Outcrop reservoir analogous and porosity changes in continental deposits from an extensional basin: the case study of the upper Oligocene Sardina graben system, Italy

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Abstract

Several recent hydrocarbon discoveries were detected in extensional basins, filling depositional areas located on the flanks or partially over the margins of fault-bounded tectonic highs. These sectors are diffusely characterised by terrestrial and shallow-marine successions, which show complex geometrical relationships due to the tectonic evolution of these mini-basins. The degree of seismic resolution and the punctual lithostratigraphic data coming from well logs do not allow suitable reconstructions of these plays and, thus, the use of good outcrop analogues is crucial in their reservoir characterisations.

In this paper, we present the results of a sedimentological study carried on continental deposits filling a segment of the Oligo-Miocene southern-eastern margin of the Sardinia Graben System, in the central-western Mediterranean. This well-exposed terrestrial succession results from the erosion of Palaeozoic metamorphic and magmatic basement rocks exposed along the basin margin. Our field observations demonstrate as these proximal environments were tectonically isolated from the open sea, as suggested by the absence of lateral stratigraphic continuity to more distal coastal or shallow-marine deposits.

Continental sediments exhibit changes both in thickness and lateral extensions due to the existence of several endorheic depocentres, which were scattered across the basin margin and aligned along major normal faults. This setting controlled the accumulation of coarse-grained eluvio-colluvial, alluvial and fluvial facies associations characterised by a number of textural features and stratal geometries.

Based on the analysis of a number of exposed stratigraphic sections, the main depositional processes were identified for each specific facies association. Due to the grain-size of the dominant deposits, porosity were estimated by using an image analysis software on high-resolution digital photographs from a number of outcrop samples. The results show how porosity changes dramatically across the reconstructed sections due to the complexity of the reciprocal geometrical passages among all these lithofacies.

Sediments were thus grouped into specific depositional systems, including colluvial and alluvial fans and river braidplains. The dominance of one of these systems into the others and the different nature of sediment occupying each depositional areas were interpreted as the response to the interplay between the capacity generated by the vertical tectonic displacement of major normal-faults and the interception of the base-level with the topography of these mini-basins. Our observations suggest six possible depositional scenarios that resume as many reservoir types in fault-controlled half-grabens with dominant continental lithofacies.

Key-words: *extensional basins*; *continental deposits*; *porosity*; *late Oligocene*; *Sardinia Graben system*; *depositional processes*; *depositional systems*; *reservoir analogues*.

1. Introduction

Many recent hydrocarbon discoveries were found in extensional basins, filling depositional areas located on the flanks or partially over the margins of fault-bounded tectonic highs (e.g., the upper Jurassic-lower Cretaceous in southwest Alabama, USA; the Miocene Mumbai High Field, western offshore India; the Triassic-Jurassic around the Utsira, Frøya and Mandal highs, Norwegian Sea; upper Jurassic in the Strathspey-Brent-Statfjord half graben, northern North Sea; Mink & Mancini, 1995; Davies et al., 2000; McLeod et al., 2002; Vasudevan et al., 2012). Most of these plays derive from sedimentary basins subjected to extensional tectonic regimes. Commonly, graben and half-graben petroleum systems exhibit depositional architectures, which consist of distinctive stratigraphic expansion of the seismic reflectors toward the bounding faults, indicating syn-tectonic deposition (e.g., Blair and Bilodeau, 1988; Gawthorpe et al., 1994). In many of these examples, coarse-grained continental deposits adjacent to the major fault zone (Trudgill, 2002) represent sedimentation associated with the initial stage of tectonic fragmentation. These deposits evolve laterally or vertically to sand-rich shallow- to deeper-marine sediments during the tectonic development of the basin. In a reservoir perspective, these latter deposits are usually retained more profitable respect to their fully continental counterparts, because sand-rich and, therefore, characterised by very good porosity and permeability properties. However, many recent case studies also revealed unexpected very-good oil and gas reservoirs entrapped in the continental basement-derived successions filling fault-controlled mini-basins (e.g., Jackson et al., 2010). These depressions usually consist of 100s-to-1,000s m long grabens and half-grabens located on top of tectonically-fragmented wide areas thought as tectonic 'terraces', which connect the marginal 'platforms' to the deeper basins (e.g., the middle-upper Jurassic in the North Sea rift basin; Davies et al., 2000).

Although very common along the margins of many extensional basins (e.g., Steel & Wilson, 1975), fault-adjacent continental sediments are often difficult to differentiate from subsurface core datasets or they are often under a good seismic resolution to be properly assessed and evaluated. Moreover, coarse-grained deposits are commonly difficult to interpret from core data, because characterised by indistinct textural features or not well-defined sedimentary structures. Therefore, when exposed and preserved, ancient basement-derived continental facies represent useful outcrop analogues to disentangle their palaeo-environmental meaning, the reciprocal lateral/vertical stratigraphic relationships and to evaluate their reservoir potential for similar subsurface oil-bearing successions.

The present study documents the sedimentological features and the depositional architectures of upper Oligocene coarse-grained continental deposits (the Ussana Formation, *Auct.*) accumulated across the SE margin of the so-called Sardinia graben system (Cherchi, 2008; Oggiano et al., 2009) (Fig. 1A and 1B). This basin boundary zone underwent an early phase of tectonic extension, which resulted in the formation of a generation of isolated or interconnected grabens and half-grabens which were variously filled by continental conglomerates and sandstones (Fig. 1C) (Sowerbutts & Underhill, 1998; Casula et al., 2001).

During this initial tectonic fragmentation, different types of fault-related composite depositional systems formed, where colluvial, alluvial and fluvial sediments were adjacently accumulated with varying relative volume percentages and porosity vertical/lateral trends.

Our observations, deriving from facies analysis carried out on a number of vertical sedimentological logs and physical stratigraphic correlations, allowed us to reconstruct: (i) the main depositional processes at the origin of the various detected lithofacies; (ii) the lateral/vertical relationships between the types of recognised sediments, including eluvio-colluvial, alluvial and fluvial lithofacies accumulated in many of these half-graben depressions, and (iii) the various depositional systems and their reservoir potential. All these elements can be jointly used as tool to successfully evaluate the best-productive sectors in similar hydrocarbon-bearing sedimentary rocks.

2. Geological setting of the Oligo-Miocene Sardinia graben system

The Oligo-Miocene Sardinia graben system (Cherchi and Montadert, 1982; Rehault et al., 1984; Cherchi et al., 2008) developed since the late Oligocene onwards in a N-S-elongated area presently comprised between the Gulf of Asinara to the north and the Gulf of Cagliari to the South (Fig. 1B).

This basin resulted from the extensional regime that affected the Iberian-Europe Region at about 34 Ma, and was originated by the complex interplay of normal fault systems that dissected part of the so-called ‘Corsica-Sardinia microplate’ (Casula et al., 2001). Other authors consider this basin as the result of a multiphase extension and transtension in an intra- or back-arc setting, occurred as the Corsica-Sardinia microplate rotated from Eurasia in the Western Mediterranean from 21 to 15 Ma (Carmignani et al., 1994; Vigliotti and Langenheim, 1995; Vially and Trémolières, 1996; Facenna et al., 2002).

The pre-Oligocene basement comprises metamorphic and magmatic rocks of Ercinian origin (Sowerbutts and Underhill, 1998; Casula et al., 2001; Oggiano et al., 2009), including thin middle Eocene continental covers (Barca & Costamagna, 2010) intensely fractured and weathered. The overlying upper Oligocene continental deposits, known as the Ussana Fm (Cherchi and Montandert, 1984; Eschard, 1987), accumulated during the first stages of a tectonic fragmentation or basin opening (‘syn-rift stage’ according to Casula et al., 2001), and were transgressively buried by lower Miocene marine sediments (Simone et al., 2011; 2012). This succession was then exhumed and partially incised by subaerial exposure as consequent of the Plio-Quaternary regional uplift.

The present-day subsurface structure of the Sardinia graben system, interpreted on the basis of seismic-based cross sections (Casula et al., 2001), consists of major normal faults, tilted blocks and transverse structures (Fig. 1C). The basin shows a larger width of the extensional system compared to the exposed graben (Fig. 1C), where marginal sediments, which are the focus of the present study, are today well exposed in outcrop.

2.1 The upper Oligocene continental Ussana Fm

The upper Oligocene Ussana Fm diffusely crops out in southern Sardinia, forming elongated deposits parallel to the main fault zones or occupying isolated sub-basins. It develops on the Palaeozoic basement or erosionally overlies the Eocene Cixerri Fm (Fig. 2). The Ussana deposits are considered coeval with other shallow- and deeper-marine sediments, including the “Calcari di Isili” and “Sabbie di Gesturi” formations, whereas it is overlain by the lower Miocene “Marmilla Fm”. In this sector of Sardinia, the Miocene succession ends upward with transgressive conglomerates and marls of the “Marne di Gesturi” Fm (Fig. 2) (Funedda et al., 2011).

Pecorini & Pomesano Chierchi (1969) firstly define the “Ussana Formation” as a coarse-grained succession that recorded the initial stage of the syn-rift opening in the south-central Sardinia during the middle-upper Oligocene (Leone et al., 1984; Trémolières et al., 1984; Assorgia et al., 1995; Eschard, 1987; Casula et al., 2001). Based on its relationships with the overlying lower Miocene marine deposits, and from the occurrence of localised Oligocene volcanic clasts, the Ussana Fm was dated at the late Oligocene-early Aquitanian(?) age (Pecorini & Pomesano Chierchi, 1969).

This coarse-grained succession diffusely occurs at the footwall of fault escarpments, directly overlying the pre-Oligocene basement. It mainly consists of non-marine, subaerial sediments (Cherchi and Montadert, 1982; 1984), interpreted as fault-scarp talus and alluvial fan deposits with stream-channel reworking (Sowerbutts and Underhill, 1998), and retained laterally continuous to marine sediments (Casula et al., 2001).

The Ussana Fm is found only along the border of the basin and shows in outcrop thicknesses ranging from a few meters up to 200 m, because related to isolated or partially interlinked different depocentral zones (Simone et al., 2011; 2012). However, Barca et al. (2005) documented up to 300 m for the Ussana Fm, whereas thicknesses up to 500 m were reconstructed from the ‘Marcella well’ located offshore the Gulf of Cagliari (Casula et al., 2001).

In detail, the Ussana deposits consist of continental breccias and conglomerates often immersed in a red, violaceous sandy-clayey matrix, associated with sandstones and, less frequently, mudstones (Fig. 3). These sediments frequently form unorganised 5-15-m-thick lithosomes, or they are included in up to 50-60-m-thick wedge-shaped bodies containing large-scale low-angle erosional surfaces, a number of lower-rank discontinuities and 0.5-to-5-m-thick trough/planar cross stratasets. Clast-supported, chaotic, channelised and graded-boulder-pebble conglomerates with a poorly sorted sand-gravel matrix, red colouration and a general lack of fossils also characterise this formation (Sowerbutts and Underhill, 1998).

3. Methods and datasets

The general observations, phtotomosaic linedrawings and stratigraphic log measurements reported in the present study were obtained from the Ussana deposits presently exposed along the southern sector of the Sardinin Graben system, NE of Cagliari, between the villages of Sinnai, Soleminis, Donori and Ussana (Fig. 1B). Today, this area corresponds to the eastern margin of the younger Campidano Graben, which superposed on the previous Sardinia Graben system during the Plio-Pleistocene.

Facies analysis was carried on a number of exposed sections and outcrops listed in Tab. 1. Data collected in this study mainly derive from field observations of natural and artificial sections (e.g., road cuts, quarries, and cliffs) providing three-dimensional exposures.

Coarse-grained accumulations of detrital clastic sediments represent the dominant volume of the Ussana Fm observed in outcrop. A process-based analysis were focused on these deposits, which reveal complex primary depositional geometries, strataset architectures and internal sedimentological and textural features, including grain size, roundness and shape of the pebble-size clasts, lithological composition, etc.

Since no thin section or micro-core sample have successfully been obtained from the observed deposits, due to the coarse-grained nature of the clastic sediments and to their frequent scarce degree of cementation, porosity was indirectly estimated by using an image analysis software (Image-J ®) from outcrop digital photographs. Sediment images were acquired in high resolution (2400 dpi), 20-cm-sided pictures, obtained in absence of direct solar light, in order to avoid shadows or anomalous illumination. Subsequently, each image was analysed and digitally converted in binary format (black-and-white), in order to capture pores and fractures in shadow areas and fulfilled parts in light areas (Fig. 4). Then, the area percentage for each photograph sample considered was calculated based on the total amount of black sectors.

