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The role of sediment supply in large-scale stratigraphic architecture of ancient Gilbert-type deltas (Pliocene Siena-Radicofani Basin, Italy)

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Abstract

Aggradation, progradation and retrogradation are the main patterns that define the large-scale architecture of Gilbert-type deltas. These patterns are governed by the ratio between the variation in accommodation space and sediment supply experienced during delta growth. Sediment supply variations are difficult to estimate in ancient settings; hence, it is rarely possible to assess its significance in the large-scale stratigraphic architecture of Gilbert-type deltas. This paper presents a stratigraphic analysis of a Pliocene deltaic complex composed of two coeval and narrowly spaced deltaic branches. The two branches recorded the same tectonic- and climate-induced accommodation space variations. As a result, this deltaic complex represents a natural laboratory for testing the effects of sediment supply variations on the stratigraphic architecture of Gilbert-type deltas. The field data suggest that a sediment supply which is able to counteract the accommodation generated over time promotes the aggradational/progradational attitude of Gilbert-type deltas, as well as the development of thick foreset deposits. By contrast, if the sediment supply is not sufficient for counterbalancing the generated accommodation, an aggradational/retrogradational stratigraphic architecture is promoted. In this case, the deltaic system is forced to withdraw during the different phases of generation of accommodation, with the subsequent flooding of previously deposited sub-horizontal topset deposits (i.e., the delta plain). The subsequent deltaic progradation occurs above these deposits and,

consequently, the available space for foresets growth is limited to the water depth between the base-level and the older delta plain. This leads to the vertical stacking of relatively thin deltaic deposits with an overall aggradatational/retrogradational attitude.

Keywords: Gilbert-type delta, shoal-water delta, delta stratigraphic arrangement, sediment supply, accommodation.

1. Introduction

Gilbert-type deltas have been extensively described in many tectonically active and quiescent basins (e.g., Ethridge and Wescott, 1984; Colella, 1988; Nemec and Steel, 1988; Leren et al., 2010) and have attracted the attention of sedimentary geologists predominantly for their importance as indicators of the infill history of basins. This is particularly relevant for coarse-clastic basin margins, where bio-stratigraphic age control is generally poor and the stratigraphic arrangement of Gilbert-type deltas has been used as a tool for refining the reconstruction of basin fill patterns and basin subsidence kinematics (Postma, 1995).

The large-scale architecture of Gilbert-type deltas is defined by three main patterns: progradation, aggradation and retrogradation (e.g., Postma, 1995; Marzo and Steel, 2000). These patterns are generally identified by the trajectory of the topset/foreset transition point (also called "topset breakpoint path" by some authors, e.g., Backert et al., 2009) along the sedimentary succession (Helland-Hansen and Martinsen, 1996; Mortimer et al., 2005). These stratigraphic patterns are essentially governed by two allocyclic driving factors: i) the accommodation space variations, and ii) the type and amount of sediments supplied to the deltaic systems by rivers (Posamentier and Allen, 1993; Dorsey et al., 1995; Postma, 1995; Bijkerk et al., 2014). Autocyclic processes (e.g., delta-lobe switching) may secondarily influence the architecture of deltas, although they generally do not dramatically modify the overprint given by allocyclic driving factors to the final stratigraphic architecture.

The creation/degradation of accommodation space results from the combination of global sea-level variations and vertical movements within the basin. In turn, the combination of global sea-level variations, basin subsidence and sediment supply define the stratigraphic architecture of sedimentary successions and the shoreline trajectory pattern (cf., Posamentier and Allen, 1999; Coe et al., 2002; Catuneanu, 2002). Global sea-level variations are easily predictable from the Pliocene to present (Haq et al., 1987; Miller et al., 2005) and the basin subsidence history can be deduced by micropalaeontological, structural, seismic and geophysical data. On the contrary, the type and amount of sediment supplied to deltas are difficult to estimate in ancient settings, even though they play a crucial role in the formation and growth of deltas (López-Blanco et al., 2000; Marzo and Steel, 2000; Carvajal et al., 2009; Bijkerk et al., 2014). Variations in sediment yield can be connected for several factors, such as climatic changes, tectonics, geology of the drainage basin, inherited basin relief, etc. (cf., Schumm and Lichty, 1965), which often act unpredictably.

The aim of this paper is to understand the role of sediment supply on the stratigraphic architecture of ancient Gilbert-type deltas. For this purpose, a Pliocene Gilbert-delta complex located in the Siena-Radicofani Basin (Tuscany, Italy) has been investigated in accordance with sedimentological and stratigraphic criteria. The delta complex is composed of two different branches, situated ~300 m apart, and supposed coeval based on the lateral tracing of two key stratigraphic surfaces that mark the beginning and the end of the Gilbert-type related deposition. The two branches show an overall similar stratigraphic evolution, with basal shoal-water delta deposits passing upward to Gilbert-type delta deposits, which are in turn abruptly overlain by shoal-water delta deposits. However, the Gilbert-type delta deposits in the two branches display a marked difference in their stratigraphic arrangement.

The coeval timing of the two delta branches ensures that climate-induced base-level fluctuations influenced the delta complex built up in the same way. Moreover, the shoal-water delta deposits at the base and top of the succession narrowly constrain the accommodation space experienced during Gilbert-delta build-up, suggesting that subsidence acted uniformly in the area during deposition. Consequently, it is considered that the observed differences in the stratigraphic architecture are only attributable to differential sediment supply feeding the different delta branches.

2. Geological setting

The study area is located in the central part of the Siena-Radicofani Basin, close to the traditionally accepted boundary between the Siena and Radicofani sub-basins (southern Tuscany, Italy; Fig. 1A, B). These sub-basins have been considered as independent basins for a long time. Recently, however, Brogi (2011) demonstrated that they belong to the same tectonic depression and for this reason the term "sub-basins" is adopted. The Siena-Radicofani Basin (which also includes the Casino sub-basin to the north) is one of the most important post-collisional basins of the inner Northern Apennines (Costantini et al., 2009). Post-collisional basins correspond to a series of NNW-SSE trending tectonic depressions developed since the middle Miocene (Jolivet et al., 1998; Brunet et al., 2000), in which continental and marine sediments accumulated since the Miocene until the Quaternary.

The Siena-Radicofani Basin is traditionally interpreted as having developed in extensional settings and records a basin-and-range structural architecture (Martini and Sagri, 1993; Carmignani et al., 1995; Jolivet et al., 1998; Pascucci et al., 1999; Carmignani et al., 2001). Brogi (2011) proposed a more complex history, which sees the basin originating due to the activity of Serravallian/late Messinian staircase extensional detachments. These produced a bowl-shaped structural depression, which is partially modified by high-angle normal fault systems active during the Pliocene. Other authors interpreted the Basin as a thrust-top basin developed in a compressional tectonic setting (Finetti et al., 2001; Bonini and Sani, 2002).

2.1 Neogene sedimentation

Sedimentation in the Siena-Radicofani Basin starts in the late Miocene when deposition of a fluvio-lacustrine succession occurred. Miocene deposits unconformably overlie pre-Neogene bedrock and are presently exposed in limited areas. These sediments are in turn overlain unconformably by Pliocene deposits (Costantini et al., 2009) which accumulated since the early Zanclean until the late Piacenzian/earliest Gelasian (Bossio et al., 1992; Martini et al., 2011, 2013, 2016; Arragoni et al., 2012; Martini and Sandrelli, 2015).

The Pliocene succession is mainly represented by nearshore marine deposits close to basin margins, which pass basinwards to offshore fines. Episodes of continental sedimentation have been reported in the lower part of the Pliocene succession close to the Siena sub-basin margins (Bossio et al., 1992, 1993; Aldinucci et al., 2007; Manganelli et al., 2010, 2011; Martini et al., 2011; Bianchi et al., 2013). Individual sub-basins recorded different infilling histories, generally related to the time intervals when deposition occurred. Synthetic stratigraphic columns of the sedimentary successions exposed in the central sectors of the Siena and Radicofani sub-basin are proposed in Fig. 1C. Figure 1C also reports the stratigraphic column of the sedimentary succession exposed in correspondence to the bedrock high that marks the traditionally accepted Siena/Radicofani sub-basins boundary (i.e, the so called “Pienza high”, data derived from Marini, 2001; Antoni et al., 2005). Among the several and marked differences in the depositional infilling history of these areas, it is important to highlight that marine settings persisted in basinal areas during the Pliocene. A low-magnitude intra-Pliocene base-level fall (occurred within the MPl3 biozone) is recorded only in the surrounding of the “Pienza high”, where lacustrine limestones and fluvial conglomerate occur within the Pliocene succession. Continental settings in which these deposits accumulated have been interrupted by a relative sea-level rise occurred at top of the Zanclean (MPl4 biozone) that restored marine settings (Marini, 2001).

Marine settings ended due to a regional uplift which affected southern Tuscany since the Piacenzian (Marinelli, 1975; Bossio et al., 1993). Quaternary deposition is documented by discontinuous outcrops of sandy-gravelly alluvial deposits (Aldinucci et al., 2007; Bianchi et al., 2013; Brogi et al., 2014).

The investigated area is located close to the "Pienza high" and previous stratigraphic studies have been performed in this area adopting lithostratgraphic criteria (Bonini and Sani, 2002; Antoni et al., 2005).

The succession deposited during the Zanclean (MNN14/15 biozone of nannoplancton biostratigraphy; Martini et al., 2015) and according to Bonini and Sani (2002) and Antoni et al. (2005) it is mainly composed of coarse-grained and steeply inclined (up to 30°) conglomerate beds overlain by sub-horizontal sandstone. Bonini and Sani (2002) interpreted the angular unconformity between the conglomerate and the sandstone as connected to an intra-Pliocene uplifting pulse.

3. Methods

The study uses conventional geological field methods, including: i) mapping based on facies association concepts (at 1:5000 scale); ii) bed-by-bed sedimentological logging of twelve sections (about 320 m of measured succession); iii) collection of palaeocurrent indicators; and iv) line-drawing of architectures on photomosaics of four selected outcrops (up to 400 m long and 80 m high). The location of measured sections, as well as of the outcrops selected for line-drawings, is reported on Figure 2. The area is vegetated by tall trees, thus offering limited opportunities to take good photographical records of extensive outcrops. In order to overcome this problem, large outcrops are featured as line-drawings and important features are detailed in close-up photos.

The sedimentological analysis is based on the concept of facies association, i.e., assemblages of spatially and genetically related facies that are the expression of different sedimentary environments (Walker and James, 1992). The descriptive sedimentological terminology is from Harms et al. (1975, 1982) and Collinson et al. (2006).

The term “flooding surface” is used in accordance with its classical meaning (cf., Van Wagoner et al., 1988), i.e., the surface connected to a transgressive pulse that separates shallower-water strata below from deeper-water strata above. However, in deltaic settings, autocyclic factors (i.e., not connected with base-level fluctuations) can produce vertical facies superimposition that resembles those typically connected to flooding surfaces. The term “deactivation surfaces” has been introduced to describe settings where vertical facies superimpositions have an ambiguous significance and could be related either to flooding events or to autocyclic lobe avulsion processes.

The term EDU (elementary deltaic unit) is used according to Ambrosetti et al. (2017), i.e., to indicate an assemblage of vertically stacked and genetically related facies that document the progradation of the deltaic system. EDUs are the stratigraphic expression of delta lobes, i.e., the sedimentary body forming at the river mouth. Individual EDUs are bounded by flooding/deactivation surfaces and, consequently, EDUs are equivalent to parasequences only if the progradation is interrupted by flooding surfaces, whereas they do not coincide with parasequences if the progradational trend is interrupted by deactivation surfaces connected to autocyclic processes, such as delta lobe switching. The term “parasequence” is used in accordance with the definition of Van Wagoner et al. (1988) taking into account the suggestions of Arnott (1995).

The term “delta branch” is used to indicate the area interested by deltaic deposition in which the sediments have been provided by the same distributive system. As a consequence, each delta branch record a complex depositional history, that includes lobe superimposition, lateral lobes stacking and lobe shifts.

4. Results

Ten facies associations have been identified on the basis of sedimentological and stratigraphic features. Each facies association is representative of a well-defined depositional environment; their features are described and interpreted below and summarised in Table 1. Facies associations are described in the main text from distal to proximal. Eight facies associations are the expression of deposition in a deltaic environment, one is the expression of wave- winnowing processes acted in nearshore settings, and another one is the expression of continental deposition.

The distribution of sedimentary facies (Fig. 2) document that Gilbert-type deposition occurred in two deltaic branches (hereafter DB1 and DB2). As commonly observed in deltaic systems, coarse-grained facies typify the axial portion of each delta branch (see Fig. 2), while finer sediments occur in distal (pro-delta) and lateral (interlobe) positions. The two delta branches are spaced at about 300 m in basinward positions, while they are in contact with each other in landward position. Consequently, the spatial distribution of the two branches resembles two divergent aprons with the apical position located in the same area.

