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SEDIMENTATION AND BASIN-FILL HISTORY OF THE PLIOCENE SUCCESSION EXPOSED IN THE NORTHERN SIENA-RADICOFANI BASIN (TUSCANY, ITALY): A SEQUENCE-STRATIGRAPHIC APPROACH

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Key words: Sequence-stratigraphy; Siena Basin; paralic deposits; Northern Apennines; intermontane basin.

Abstract. Basin-margin paralic deposits are sensitive indicators of relative sea-level changes and typically show complex stratigraphic architectures that only a facies-based sequence-stratigraphic approach, supported by detailed biostratigraphic data, can help unravel, thus providing constraints for the tectono-stratigraphic reconstructions of ancient basins. This paper presents a detailed facies analysis of Pliocene strata exposed in a marginal key-area of the northern Siena-Radicofani Basin (Tuscany, Italy), which is used as a ground for a new sequence-stratigraphic scheme of the studied area. The study reveals a more complex sedimentary history than that inferred from the recent geological maps produced as part of the Regional Cartographic Project (CARG), which are based on lithostratigraphic principles. Specifically, four sequences (S1 to S4, in upward stratigraphic order) have been recognised, each bounded by erosional unconformities and deposited within the Zanclean-early Gelasian time span. Each sequence typically comprises fluvial to open marine facies, with deposits of different sequences that show striking lithological similarities.The architecture and internal variability shown by the studied depositional sequences are typical of low-accommodation basin-margin settings, that shows: i) a poorly-developed to missing record of the falling-stage systems tract; ii) a lowstand system tract predominantly made of fluvio-deltaic deposits; iii) a highstand system tract with substantial thickness variation between different sequences due to erosional processes associated with the overlying unconformity; iv) a highly variable transgressive system tract, ranging from elementary to parasequential organization.

INTRODUCTION

Sequence stratigraphy has proven to be an effective tool for the genetic understanding of sedimentary successions and stratigraphic predictions in both hydrocarbons exploration and exploitation (Flint et al. 1998; Posamentier & Allen 1999; Hampson et al. 2004; Catuneanu 2006). Thus, the application of modern sequence-stratigraphic concepts is crucial to provide insights into the tectono-stratigraphic history of basin-margin low-accommodation paralic deposits, where even minor sea-level fluctuations result in significant facies shifts and where hinterland conditions (e.g. climate, tectonics) govern the sediment supply (cf. Catuneanu 2006; Catuneanu et al. 2009; Helland-Hansen 2009). However, sequence stratigraphy of paralic deposits may sometimes be difficult to apply as these deposits typically contain lower rank surfaces originated by autocyclic processes that can be difficult to distinguish from allocyclic (i.e. sequence-stratigraphic) surfaces (e.g. flooding vs. deactivation surfaces in deltaic setting - see Martini et al. 2017). Additionally, low-accommodation paralic successions may lack some systems tracts, while some others can be of reduced thickness, thus bringing stratigraphic complexity and possible interpretation problems particularly where the successions are characterized by poor lithological variability.

In this framework, the northern margin of the Pliocene Siena-Radicofani Basin (Tuscany, Italy) represents an excellent natural laboratory to test facies-based sequence-stratigraphic principles on a basin-margin low-accommodation paralic succession with poor lithological variability (Costantini et al. 1982; Lazzarotto et al. 2005a, b) and detailed biostratigraphic data (Martini et al. 2011). The succession has been recently mapped according to lithostratigraphic principles as part of Regional Cartographic Project (CARG) and was previously

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interpreted as a single transgressive-regressive cycle (Costantini et al. 1982).

The main objectives of this paper are: i) to determine the sequence stratigraphy and geological history of the investigated deposits through facies-based identification of key stratigraphic-surfaces with their nature, rank and areal extension assessed by outcrop-based analysis of stratal terminations and field mapping; ii) to provide a case study where the issues regarding the adoption of sequence stratigraphy in marginal settings are addressed and solved thanks to a solid facies-based approach; and iii) to contribute to the understanding of the architectural variability of low-accommodation successions.

GEOLOGICAL SETTING

The intermontane basins of the Northern Apennines

The Siena-Radicofani Basin is one of the Neogene-Quaternary intermontane basins of the Northern Apennines (Fig. 1A), a Tertiary fold-and-thrust belt resulted from the interaction between the Adria and Corsica–Sardinian microplates, in the framework of the larger-scale collision of Africa with Eurasia (Carmignani et al. 2001 and references therein). These basins developed in the westernmost sector of the Northern Apennines since the early-middle Miocene as NW- to NNW-elongated (up to 200 km long) and relatively narrow (up to 25 km wide) morpho-structural depressions, crossed transversally by NNW-SSE-oriented tectonic lineaments (Pascucci et al. 2007 and references therein).

The tectonic setting responsible for the formation and evolution of these basins is still a matter of debate. Traditionally, they have been interpreted as grabens and half-grabens related to an extensional regime which was active since the late Miocene in the inner Northern Apennines (Jolivet et al. 1988; Carmignani & Kligfield 1990; Martini & Sagri 1993; Pascucci et al. 1999, 2006, 2007; Carmignani et al. 2001). However, contractional structures locally present within the sedimentary infill of some of the basins (Pertusati et al. 1978; Plesi & Cerrina Feroni 1979) have also been interpreted by some authors (Bernini et al. 1990; Boccaletti et al. 1991) as evidence of compressional pulses related to the activity of thrust fronts which occasionally interrupt the overall extensional setting. The subsequent use of both structural data (Boccaletti et al. 1995; Bonini & Moratti 1995; Landi et al. 1995) and geophysical studies (Ponziani et al. 1995) resulted in a new paradigm for the Tuscan post-collisional basins. A compressional tectonic activity was then suggested to be responsible for their structural development, with extensional features representing second-order structures accommodating main thrusts activity. In this view, these basins were considered as thrust-top basins within a polyphase compressive regime acting until the Quaternary age (Boccaletti & Sani 1998; Bonini 1999; Finetti et al. 2001; Bonini & Sani 2002). Recently, some of these basins have been re-interpreted in the context of extensional tectonics as hanging-wall basins related to the lateral segmentation of competent levels of substratum and the collapse of overlying, less competent, levels (Brogi & Liotta 2008; Brogi 2011).

The Siena-Radicofani Basin

The Siena-Radicofani Basin (Fig. 1B) is a tectonic depression extending for more than 70 km in a NW-SE direction (Fig. 1A). Although past works referred to the Siena and Radicofani basins separately, recent studies (Brogi 2011; Brogi et al. 2014) have highlighted a common structural evolution, with tectonic features extending from one basin to the other. This configuration supports the notion of a single basin, that also includes a minor depression (i.e. the Casino Basin of Lazzarotto & Sandrelli 1977) located in the northernmost part of the Siena-Radicofani trough, ca. 10 km NW of Siena (Fig. 1A). Accordingly, the Siena-Radicofani Basin is intended here to consist of three elements (from South to North): i) Radicofani sub-Basin; ii) Siena sub-Basin and iii) Casino sub-Basin.

The Siena-Radicofani Basin has traditionally been considered an extensional basin, either a half graben with an eastern master fault (Costantini et al. 1982; Collettini et al. 2006), or a hanging-wall basin (Brogi 2011; Brogi et al. 2014). A thrust-top basin interpretation was also proposed (Bonini & Sani 2002).

The basin infill has been previously subdivided (Bonini & Sani 2002) into 4 unconformity-bounded stratigraphic units (UBSU *sensu* Salvador 1984; SU1 to SU4, from the oldest). Units SU1

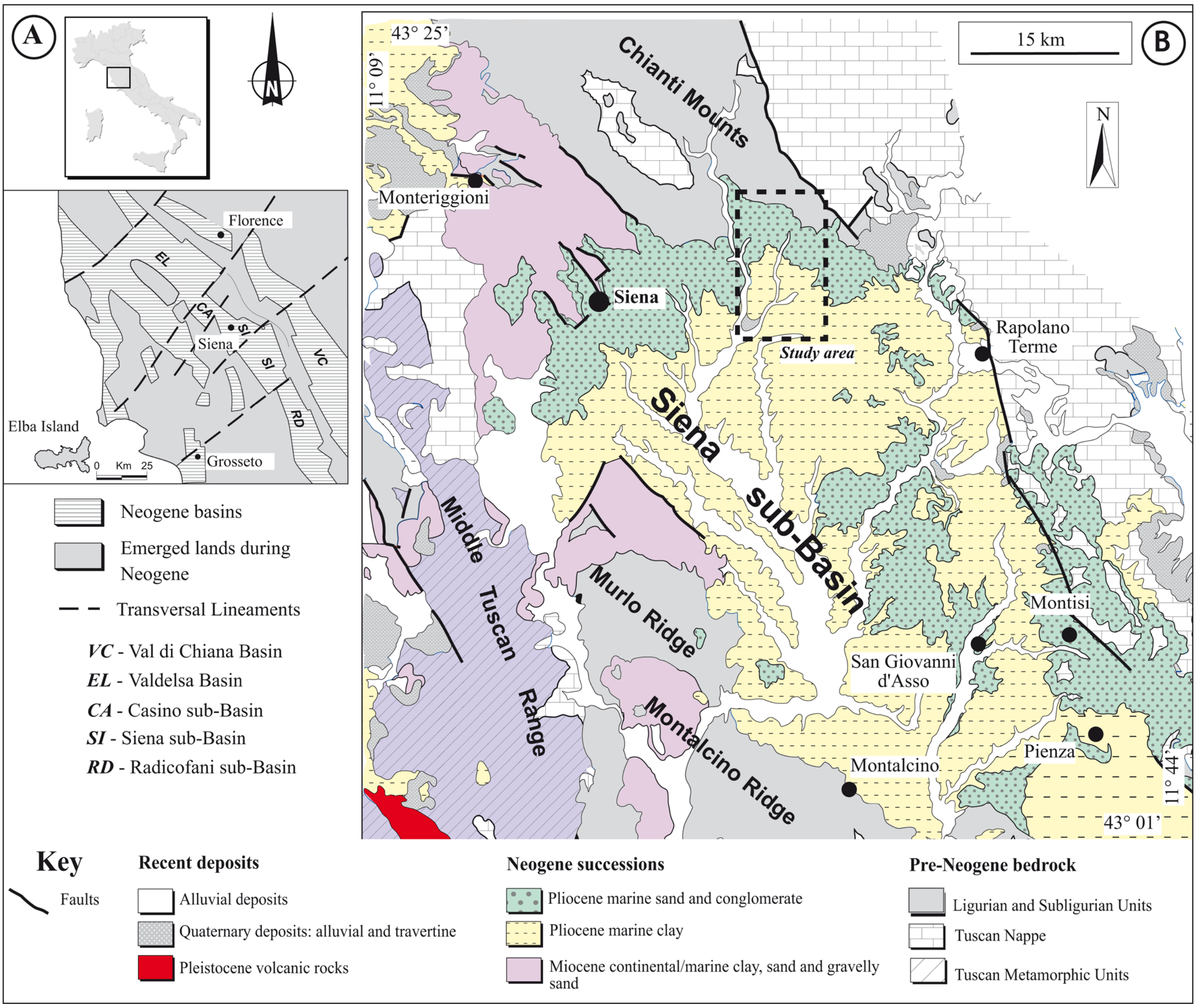


Fig. 1 - A) Simplified tectonic sketch of the Northern Apennines. B) Geological map of the Siena Basin (after Brogi 2014).

consist of late Serravallian, continental to shallow-marine sandstones and conglomerates (Ponsano sandstone: Foresi et al. 2003 and references therein). This unit crops out in a small sector of the Casino sub-Basin and is documented in the subsurface of the Radicofani sub-Basin (Liotta 1994). Unit SU2 is largely exposed in the Casino sub-Basin and consists of late Tortonian–Messinian, lacustrine lignite-bearing mud and sand with subordinate limestones and Bythinia-bearing marls, locally comprising fluvio-deltaic conglomerates (Lazzarotto & Sandrelli 1977). In the Siena sub-Basin, this unit is documented only in the subsurface of its western sector (Bonini & Sani 2002; Brogi 2011). Unit SU3 crops out discontinuously in the western margin of the Siena sub-Basin, where it unconformably overlies pre-Neogene bedrock units (Bonini & Sani 2002; Costantini et al. 2009; Brogi 2011). It is comprised of fluvio-deltaic conglomerates interbedded with, and passing to, lacustrine mud locally containing lignite and marl intercalations (Lazzarotto & Sandrelli 1977). Unit SU4, which is the focus of this study, is extensively exposed in the Siena sub-Basin, where it unconformably overlies unit SU3 and the basin bedrock. Previous studies on SU4 mainly focused on lithostratigraphic (Fig. 2) and biostratigraphic features (Costantini et al. 1982; Bossio et al. 1992, 1993; Costantini et al. 2009), whereas it has been investigated following modern sedimentological and sequence-stratigraphic concepts only during the last years (Martini et al. 2011, 2013, 2016, 2017; Arragoni et al. 2012; Brogi et al. 2014, Martini & Sandrelli 2015).

