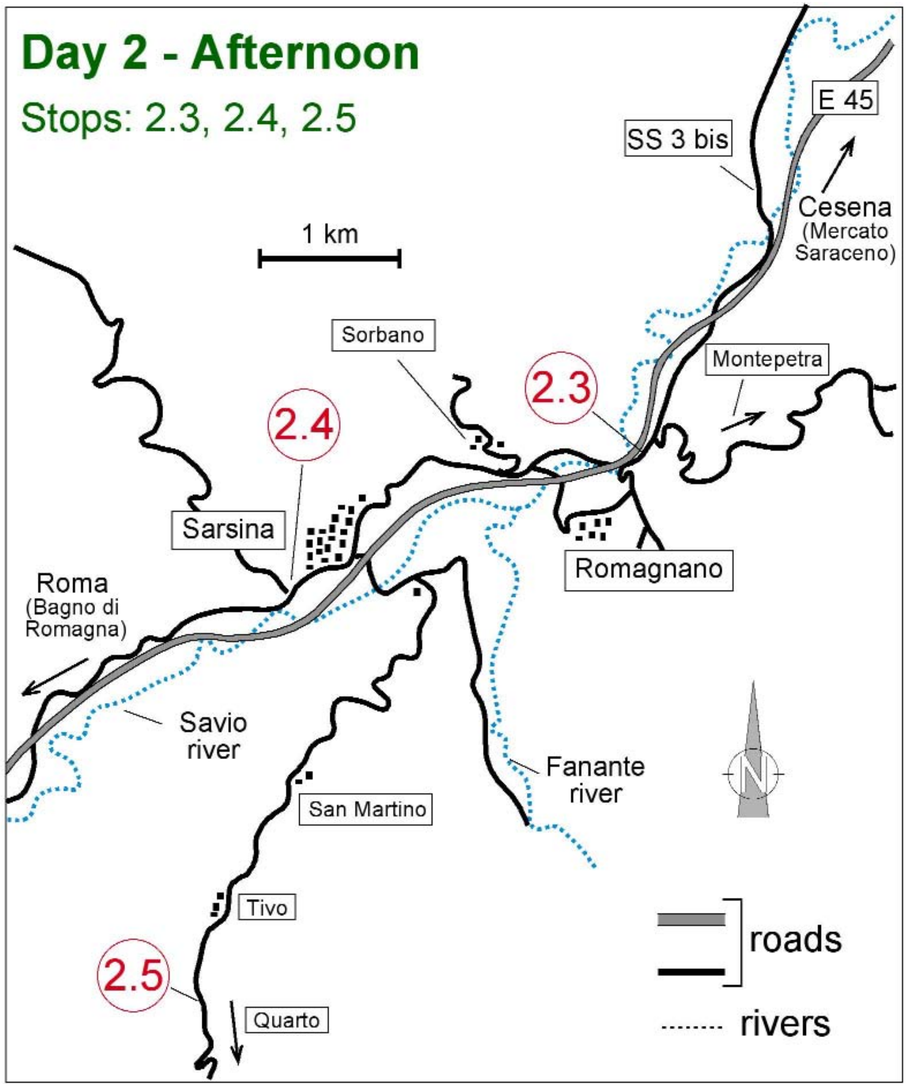


Fig. 51 - Schematic cross-sections showing the evolution of the MAF foredeep basin. Top left, the situation during the middle Tortonian period (datum: top of the Castel del Rio system) is illustrated, while, on the right, the fragmentation of the former foredeep basin and formation of shallow piggy-back basins during the late Messinian period are shown (see Fig. 5 for the location of the Forlì line, modified from Ricci Lucchi and Ori, 1985, in Roveri et al. 2002)). In the diagram below, a model showing a correlation between Fontanelice and Sarsina-M. Saraceno systems is also shown (from Roveri et al., 2002 published upon the Author's permission).

DOI: 10.3301/GFT.2012.03

DAY 2 (afternoon) – Savio Valley



Stop 2.3: Romagnano: sand-rich low efficiency turbidites

Stratigraphic unit: MAF outer stage, sequence T_2 (Ricci Lucchi, 1986), Sarsina-M. Saraceno mixed turbidite system (Mutti et al., 2002a).
Age: late Tortonian.
Main features to observe: facies characteristics of mixed low efficiency turbidites deposited in a structurally-confined basin.
Main outcrop references: Ricci Lucchi (1981); Ricci Lucchi & Ori (1985); Mutti et al. (2002a, b; 2003; 2007); Tinterri & Muzzi Magalhaes (2009, 2011).

Description: The stratigraphic log along the road-cut is some 20m thick and consists of a variety of sandstone facies ranging from thick and coarse-grained graded beds with abundant dewatering structures and Ophiomorpha burrows to relatively thin and fine-grained beds with well-developed horizontal laminae and climbing ripples (Fig. 54). The succession grades upward into a mudstone-dominated member containing thin sandstone beds with very thin and closely-spaced sandstone-mudstone couplets.
The beds of this succession have been interpreted as typical Type-B mixed turbidite deposits by Mutti et al. (2002b; 2003) and their characteristics are illustrated in Figs. 52, 53. In particular in this outcrop, the typical facies sequence shown in Fig. 50 can be observed (see also Stop 2.4).

DOI: 10.3301/GFT.2012.03

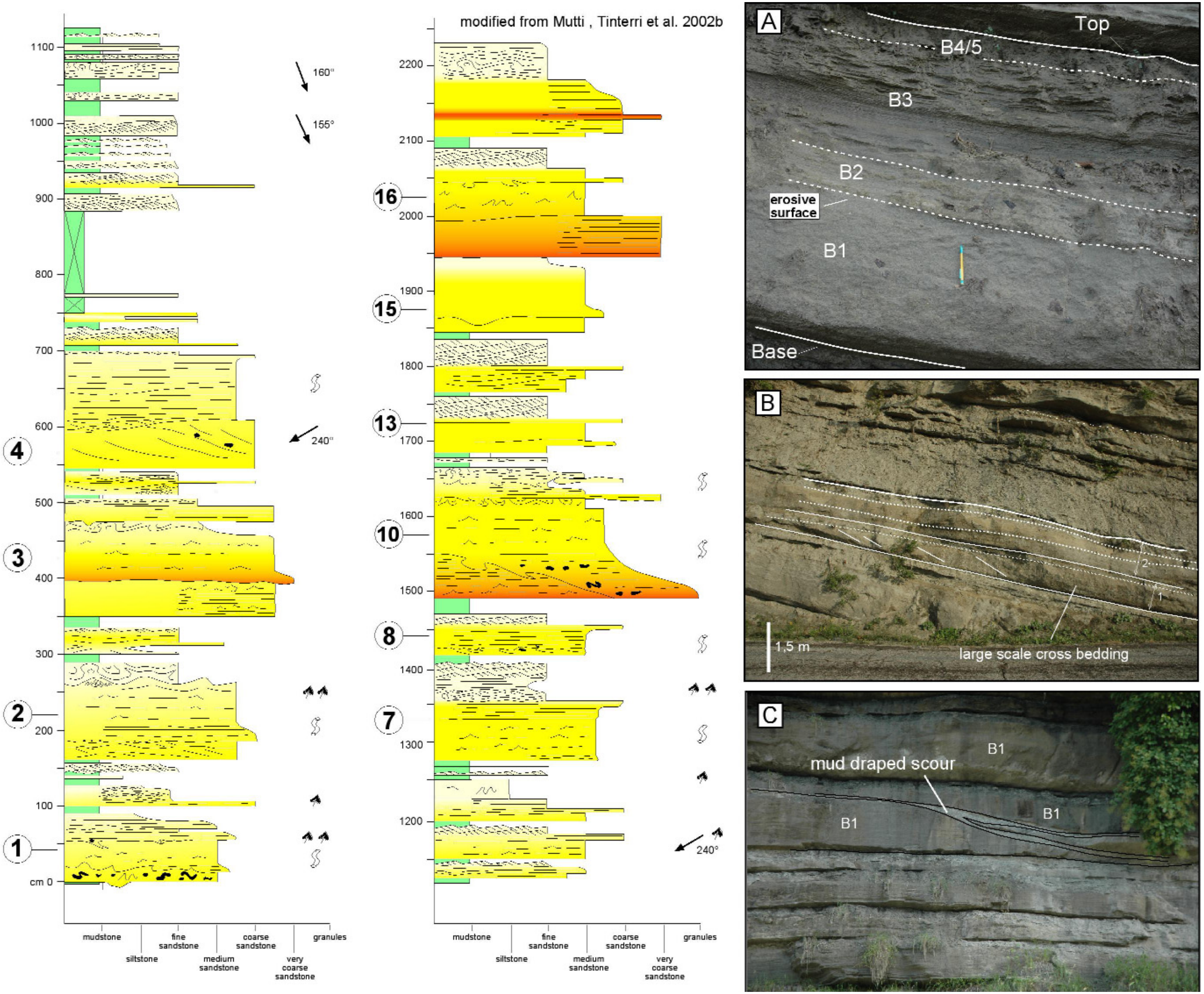


Fig. 52 - On the left the representative log of the Sarsina mixed turbidite system is shown (modified from Mutti et al., 2002b). A) Typical facies sequence of a low-efficiency Type-B mixed system (compare with Fig. 49 or 53C); B) Coarse-grained and relatively well-sorted cross-stratified sandstone; C) Thick sandstone bed consisting of B1 facies characterized by a mud draped scour as meant by Mutti & Normark (1987; 1991).

DOI: 10.3301/GFT.2012.03

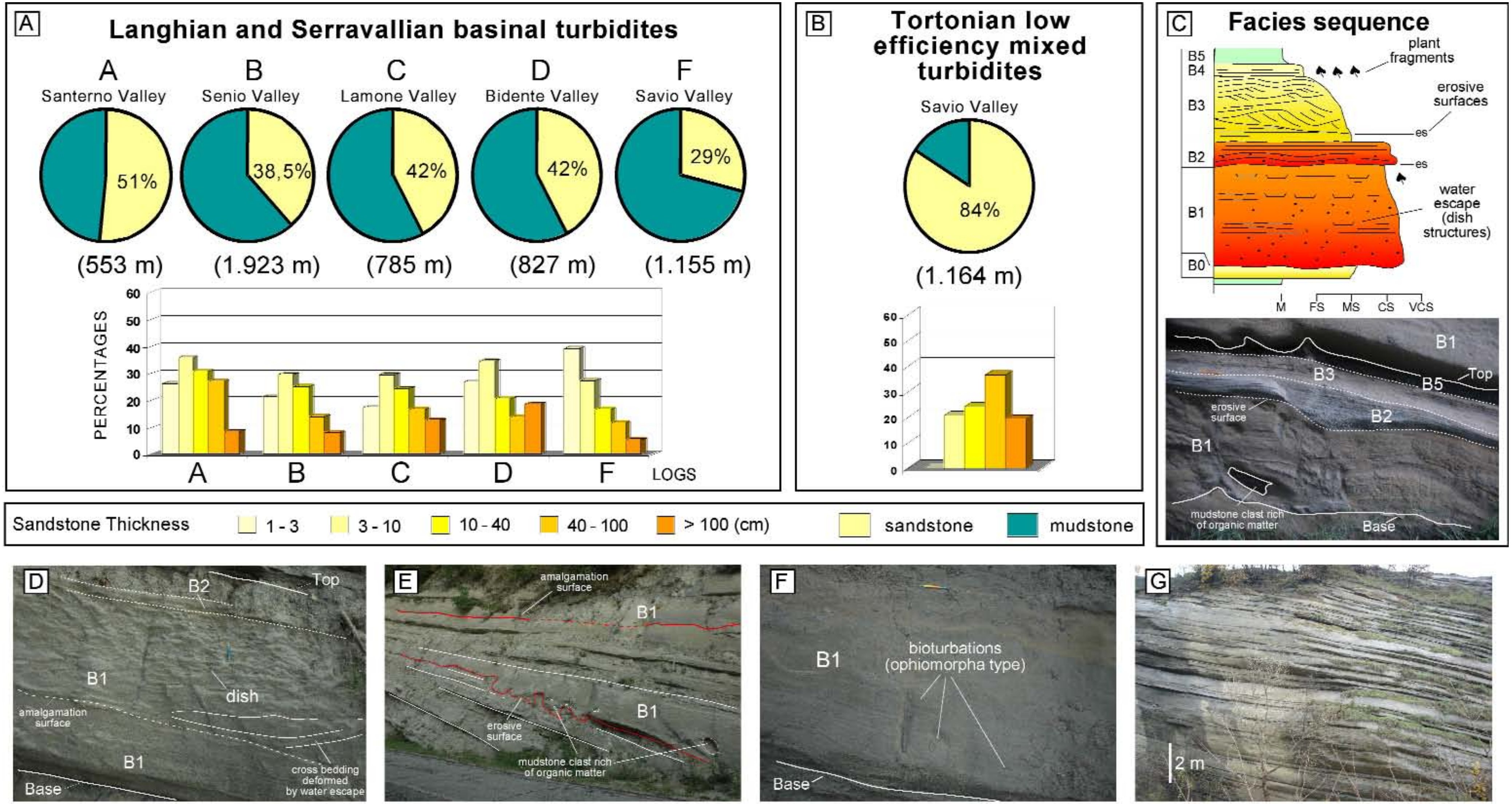


Fig. 53 - A and B) Down-current variation of the Net to Gross respectively in the Langhian and Serravallian turbidites and in the Tortonian mixed depositional systems in the Savio valley (see also Fig. 34, from Tinterri & Muzzi Magalhaes, 2011). A high value of about 84% is also evident in the panoramic view shown in G; C) Sedimentary characteristics of sand-rich mixed deposits as described by Mutti et al. (2003, see their Fig. 10B; see also Fig. 50); D) Crude laminated division B1 characterized by dish structures, E) Examples of amalgamations and erosive surfaces, F) Ophiomorpha-type burrows characterizing B1 division.