4. Results

4.1 Description and interpretation of facies associations

The Ussana Fm is mostly formed by eluvial, colluvial, alluvial and fluvial deposits. The relative abundance of these four facies associations is highly varying from place to place (Fig. 5) and depends on the relative position of the analysed succession with respect to the distance from the basement or from the main faults. The grain-size dominance observed in the studied sections is summarised in the ternary diagram of Fig. 5. This plot shows as: (i) coarse-grained sediments abound in the eluvio-colluvial facies associations, whereas sandstones are very scarce or virtually absent; (ii) in the alluvial-dominated associations, the sandstone content increases, even if in minor percentage compared to the gravel/conglomeratic sediments; (iii) sand-rich deposits are dominant over the coarser deposits in fluvial-dominated facies associations.

4.1.1 Facies association 1: Eluvial deposits

In this facies association, coarse-grained clastic horizons discontinuously distributed along the SE-NW-trending margin of the Sardinia graben system (e.g., Sinnai, Soleminis, S. Nicolò, Dolianova and Sa Domu e s'Orcu sections – Fig. 1) are included.

Sediments consist of basement-derived clastic accumulations or weathered horizons, whose thicknesses vary greatly from place to place (Fig. 6A). The general features of these deposits are, therefore, intimately related to the nature of the bedrock they lie over (Figs. 6B and 6C).

Generally, this association forms 2-3 m up to 6-7 m thick mantles consisting of rock fragments with angular shape that drape the underlying units.

Based on the type of basement rock, i.e., metamorphic or granitoid, which are the main lithotypes observable in the study area, this association has been subdivided into three facies: *1a*, *1b* and *1c* (Tab. 1). Facies *1a* includes structureless very immature breccia deriving from reddish meta-sandstones (Fig. 7A). Angular and sub-angular clasts range in diameter from a few millimetres (granules) to tens of centimetres (Fig. 7A). Facies *1b* shows very similar textural features, but differs in the source rock lithology, which is represented by meta-siltstones (Fig. 7B). These two facies display very chaotic textures, totally unsorted clasts, and absence of any strata or internal structures. Facies *1c* derives from the consumption of a surficial regolith mantle of diorites and grano-diorites (Fig. 7C). This type of source rock often generates a weathered horizon which simulates a sand-size deposit with apparently mature textures, although the deposit is still attached to its original substratum. In outcrop, this facies often forms structureless yellowish deposits with grain size ranging from coarse sand to granule.

In general, porosity evaluated in such type of facies association increases from the internal rock volume, where the core is still undegraded or poorly fragmented, toward the surface where weathering/fracturing involve the most external part of the basement rocks. In detail, the estimated porosity indicates ranges of 2.7-4.6% for facies *1a*, 5-7.8% for facies *1b* and 3-6% for facies *1c* (Tab. 1).

4.1.2 Interpretation

Facies association 1 represents eluvial deposits deriving from different types of weathered or fractured bedrocks, left over by soil degradation and still localised very close or virtually still attached to the source rock. These ‘alterites’ or ‘regolith’ deposits mantle their original substratum without any significant movement and are thus deprived of any physical form (i.e., strata) or distinctive geometry (Starkel, 1987; French, 1992). Eluvial deposits observed in the Ussana Fm show various ‘maturity’ stages, depending on the degree of weathering, which is not simply a function of the time of exposure and consequent consumption, but also of their state of fracturing, faulting and, importantly, on their primary compaction and resistance to erosion. Facies *1a*, *1b* and *1c* represent the three most recurrent examples of eluvial deposits that often coexist laterally in adjacent positions (Fig. 6C). This interval with highly-varying thickness may generate a surficial rock horizon characterised by a primary porosity commonly less than 10%. Therefore, when lacking of any other associated type of sedimentary deposit (see the following sections), these lithofacies have not good reservoir properties.

4.1.3 Facies association 2: colluvial rockfall/debrisfall deposits

Facies association 2, documented in the sections of Sa Domu e s'Orcu, Sinnai, Soleminis, Dolianova, S. Nicolò Gerrei and Barrali (see Figs. 1 and 5), form lenticular, 3-4 m up to 20-25 m thick deposits commonly lying on, or laterally adjacent, to the Palaeozoic basement units. The nature of such contacts can be either stratigraphic or tectonic (i.e., adjacent to fault scarps). Internally, this association can be distinguished from the previous deposits because of a first faint organisation in strata and stratasets, which thus implies a variable amount of transport before the accumulation.

This association includes facies *2a* and *2b*. Sediments generally consist of immature, very angular monomictic breccia (facies *2a* in Fig. 8A), locally associated with mature sub-rounded to rounded coarse gravel (*2b* in Fig. 8B). These two facies form wedges which are generally structureless or internally organised into inclined tongue-shaped beds, 0.2 to 1.0 cm thick, normal graded and with openwork texture (Figs. 9 and 10A). Openworks are often infilled by a detritic, secondary finer material, deriving from the consumption of the weathered primary clasts. This sandy matrix is locally well sorted and frequently laminated (Fig. 10B), where single laminae are given by abrupt changes in grain size of the component clasts. Cobbles and boulders, sheltering clusters of fine gravel, are also present (Fig. 10C). In the section of S. Nicolò Gerrei (Fig. 10D), this facies association forms linguoid strata of breccias and gravels with 10°-15° slope inclination. Strata exhibit alternate normal and inverse grading (Fig. 10E).

The inferred porosity varies greatly from place to place, depending on the portion where it has been evaluated. In general, porosity in both the deposits of facies *2a* ranges from 4.7% up to 8%, due to the presence of the finer (sand-size) matrix filling the gravel interstices, whereas it increases noticeably (10-15%) in the deposits of facies *2b* because of the diffused openwork texture (Tab. 1).

4.1.4 Interpretation

Sediments of facies association 2 are considered to be of colluvial origin, deriving from clastic slope-waste material, which is typically coarse grained and immature, deposited in the lower part and foot zone of a mountain slope or other topographic escarpment (Holmes, 1965; Bates and Jackson, 1987; Blikra and Nemec, 1993; Nemec and Kazanci, 1999; Leopold and Völkel, 2007). Rock fragmentation derives mainly from inter-clast impact and consequent disintegration during sediment-gravity processes of downslope rolling, sliding and bouncing of single or clustered clasts (Blikra and Nemec, 1998). Sediment remobilisation thus occurs along steep (30°-40°) slope surfaces, as these deposits were transported mostly by the gravity force, under the form of (dry) rockfalls and debrisfalls. In rockfalls, sediments are directly produced by primary rock fragmentation deriving from weathered or fractures source rocks. In debrisfalls (Holmes, 1965) sediments move in a way mechanically analogous to rockfalls, but the involved clasts derive from older, re-sedimented gravel, rather than freshly fragmented bedrock. This difference from rockfalls results in a relatively mature deposit, including sub-rounded to well-rounded clastic elements (Blikra and Nemec, 1998), which often differs markedly with the resting part of the immature deposits.

These observed colluvial deposits were thus not mobilised by significant water flows, except for the finer clastic matrix eventually present and filling the openwork interstices. Laminated fines filling the inter-spaces (Fig. 11) suggest the intervention of minor fluids (water) that transport and organise into lamina-sets the finest material after the main phases of rockfall and consequent accumulation. The coarse-grained fraction, formed by very immature gravel, often shows imbricated stack of clasts in the direction of slope. Couples of coarse- and fine-grained material form fining-upward strata (Fig. 11).

In terms of overall porosity, the trend evaluated from the core rock toward its surface is initially analogous to eluvial deposits. It differs substantially only around the most external sediment portion, because of the presence of the fine matrix, deriving from the intra-clast impacts, which fills the interstices reducing considerably the primary porosity at less than 10%.

4.1.5 Facies association 3: alluvial debrisflow deposits

This facies association dominantly crops out in the sections of Ussana, Soleminis and Donori and, in minor proportion, in the sections of Sa Domu e s'Orcu and Sinnai (Figs. 1 and 5). The exposed total thickness of this association is up to 30 m, but higher thicknesses are not excluded in areas where the base of the succession is not visible.

Sediments of this association form two facies: *3a* and *3b*. Facies *3a* characteristically consists of mature and very mature sub-rounded and rounded polymictic gravels and conglomerates, with clasts ranging in size from pebbles up to boulders. Clast- to matrix-supported assemblages without any apparent preferential fabric in their spatial distribution (Fig. 12A) represent the dominant texture. As consequent of a very rapid deposition, local angular clasts admixed to sub-rounded gravels can be observed (Fig. 12B). Strata often are sharp-based, marked by contrasts of the gravel medium grain size (Fig. 12C). Facies *3b* forms intercalations of the previous deposits and can be distinguished based on a dominant sandier matrix, compared to facies *3a*. Facies *3b* consists of poorly-sorted and structureless very-coarse sand and granules with sporadic scattered pebbles (Fig. 12D).

Both these facies form a few meter thick, tongue-shaped beds describing massive layers intercalated with trough cross-stratified bedsets with erosive bases (Fig. 12D). In outcrop, strata form fan-shaped lithosomes characterised by radial distribution of strata dips and relative palaeocurrents appreciable on clast imbrications (Figs. 13A and 13B). At the base of the Donori section (Fig. 13C), strata form complex inclined cross stratification motifs. Cross strata become slightly sub-horizontal in strike view (Fig. 13D), showing channel-complex filled by cobbles and boulders (Fig. 13D).

The estimated porosity percentage strictly varies in accordance to the grain size of the single facies: 1.6-2.9% for the coarse-grained deposits of facies *3a*, and 1.7 up to 4.8% for the finer deposits of facies *3b* (Tab. 1). This latter wide range depends on the percentage of sandy matrix within gravel strata.

4.1.6 Interpretation

The deposits described in the facies association 3 include a large variety of textures that concur to indicate an alluvial setting dominated by debrisflow and minor debrisfall processes. The variable amount of fine matrix between the two facies *3a* and *3b* indicates two types of debrisflows, characterised by difference in the viscosity of the surge during its movement and, consequently, the velocity of emplacement of each single bed.

In the matrix-poor deposit of facies *3a* (often characterised by coarse-grained matrix), the accumulation resulted in lenticular beds with imbricate or complex stacking, often with openwork textures (Fig. 14A). The process of accumulation occurs in absence of relevant viscosity, generating a 'low-viscosity debrisflow' (Fig. 14A). On the contrary, debrisflow deposits of facies *3b* are characterised by matrix-supported texture, with the presence of large 'floating' clasts, especially with platy shapes, forming inverse graded strata (Fig. 14B). When the matrix is mud-dominated, the behaviour of the debrisflow is visco-plastic, generating a 'high-viscosity debrisflow' (Fig. 14B). Angular elements which appear strictly associated with well-rounded clasts, result from inter-clast fragmentation occurred during the transport.

The inferred environment suggests the presence of a high-gradient depositional profile, descended by gravity-driven sediment massflows where, occasionally debrisfalls occurred in the steepest part of the systems (e.g., channel margins). This environment can be related to a proximal alluvial fan system or to minor laterally-coalescent fans. Therefore, inclined cross strata result from switching phenomena of the fan deposition, whereas cobble- and boulder-size channel-fills represent distributary systems of the alluvial fan complex.

4.1.7 Facies association 4: fluvial streamflow deposits

This facies association includes the most sand-prone deposits observed in the investigated sections of Ussana Fm. Outcrops of facies association 4 occur in the sites of Soleminis, Dolia Nova and, more diffusely, near Donori (see Fig. 1). The exposed total thickness of this association is up to 80-110 m, but higher thicknesses up to 200 m are inferred by well data.

The association includes facies *4a* and *4b*. Facies *4a* consists of scattered or randomly clustered boulders and cobbles forming clast- to matrix-supported polymictic deposits. Mature and very mature sub-rounded and rounded gravels are organised into lenticular 0.5 to 6-7 m thick strata with erosive bases and gradational tops (Fig. 15A), forming channels which exhibit normal to inverse grading, trough cross-stratified and inclined beds (Fig. 15B). In the section of Dolia Nova, inclined strata form up to 6 m thick lithosomes (Fig. 15C).

In some place (Soleminis sections), facies *4a* results variously interbedded with horizontal tabular stratasets made up of brown-reddish sandstones and siltstones of facies *4b*. Internally, sandstones include medium to coarse, very coarse sand and granules with scattered small pebbles and often exhibit plane-parallel and cross lamination (Fig. 16A). Siltstones form tabular or lenticular strata up to 0.6 m thick, interbedded with gravel thin layers of facies *4a* (Fig. 16B). Internally, siltstones are structureless or indistinctly laminated, but very rich in organic matter and carbonaceous fragments (Fig. 16C).

