PS Evolution and History of Filling of Early Pleistocene, Coarse-Grained Slope Canyons (Peri-Adriatic Basin, Central Italy)*

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Abstract

The early Pleistocene stratigraphic succession of the Peri-Adriatic Basin, eastern central Italy, records the filling of an elongate, north-south oriented piggy-back basin located east of the growing Apennine fold-thrust belt. During the Gelasian (2.58-1.80 Ma), gravel- and sand-sized sediments derived from the central Apennines were abundantly supplied into the basin through a series of transverse to longitudinal slope erosional fairways. These sediment conduits are preserved in the rock record as a series of exceptionally exposed canyon-fill successions that provide a rare opportunity to evaluate, from an outcrop perspective, how this type of deepwater depositional system evolves and fills under the indirect effects of glacio-eustatic sea-level changes. The present study uses stratigraphic sections, photopanels, paleocurrent data, and careful lithological mapping to constrain the internal organization of four of these canyon fills, which we refer to as the Ascensione, Castignano, Offida, and Notaresco canyons. A detailed facies analysis suggests that a variety of subaqueous gravity flows were involved in sediment transport and deposition, including slumps, cohesive debris flows, and high- and low-density turbidity currents.

Four main lithofacies that reflect major depositional elements have been identified within the canyon-fill successions and are: (i) clast-supported conglomerates (gravel-rich channel complexes); (ii) medium- to thick-bedded sandstones (channel terminus lobes); (iii) medium- to very thin-bedded sandstones (levee-overbank); (iv) pebbly mudstones and chaotic beds (mudstone-rich mass-transport deposits). The canyon-fill strata are organized in lithofacies sequences that tend to follow a predictable pattern and to define vertically stacked fining-upward packages, resulting in highly cyclic successions. Each of these fining-upward packages comprises the sedimentary record of discrete phases of canyon activity, showing transition from a higher energy depositional style to a lower energy mode of sedimentation interrupted by a period of erosion and bypass of sediment to areas further downslope. These recurring fluctuations in canyon activity and sedimentary regime are thought to be related to the switching on and off of coarse clastic sediments to the deepwater basin that, in turn, likely resulted from the contemporary glacio-eustatic changes in sea level.

EVOLUTION AND HISTORY OF FILLING OF EARLY PLEISTOCENE, COARSE-GRAINED SLOPE-CANYONS (PERI-ADRIATIC BASIN, CENTRAL ITALY)

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Geological and Stratigraphic Setting

The Apennines fold-and-thrust belt and associated foreland basin system started to develop during the Oligocene and propagated progressively toward east and east-northeast in relation to the westward, oblique underthrusting of the continental Adria plate. The Peri-Adriatic basin is the Plio-Pleistocene central Apennines foreland system. In the Marche-Abruzzi sector (Fig. 1), the basin hosts the most peripheral extension of the Apennines thrust-and-fold belt, which comprises north-trending, easterly directed systems of imbricated thrust sheets developed during late Miocene to early Calabrian times at the expense of the thick Meso-Cenozoic cover of the Adria plate margin. On the whole, these thrust sheets appear to propagate in a forward-breaking sequence and are increasingly younger from west to east. Three main systems of imbricated thrust sheets have been recognised: from west to east they are the Montagna dei Fiori (MF), the Bellante (Be), and the Costiera (Co) fronts. In the hanging wall of the MF front the carbonate substratum crops out, whereas the other three fronts are in large part buried beneath a thick syntectonic succession of Plio-Pleistocene siliciclastic sediments and only known from published drilling and seismic-reflection datasets.

The complicated tectonic deformation history of the Apennine foreland system is clearly recorded in its siliciclastic fill, which is irregularly punctuated by regional-scale unconformities that represent discrete phases in basin development. The regional physical-stratigraphic framework adopted herein is that proposed by Artoni (2007). This scheme consists of twelve allostratigraphic units (referred to as pre-ev, ev, p-ev1, p-ev2, and Unit 1 to Unit 8) bounded by unconformities of tectonic origin (u1 to u12) that are particularly accentuated along the basin margin. Four of these units (pre-ev, ev, p-ev1, p-ev2) are upper Tortonian-Messinian in age, whereas the remaining eight (Unit 1 to Unit 8) were deposited during the Plio-Pleistocene (Fig. 2).

From the early Calabrian onwards, the foreland propagation of thrust fronts ceased and the basin underwent a rapid phase of tectonic uplift. During this phase, sediments are typified by a distinct upward-shoaling trend from upper slope hemipelagic mudstones to a cyclothemic succession of shallow-marine and fluvial deposits (Unit 7). Sediments of this unit, reflecting the overall basinward progradation of a linked shelf-slope-basin depositional system, are finally overlain by a thin succession of fluvial gravels of middle Pleistocene age (Unit 8), which completed the general shallowing-upward pattern of the basin fill.

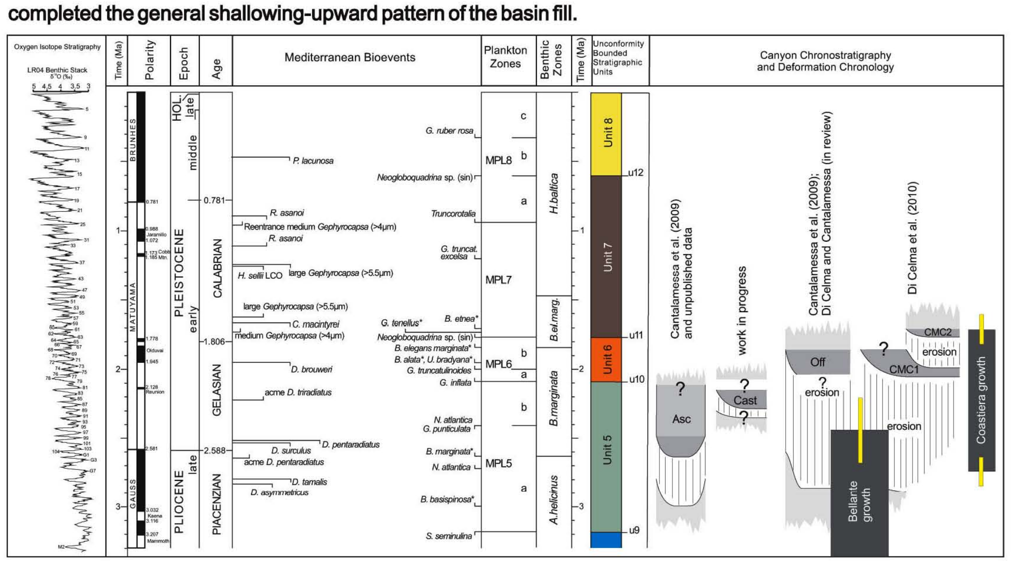


Figure 2: Pliocene-Pleistocene biostratigraphic scheme showing the most significant bioevents of the Mediterranean region. The benthic $\delta^{18}O$ isotope stack is from Lisiecki and Raymo (2005). Geomagnetic polarity reversals, stage boundaries age, and age estimates of calcareous nannoplankton and planktonic foraminifer datum events are based on ATNTS2004 (Lourens et al., 2004). Age estimation of selected bioevents (*) from Pasini and Colalongo (1994), Patacca and Scandone (2004) and reference therein. The ages of the unconformity-bounded stratigraphic units are from Artoni (2007); deformation chronology from Tozer et al. 2006.