DOI: 10.3301/GFT.2012.03

More precisely, in this system the main sedimentary characteristics are:
1) a high sand content proven by a sandstone-mudstone ratio of about 84% (see Fig. 53B compared to Fig. 53A showing the sandstone-mudstone ratio of the underlying basinal turbidite deposits); **2)** beds characterized by facies sequences completely different from those of the underlying basinal turbidites, characterized by inverse to normal grading with internal erosive surfaces (see Fig. 53C); **3)** a high percentage of bed amalgamations, often highlighted by highly erosive surfaces (Fig. 53E); **4)** a high percentage of massive sandstone with dewatering structures (Fig. 53D); **5)** the absence of Type 1 debrite beds; **6)** an increase, compared with the underlying stratigraphic units, in the bioturbation degree (Fig. 53F), in which Ophiomorpha-type trace fossils become very common; **7)** in this outcrop, there is also a large scale cross-stratified unit, which can be interpreted as a tractional bed-load feature at the base of a bypassing turbulent flow. These sedimentary structures are very similar to facies F6 in basinal turbidites (see Fig. 6) and can be seen as a division B2 characterized by megaripple structures (see Figs. 52B, 54). **8)** mud draped scours, i.e. erosions related to sudden flow deceleration, which can produce hydraulic jump phenomena (Fig. 52C). **9)** cyclicity represented by an alternation of decametre-thick sandstone lobes and fine-grained intervals, much more developed than the underlying Langhian and Serravallian basin plain turbidites. In particular, the mudstone-dominated succession, which conformably overlies the sandstone unit exposed along the road-cut, consists of thin sandstone beds and sandstone/mudstone couplets that can be interpreted, mostly on the basis of a comparison with the Eocene of the south-central Pyrenees, as a prodeltaic mudstone wedge (see Mutti et al., 2002a; 2003).

As mentioned above, based on these sedimentary characteristics, the thick bedded and coarse-grained sandstone packages can be interpreted as proximal depositional lobes or channel lobe transition deposited by immature (poorly efficient) turbidity currents probably triggered by the combined effect of severe flood events and/or ensuing failure of fluvio-deltaic deposits evolving into a structurally-confined basin.
In the formation of the low efficiency mixed facies sequences of Figs. 52A and 53C, the role of capacity-driven deposition with concomitant development of turbulent energy induced by flow decelerations associated to morphologic confinements should also be considered (see Fig. 54, Tinterri & Muzzi Magalhaes, 2011 and discussion in section 6). In particular, division B2 and its erosive base can be interpreted as related to the deposition and reworking of the top of division B1 associated to a bypassing turbulent flow. The formation of the latter would be favoured by sediment concentration drops and relative increase in turbulent energy, produced by the deposition of division B1, induced by the decelerations due to morphologic confinements of the basin. It is here deemed that strong bypass processes could occur, if the development of turbulent energy is sufficiently high due to strong

DOI: 10.3301/GFT.2012.03

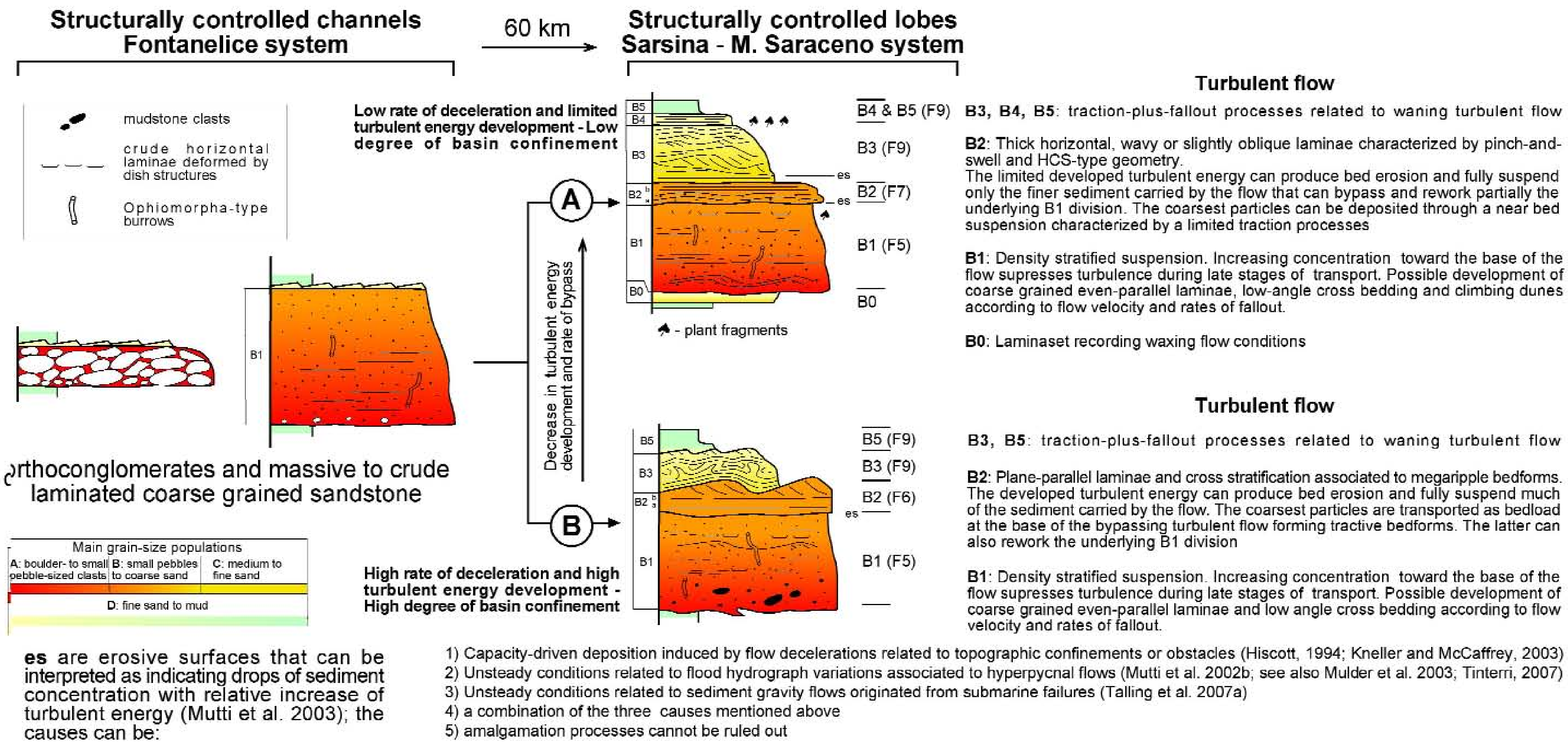


Fig. 54 - Two different low efficiency "mixed" turbidites facies sequences in relation to basin confinement degree, due to a structural control. A) facies sequence characterizing the MAF Tortonian mixed deposits, as described by Mutti et al. (2003). All things being equal, it is interpreted as being deposited in a basin with a relatively low degree of confinement; B) facies sequence interpreted as being deposited in a relatively highly confined basin. Both are inspired by figure 26, in which, based on the degree of deceleration induced by slope changes in topographic obstacles, massive sandstone (F5, analogous to B1) can pass upward into plane-parallel coarse grained laminae (F7, analogous to facies B2 with low-angle undulated laminae as shown in A) or into cross bedding associate to megaripple bedforms (F6 analogous to facies B2 with megaripple bedforms illustrated in B) (from Tinterri & Muzzi Magalhaes, 2011). This facies scheme can suit very well the Fontanelice-Sarsina system; the facies filling the structurally controlled Fontanelice channels consist of orthoconglomerates and coarse grained massive sandstone, while in the Sarsina area (60km down-current) the beds are characterized by the typical facies sequence illustrated in A (see also figure 49).

DOI: 10.3301/GFT.2012.03

decelerations related to high degree of structurally-controlled confinement. In this case, the undulated laminae of division B2 could be replaced by megaripples with well developed cross bedding. On this basis, the presence of undulated laminae or megaripples in division B2 can depend on the rate of deceleration associated to the degree of structurally controlled confinement of the basin. All things being equal, facies sequences characterized by division B2 consisting of low-angle undulated laminae (Fig. 54A) could be interpreted as associated to basins with a relatively lower degree of confinement. On the contrary, facies sequences characterized by division B2 consisting of megaripples could be seen as associated to basins with a higher degree of structurally-controlled confinement (Fig. 54B). From this point of view, a strong analogy is believed to exist with the concepts introduced by Mutti et al. (2003), according to which the transformation of a high density turbidity current in a dilute turbulent flow takes place through two different and probably intergradational facies sequences, and to which massive to crudely laminated F5 facies (analogous to B1 facies) can be overlain by even, parallel, coarse grained laminae F7 (a B2 analogous with undulated laminae) or by well sorted cross bedding F6 (a B2 analogous with megaripple cross bedding) depending on the rate of deceleration induced by the degree of confinement (see Fig. 26, Mutti et al., 2003). These type of facies, as mentioned in sections 4 and 5, are very similar to the underlying structurally-confined Paretaio turbidites.

In general, the MAF is characterized by beds with facies sequences similar to that illustrated in Fig. 54A, while examples characterized by facies sequences with megaripple division B2 (Fig. 54B), interpreted as delta-fed mixed turbidite systems with a higher structural confinement, are the Late Eocene/Early Oligocene Annot Sandstone in southern France and the Messinian Laga Formation (Tinterri & Muzzi Magalhaes, 2011). Furthermore the substantial absence of type 1 debrite beds in the Tortonian deposits can be explained, as mentioned in section 6, by the fact that the progressive closure of the foredeep can humper the ability of the flows to travel and erode a large amount of mud especially in the proximal areas. The decelaration of relatively mud-poor high density turbidity currents (i.e. low eficiency turbidity currents by Mutti, 1979) in a narrowed foredeep favour the formation of thick massive facies with dewatering structures rather than type 1 beds.
Following the model in figure 51, these deposits can be correlated up-current with the Fontanelice channels in the Santerno valley (Stop 2.2), which can be interpreted as structurally controlled conduits. Consequently, if the Fontanelice system represents a transfer zone, the Sarsina system in the Savio Valley (i.e. 60km down-current) records a depositional zone represented by proximal sandstone lobes or by a channel-lobe transition, as testified by the occurrence of B1 (F5) overlain by B2 (F7), large-scale cross stratified units (B2 with

DOI: 10.3301/GFT.2012.03

megaripple geometry) and mud draped scours (as meant by Mutti & Normark, 1991), which suggest sudden flow decelerations and bypass of turbulent flows. The low efficiency mixed turbidites of the Sarsina system record the deposition of grain size population B (coarse to very coarse grained sand) and the bypass of a great part of the grain size population C (medium-grained sand) and D (fine grained sand to mud).

Stop 2.4: Sarsina: sand-rich low efficiency turbidites

Stratigraphic unit: MAF outer stage, sequence T_2 (Ricci Lucchi, 1986), Sarsina-M. Saraceno mixed system (Mutti et al., 2002a).
Age: late Tortonian.
Main features to observe: facies characteristics of mixed turbidite systems deposits.
Main outcrop references: Ricci Lucchi (1981); Ricci Lucchi & Ori (1985); Mutti et al. (2002a b, 2003, 2007).

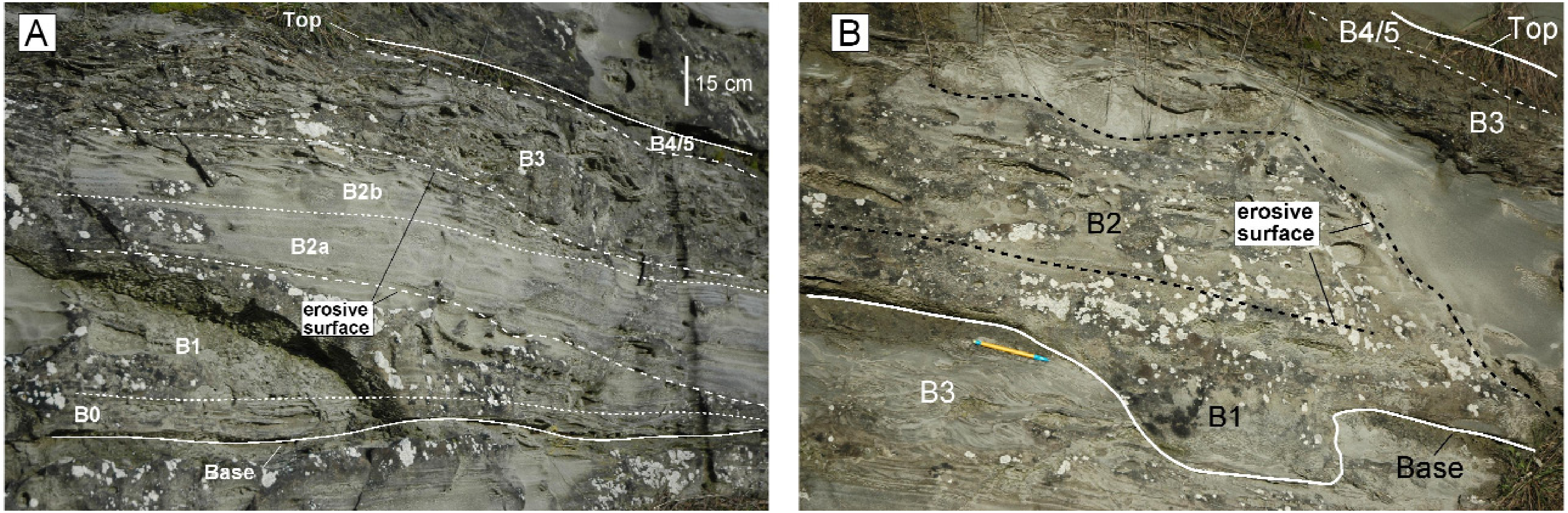


Fig. 55 - A and B) Beds in which the typical facies sequences of Type-B mixed system can be observed (see also Fig. 49). Note the well-developed erosive surfaces usually characterizing divisions B2 and B3 (see Figs. 49, 54 and Mutti et al., 2002b).