In the sectors where this facies association shows the maximum outcrop thicknesses (e.g., Donori), 3-5-m-thick gravel strata show a good lateral continuity, forming 20-25-m-wide lithosomes, internally organised into foreset beds laterally-accreting onto erosive bases (Fig. 16D).

The estimated porosity percentage varies greatly between the gravel-rich strata and the sand-rich intercalations, ranging from 2.8% up to 15%, respectively (Tab. 1). In case of 'clean' sandstone strata, porosity can be as high as 28%.

4.1.8 Interpretation

The deposits included in the facies association 4 record fluvial systems, characterised by braided channel morphology with localised larger distributaries with local meandering forms dominated by streamflow processes. This association, which is generally observable in high-gradient, foot slope hills in modern environments, includes ephemeral streams characterised by presence of water and mass transport only during the high energy stages of the fluvial current and in which sediments are deposited by repeated, but time out-distanced, episodes resulting in the deposits described in the facies *4a*. On the contrary, where the river system forms larger channels, they can reproduce meanders with sinusoid geometries and resulting in laterally-migrating point-bar deposits. In the inter-channel, flood-plain fringes, sediments are fine-grained and the deposition occurs only after major flooding events characterised by sheetflows capable to transport minor bedload pebbles and major suspended fines resulting in overbanks. These sectors, recorded in the deposits of facies ***4b***, are often dry during seasonally arid episodes, and site of the development of vegetation that justifies the abundant presence of bioturbation and carbonaceous debris.

In terms of porosity, such alternation of channel-fills and inter-channel deposits, generates vertical and lateral abrupt changes, consisting of high-porosity lenticular beds bounded by lower-porosity or virtually un-porous thinner intercalations.

5. Discussion

The types of sediments documented along the southern-eastern margin of the Sardinia graben system recorded fully continental lithofacies as, in this part of the basin margin, no one of the observed stratigraphic sections have shown lateral transitions to correlative shallow-marine deposits. These clastic sediments belong to the upper Oligocene Ussana Fm, which is erosionally overlain by lower Miocene marine deposits (Simone et al., 2011; 2012; Longhitano & Tropeano, 2014). The Ussana Fm includes coarse-grained lithosomes, which are generally considered of scarce importance when detected in subsurface for a reservoir characterisation purpose. However, our results indicate as the detailed facies analysis and internal distinction among the different types of terrestrial deposits, including eluvio-colluvial, alluvial and fluvial, points out relevant vertical/lateral porosity changes due to their internal distinctive heterogeneities. These variations may cover a wide range of porosity from 1-2 % up to 25-30% (see Tab. 1).

The Ussana deposits formed at the base of piedmont reliefs in isolated or interlinked tectonic depressions delimited by Palaeozoic metamorphic and magmatic block-faulted units. This setting generated a number of very different morpho-tectonic depocentres characterised by variable 'capacity' (i.e., the accommodation space in continental realm). These conditions influenced the reciprocal role of the three types of dominant processes which were inferred from the observation of these sediments (i.e., colluvial-, alluvial- or fluvial-dominated). In turn, the role of these processes on the sediment transport and accumulation influenced the resulting different types of depositional systems.

Based on the different tectonic displacement which controlled each single or coalescent depositional areas on this margin of the Sardinia graben system, and on the subsequent episode of tectonic fragmentation related to the late Oligocene extensional evolution, these three main types of systems developed generating highly-varying thicknesses and depositional architectures. The various documented settings suggest different types of possible reservoirs that will be discussed in the next sections.

5.1 Sedimentary fabric and porosity profiles

The terrestrial realm represents a primary area for production of coarse-grained sediment accumulations (Collinson, 1982). As observed in many modern continental settings, pebble-, cobble- and, more rarely, boulder-size clastic accumulations may form arrays of steep fans, often coalescing into aprons, developed along the slopes of valley sides and basin margins, or transported across plains for kilometric distances (Blair & McPherson, 1999). Sedimentary processes can vary greatly based on the role exerted by water in the sediment transport and deposition. The resulting deposits can thus be included in two main different categories of avalanches (e.g., Blikra & Nemec, 1998; see their fig. 6): (i) eluvio-colluvial deposits are generally accumulated after mass-transport processes related to the effect of gravity and in absence of relevant waters, such as *rockfalls* and *debrisfalls*; (ii) alluvial and fluvial deposits are instead generated by the dominant transport exerted by water flows, including *debrisflows* and *streamflows*. These sedimentary processes occur in continental depositional environments which form specific systems, such as colluvial and alluvial fans, often associated with braided or meandering rivers (Leeder and Gawthorpe, 1987).

Continental coarse-grained deposits (i.e., including pebble-, to cobble-, to boulder-size clastic elements) are commonly characterised by high values of porosity (up to 30-35%), compared to other finer-grained rocks (Brayshaw *et al*., 1996), owing to the average dimension of the inter-particles spaces which is proportional to the clast grain size. However, porosity in coarse-grained rocks can be also reduced when openwork textures are infilled by fine-grained fractions.

The dominant grain size mode of the resulting deposit depends upon a number of factors, including: (i) relative distance between sediment source and sink, (ii) gradient of depositional profile, (iii) climate, i-e., amount of meteoric-derived water feeding the system, (iv) nature and preservation state (i.e., weathering, fracturing) of the source rock; (v) dimension of the bypass areas (= amount of the sedimentary transport) (Boothroyd, 1972).

In terms of porosity, distinguishing eluvial from colluvial accumulations implies a different setting for fluid transmission or reservoir. In general, an eluvial accumulation is characterised by coarse-grained clastic elements, forming gently-inclined (2°-3°) slopes, along which no significant gravity-driven movements occur (Fig. 17A). The eluvial 'mantles' generally involve the external portion of a weathered rocky mass, through the formation of a horizon of variable thickness (from 0.5 up to 5-6 m) (Starkel, 1987; Leopold & Völkel, 2006). In tight/fractured rocks (e.g., limestone, basalts, metasandstones and metasiltsones, etc …), this 'regolite' thickness (Fig. 17A) has an openwork texture in the external peel, whose interstices decrease in size and in abundance towards the most internal part of the rocky mass, where the material is virtually compact (Fig. 17A). This condition results in widening-upward, open-space intervals and a consequent upward increase of porosity.

Conversely, colluvial deposits can form thicker horizons due to the accumulation of large block during their gravity-driven downward slope (this is true especially in case of rockfalls) (Fig. 17B) (French, 1992; Blikra & Nemec, 1998; Leopold & Völkel, 2006). Sedimentary accumulations assume steeper profiles (>15°) and exhibit a mixture of coarse- to fine-size detritus. Fines, deriving from intra-clast impacts, fill the most surficial openwork spaces during the process of rockfall (Rahn, 1986; Blair & McPherson, 1994) (Fig. 11), infilling only the most external portion of the rock volume, whereas the internal core may be virtually free of fine and characterised by fracture-induced open spaces. Consequently, this typical assemblage results in a porosity that increases toward the surface of the rocky mass, but then it decreases in proximity of the most external layer, where fines abound (Fig. 17B).

Distinction between debrisfall and rockfall is also crucial in order to assess porosity and consequent real reservoir volume in colluvial deposits. Firstly: the difference in the textural maturity between the two resulting deposits has important implications to the debris internal assemblage and inter-pore distribution; usually, very-well sorted and texturally mature gravels have very good porosity, compared with immature breccia which often contain abundant secondary matrix. Secondly: primary-fragmented breccia is usually more prone in producing fines during a gravity-driven mass transport respect to well-rounded clasts, which offer no many parts (i.e., edges) for impacts and consequent debris. Thirdly: as demonstrated by our observations, debrisfall accumulations tend to form thicker lithosomes, especially in proximity of half-graben footwall areas, if compared to rockfall deposits whose thickness is related only to the state of preservation of the adjacent source rock.

Debrisflow-dominated facies revealed thick successions in our studied section of the Ussana Fm. Debrisflows diffusely characterise both alluvial fans and fluvial systems, which dominantly developed in footwall sectors of the half-graben basin under high tectonic subsidence and consequent high capacity. The relative filling of these areas allowed to the accumulation of 100-150-m-thick clastic lithosomes with different internal features.

In the observed facies associations, debrisflow deposits consist of pebbly to boulder gravel-supported beds often containing a variable percentage of finer matrix. This latter varies from muddy, poorly sorted sand to nearly sandy granule gravel. Debrisflows can be generally classified as cohesive or cohesionless (Nemec and Steel, 1984) based on the amount of finer matrix associated with the coarser fraction that influence the overall viscosity of the process (i.e., a cohesive debrisflow usually results in a matrix-rich deposit, whereas a cohesionless debrisflow may generate openwork conglomerates). Consequently, porosity can vary greatly also within alluvial debrisflow-generated deposits, depending on the type of the dominant process acting during sediment accumulation (see plot in Tab. 1).

Streamflow processes occur as linear (channelised) concentration of clast transport in presence of abundant water, also able to move elements of large dimensions, such as cobbles and boulders. Since the hydraulic regime of this process is characterised by an oscillating power, due to the alternation of high-energy water stages and waning water stages, the resulting clastic assemblage is represented by variable textures forming bedded conglomerates (Steel and Thompson, 1983). Streamflow deposits are indeed characterised by bimodal, matrix-rich layers, overlain by fine, filled framework and by coarse, open framework (Fig. 18). Generally, openwork textures characterise channelised lithosomes, especially in their coarse-grained intervals, whereas infilled textures are frequent in the topmost channels whereas overbank deposits can result in 'clean' (matrix-free) sandstone (Fig. 18). These processes are often associated with erosion of the underlying deposits, especially in case of coarse-grained streamflows (Fig. 19A). That results in successions frequently characterised by irregular scour surfaces, filled by normal graded, very coarse bedsets (Fig. 18). In terms of porosity, such vertical textural assemblage is observable within 10-50-m-wide and 10-15-m-thick lenticular lithosomes (see again Fig. 15C), characterised by a scarce porosity (4-5 %) in the lowermost 1/3 interval, which increases dramatically (up to 20-30 %) in the overlying 2/3 interval (Fig. 18). Because of the repeated nature of such textures, these channel-fill deposits are thought to be very good reservoir or mini-compartments in streamflow-dominated fluvial deposits (e.g., Tyler et al., 1994; Deutsch and Wang, 1996).

5.2 Depositional systems recognisable in the Ussana Fm.

The distinction between gravity-driven 'non-watery' processes, due to the intervention 'dry' mass-waste transports (rock- and debrisfalls) and 'watery' sedimentary processes, characterised by 'wet' (debris and stream) flows, discussed in the previous section allowed us to distinguish a number of types of facies and facies associations (Tab. 1). The sedimentary expression of such groups of facies indicates specific depositional environments that belong to three main types of continental depositional systems: (i) colluvial fans, (ii) alluvial fans, and (iii) braided river systems. It is not often easy to distinguish the product of these distinct systems from the sedimentological record, especially from well core datasets; this is the reason why, particularly for deposits recording the two first systems, their sedimentary products were often confused in the past and included in unique systems (e.g., 'debrisflow-fans' or 'gravity-flow-fans' described by Blair & McPherson, 1994a,b). However, our facies partitioning helped us to separate colluvial- and alluvial- from fluvial-derived successions and relative depositional systems, although their sedimentary facies associations often occur repeatedly alternating in our measured stratigraphic columns, possibly indicating a syn-depositional coalescence of colluvial talus and alluvial fans with adjacent fluvial braidplains (Fig. 19; Leeder and Gawthorpe, 1987).