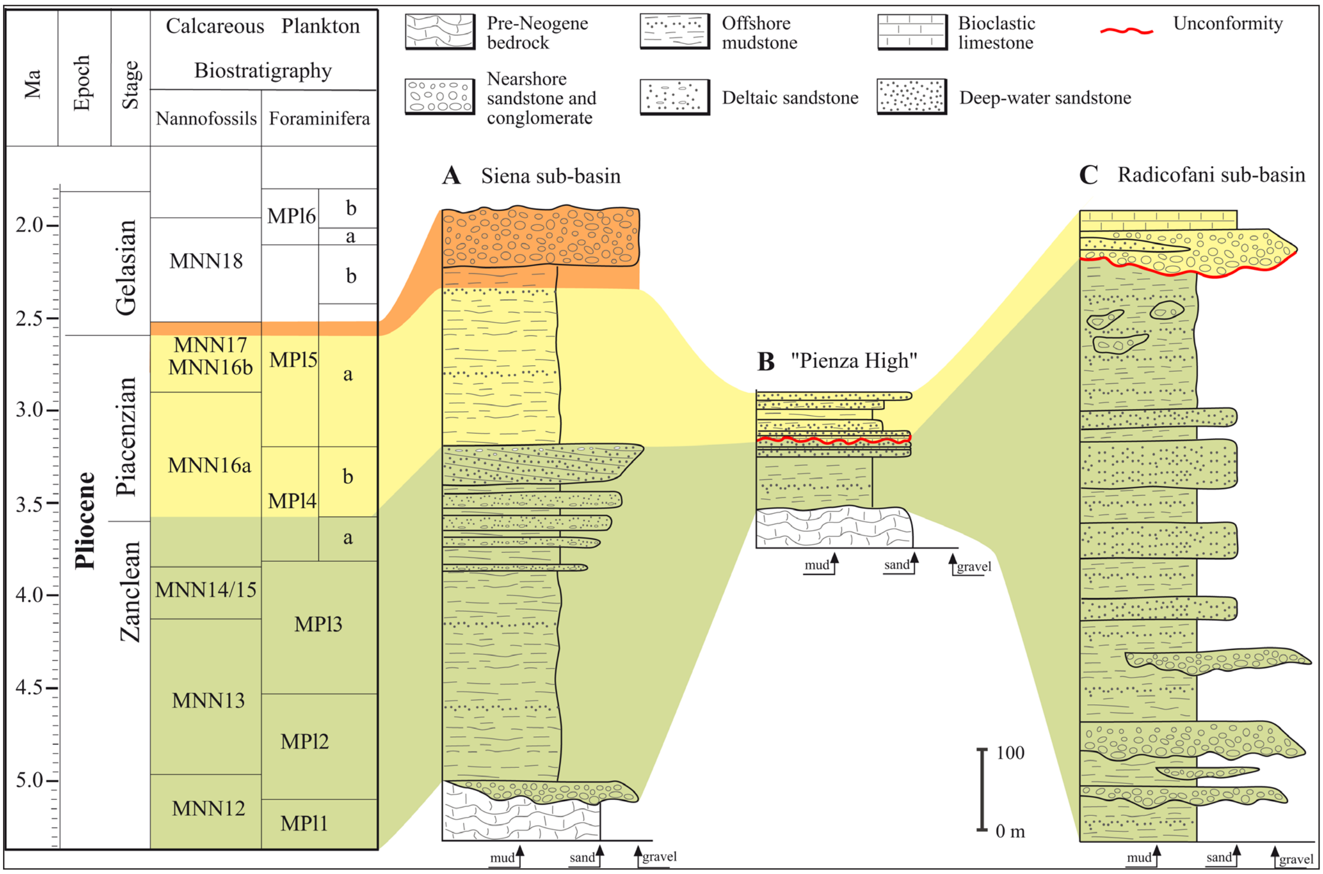


Fig. 2 - Simplified stratigraphic columns of the Pliocene succession of the Siena-Radicofani Basin [data are: i) for the Siena sub-basin derived from Bossio et al. 1992, 1993; Gandin & Sandrelli 1992; Riforgiato et al. 2005; Martini & Sandrelli 2015; Martini et al. 2016; ii) for the Radicofani sub-basin from Liotta & Salvatorini 1994].

Unit SU4 is up to 600 m thick (Bonini & Sani 2002; Brogi 2011) and consists of Zanclean-early Gelasian marine deposits (Fig. 2) with subordinate alluvial sediments. The unit starts with fluvial sandy conglomerates and floodplain organic-rich silty clays grading upward to offshore silty clays (Bossio et al. 1992). These are in turn overlain by regressive shallow-marine sand and conglomerates (Fig. 2). Following a regional uplift, the basin emerged in the latest Piacenzian-early Gelasian (Martini et al. 2016) and was later dissected by fluvial networks. The evolution of such fluvial networks (Aldinucci et al. 2007; Bianchi et al. 2013; Iacoviello & Martini 2013) and renewed faulting along the eastern basin margin (Bianchi et al 2015a, b) promoted the localised deposition of alluvial sands and gravels (Unit SU5), which rest unconformably on both Pliocene strata and pre-Neogene bedrock.

Within the studied area (which extends for more than 45 km^2 along the northern margin of the Siena sub-Basin, see Figs. 1B and 3), the deposits of unit SU4 onlap the Chianti Mounts, a morpho-structural pre-Neogene bedrock feature that separates the Siena sub-Basin from the early Piacenzian continental Upper Valdarno Basin (Fidolini et al. 2013 and references therein). The Chianti Mounts were the source area for the sediments accumulated in the northern sector of the Siena-Radicofani Basin.

Previous stratigraphic work on this area comprises 1:10.000 lithostratigraphic maps prepared as part of the Regional Geological Mapping projects (Lazzarotto et al. 2005a, b) and one 1:10.000 allostratigraphic map (Martini et al. 2011). Other papers dealing with fossiliferous sites provide local sedimentological and stratigraphic data (Manganelli et al. 2007, 2010, 2011). The Neogene-Quaternary deposits exposed in the studied area include, from base to top (Aldinucci et al. 2007; Martini et al. 2011): 1) Zanclean/early Gelasian alluvial-to-offshore marine deposits (the focus of this study); 2) Pleistocene terraced alluvial deposits; and 3) Holocene alluvial and colluvial sediments.

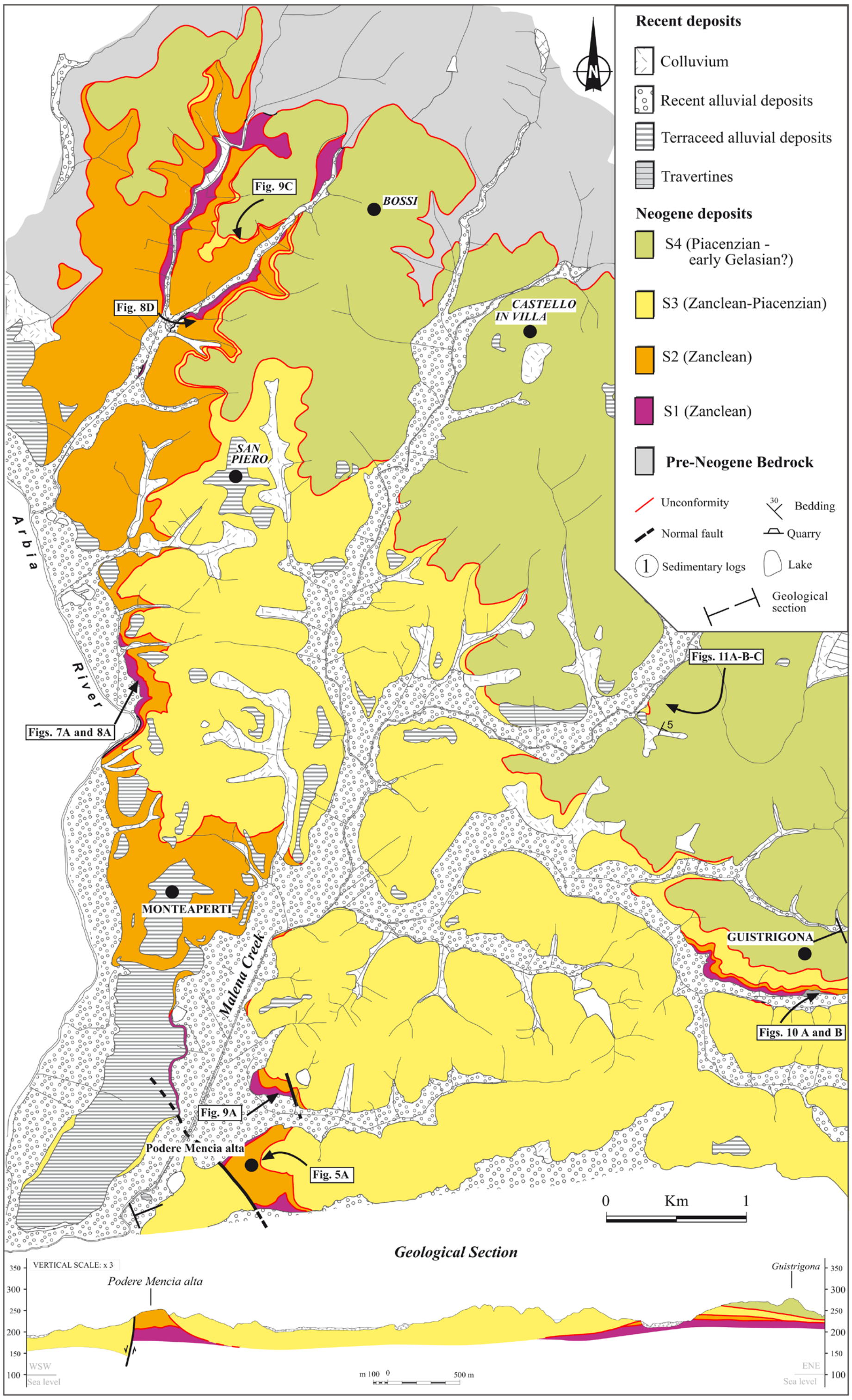


Fig. 3 - A) Synthetic geological map of the investigated area showing the distribution of sedimentary facies associations and depositional sequences. B) Geological cross section across the investigated area.

METHODS AND TERMINOLOGY

The present study was carried out using modern facies analysis and sequence stratigraphic principles. Fifteen sedimentary facies (hereafter facies) were recognised by the analysis of logged stratigraphic sections and subsequently grouped into six facies associations. A facies association is considered here as an assemblage of spatially and genetically related facies appertaining to a specific sedimentary environment (Walker & James 1992). The descriptive sedimentological terminology used herein is in accordance with Collinson et al. (2006) and Harms et al. (1982).

The analysis of the stratigraphic architecture is based on field correlation of key stratal surfaces, which are represented by basin-wide erosional surfaces manifested by truncations, with or without facies shift across them. Key-stratal surfaces, firstly identified in photo-mosaics and measured logs, were traced/walked out in the field in order to correlate them across the whole area and accurately describe the architecture of the basin-fill succession. Photo-mosaics were taken of the most significant cliff-face exposures in order to map out stratal key surfaces and large-scale architectural elements. Selected sections were logged at the centimetre scale and the resulting data were coupled to the corresponding photo-mosaics.