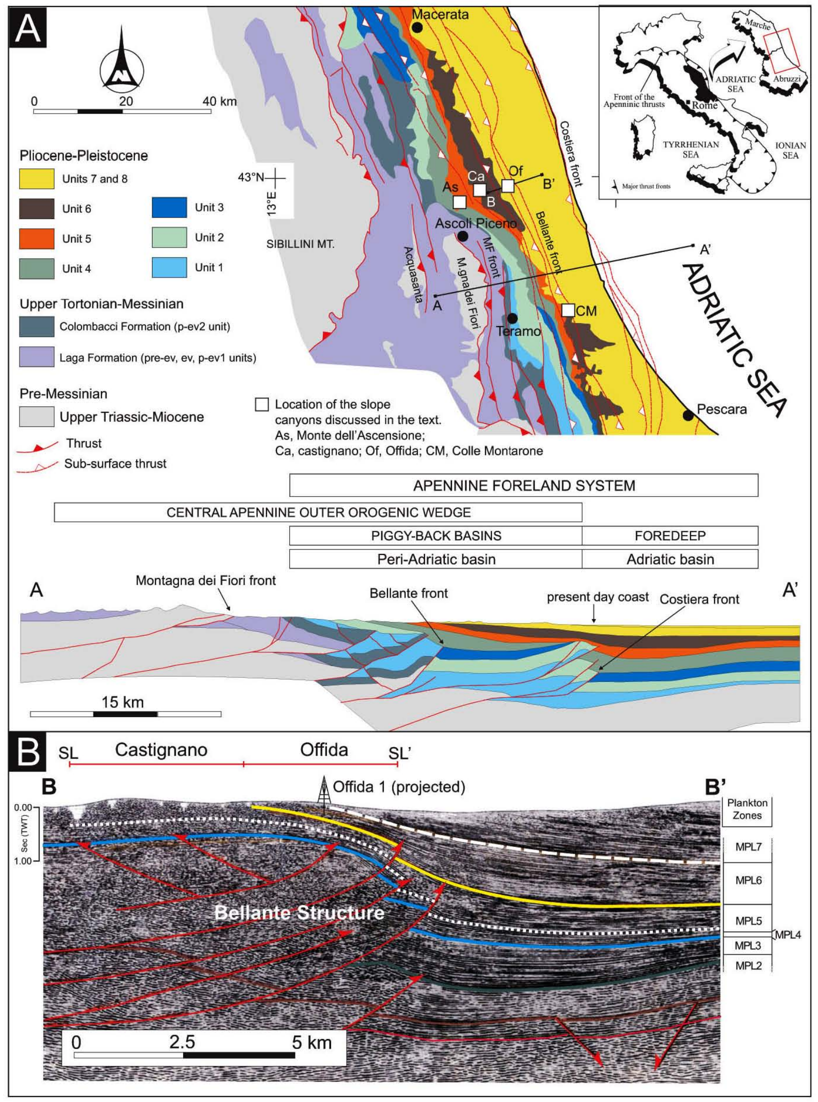


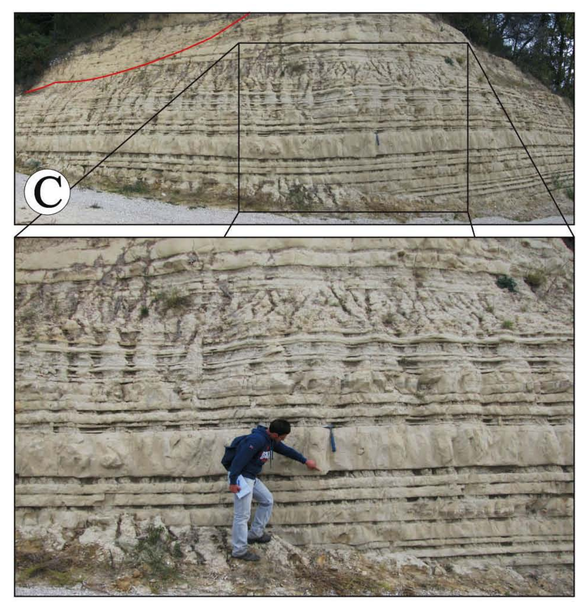
Figure 1: (A) Generalized tectonic map of eastern central Italy showing the location of the study areas. (B) Southwest-northeast 2-D seismic line (FTR-19-81) across the inner margin of the basin (courtesy of Ministero dello Sviluppo Economico et al., 2010) showing the large-scale clinoforms of the slope system that prograded eastward into the Peri-Adriatic basin during the Pleistocene (for location of this seismic line see Figures 1A and 2) and locations of the Castignano and Offida canyons.

Canyon Fill

Strata in the canyon fill succession are organized into four recurrent lithofacies, each corresponding to a specific deep-water depositional element: (A) clast-supported conglomerates (LF-A, channel complexes); (B) thick-bedded sandstones (LF-B, channel complexes); (C) medium- to thin-bedded sandstones and mudstones (LF-C, levee-overbank); (D) pebbly mudstones and chaotically bedded mudstones (LF-D, mass-transport complexes).

LF-A: This lithofacies consits of clast-supported conglomerates with interbeds of medium-bedded sandstones. Clasts are well-rounded and dominantly extra-formational (mostly limestones). Strata in this lithofacies are very lenticular.

LF-B: Dominated by thick-bedded sandstone, this lithofacies also contains minor ammounts of conglomerate, thin-bedded sandstone and interbedded sandstone and mudstone. The thick-bedded sandstones are graded, laminated, lenticular, and commonly display dish structures.



LF-D: Close-up of the unsorted fabric exhibited by gravelly mudstones, characterized by a chaotic mixture of extra-formational well-rounded clasts and brecciated jumbles of mudstone intraclasts.

LF-C: This lithofacies includes a combination of thin-bedded sandstone and interbedded sandstone and mudstone lithologies. In most locations these beds are organized into an unward-fining and -thinning succession. In this photo, it is composed of tabular, medium- to thin-bedded sandstones displaying Bouma Ta to Ta-c divisions separated by a series of slightly recessive packets of Te turbidites. The tabular geometry is indicative of deposition in a relatively unconfined setting.

ASCENSIONE CANYON

The Gelasian (early Pleistocene) clastic fill of the Peri-Adriatic basin features a series of readily accessible coarse-grained submarine canyon fills surrounded by a thick succession of slope mudstones. The most prominent of these are the Monte Ascensione Canyon, the Castignano Canyon, the Offida Canyon, and the two canyon fills exposed at Colle Montarone. The Monte Ascensione Canyon is arguably the largest and most spectacular of these ancient canyon fills and consists of a north to south elongated body that is about 10 km long and up to 4 km wide. It is dissected by west-east trending river valleys that provide depositional strike-oriented cross-sections distributed along different positions of the regional submarine slope depositional profile. To reconstruct the spatial organization of the canyon fill, three seismic-scale correlation panels have been built (Figure 1): the most proximal Monte Ascensione panel to the south (Figure 2), the Tesino River panel in the middle (Figure 3), and the most distal Aso River panel to the north (Figure 4). One of the most conspicuous attributes of the Monte Ascensione canyon-fill is its pronounced cyclic packaging, resulting from several pulses of erosion and fill. The lithofacies listed above combine to form a number of discontinuity-bound stratal packages, or high-frequency depositional sequences, each characteristically having an overall fining-upward character. Given the severe icehouse climatic regime during the Pleistocene, the cyclic arrangement is most reasonably attributed primarily to repeated glacio-eustatic fluctuations in global sea level, which regulated the flux of terrigenous clastic sediment to the slope and basin-floor settings.

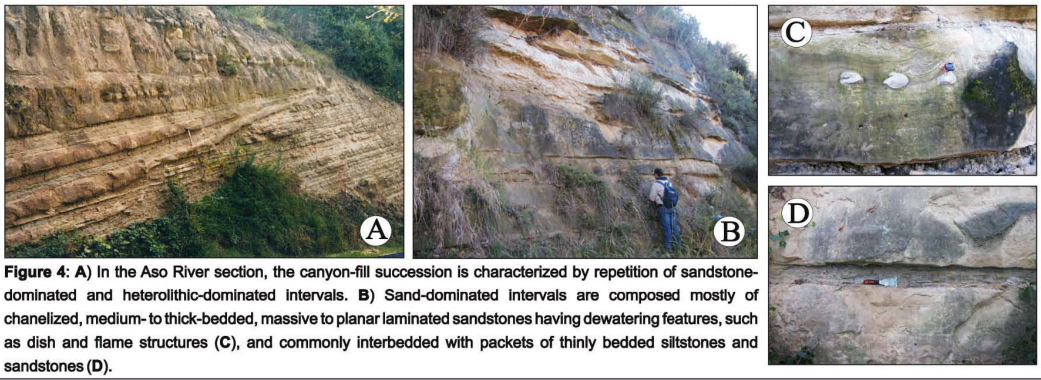


Figure 4: **A**) In the Aso River section, the canyon-fill succession is characterized by repetition of sandstone-dominated and heterolithic-dominated intervals. **B**) Sand-dominated intervals are composed mostly of chanelized, medium- to thick-bedded, massive to planar laminated sandstones having dewatering features, such as dish and flame structures (**C**), and commonly interbedded with packets of thinly bedded siltstones and sandstones (**D**).

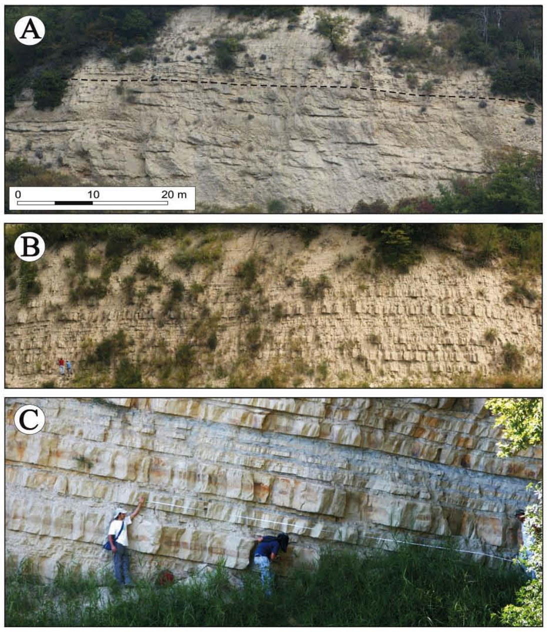


Figure 3: **A**) In the Tesino River section the canyon fill is mostly composed of conglomerate packages immediately overlain by packages of alternating sandstones and mudstones displaying fining- and thinning-upward trends (**B**). The dashed line highlights the abrupt vertical transition between the two lithofacies. **C**) Note as these heterolithic packages are characterized by the occurrence of different sets of fractures.