Blikra and Nemec (1993) arguably pointed out the distinctive morpho-sedimentological features and main differences between continental fans of colluvial and alluvial origin. These authors list the main diagnostic features that should be recognised in depositional systems that, as observed in many present-day hill-slope continental areas, develop in adjacent positions and sourced by coalescent processes of different nature (e.g., Blair, 1999) (Fig. 20). The main differences are related to the absence/presence of a relevant catchment area at the shoulder of each fan. In colluvial fans, debris volumes derive from mountain-slope ravines whose fracturing produces ‘fresh’ rock fragments which accumulate at the base of the cliff. Sediments form talus of very immature gravels characterised by 15°-to-45° angle of internal friction and consequent depositional slope and with a fining-upward grain-size distribution (Fig. 20A). On the contrary, alluvial fans result from the accumulation of sediments transported for a given distance across an intramontane valley or canyon (‘fiumara’ of Sabato & Tropeano, 2004) and deposited at their mouth along a mountain-foot plain. Clasts are generally coarser near the apex, because the rapid deposition of the heaviest material by the river current, whereas they fine towards the distal fan (Blair, 1987a,b), assuming depositional slope angles between 1°-5° and 10°-15° (Boothroyd, 1972). In streamflow-dominated examples (Leeder, 1999), alluvial fans can be associated with the occurrence of entrenching distributary channels of various dimension. In the rock record, these latter may be confused with single river systems rather than ‘accessory’ elements of a larger alluvial fan (Fig. 20B). These two depositional systems are generally sourced by entry points, which are perpendicularly-oriented with respect to the main (faulted or not) basin margin (Gawthorpe et al., 1994). Particularly for alluvial fans, palaeocurrent patterns indicate fan-shaped directions which are strongly contrasting with measurements detected in fluvial braidplains. These latter systems occupy the central depocentre in half-graben continental basins (Leeder and Gawthorpe, 1987) and represent a depositional system largely recognised in the studied sedimentary successions of the Ussana Fm.

Braided-type, streamflow-dominated fluvial systems diffusely occur in modern high-gradient piedmont valleys. They show general sediment transport directions which are perpendicularly-oriented with respect the laterally-adjacent colluvial and alluvial fan systems (Fig. 20C). Rivers often occupy narrow, tectonically-confined 1-2-km-wide valleys which allow to the development of ephemeral entrenched fluvial channels. On the contrary, in case of larger (>2-3-km-wide) half-grabens, fluvial systems tend to develop more stable channel belts (with associated short-lived smaller channels), often forming small-size meanders and related point-bar deposits. Such systems are inferred from the sandstone-rich successions detected in many of the studied stratigraphic successions near Donori, where tabular-based foreset units indicate filling of long-lived fluvial channels. In modern braided rivers, the pulsation of the water flows causes the accretion of longitudinal bars, where gravel openwork, bimodal gravel and sand and very well sorted sand can be deposited (Fig. 20C). These deposits show very different porosity features and, in the rock record, they are often compartmentalised because of the lateral adjacency of different sediment textures.

5.3 Reconstruction of a depositional scenario and implication for reservoir analogues

The four facies associations detected in the various stratigraphic sections from the study area allows us to reconstruct a palaeogeographic scenario for this margin of the Sardinia graben system during the late Oligocene.

According to a number of authors (e.g., Carmigniani et al., 1994; Casula et al., 2001; Faccenna et al., 2002, among others), this part of Sardinia underwent a relevant extensional tectonic episode during the early stage of the basin opening. This stage was characterised by a diffuse state of basement fragmentation which resulted in a wide block-faulted basins or sub-basins, as it is typical when an initial extensional stage involves wide continental areas (Gupta et al., 1998; Gawthorpe and Leeder, 2000; Cowie et al., 2005). Single or interlinked normal fault zones affected this region resulting in the formation of a series of endorheic depressions or depocentral zones. Their sediment capacity was related not only to the amount of the local tectonic displacement, which is maximum near the centre of the fault and decreases to zero at the fault tips (Schlische, 1995), but also to the interception of the "base profile" with topography in case of alluvial/fluvial sedimentation (Quirk, 1996). Such interplay influenced the nature (eluvio-colluvial, alluvial and/or fluvial), the highly varying aerial distribution and relative thicknesses of the lithofacies recognised across the studied areas.

Based on our observations, two main scenarios were reconstructed across half-graben depositional areas, related to different ratios between amount of tectonic displacement of the master fault and sediment accumulation rates. (i) The first setting is characteristic of those areas where a low amount of tectonic displacement produced a rapid sedimentary infill. In this framework, the along-dip system distribution roughly resembles that suggested by Blair & McPherson (1994) for similar fault-attached deposits, and shows volumetrically relevant colluvial breccia, merging to moderately thick alluvial conglomerates and thin fluvial braidplain sandstones with frequent muddy intercalation (Fig. 21A). This assemblage resulted from the lateral adjacency of 10-20-m-thick colluvial aprons with alluvial fans sourced from the footwall high. In this setting, the low amount of tectonically-generated capacity induced the formation of ephemeral fluvial streams, with sediment transport directions oriented parallel to the main fault and characterised by abundance of floodplain mud-rich deposits pinching out toward the hanging wall (Fig. 21A). (ii) The second morpho-tectonic setting is inferred for depocentral areas which underwent relevant amount of tectonic vertical displacement exceeding the rate of sediment accumulation (Fig. 21B). That resulted in volumetrically negligible colluvial/alluvial deposits, laterally adjacent to thick (100-200 m) fluvial succession consisting of conglomeratic channel-belts intercalated with sand-rich inter-channel deposits with palaeocurrent directions pointing parallel to the master fault. These latter were possibly confined by hanging-wall-sourced alluvial and colluvial fans (Fig. 21B).

Differences in porosity evaluated from these two reconstructed end-members, among different types of terrestrial deposits is highlighted in the plot of Fig. 22A). All porosity values are plotted from the left to the right side of the diagram according to their relative position along a hypothetical depositional profile. Here, sediments virtually pass from eluvial/colluvial, to alluvial and to fluvial deposits. As observed in the Soleminis 1 section, this transition realizes in a few tens of meters in the small systems accumulated near the inner basin margins (Fig. 22B), but can reach some hundreds of meters toward the outer basin margin. The plotted porosity values along the same depositional profile, sharply match with the internal complexity of each facies associations. Indeed, due to the abundance of openwork textures, eluvial/colluvial deposits (Figs. 22C) offer a good porosity (estimated values up to 8%). These values decrease toward the alluvial and fluvial deposits (1.5-3.5%), where matrix-rich, high-viscosity debrisflow deposits represent the dominant sediments (Fig. 22D). These values present picks of higher percentages of porosity in the final part of the profile (up to 25-28%), where channelised, streamflow deposits exhibit diffuse open framework in the clast fabrics, generating better conditions for porosity (Fig. 22E).

In general, the different stratigraphic frameworks documented across the south-eastern margin of the upper Oligocene Sardinia graben system can be summarized into six types of reservoir analogues, on the basis of the bi-dimensional internal complexity and nature of composing sedimentary units (Fig. 23). Basal assumption of this subdivision is that the eluvio-colluvial, alluvial and fluvial origin of the sedimentary successions filling these areas was strictly dependent on the interception of the relative base level with the topography (‘base profile of Quirck, 1996).

The simplest model resembles half-graben depocenters located across the inner basin margin, characterized by low accommodation and in absence of any base level crossing the topography (Fig. 23A). Footwall-derived breccia was accumulated at the base of the master fault escarpment, forming isolated colluvial fans. The stratigraphic signature of such elementary depositional scenario consists of a uninterrupted sequence of unorganized immature clastic debris, directly lying on top of weathered/fractured basement. In the investigated sectors, such examples were abandoned in an internal high marginal position respect to the rest of the younger sedimentary basin-fill marine succession. In subsurface successions, these colluvial deposits can be overlying by transgressive shallow-to deeper-marine strata. In case of depocenters with similar amount of thectonic displacement by affected by the occurrence of capacity created by the interception of the hangingwall base and the base level, colluvial deposits coexist with alluvial fans, prograding toward the half-graben center from small, ephemeral catchment areas located on the footwall high (Fig. 23B). The stratigraphic sequence, based on which we interpreted the second depositional framework, is a coupled succession of an underlying colluvial, rock-/debrisfall-dominated interval, abruptly or gradually passing upward to an alluvial, debrisflow-dominated interval. This stratigraphic sequence can be associated to uppermost thin fluvial, streamflow deposits in case of fluctuating base-level rises (Fig. 23C).

If the first three models summarize different depositional settings typical of inner basin margin, more complex stratigraphic assemblages were detected toward the outer basin margin. In areas where the base level was in a more elevated position respect to the previous examples, colluvial/alluvial, footwall-derived systems passed laterally and upward to fluvial, braided-type streamflow deposits, characterized by entrenched coarse-grained channelbelts and gravel overbanks (Fig. 23D). Other more complex settings are represented by mini-basins characterized by an increasing in accommodation due to a progressive rising of the base level (Figs. 23E and 23F), Fluvial deposits aggraded generating long-lived channel belts and sand-rich overbank and floodplain strata. The resulting stratigraphic sequences formed fining-upward 100s-m-thick successions characterized by volumetrically dominant fluvial sandstones and minor associated colluvial and alluvial gravelstones.

6. Conclusions

Even if often associated with the same deposit and referred to unique depositional environments, eluvio-colluvial, alluvial and fluvial sedimentary processes can be distinguished based on a detailed facies analysis study achieved on continental coarse-grained deposits belonging to the upper Oligocene Ussana Fm in the Sardinia graben system. This difference, based on the documentation of the sedimentological characteristics of these deposits (including textural features, sedimentary structures, stratal architectures and bounding surfaces), allowed us to recognise also different, but intimately associated, depositional systems, such as colluvial and alluvial fans connected with fluvial braidplains. Such systems rapidly filled a number of km-scale depocentral areas generated across the south-eastern basin margin during an initial extensional phase of the opening of the Sardinia graben. These mini-basins developed as grabens and half-grabens tectonically-controlled by complex arrays of normal faults, roughly parallel to the basin axis, which influenced the sedimentation during their displacement, generating footwall-directed stratigraphic expansions and overall wedge-shaped depositional architectures. Based on the ratio between sedimentation and fault displacement, two main depositional scenarios were reconstructed: (i) a setting where the sediment accumulation rate exceeded the amount of the fault displacement, and (ii) the opposite condition, where the activity of the master fault produced more space than the overall quantity of sedimentary infill. These two sets generated a different lateral distribution and relative thicknesses of eluvio-colluvial, alluvial and fluvial systems filling the half-grabens, resulting in specific reservoir analogues with different porosity lateral properties.

These two settings were thus extended to larger, graben-scale frameworks which were reconstructed across the basin margin. These six models are represented by different distinctive stratigraphies and vertical facies stacking which are related to a different amount of local tectonic displacement interplaying with the base profile. The resulting depositional architectures can be used as tool in order to predict the types of deposits in analogous reservoirs and their internal heterogeneities.

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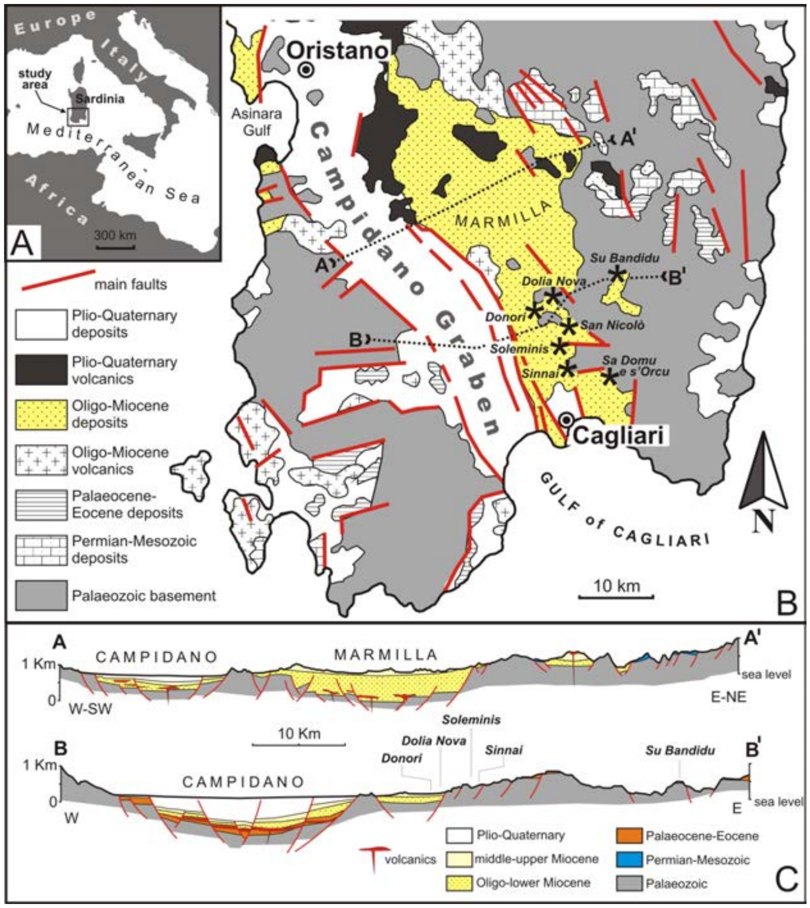

Fig. 1. (A) Regional location of the Sardinia in the western Mediterranean. (B) Geological sketch of the central-southern Sardinia. Asterisks indicate the main stratigraphic sections analysed in the present study (modified from Casula et al., 2001). (C) Geological cross sections across the studied sectors (redrawn from Casula et al., 2001).