DOI: 10.3301/GFT.2012.03

Description: This outcrop shows various graded sandstone beds (Fig. 55), which exhibit the typical facies sequence illustrated in Figs. 49 and 54. These beds are essentially similar to those studied in the previous Stop 2.3 and, therefore, can be described and interpreted according to the same sequence of internal depositional divisions (see Fig. 54).

Stop 2.5: San Martino, Unit V deposits in an outer structural element

Stratigraphic unit: MAF transition between inner and outer stage, sequence S (Ricci Lucchi, 1986); Unit V (Muzzi Magalhaes & Tinterri, 2009).
Age: Serravallian.
Main feature to observe: sedimentary characteristics of basin plain turbidites in an outer structural element (Log G, see Figs. 34, 36); relation between paleocurrent variations in Log G and MTC depositions in Log B, i.e. in an inner structural element (see Fig. 56).
Main outcrop references: Muzzi Magalhaes, 2009; Muzzi Magalhaes & Tinterri (2010); Tinterri & Muzzi Magalhaes, 2009; 2011).

Description: Log G deposits belong to stratigraphic Unit V (see Figs. 34, 36) and are time equivalent to Firenzuola and Paretaio turbidite systems (see Fig. 34 and Stop 1.5). This Unit has been correlated between Logs B and G (see Fig. 56; see also Fig. 34 for the logs location).
In the inner Ridracoli structural element (included between M. Nero and M. Castellaccio thrusts in Figs. 5, 34), the thick massive beds in the more western proximal zone (Log B; Fig. 36D and L) pass down-current into very thin beds and mudstone deposits associated to the Verghereto marls (see Log F in Figs. 5, 36 and Stop 3.2). Conversely, in the outer structural elements (to the north of the Civitella thrust), in which Log G is located (Figs. 5, 34), the turbidity currents related to Unit V were not blocked, but were able to bypass the Verghereto structural high. This structural control is highlighted by the diffuse presence of Type-3 beds (Fig. 57). In particular, the analysis of the paleocurrents deriving from sole casts indicates transport directions mainly towards the east, which is likely due to the presence of a topographic high located in south-western zones with respect to the location of Log G, and related to the Civitella thrust front (Figs. 5 and 56C).

DOI: 10.3301/GFT.2012.03

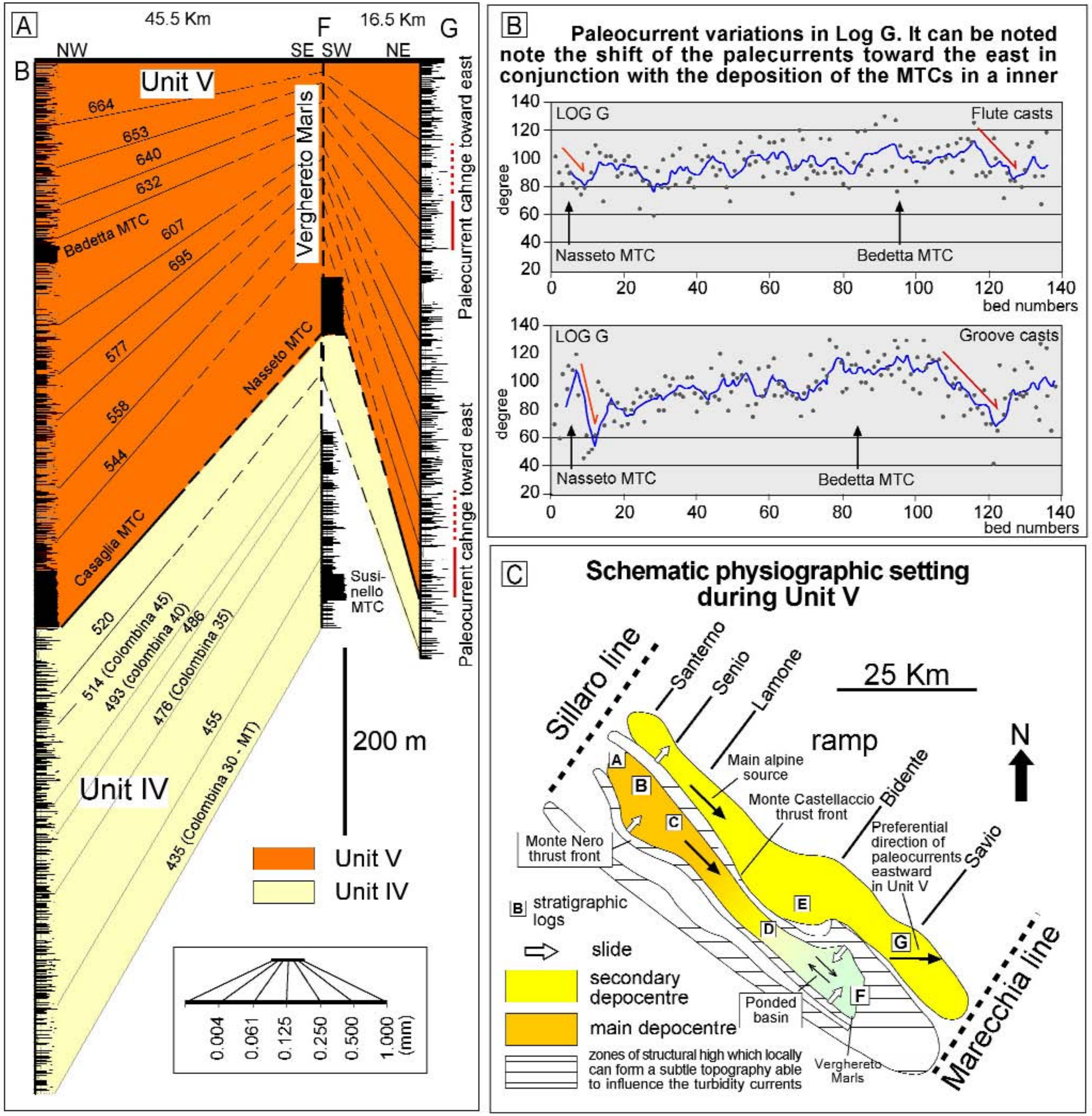


Fig. 56 - **A)** Stratigraphic cross-section concerning only the youngest portion of Logs B and G; it consists of the stratigraphic succession above bed 435 (Colombina 30 or MT Montellero key bed by Martelli et al., 1994) (from Muzzi Magalhaes & Tinterri, 2010). See figure 34 for the location of the logs; **B)** A diagram showing the paleocurrent variations in log G resulting from flute casts and groove casts. Please, note the evident change in paleocurrent directions (red arrows) at the time of the deposition of the Nasseto and Bedetta MTCs in log B, i.e. in a more internal structural element (see Fig. 34 for the location of the logs); C) Diagram illustrating the schematic physiographic setting of Unit V. The eastward-directed paleocurrents in log G during the deposition of Unit V are also indicated.

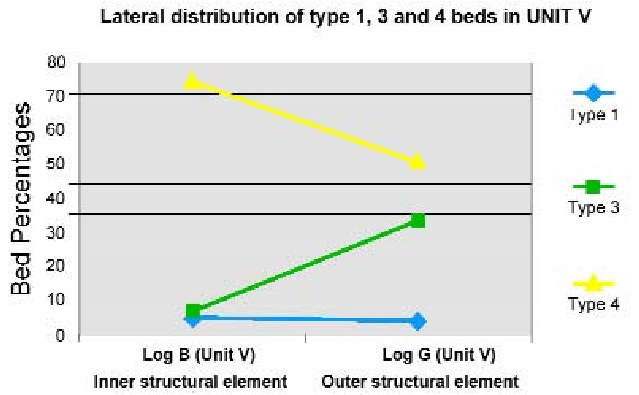


Fig. 57 - Downcurrent facies variation in Unit V.

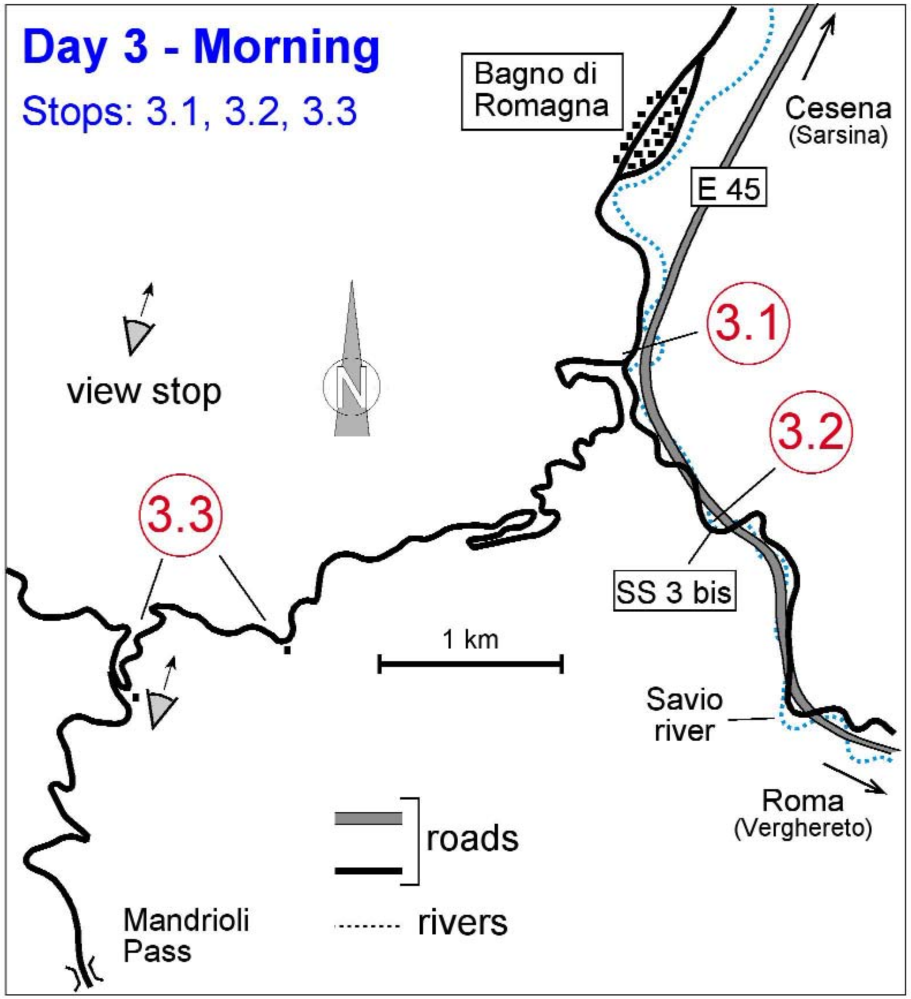
The deposition of the Nasseto and Bedetta MTCs in the internal Ridracoli structural element (Logs B, F) coincided with a change in the paleocurrent towards the east/northeast in Log G (i.e. in a more external structural element), as if in these periods there was an in-sequence thrust propagation of the fronts, both in internal (M. Nero and M. Castellaccio thrusts) and external zones (Civitella and S. Sofia thrusts). This phase of thrust propagation would have produced the Nasseto and Bedetta MTCs in the internal Ridracoli structural element (Log B), while in more external zones (Log G), it would have produced only a topographic high related to the Civitella or S. Sofia thrust fronts, which would have induced the paleocurrent deviation towards the east and northeast (see Figs. 56C and 34 for the exact location of Logs B and G and the thrust fronts). These data further reinforce the correlation between Log B (Senio Valley) and Log G (Savio Valley).

DOI: 10.3301/GFT.2012.03

DAY 3 (morning) – Savio Valley

Day 3 will be spent in the Savio Valley and we are going to observe the basinal turbidites of the basal part of Units I, II and IV (see Fig. 36). We are going to discuss some specific types of beds that are crucial to understand the morphology created by the tectonic uplift.

In the last Stop (3.4) we will discuss the facies of the structural high of the Verghereto area (see Figs. 34 and 36).



Stop 3.1: Io key bed

Stratigraphic unit: MAF inner stage, Sequence L (Ricci Lucchi, 1986), Unit I (Muzzi Magalhaes & Tinterri, 2010).
Age: Langhian.
Main features to observe: Io Key bed (base of Unit I);
Main outcrop references: Muzzi Magalhaes (2009); Muzzi Magalhaes & Tinterri (2010); Tinterri & Muzzi Magalhaes (2011).

Description: the Io key bed is the lowest basinwide stratigraphic marker of the stratigraphic succession studied (Fig. 58). It can be traced in a large part of the stratigraphic succession between the Santerno and Savio Valleys. It has a southern provenance and hybrid composition like the Contessa key bed (see Stop 1.4).