Gilbert-type deposits are sandwiched between shoal-water deltaic deposits in both delta branches. The stratigraphic boundaries of the Gilbert-type deposits correspond to two surfaces that can be traced laterally throughout the entire investigated area and for this reason it has been used as a key surface for lateral correlation between the two delta branches. They are named TS1 (lower boundary) and TS2 (upper boundary). Surface TS1 is associated with: i) wave-winnowed lag deposits flooring a low-relief erosional surface; and ii) the drowning of the basal shoal-water deltaic system. As a consequence, TS1 corresponds to a transgressive surface associated with a major flooding event. Surface TS2 is also connected with wave-winnowed lag deposits flooring an erosional surface and documenting a transgressive event, but it also marks the abrupt deposition of shallower deposits (shoal-water delta sediments) on top of bottomset and foreset deposits (see Fig. 8A,B). As a consequence, TS2 can be interpreted as a composite surface originated due to a relative sea-level fall (responsible for the superimposition of shallower facies above deeper one) combined with a subsequent transgression. These two events are also recognized in the surrounding area (see Fig. 1C, “Pienza High” stratigraphy), where they have led to the localized deposition of continental lacustrine sediments above marine deposits, which are in turn overlain by shoreface sandstones. The detailed stratigraphic architecture of each delta branch is described in section 4.2.

4.1 Sedimentology

4.1.1 Offshore to prodelta deposits

Description

These deposits consist of thick and monotonous successions of grey mudstone, rarely containing cm-thick and tabular silty-sandstone beds. Mudstone beds are tabular and generally structureless due to the pervasive bioturbation, while only occasionally a faint of lamination is observable. Mudstone beds are generally poor in organic matter and locally contain marine mollusks (e.g., *Chlamys, Venus, Naticarius,* etc.). The sandstone beds show sharp bases and tops and they are normally graded and internally structureless or plane-parallel laminated. Low-angle cross-laminations can also be observed at time in the upper part of the beds. Organic debris (e.g., plant, wood and leaves) and clay chips occur occasionally in the basal part of the beds.

Interpretation

These deposits are interpreted as the expression of deposition in an open marine setting that is relatively close to a shoreline and/or to fluvial inputs. The predominance of fine-grained sediments suggests a deposition due to suspension fallout in offshore/prodelta marine setting (Johnson and Baldwin, 1996). The uncommon sandstone beds were probably emplaced by major hyperpycnal flows generated by river floods, where the genetic connection with river mouths is supported by the occurrence of plants remains, as commonly documented in similar settings (e.g., Plink-Björklund and Steel, 2004; Martini and Sandrelli, 2015).

4.1.2 Delta front deposits of shoal-type deltas

Description

This facies association predominantly consists of poorly- to moderately-sorted sandstone with subordinated siltstone and conglomerate, forming coarsening-upward units up to 5-10 m thick, characterized by tabular to slightly convex upward geometries at outcrop scale (Fig. 3A). Sandstone are mainly expressed by two facies: i) thick (0.5-2 m) plane-parallel laminated beds, locally structureless due to intense bioturbation, often forming m-thick amalgamated sandy packages; ii) low-angle cross-laminated sandstone and gravelly sandstone. The former facies typical typify the lower part of coarsening-upward units, while the latter the upper one. Shell-rich sandstone beds, with bivalve in life position (including *Pinnidae*, Fig. 3B) often occur. Siltstone beds (cm-thick) typically occur in the lower portion of coarsening-upward units and they are rich in sandy matrix, plane-parallel laminated and poorly bioturbated. Plant debris and leaves remains are common both in the sandstone and the siltstone beds.

Interpretation

The features of this facies association indicates that deposition occurred in a proximal delta front environment of shoal-water type deltas, where depositional processes are dominated by frequent and conspicuous sediment supply from a land-derived source (i.e., fluvial input). This limits the deposition of fines, that are then pushed out in more distal settings. The deltaic nature of these deposits is also supported by: i) the moderate sorting of sediments; ii) the common occurrence of terrestrial plant remains, indicating a close terrestrial source of sediment; and iii) the overall geometries, typical of delta lobes of shoal-water deltas.

The thick plane-parallel laminated sandstone packages are also typical of such environments and they result from sustained underflows emanated from river mouths during river floods (Plink-Björklund and Steel, 2004; Petter and Steel, 2006; Martini and Sandrelli, 2015). The features of siltstone beds (i.e., preservation of laminae and scarce bioturbation) suggest higher sedimentation rates (Martini and Sandrelli, 2015), compatible with an emplacement related to land-derived low-density hypo- and hyper-pycnal flows during stages of low discharge (Nemec, 1995). Shell-rich beds are representative of stages of low sediment supply, when infaunal organisms can colonize the sea-floor. These stages are attributed to transgressive pulses or to the temporary deactivation of the deltaic system.

4.1.3 Mouth-bar deposits of shoal-type deltas

Description

Deposits of this facies association typically overlies delta front deposits and consist of sandstone, with subordinated conglomerate and gravelly sandstone (Fig. 3C). Fines are generally uncommon. Mouth-bar deposits are arranged in 2-5 m thick units, characterized by coarsening-upward trends and well-marked convex upward geometries at outcrop scale.

Mouth-bar deposits mainly consist of: i) plane-parallel stratified sandstone beds, often showing a basal erosional scour, marked by the alignment of granules and pebbles; ii) dm-thick, normally graded, structureless to plane-parallel and/or planar cross-stratified gravelly and coarse-grained sandstones, with occasional mud clasts; iii) fine-grained and (symmetrical) rippled sandstones, that usually occur in the upper part of the mouth-bar successions; iv) single-clasts alignments of gravels (pebble- to cobble-sized), overlying slight erosional scours and overlaid in turn by finer-grained sediments (medium- to fine-grained sandstone); and v) cm-thick massive to plane-parallel laminated sandy mudstone beds.

Interpretation

The overall features of this facies association (including the geometries, the stratigraphic position in respect to delta front deposits, the coarsening-upward trend and the constituent facies) suggest that sedimentation occurred in a mouth-bar environment, where sediments are directly supplied by distributary channels. In these settings, the deposition is mainly related to sustained underflows connected to river-related floods (i.e., hyperpycnal flows; Mulder and Alexander, 2001; Mulder et al., 2003; Plink-Björklund and Steel, 2004; Petter and Steel, 2006; Olariu et al., 2010). Mouth-bar deposits were at times reworked by fair-weather waves, as revealed by rippled sandstone, confirming that the deposition occurred in relative shallow settings (above fair-weather wave base). Single-clast alignments of gravels are the expression of residual lags connected to wave-winnowing processes during transgressive pulses.

4.1.4 Distributary channel deposits of shoal-type deltas

Description

These deposits consist mainly of sandy conglomerate with subordinate sandstones arranged in fining-upward lithosomes, forming erosional based and lens-shaped bodies, up to 2-3 m thick and 3-10 m wide (Fig. 3C). Distributary channel deposits erosionally overlay mouth-bar deposits and show concave upward bases and flat tops (Fig. 3C). At places, internal erosional surfaces are recognized within distributary channel deposits.

Gravels are pebble- to cobble-sized and form 20-30 cm thick clast-supported beds, structureless to crudely plane-parallel stratified. Clast imbrications (b(i)a(t) and a(i)a(p)) sometimes occur. Gravel beds occasionally grade into massive or plane-parallel laminated coarse-grained sandstones. Individual beds are typically amalgamated and clasts are often encrusted by barnacles showing no evidence of reworking.

Interpretation

Based on the geometrical features, the fining-upward trend and the stratigraphic position, these deposits are interpreted as distributary channel-fill deposits (Li and Bhattacharya, 2014). Distributary channels represent the prolongation of river channels within the delta plain and supply sediments directly to the mouth-bars and to the deltaic system.

Sedimentary facies resemble the typical facies recognizable in fluvial channel-fill deposits (Smith, 1974; Bridge, 2003), except for the clasts encrusted by barnacles that document the close genetic relationship between the distributary channel deposits and the marine deltaic environment. The fining-upward trend is indicative of the progressive infilling and abandonment of channels and internal erosional surfaces suggest a multi-storey infill history (Ambrosetti et al., 2017).

4.1.5 Bottomset deposits of Gilbert-type deltas

Description

These deposits consist of poorly sorted sandstone with subordinate silty mudstone beds, typically sub-horizontal to gently inclined seaward (0 to 5°, Fig. 4A). Bottomset deposits commonly occur directly downdip and stratigraphically below toeset and foreset deposits (Fig. 4A).

Sandstone are fine-grained, weakly sorted, structureless or faintly plane-parallel laminated (Fig. 4B, C). Sandstone beds commonly contain isolated and rounded gravel clasts, dispersed within beds or segregated into flat stringers (Fig. 4B, C). Mudstone beds are thin and discontinuous, often massive due to bioturbation.

Interpretation

Features of this facies association and the genetic relation with toeset and foreset deposits suggest the deposition in delta bottomset settings of Gilbert-type delta lobes (Colella, 1988; Massari and Colella, 1988; Sohn et al., 1997). Depositional processes in this environment are strongly influenced by the decrease in delta slope occurring at the transition between Gilbert-delta foreset and bottomset, causing the deposition by the dumping of sand load from high-density turbidity currents (*sensu* Lowe,1982). Isolated gravels within sandstone beds could be debris-fall "outrunners" (Nemec, 1990; Sohn et al., 1997) or clasts rolled in isolation by the sandy turbidity currents (Postma and Roep, 1985). Mudstone beds were emplaced due to low-density hypo- and hyper-pycnal flows connected to river-mouths.

4.1.6 Toeset deposits of Gilbert-type deltas

Description

These deposits consist of conglomerate with subordinate sandstone, typically sub-horizontal to gently inclined seaward (0 to 10°). Toeset deposits occur above bottomset deposits or are interbedded within them and typically occur downdip to the delta foreset deposits (Fig. 4A). Toeset deposits show similar facies to foreset deposits and mainly differ for the bedding dip angle, higher in foreset beds. Conglomerate beds mainly consist of: i) mounded, clast-supported and distribution-type to coarse-tail inverse graded beds (Fig. 4D), with occasional vertical oriented clasts (Fig. 4E); and ii) matrix (sand) supported and crudely normal graded beds. Gravels are moderately to well rounded, with their size ranging from small pebble to large cobble. Angular clasts (i.e., debris) and blocks of cemented sediments have occasionally been found. Clasts are commonly encrusted by oysters and barnacles or bored by *Lithophaga* sp., even if such remains are commonly abraded. Sandstone beds are normally graded, structureless or locally bearing plane-parallel lamination at the top of the beds.

Interpretation

The genetic relation with foreset and bottomset deposits, combined with the features of constituent facies, suggests the deposition in delta toeset settings of Gilbert-type delta lobes (Colella, 1988; Massari and Colella, 1988; Sohn et al., 1997). In these settings, mounded and clast-supported conglomerate testify the “freezing” of debris flows at the toe of the delta slope (Nemec, 1990; Sohn et al., 1997), whereas matrix-supported conglomerates are attributed to the accumulation of clasts at the toe of the delta slope due to debris fall processes. Sandstone beds were emplaced due to high-density turbidity currents.

4.1.7 Foreset deposits of Gilbert-type deltas

Description

These deposits consist of seaward-inclined (20 to 35°) conglomerate beds and subordinated gravelly sandstone (Fig. 4A, F), vertically stacked up to form thick bodies (up to 60 m), stratigraphically overlying bottomset and toeset deposits. The depositional dip of foreset beds typically diminishes downdip and merges with sub-horizontal beds of bottomset and toeset facies associations. Locally, however, inclined foreset beds sharply overlie bottomset deposits.

Conglomeratic beds are 10 to 100 cm thick (Fig. 4F) and consist of pebble to cobble gravel (with occasional boulders) and include the following facies: i) tabular to lenticular openwork beds, with larger clasts in the downdip part; ii) tabular or mounded beds, matrix (sand) supported and structureless, generally non-graded or occasionally showing coarse-tail inverse grading (Fig. 4F) or shear-banding (Fig. 4G); and iii) tabular, weakly graded and structureless conglomerate beds with erosional bases. Gravel clasts of these facies are frequently bored by *Lithophaga* sp., although these structures are clearly re-worked and abraded. Sandstone beds are composed of coarse-grained sand with scattered gravels, generally cross-stratified upslope or structureless.

Interpretation

The overall features of this facies association indicate a deposition in the foreset setting of a Gilbert-type delta (*sensu* Gilbert, 1885; Barrell, 1912; Colella, 1988), where deposition is strongly related to subaqueous sediment-gravity processes connected to collapses of the upper part of the Gilbert-type delta complex (Nemec, 1990). In detail, openwork conglomerate are attributed to debris fall processes, while matrix-supported and mud-free beds are related to cohesionless debris flow processes (*sensu* Nemec and Steel, 1984). Shear bands within these deposits testify syn-depositional internal thrusting due to rapid braking of flows (Massari, 1984; Nemec, 1990; Gobo et al., 2014b). Erosional based beds are the expression of deposition from high-density and turbulent sediment-laden flows (*sensu* Lowe, 1982). Sandstone beds deposited due to low-density turbidity currents (*sensu* Lowe, 1982) subjected to a hydraulic jump in delta-slope chutes (Nemec, 1990; Nemec et al.,1999; Gobo et al., 2014a,b).