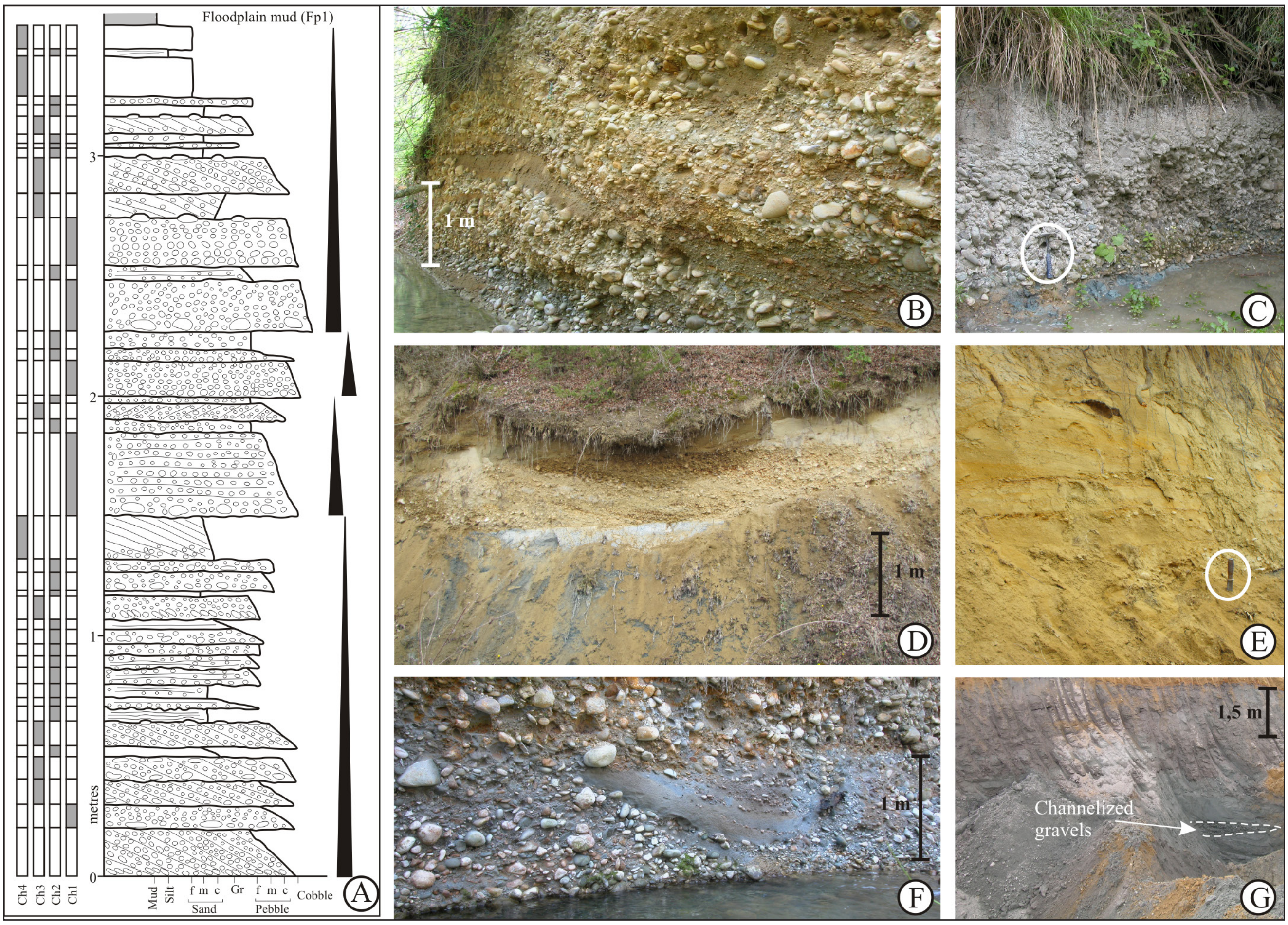


Fig. 4 - A) Sedimentary log of fluvial channel-fill deposits. Note the overall upward-finning trend, with the occurrence of upward-coarsening gravel packages, expression of longitudinal-bars deposits (Facies Ch2). Floodplain muds occur at the top of the gravelly channel-fill deposits. B) Outcrop expression of the lower part of the sedimentary log in A. C-D) Close-up view of the sharp boundaries between coarse-grained channel fill deposits and the underlying floodplain muds. E) Close-up view of sandy sediments of Facies Ch3. F) Trough-cross stratified pebbly sand, representing Facies Ch4. G) Lenticular and erosionally-based gravels (Facies Fp2) encased in fine sediments of Facies Fp1. Such facies association typify floodplain deposits.

In this paper, the four-fold system tract scheme by Hunt and Tucker (1992) is adopted for the sequence stratigraphic interpreation of the analysed succession. Chronostratigraphic data for the different sequences are after Martini et al. (2011, 2016).

FACIES ANALYSIS AND SEDIMENTARY ENVIRONMENTS

Facies associations, defined through sedimentological analysis, were grouped in three broader classes of deposits. Each class is representative of large-scale depositional environments, such as alluvial (facies associations CH and FP) and coastal marine settings, the latter including both deltaic (facies association SD) and non-deltaic (facies associations SP, ND and OF) deposits.

Individual facies associations are described and interpreted below. A synthesis of their features is reported in Table 1.

Facies association CH: fluvial channel deposits

This facies association consists of <3 m thick, erosionally based sandy gravel lithosomes (Fig. 4A) typically characterized by a fining upward trend. It comprises four facies, namely Ch1, Ch2, Ch3 and Ch4.

Facies Ch1 occurs at the base of CH lithosomes as <25 cm thick beds of massive to crudely plane-parallel stratified gravel (Fig. 4A) locally grading to massive and/or plane-parallel laminated coarse-grained sand. Gravel is clast-supported and pebble- to cobble-sized with occasional imbricated b(i)a(t) and a(i)a(p) fabric of the blade-shaped clasts. Coalified wood fragments are locally present. Beds are laterally discontinuous with uneven erosional based, either isolated or stacked one upon another forming bedsets <50 cm thick. Deposits of facies Ch1 are overlain by horizontally- (facies Ch2) and/

or cross-bedded (facies Ch3) sandy gravel with internal discontinuous erosional surfaces and subordinate sand intercalations (Figs 4B-E).

Facies Ch2 occurs as <1 m thick and slightly coarsening-upward bedsets formed by <20 cm thick, sub-horizontal tabular beds made of moderately sorted pebbles and cobbles with minor sand intercalations (Figs 4B-C). Sandy matrix is common, although isolated open framework beds are locally present. Beds are either crudely plane-parallel stratified with imbricated gravels or massive and normally graded, occasionally passing to coarse sand.

Facies Ch3 occurs as <1.5 m thick bedsets formed by low-angle (<15°) dipping beds of pebble- to cobble-sized gravels (Fig. 4D) with variable amount of sandy matrix, and occasionally of medium-coarse sand (Fig. 4E). Bedsets locally fine upward and dip obliquely to palaeo-transport direction, as deduced from imbrication of basal gravels (facies Ch1). Deposits of facies Ch2 and Ch3 are locally erosionally overlain by lensoid bodies of massive and/or trough-cross stratified medium-to-coarse pebbly sand with occasional strings of pebbles, representing facies Ch4 (Fig. 4F).

Interpretation. Facies association CH deposited within fluvial channels characterized by the presence of gravelly bars migrating downstream (i.e. Ch2) or obliquely to the main flow (i.e. CH3) onto a channel-floor lag (Ch1). Specifically, the horizontal-bedding of facies Ch2 can be linked with longitudinal bars (Bluck 1982; Miall 1985; Nemec & Postma 1993), whilst cross-bedded gravel of facies Ch3 typifies bank-attached bars (Bridge 1993; Billi et al. 1987). In this context, the lensoid gravelly sands of facies Ch4 reflect deposition in short-lived, small channels cut on top of the bars bodies. The limited exposures of these deposits prevented a detailed architectural analysis and, consequently, a clear detection of a specific fluvial style, although the above-mentioned features would point to a multichannel system with highly mobile bars.

Facies association FP: Floodplain deposits

This facies association is comprised of two facies referred to as facies Fp1 and Fp2.

Facies Fp1 consists of heterogeneous grey mud intercalated with tabular beds of very fine- to medium-grained sand, and rare gravel strings. Deposits of this facies range from wholly muddy units (up to 2 m thick) to heterolitic intervals made of alternating millimetres-to-centimetres thick layers of sand and mud (Fig. 4G). Mud is massive, at places mottled, and contains isolated pedogenic horizons with plant-root casts, including trees remains, or calcrete. Continental gastropods (Manganelli et al. 2007, 2011) and localised accumulations of plant debris are also present. Sandy beds are from <1 to 30 cm thick, sharp- to erosionally-based, sometimes with evidence of soft-sediment deformation. Upper bed contacts are typically sharp, flat-to-current rippled, less frequently gradational to overlying mud. Internally, these beds range from massive, normally graded to plane-parallel laminated, ripple cross-laminated or more rarely cross-stratified. Lignite seams (<5 m thick) were also reported from these deposits during old mining activity (De Castro & Pillotti 1933), although they are no longer exposed. Facies Fp2 is less common that Fp1 and is represented by broadly lenticular erosionally-based sandy gravel bodies typically <1 m thick that erosionally overlie sandier intervals of the former facies association (Fig. 4G). Facies Fp2 deposits consist of decimetres-thick, massive to plane-parallel stratified pebble gravel beds with minor massive and/or plane-parallel and occasional trough cross-stratified sand. Beds are often discontinuous at outcrop scale and characterised by repeated scouring.

Interpretation. Sedimentological features of facies Fp1 and Fp2 indicate deposition in a poorly-drained floodplain setting (Miall 1996; Jones et al. 2001) with local development of long-lived mires (lignite seams). In particular, facies Fp1 resulted from overbank flood sheets and crevasse splays, with suspension fallout of mud in ephemeral ponds formed after flood events, and sheets of sand deposited as splays both in tractional and non-tractional manner (Tunbridge 1984; Jones et al. 2001). Few ponds were possibly persistent enough to develop anoxic/dysoxic conditions, as attested by the preservation of thinly laminated, often carbonaceous mud and sand layers. Mud bears evidence of later modification by subaerial exposure (caliche and mottled appearance, cf. Alonso-Zarza 2003), although the absence of mature paleosols suggests relatively high rates of floodplain aggradation. Sand-rich, crevasse-splay intervals of fa-

Facies Association	General features and component facies	Interpretation
CH **(Fluvial-channel fill)**	Erosionally based, upward-concave, sandy gravel lithosomes which typically finning-upward trends. Coalified wood fragments are common. Single lithosomes are typically < 3 m thick and typically consist from the base of the following facies: i) **Ch1**: basal massive or crude plane-parallel stratified grave, clasts-supported, pebble- to cobble-sized; ii) **Ch2**: sandy-gravel bedsets (< 1 m thick), horizontally or cross-bedded stratified, with common internal erosional surfaces and subordinate sand intercalations; iii) **Ch3**: lensoid bodies of massive and/or trough-cross stratified medium-to-coarse pebbly sand with occasional strings of pebbles.	CH sediments deposited within fluvial channels characterized by gravel-dominated bars (facies **Ch2**, Smith 1974; Bluck 1982; Miall 1985; Bridge 1993; Nemec & Postma 1993) migrating onto channel-floor gravelly lags (facies **Ch1**). In this context, the lensoid gravelly sands of facies **Ch3** reflect tractional and non-tractional deposition in short-lived scour-like small channels (Jopling 1965) at the top of bars deposits.
FP **(Floodplain deposits)**	Fine-grained dominated deposits closely associated with CH fluvial channels sediments. **FP** deposits are characterized by widespread features suggesting subaerial exposures, like: i) pedogenic horizons with oxidized plant-root casts; ii) calcrete; iii) fossilized continental gastropods; and iv) localised accumulations of plant debris up to form coal seams (< 5 m thick). Two main facies are recognizable: i) **Fp1**: heterogeneous grey mud (often massive and mottled) intercalated with tabular beds of very fine- to medium-grained sand, and rare strings of gravel. Sandy beds are from < 1 to 30 cm thick, sharp- to erosionally-based, while upper bed contacts are typically sharp, flat-to-current rippled, less frequently gradational to overlying mud. Internally, these beds range from massive, normally graded to plane-parallel laminated, ripple cross-laminated or more rarely cross-stratified; ii) **Fp2**: broadly lenticular erosionally-based sandy gravel bodies typically < 1 m thick that erosionally overlie sandier intervals of **CH** facies association. Internally, these deposits consist of decimetres-thick, massive to plane-parallel stratified pebble gravel beds with minor massive and/or plane-parallel and occasional trough cross-stratified sand beds.	Sedimentological features and the occurrence of coal seams, indicate a poorly-drained floodplain environment (Miall 1996; Jones et al. 2001) with long-lived local mires. Facies **Fp1** resulted from overbank flood sheets and crevasse splays; mud deposited from suspension during flood events within ephemeral ponds, and sheets of sand deposited as splays from the channel margins both in tractional and non-tractional manner (Tunbridge 1984; Jones et al. 2001). Mud bears evidence of later by subaerial exposure (caliche and mottled appearance), although the absence of mature paleosols suggests relatively high rates of floodplain aggradation. Sand-rich, crevasse-splay intervals of facies **Fp1** are locally overlain by crevasse-channel deposits of facies **Fp2**, characterised by traction sedimentation and/or raping dumping of gravel and sand.
SP **(Spit deposits)**	**Sp** deposits consists of two facies (**Sp1** and **Sp2**), with facies **Sp1** typifying a clinostratified (20-25°) sandbody downlapping the sub-horizontal facies **Sp2**. Forest inclination point to a sediment transport direction oblique respect than the supposed basinward direction. **Sp1** deposits consists of medium- to coarse-grained, well-sorted sand beds, with occasional fragments of marine shells, and rare millimetres-thick silty interbeds, especially in the lowermost part of the foreset package. Beds are often pervasively bioturbated, hence structureless, although with occasional normal grading. When primary sedimentary structures are recognizable they consist of plane-parallel to low-angle stratification. Facies **Sp2** consist of horizontally-bedded, fine-grained silty sand with marine shell fragments.	Spit bar deposits, with the facies **Sp1** representing avalanche-dominated, steeply dipping spit-platform foreset (Nielsen & Johannessen 2008). **Sp2** deposits represents the bottomset of the spit system.

Tab. 1a - Synthesis of the main features of the recognized facies association (continue).

cies Fp1 are locally overlain by crevasse-channel deposits of facies Fp2, the latter characterised by traction sedimentation and/or rapid dumping of gravel and sand.

Facies association SP: Spit deposits

This facies association is limited to an isolated outcrop at the top of Mencia Alta hill (southern part of the study area: Fig. 5A). It consists of two facies (Sp1 and Sp2), with facies Sp1 typifying a clinostratified sandbody downlapping facies Sp2.