DOI: 10.3301/GFT.2012.03

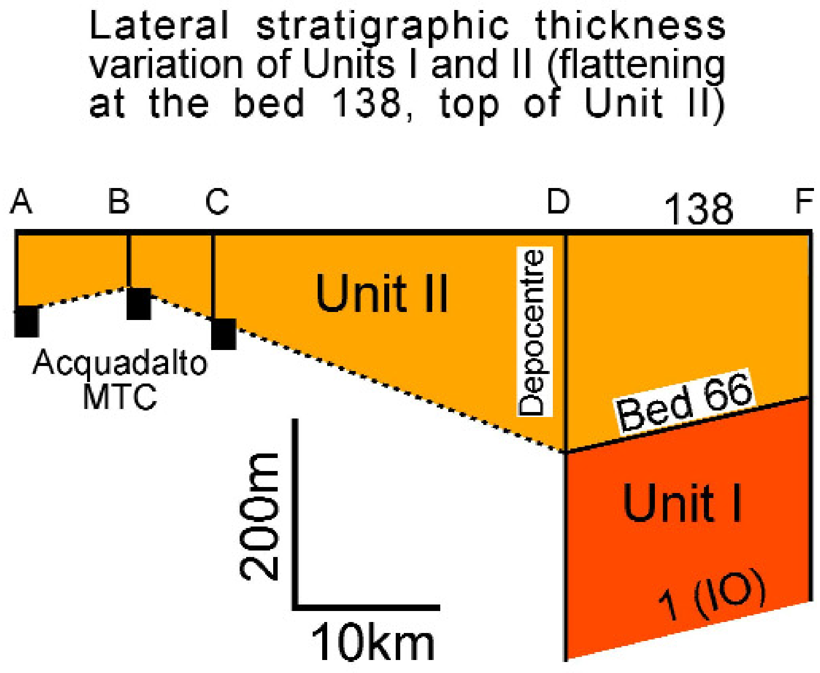


Fig. 58 - On the left, a simplified stratigraphic cross section showing the basal Units I and II (see Fig. 36). On the right , the Io key bed (Imolavilla key bed, by Martelli et al., 1994). The Io key bed is Bed 1 and represents the base of the entire stratigraphic succession studied (see Fig. 36).

Stop 3.2: Bed 66 (Type-2 bed indicating the base of Unit II)

Stratigraphic unit: inner stage, Sequence L (Ricci Lucchi, 1986), Units II (Muzzi Magalhaes & Tinterri, 2010).
Age: Langhian.
Main features to observe: bed 66 (Fig. 59B), i.e. a Type-2 bed indicating the base of Unit II; its relationship with Acquadalto MTC will be discussed (see Stop 1.2 and Fig. 36A, 40).
Main outcrop references: Muzzi Magalhaes (2009); Muzzi Magalhaes & Tinterri (2010); Tinterri & Muzzi Magalhaes (2011).

Description: Bed 66 marks the base of Unit II and is interpreted as related to the Acquadalto MTC (Figs. 40, 59A). The base of Unit II is characterized by a tectonic uplift able to generate the Acquadalto MTC to the north (Logs A, B and C) and a Type-2 bed (bed 66) to the south (Logs D, F) (see Stop 1.2 and Figs. 40, 59A). The correlation between the Acquadalto MTC, which does not outcrop in the southern zones, and bed 66 is supported by:

1) the nature of this bed type (see paragraph 3.1 and Figs. 7 and 60);

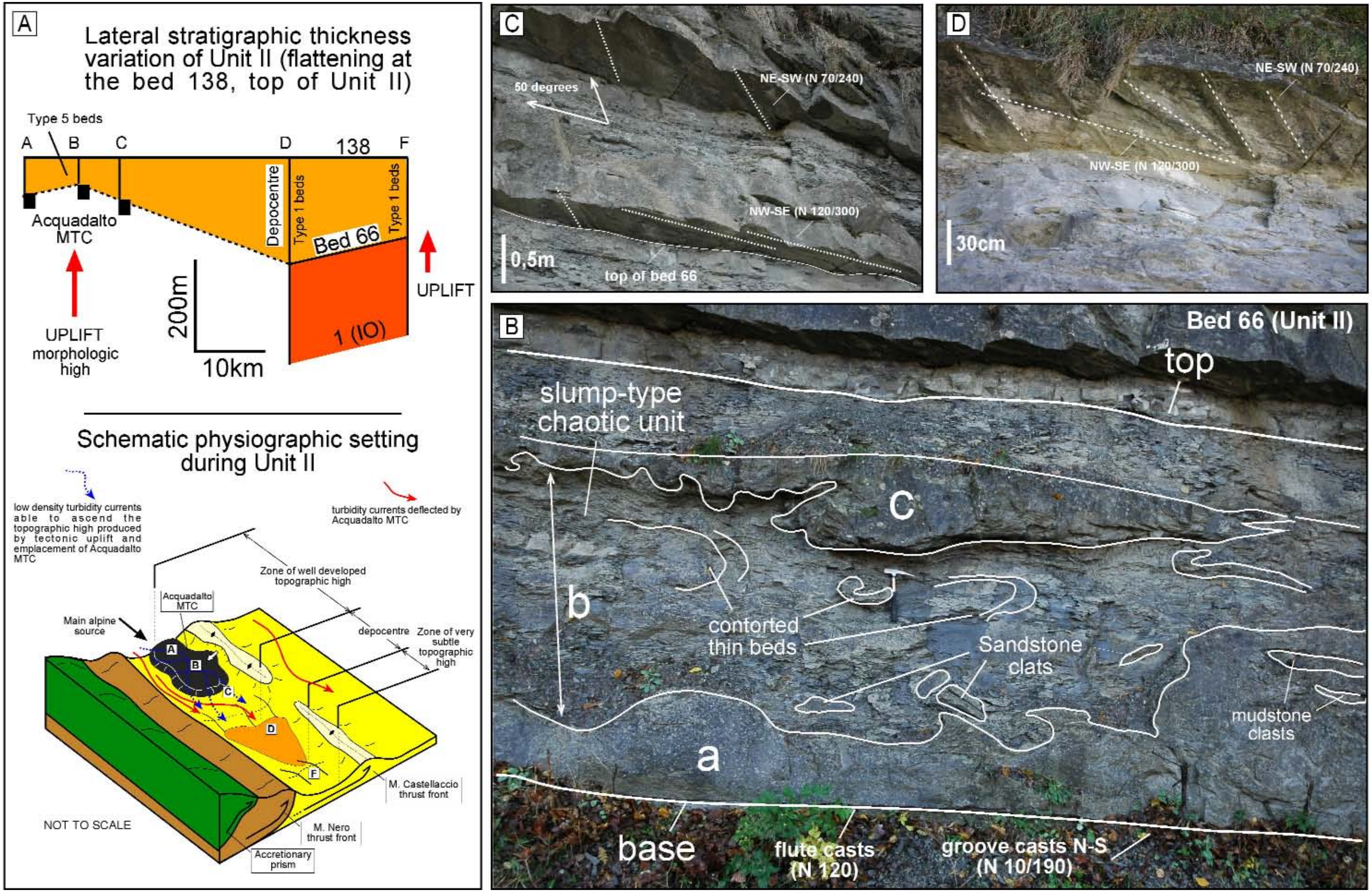
2) the presence, directly above bed 66, of beds showing clear paleocurrent changes (Fig. 59C, D);

3) a clear increase in the percentage of Type-1 beds above bed 66, which, in Log D, goes from 30% of Unit I to 40%. Therefore, the highest percentage of Type-1 beds, in all the stratigraphic succession studied, is in Log D and E of Unit II above bed 66 (Figs. 36D, E, F; see also Fig. 40B). This is interpreted as related to the presence of a synsedimentary high, located up-current (Acquadalto MTC), passing into more southern zones, through a slope change, in the depocenter of the Bidente Valley (Logs D and E). This physiographic setting had to be particularly favourable to the formation of these types of bed, by promoting erosive processes of mudstone deposits in the northern part, above and laterally the Acquadalto topographic high, as well as decelerations in the southern zones, due to the slope change (see also Stop 1.2 and Fig. 40);

4) the correlation between Logs D and F in Figs. 36A, 59A, which shows that Unit I thickness remains isopach, while Unit II shows an evident thickness decrease in Log F, which is interpreted as due to a first subtle uplift of the southern Verghereto area. This clearly shows the tectonic control above bed 66.

Fig. 59 - **A)** Simplified cross section and physiographic setting of Unit II (see also Stop 1.2); **B)** Detail illustrating bed 66 that shows the typical facies sequence of a Type-2 bed (this bed marks the base of Unit II in the south-eastern zones (log F) and is characterized by two types of sole casts indicating two different types of paleocurrents, i.e. groove casts indicate N-S direction while flute casts indicate paleocurrents toward the south-east; **C** and **D)** paleocurrent changes in the beds just above bed 66 (from Tinterri & Muzzi Magalhaes, 2011).

DOI: 10.3301/GFT.2012.03



DOI: 10.3301/GFT.2012.03

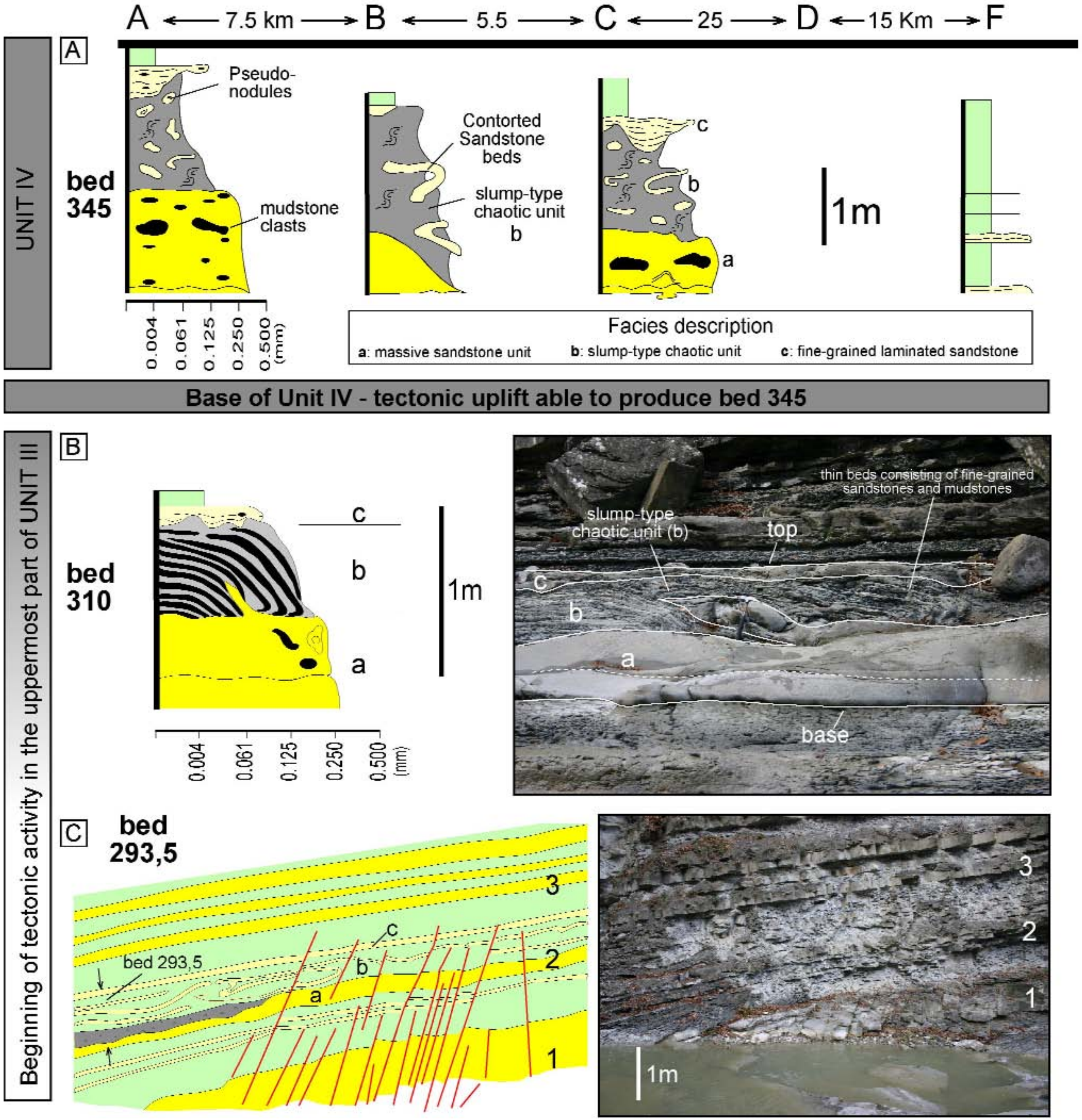


Fig. 60 - Diagrams showing different Type-2 beds around the basal boundary of Unit IV. These beds are similar to bed 66, which marks the base of Unit II (see Stop 3.2 and Fig. 59).
A) Diagram showing bed 345 facies tract, which marks the base of Unit IV (see Fig. 36 for the location of the logs). In particular, slump unit "b" is particularly well developed in log B, where high irregular and lenticular basal sandstone can be observed;
B and **C)** Type-2 beds in log A interpreted as resulting from the initial phases of structural uplift occurring in the upper part of Unit III (above the Colombina 5 key bed), which herald the tectonic uplift able to produce bed 345 illustrated in A. In particular, bed 310 can be traced laterally in metre-thick MTCs (see Fig. 36D), while in C a series of small synsedimentary faults can be observed, which are able to produce bed 293.5 interpreted as representing the initial phase of a Type-2 bed formation.