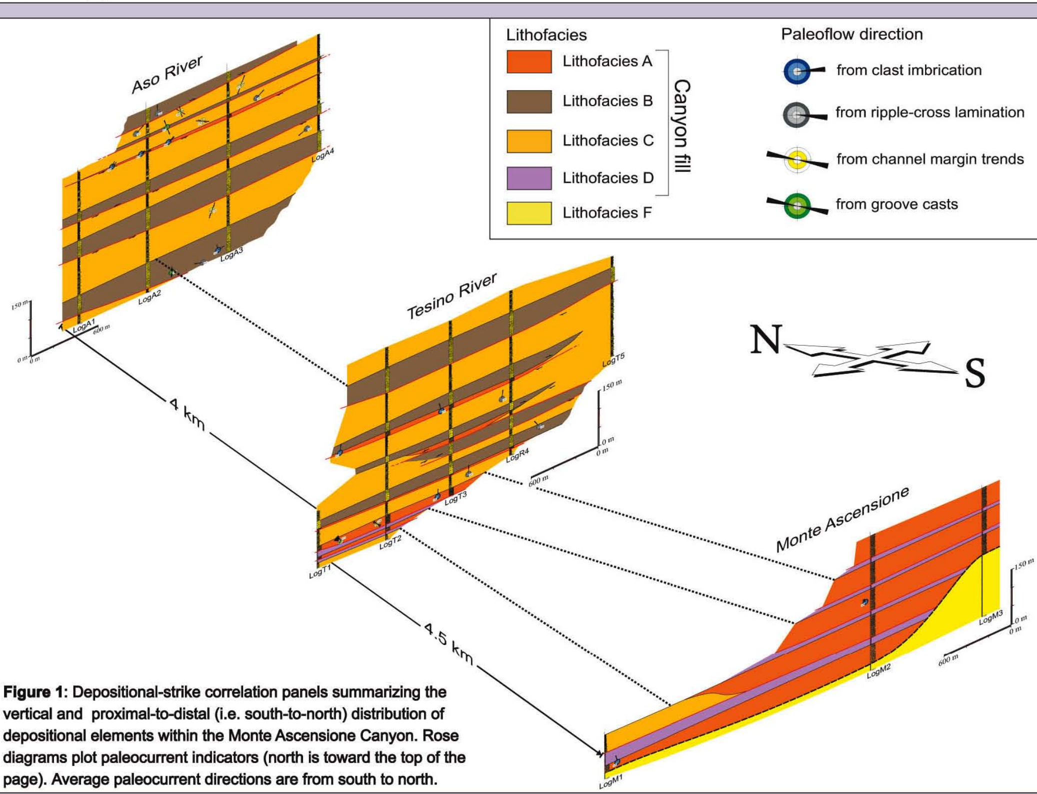


Figure 1: Depositional-strike correlation panels summarizing the vertical and proximal-to-distal (i.e. south-to-north) distribution of depositional elements within the Monte Ascensione Canyon. Rose diagrams plot paleocurrent indicators (north is toward the top of the page). Average paleocurrent directions are from south to north.

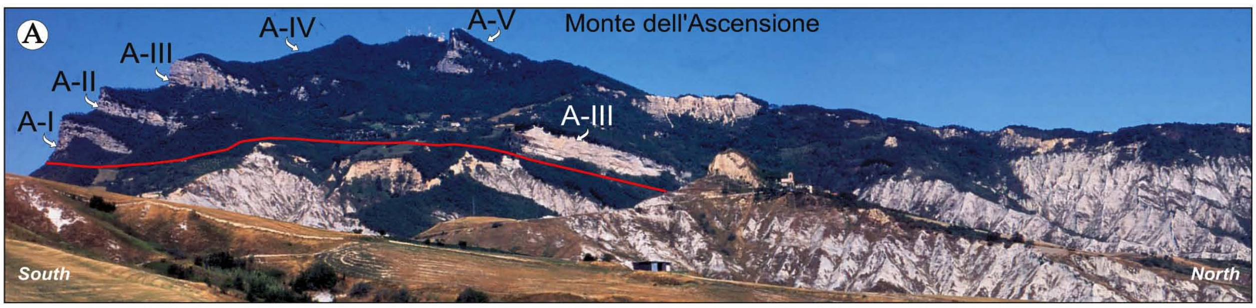
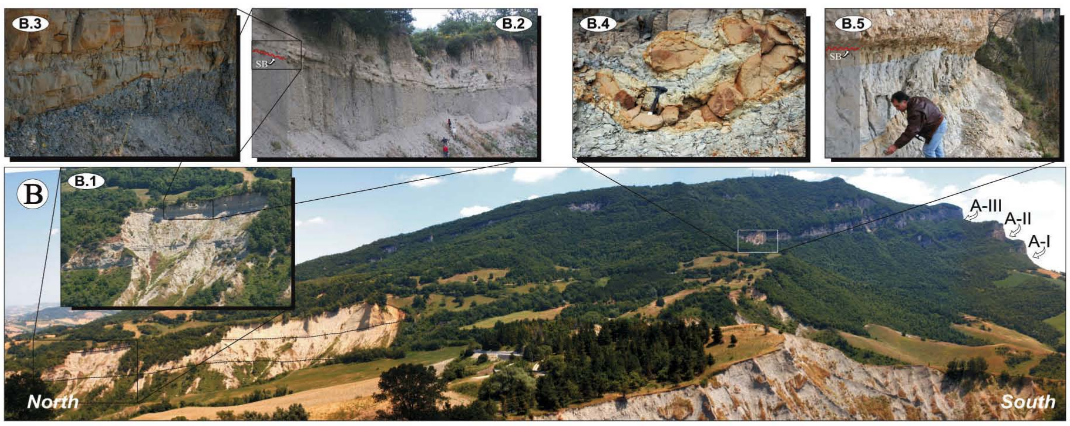


Figure 2: **A**) Panoramic view of Monte Ascensione showing the stack of five conglomerate and intervening fine-grained intervals encased in homogeneous hemipelagic mudstones. The cyclic sedimentation reflects the intermittent supply of sediment from a significant siliciclastic source and each pair of one gravel-dominated interval and one debrite-dominated interval is interpreted to represent a depositional sequence. Note the topographic confinement of the first two gravel-prone intervals.



B) Depositional-dip panoramic view of the proximal portion of the Ascensione Canyon. **B.1** to **B.3**) Panoramic and close-up views of the sharp contact between the debrite in the upper part of sequence A-I and the overlying thin-bedded sandstones and mudstones interpreted as levee-overbank deposits. This contact marks the base of sequence A-II. **B.4**) Close-up view of the debrite in the upper part of sequence A-II. The deposit displays gravel-size extraclasts, brecciated jumbles of mudstone intraclasts, and large, soft-sediment folds. **B.5**) The boundaries between successive sequences are expressed by sharp erosional surfaces across which a relatively coarse-grained interval overlies a relatively fine-grained interval. This contact marks the base of sequence A-III.

CASTIGNANO CANYON

Lithofacies A (LF-A)

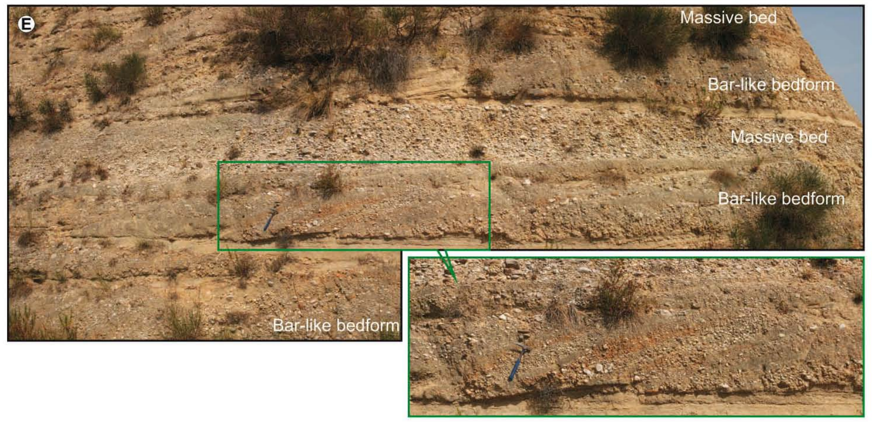


Figure 1: Lithofacies A. Dip-oriented exposure showing cross-bedded conglomerates, with foresets up to 1 m high, interstratified with more sheetlike, massive conglomerates and thinly-bedded sandstones and siltstones. Large-scale, cross-bedded conglomerates, generally associated with proximal turbidite systems, are the product of bypassing, high-density turbulent flows with thick tractional loads at the base and are interpreted as midchannel transverse bars. Palaeocurrent measurements from clast imbrication within the massive beds are consistent with those from the bars cross-sets and indicate a northwestward flow direction (to the left). Inset shows a detail of a coarse-grained bar.