4.1.8 Topset deposits of Gilbert-type deltas

Description

These deposits are relatively uncommon in the studied area and display a facies assemblage and internal architecture similar to distributary channel deposits. Bedding is sub-horizontal and topset deposits occur directly above the Gilbert-type delta foreset. Toeset sediments are generally coarser grained than the distributary channel deposits.

Interpretation

Based on the previously addressed considerations for distributary channel facies association, topset deposits represent the prolongation of river channels within the delta plain that supplies sediments directly to the deltaic system. The stratigraphic position of these deposits above foreset one allow to consider them as the topset deposits (i.e., alluvial distributary plain) of a Gilbert-type delta.

4.1.9 Wave-winnowed lag deposits

Description

These deposits consist of conglomerate with abundant mud-free sandy matrix, forming individual and relatively thin beds (10-50 cm) at the top of the deltaic deposits. Beds are erosionally-based, normally graded and range from sheet-like gravel beds to discontinuous horizons of scattered or clustered gravel clasts. Broken shell remains are common within the sandy matrix and clasts are often encrusted (*Ostrea lamellosa*, *Balanus* sp.) and bored by *Lithophaga* sp.

Interpretation

The overall features and fossil content indicate deposition as gravel lags originated due to wave-related winnowing processes on the sea-floor (Hwang and Heller, 2002; Cattaneo and Steel, 2003). These processes typically occur during relative sea-level rises and caused the partial erosion of previously deposited sediments, the concentrations of gravel clasts up to form gravel pavements and the removal of fine-grained sediments that are pushed-out in distal position.

4.1.10 Slope and Alluvial fan deposits

Description

These deposits are only exposed in a limited area, limiting their detailed sedimentological investigation (Fig. 5A,B). They consist of poorly sorted pebble to boulder gravels bearing a great amount of interstitial sandy matrix, internally disorganized to crudely normally graded with an a(p) or a(p)a(i) fabric of elongate clasts. Beds are tabular, up to 1m thick and often amalgamated. Clasts are not encrusted or bored by marine organisms.

Interpretation

The limited exposures of such deposits prevent a detailed interpretation of the depositional environment. However, the features suggest a deposition due to debris flow processes (Nemec and Steel, 1984) in a sub-aerial environment, possibly connected to an alluvial fan system (Fidolini et al., 2013). This is confirmed by the lack of marine organism traces within these deposits.

4.2 Stratigraphic architecture

4.2.1 Stratigraphic architecture of delta branch 1 (DB1)

Investigations on DB1 have been mainly carried out on two outcrops that document the proximal to distal evolution of the deltaic system. Paleocurrent data collected in topset deposits indicate a main WSW transport direction (see rose diagrams in Fig. 5). The landward outcrop is approximately parallel to the main direction of progradation of the deltaic system (Fig. 5), while the basinward outcrop is approximately perpendicular to it (Fig. 6).

The DB1 succession starts with shoal-water delta sediments, expressed landwards by fluvial-like distributary channel deposits (Fig. 5A,B), passing basinwards to gently and seaward-inclined mouth-bar deposits. The latter are erosionally overlain in places by gravelly distributary channel sediments (see left corner of Fig. 6A,B). Basinwards, at least two shoal-water elementary deltaic units (hereafter EDUs) displaying a vertical parasequence-like arrangement can be identified. Channel basal scours have a concave-up profile and channels are relatively small in size (1 to 5 m wide and 1-2 m deep, Fig. 6B).

Shoal-water delta deposition is abruptly interrupted in both outcrops: i) in landward position, the distributary channel sediments are overlain by 3 m thick continental deposits (slope and alluvial fan facies association), overlain in turn by a 50 cm thick sandstone bed pertaining to the wave winnowed lag deposits and by an 8 m thick and poorly exposed bottomset deposits (Fig. 5A,B); ii) basinward (Fig. 6B), shoal-water delta deposits are gently shaped by an erosional surface that marks the base of a thin (50 cm) gravel lag (wave winnowed deposits) above which offshore to prodelta mudstones occur. The surface marked by the base of the wave winnowed lag deposits corresponds to the aforementioned key-surface TS1.

Gilbert-type delta deposition starts above TS1 in both the investigated outcrops (Figs. 5A, 6B). In landward position (Fig. 5A), Gilbert-type deposits are mainly expressed by proximal and coarser facies forming m-thick package of sediments characterized by a well-marked coarsening- and shallowing-upward trend, which are bounded by deactivation surfaces. Deactivation surfaces can be interpreted as flooding surfaces *s.s.* when they mark the instauration of marine settings above topset deposits (see Fig. 5A,E,F for examples). At a larger scale, EDUs are vertically stacked and display the progressive landward migration of the topset/foreset transition point. The present day erosional relief prevents to observe the topset/foreset transition point of the upper EDU, that however, is characterized by coarser and thicker foreset deposits that spread over older deposits (Fig. 5A). Gilbert-type deposits are abruptly and sharply overlain by a 50 cm thick wave-winnowed lag deposits (Fig. 5A) that, in turn, are overlain by shoal-water delta sandstones (facies associations delta front and mouth-bar, up to 15-20 m in thickness as deducible by the geological map on Fig. 2). The surface marked by the base of these wave-winnowed lag deposits corresponds to the key-surface TS2. Basinwards, Gilbert-type deposition is mainly expressed by proximal to distal facies associations (foreset, toeset and bottomset), while topset deposits are absent (Fig. 6A, B). Also in this case, the succession results from the vertical stacking of EDUs, each capped by a flooding/deactivation surface that marks the deactivation of the delta lobe. Lobe deactivation processes are generally sharp, only occasionally gradual as testified by fining-upward trends and the retrogradational attitude of overlying beds. Avulsion processes are locally documented by the lateral emplacement of different deltaic lobes with a "compensational stacking pattern" (i.e., sedimentation in the depression between two lobes). This is particularly evident in the stratigraphically lower Gilbert-type delta lobe, which deposited in the depressed inter-lobe area of the older shoal-water deltaic deposits, onlapping on the inherited morphology (Fig. 6B). At a large scale, the vertical stacking of EDUs displays a progressive increase of fine-grained sediments (bottomset deposits) over coarser sediments (toeset and foreset deposits) towards the upper part of the outcrop. Unfortunately, the upper part of the succession is unexposed preventing the investigation of the entire succession up to the upper shoal-water delta deposits. The overall thickness of Gilbert-type deposits in DB1 is about 65 m.

4.2.2 Stratigraphic architecture of delta branch 2 (DB2)

Investigations on DB2 have been carried out on several outcrops that well document the proximal (Fig. 7) to distal (Fig. 8) evolution of the system. Foreset dips (Figs. 2, 8A) suggest a main NW direction of progradation of the deltaic system. The investigated outcrops are parallel and orthogonal to this direction.

Similarly to DB1, deposition in DB2 started with shoal-water delta deposits (Fig. 7A). These deposits are expressed landward generally by coarse-grained distributary channel deposits, with subordinated gravelly sandstone mouth-bar deposits forming m-thick elementary deltaic units that are vertically stacked in a parasequence-like arrangement (Fig. 7A, B). Such deposits pass basinward to gently and seaward-inclined mouth-bar deposits, only locally erosionally overlain by gravelly-rich distributary channel sediments. Distributary channels in DB2 are thicker and wider than those in DB1 (individual channels are up to 5 m high and at least 10-20 m wide). Additionally, these deposits generally comprise coarser sediments than those in DB1 and contain large mud clasts (Fig. 7C), which suggest a greater fluvial energy for the distributive system of the DB2 shoal-water delta.

Shoal-water deposition was abruptly replaced by Gilbert-type related deposits through a sharp surface that can be laterally correlated to the aforementioned TS1 surface. Gilbert-type deposition across the entire area starts whit bottomset deposits, even if the thickness of these deposits diminishes towards landward positions. In the most landward located outcrops, bottomset deposits are expressed by a thin fine-grained sandstone bed containing remains of marine shells overlying distributary channel sediments (Fig. 7A).

Above bottomset deposits, Gilbert-type delta foreset deposits spread over the entire DB2 branch (Figs. 7A, 8A) forming a coarse-grained wedge, reaching a maximum thickness of about 50-60 m and bounded at its top by a deactivation surface that marks the end of foreset-related deposition (Fig. 8A). Foreset deposits display a progressive increase in bed inclination, passing from 15-20° in the lower part of the succession up to 28-35° in the upper part (Fig. 8A). Stratigraphic evidence connected to deactivation surfaces can be recognized only at the toe of this coarse-grained wedge (as testified by the superimposition of bottomset deposits above foreset and toeset sediments, Fig. 8A-D), while they are not recognizable in the upper part of the wedge. Aa a consequence, these Gilbert-type foreset deposits form a single elementary deltaic unit.

The deactivation surface at the top of foreset deposits marks the beginning of finer-grained deposition, expressed by the vertically stacking of two EDUs expressed exclusively by bottomset and toeset deposits, forming a thick wedge (left side of the outcrop in Fig. 8A,B). Toeset deposits are characterized by the occurrence of debris and blocks, predominantly made of cemented sandstone (Fig.

9A-C) and subordinated cemented conglomerate (Fig. 9A,B,D). Blocks of cemented sandstone contain remains of marine mollusks indicative of a nearshore environment (e.g., *Venus*, *Turritella*, *Chlamis*). The Gilbert-type succession is truncated at its top by a relatively flat erosional surface (corresponding to TS2 surface in DB1, Fig. 8A,B) that marks the base of a 50 cm thick and laterally persistent bed of wave-winnowed lag deposits. Above this bed, sandy shoal-water deposits (facies associations delta front and mouth-bar) occur throughout the investigated area, with average thicknesses ranging between 20 and 30 m (Fig. 8A,B).

4.2.3 Deposition in intra-branches areas

Observations in intra-branches areas (i.e., the area between DB1 and DB2) were made along a small creek incision (see Fig. 2, log 12) where the succession is relatively well exposed (Fig. 10). Sedimentation starts at the base with shoal-water delta mouth-bar deposits abruptly overlain by bottomset deposits via the aforementioned TS1 surface, which is expressed by a 20-30 cm thick gravel lag (wave winnowed lag deposits). Bottomset deposits are only occasionally interbedded with m-thick toeset and foreset sandstone and conglomerate beds (Fig. 10). The ratio between fine-grained and coarse-grained facies is higher than the axial portion of DB1 and DB2 (i.e., fine-grained facies are dominant). At the top of the succession, bottomset deposits are sharply overlain by shoal-water delta front sandstones.

5. Discussion

The investigated succession documents basal shoal-water delta deposits passing upward to Gilbert-type deposits, in turn overlain by shoal-water delta deposits. Similar stratigraphic organizations are commonly described for active tectonic settings in which the changes in deltaic style are mainly connected to variations in subsidence-related accommodation (Dorsey et al., 1995; Garcìa-Garcìa et al., 2006; Ghinassi, 2007). In similar settings, thick Gilbert-type deltaic successions are generally connected to stages of rapid subsidence and high sedimentation rates (Dorsey et al., 1995), while thick and vertically stacked shoal water-type deltaic successions typify stages characterized by low to moderate rates of subsidence and low sediment supply (Garcìa-Garcìa et al., 2006; Ghinassi, 2007). The large-scale stratigraphic architecture of Gilbert-type deltas is strongly influenced by the available accommodation space and the supply of sediments (and their interplay), which are in turn controlled by tectonic and eustasy (cf., Postma 1990a, b; López-Blanco et al., 2000; Marzo and Steel, 2000). The variation of accommodation experienced during the building-up of ancient Gilbert-type deltas can be easily quantified when enough stratigraphic constraints occur. On the contrary, this is generally difficult to estimate in ancient settings. For this reason, its potential role on governing the stratigraphic style of deltas is often neglected and changes in stratigraphic patterns of deltas have been usually interpreted as almost exclusively related to tectonic- and/or climate-related variations in accommodation.

6.1 Depositional history of the deltaic complex

The large scale stratigraphic architecture of Gilbert-type deposits appears very different in the two investigated branches. In DB1, Gilbert-type deposits result by the vertical stacking of EDUs in an overall retrogradrational and aggradational stacking pattern, deducible by: i) the progressive landward migration of the topset/foreset transition point in the landward located outcrop; and ii) the progressive increase of finer-grained and deeper bottomset facies than toeset and foreset one towards the upper part of the basinward-located outcrop. In contrast to this generalized retrogradational/aggradational attitude, the younger stratigraphic EDU in the landward-located outcrop (see Fig. 5A) is characterized by the spread of coarse-grained foreset facies over a wide area, suggesting a progradational motif. Unfortunately, the upper part of the basinward-located outcrop is not exposed, therefore preventing the investigation of the seaward stratigraphic counterpart.