Facies Sp1 occurs as a 12 m thick package of sandy foreset inclined at 20°-25° (Fig. 5A) respect than the underlying and sub-horizontal facies Sp2

Facies Association	**General features and component facies**	**Interpretation**
SD **(Shoal-water delta deposits)**	Deposits of facies association **SD** finclude two facies, namely facies **Sd1** and **Sd2**: i) **Sd1**: coarsening-upward tabular to broadly lenticular lithosomes made of sand with minor mud and gravel. Beds are sub-horizontal or gently sloping (< 10°) basinward. Sand is fine- to medium/coarse-grained, moderately sorted. Marine molluscs fragments, mud intraclasts and pebble stringers are common. Beds are massive and normally graded or plane parallel- and cross-stratified, either with planar or trough cross sets; ii) **Sd2** erosionally overlies **Sd1**deposits and consists of fining-upwards lensoid lithosomes up to 2 m thick either gravel- or, less frequently, sand-dominated. Gravel-dominated lithosomes are clast-supported. Sand-dominated lithosomes mainly consists of trough cross-stratified medium/coarse sand above a basal pebble lag. Subordinate deposits are represented by massive to laminated mud.	Deposition in a shoal-water delta depositional environment (Leeder et al. 1988; Postma 1990; Martini & Sandrelli 2015). In detail, facies **Sd1** are the expression of prograding mouth bars, while deposits of facies **Sd2** represent distributary-channel deposits.
ND **(Nearshore deposits)**	Deposits of this facies association include three facies, namely **Nd1**, **Nd2** and **Nd3**. Facies **Nd1** consists of well-sorted medium- and fine-grained sand locally bearing granules and pebbles either scattered or concentrated in stringers and/or beds with erosional to depositional contacts. Sand beds are mainly massive due to bioturbation or plane-parallel laminated with internal truncation surfaces. Sedimentary structures are rare and represented by ripple cross-lamination, symmetrical and asymmetrical ripple forms, and swaley cross-stratification. Marine fossils occur as entire shells or as fragments. Facies **Nd2** consists of two sub-facies: **Nd2a** that consists of pebble- to cobble-grade gravel with interstitial siliciclastic medium-coarse sand and occasional shell fragments; and **Nd2b** that occurs as mixed, siliciclastic-carbonate deposits made of dominantly medium-grained sand and shell fragments, with occasional bivalve shells in life position. Facies **Nd3** consist of well-sorted, bioturbated fine-grained sand with subordinate coarse- to medium-grained sand and mud. Sandstone beds are either massive or laminated (plane-parallel, ripple-cross lamination and hummocky cross-stratification), sometimes even normally graded. Mud occurs as 3-10 cm thick, bioturbated and massive beds. Marine molluscs are common.	Sedimentary features of facies association ND point to a deposition in a wave-dominated nearshore setting. Specifically, facies **Nd1** represents a wave-dominated upper shoreface (Johnson and Baldwin 1996 and reference therein). Facies **Nd2a-b** still represents a shoreface setting, however its peculiar sedimentological and stratigraphic features point to sediment starvation and suggests a condensed, upper shoreface settings. Facies Nd3 is indicative of deposition in a lower shoreface settings (Hampson 2000; Clifton 2006), i.e. between the fair-weather and the storm wave base.
OF **(Offshore transition and offshore deposits)**	These deposits consist of two facies, namely facies **Of1** and facies **Of2**. Facies **Of1** consists of massive and bioturbated silty mud with interbedded thin (<30 cm) and hummocky cross-stratified sandstone beds showing an erosional base and a sharp and rippled top. Facies **Of2** consists of massive and thoroughly bioturbated, seldom poorly stratified greyish silty- clays and clayey sandy silt. Fossils are represented by abundant calcareous planktonic and benthonic microfauna, and by marine molluscs.	The feature of facies **Of1** points to deposition in an offshore transition environment (Reading and Collinson, 1996), where suspension fallout of mud during fair-weather conditions was interrupted by sand deposition during storms. The features of facies **Of2** suggest sedimentation by suspension fallout within an offshore marine setting, i.e. below the storm wave base (cf. Walker & James 1992; Reading & Collinson 1996).

Tab. 1b - Synthesis of the main features of the recognized facies association.

deposits. Foreset dips basinward and consists of medium- to coarse-grained, well-sorted sand beds, with occasional fragments of marine shells, and rare millimetres-thick silty interbeds, those mainly occur in the lower part of the unit. Truncations are common and show both convex and concave erosional profiles. Foreset are often pervasively bioturbated, hence structureless, although with occasional normal grading, with *Thalassinoide*s as the dominant ichnogenera. Where primary sedimentary structures are recognizable they consist of plane-parallel to low-angle stratification.

Facies Sp2 underlain facies Sp1, and is comprised of about 3 m of poorly exposed, horizontally-bedded, fine-grained silty sand with marine shell fragments.

Interpretation. The compound foreset of well-sorted and bioturbated sand precludes a sandy Gilbert-type delta interpretation (c.f. Muto & Steel 1997). Deposits of facies associations SP are interpreted as a spit system (Meistrell 1972; Nielsen et al.1988; Nielsen & Johannessen 2008, 2009), where the sandy facies Sp1 represents spit-platform foreset prograding onto silt-rich sandy bottomset, with the latter typified by the poorly-exposed facies Sp2. Although the severe bioturbation affecting these facies prevents a detailed interpretation of depositional processes, steeply dipping foreset support the notion of an avalanche-dominated spit platform prograding in relatively deep water, with occasional suspension fallout of silt below the fair-weather wave base (cf. Nielsen et al. 1988), and possibly storm-related, stratified deposits. This interpretation is also supported by the lack of fluvial/distributary channels deposits on top of foreset one, as typically excepted for Gilbert-type delta deposits.

Facies association SD: Shoal-water delta deposits

Deposits of facies association SD are extensively exposed along the basin margin and include two facies, namely facies Sd1 and Sd2. Facies Sd1 consists of coarsening-upward, tabular to broadly lenticular 2-5 m thick sandy lithosomes with minor mud and gravel (Figs 5B-E). Beds are sub-horizontal to gently dipping (<10°) basinward. Sand is typically fine- to medium/coarse- grained, moderately sorted and locally bearing broken shells of marine molluscs, mud intraclasts and granule/fine pebble stringers (Fig. 5C). Sand occurs as <45 cm thick beds with sharp, locally scoured and loaded bases, and typically sharp tops with occasional symmetrical or asymmetrical ripple forms (Figs 5F-G). Sand beds range internally from massive and normally graded to plane parallel- and cross-stratified, either with planar (Fig. 5H) or trough cross sets. Bioturbation is common and typically decreases upward within individual lithosomes. Gravel is pebble-sized and occurs as normally graded, massive and tabular beds <15 cm thick. Mud is represented by <5 cm thick, commonly bioturbated beds rich in plant debris.

Facies Sd2 consists of fining-upwards, <2 m thick lensoid gravel to sand lithosomes erosionally overlying facies Sd1 (Fig. 5I). Gravel-dominated lithosomes are made of pebbles and cobbles, those are moderately sorted and characterized by a clast-supported, sand-filled texture. Beds of gravel are <40 cm thick, lens-shaped and stacked erosionally upon one another with some lateral offset. They are typically massive and normally graded; occasionally plane parallel-stratified (Fig. 5I). Sand-dominated lithosomes mainly consists of trough cross-stratified medium/coarse sand above a basal pebble lag. Subordinate deposits are represented by massive to laminated mud (Fig. 5C).

Interpretation. The geometry, stacking pattern, and internal characteristics of facies association SD are indicative of a shoal-water delta setting (Leeder et al. 1988; Postma 1990; Martini & Sandrelli 2015), also referred to as mouth bar-type delta (Dunne & Hempton 1984; Wood & Ethridge 1988). Specifically, lithosomes of facies Sd1 are ascribed to prograding mouth bars locally underlain distributary-channel deposits of facies Sd2. Mouth bars were characterized by frictional, homopicnal effluent conditions with deposition of sand and gravel (Fidolini & Ghinassi 2016). During periods of lower discharge, suspension fallout from hypopycnal effluent dominated. The local presence of symmetrical ripple forms points to wave winnowing of river-fed deposits.

Facies association ND: Nearshore deposits

Deposits of this facies association form 3-10 m thick, fining- and coarsening-upwards lithosomes of facies Nd1, Nd2 and Nd3 (Fig. 6A). Facies Nd1 consists of well-sorted medium- and fine-grained sand locally bearing granules and pebbles either scattered or concentrated in stringers and/or beds with erosional to depositional contacts (Figs 6A-B). Gravel beds occur as a clast-supported, sand-filled framework of spherical pebbles and/or cobbles, with evidence of bioerosion (e.g. lithophaga traces) and/or barnacle or oyster colonization (Fig. 6C). Sand beds are mainly massive (sometimes with evidence of a pervasive bioturbation) or plane-parallel laminated with internal truncation

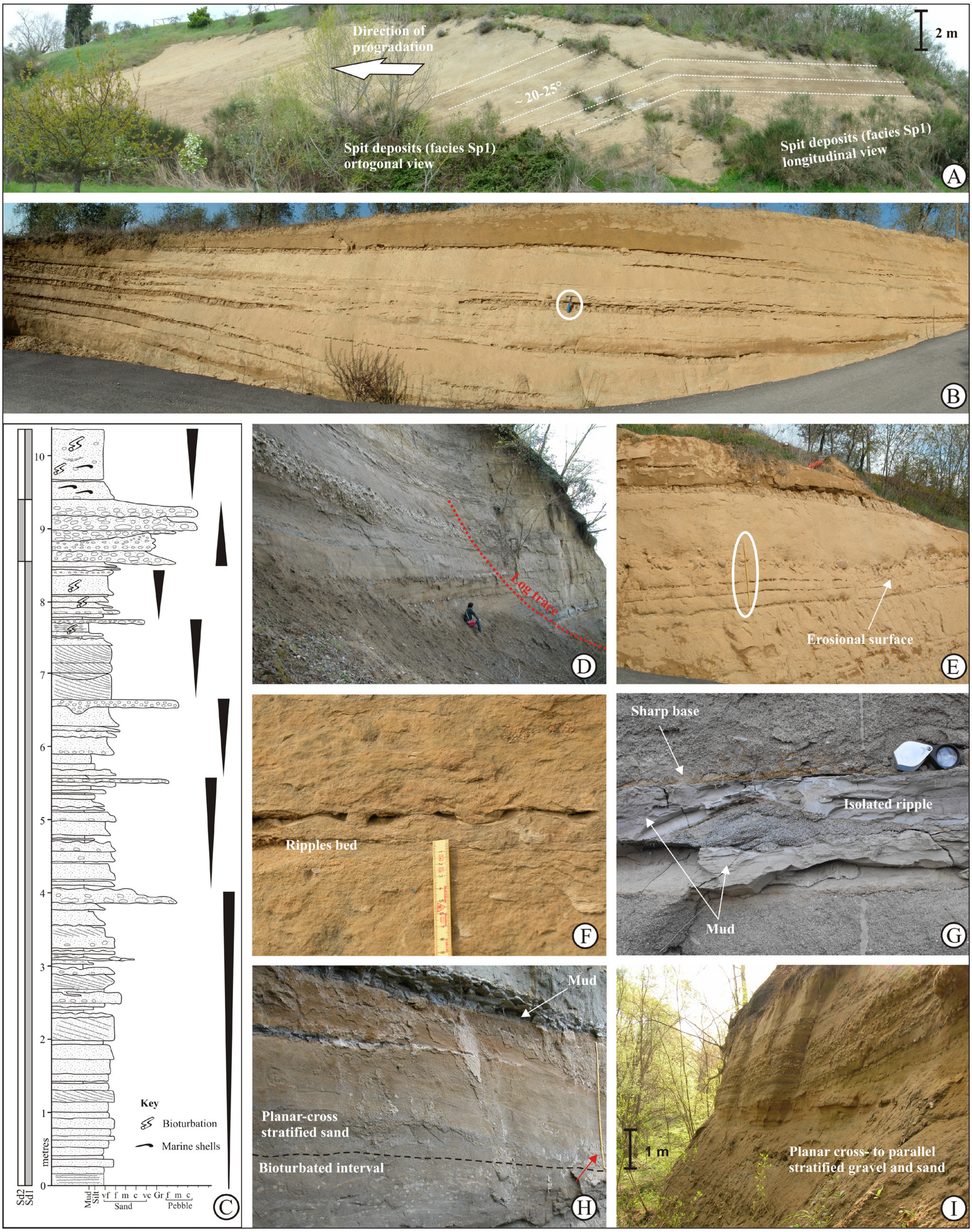


Fig. 5 - A) Ortogonal and longitudinal view of seaward inclined beds of facies Sp1 (i.e. spit-platform foresets). B) Lithosome of facies Sd1 dominantly made of sand with subordinate mud and gravel (hammer for scale). C) Typical sedimentary expression of deltaic (shallow water) deposits. D) Outcrop view of deltaic deposits described in the log in C. Note the coarsening-upward sandy-dominated deposits (facies Sd1) erosionally overlie by finning-upward gravels (distributary channel deposits, facies Sd2). E) Erosional surface within Sd2 deposits (meter for scale). F) Ripples bed capped by a thin mud drape. G) Typical expression of Sd1 sediments: note the sharp base and top of sandy beds and the occurrence of isolated ripple within muddy beds (hand lens for scale). H) Planar-cross stratified bed of facies Sd1 (meter for scale). I) Aspects of Sd2 deposits (distributary channels fill).