Lithofacies C (LF-C)

Figure 3: Lithofacies C. Close-up of thin-bedded, sharply-based, very fine-grained sandstone beds with current ripple lamination (Tc) that alternate with centimetre-scale mud drapes (Te) in subequal proportion to produce typical wavy bedded intervals (downcurrent is to the right). A 25 cm long spatula for scale.

Lithofacies D (LF-D)

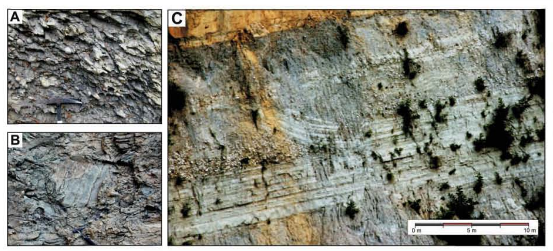


Figure 4: Lithofacies D. **A**) Close-up of typical pebbly mudstones and **B**) clast-supported clay breccias. Hammer for scale. **C**) Erosional mechanism arrested in the process of hydraulic jacking up and delamination of the substrate. Note the stratified package of sandstones partially broken off from the underlying strata and protruding upward into the overlying pebbly mudstones. This evidence suggests that the intraformational blocks occurring within the mass-transport complex have been ripped up from the underlying strata.

Lithofacies B (LF-B)

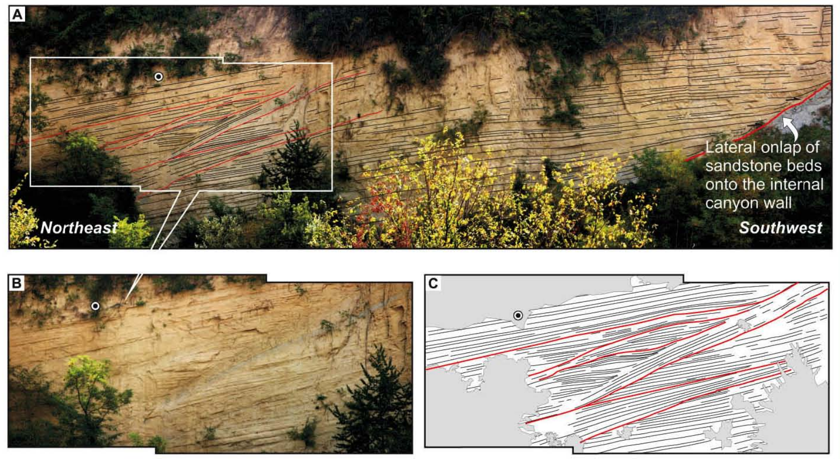
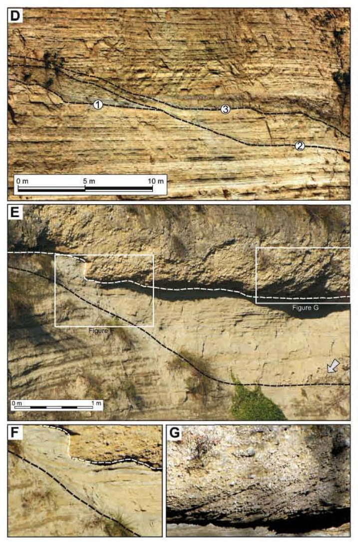


Figure 2: Lithofacies B. **A**) Panoramic view and line drawing of a northeast-southwest-trending outcrop in the vicinity of Castignano. This section provides a cross sectional view nearly perpendicular to the northwest-southeast-trending canyon margin. Circles with dots depict sediment gravity flow direction out of the plane of the outcrop (towards the viewer). The pronounced onlap of deep-water sandstones onto the northwest-southeast-trending internal wall of the fossil submarine canyon is exposed at the right-hand side of picture. **B**) Uninterpreted, enlarged view of the boxed area in figure **A**. **C**) Line-drawing interpretation of figure **B** highlighting the complex "cut and fill" stratal architecture resulting from the stacking of channel-margin remnants during repeated erosion-deposition cycles (red lines indicate channel-bounding surfaces). Channel-margin deposits are represented by a series of vertically stacked bedding packages with discordant bedding orientation. Sandstone beds become increasingly thin-bedded and fine-grained laterally towards the channel margins and either thin to pinch out by onlap onto, or continue up onto the bounding erosional surfaces, forming composite drapes of inclined, thinly interbedded sandstones and siltstones. This relationship indicates that the highest energy and most competent parts of the flows were confined to the deepest parts of the active channels and that only the more dilute, higher parts of the flows lapped onto the channel margin.



Photographs of channel-bounding erosional surfaces within LF-B (dashed lines indicate erosional contacts). **D**) Detail of a series of downcutting events (numbered 1-3 in ascending stratigraphic order) that bound horizontally-bedded sandstones and two remnants of channel-margin deposits composed of thin-bedded sandstone and siltstone that thin and onlap the underlying surfaces and are truncated by younger erosion surfaces. Note as the fill of the younger erosion surface (surface 3) is composed of well-stratified, non-amalgamated, medium- to thin-bedded sandstones that abruptly onlap the channel margin without lateral facies changes. **E**) Photograph of eastward-dipping erosion surfaces that define three distinct channel fills. The lower surface displays a steep portion deeply cutting into the underlying channel-fill sandstones and a flat-lying portion in the channel axis that is nearly parallel with underlying strata. A lenticular conglomerate, interpreted as a basal lag, occurs immediately above the erosion surface in the channel axis (arrow). **F**) Close-up showing the lower erosion surface incising bedded sandstones and overlain by draping to convergent thin-bedded sandy turbidites and laminated siltstones. **G**) Close-up of the conglomerate lags at the base of the younger channel-fill showing inclined stratification that is regarded as indicative of a significant bed load transport by bypassing, largely non-depositing flows.