A different stratigraphic arrangement is observable in DB2. A key feature of the deposits pertaining to this delta branch is the absence of topset deposits above the foreset sediments. The topset deposits are likely to have been completely eroded during the geological events that originated the surface TS2 (i.e., a base-level drop followed by a ravinement scouring associated with a transgressive event). The lack of topset deposits prevents the identification of the topset/foreset transition point. However, a dominantly progradational/aggradational attitude is suggested by other elements, such as: i) the spreading of foreset deposits over bottomset and toeset deposits over a distance of more than 400 m (see Fig. 8A), suggesting a strong progradation of the system; ii) the recognition of deactivation surfaces only at the toe of foresets, indicating a relatively continuous sediment supply that generally typifies the progradational phases; and iii) the progressive increase in bed inclination towards the upper part of the succession, that suggests the progressive increase of available accommodation space over time, as classically expected for aggradational settings.

The "wedge" of toeset and bottomset deposits that overlie the foreset ones in DB2 indicates that a delta avulsion process occurred. However, toeset deposits display a peculiar composition, including blocks of sediments eroded and re-worked by previously deposited nearshore sediments (sandstone blocks with marine fauna, Fig. 9A-C) and foreset deposits (cemented conglomerates, Fig. 9A,B,D). This evidence suggests that the deposition of toeset sediments occurred during a base-level drop that led to the subaerial exposure and subsequent erosion of previously deposited sediments. The predominance of blocks eroded by nearshore settings, when compared to those derived by foreset deposits, suggests that erosional processes affected mainly nearshore and topset deposits and only partially Gilbert-type foresets. The stratigraphic position of this “wedge”, just below the surfaces TS2, suggests that these toeset beds could be emplaced during the onset of the base-level drop that originated the composite surface TS2.

From a regional point of view, the angular unconformity between coarse-grained and stepped inclined conglomerate and the overlying sub-horizontal sandstone (Fig. 8A,B) has been interpreted by Bonini and Sani (2002) as the expression of an intra-Pliocene tectonic phase that caused the tilting of the basal conglomerate before the deposition of the upper sandstone occurred. This interpretation is not supported by the data presented in this work because: i) the conglomerate dips are comparable with the typical clinostratification expected for foreset deposits of Gilbert-type deltas; ii) the underlying sub-horizontal shoal-water delta deposits document that the succession is not tectonically tilted; and iii) the origin of the aforementioned angular unconformity results from a relative sea-level drop and a subsequent transgression. These considerations allowed to estimate the total accommodation space experienced during the Gilbert-type delta deposition. This is approximately 60-65 m as documented by the thickness of Gilbert-type deposits. Moreover, the thickness of Gilbert-type deposits is comparable in both delta branches, thus indicating that the subsidence acted uniformly in the area, and that the two branches experienced the same amount of accommodation.

6.2 Depositional time-framework of DB1 and DB2

Deltaic morphodynamic processes (such as deltaic lobe progradation or avulsion) generally acted in rapid time-spans of ten to thousands of years (cf., Wellner et al., 2005; Edmonds et al., 2009; Blum and Roberts, 2012) and this make generally difficult to investigate the depositional time-framework of deltas in ancient settings. The investigated deltaic complex provides helpful data in order to investigate the depositional relationship between the two delta branches:

- The lower and upper boundaries of the Gilbert-type deposits correspond to two time-equivalent and laterally traceable surfaces (TS1 and TS2, respectively) which act as stratigraphic time-constraints for Gilbert-type delta deposition. Calcareous nannoplankton data provided by Martini et al. (2015) document that in both branches the sediments between TS1 and TS2 deposited during in a relatively short time-interval of about 280 Kyr (i.e. within the MNN14/15 biozone of nannoplancton biostratigraphy, dated at the time interval 4.13-3.85 Ma according to the biostratigraphic scheme of Rio et al., 1990);
- Deposition in intra-branches areas is finer-grained than in the axial portion of each delta branch, as typically expected for deposition in the area between two coeval and adjacent deltaic branches;
- Above TS1, the thickness of fine-grained transgressive deposits is similar in both delta branches, suggesting that coarse-grained Gilbert-type foreset deposition started immediately above the transgressive event in both delta branches. In the case of a diachronous deposition of Gilbert-type foreset deposits in the two delta branches, it would be logical to expect different thicknesses of fine-grained deposits, i.e. thicker in the branch were foreset deposition started later.

Stratigraphic evidence suggest a coeval deposition in both delta branches. Moreover, an additional indication on this regard is provided by the upper part of the succession, that documents: i) an “anomalous” progradational attitude of the upper EDU in DB1, and ii) evidence of deposition during an overall base-level drop in DB2 (recycled sediments in toeset deposits). Since the surface TS2 records an erosional phase which occurred during a relative base-level fall and the following transgression, it would be plausible to consider that the sediments just beneath this surface would have been deposited during the base-level drop. Consequently, the progradational attitude recorded in DB1 and the avulsion process combined with sedimentation of the recycled sediments in DB2 would be connected to the same external controlling factors, i.e. the relative sea-level drop that originated the surface TS2.

6.3 Role of sediment supply on the stratigraphic architecture of Gilbert-type deltas

The stratigraphic arrangement of deltas (or more in general of siliciclastic sedimentary successions) has been largely governed by the so-called “A/S ratio” (hereafter A/S, cf., Jervey, 1988; Muto and Steel, 1992, 1997), where “A” indicates the rate of change of accommodation and “S” the rate of sediment supply.

Even though the rate of sediment supply deeply influences the arrangement of deltas, a correct evaluation of this parameter is generally possible only in present-day settings (where the amount/type of sediments transported by the distributary system to the delta can be measured) while it is extremely difficult in ancient settings. The role of sediment supply variations on the resulting stratigraphic features of coarse-grained fan-deltas has been addressed by a number of studies (López-Blanco et al., 2000; Marzo and Steel, 2000; López-Blanco, 2006) that have highlighted how the variation in sediment supply over time governs the stratigraphic arrangement of both fundamental transgressive-regressive sequences (i.e., high-frequency) and transgressive-regressive megasequences deposited over a time span of some million years (López-Blanco et al., 2000). Some points remain, however, poorly investigated, for example the stratigraphic arrangement of deltaic systems fed by multiple and coeval fluvial entry points, each providing a different amount of sediments.

The deltaic complex analyzed here represents a natural laboratory for testing the role of sediment supply in the stratigraphic architecture of Gilbert-type deltas because: i) the amount of created accommodation is known and it is the same in both delta branches; ii) the coevality of the delta branches ensures that climate-induced base-level fluctuations influenced the delta complex in the same way; and iii) the subsidence acted uniformly in the whole area during deposition. These considerations imply that the rate of change of accommodation (A) can be considered the same in both delta branches (i.e., constant), in turn implying that the only unknown variable for the $^{A}/_{S}$ ratio is the rate of sediment supply (S). Consequently, it can be assumed that the variable "S" is the only responsible for the observed differences in the stratigraphic architecture on the two delta branches.

Gilbert-type deposits in DB1 (Figs. 5, 6) are composed of several vertically stacked EDUs showing an overall retrogradational/aggradational stacking pattern in which younger foreset deposits grow on the top of previously deposited topset deposits (Fig. 5A). This stratigraphic organization indicates that the Gilbert-type delta experienced, during its depositional history, the alternation of phases of delta progradation (i.e., $^{A}/_{S} < 1$) and phases characterized by the rapid creation of accommodation space, in which the sediment supply is not enough to counterbalance the generated space ($^{A}/_{S} > 1$). The latter phases are characterized by the drowning of the system and by the inundation of the delta plain (i.e., topset deposits, see Fig. 11 – Stages 2 and 3). As a consequence, the following new progradation of the deltaic system occurs above the delta plain (Fig. 11 – Stages 4 and 5) and, consequently, the available space for foresets growth corresponds to the water depth between the base-level and the previously deposited delta plain sediments (i.e., topset deposits). If the deltaic progradation exceeds the older topset/foreset brink zone, foreset deposits can advance into deeper water where the total available space results from the underfilled space generated by previously occurred pulses of accommodation generation, as documented by the upper EDU in Figure 5A.

A different organization is recognizable in DB2, where the main part of Gilbert-type deposits is expressed by a single EDU characterized by: i) an overall progradational and aggradational attitude; ii) high foresets, up to 60 m in thickness; iii) the progressive increase of delta foreset beds inclination towards the upper part of the succession (Fig. 8A); and iv) the occurrence of deactivation surfaces connected with pulses of increasing in accommodation only at the toe of the delta foresets (Fig. 8A, C).

These pieces of evidence suggest that in DB2 the amount of sediment supplied to the river mouth was enough to balance and overcome the pulses of accommodation space creation experienced during the Gilbert-type delta growth, promoting the contemporaneous aggradation and progradation of the system (Fig. 12, Stages 1 to 4).

Some stratigraphic features suggest that the difference in sediment supply in the two branches may have been inherited from the older shoal-water deposits. In particular, the thickness and the width of distributary channels of the basal shoal-water delta suggest a more conspicuous sediment supply for DB2, compared to DB1.

The presented data highlight that the stratigraphic architecture patterns of Gilbert-type deltas may be dramatically influenced by the amount of sediments delivered at the river mouths or, more in detail, by the capacity of the sediment supply to counteract the pulsating accommodation space generation. As documented, sediment supply variations can drastically change within the same deltaic complex and over short distances.

6. Conclusions

Large-scale stratigraphic architectures of Gilbert-type deltas have commonly been used as a tool to refine the basin-fill history of coarse-grained and marginal successions. Architectural styles are typically expressed by aggradational, progradational and retrogradational patterns resulting from the interplay between the generated accommodation and the sediment supply experienced during deltas built-up. In ancient settings, however, the quantification of the amount of sediments delivered to the deltaic system is extremely difficult and for this reason many studies frequently neglected this parameter or assumed it constant.

This paper provides new insights on the role of sediment supply on the large-scale stratigraphic architecture of Gilbert-type deltas, based on the results of the investigation of a Pliocene deltaic complex composed of two coeval deltaic branches. The two branches experienced the same accommodation space variations during deposition and climate-induced sea-level fluctuations affected the two branches in the same way. The narrowly constrained "accommodation history" provides a rare opportunity to discern the role of sediment supply in the stratigraphic architecture of ancient Gilbert-type deltas.

In detail, the deltaic branch characterized by a great sediment supply shows foresets up to 60 m high characterized by a progradational and aggradational trend. Moreover, foreset bed dips display a progressive increase towards the upper part of the succession. Stratigraphic evidence of deactivation surfaces connected to small-scale flooding events or lobes avulsion processes are recognizable only at the toe of the delta body. The overall stratigraphic features indicate that the sediment supply was sufficient to counteract and overcome the accommodation generated during deposition. Conversely, the delta branch that received a minor amount of sediment displays a completely different stratigraphic organization characterized by thin delta foresets (of 2-5 m), vertically stacked to form an aggradational and retrogradational stacking pattern. Such an organization suggests that the sediment supply is not sufficient to counterbalance the accommodation space generated during episodic pulses, forcing the deltaic system to withdraw. The landward retreat of the system implied the inundation of the delta plain, over which new foresets grew and prograded. The available space for foresets growth does not correspond to the basin depth but rather to the depth of water between the base-level and the previously deposited delta plain.

This study provides field evidence documenting the role of sediment supply in the large-scale stratigraphic architecture of Gilbert-type deltas, up to generate completely different stratigraphic architectures. The amount of sediment delivered to river mouths can drastically change over short distances (i.e., within the same deltaic complex) and, therefore, caution is necessary when using large-scale stratigraphic architecture of Gilbert-type deltas as a tool to refine the basin-fill history when information about the sediment yields is lacking.

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Figure Captions

Fig. 1. (A) Tectonic sketch of the Northern Apennines. (B) Simplified geological map of the Siena Basin (after Bossio et al. 1992, 1993 and Brogi, 2011). (C) Synthetic stratigraphic columns of the Pliocene sedimentary infill in various sectors of the Siena-Radicofani basins and their bio- and chrono-stratigraphic correlation (data for the Siena sub-basin derived from Bossio et al., 1992, 1993; Martini and Sandrelli, 2015; Martini et al., 2015; data for the Radicofani sub-basin derived from Liotta and Salvatorini, 1994).

Fig. 2. Geological map of the investigated area with locations of measured sections.

Fig. 3. Main features of shoal-water delta deposits. (A) Slight-lobate and poorly sorted sandstone, organized in coarsening-upward lithosomes that typifies delta front deposits (woman for scale is *ca.*

170 cm tall). (B) Pen shells in life position, associated to other shell fragments, within delta front deposits (cap lens is 5.5 cm in diameter). Shell-rich beds are associated with sediment starvation settings connected to flooding surfaces and/or delta lobes avulsion processes. (C) Coarsening-upward and slight lobate gravelly sandstone of mouth-bar facies association , erosionally overlain by fining-upward sandy conglomerate of distributary channel facies association.