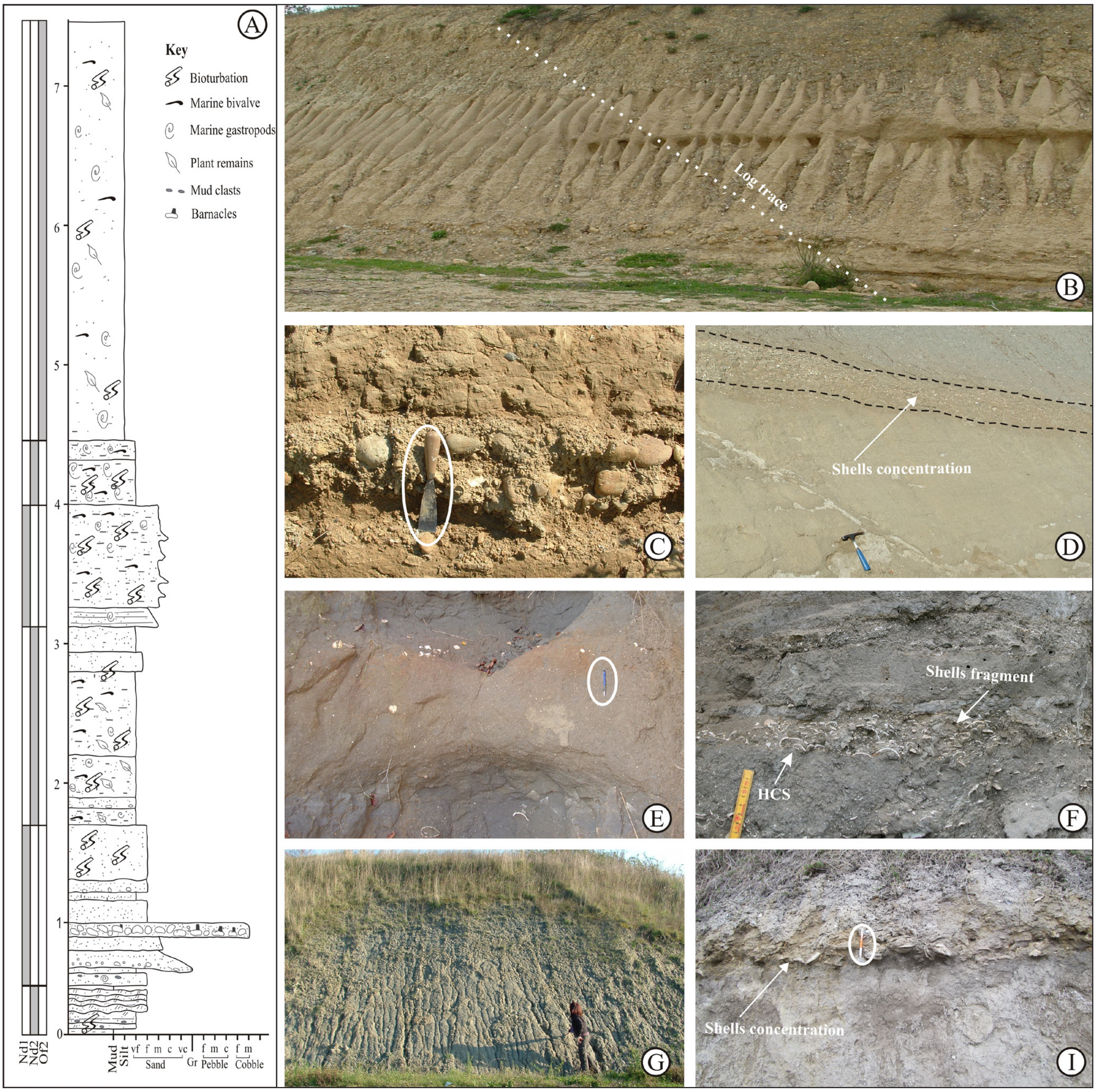


Fig. 6 - A) Sedimentary log of a shoreface succession passing upward to offshore sediments. B) Outcrop view of the logged section. C) Erosionally based gravels within Nd1 sediments (spatula for scale). D) Shell bed of the facies Nd2 resting on an high-relief unconformity (hammer for scale). E) Decimeter thick sandy bed within fine-grained sand of facies Nd3 (pencil for scale). F) Shell fragments concentrated at the base of a hummocky cross-stratified bed. G) Classical aspects of offshore deposits. I) Shell bed within offshore deposits (pencil for scale).

surfaces. Sedimentary structures are rare and represented by ripple cross-lamination, symmetrical and asymmetrical ripple forms, and swaley cross-stratification. Marine fossils (e.g. *Ostrea*, *Tellina*, *Turritella*, *Natica* and *Panopea*) are often dispersed within the sand either as entire shells or as fragments, locally forming thin shell-rich layers with bivalves commonly convex-upward.

Facies Nd2 shows an erosional lower boundary and a transitional top either to sand-dominated facies Nd3 or to offshore fines of facies association OF (see next section). It is represented by two sub-facies, Nd2a and Nd2b. Sub-facies Nd2a (max 40 cm thick) consists of pebble- to cobble-grade gravel with interstitial siliciclastic medium-coarse sand and occasional shell fragments. Evidence of bioerosion and serpulids encrustations locally characterize gravel clasts.

Sub-facies Nd2b (Fig. 6D) occurs as mixed, siliciclastic-carbonate deposits (max 50 cm thick) made of dominantly medium-grained sand and shell fragments, with occasional bivalve shells in life position. Facies Nd3 is made of well-sorted, bioturbated fine-grained sand with subordinate coarse- to medium-grained sand (Fig. 6E), occasional mud interbeds and stringers of granules and rounded fine pebbles. Sand occurs as 5-35 cm thick beds with erosional and sharp bases, and fairly sharp, planar, rippled or hummocked upper boundaries (Fig. 6E). Internally they are either massive or laminated (plane-parallel, ripple-cross lamination and hummocky cross-stratification), locally showing normal grading. Mud occurs as 3-10 cm thick, bioturbated and massive beds. Marine molluscs (e.g. *Cardium*, *Venus*, *Amusium*, *Panopea*) are common, either as fragmented, disarticulated valves or specimens in life position, and can occur dispersed within the sediment or concentrated at the base of some hummocky cross-stratified beds (Fig. 6F).

Interpretation. Sedimentary features of facies association ND are consistent with a wave-dominated nearshore setting. Specifically, facies Nd1 represents a wave-dominated upper shoreface (Clifton 1976, 2006; Kumar & Sanders 1976; Walker & Plint 1992; Ainsworth & Crowley 1994; Johnson & Baldwin 1996), where storm events are manifested by truncation surfaces, swaley cross-stratification and stringers of beach-delivered gravels, whereas fair-weather conditions are testified by ripple forms, plane-parallel lamination and bioturbation.

Facies Nd2a-b still represents a shoreface setting, however its peculiar sedimentological and stratigraphic features point to sediment starvation and suggest a condensed, upper shoreface setting.

Finally, the presence of mud layers along with a high degree of bioturbation and finer grain size of facies Nd3 is indicative of relatively deeper conditions compared to facies Nd1 (Hampson 2000; Clifton 2006). In this setting, short-term rises of fair-weather wave base would promote deposition of muddy interlayers in a dominantly sandy bottom otherwise affected by quasi-perennial wave action. Highly burrowed horizons represent periods of stable floor, low sedimentation rate and incipient colonization by benthic fauna. Significant phases of sediment winnowing are indicated by shell layers with bivalve in convex-upward positions.

The paleogeography of the Siena Basin suggests a relatively shallow wave base, and a limited downdip extent of the shoreface zone. Similar conditions are commonly documented in Pliocene nearshore deposits of the inner Northern Apennines (e.g. Nalin et al. 2010), and are consistent with partly sheltered, non-oceanic coasts (Clifton 2006).

Facies association OF: Offshore transition and offshore deposits

Deposits of this facies association form the typical Badlands landscape (locally referred to as “Crete”) of Siena neighbourhood. They are comprised of two facies, namely facies Of1 and facies Of2. Facies Of1lies landward of facies Of2. It is poorly represented in the study succession and consists of massive and bioturbated silty mud with interbedded of fine- to medium-grained sand. Sand beds are <30 cm thick with show erosional base and sharp, often rippled top, and internal hummocky cross-stratification. Shells locally occur at the base of sandy beds, and bivalve shells show a convex-upwards orientation.

Facies Of2 consists of 3-70 m thick bodies of typically massive and thoroughly bioturbated, seldom poorly stratified greyish silty- clays and clayey sandy silt (Fig. 6G). Fossils are represented by abundant calcareous planktonic and benthonic microfauna, and by marine molluscs (e.g. *Dentalium, Chlamys, Aporrhais*, etc.), either dispersed or concentrated as thin shell beds with most specimens in life position. A continuous, about 30 cm thick shell bed (Fig. 6H) mainly made of *Ostrea*, *Pecten* and *Clamys* in a scarce, very fine sand-silt matrix is present at the base of a thick, basin-wide OF package.

Interpretation. Alternation of mud and hummocky cross-stratified sand of facies Of1 points to an offshore transition environment (Reading & Collinson 1996), where suspension fallout of mud during fair-weather conditions was interrupted by sand deposition by storm-induced, combined and oscillatory flows. The fine-grained nature and paleontological content of facies Of2 suggest sedimentation by suspension fallout in an offshore marine setting, i.e. below the storm wave base (cf. Walker & James 1992; Reading & Collinson 1996). In this setting, concentrations of shells are interpreted as sediment starvation times (Kidwell 1991; Brett 1995).

Sequence	Unit	Lower bounding surface	Upper bounding surface	Dominant deposition	Sequence stratigraphic interpretation
	S4c	Maximum flooding band MFS3	Unconformity UN5	Deltaic	HST
S4	S4b	Wave-ravinement surface RS5	Maximum flooding band MFS3	Deltaic to shoreface	TST
	S4a	Unconformity UN4	Wave-ravinement surface RS5	Deltaic	LST
	S3d	Ravinement surface of marine erosion RSME2	Unconformity UN4	Deltaic	FSST
S3	S3c	Maximum flooding surface MFS2	Ravinement surface of marine erosion RSME2 or Unconformity UN4 (close to basin margins)	Offshore	HST
	S3b	Wave-ravinement surface RS4	Maximum flooding surface MFS2	Shoreface	TST
	S3a	Subarieal unconformity UN3	Wave-ravinement surface RS4	Fluvial	LST
	S2c (exposed only at one locality)	Maximum flooding band MFS1	UN3	Spit	HST?
S2	S2b	RS3	UN3 or maximum flooding band, MFS1	Shoreface to deltaic	TST
	S2a	UN2	RS3	Fluvial to deltaic	LST
	S1c	RS2	UN2	Shoreface	TST/HST (?)
S1	S1b	RS1	RS2	Shoreface to deltaic	TST
	S1a	UN1	RS1	Alluvial	TST (?)

Tab. 2 - Synthesis of the main features of the recognized depositional sequences and system tracts. See figure 12 for the chronostratigraphic extension of each sequence.

Silt fraction of both facies represents either river borne sediments introduced in the marine basin by floods, or shoreface-derived, low-density flows triggered by storms.

DEPOSITIONAL ARCHITECTURE AND SEQUENCE-STRATIGRAPHY

The analysis of the stratigraphic architecture of the studied deposits is based on field correlations of key stratal surfaces, which are represented by basin-wide erosional surfaces manifested by truncations with or without facies shifts across them. The identification of these surfaces allowed to define four depositional sequences, namely S1 to S4, in ascending stratigraphic order (see Table 2 for a synthesis).

Sequence S1

This sequence is exposed in limited outcrops, mainly in the northern part of the study area, where it reaches the maximum thickness of about 45 metres. A regional angular unconformity (hereafter UN1) separates this sequence from the underlying pre-Neogene bedrock, although this surface is not exposed in distal areas. Sequence S1 is bounded at the top by the composite unconformity surface UN2, which is expressed landwards by a subaerial unconformity passing basinwards to a correlative conformity expressed by a regressive surface of marine erosion (Fig. 7A). UN2 is overlain by deposits of sequences S2 and S3. The recognition of two wave-winnowed surfaces (hereafter RS1 and RS2) enabled to subdivide S1 into three units, named S1a-c.