Outcrop characterization

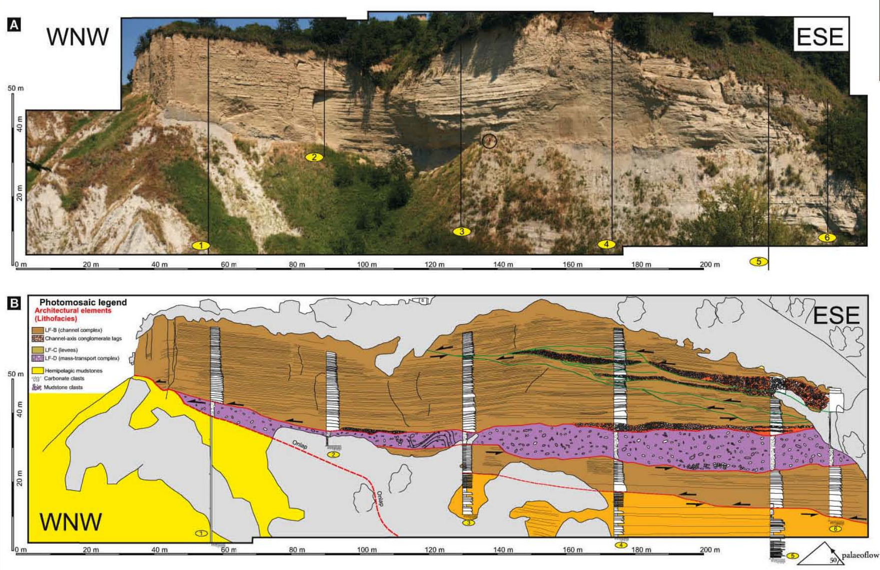
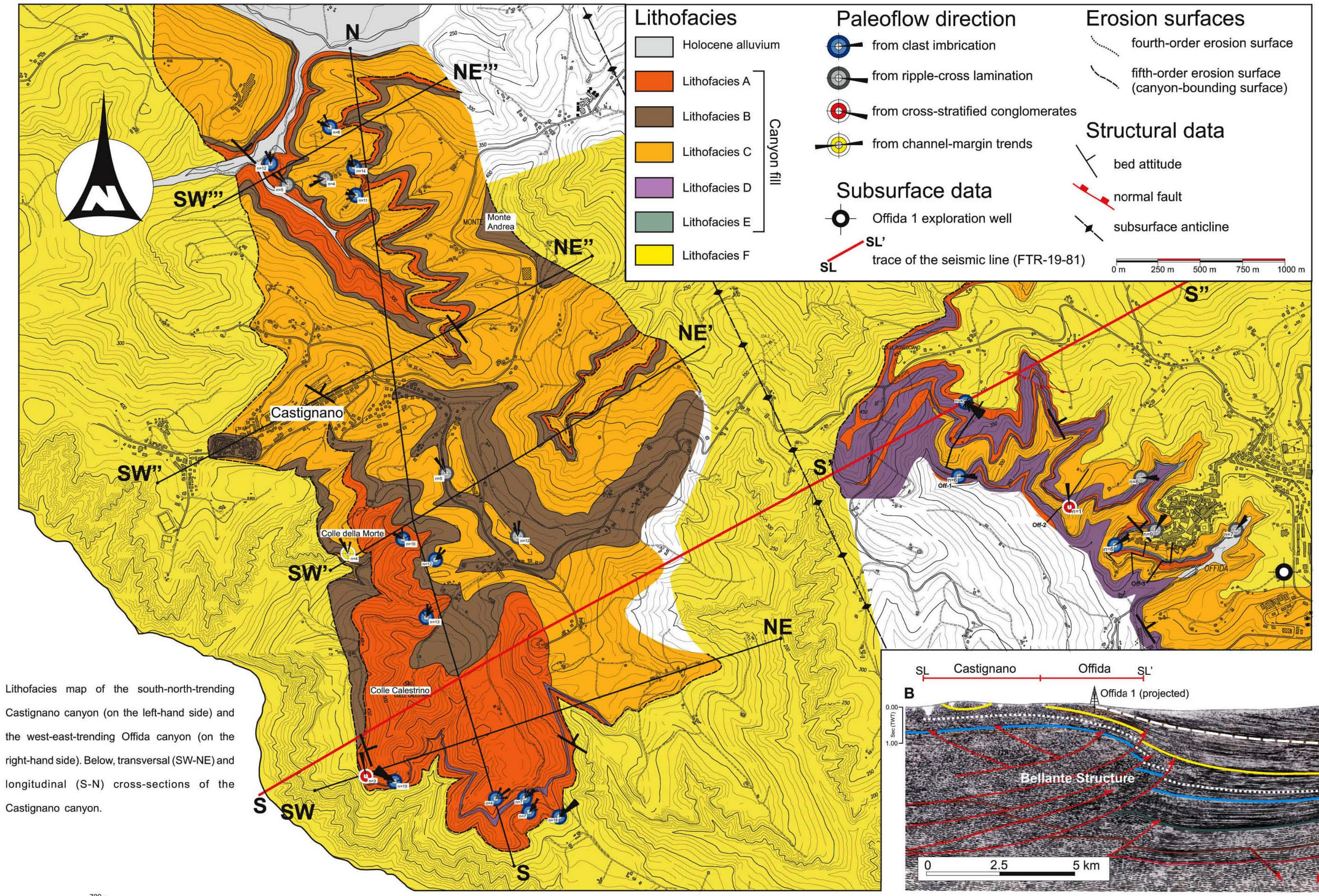


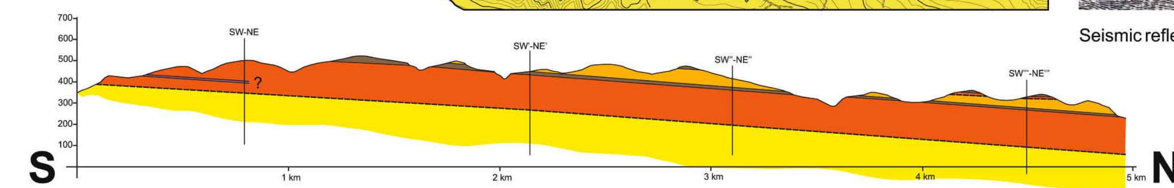
Figure 5: Outcrop characterization of the south face of the Colle della Morte cliff, Castignano. **A**) Uninterpreted photopanel showing the location of the measured sections (encircled person for scale). The average palaeocurrent direction is 350° and oriented obliquely (from right to left) into the plane of the outcrop. Alternations between aggradational and incisional stages, which are considered to reflect the stratigraphic response to short-term changes in flow parameters and sediment flux in an overall long-term aggradational system, occur at multiple scales and represent one of the characteristic features of the Castignano canyon system. **B**) Line drawing showing distribution of principal lithofacies (depositional elements).
The mass-transport complex (LF-D), mostly composed of pebbly mudstones, angular intraformational silt–mud clasts, and tightly folded, soft-sediment-deformed mudstones, is up to 10 m thick and erodes into the underlying thinly bedded sandstones laid down during gradual channel-complex deactivation (see also **Figure 4C**). Rejuvenation of the sediment-transport pathway led to erosive flushing of the conduit by energetic and turbulent flows and initiation of a new turbidite complex. The resulting concave-upwar erosion surface forms its lower boundary. Initial erosion and sediment bypass are indicated by discontinuous conglomerate lags that mantle in part the erosion surface and are interpreted to reflect later reworking and winnowing of the underlying pebbly mudstones. Subsequent backfill commenced with an aggrading succession of flat-bedded sandstones that gradually onlap onto the basal erosional surface and were deposited from largely depositional flows. Within this sand-prone package, both bed thickness and grain size decrease gradually upward defining overall fining- and thinning-upward trends that may be related to a progressive decrease in sediment caliber and sand content. To the east, the aggradational element is deeply re-incised by a channel complex, whose confining surface is composite and presents the characteristic "step and flat" geometry resulting from the stacking of numerous separate erosional events. The channel-complex margin records a complex history of numerous cycles of erosion, bypass, and backfilling early in the channel-complex history, before later, more aggradational, backfilling. It is characterized by stacked erosion surfaces and erosional remnants of several sandstone channel fills, which consist of relatively flat-lying, medium bedded sandstones that onlap the underlying erosion surfaces and are truncated by younger erosion surfaces. Conglomerate lags, up to 5 m thick, are well-developed only in the deepest parts of individual channels.

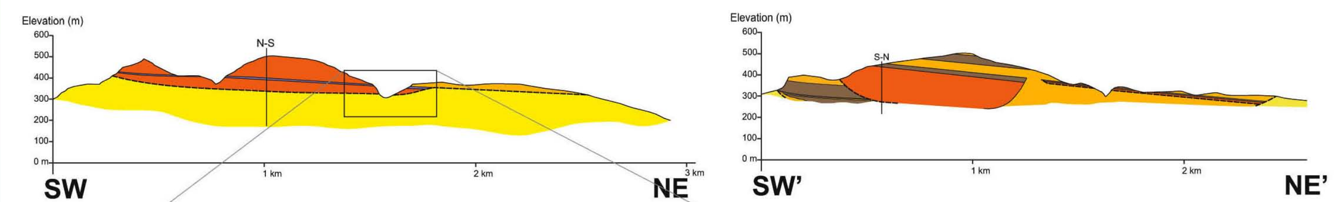
GEOLOGICAL MAP OF CASTIGNANO AND OFFIDA CANYONS

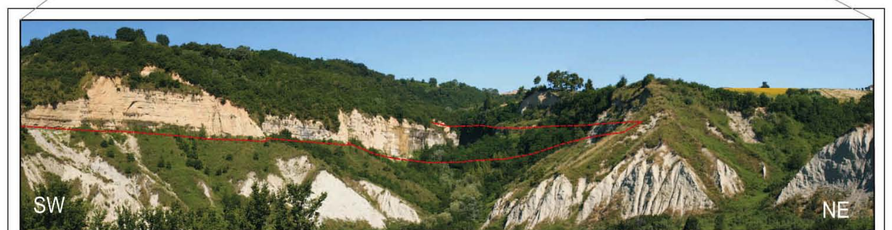


Lithofacies map of the south-north-trending Castignano canyon (on the left-hand side) and the west-east-trending Offida canyon (on the right-hand side). Below, transversal (SW-NE) and longitudinal (S-N) cross-sections of the Castignano canyon.

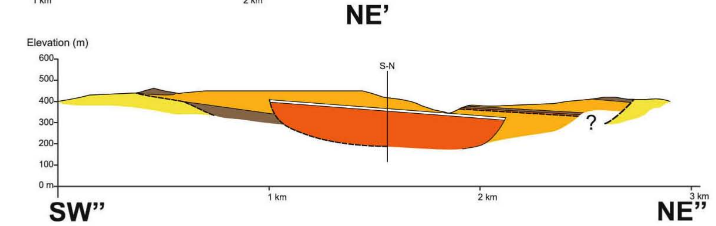
Seismic reflection profile (FTR-19-81).

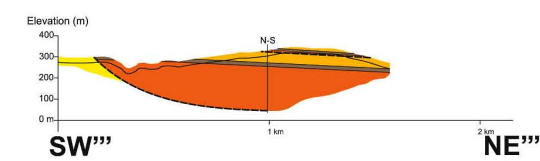






Panoramic view showing the eastern margin of the Castignano canyon. Note the lateral pinch-out of the conglomerate lithofacies highlighted by the red dashed line.