DOI: 10.3301/GFT.2012.03

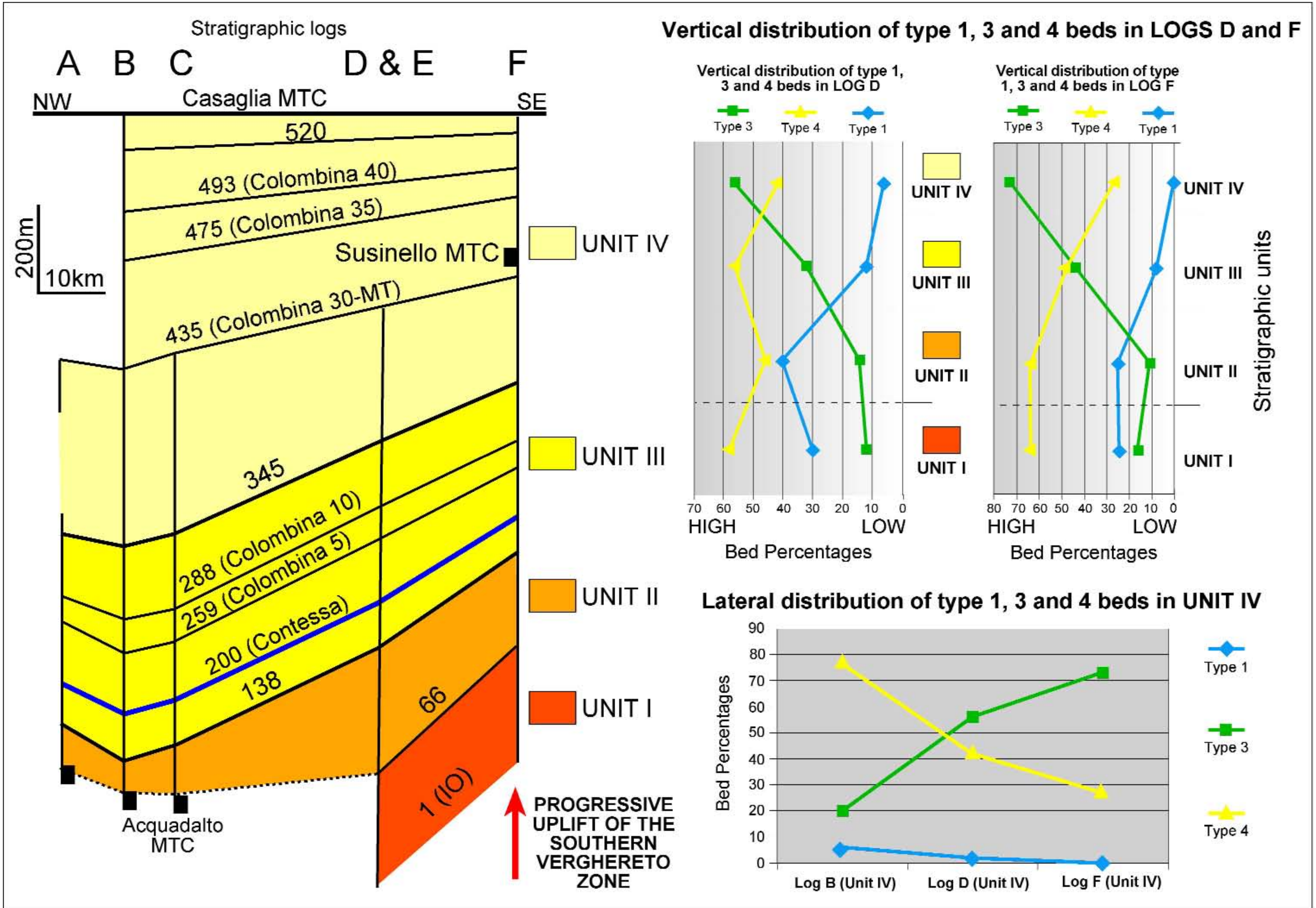
Stop 3.3: Ponded turbidites of Unit IV in the Mandrioli area

Stratigraphic unit: MAF inner stage, sequence S (Ricci Lucchi, 1986); Unit IV (Muzzi Magalhaes & Tinterri, 2010).
Age: Serravallian.
Main features to observe: ponded basin-plain turbidites (Figs. 63A and 63B) and MTCs in Mandrioli pass area (Log F in Figs. 34 and 36).
Main outcrop references: Ricci Lucchi (1981; 1986); Mutti et al. (2002b); Lucente (2004); Muzzi Magalhaes (2009); Muzzi Magalhaes & Tinterri (2010); Tinterri & Muzzi Magalhaes (2011).

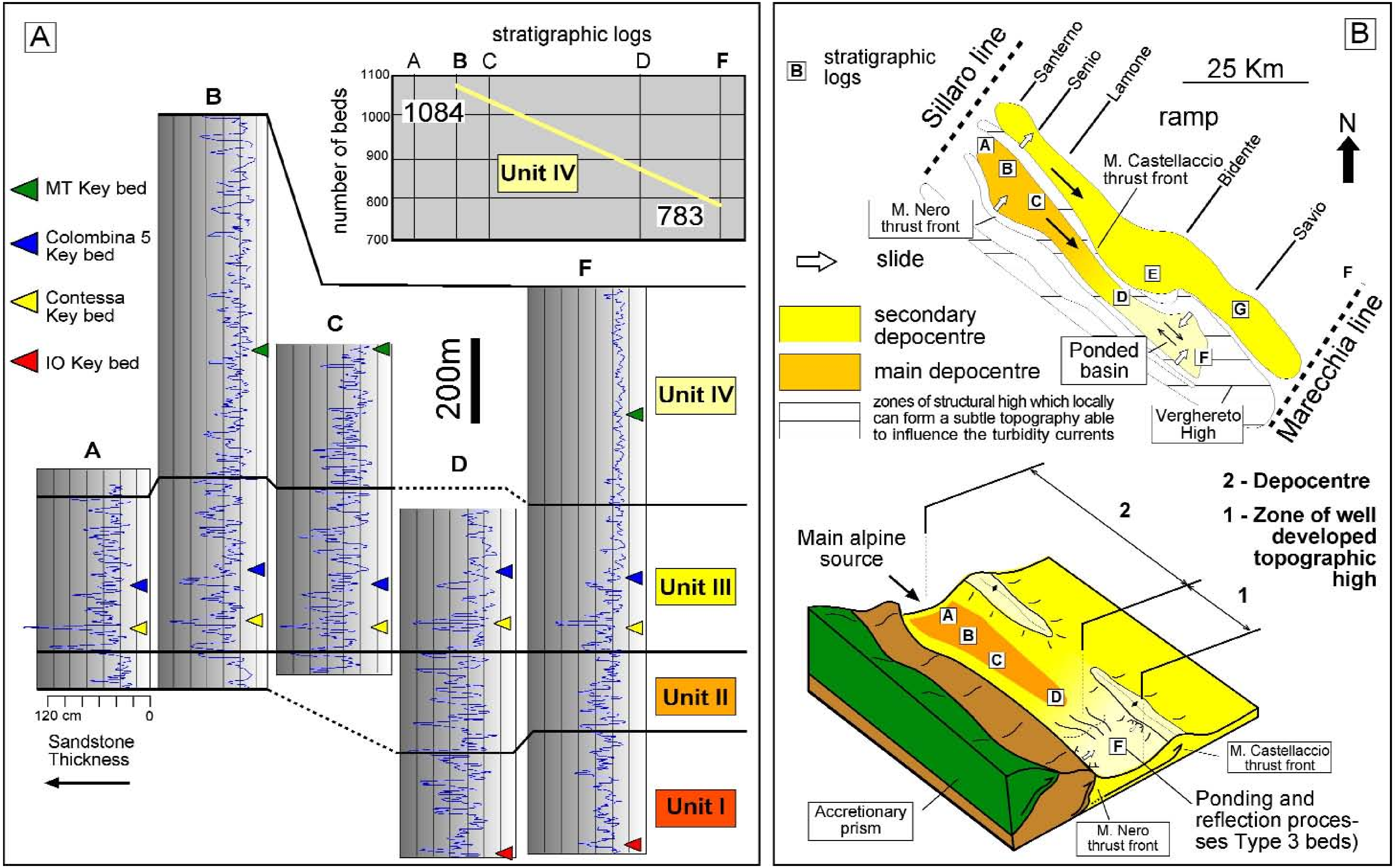
Description: In this area, we will observe the classic basin-plain turbidites (as meant by Mutti & Ricci Lucchi, 1972) in the distal zone of Unit IV (see Log F in Fig. 34 and 36). This Unit, included between bed 345 (a Type-2 bed, Fig. 60A) and the Casaglia/Nasseto MTC, has a thickness of about 800m in Log B and of 550m in Log F with a down-current thinning gradient of 5.5m/km, which is about nine times greater than that of Unit III (0.65m/km). At the boundary between Units III and IV, moreover, a change in sedimentation conditions is recorded by a drastic increase in Type-3 beds and a decrease in Type-4 and -1 beds (Fig. 61); in particular, within Unit IV, the percentage of Type-3 beds increases markedly in a down-current direction (Fig. 61). These evidences are related to the progressive uplifting of the basin's southern portion (Verghereto zone, see Figs. 5 and 34), which also led to the formation of the intraformational Susinello MTC and later on, the Nasseto MTC (Figs. 36D, 63). The beginning of this uplift was already evident in the upper part of Unit III (above bed 259, Colombina 5), where some Type-2 beds, such as bed 310 (Fig. 60) laterally related to metre-thick mass-transport units (see the black dashes in log C of Fig. 36D) and bed 293.5, can be observed (Fig. 60C). These bed types heralds bed 345 (the base of Unit IV) and further confirm the predictive nature of these bed types that are related to tectonic uplift (see section 3.1).

Fig. 61 - On the left, a simplified stratigraphic cross section showing the drastic thickness decrease in Unit IV towards the south-east (i.e. towards the Verghereto high, see Figs. 34 and 36 for the location of the logs). On the right, vertical distribution of Type-1, -3 and -4 beds in distal logs D and F is shown (the paleocurrents are directed towards SE). In these diagrams the progressive upward increase in Type-3 contained-reflected beds related to the progressive uplift of the Verghereto area can be observed. Similarly, the lateral distribution of Type-1, -3 and -4 beds within Unit IV highlights an evident increase in Type-3 beds towards the SE, i.e. towards the Verghereto high.

DOI: 10.3301/GFT.2012.03



DOI: 10.3301/GFT.2012.03



DOI: 10.3301/GFT.2012.03

Fig. 62 - **A)** Stratigraphic cross section where the logs are represented by thickness variations of the sandstone unit of the beds. Thickness variation is represented using the moving average method (from Muzzi Magalhaes, 2009; Tinterri & Muzzi Magalhaes, 2011). Please, note the progressive bed thinning in log F in the upper part of Unit III and in Unit IV, due to the uplift of the southern Verghereto area. In **B**, a diagram showing the lateral distribution of the number of beds in Unit IV between logs B and F. C) Diagram illustrating the schematic physiographic setting of Units IV. The slide provenance is taken from Lucente (2004).

The depositional setting of Unit IV, therefore, indicates that most of these beds formed in an elongate sub-basin aligned NW-SE and tapered toward the SE, due to the uplift of the Verghereto area (Fig. 62). The turbidity currents flowing toward the SE after having deposited most of their coarser sediment in the Santerno Valley (Log B) encountered the topographic obstacle of the Verghereto "high". This tectonically-controlled feature generated ponding, reflection and deflection processes, which allowed the deposition of turbidite beds with facies sequences very similar to those of the contained-reflected beds by Pickering & Hiscott (1985) and Remacha et al. (2005), (see Figs. 63A and 63B). Furthermore, the decrease in the number of beds (Fig. 62B) also testifies that only 72 % of the beds and, consequently, of the turbidity currents were able to ascend this southern structural high at the time of Unit IV.

DOI: 10.3301/GFT.2012.03

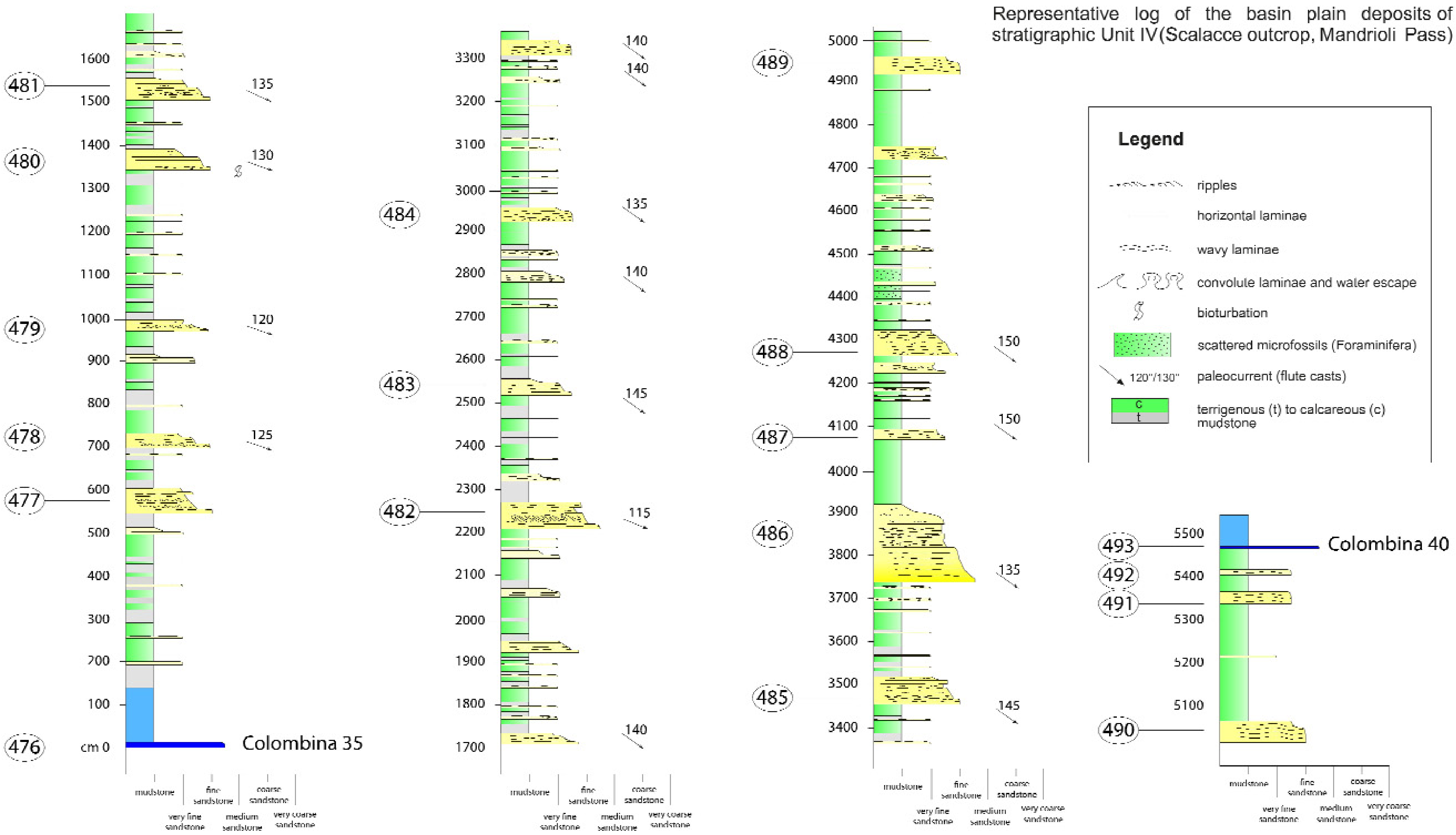


Fig. 63A - Representative log of the basin plain deposits of stratigraphic Unit IV in Log F (Savio Valley, Mandrioli Pass) (modified from Muzzi Magalhaes, 2009). The stratigraphic interval is included between two key beds: Colomina 35 and Colombina 40. See figures 61 and 62 for the location of the stratigraphic log F. The beds shown in figure 63B can be also observed.