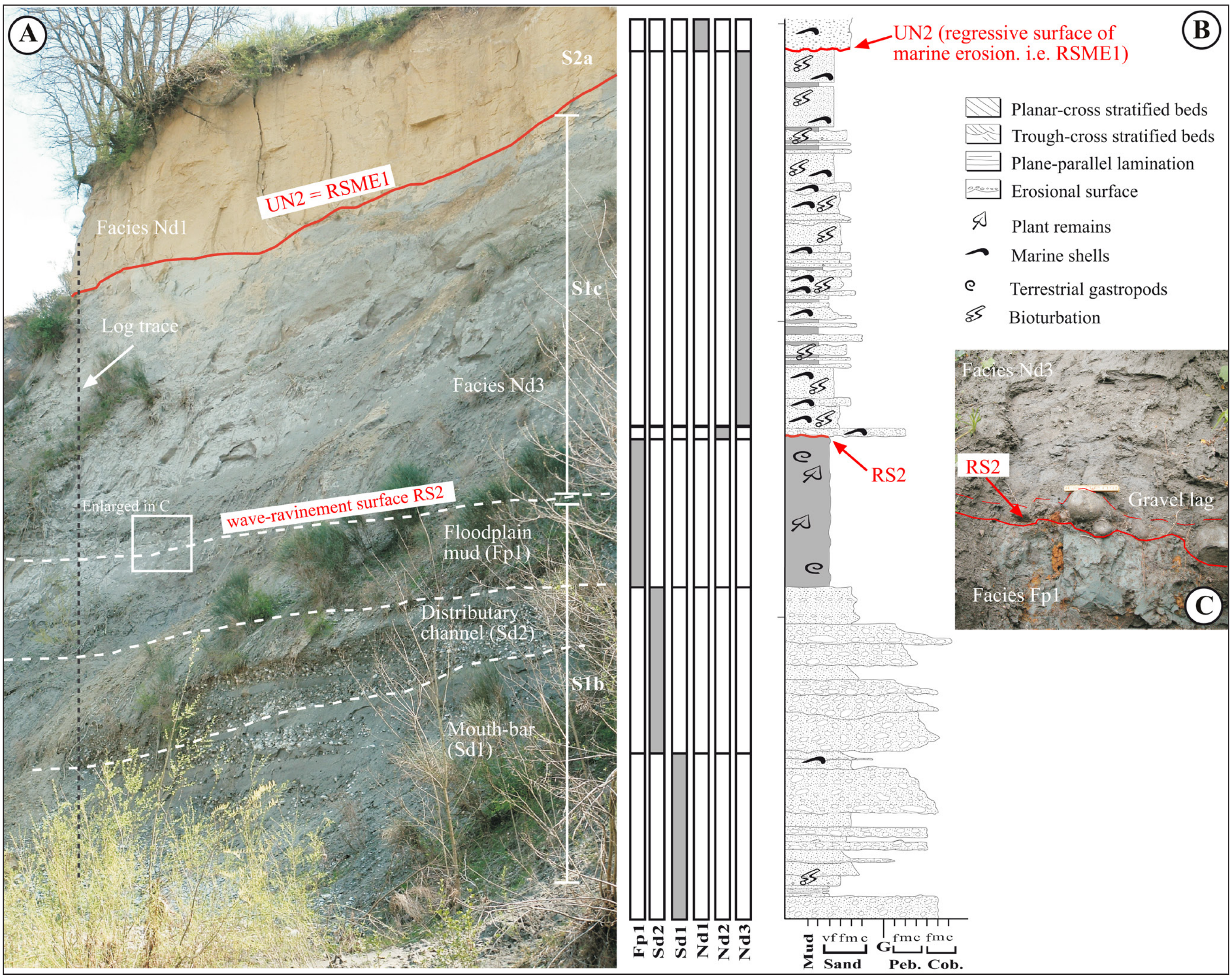


Fig. 7 - A) Line-drawing showing the internal architecture of the uppermost part of Sequence S1 and its upper boundary. B) Sedimentary log of the rock exposure in A. C) Close-up view of the wave-ravinement surface RS2.

Unit S1a is at least 10 m thick and consists of alluvial deposits comprised of: i) floodplain mud with minor sands and lignite seam (facies association FP); and ii) subordinate lensoid lithosomes of fluvial sandy gravels (facies association CH).

Unit S1b (<9 m thick: Fig. 7A) is bounded at the base by the wave-winnowed surface RS1, which is floored by a sandy gravel lag of facies Nd2a. The overlying deposits show a shallowing-upward trend manifested by, in upward stratigraphic order (Figs 7A-B): i) bioturbated fine-grained shoreface sand (facies Nd1); ii) mouth-bar sand and gravel (facies Sd1); iii) gravelly distributary channels (facies Sd2); and iv) floodplain mud with root traces (facies Fp1).

Unit S1c (<15 m thick) is bounded at the base by the wave-winnowed surface RS2 (Figs 7A-C), and is topped by UN2 (Fig. 7A). The facies are vertically stacked to form an asymmetric, deepening-to-shallowing upward nearshore motif. Surface RS2 (Fig. 7C) is paved by a sandy gravel lag (<15 cm) with cobbles and pebbles, occasionally showing evidence of bioerosion and serpulids encrustations (facies Nd2). This bed is overlain by a few meters of lower shoreface bioturbated sand with scattered mud layers (Nd3), passing upward to predominantly upper shoreface (Nd1) and distal mouth-bar (Sd1) sandy deposits (Figs 7A-B).

The sequence S1, which deposited during the Zanclean period, and in particular its marine deposits can be ascribed to the MPl3 Zone of the planktonic Foraminifera and upper MNN13 Zone-MNN14/15 intervals of calcareous nannofossils zonation (Martini et al. 2011).

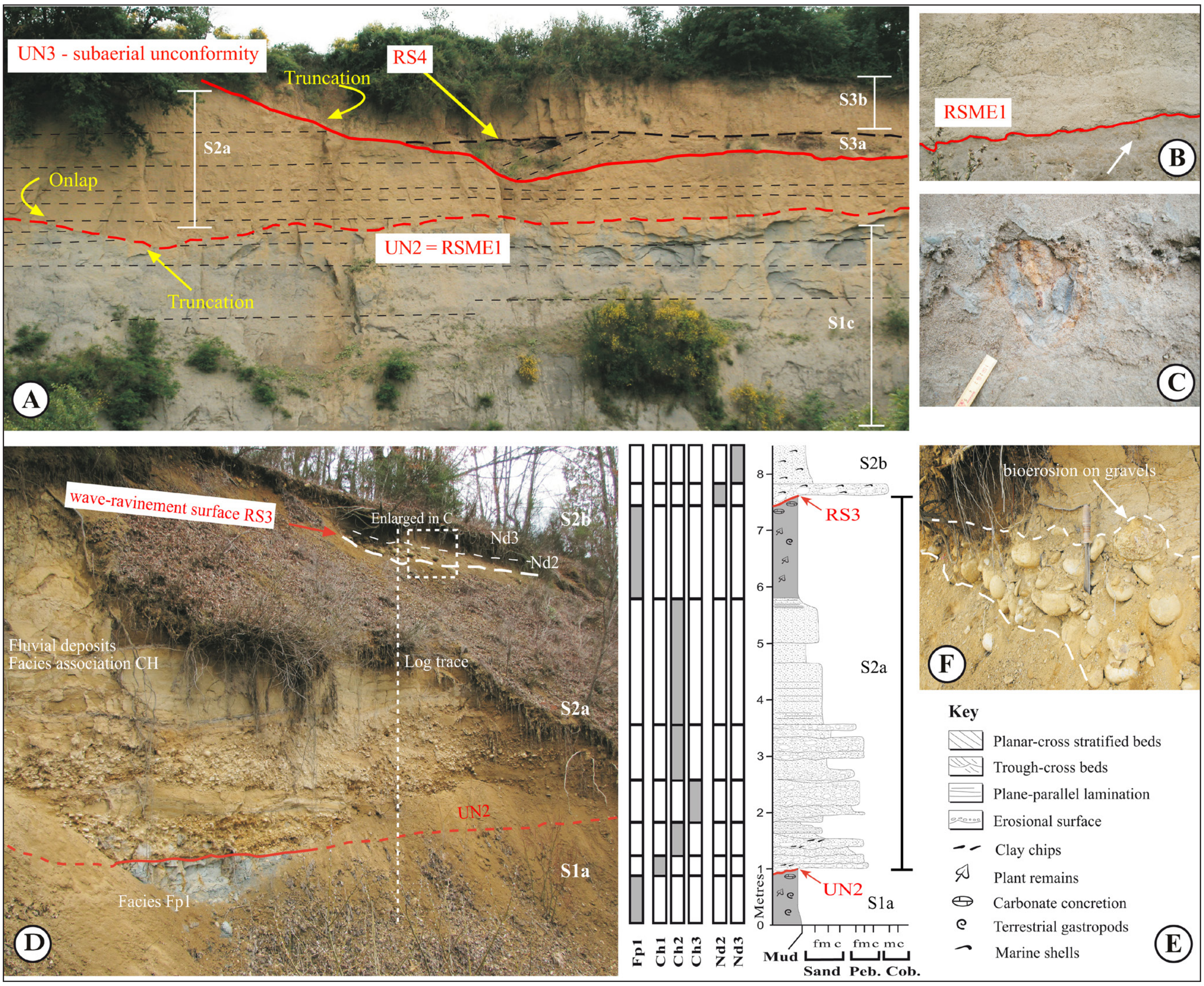


Fig. 8 - A) Panoramic line-drawing showing the boundaries of Sequence S2 and internal stratal terminations. Note as the sequence is deeply eroded by the erosion associated with the upper bounding subaerial unconformity UN3. B) *Glossifungites* ichnofacies penetrates downward from the RSME1. C) Close-up view of an *Arenicoles* burrows. D) Landward expression of Sequence S2: unit S2a is there entirely composed of fluvial deposits (facies association CH), separated from the overlying S2b through a wave-ravinement surface (RS3) indicating a flooding events. E) Sedimentary log of the outcrop in D. F) Close-up view of surface RS3.

Sequence stratigraphic interpretation. In a sequence-stratigraphic perspective, key-stratal surfaces and facies stacking patterns of sequence S1 show an overall transition from a continental to a marine realm. However, the sequence stratigraphic attribution of the basal S1a unit is problematic, as it often happens for continental deposits in which classical sequence-stratigraphic surfaces are not easily identifiable. Lignite-rich fluvial successions similar to unit S1a are typically described in high-accommodation settings (Shanley & McCabe 1991; Wright & Marriot 1993), which in coastal areas are generally associated with marine transgressive conditions. In this view, the wave-winnowed surface RS1 can be interpreted as a within-trend ravinement surface (Catuneanu 2006) separating continental (unit S1a) from overlying marine (S1b) transgressive deposits, with unit S1a therefore representing the continental portion of a TST. In this framework, units S1b-c document successive transgressive conditions in a marine realm, where progradational episodes are documented by the parasequential stacking pattern. Units S1c are likely to have accumulated at the TST/HST transition, although, the lack of a clearly detectable maximum flooding surface prevents the correct distinction between the TST and the HST (cf. Martini et al. 2013).

Sequence S2

This sequence shows major thickness varia-

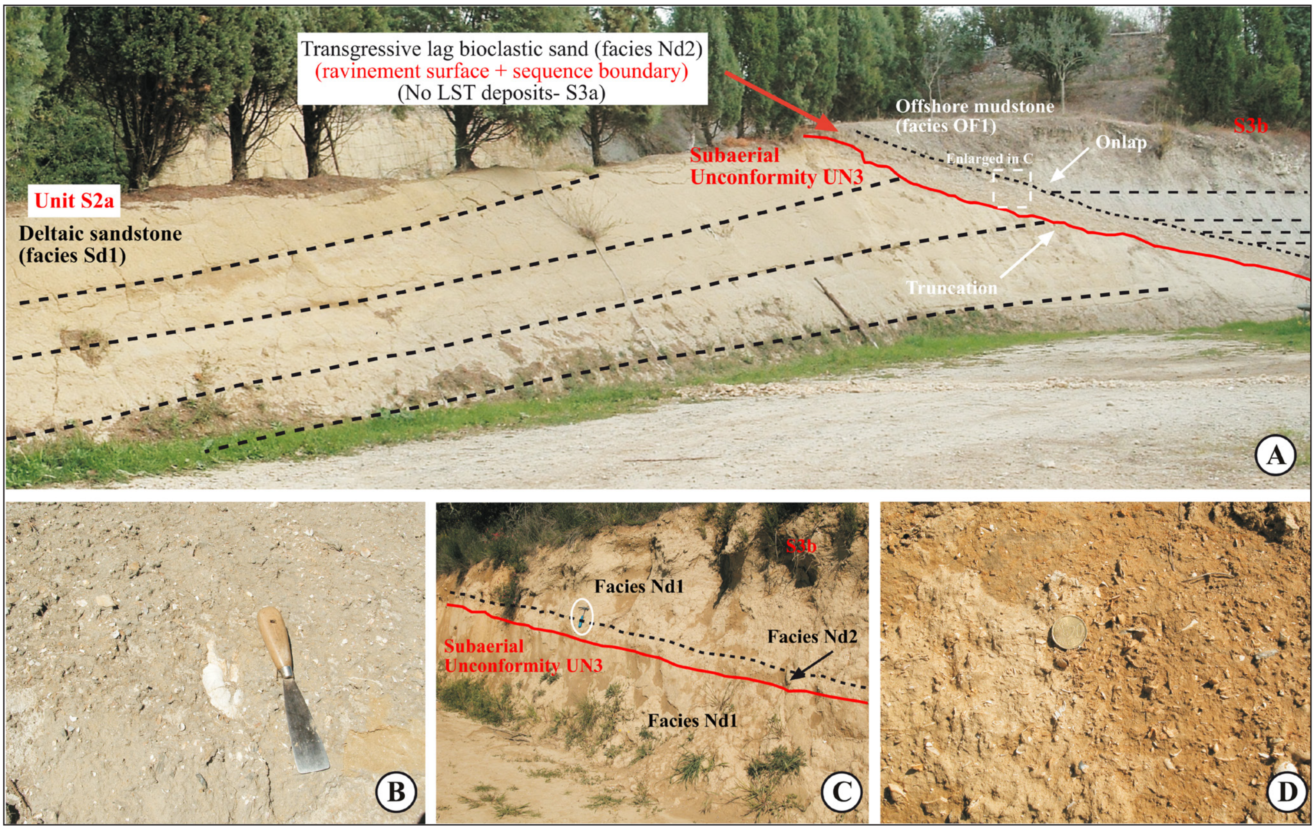


Fig. 9 - A) Outcrop expression of the high-relief erosional surface related to a subaerial unconformity UN3 that separates S2 and S3. Note as such surface is paved by a bioclastic sandy bed (facies Nd2) expression of a wave ravinement surface. This is in turn overlain by offshore sediments. B) Close-up view of the shell bed (facies Nd2) upon the sequence boundary (spatula for scale). C) Landward expression of the same surface, note as this is overlain by upper shoreface sediments of facies Nd1 (hammer for scale is encircled). D) Close-up view of facies Nd2 sediments in landward position, note the enrichment in sandy matrix (coin for scale).