OFFIDA CANYON

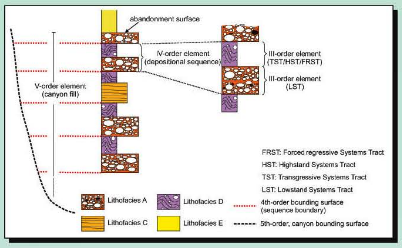


Figure 1: Architectural element scheme (Ghosh and Lowe, 1993) and sequence stratigraphic framework used to describe this canyon fill. Individual lithofacies are third-order architectural elements and represent the basic building blocks considered in this study. Erosionally bounded, fining-upward lithofacies successions define fourth-order architectural elements (depositional sequences). Each sequence typically contains a lower channel-levee complex (lowstand systems tract) and a higher mass-transport complex (transgressive to forced regressive systems tracts).

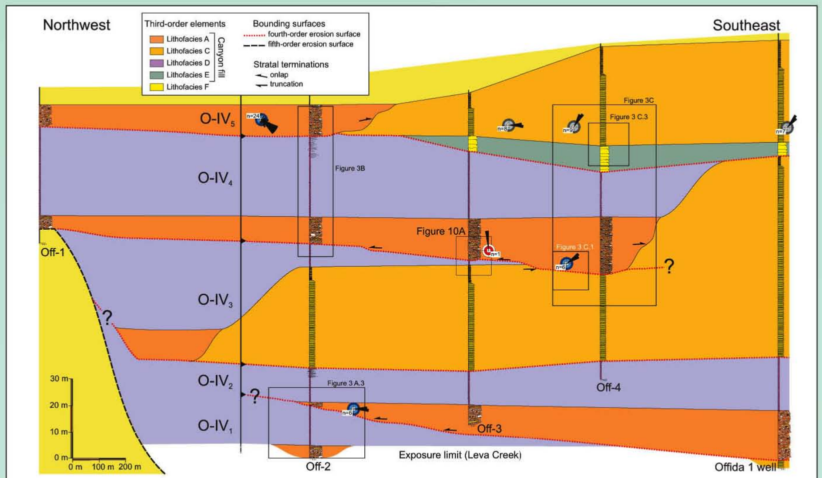


Figure 2: Depositional-strike correlation panel (paleoflow is into the page) illustrating lithofacies distribution and stratal surfaces of the Offida Canyon (vertical exaggeration ×10). This panel has been compiled integrating three measured sedimentary logs, stratigraphy recorded in the Offida 1 well, field-based mapping, and photomosaic tracing. Rose diagrams plot paleocurrent indicators (north is toward the top of the page). The infill of the Offida canyon occurred through multiple cycles of activity, each involving: (i) development of a canyon-wide erosional surface; (ii) an initial depositional stage dominated by coarse channel sedimentation, possibly braid-like in character, with conglomerate-filled channels flanked by broad sandy levees; and (iii) waning of turbidity flow deposition and accumulation of a canyon-wide sheet of mudstone-rich mass-transport complex. Based on paleocurrent data from imbricate pebbles, paleoflow direction within channels is to the east and to the southeast. Paleoflow direction from ripple-cross lamination within the sandy levee deposits is to the east and the northeast. Boxes outline locations of various figures.

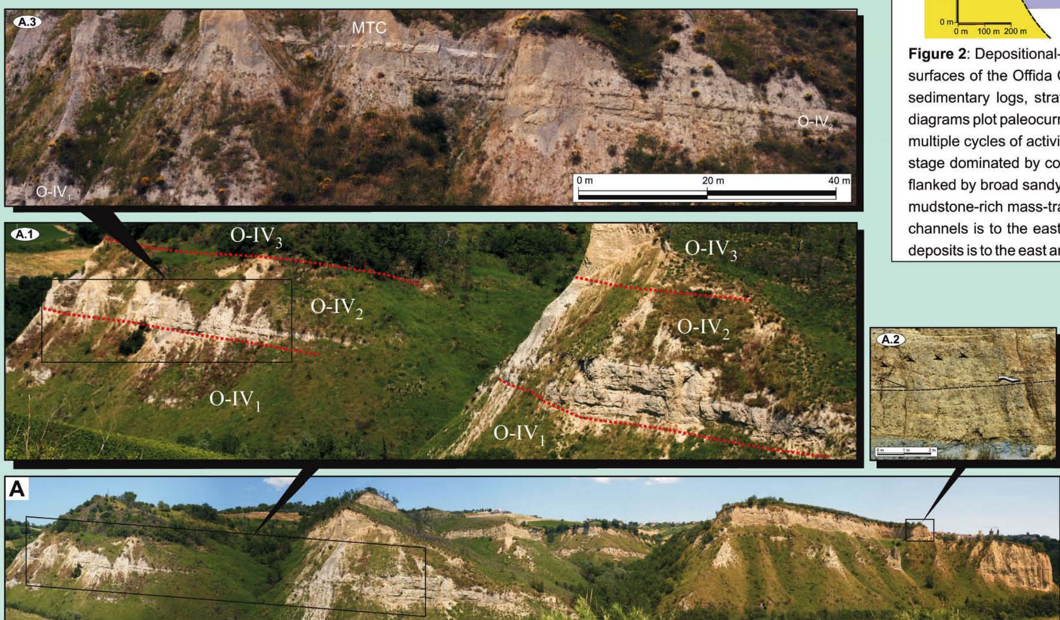


Figure 3: Outcrops in the vicinity of the village of Offida provide exposures of Gelasian (early Pleistocene) coarse-grained strata that have been deposited within a deep-water slope canyon deeply incised into hemipelagic mudstones. The canyon fill is constructed of several stacked high-frequency sequences. Individual sequences (O-IV), up to 50 m thick, consists of a basal channel-levee complex (channel-fill conglomerates, LF-A; levee thin-bedded sandstones and mudstones, LF-C; and frontal splay sandstones, LF-E) overlain by a mass-transport complex (LF-D) comprising pebbly mudstones and tightly folded slumped horizons (**B.1**). **A**) Conglomerates form a series of laterally extensive packages that thin, pinchout, and onlap northwestwards against a thick succession of hemipelagic mudstones. The sequence boundaries at the base of these sequences are sharp erosional surfaces interposed between LF-D and the overlying LF-A. Turbulent flows passing through the channels were large, highly energetic, and strongly stratified, with the coarsest portions near the base and the finer, least concentrated portions near the top. As these flows passed through the channels, the upper, more dilute portions of the flows were allowed to escape the channels, leading to formation of a thinning and fining upwards levee succession (LF-C).

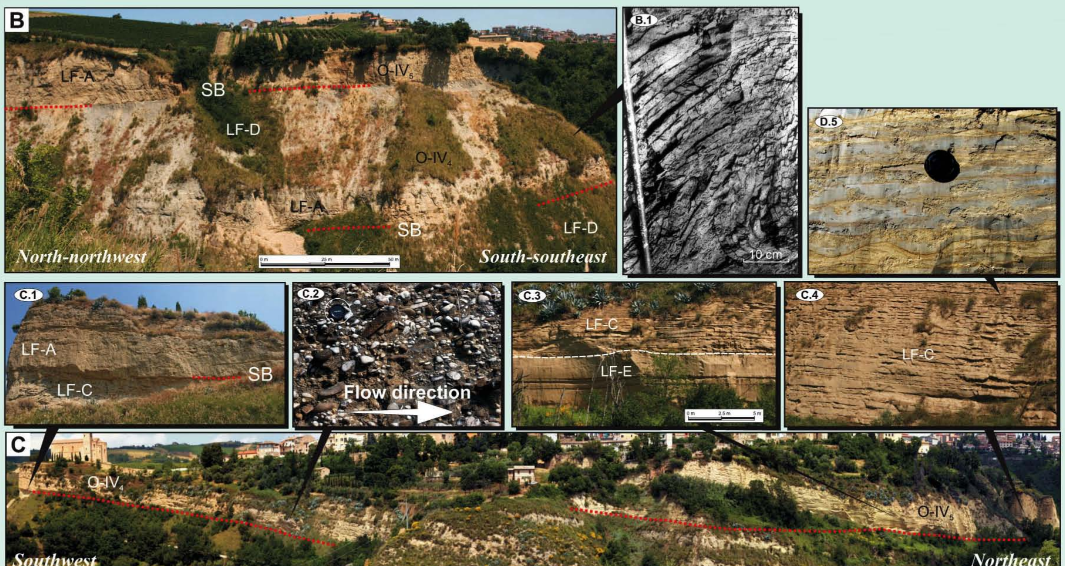


Figure 3. B and **C**) Panoramic views of the fourth (O-IV$_4$) and fifth (O-IV$_5$) depositional sequence at two different sites. At both these sites, sequence O-IV$_4$ consists of basal conglomerates (LF-A) overlain by pebbly mudstones (LF-D). At the site in figure **C**, the coarse-grained interval of sequence O-IV$_5$ consists of turbidite sanstones (compare thicknesses and lithofacies with the same sequences shown in **B**). Conglomerate facies are the typical deposits of high-density flows whereas the Bouma sequence characterizes the deposits of low-density and fully turbulent flows. (**C.1**) and (**C.2**) Large view and detail of LF-A deposits showing large planar clasts that exhibit upcurrent-dipping imbrication. (**C.3**) General view at Fosso Borgo Cappuccini, showing lower, medium- to thick- bedded, partially amalgamated, sheet-like sandstones (LF-E) overlain by thinner bedded sandstones (LF-C). The dashed line highlights the abrupt vertical transition between the two lithofacies. (**C.4**) Panoramic view of a thinning and fining upward sandstone package (interpreted as levee deposits) showing well-developed, base-missing Bouma internal structures. (**C.5**)) Detail of the upper portion of LF-C, consisting of thinly interbedded, sand-mud couplets producing wavy and lenticular beddings.