Fig. 4. Main features of Gilbert-type delta deposits. (A) Stratigraphic relationship between bottomset, toeset and foreset deposits (man for scale is *ca.* 180 cm tall). (B-C) Isolated clasts within sandstone and sandy mudstone beds of bottomset facies association. (D) Distribution-type inverse graded and sub-horizontal conglomerate bed that typifies toeset deposits. (E) Conglomerate bed (toeset facies association) characterized by abundant sandy matrix and vertically aligned long clasts, interbedded with sandy bottomset deposits (metre stick for scale is 10 cm long). (F) Vertically stacked conglomerate beds of foreset facies association. (G) Shear-bands within a conglomerate bed of foreset deposits (encircled hammer for scale is 28.5 cm long).

Fig. 5. Stratigraphic architecture of delta branch 1, landward located outcrop: (A) Line-drawing (vertical scale = horizontal scale), sedimentological logs and palaeocurrent data of the investigated outcrop. Note the overall retrogradational/aggradational attitude of Gilbert-type deposits, marked by the landward migration of the topset/foreset transition point. Main features are detailed in the following figures. (B) Basal part of the outcrop where the basal distributary channel deposits are abruptly overlain by slope and alluvial fan deposits (man for scale is 1.80 cm tall). (C) Sub-horizontal sandy conglomerate of topset facies association overlain by foreset deposits through an intervening flooding surface. (D) Sandy foreset deposits exposed in the basinward part of the outcrop. (E-F) Close-up view

of a mudstone bed (bottomset facies association) marking a transgressive event and indicating a temporary starving of coarse-grained sediments.

Fig. 6. Stratigraphic architecture of delta branch 1, basinward located outcrop: (A) Picture of the investigated cliff with location of log traces. (B) Line-drawing and sedimentological log of the outcrop in Fig. 6A (vertical scale = horizontal scale). Note the overall retrogradational/aggradational attitude of Gilbert-type deposits, marked by the progressive increase of fine-grained facies toward the upper part of the outcrop.

Fig. 7. Stratigraphic architecture of delta branch 2, landward located outcrop. (A) Line-drawing of the investigated outcrop (see Fig. 2 for location). Vertical scale = horizontal scale. Surface TS1 marks the transition between the basal shoal-water delta deposits and the Gilbert-type delta related sediments. (B) Close-up view of the stratigraphic relationship between mouth-bar and distributary channel deposits of the basal shoal-water delta. Man for scale (encircled) is 1.80 m tall. (C) Close-up view of a large mud clast within distributary channel deposits (woman for scale is 1.65 m tall).

Fig. 8. (A) Correlation panel showing the stratigraphic evolution and architecture of delta branch 2. (B) Basinward located outcrop where it is possible to observe the upper part of the succession (the lower shoal-water delta deposits are shown on Fig. 7). Note the progradational attitude of foreset deposits. Local deactivations are evidenced only at the toe of the delta lobe by the superimposition of bottomset/toeset deposits above foreset deposits. (C) Detail of the facies association transition occurring at the toe of the Gilbert-type foreset. (D) Close-up view of the transition between foreset and bottomset deposits.

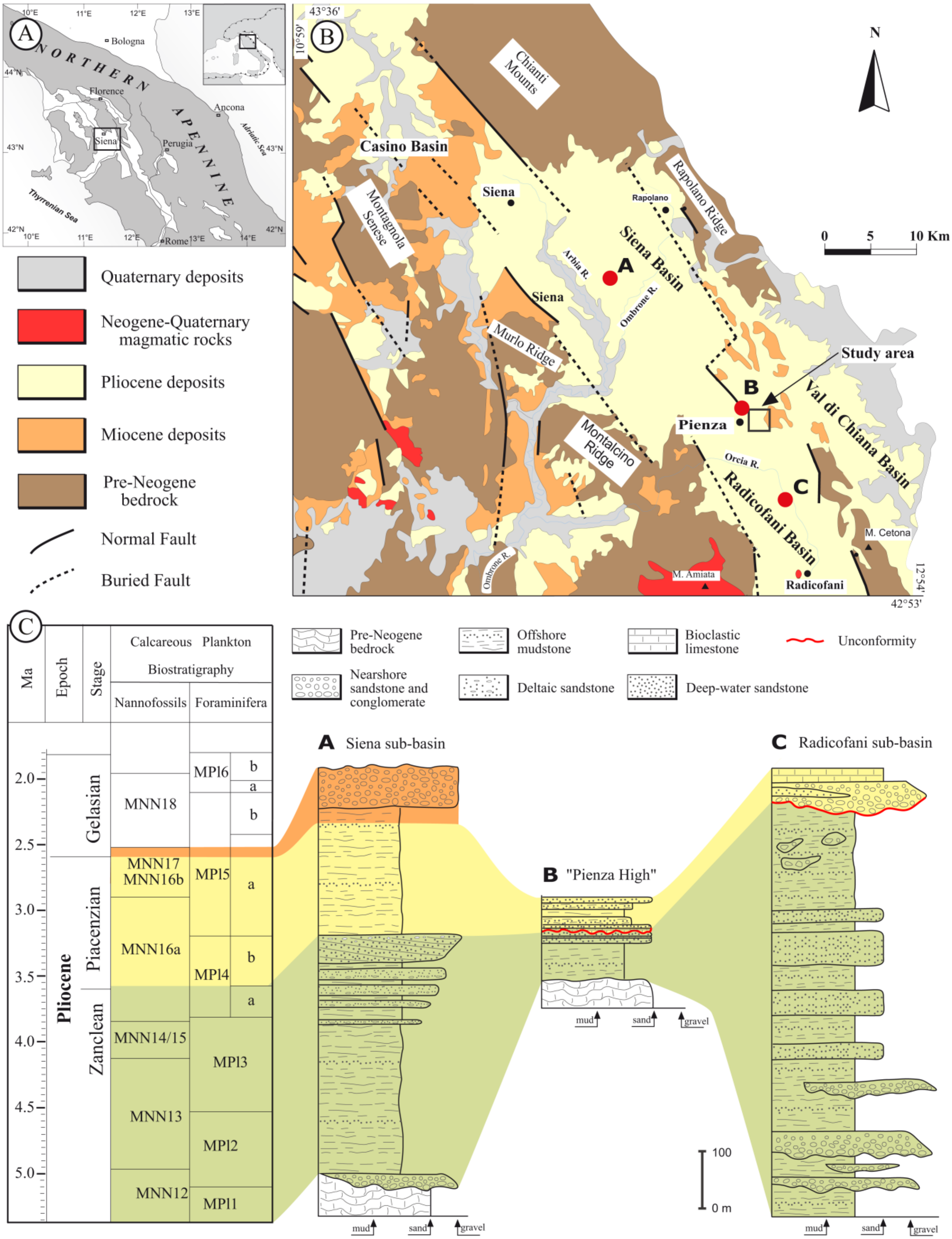
Fig. 9. (A) Enlargement of the basal portion of log "9" of Figure 8A. Note the occurrence of recycled sediments expressed by blocks of cemented sandstone and conglomerate. (B-C-D) Field expression of toeset deposits containing blocks of cemented sandstone (encircled by a yellow solid line) and conglomerate (encircled by an orange solid line). The sandstone blocks contain shell remains indicative of a nearshore environment, while the blocks of cemented conglomerate show sedimentological features similar to those of the foreset deposits. Hammer for scale is 28.5 cm long.

Fig. 10. Sedimentary log collected between the two branches. See Figure 2 for location of log.

Fig. 11. Depositional model for Gilbert-type deltas developed in settings characterized by a relatively low sediment supply and pulsating accommodation creation. Model is derived by data collected in DB1.

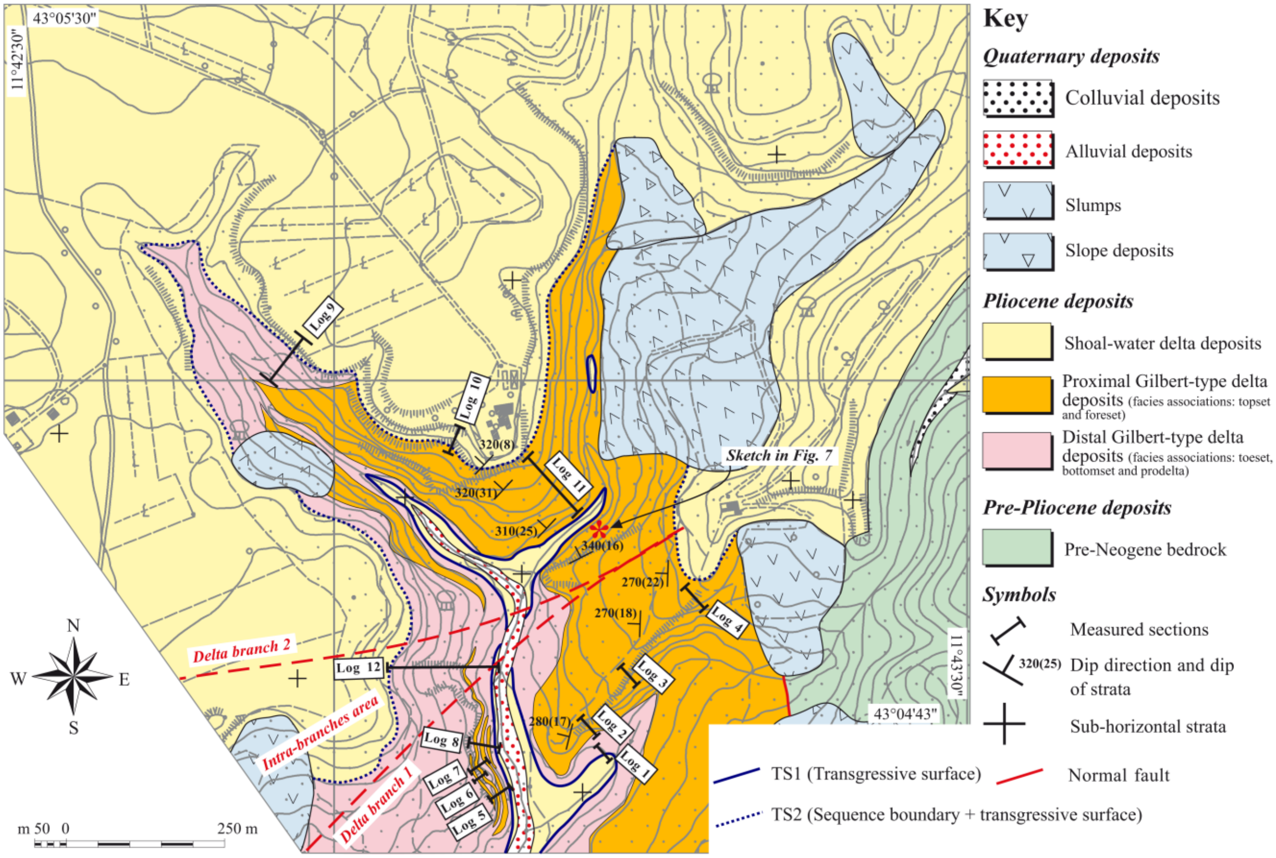
Fig. 12. Depositional model for Gilbert-type deltas developed in settings characterized by a relatively high sediment supply and pulsating accommodation creation. Model is derived by data collected in DB2.

Table 1. Summary of main features in the recognized facies associations.