tions (from a few meters to some 50 m thick) due to the variable erosional relief of its upper bounding unconformity (UN3, see next section). Sequence S2 is sand-dominated and extensively exposed in a N-S-trending belt located along the westernmost border of the studied area. It is separated from the pre-Neogene bedrock and sequence S1 (Fig. 3) by an intervening unconformity, namely surface UN2. Close to the basin margin, surface UN2 corresponds to a subaerial erosional surface, which is typically wave-reworked (hereafter RS3), where basal fluvial deposits (facies association CH, Fig. 8D) are lacking and sequence S2 starts with nearshore deposits (facies association SH). Basinwards, surface UN2 passes into a correlative conformity (locally expressed by the regressive surface of marine erosion RSME1, see Fig. 7A), and evidence of subaerial exposure is lacking.

The recognition of two surfaces with a sequence stratigraphic meaning (RS3 and MFS1) allowed to subdivide this sequence into three units, i.e. S2a-c. Unit S2a (<8 m thick: Fig. 8D) is bounded at the base by the composite unconformity UN2 and by a wave-winnowed surface (RS3) expressed by a 30 cm thick bed of facies Nd2 (Figs 8D-F) at its top. The deposits in units S2a are mainly exposed close to the basin margins, where they comprise fluvial deposits (facies association CH) showing a marked fining-upward trend. The fluvial deposits pass basinwards to sandy and coarsening-upward shoal-water delta deposits (facies association SD, Fig. 9A).

Unit S2b is typically comprised between the wave-winnowed surface RS3 and the subaerial unconformity UN3, with the only exception of the south-westernmost portion of the study area, ("Mencia Alta" locality), where it is overlain by unit S2c through the interposition of surface MFS1. The deposits in unit S2b range from a few meters to some 40 m in thickness due to the erosional nature of the top-bounding unconformity UN3. These deposits mainly consist of mouth-bar sand and gravel (facies Sd1) passing laterally and distally to bioturbated fine-grained shoreface sand (facies Nd1 and Nd3, Figs 8A-D), which in turn grades upward and grades basinwards to offshore fines (facies association OF). At "Mencia Alta", surface MFS1 lies within the latter deposits (facies Of2) and it is better described as a rock-band marking a gradual increase in coarse sediments. As a consequence, unit S2c starts with <10 m of offshore sandy mud of facies Of2 underlying by sandy spit deposits (facies association SP). According to Martini et al. (2011), this unit is ascribable to the late Zanclean (MPL4a Sub-zone of Foraminifera, lowermost part of the MNN16a Zone of calcareous nannofossils).

Sequence stratigraphic interpretation. The recognized basal composite unconformity UN2 documents a relative sea-level drop manifested in proximal areas by the subaerial exposure and erosion of underlying S1 sediments, with the development of large-scale erosional features filled with the fluvial facies of unit S2a. Unconformity UN2 passes basinwards into a correlative conformity overlain by deltaic deposits of unit S2a. S2a deposits are in turn bounded at their top by a wave-winnowed surface (RS3) that records a flooding event, and thus represents the transgressive surface. According to these stratigraphic constraints, unit S2a represents the LST, while the overlying fine-grained deposits of unit S2b belong to the TST.

The attribution of unit S2c is more problematic due to the presence of fragmented exposures. This unit rests onto offshore fines (facies Of2) of unit S2b (TST) and starts with similar, although slightly coarser, facies passing upwards to a spit system. As a consequence, unit S2c developed under regressive conditions and hence it could be ascribed to the HST. In this view, surface MFS1 corresponds to a maximum flooding band containing the maximum flooding surface which is not clearly recognizable as a condensed surface, as commonly documented in proximal marine environments (cf. Martini et al. 2013).

Sequence S3

This sequence is delimited at its base by the aforementioned high-relief erosional unconformity UN3 and at its top by composite unconformity UN4 (see next section). Four depositional units (referred to as S3a-d in ascending stratigraphic order) have been recognized on the basis of the occurrence of internal key stratigraphic surfaces, such as: i) a wave-winnowed surface (RS4); ii) a basin-scale surface of sediment starvation (MFS2); and iii) a regressive surface of marine erosion (RSME2) associated with an abrupt facies shift.

Unit S3a is made of 1-5 m thick discontinuous fluvial gravel and sand (facies association CH, Fig. 8A) overlying the basal unconformity UN3 and bounded at the top by the wave-ravinement surface RS4. In some places, unconformity UN3 is directly re-shaped by the wave-ravinement surface RS4 and S3a deposits are missing.

Unit S3b overlies surface RS4 and starts with a <40 cm thick bioclastic coarse-grained sand (facies Nd2a, Figs 9B-C-D-E). This facies is typically overlain by a <1 m thick upward-fining shoreface deposits (facies association ND, Figs 9D and 10A, B), which are in turn overlain by a <30 cm shell bed (facies Nd2b) with abundant bivalves in life position (Figs 10A-B).

These latter deposits mark the base of unit S3c. This key bed occurs with minimal lithological changes in the whole studied area and represents a surface of sediment starvation (MFS2). Unit S3c is 4 to 70 m in thickness and is mainly composed of a monotonous succession of offshore fines (facies associations OF, Fig. 10B) passing to very fine-grained lower shoreface sand (facies Nd3) in the immediate proximity of the basin margin. In this area, units S3a-b are absent and unit S3c directly overlies the abovementioned shell bed paving unconformity UN3. Unit S3c is typically bounded at the top by a subaerial erosional unconformity (UN4), except in distal sectors of the studied area where it is abruptly overlain by fluvio-deltaic gravel and sand (facies associations CH and SG) through an intervening gently-scoured surface (RSME2). The sands and gravels constitute unit S3d and form a coarsening- and shallowing-upward succession up to 8 m thick and bounded at the top by unconformity UN4.

Biostratigraphic constraints (Martini et al. 2011) suggest that the deposition of sequence S3 started in the late Zanclean (MPL4a sub-zone) and persisted until the earliest middle part of Piacenzian stage (MPL4b sub-zone).

Sequence stratigraphic interpretation. The origin of the basal subaerial unconformity UN3 is related to a prominent relative sea level fall, causing the emersion of

Fig. 10 - A) Outcrop expression of the sequence boundary UN3 and of its relation with sequences S2 and S3. In the upper part of the picture is possible to observe the condensation level (facies Nd2) that correspond to a maximum flooding surface that divide S3b (TST) from S3c (HST). B) Internal organization of sequence S3 in seaward position: note as lowstand deposits (S3a) are lacking and transgressive deposits (S3b) occur directly above the sequence boundary (UN3). A thin shell bed (facies Nd2) indicating starvation related to a maximum flooding surface, divides transgressive sediments (S3b) by highstand one (S3c).

a wide area with the associated development of a degradational fluvial network and valley incision. Accordingly, unit S3a represents local fluvial deposition during the LST and the overlying unit S3b can be ascribed to a TST. As a consequence, the wave-winnowed surface RS4 corresponds to the transgressive surface marking the boundary between the LST and TST.

This transgression induced a marked sediment starvation (manifested by the accumulation of shell-rich Nd2 deposits over a wide area) and caused the drowning of the valley and its interfluves, as attested by the occurrence of Nd2 deposits directly above unconformity UN3, where fluvial LST deposits are absent. In this setting, the shell-rich bed at the top of unit S3b is interpreted as a "downlap shell bed" (*sensu* Kidwell 1991; Kondo et al. 1998), a key bed manifesting a maximum flooding surface with associated sediment starvation that favoured the proliferation of benthic fauna. The offshore S3c mud resting on this surface is therefore considered the expression of the HST. Finally, the abrupt facies change represented by the superimposition of unit S3d on S3c, namely coarse fluvio-deltaic deposits over offshore fines, testifies a marked basinward shift of proximal facies following a relative sea-level fall, with accumulation of FSST deposits (i.e. unit S3c).

Sequence S4

Sequence S4 crops out extensively in the eastern sectors of the investigated area, where it rests unconformably onto both pre-Neogene bedrock and older Pliocene units (Fig. 3). It is predominantly made of sand with minor gravels and mud deposited in a variety of depositional environments, ranging from alluvial to marine.

The basal sequence boundary (UN4) is expressed landwards by a subaerial erosional surface, passing basinwards to a correlative conformity. The

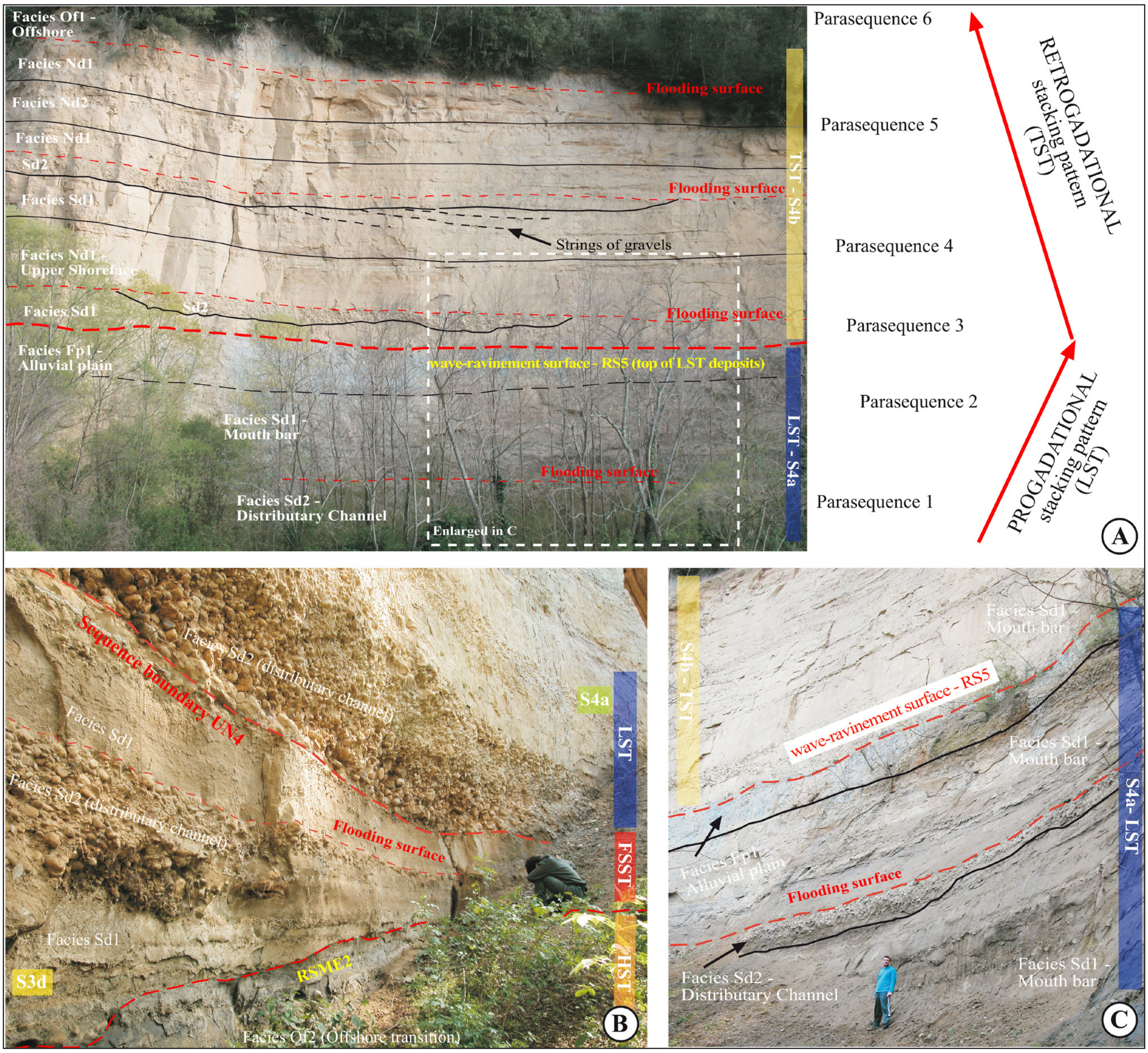


Fig. 11 - Outcrop expression of Sequence S4 main features at the Poggio Bonelli outcrop. A) Panoramic-view of the LST and TST deposits of Sequence S4. The line-drawing highlights facies boundaries and sequence-stratigraphic surfaces. Note the internal arrangement in well-developed parasequences. B) Close-up view of the S3/S4 transition. Note the ravinement surface of marine erosion (RSME) that typifies the boundary between FSST and HST deposits of Sequence S3. S4 LST deposits overlie coarse-grained FSST-related deposits. C) Close-up view of the transition between unit S4a (LST deposits) and unit S4b (TST deposits).

subaerial portion of UN4 is characterized by a high erosional relief that locally defines a paleovalley morphology. Sequence S4 is bounded at the top by a regional subaerial erosional unconformity (UN5) related to the late Piacenzian-early Gelasian emersion of the basin (Marinelli 1975; Bossio et al. 1992, 1993). The recognition of internal key stratigraphic surfaces (RS5 and MFS3) enabled to divide sequence S4 into three units, labelled S4a, b and c in upward stratigraphic order.