DOI: 10.3301/GFT.2012.03

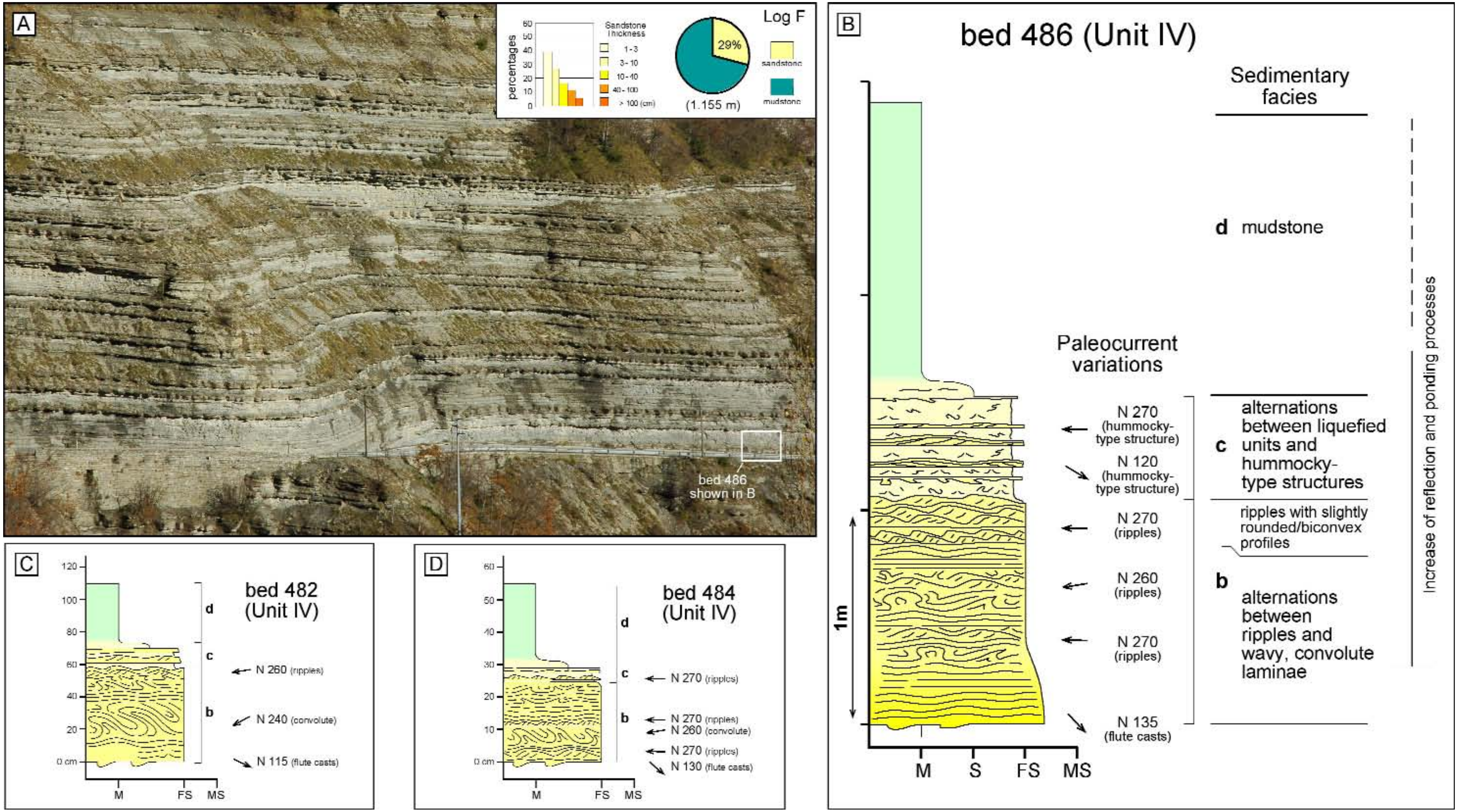
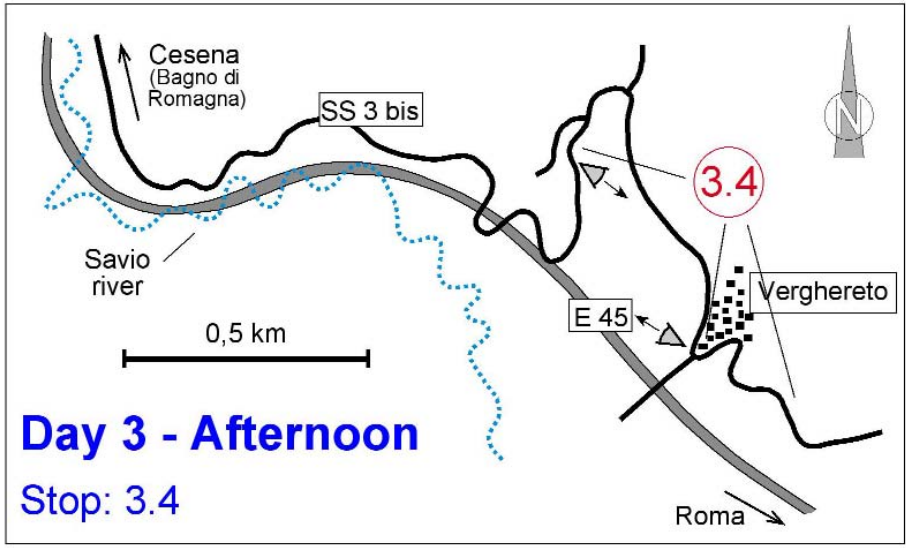


Fig. 63B - **A)** Overview of the Scalacce outcrop (Mandrioli Pass) showing the structurally-controlled basin plain deposits of Unit IV (log F, see Figs. 34, 36 and 63). In the square above, the net to gross and bed thickness distribution in log F are also shown; **B**, **C**, **D)** Examples of Type-3 beds characterized by clear paleocurrent variations (stratigraphic Unit IV, log F). These beds have the typical vertical facies sequence of contained-reflected (ponded) beds (the letters indicate the facies shown in Fig. 7). See figure 63A for the location of these beds.

DOI: 10.3301/GFT.2012.03

DAY 3 (afternoon) – Savio Valley

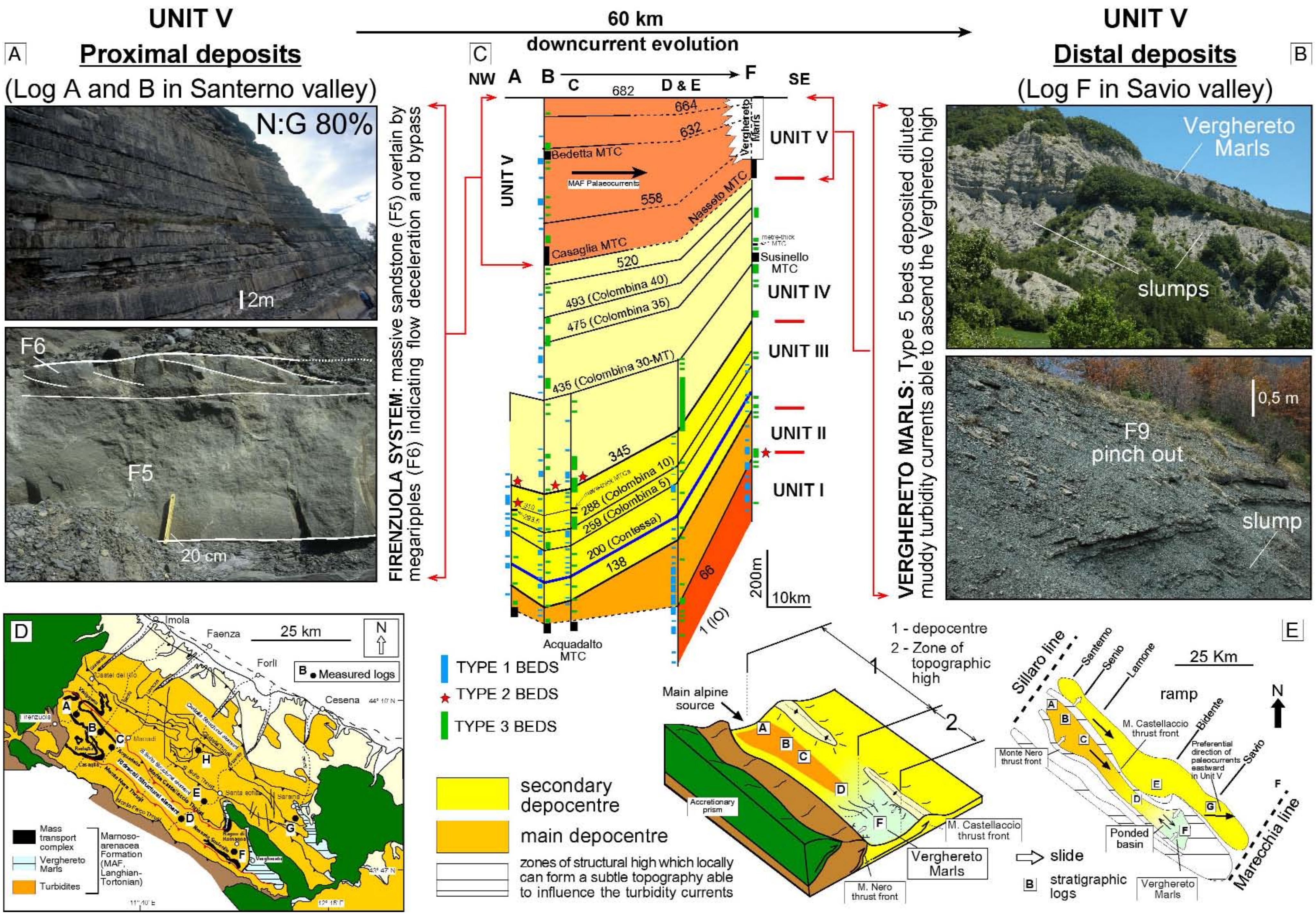
Stop 3.4: Verghereto



__Stratigraphic unit__: MAF inner and outer stage, sequences S and T (Ricci Lucchi, 1986); Unit V (Muzzi Magalhaes & Tinterri, 2010).
__Age__: Serravallian-Tortonian.
__Main features to observe__: Verghereto marls and MTCs (Figs. 34, 36).
__Main outcrop references__: Ricci Lucchi (1981; 1986); Mutti et al. (2002b); Lucente (2004); Bonini (2006); Muzzi Magalhaes (2009); Muzzi Magalhaes et al. (2008c); Muzzi Magalhaes & Tinterri (2010).

Description: Verghereto marls belong to stratigraphic Unit V (Figs. 36D, 64C) and consist mainly of hemipelagic, calcareous deposits and turbidite mudstones, in which very fine and thin laminated graded beds often showing pinch out geometries can be found; slump units are also very common (Fig. 64B). The basal boundary of this unit is marked by an evident tectonic phase, able to produce the Casaglia and Nasseto mass-transport complexes, which are here considered time-equivalent, as already suggested by Ricci Lucchi (1981, 1986) and Lucente & Pini (2002). In the internal structural element (included between M. Nero and M. Castellaccio thrusts, see Fig. 34) the thick beds in the more westerly proximal zone (Log B) characterised by a high sandstone/mudstone ratio (0.66) pass down-current into mudstone deposits of Verghereto marls (Fig. 64A, B, C). These marls (Early Serravallian-Late Tortonian in age; see also Amorosi, 1987; Martelli et al., 1994), were deposited above a structural high beginning from the Nasseto mass-transport complex, and they can be interpreted as related both to dilute turbidity currents, able to rise the topographic high and hemipelagic sedimentation. This structural and topographic high, which was already present during the deposition of Unit IV and, at least in part, during Unit III (see Figs. 36, 38), became particularly marked during Unit V. The deposition of the Verghereto marls substantiates its further uplift during the deposition of Unit V (Fig. 64C).