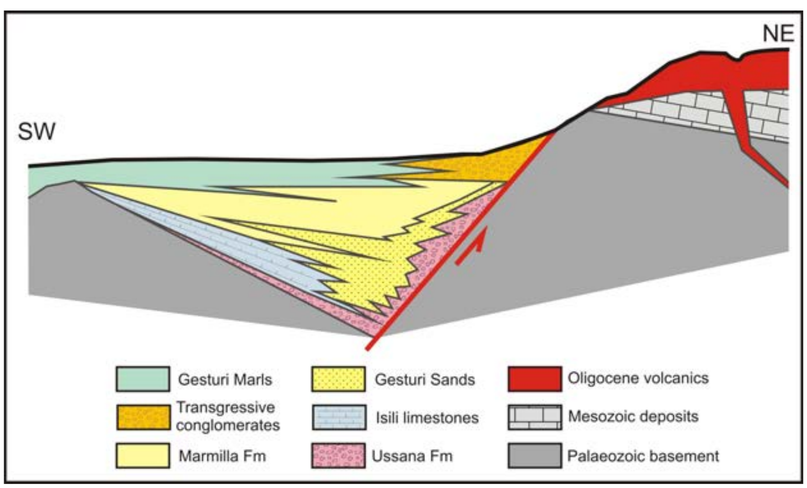

Fig. 2. Tectono-stratigraphic sketch across the studied area, showing the lateral/vertical relationships between the Paleozoic-Mesozoic units and the overlying Oligo-Miocene deposits (redrawn, from Carmigniani et al., 2001).

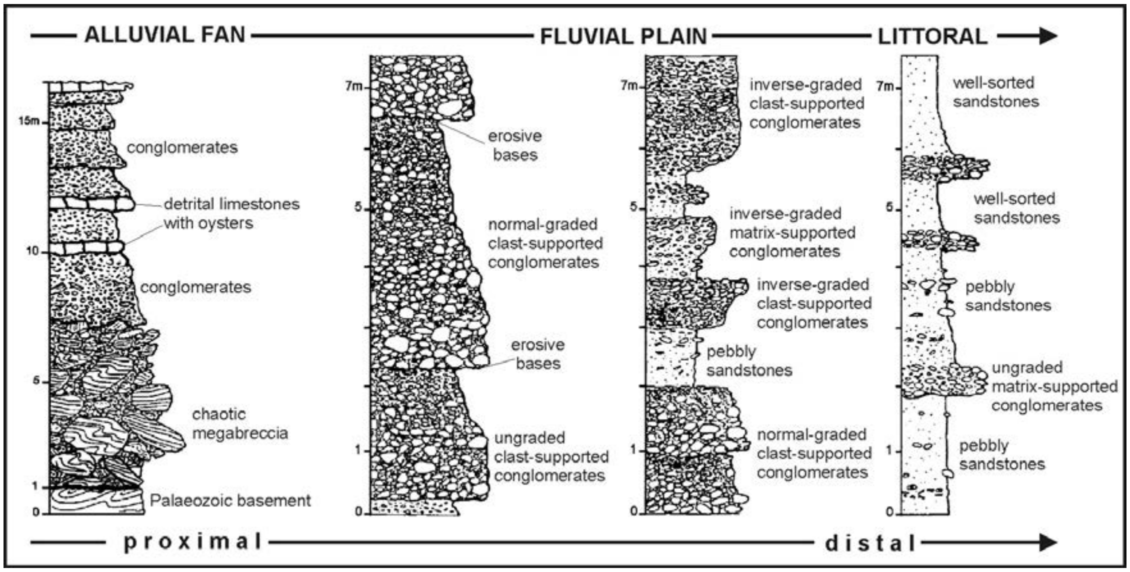

Fig. 3. Stratigraphic columns summarizing the main grain size features and stratal pattern observable in the Ussana Fm. Columns are reported from continental to shallow-marine deposits from the left to the right of the sketch (modified, from Casula et al., 2001).

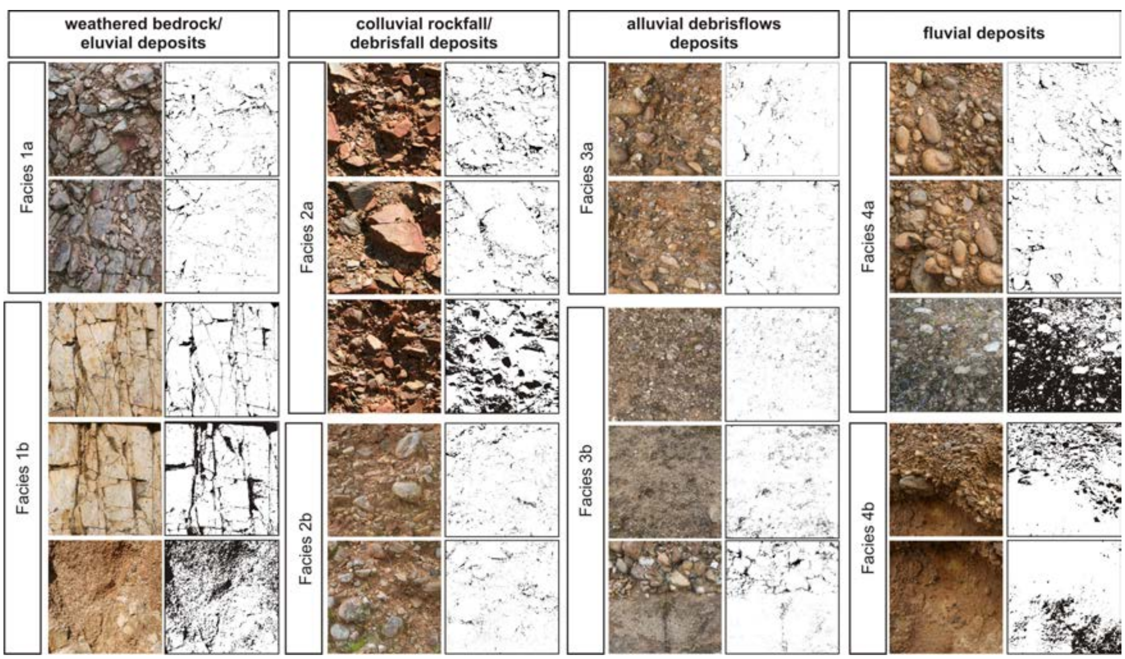

Fig. 4. Porosity estimation from image analysis of outcrop photographs of the main sedimentary facies recognised in the Ussana Fm. Photograph on the left and binary image of the porosity (black & white) on the right.

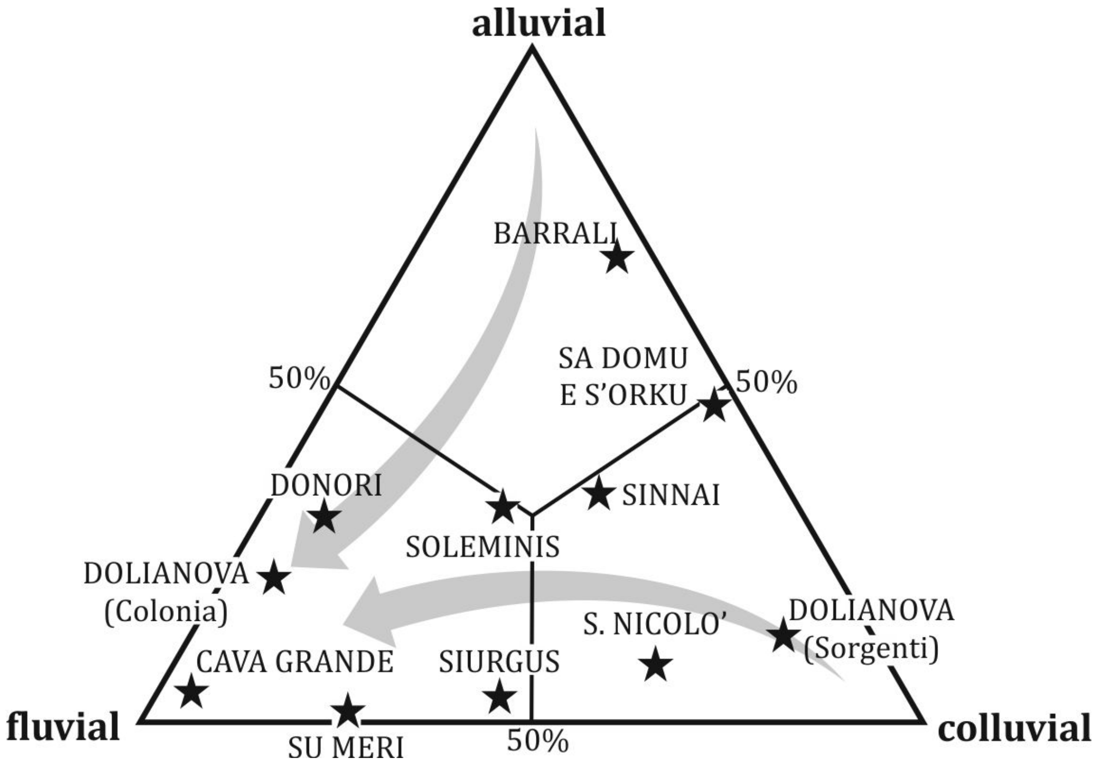

Fig. 5. Ternary distribution of the main stratigraphic sections analysed in the present study. Deposits were distinguished based on the volumetric occurrence of eluvio-colluvial, alluvial and fluvial facies associations. The grey arrows indicate the progressive enrichment in sandstone observed among all the analysed sections.

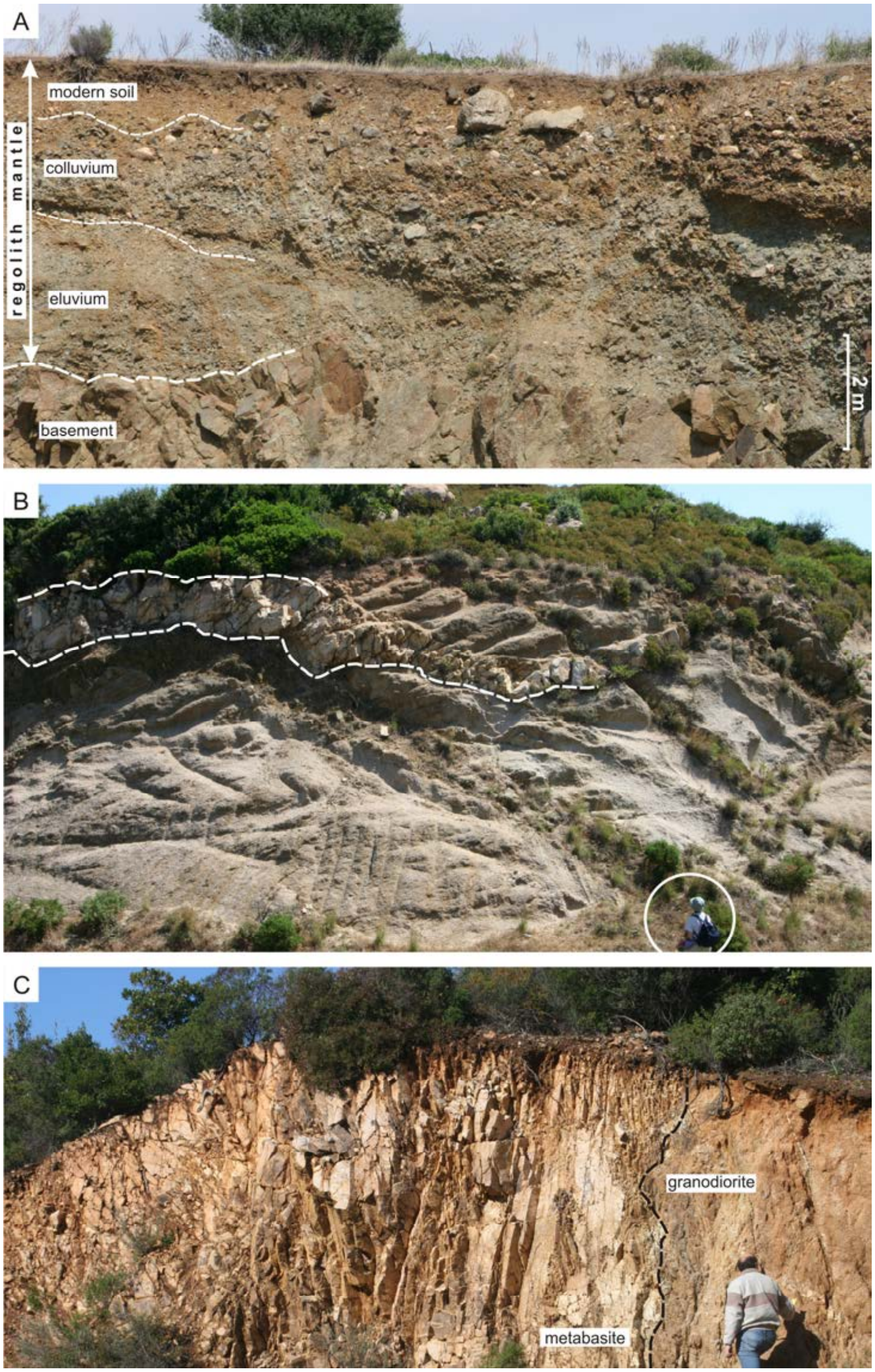

Fig. 6. Outcrop photographs of facies association 1. (A) Vertically-stacked transitions between weathered basement made up of meta-sandstones, passing upward to a 1.5 m thick regolith mantle and to 2.2 m thick eluvial/colluvial horizon (Sinnai section). (B) Grano-diorites crosscut by a basic dike (white dashed line) in the Sa Domu e S'Orcu section. (C) Intensely fractured meta-basites in the core of a sub-vertical intrusive dike and laterally adjacent to non-fractured granodiorite (Sa Domu e S'Orcu section).