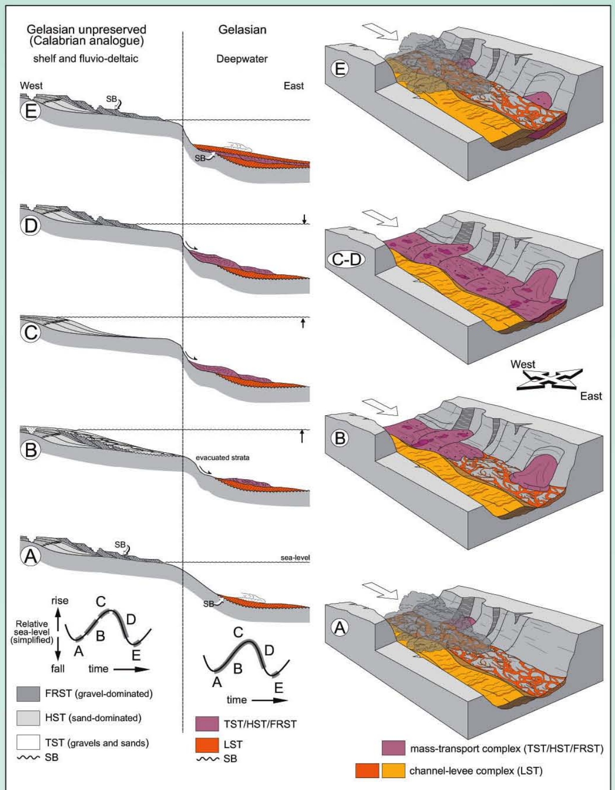


Figure 4: A shelf-to-slope profile relating recurring relative sea-level oscillations to the timing of stratal surfaces and systems tracts development within deep-water sequences and schematic bird-eye view of the Offida Canyon at different stages in its evolution. **A**) Introduction of large amounts of clastic detritus to the slope occurred at and around the lowest point of relative sea-level, when accommodation for coarse-grained sediment on the exposed shelf was at a minimum, the shoreline was situated below the contemporary shelf edge, and the Offida Canyon was connected to fluvial and littoral sediment-supply sources. Initially, the canyon acted as an area of erosion and sediment bypass, creating what we interpret as a deep-water sequence boundary corresponding with a surface of subaerial exposure on the shelf. As relative sea level started to rise, the Offida Canyon became depositional, but only some of the transported sediments were accumulated inside the canyon. At this time, a multiple-channel braidplain was the principal locus of conglomeratic deposition from high-density turbidity currents (LF-A), while sand-, silt- and mud-grade materials were in part sequestered in adjacent levee environments (LF-C) and in part transported further downslope. **B**, **C**, and **D**) Coarse-grained sediment input into the submarine canyon ceased during the subsequent transgressive, highstand and early falling stages of a relative sea level, when coastal sediment sources were displaced sufficiently far away from the contemporary shelf edge to prevent a direct supply of sediment to the slope. At this stage, active turbidite deposition was interrupted and plugging of the channel-levee complex with mass-transport complex deposits (LF-D) was the dominant depositional process operating within the filling canyon. **E**) The cycle was completed when relative sea-level returned near its lowest position and the submarine canyon resumed its role as a conduit for transport of coarse-grained clastic detritus into deeper parts of the basin. Rejuvenation of the sediment-transport pathway resulted in erosive flushing of the conduit and initiation of a new channel-levee complex by thick, gravel-rich turbidity currents.

COLLE MONTARONE CANYON

ABSTRACT: This study deals with the detailed sedimentology, strata architecture, and high-resolution sequence-stratigraphic interpretation of two canyon fills, informally named CMC1 and CMC2 (acronyms for Colle Montarone Canyon 1 and Canyon 2, respectively), exposed in northern Abruzzi (eastern central Italy). Collectively, these two systems are referred to as the Colle Montarone Canyon Complex (CMCC). Following the hierarchical architectural element scheme developed by Ghosh & Lowe (1993) for deep-water sediment gravity flow strata, the CMCC can be described in terms of five orders of architectural elements and their bounding surfaces. Third-order architectural elements are comprised of stacks of similar sedimentation units and correspond to mappable lithofacies. Four distinct lithofacies form the basic units of this study: (i) clast-supported conglomerates (LF-A); (ii) thin-bedded sandstones and mudstones (LF-C); (iii) very thinly-bedded mudstones (LF-G); (iv) pebbly mudstones and chaotically bedded mudstones (LF-D). Fourth-order architectural elements are characterized by cyclically stacked, genetically related third-order elements. Clusters of fourth-order elements are separated by fifth-order surfaces having tens of metres of topographic relief and represent fifth-order elements (slope canyons). Two discrete fifth-order architectural elements comprise the studied succession (i.e., CMC1 and CMC2).

CMC1 fifth-order element (late Gelasian)

The basal surface of this slope canyon is poorly exposed but crops out in the northern portion of the studied area, where it cuts deeply into the underlying slope mudstones. Its dimensions are beyond the size of the outcrop, but most probably exceeded 2 km in width and 120 m in depth.

This fifth-order element includes at least three laterally offset, stacked fourth-order elements, separated by canyon-wide unconformities. A typical fourth-order element is fining-upward and comprises a basal, lenticular-shaped channel-belt (LF-A) flanked and overlain by low net-to-gross levee deposits (LF-C). The basal coarse-grained channel-belts and adjacent levee deposits form high net-to-gross channel-levee systems laterally confined within the slope-canyon fairway. Paleocurrent readings from the conglomerate channel belts (LF-A) range from N010° to N110° with mean easterly dispersal direction (ca N080°). By contrast, paleocurrent measurements from vertically and laterally adjacent levee-overbank deposits (LF-C) show a fairly constant N030° average transport direction, deviating away by ca 50° with respect to that estimated from channel-fill deposits. These low net-to-gross sediments might be levee overbank deposits due to spillover from channels located outside (probably to the south) the present outcrop area.

CMC2 fifth-order element (early Calabrian)

This element represents the fill of a west-east trending fairway, at least 1.5 km wide and over 45 m deep, incised into sediments of the underlying CMC1. It does consist of a stack of several fourth-order elements, each of which includes a coarse-grained component (LF-A and/or adjacent LF-C) forming prominent bluffs, overlain by a fine-grained component (LF-D) forming recessive and poorly exposed slopes. Sparse paleocurrent indicators within the conglomerate channel belts suggest an average paleoflow direction of N080°. Fold asymmetry within the mass-transport deposits is characterised by a distinct northwest-verging direction. The gross slump-dip direction of N340° has been estimated assuming that slump folds predominantly verge downslope and that their axes are aligned approximately parallel to the strike of the paleoslope.

Sequence stratigraphy

A remarkable aspect of the stratigraphy of both these canyons is the cyclic nature of their fill. Between successive cycle-bounding unconformities, the principal lithofacies recognized within the CMCC recur in consistent fining-upward stacking patterns (fourth-order elements). This vertical arrangement records high-frequency fluctuations in canyon activity and depositional regime and can be related to cycles of relative sea-level change and associated events at the corresponding shelf edge. In terms of sequence stratigraphy, each fourth-order elements is interpreted to represent a high-frequency (decametre-scale) depositional sequence. Two different sequence motifs have been recognized. Type 1 sequences, typical of CMC1, comprise a basal high net-to-gross channel-levee system (LST) followed by a lower net-to-gross succession of thinly interbedded sandstones and mudstones displaying a general fining- and thinning-upward trend (TST). Type 2 sequences, which characterize the infill of CMC2, display a lower high net-to-gross channel-levee system (LST) that is immediately overlain by mud-prone mass-transport deposits (TST to FSST). Based on the tight chronostratigraphic constrains available, sequences are interpreted as the deepwater sedimentological expression of repeated obliquity-driven eustatic oscillations in sea level.