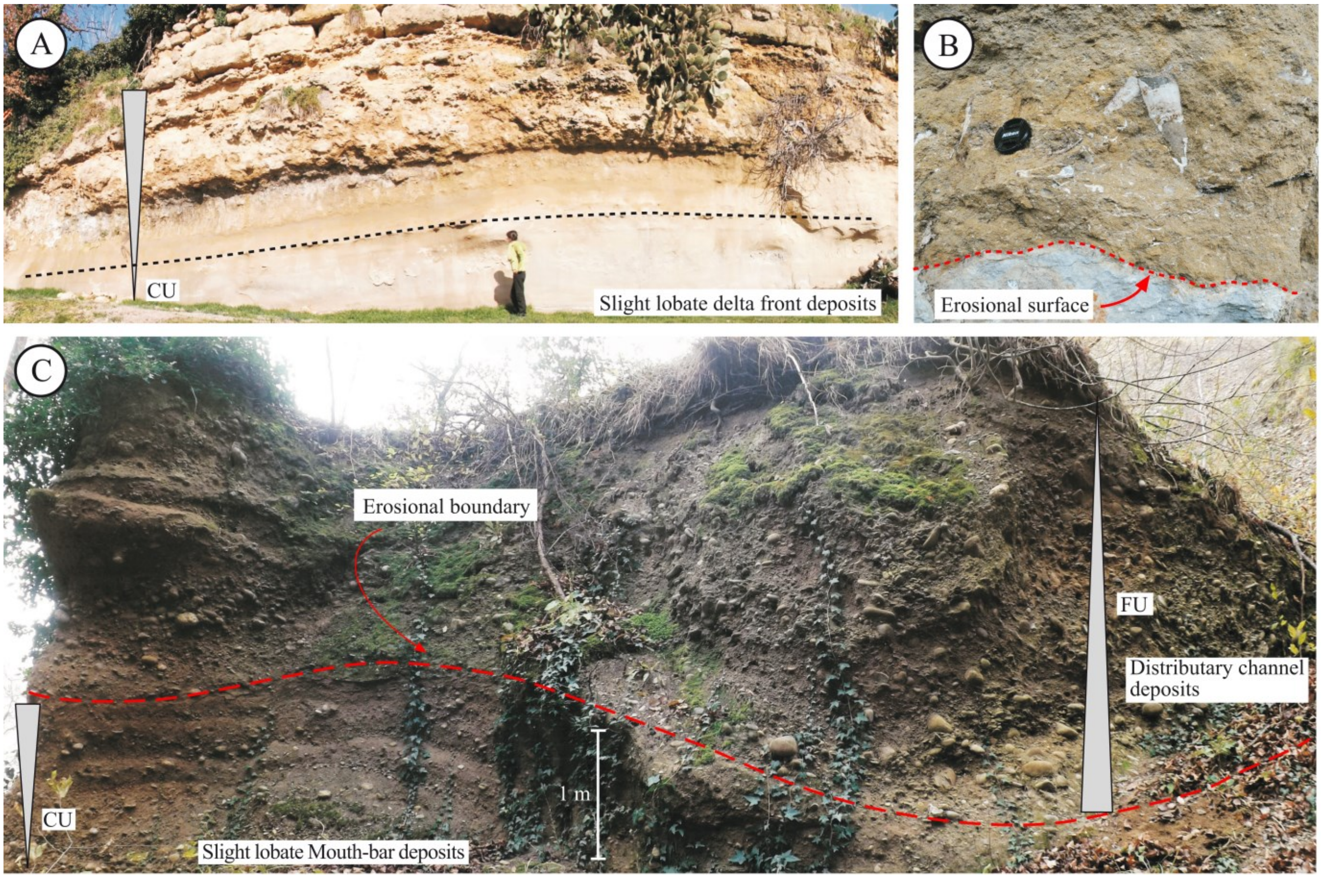

A
NORTHERN APENNINE
Bologna
Florence
Ancona
Siena
Perugia
Adriatic Sea
Thyrrenian Sea
Rome
Quaternary deposits
Neogene-Quaternary magmatic rocks
Pliocene deposits
Miocene deposits
Pre-Neogene bedrock
Normal Fault
Buried Fault
B
43°36'
10°59'
12°54'
42°53'
Chianti Mounts
Casino Basin
Siena
Rapolano
Rapolano Ridge
Montagnola Senese
Siena Basin
Arbia R.
Ombrone R.
Murlo Ridge
Study area
Val di Chiana Basin
Pienza
Montalcino Ridge
Orcia R.
Radicofani Basin
M. Cetona
M. Amiata
Radicofani
0 5 10 Km
N
C
Ma
Epoch
Stage
Calcareous Plankton Biostratigraphy
Nannofossils
Foraminifera
Pliocene
Gelasian
Piacenzian
Zanclean
MNN18
MNN17 MNN16b
MNN16a
MNN14/15
MNN13
MNN12
MPl6
MPl5
MPl4
MPl3
MPl2
MPl1
Pre-Neogene bedrock
Nearshore sandstone and conglomerate
Offshore mudstone
Deltaic sandstone
Bioclastic limestone
Deep-water sandstone
Unconformity
A Siena sub-basin
B "Pienza High"
C Radicofani sub-basin
mud
sand
gravel
100
0 m