Fig. 7. Photograph details of facies association 1. (A) Reddish colour, very immature breccia made up of metasandstones of facies 1a. (B) Fractured meta-siltstones of facies 1b. (C) Massive accumulation of sandand gravel-sized clasts derived from the intense weathering of a grano-dioritic basement.

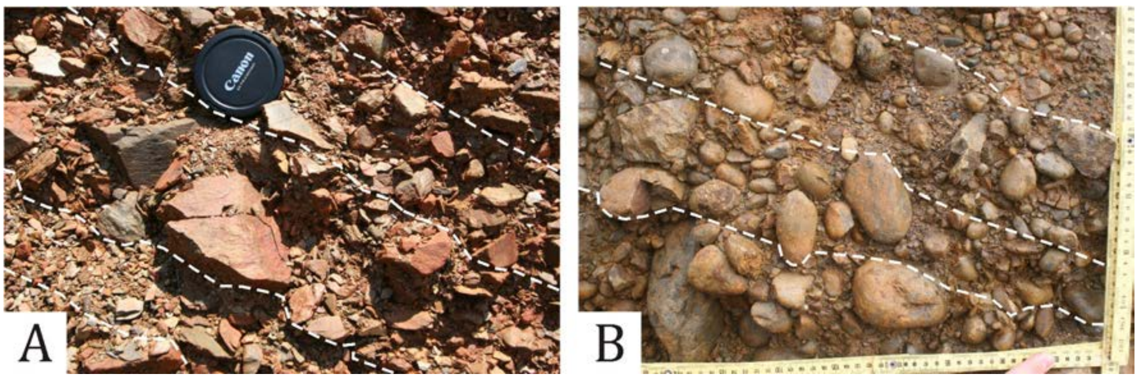

Fig. 8. Comparison between sediments of facies 2a and 2b. (A) Facies 2a is characteristically composed of subangular clasts, whereas in the facies 2b (B) clasts are sub-rounded and matrix-supported.

Fig. 9. Outcrop section near Dolianova (Sorgenti), showing primary depositional architectures in coarse-grained strata of facies 2a, directly attached to the basement and with decreasing angle of repose.

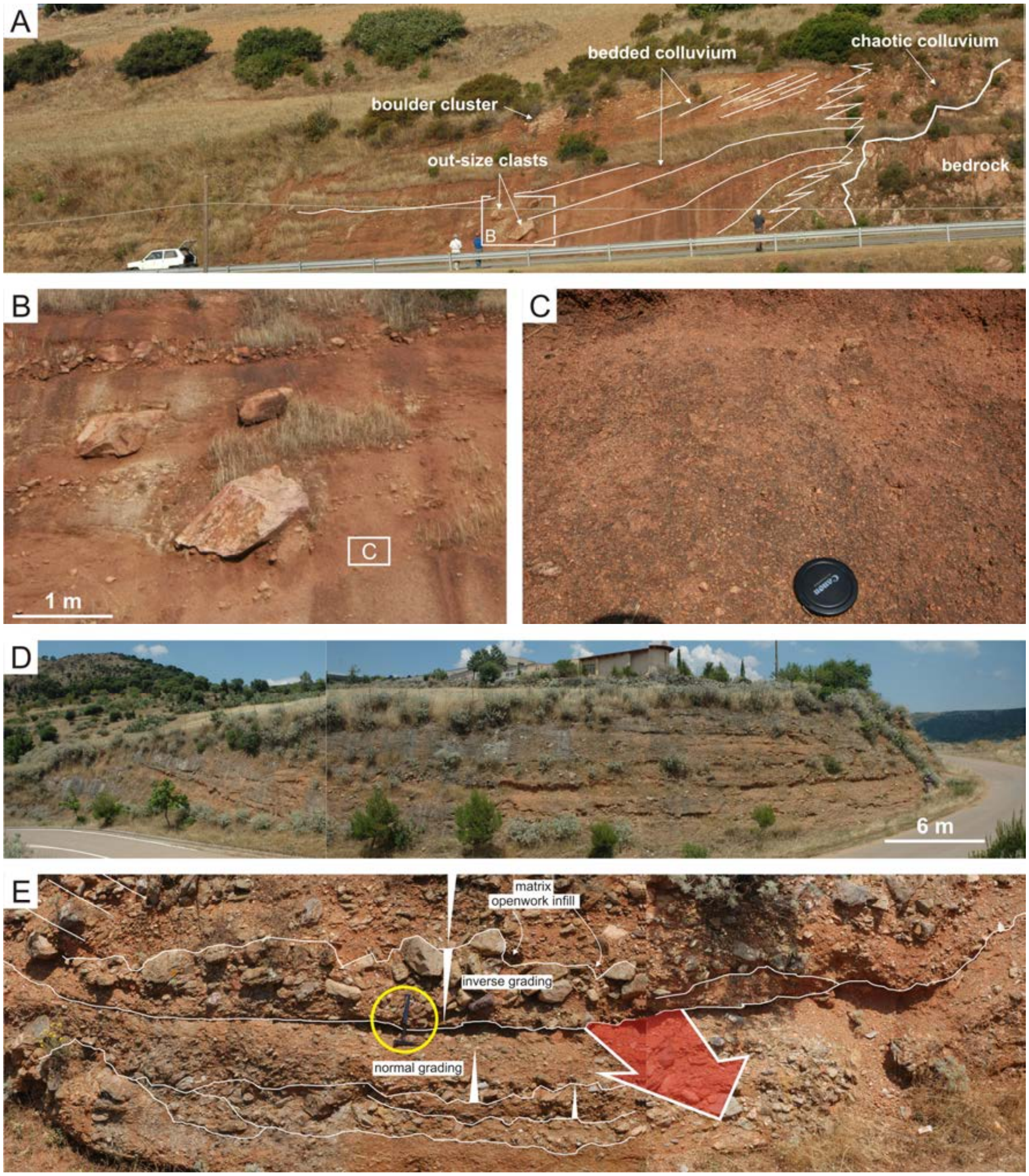

Fig. 10. Outcrop photograph of facies association 2. (A) Barrali section showing the relationship between the bedrock and colluvial chaotic deposits passing to bedded deposits (progradation is toward the left). (B) Detail of the previous outcrop, showing large clasts, sheltering 'pockets' of fine gravel. (C) Fine gravel matrix from the previous photo (the camera cap as scale is 10 cm of diameter). (D) S. Nicolò section, showing linguoid strata of coarse-grained colluvium with slope direction toward the right. (E) Detail of the previous outcrop, where normal and inverse graded beds alternate (the arrow indicates the slope dip). Note the fine gravel matrix filling the openwork interstices at the top of a bed (hammer as scale is 35 cm long).

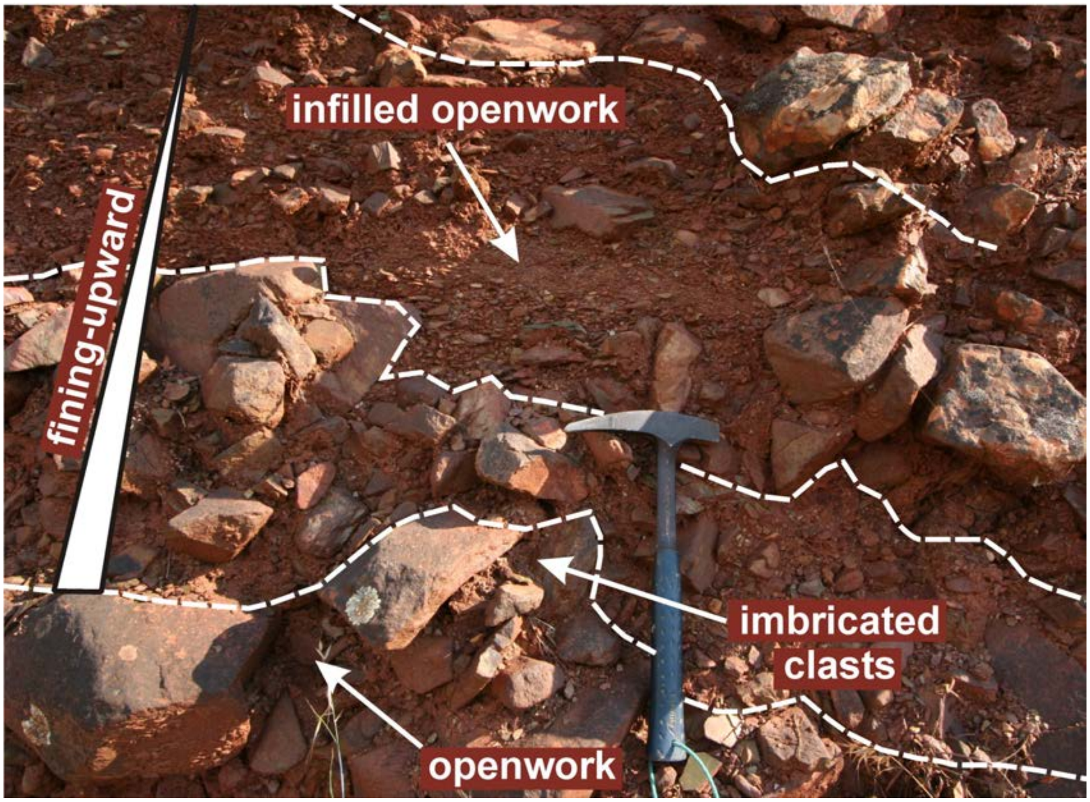

Fig. 11. Vertical cross-section of a rockfall deposit documented in the Ussana colluvial deposits. Note the bedding surfaces (dotted lines) and the textural features typical of such lithofacies (hammer is 35 cm long).