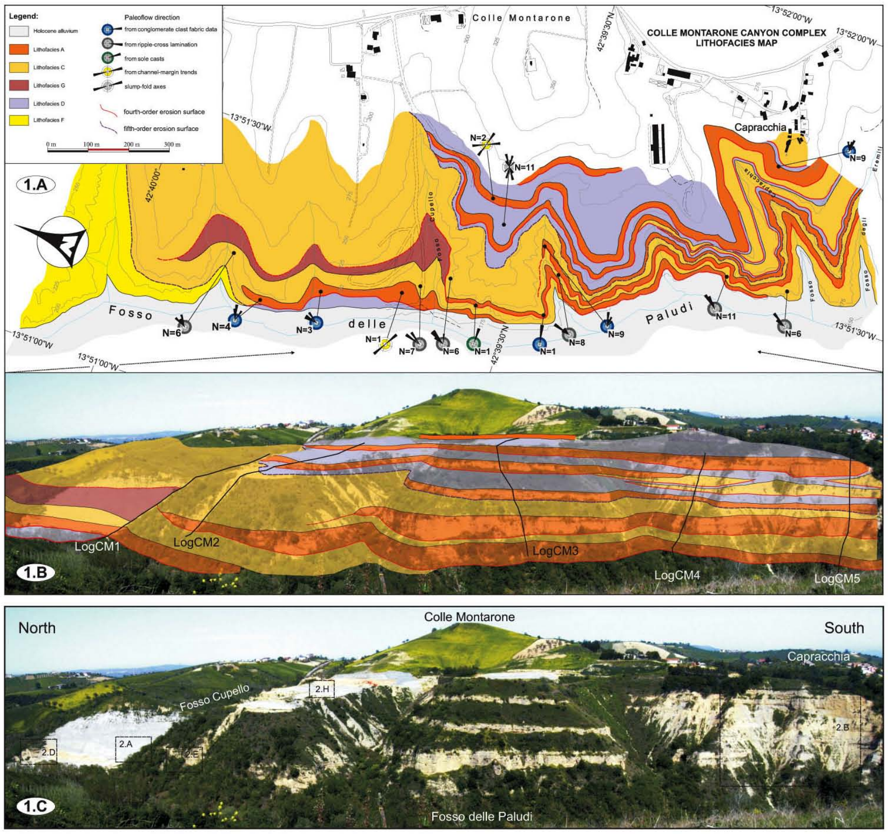


Figure 1. (**A**) Lithofacies map (original mapping at 1:5,000 scale) and uninterpreted (**C**) and interpreted (**B**) photomosaic of the west face of Colle Montarone showing the architecture of main third-, fourth- and fifth-order elements. These sediments are exposed as a homoclinal succession gently dipping to the east. Rose diagrams are shown to document the dispersal patterns in the studied area (general palaeoflow direction was approximately into the plane). Areas defined by dashed boxes outline locations of outcrops shown in Fig. 2. Thick black lines indicate location of measured section LogCM1-5 shown in Fig.3.

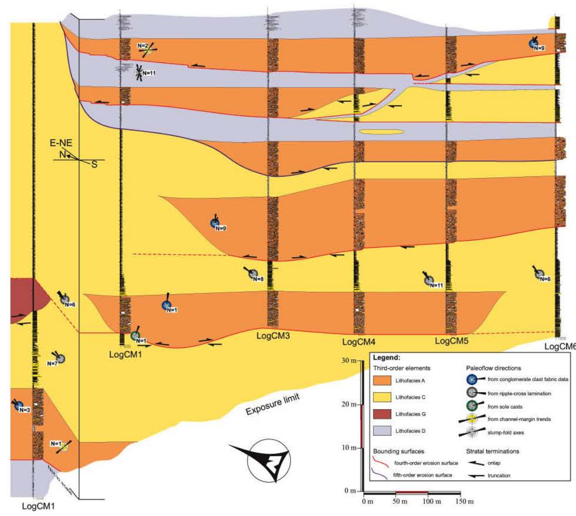


Figure 3. Two-dimensional correlation panel across the central portion of the Colle Montarone canyon complex constrained by six measured sections (which total ca 500 m of measured section), field-based mapping and photomosaic tracing (vertical exaggeration ca ×6.5).

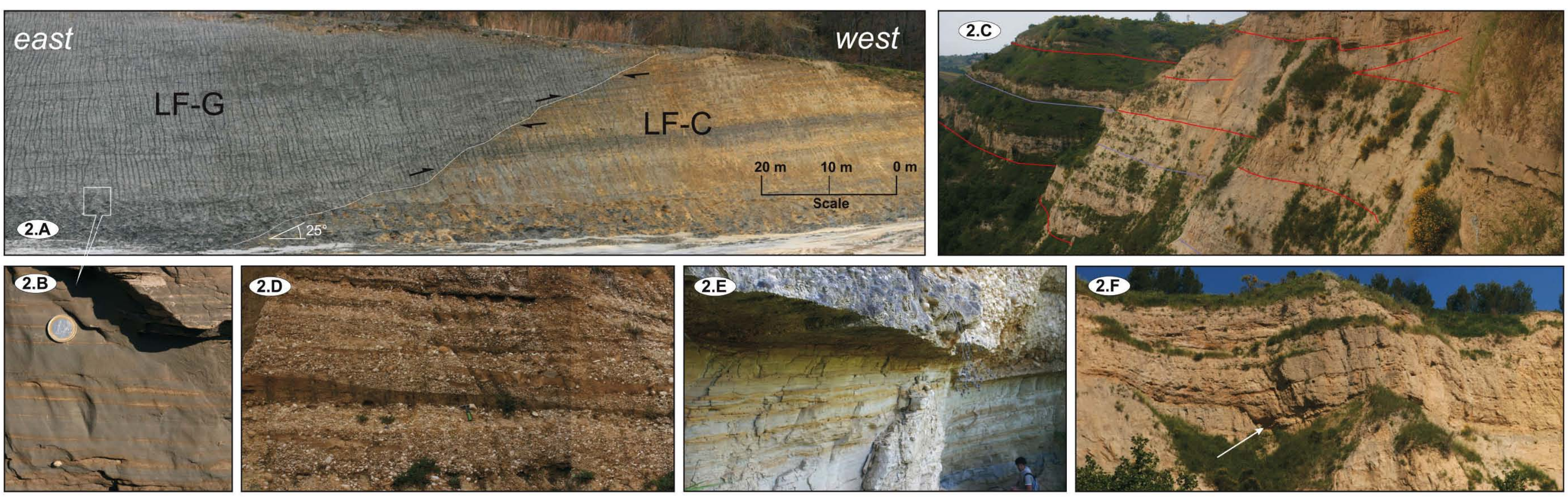
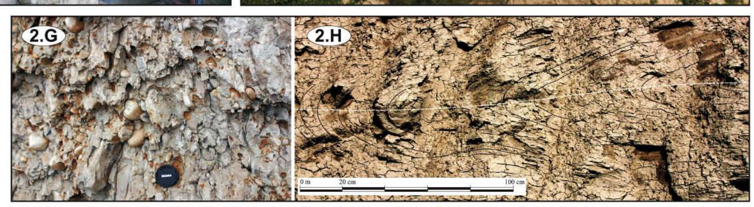


Figure 2. A) Photopanel of the prominent, steep-sided erosion surface cutting into thin-bedded sandstone and mudstone turbidites. The erosion surface is overlain by very thinly bedded mudstones that lap out against the erosional margin (**B**). **C**) Northward view of the CMC2 clastic fill illustrating its pronounced cyclic architecture. This outcrop, clearly indicates radical changes in the sedimentary processes operating during canyon filling and is interpreted as a cyclical combination of active fill (high net-to-gross channel-levee systems) and "passive" fill (low net-to-gross channel-levee systems or mass-transport deposits). **D**) Close-up of the well-rounded, pebble and cobble conglomerate of the lowermost package occurring within CMC1. The largest observed clast is in excess of 1 m across. Most clasts have mollusc borings, showing that they resided for at least some time in the littoral zone; reworked, thick-walled oyster-shell fragments and other shallow-marine faunas are also common within the conglomerate. Individual conglomerate beds range from 20 cm to over 2 m thick and inverse, normal, and inverse-to-normal size grading are well-developed. The conglomerate includes common lenses of sandstones, which are generally less than 50 cm thick and dominated by massive to normally-graded S3 divisions of Lowe (1982). Hammer at centre for scale. **E**) Close-up of the low-relief erosional surface interposed between thinly bedded, current-structured sandstones, siltstones and mudstones of the levee facies and the overlying channelized conglomerates. The southward increase in thickness of the conglomerate package reflects progressivelydeeper incision into the underlying strata.



F) Detail of a conglomerate package occurring within CMC2 showing the stepped erosion surface at its base that cut deeply into the underlying pebbly mudstones. **G** and **H**) Details of the mass-transport deposits composed of interbedded pebbly mudstones and thinly bedded mudstones showing large, recumbent soft-sediment folds.