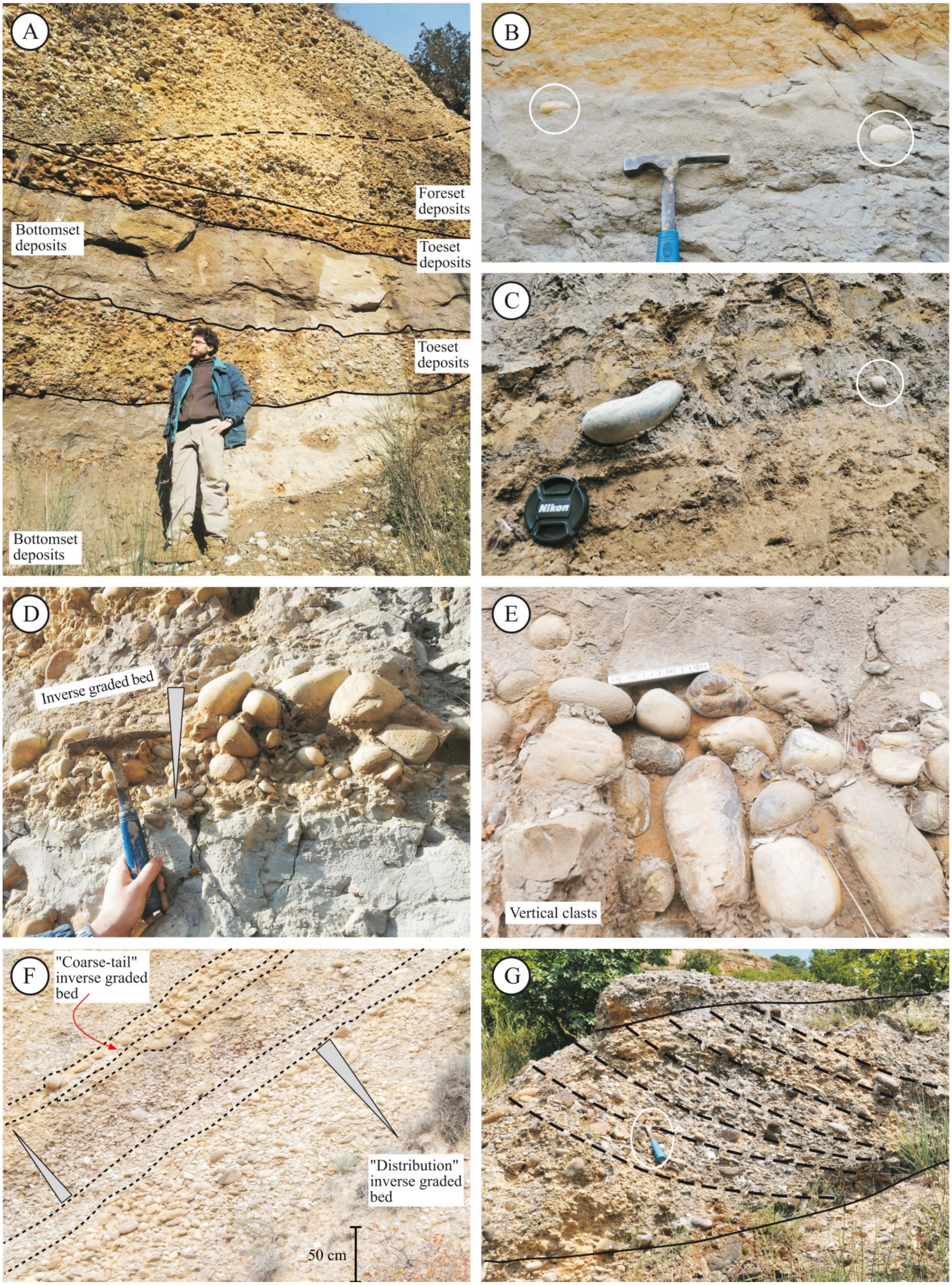
1041

1042

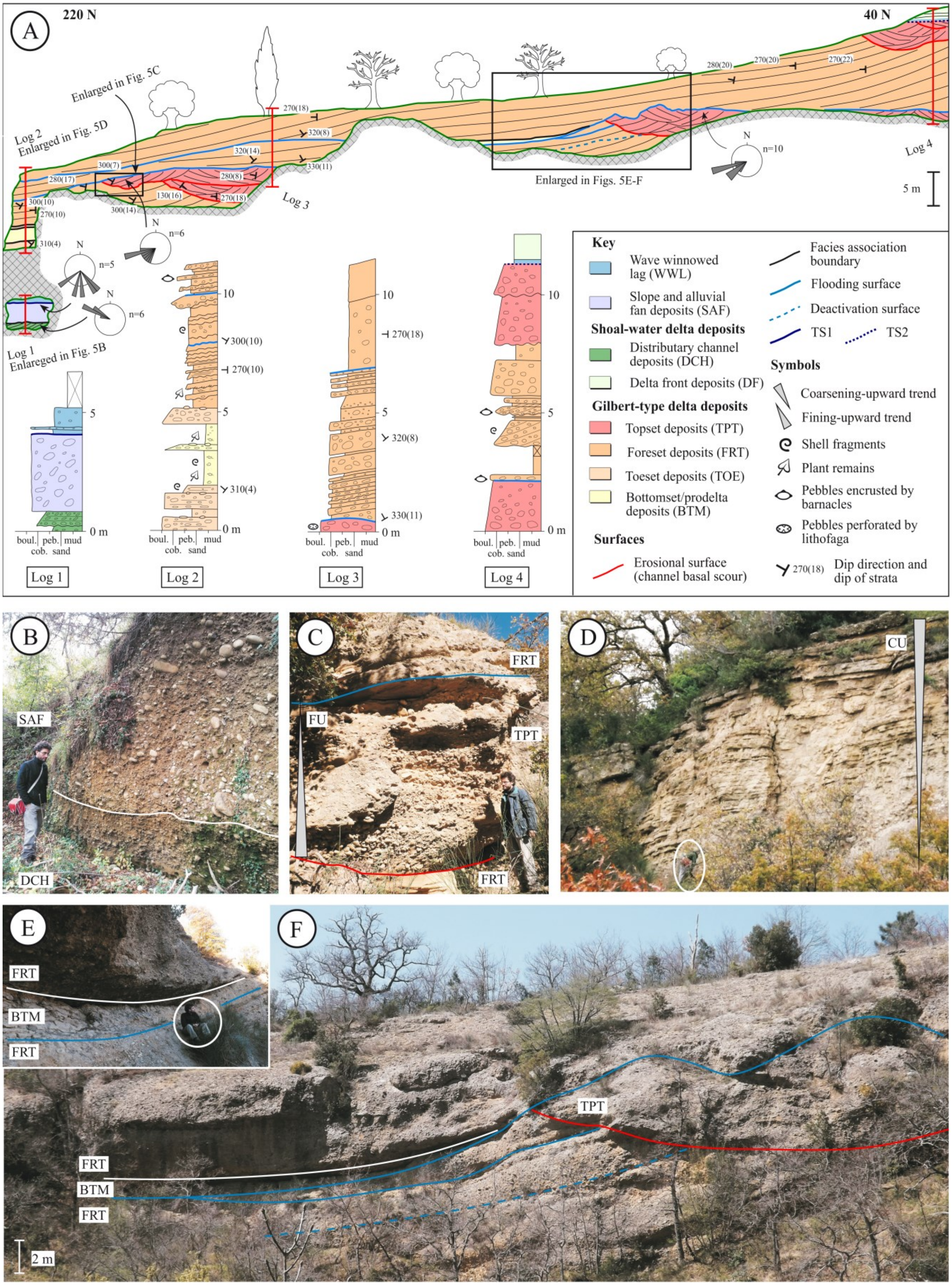


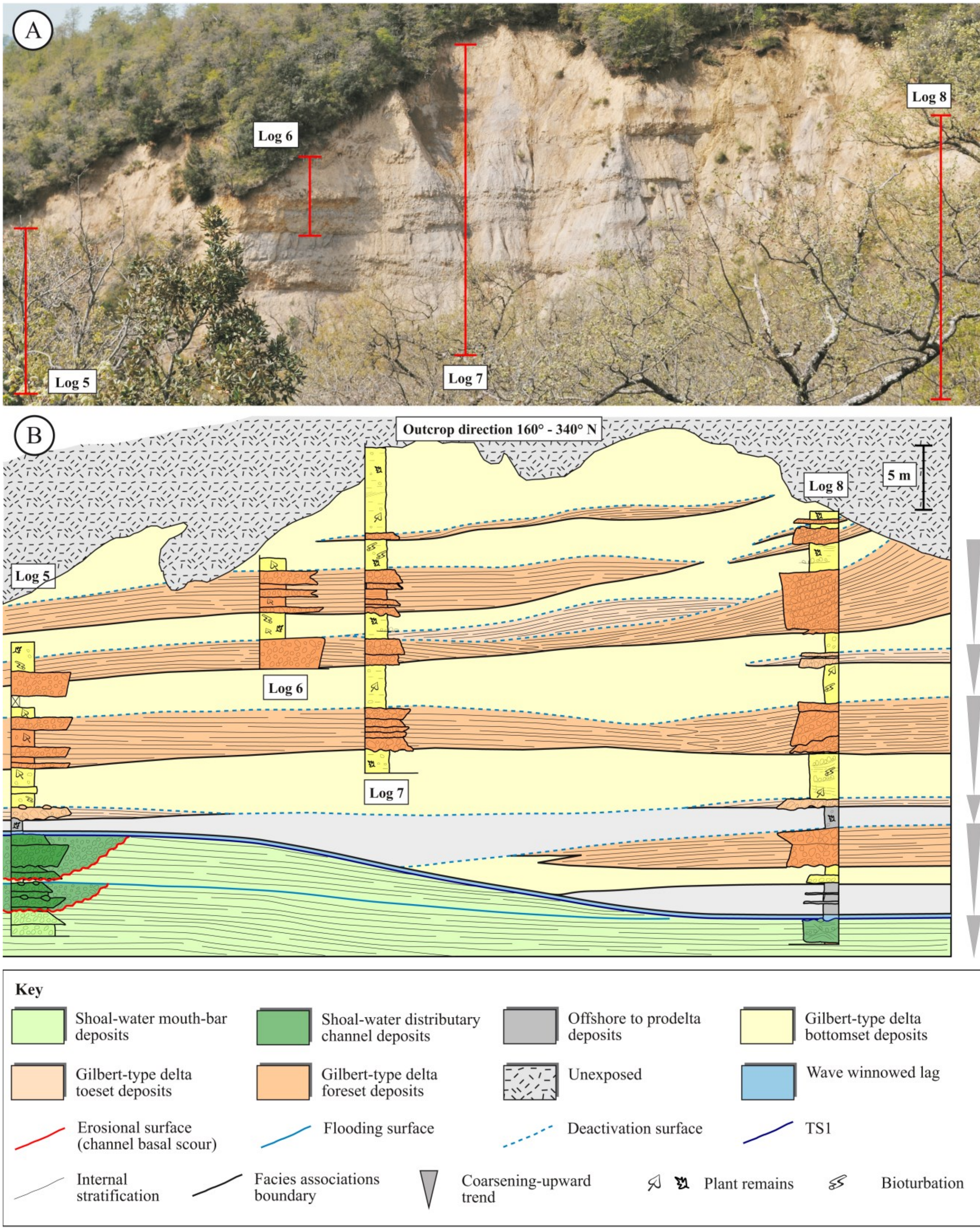
43°05'30"
11°42'30"
11°43'30"
43°04'43"
Key
Quaternary deposits
Colluvial deposits
Alluvial deposits
Slumps
Slope deposits
Pliocene deposits
Shoal-water delta deposits
Proximal Gilbert-type delta deposits (facies associations: topset and foreset)
Distal Gilbert-type delta deposits (facies associations: toeset, bottomset and prodelta)
Pre-Pliocene deposits
Pre-Neogene bedrock
Symbols
Measured sections
320(25) Dip direction and dip of strata
Sub-horizontal strata
TS1 (Transgressive surface)
Normal fault
TS2 (Sequence boundary + transgressive surface)
Sketch in Fig. 7
Delta branch 2
Delta branch 1
Intra-branches area
Log 1
Log 2
Log 3
Log 4
Log 5
Log 6
Log 7
Log 8
Log 9
Log 10
Log 11
Log 12
320(8)
320(31)
310(25)
340(16)
270(22)
270(18)
280(17)
N
S
W
E
m 50 0
250 m

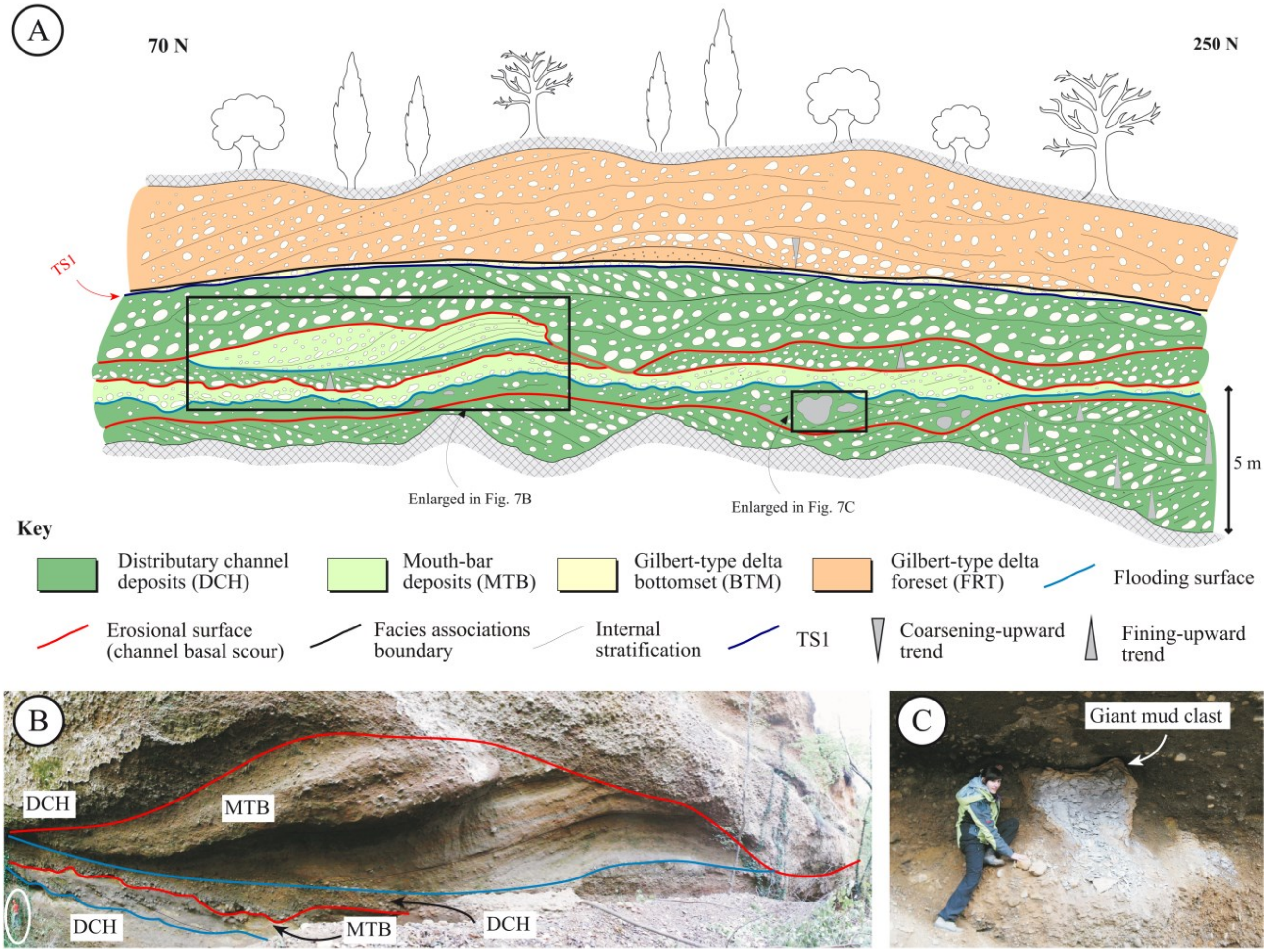

A
CU
Slight lobate delta front deposits
B
Erosional surface
C
Erosional boundary
FU
Distributary channel deposits
1 m
CU
Slight lobate Mouth-bar deposits


A
Foreset deposits
Bottomset deposits
Toeset deposits
Toeset deposits
Bottomset deposits
B
C
Nikon
D
Inverse graded bed
E
Vertical clasts
F
"Coarse-tail" inverse graded bed
"Distribution" inverse graded bed
50 cm
G

1047

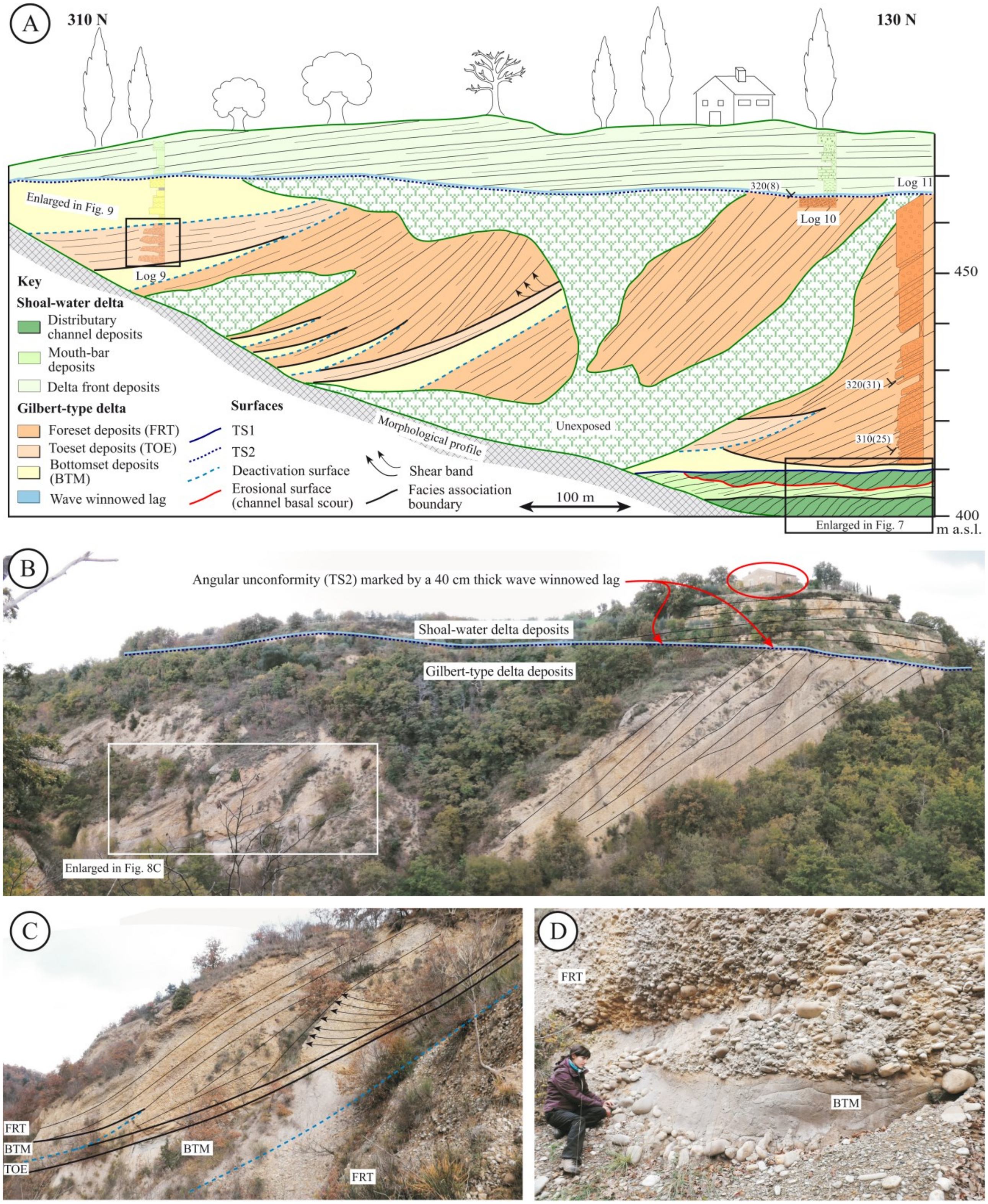

A
220 N
40 N
Enlarged in Fig. 5C
Log 2
Enlarged in Fig. 5D
Log 3
Log 4
Log 1
Enlarged in Fig. 5B
Enlarged in Figs. 5E-F
5 m
n=10
n=6
n=5
n=6
270(18)
320(8)
320(14)
330(11)
300(7)
280(17)
280(8)
130(16)
270(18)
300(10)
270(10)
300(14)
310(4)
280(20)
270(20)
270(22)
boul. peb. mud
cob. sand
Log 1
Log 2
Log 3
Log 4
Key
Wave winnowed lag (WWL)
Slope and alluvial fan deposits (SAF)
Shoal-water delta deposits
Distributary channel deposits (DCH)
Delta front deposits (DF)
Gilbert-type delta deposits
Topset deposits (TPT)
Foreset deposits (FRT)
Toeset deposits (TOE)
Bottomset/prodelta deposits (BTM)
Surfaces
Erosional surface (channel basal scour)
Facies association boundary
Flooding surface
Deactivation surface
TS1
TS2
Symbols
Coarsening-upward trend
Fining-upward trend
Shell fragments
Plant remains
Pebbles encrusted by barnacles
Pebbles perforated by lithofaga
270(18) Dip direction and dip of strata
B
SAF
DCH
C
FRT
FU
TPT
FRT
D
CU
E
FRT
BTM
FRT
F
TPT
FRT
BTM
FRT
2 m