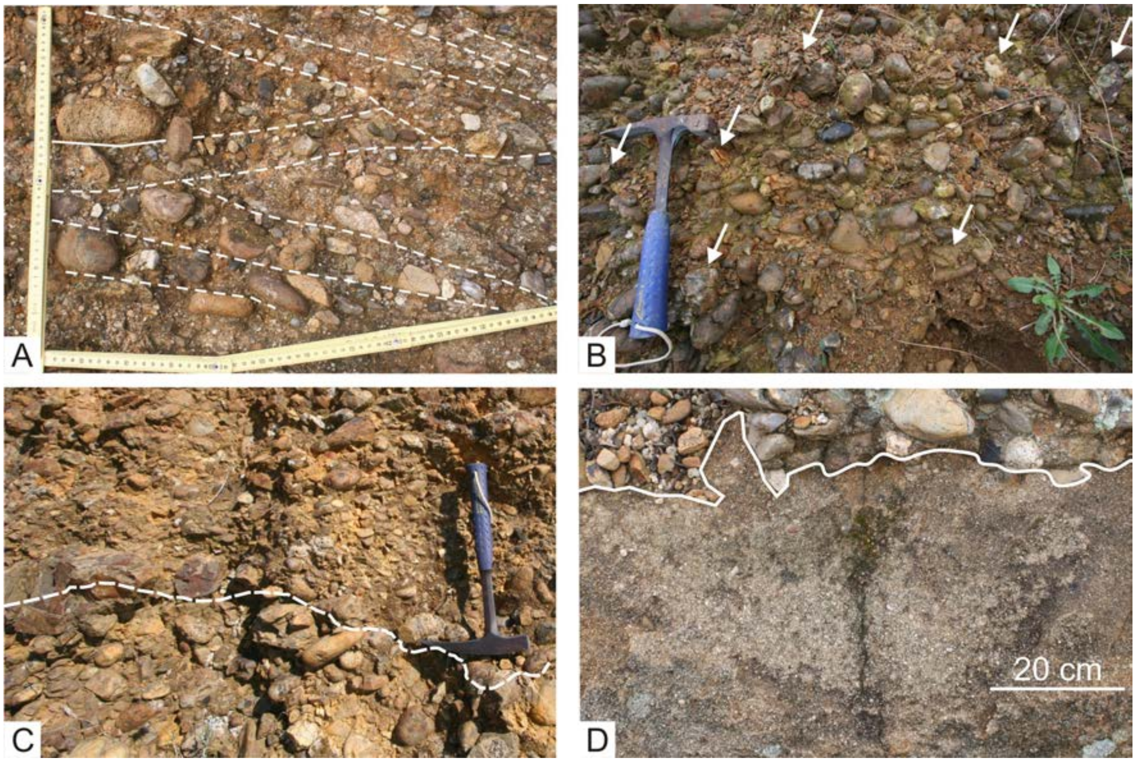

Fig. 12. (A) Trough cross-stratification in the gravels of facies 3a (the vertical scale is 20 cm). (B) Locally, angular clasts (arrows) are associated with sub-rounded gravels (hammer is 30 cm long). (C) Example of discontinuity stratal surface marked by grain size breaks. (D) Detail of a sandy intercalation of facies 3b (note the erosive contact of the overlying deposit of facies 3a).

Fig. 13. (A) Outcrop section and (B) interpretative line-drawing of facies association 3 observed at the Sa Domu e s'Orcu section, showing the spatial relationships between the two facies 3a and 3b (the road cut is along-strike oriented with respect to the main stratal progradation indicated by the arrows). (C) Base of the Donori section, showing inclined, tongue-shaped coarse-grained strata of facies 3a, alternating fine-grained interlayers of facies 3b. (D) Laterally, these facies exhibit channel-complex filled by cobbles and boulders. These geometries are interpreted as the main architectural elements of distributary streams belonging to an alluvial fan system.

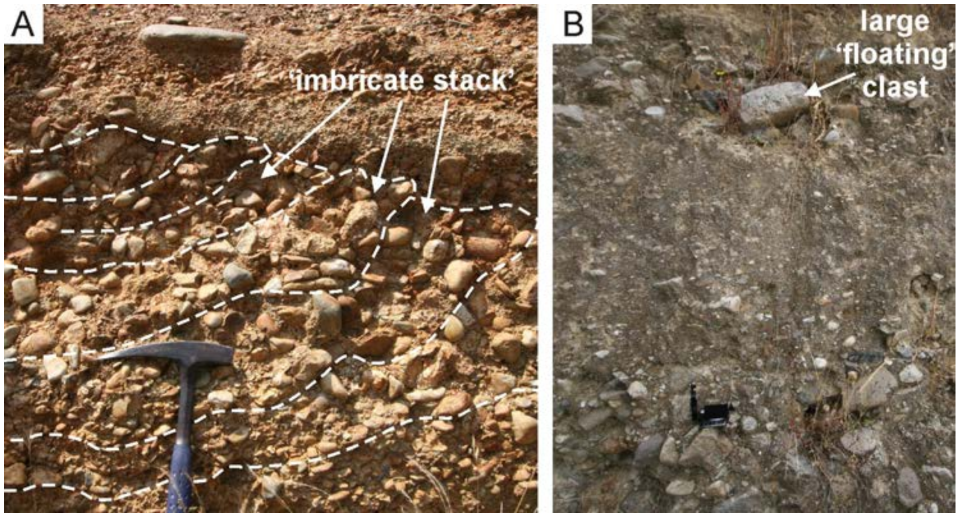

Fig. 14. (A) Imbricate lateral stacking of coarse-grained bodies indicating a palaeo-direction of transport and possibly generated by low-viscosity debrisflows (hammer is 30 cm long). (B) Normal- to inverse-graded pebbly sandstone deposit recording a high-viscosity debrisflow (the compass as scale has a 5 cm side).

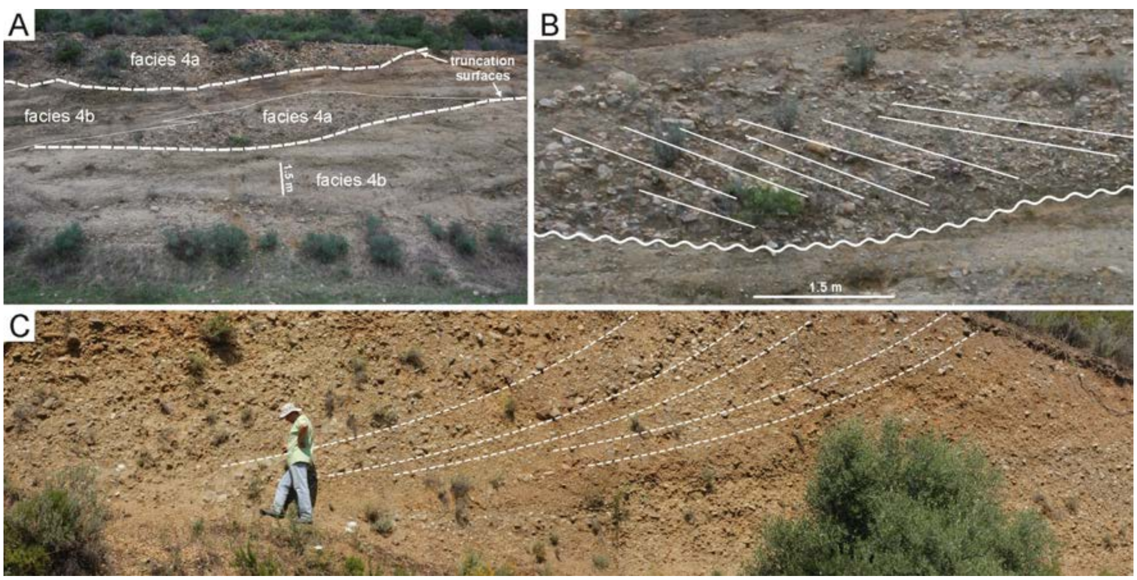

Fig. 15. Outcrop views of the facies association 4. (A) Gravel beds of facies 4a pinching-out laterally and alternating horizontal-bedded sandstones of facies 4b, bounded by basal truncation surfaces. (B) Detail of the previous photograph, showing internal inclined bedding of facies 4a indicating lateral (rightward) accretion. (C) The same feature often characterises thicker strata (A and B are from the Donori 1 section, C is from the Dolianova section).

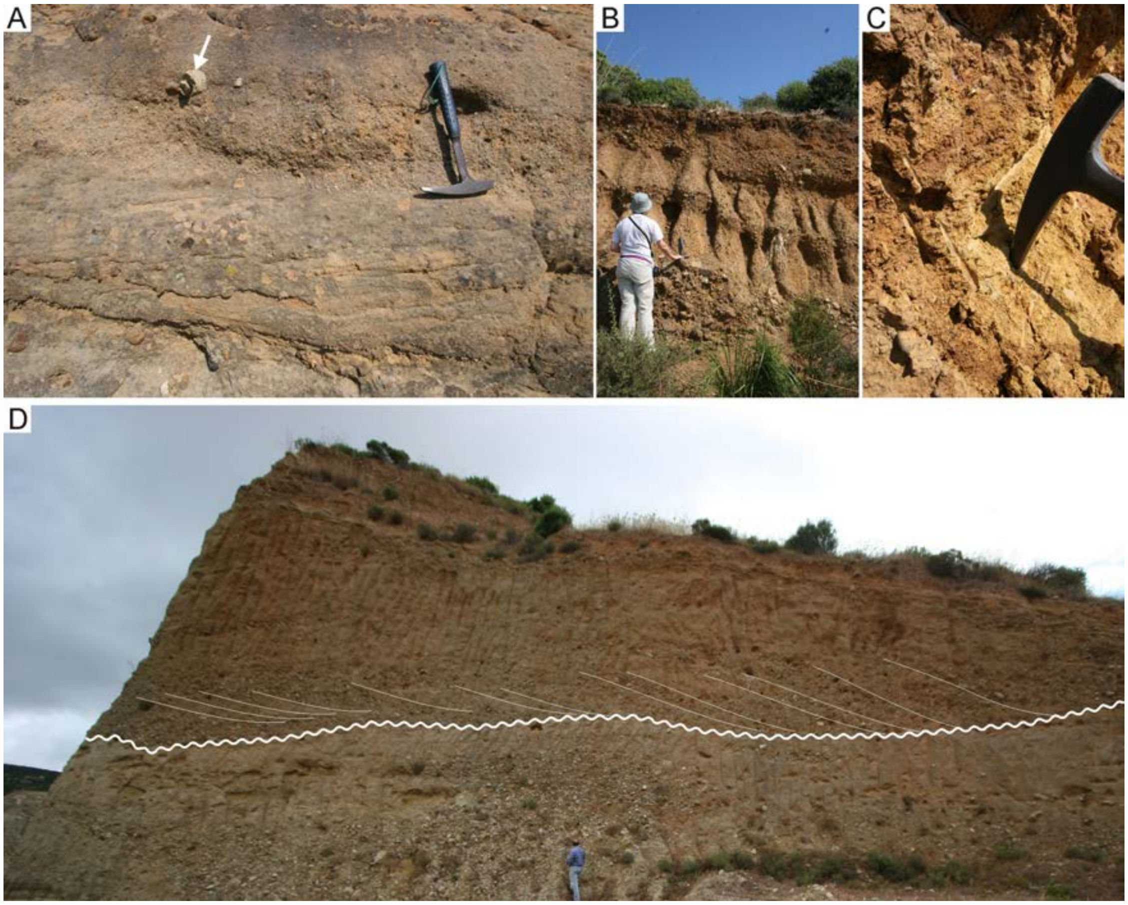

Fig. 16. (A) Laminated sandstones of facies 4b observed at the Donori section (arrow indicates an out-size pebble, randomly present within this deposit). (B) Siltstones layers interbedded to gravel thin horizons in the Soleminis 1 section. (C) Detail of the reddish siltstone. (D) Lateral accretion recorded by inclined gravel beds (white lines) prograding on to an erosive base (undulate white line). The lithosome is ~3.5 m thick bed and represents the deposits of facies 4a, encased in the sandstones of facies 4b (ItalCementi Quarry).

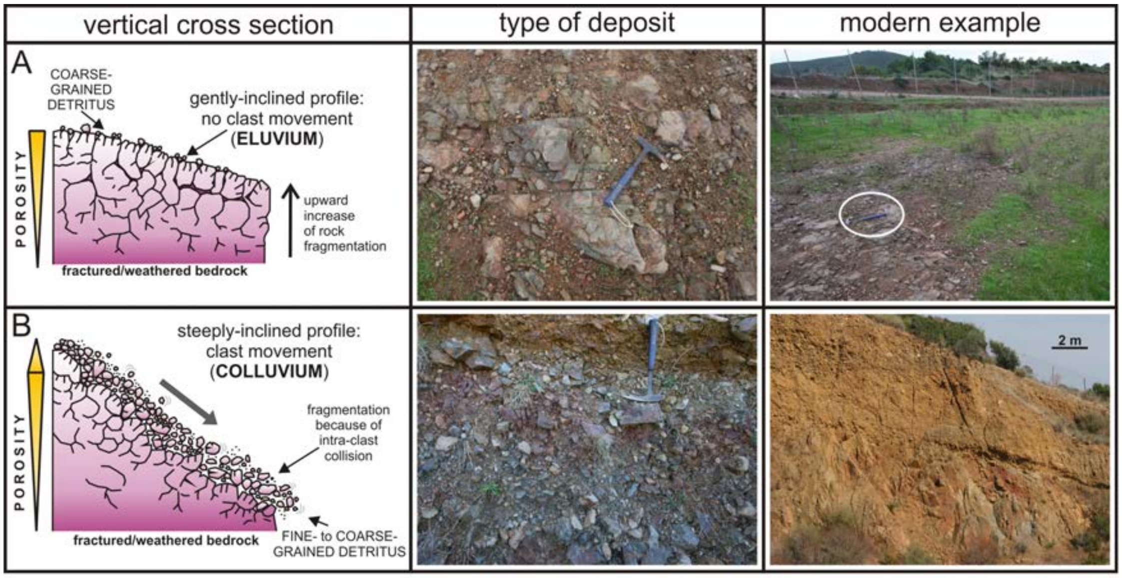

Fig. 17. Conceptual models of (A) eluvial and in (B) colluvial processes, with comparison between textural assemblages of the resulting deposits. Field modern examples are also shown from the Soleminis and Sinnai sections, respectively (hammer as scale is 30 cm long).