DOI: 10.3301/GFT.2012.03



DOI: 10.3301/GFT.2012.03

Fig. 64 - Down-current evolution of the facies of Unit V in the inner "Ridracoli" structural element included between M. Nero and M. Castellaccio thrust fronts (see geologic map in D). **A)** Tabular thick beds of the Firenzuola turbidite systems in the Santerno Valley, characterized by a net to gross of about 79% (see also Fig. 34). These strata are deposited in the innermost margin of the foredeep above the Casaglia MTC; below, an example of a sandstone bed characterizing the Firenzuola system. It consists of a massive to crude laminated coarse grained sandstone (F5) and an overlying well-sorted coarse grained sandstone reworked in megaripples (F6) (see also Fig. 26-B). These facies indicate strong deceleration and bypass processes related to the structural confinement that is typical of this stage. In the Ridracoli structural element, the deposits illustrated in A pass down-current into Verghereto marls, which are shown in **B**. In particular, the photographs illustrate a panoramic view of Verghereto marls in the type locality near the village of Verghereto (see map in D) and a detail showing pinch-out geometry of some fine grained beds (F9) and slump units. In **C**, a simplified stratigraphic cross section highlights as this down-current facies change in Unit V is related to the uplift of the southern Verghereto area (see map in **D** for the location of the logs). In **E**, a simplified diagram showing the physiographic setting of Unit V is also shown (compare to Stop 2.5).

Verghereto marls, however, are preserved, thanks to a large fault with a NW-SE direction and a dip slip of about 600m, inferred from the juxtaposition of the Colombina 5 key bed with the Nasseto mass-transport unit in the Verghereto area (Fig. 65; see also Muzzi Magalhaes et al., 2008b; Muzzi Magalhaes & Tinterri, 2010 and Bonini, 2006 for more details). This fault was probably active after the deposition of Verghereto marls, and, therefore, after the Tortonian, and was probably related to a complex structure associated to the Forlì alignment (as meant by Roveri et al., 2002; 2003), i.e. the structural alignment between Verghereto and Faenza in figure 5.

DOI: 10.3301/GFT.2012.03

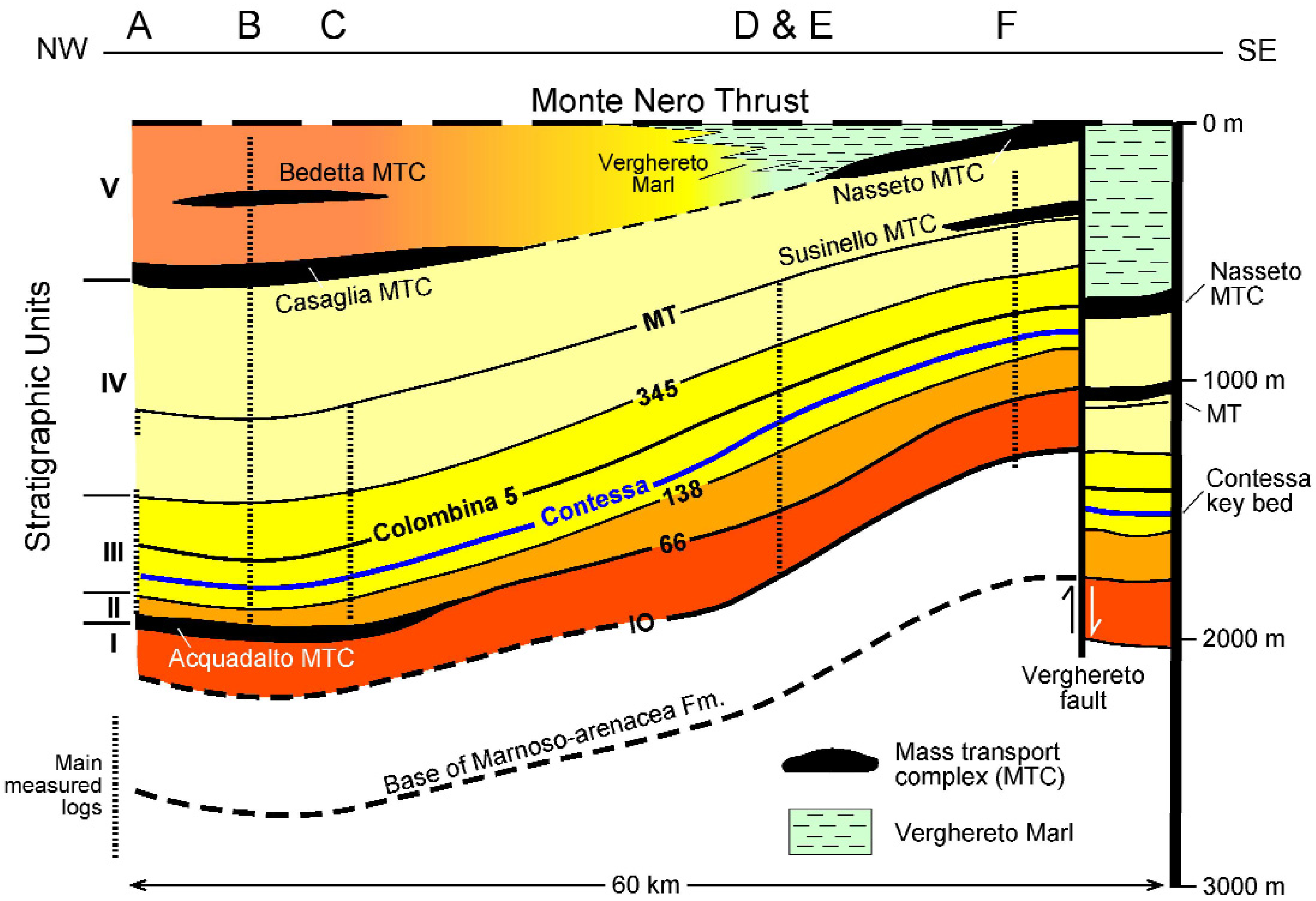


Fig. 65 - Simplified geological cross-section of the stratigraphic succession studied in the Ridracoli structural element located between the M. Nero and M. Castellaccio thrusts (see Fig. 64 D for the location of the logs) (from Muzzi Magalhaes et al., 2008c; Muzzi Magalhaes & Tinterri, 2010).

DOI: 10.3301/GFT.2012.03

memorandum

DOI: 10.3301/GFT.2012.03

References

Allen P.A. & Homewood P.N. (1986) - Foreland basins. IAS Special Publication, 8, Oxford: Blackwell Scientific, 453pp.

Amorosi A. (1987) - Analisi delle relazioni stratigrafiche tra la “Marnoso-arenacea” e le “Marne di Verghereto” nella sinclinale di San Piero in Bagno (Appennino Forlivese). Giorn. Geol., 49/2, 103-110.

Amy L.A. & Talling P.J. (2006) - Anatomy of turbidites and linked debrites based on long distance (120 x 30 km) bed correlation, Marnoso-arenacea Formation, Northern Apennines, Italy. Sedimentology, 53, 161-212.

Amy L.A., Talling P.J., Peakall J., Wynn R.B. & Arzola Thynne R.G. (2005a) - Bed geometry used to test recognition criteria of turbidites and (sandy) debrites. Sedimentary Geology, 179,163–174.

Amy L.A., Peakall J. & Talling P.J. (2005b) - Density and viscosity-stratified gravity currents: insights from laboratory experiments and implications for submarine flow deposits. Sedimentary Geology, 179, 5–29.

Argnani A. & Ricci Lucchi F. (2001) - Tertiary silicoclastic turbidite systems of the Northern Apennines. In: Anatomy of an orogen: the Apennines and adjacent Mediterranean basins (Eds., Vai G.B. & Martini I.P.,), Kluwer Academic Publishers, Dordrecht-Boston-London, 327-350.

Artoni A., Di Biase D., Mutti E. & Tinterri R. (2000) - Control of thrust propagation on turbidite sedimentation. EAGE Conference on Geology and Petroleum Geology of the Mediterranean and Circum-Mediterranean Basins: Malta, October, Extended Abstracts Book, C21.

Baas J.H., Best J.L., Peakall J. & Wang M. (2009) – A phase diagram for turbolent, transitional and laminar clay suspension flows. Jour. Sed. Res., 79, 162-183.

Baas J.H., Best J.L. & Peakall J. (2011) – Depositional processes, bedform development and hybrid bed formation in rapidly decelerated cohesive (mud-sand) sediment flows. Sedimentology, in press.

Benini A., Farabegoli E. & Martelli L. (1991) - Stratigrafia e paleogeografia del Gruppo di S. Sofia (alto Appennino Forlivese). Memorie Descrittive della Carta Geologica d’Italia, 46, 231-243.

Bonini M. (2006) - Detachment folding – related Miocene submarine slope instability in the Romagna Apennines (Italy). J. Geophys. Res. 111, B01404, 12pp.

Capozzi R., Landuzzi A., Negri A. & Vai G.B. (1991) - Stili deformativi ed evoluzione tettonica della successione Neogenica Romagnola. Studi Geologici Camerti, 1, 261-278.

Cattaneo A. & Ricci Lucchi F. (1995) - Long distance correlation of sandy turbidites: a 2,5 Km long cross section of Marnoso arenacea, Santerno Valley, Northern Apennines. In: Atlas of deep water environments: architectural style in turbidite systems (Eds. K.T. Pickering, R.N. Hiscott, N.H. Kenyon, F. Ricci Lucchi & R.D.A. Smith). Chapman & Hall, 303-306.

Cerrina Feroni A., Martelli L., Martelli P. & Ottria G. (2002) - Structural-geologic map of Emilia Romagna Apennines, 1:250.000. Regione Emilia Romagna e Consiglio Nazionale delle Ricerche (CNR), SELCA Firenze.

Chan M.A. & Dott R.J. (1983) - Shelf and deep-sea sedimentation in Eocene forearc basin, western Oregon – Fan or non-fan? AAPG Bulletin, 67, 2100-2116.

DOI: 10.3301/GFT.2012.03

Conti S. (2001) - Gli intervalli pelitici della Formazione Marnoso-arenacea del Mugello (Miocene medio): relazioni fra tettonica, fluidi freddi e instabilità sedimentaria. Boll. Soc. Geol. It., 120, 125-138.

Covey M. (1986) - The evolution of foreland basins to steady state: evidence from the western Taiwan foreland basin. In P. A. Allen, & P. Homewood (Eds.), Foreland Basins. IAS Special Publication 8, Oxford: Blackwell Scientific, pp. 77–90.

De Donatis M. & Mazzoli S. (1994) - Kinematic evolution of thrust-related structures in the Umbro-Romagnolo Parautochthon (Northern Apennines, Italy). Terra Nova, 6, 563-574.

de Jager J. (1979) - The relation between tectonics and sedimentation along the “Sillaro line” (northern Apennines, Italy). Geologica Ultraiectina, 19, 97pp.

di Biase D. & Mutti E. (2002) - The “proto adriatic basin”. In: Revisiting turbidites of the Marnoso-arenacea Formation and their basin-margin equivalents: problems with classic models (Eds E. Mutti, F. Ricci Lucchi & M. Roveri), Excursion Guidebook, Università di Parma and Eni-Agip Division, 64th EAGE Conference & Exhibition, Florence (Italy), 120pp.

Edwards D.A., Leeder M.R., Best J.L. & Pantin H.M. (1994) - On experimental reflected density currents and the interpretation of certain turbidites. Sedimentology, 41, 437-461.

Gandolfi G., Paganelli L. & Zuffa G.G. (1983) - Petrology and Dispersal Pattern (Miocene, Northern Apennines). J. Sed. Petrol., 53, 493-507.

Haughton P., Baker S. & McCaffrey W. (2003) - Linked debrites in sand-turbidite systems – origin and significance. Sedimentology, 50, 459–482.

Haughton P., Davis C., McCaffrey W. & Barker S. (2009) - Hybrid sediment gravity flow deposits – Classification, origin and significance. Marine and Petroleum Geology, 26, 1900–1918.

Heller P. & Dickinson W.R. (1985) - Submarine ramp facies model for delta-fed, sand-rich turbidite systems. AAPG Bulletin, 69, 960-976.

Hiscott R.N. (1994) - Loss of capacity, not competence, as the fundamental process governing deposition from turbidity currents. Journal of Sedimentary Research, 64, 209-214.

Kneller B.C. (1995) - Beyond the turbidite paradigm: physical models for deposition and their implications for reservoir prediction. In: Characterization of Deep Marine Clastic Systems (Eds. A.J. Hartlet & D.J Prosser). Geol. Soc. London, Spec. Publ., 94, 31-49.

Kneller B.C. & McCaffrey W.D. (2003) - The interpretation of vertical sequences in turbidite beds: the influence of longitudinal flow structure. Journal of Sedimentary Research, 73, 706-713.

Kuenen Ph.H. & Migliorini C.I. (1950) - Turbidity currents as a cause of graded bedding. Journ. Geol., 58, 91-127, Chicago.

Landuzzi A. (1994) - Relationships between the Marnoso-arenacea Formation of the inner Romagna units and the Ligurids (Italy). Mem. Soc. Geol. It., 48, 523-534.

Lowe D.R. (1982) - Sediment gravity flows; Depositional models with special reference to the deposits of high-density turbidity currents. Jour. Sed. Petr., 52, 279-297.

Lucente C.C. (2004) - Topography and paleogeographic evolution of a middle Miocene foredeep basin plain (Northern Apennines, Italy). Sed. Geol., 170, 107-134.

DOI: 10.3301/GFT.2012.03

Lucente C.C. & Pini G.A. (2002) - Mechanisms of emplacement and significance of chaotic bodies embedded in turbidite successions of the northern Apennines. In: Revisiting turbidites of the Marnoso-arenacea Formation and their basin-margin equivalents: problems with classic models (Eds. E. Mutti, F. Ricci Lucchi & M. Roveri), Excursion Guidebook, Università di Parma and Eni-Agip Division, 64th EAGE Conference & Exhibition, Florence (Italy), 120 pp.

Lucente C.C. & Pini G.A. (2003) - Anatomy and emplacement mechanism of a large submarine slide within a Miocene foredeep in the northern Apennines, Italy: a field perspective. Am. J. Sci., 303, 565-602.