Unit S4a overlies sequence boundary UN4 and is topped by a wave-winnowed surface (RS5). This unit shows its maximum stratigraphic development at distal areas, in the southern portion of the studied areas (e.g. Poggio Bonelli outcrop, Figs 11A-C), where it starts with shoal-water delta deposits (facies association SD) consisting of distributary channel sandy gravel (facies Sd1), passing upwards to mouth bar deposits (facies Sd2) and to floodplain mud (facies association FP). Such deposits are vertically stacked in two parasequences, showing a progradational-aggradational stacking pattern. The uppermost floodplain deposits of units S4a are paved by a shell-rich gravel lag representing a ravine-

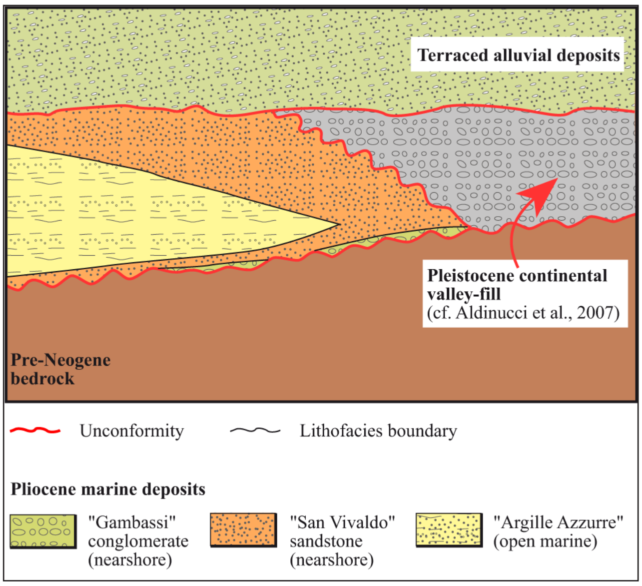


Fig. 12 - Relationship between lithostratigraphic formations in the investigated area (after Lazzarotto et al. 2005a, b). Note as Pliocene marine deposits form a single transgressive-regressive cycle.

ment surface (RS5) that marks the base of unit S4b with the restoration of a fully marine setting. This unit is made of an overall retrogradational set of marine parasequences recording a transition from sand-prone nearshore (deltaic-to-lower shoreface) deposits (facies associations SD and ND) to offshore fines (facies associations OF; Fig. 11A). Offshore deposits record the deepest depositional conditions of sequence S4 and, in a simplified view, the maximum landward retreat of coastal systems. However, the lacking of clear indicators for sediment starvation (e.g. shell beds, Kidwell 1991; Di Celma et al. 2005; and/or glauconite-rich layers, Amorosi 1997) prevents from detecting the maximum flooding surface. Consequently, the term "maximum flooding band" (MFS3) is used, as for Sequence 2, to represent the upper boundary of unit S4b.

The overlying unit S4c is made of offshore mud (facies association OF) grading upwards into shallow-water deltaic sand with subordinated gravels (facies association SD). It forms an overall coarsening upward succession with an internal parasequential organization.

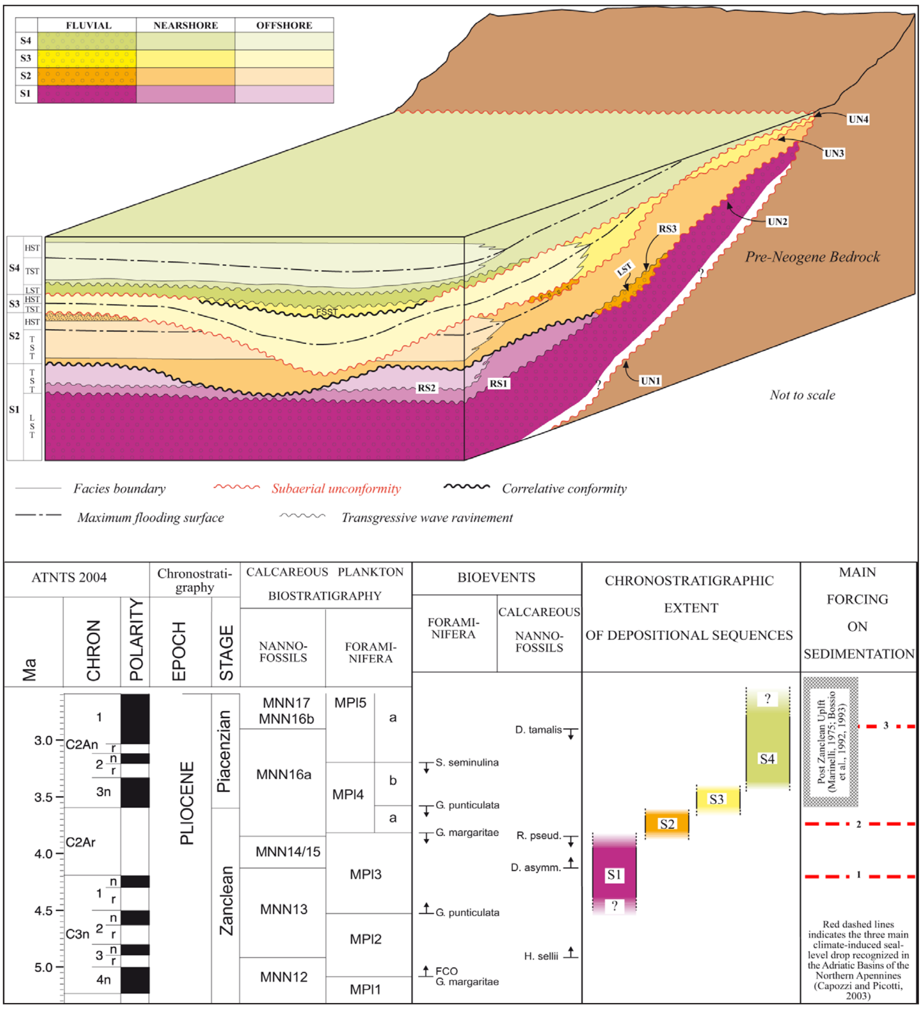
Sequence stratigraphic interpretation. In a sequence-stratigraphic perspective, key-stratal surfaces and the progradational-aggradational nature of sequence S4 suggest that the basal unit S4a corresponds to a LST. Continental deposits at the top of unit S4a were partially re-worked during the subsequent transgression, as evidenced by the transgressive lag connected with the wave-ravinement surface (RS5) that marks the base of unit S4b. Such basal key-stratal surface and internal retrogradational stacking of compositional parasequences are consistent with the TST nature of unit S4b. Finally, the progradational motif documented by unit S4c, along with its stratigraphic position, is consistent with a HST deposition.

DISCUSSIONS AND CONCLUSIONS

Previous studies based on lithostratigraphic concepts interpreted the Pliocene silicoclastic deposits exposed in the northern margin of the Siena-Radicofani Basin as the result of a single marine transgressive-regressive cycle (Fig. 12) of early Zanclean- Piacenzian age (Costantini et al. 1982; Lazzarotto et al. 2005a, b). However, recent biostratigraphic data from the northern basin margin suggest that marine deposition likely continued until the early Gelasian (Martini et al. 2016). A more complex stratigraphic architecture was highlighted by Martini et al. (2011), who firstly recognized mappable unconformities in the Pliocene successions which have been used to further partition the Pliocene succession into allostratigraphic units. However, no study to date has dealt with both the internal stratigraphic architecture and depositional history of individual allounits. This paper aims at filling this gap through the use of facies analysis and sequence-stratigraphic concepts. This approach has proved to be useful for the distinction of allocyclic *versus* autocyclic surfaces, that are difficult to distinguish in paralic settings (cf. Catuneanu 2006; Catuneanu et al. 2009), leading to a possible misinterpretation of the depositional history.

The Pliocene succession exposed in the studied area is up to 150 m thick (Fig. 2) and records a time span of about 1.5 Ma (see Fig. 13). This, along with the presence of multiple and closely spaced unconformities, indicates a low accommodation setting (cf. Zaitlin et al. 2002; Leckie et al. 2004; Allen & Fielding 2007). These unconformities allowed to classify the Pliocene succession into four depositional sequences, S1 to S4 in upward stratigraphic order (Fig. 13). Each sequence deposited in a variety of sedimentary environments, spanning from allu-

Fig. 13 - Synthesis of the sequence-stratigraphic arrangement of the northern Siena-Radicofani Basin (not in scale) and their chronostratigraphic extension (after Martini et al. 2011).



vial to marine inner shelf. The internal architecture of the sequences is typical of low-accommodation basin-margin settings, with poorly-developed or no record of the FSST and a LST typically made of fluvio-deltaic deposits (cf. Allen & Fielding 2007). Transgressive deposits pertain to different depositional sequences, greatly variable in thickness from less than 1m of shoreface sand (sequence S3) to some 20 m of deltaic-to-shoreface deposits with an internal parasequential architecture (sequence S4). HST deposits comprise marine offshore to nearshore facies and are typically deeply eroded following successive relative sea-level falls. The occurrence of poorly preserved and/or deeply eroded HST deposits is typical of low accommodation settings (Zaitlin et al. 2002).

As for sedimentation controlling factors, available biostratigraphic constraints (see Fig. 13) do not allow a detailed comparison with the eustatic sequences recognized in the coeval basins of the Adriatic side of the Northern Apennines (cf. Capozzi & Picotti 2003 and reference therein). However, the absence of evidence for syn-depositional tectonic activity during the deposition of sequences S1-3, as well as their scarce gravel content, suggest a predominantly eustatic control. This is consistent with the large spatial distribution of shoal-water deltaic systems recorded by these sequences, suggesting a low subsidence rate during the delta growth (García-García et al. 2006).

Unlike sequences S1 – 3, chronological constrains and regional evidence (Marinelli 1975; Martini et al. 2001; Ghinassi et al. 2004, 2013; Aldinucci et al. 2007; Fidolini et al. 2013) suggest that the deposition of sequence S4 was mainly controlled by an uplift of the Chianti Mounts (Fig. 1) dating back to the Piacenzian period and persisting until the Gelasian and Pleistocene (Fidolini et al. 2013 and references therein). Tectonically active areas are generally characterized by a high sediment supply and high subsidence rates in nearby sedimentary basins, which promote the vertical stacking of

Gilbert-type deltaic complexes (Dorsey et al. 1995; García-García et al. 2006). In these settings, the subsidence in the basin is coeval with the uplift of the chain, whilst the high sediment supply persists after the active tectonic phases as a consequence of morphologic rebalancing due to erosion of the uplifted areas (c.f. Posamentier & Allen 1999; Fidolini et al. 2013). A marked aggradational component is a distinctive feature of sequence S4, where deltaic sedimentation also occurred during transgression, thus preventing the sediment starvation typical of transgressive conditions. This aggradational component is consistent with a high sediment supply from the uplifting/uplifted Chianti Mountains. Finally, the dominance of shoal-water deltaic deposits in sequence S4 supports the notion that shoal-water deltas can be an important building block of successions developed in settings characterized by high-accommodation and high-sediment supply (cf. Ambrosetti et al. 2017), and that the development of this kind of deltas is not limited to low-accommodation settings.

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