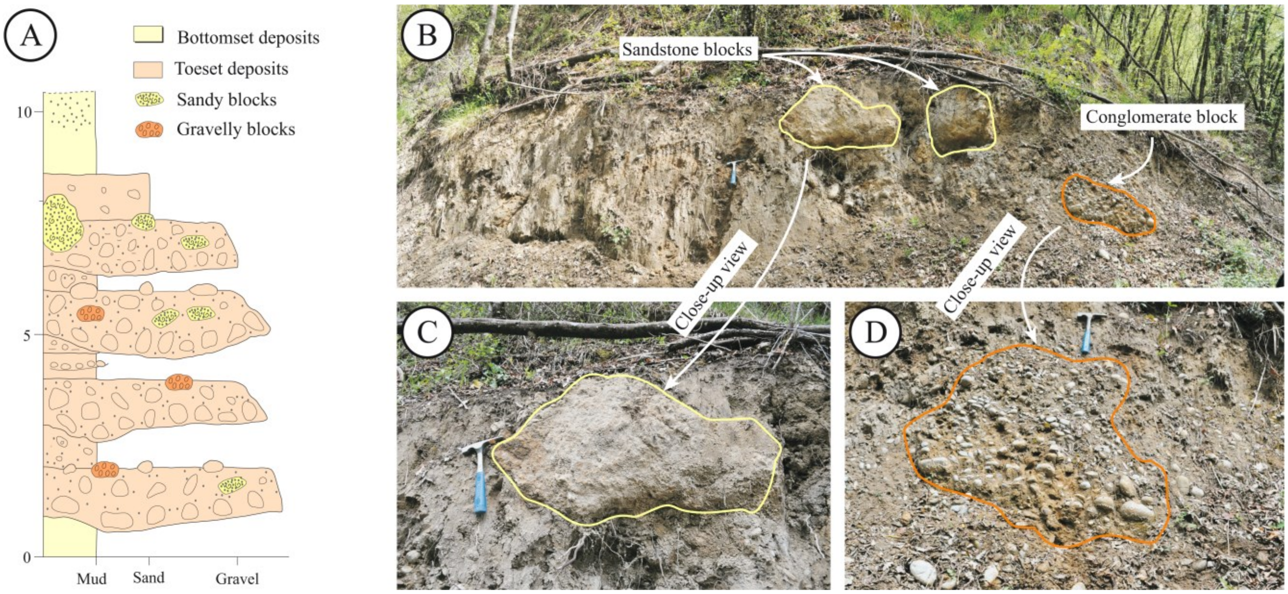

A
Log 5
Log 6
Log 7
Log 8
B
Outcrop direction 160° - 340° N
5 m
Log 5
Log 6
Log 7
Log 8
Key
Shoal-water mouth-bar deposits
Shoal-water distributary channel deposits
Offshore to prodelta deposits
Gilbert-type delta bottomset deposits
Gilbert-type delta toeset deposits
Gilbert-type delta foreset deposits
Unexposed
Wave winnowed lag
Erosional surface (channel basal scour)
Flooding surface
Deactivation surface
TS1
Internal stratification
Facies associations boundary
Coarsening-upward trend
Plant remains
Bioturbation

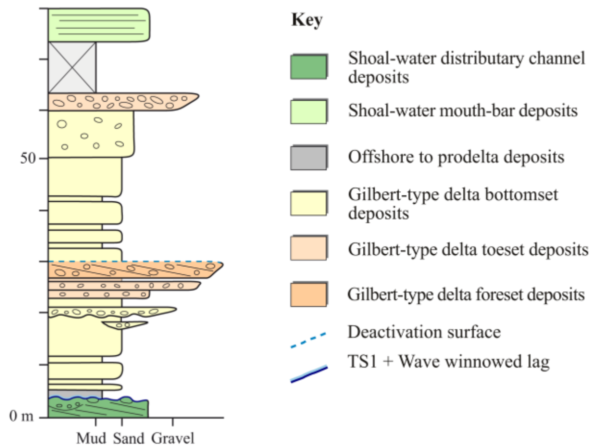

A
70 N
250 N
TS1
Enlarged in Fig. 7B
Enlarged in Fig. 7C
5 m
Key
Distributary channel deposits (DCH)
Mouth-bar deposits (MTB)
Gilbert-type delta bottomset (BTM)
Gilbert-type delta foreset (FRT)
Flooding surface
Erosional surface (channel basal scour)
Facies associations boundary
Internal stratification
TS1
Coarsening-upward trend
Fining-upward trend
B
DCH
MTB
DCH
MTB
DCH
C
Giant mud clast

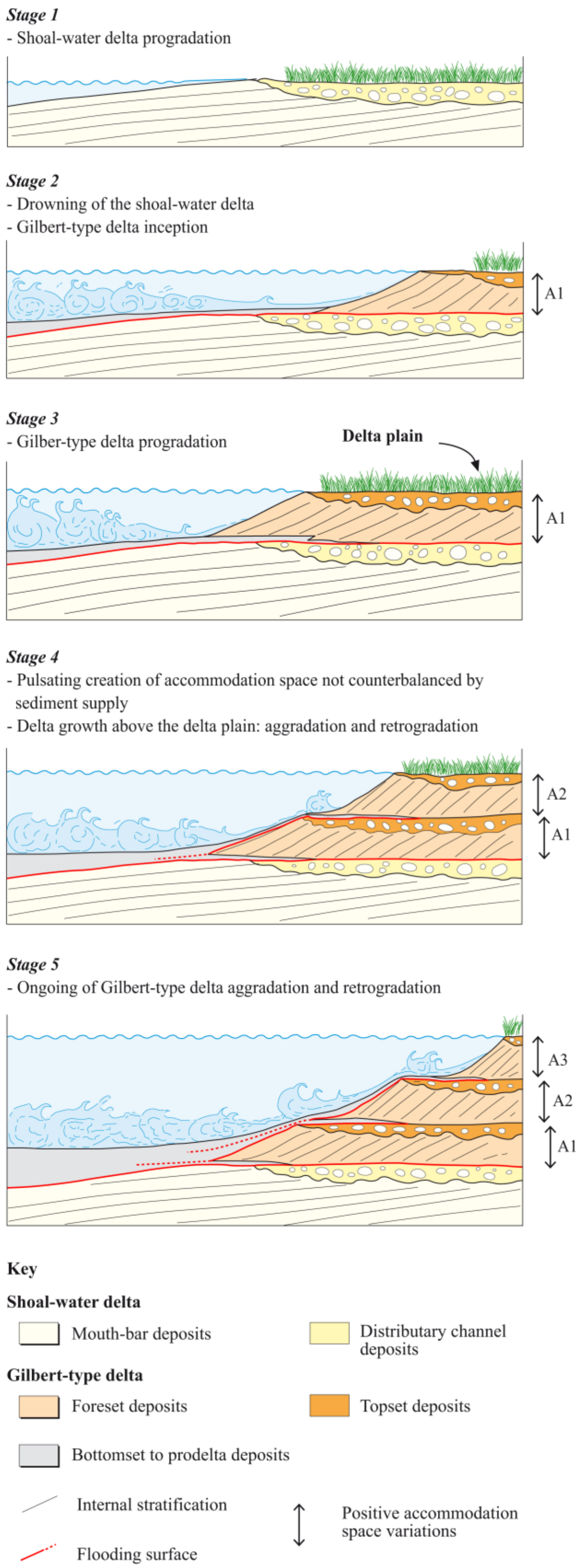
1052

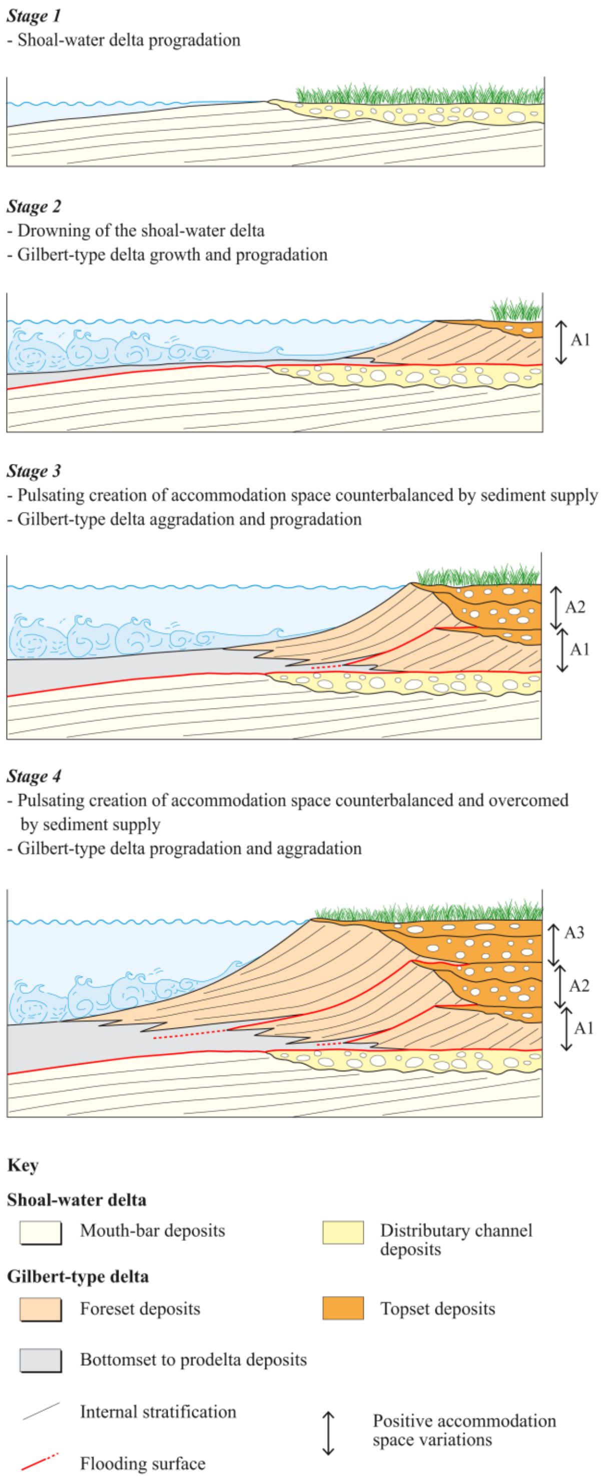
1053


A
310 N
130 N
Enlarged in Fig. 9
Log 9
320(8)
Log 11
Log 10
450
320(31)
310(25)
400
m a.s.l.
Enlarged in Fig. 7
Unexposed
Morphological profile
Key
Shoal-water delta
Distributary channel deposits
Mouth-bar deposits
Delta front deposits
Gilbert-type delta
Foreset deposits (FRT)
Toeset deposits (TOE)
Bottomset deposits (BTM)
Wave winnowed lag
Surfaces
TS1
TS2
Deactivation surface
Erosional surface (channel basal scour)
Shear band
Facies association boundary
100 m
B
Angular unconformity (TS2) marked by a 40 cm thick wave winnowed lag
Shoal-water delta deposits
Gilbert-type delta deposits
Enlarged in Fig. 8C
C
FRT
BTM
TOE
BTM
FRT
D
FRT
BTM


A
Bottomset deposits
Toeset deposits
Sandy blocks
Gravelly blocks
10
5
0
Mud
Sand
Gravel
B
Sandstone blocks
Conglomerate block
Close-up view
Close-up view
C
D


50
0 m
Mud Sand Gravel
Key
Shoal-water distributary channel deposits
Shoal-water mouth-bar deposits
Offshore to prodelta deposits
Gilbert-type delta bottomset deposits
Gilbert-type delta toeset deposits
Gilbert-type delta foreset deposits
Deactivation surface
TS1 + Wave winnowed lag


Stage 1
- Shoal-water delta progradation
Stage 2
- Drowning of the shoal-water delta
- Gilbert-type delta inception
A1
Stage 3
- Gilber-type delta progradation
Delta plain
A1
Stage 4
- Pulsating creation of accommodation space not counterbalanced by sediment supply
- Delta growth above the delta plain: aggradation and retrogradation
A2
A1
Stage 5
- Ongoing of Gilbert-type delta aggradation and retrogradation
A3
A2
A1
Key
Shoal-water delta
Mouth-bar deposits
Distributary channel deposits
Gilbert-type delta
Foreset deposits
Topset deposits
Bottomset to prodelta deposits
Internal stratification
Positive accommodation space variations
Flooding surface


Stage 1
- Shoal-water delta progradation
Stage 2
- Drowning of the shoal-water delta
- Gilbert-type delta growth and progradation
A1
Stage 3
- Pulsating creation of accommodation space counterbalanced by sediment supply
- Gilbert-type delta aggradation and progradation
A2
A1
Stage 4
- Pulsating creation of accommodation space counterbalanced and overcomed by sediment supply
- Gilbert-type delta progradation and aggradation
A3
A2
A1
Key
Shoal-water delta
Mouth-bar deposits
Distributary channel deposits
Gilbert-type delta
Foreset deposits
Topset deposits
Bottomset to prodelta deposits
Internal stratification
Positive accommodation space variations
Flooding surface