Marr J.G., Harff P.A., Shanmugam G. & Parker G. (2001) - Experiments on subaqueous sandy gravity flows: the role of clay and water content in flow dynamics and depositional structures. Geological Society of America Bulletin, 113, 1377-1386.

Martelli L., Farabegoli E., Benini A., De Donatis M., Severi P., Pizziolo M. & Pignone R. (1994) - La geologia del Foglio 265 – S. Piero in Bagno, in: La cartografia Geologica della Emilia Romagna. Servizio Cartografico e Geologico, Regione Emilia Romagna, Bologna.

Migliorini C.I. (1943) - Sul modo di formazione dei complessi tipo macigno. Boll. Soc. Geol. It., 62, 48-49.

Mulder T., Syvitski J.P.M., Migeon S., Faugeres J.C. & Savoye B. (2003) - Marine hyperpycnal flows: initiation, behaviour and related deposits. A review. Marine and Petroleum Geology, 20, 861-882.

Mutti E., (1992) - Turbidite Sandstones. San Donato Milanese, Agip-Istituto di Geologia, Università di Parma, 275 pp.

Mutti E. & Nilsen T.H. (1981) - Significance of intraformational rip-up clasts in deep-sea fan deposits. International Association of Sedimentologists, 2nd European Regional Meeting, 117-119.

Mutti E. & Normark W.R. (1987) - Comparing examples of modern and ancient turbidite systems: Problems and Concepts. In: J.K. Legget & G.G. Zuffa (Eds.), Marine Clastic Sedimentology: Concepts and Case Studies (pp. 1-38). London: Graham and Trotman.

Mutti E. & Normark W. R. (1991) - An integrated approach to the study of turbidite systems. In: Weimer P. & Link H. (Eds.), Seismic Facies and Sedimentary Processes of Submarine Fans and Turbidite Systems, pp. 75-106, Ann Arbor.

Mutti E. & Ricci Lucchi F. (1972) - Le torbiditi dell'Appennino settentrionale: introduzione all'analsi di facies. Mem. Soc. Geol. It., 11, 161-199.

Mutti E., Nilsen T.H. & Ricci Lucchi F. (1978) - Outer fan depositional lobes of the Laga Formation (Upper Miocene and Lower Pliocene), East-Central Italy. In: Sedimentation in submarine canyons, fans and trenches (Eds. D.L. Stanley & G. Kelling.), Dowen Hutchinson & Ross, 201-223.

Mutti E., Ricci Lucchi F. & Roveri M. (2002a) - Revisiting turbidites of the Marnoso-arenacea Formation and their basin-margin equivalents: problems with classic models. Excursion Guidebook, Workshop organized by Dipartimento di Scienze della Terra (Università di Parma) and Eni-Divisione Agip, 64th EAGE Conference & Exhibition, Florence (Italy), May 27-30, 120 pp.

Mutti E., Tinterri R., Benevelli G. & Cavanna G. (2002b) - Stop description: facies analysis. In: Revisiting turbidites of the Marnoso-arenacea Formation and their basin-margin equivalents: problems with classic models (Eds. Mutti, E., Ricci Lucchi, F. & Roveri, M.), Excursion Guidebook, Workshop organized by Dipartimento di Scienze della Terra (Università di Parma) and Eni-Divisione Agip, 64th EAGE Conference & Exhibition, Florence (Italy), May 27-30, 120 pp.

Mutti E., Tinterri R., Benevelli G., di Biase D. & Cavanna G. (2003) - Deltaic, mixed and turbidite sedimentation of ancient foreland basins. Mar. Petrol. Geol., 20, 733-755.

Mutti E., Tinterri R., Muzzi Magalhaes P. & Basta G. (2007) - Deep-Water Turbidites and Their Equally Important Shallower Water Cousins. American Association of Petroleum Geologists (AAPG) Annual Convention, April, 2-4, 2007, Long Beach (CA), Abstract CD, 4 p.

Mutti E., Tinterri R., Remacha E., Mavilla N., Angella S. & Fava L. (1999) - An introduction to the analysis of ancient turbidite basins from an outcrop perspective. AAPG Course Notes 39, 93 pp.

Muzzi Magalhaes P. (2009) - Stratigrafia fisica ed analisi di facies della Formazione Marnoso-arenacea affiorante fra le valli del Santerno e del Savio (Langhiano-Serravaliano, Appennino settentrionale, Italia). Ph.D. Thesis, Università di Parma, Italy, 186 pp.

Muzzi Magalhaes P. & Tinterri R. (2009) - Facies analysis on the Langhian to Serravallian turbidite deposits of the Marnoso-arenacea Formation (northern Apennines, Italy). AAPG Annual Convention, June, 7-10, 2009, Denver (Co), Abstract CD, 6 p.

Muzzi Magalhaes P. & Tinterri R. (2010) - Stratigraphy and Depositional Setting of Slurry and Contained (Reflected) Beds in the Marnoso-arenacea Formation (Langhian-Serravallian) Northern Apennines, Italy. Sedimentology, 57, 1685-1720.

Muzzi Magalhaes P., Tinterri R., Guerreiro J.P.B.C., Oliveira Filho J.S. & Basta G. (2008a) - High-resolution stratigraphy of the Langhian to Serravallian portion of the Marnoso-arenacea Formation (northern Apennines, Italy). Proceedings Annual Meeting, Italian Association of Sedimentary Geology GEOSED, Bari, september 25-26, 2008, 86-90 (download: http://www.geosed.it/index.php).

Muzzi Magalhaes P., Tinterri R., Guerreiro J.P.B.C., Oliveira Filho J.S. & Basta G. (2008b) - Sedimentology of the Langhian to Serravallian turbidite deposits of the Marnoso-arenacea Formation (northern Apennines, Italy). Proceedings Annual Meeting, Italian Association of Sedimentary Geology GEOSED, Bari, september 25-26, 2008, 82-85 (download: http://www.geosed.it/index.php).

Muzzi Magalhaes P., Tinterri R., Guerreiro J.P.B.C., Oliveira Filho J.S. & Basta G. (2008c) - New preliminary data about the Verghereto Marls (Serravallian-Tortonian, Marnoso-arenacea Formation, northern Apennines, Italy). Proceedings Annual Meeting, Italian Association of Sedimentary Geology GEOSED, Bari, september 25-26, 2008, 91-93 (download: http://www.geosed.it/index.php).

Ori G.G., Roveri M. & Vannoni F. (1986) - Plio-Pleistocene sedimentation in the Apenninic-Adriatic foredeep (Central Adriatic Sea, Italy). In: Foreland Basins (Eds. Allen P.A. & Homewood P.), IAS Spec. Publ., 8, 183–198. Blackwell Scientific, Oxford.

Parker G. (1982) - Condition for the ignition of catastrophically erosive turbidite currents. Mar. Geol., 46, 307-327, Amsterdam.

Pickering K.T. & Hiscott R.N. (1985) - Contained (reflected) turbidity from the Middle Ordovician Cloridorme Formation, Quebec, Canada: an alternative to the antidune hypothesis. Sedimentology, 32, 373-394.

Remacha E. & Fernández L.P. (2003) - High-resolution correlation patterns in the turbidite system of the Hecho Group (South-Central Pyrenees, Spain). Mar. Petrol. Geol., 20, 711-726.

Remacha E., Fernández L.P. & Maestro E. (2005) - The transition between sheet-like lobe and basin plain turbidites in the Hecho basin (south-central Pyrenees, Spain). J. Sed. Res., 75, 789-819.

Ricci Lucchi F. (1969) - Recherches stratonomiques et sédimentologiques sur le Flysch Miocène de la Romagna (Formation Marnoso-arenacea). Proc. IV Sess. Comm. Medit. Neog. Strat., Giorn. Geol. (2), 36 (4), 163-198.

Ricci Lucchi F. (1975) - Miocene paleogeography and basin analysis in the Periadriatic Apennines. In: Geology of Italy (Ed. C. Souyres), Vol.2. P.E.S.L. Castelfranco Veneto-Tripoli (1977), 129-236.

DOI: 10.3301/GFT.2012.03

Ricci Lucchi F. (1978) - Turbidite dispersal in a Miocene deep-sea plain. Geol. Mijnbouw, 57, 559-576.

Ricci Lucchi F. (1980) - Processi e meccanismi di sedimentazione. Sedimentologia, Volume 2, CLUEB Bologna, 212 pp.

Ricci Lucchi F. (1981) - The Marnoso arenacea turbidites, Romagna and Umbria Apennines. In: Excursion guidebook, with contribution on sedimentology of some italian basins (Ed. F. Ricci Lucchi), 2nd IAS Eur. Meeting, Bologna, 229-303.

Ricci Lucchi F. (1986) - The Oligocene to recent foreland basins of the Northern Apennines. In: Foreland Basins (Eds. Allen P.A. & Homewood P.), IAS Spec. Publ. 8, 105-139, Oxford, Blackwell Scientific.

Ricci Lucchi F. & Ori G.G. (1985) - Field Excursion D: syn-orogenic deposits of a migrating basin system in the NW Adriatic Foreland: examples from Emilia Romagna region, Northern Apennines. In: International Symposium on Foreland Basins (Eds. Allen P.A., Homewood P. & Williams G.), Excursion Guidebook, 137-176.

Ricci Lucchi F. & Pialli G. (1973) - Apporti secondari nella Marnoso-arenacea; 1. Torbiditi di conoide e di pianura sottomarina a Est-Nordest di Perugia. Boll. Soc. Geol. It., 92, 669-712.

Ricci Lucchi F. & Pignone R. (1979) - Ricostruzione geometrica parziale di un lobo di conoide sottomarina. Mem. Soc. Geol. It., 18, 125-133.

Ricci Lucchi F. & Valmori E. (1980) - Basin-wide turbidites in Miocene, over-supplied deep-sea plain: a geometrical analysis. Sedimentology, 27, 241-270.

Roveri M., Manzi V., Ricci Lucchi F. & Rogledi S. (2003) - Sedimentary and tectonic evolution of the Vena del Gesso basin (northern Apennines, Italy): Implications for the onset of the Messinian salinity crisis. Bull. Geol. Soc. Am., 115, 387-405.

Roveri M., Ricci Lucchi F., Lucente C.C., Manzi V. & Mutti E. (2002) - Stratigraphy, facies and basin fill history of the Marnoso-arenacea Formation. In: Revisiting turbidites of the Marnoso-arenacea Formation and their basin-margin equivalents: problems with classic models (Eds. E. Mutti, F. Ricci Lucchi & M. Roveri). Excursion Guidebook, Università di Parma and Eni-Agip Division, 64th EAGE Conference and Exhibition, Florence (Italy), 120 pp.

Sumner E.J., Talling P.J. & Amy L.A. (2009) - Deposits of flows transitional between turbidity current and debris flow. Geology, 37, 991-994.

Sylvester Z. & Lowe D.R. (2004) - Textural trends in turbidites and slurry beds from the Oligocene flysch of the East Carpathians, Romania. Sedimentology, 51, 945-972.

Talling P.J., Amy L.A. & Wynn R.B. (2007) - New insight into the evolution of large-volume turbidity currents: comparison of turbidite shape and previous modelling results. Sedimentology, 54, 737-769.

Talling P.J., Amy L.A., Wynn R.B., Peakall J. & Robinson M. (2004) - Beds comprising debris sandwiched within co-genetic turbidite: origin and widespread occurrence in distal depositional environments. Sedimentology, 51, 163-194.

Tinterri R. (2006) - Proposal for a classification scheme for combined flow sedimentary structures and the meaning of sigmoidal- and hummocky-cross stratification in facies analysis. Proceedings Annual Meeting, Italian Sedimentology Group GEOSED, Modena 26-27 september 2006, 111pp.

Tinterri R. (2007) - The Lower Eocene Roda Sandstone (South-Central Pyrenees): an Example of a Flood-Dominated River-Delta System in a Tectonically Controlled Basin. Rivista Italiana di Paleontologia e Stratigrafia, 113, 223-255.

DOI: 10.3301/GFT.2012.03

Tinterri R. (2011) - Combined flow sedimentary structures and the genetic link between sigmoidal and hummocky-cross stratification. GeoActa, 10, 43-85.

Tinterri R. & Muzzi Magalhaes P. (2009) - Types of facies tract indicating synsedimentary-structural control: an example from Miocene Marnoso-arenacea Formation, Northern Apennines, Italy. In: Stratigraphic Evolution of Deep-Water Architecture: Examples on controls and depositional styles from the Magallanes Basin, Chile (Eds. Fildani A., Hubbard S. & Romans B.), SEPM Field Conference, february 22-28, 2009, Puerto Natales, Chile, abstract book, p.60.

Tinterri R. & Muzzi Magalhaes P. (2011) - Synsedimentary structural control on foredeep turbidites: an example from Miocene Marnoso-arenacea Formation, Northern Apennines, Italy. Marine and Petroleum Geology, 28, 629-657.

Tinterri R., Drago M., Consonni A., Davoli G. & Mutti E. (2003) - Modelling subaqueous bipartite sediment gravity flows on the basis of outcrop constraints: first results. Marine and Petroleum Geology, 20, 911-933.

Tinterri R., Tagliaferri A. et al. (in prep.) - The syntectonic Paretaio turbidite unit of the Marnoso-arenacea Formation (MAF) (Late Serravallian, Northern Apennines, Italy): transition from high to low efficiency turbidites due to the closure of the MAF inner basin.

Van Vliet A. (1978) - Early Tertiary deepwater fans of Guipuzcoa, Northern Spain. In: Sedimentation in submarine canyons, fans and trenches (Eds. D.J. Stanley & G. Kelling). Dowden, Hutchinson & Ross, Strausbourg, 190-209.

DOI: 10.3301/GFT.2012.03