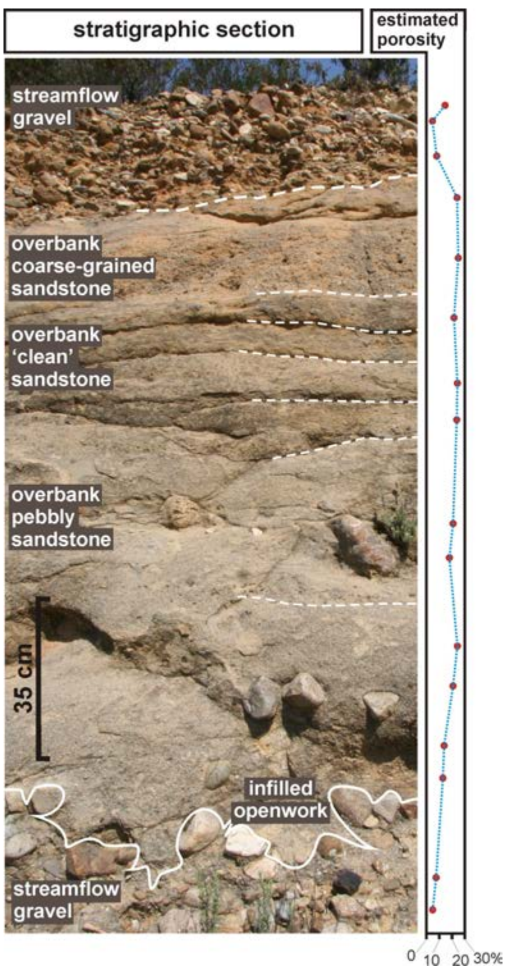

Fig. 18. Variable textures in bedded fluvial conglomerates (Donori section). Grain-size changes are attributed to varying transport populations during alternating high-, intermediate- and low-water stages occurring in floodplain environments. The resulting vertically-stacked alternations generate variations in the mean porosity of the rock volume.

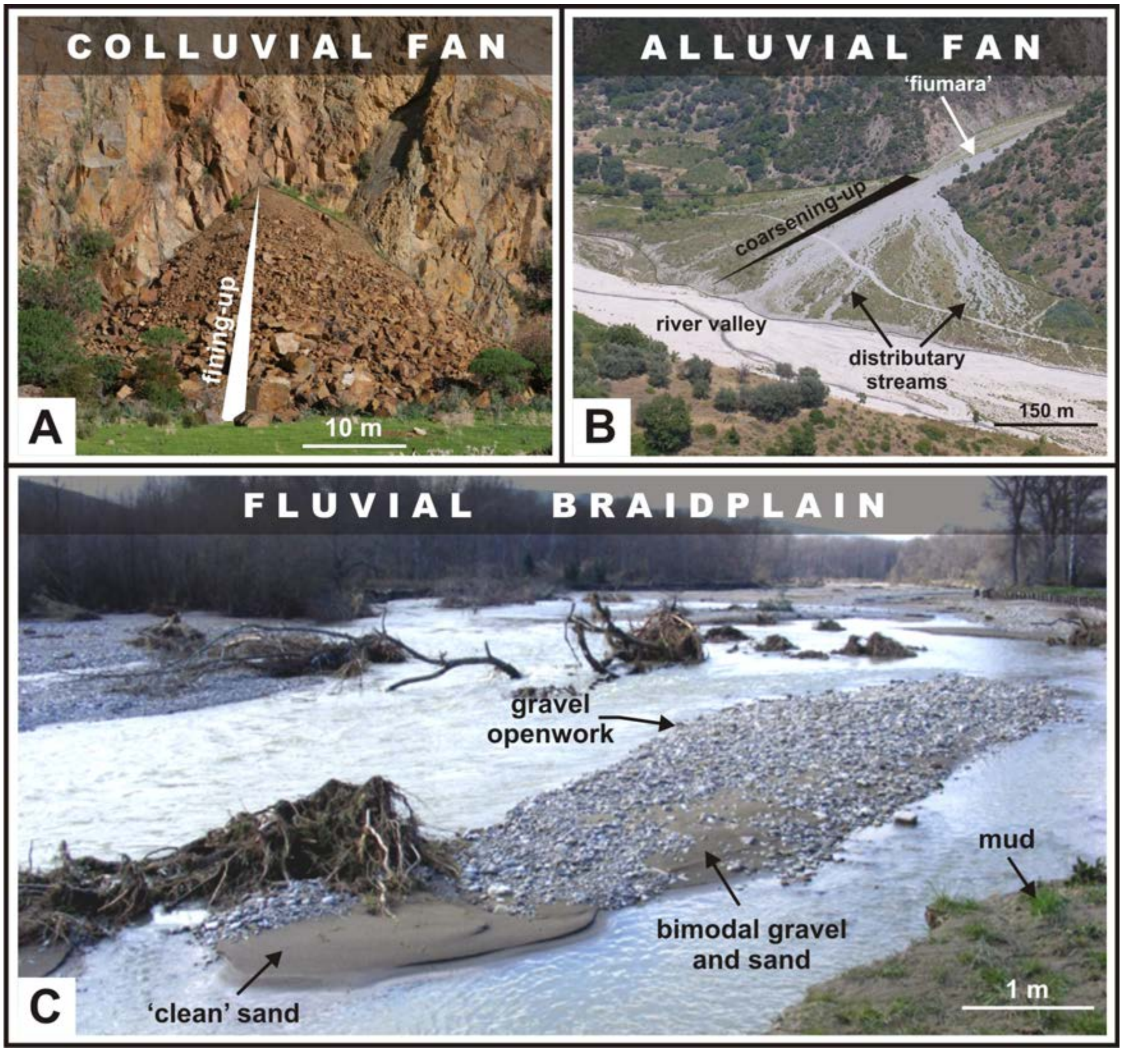

Fig. 19. Modern examples of continental depositional systems from southern Italy as analogues for the deposits investigated in the present study. (A) Colluvial fan in the Sinni area (southern Sardinia). (B) Alluvial fan around Stilo (Calabria). (C) Active braided channels of the Basento River (Basilicata).

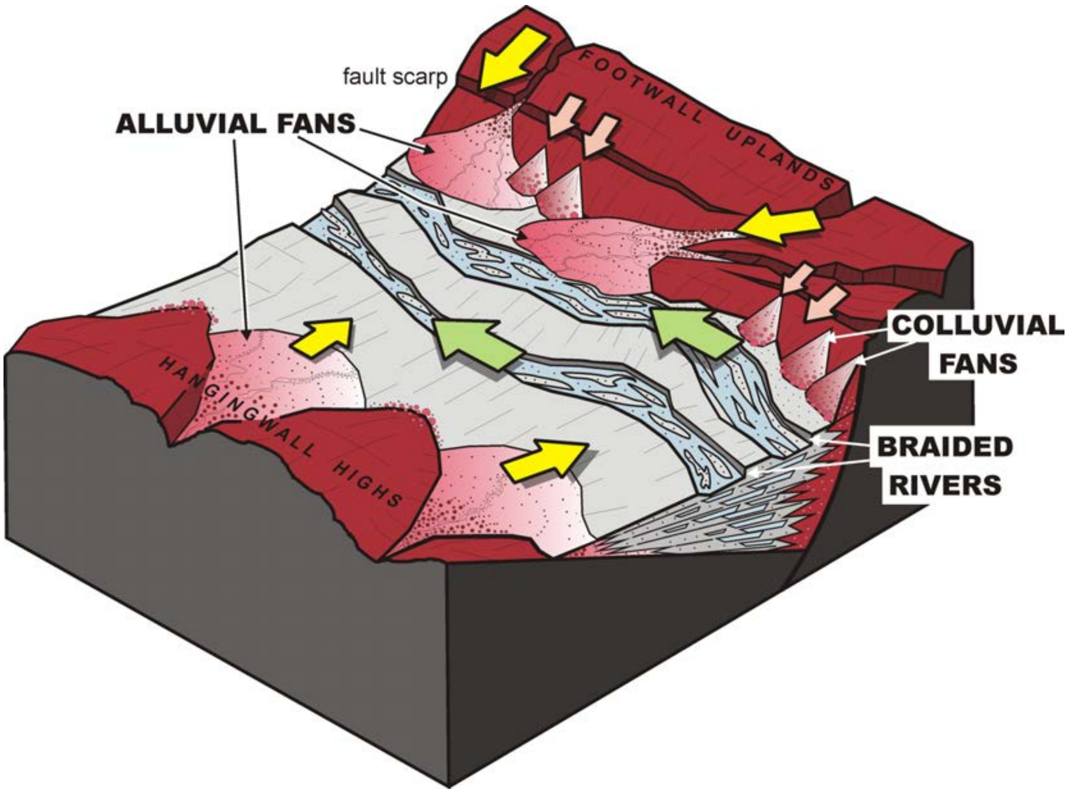

Fig. 20. Block model showing the spatial relationships between footwall-derived colluvial and alluvial fans and braided rivers developed in a half-graben continental basin. Coloured arrows indicate the main sediment transport directions (modified, from Leeder and Gawthorpe, 1987).

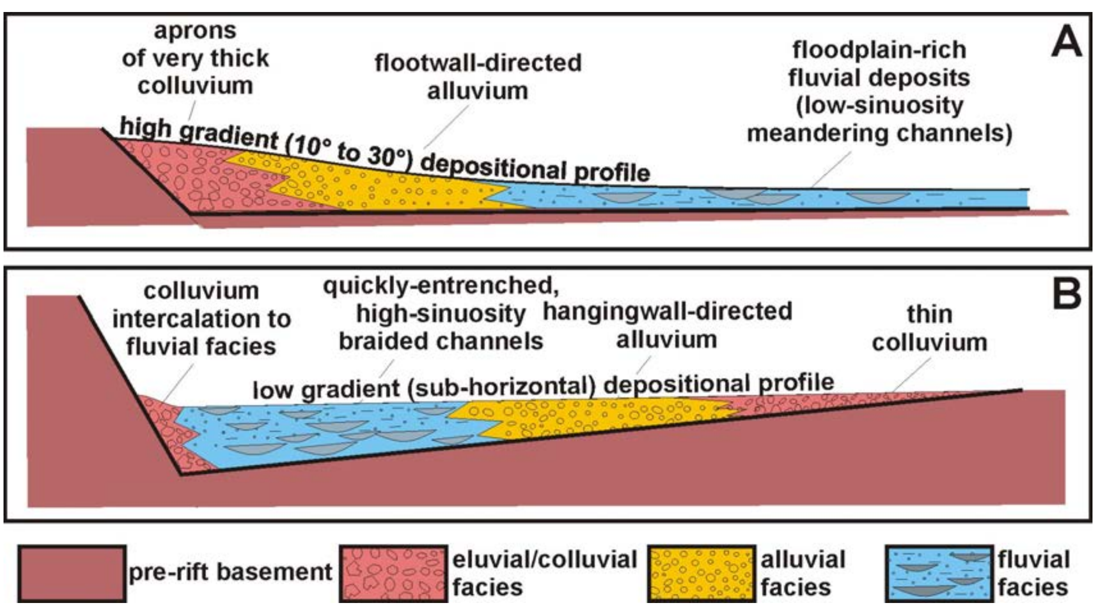

Fig. 21. The different kinematic and evolution of half-graben normal faults influence the lateral relationships between adjacent facies associations. (A) In low-displaced-faulted margins, sediments pass from colluvial, to alluvial to fluvial deposits toward the footwall. (B) In high□displaced-faulted margins, this relationship is inverted, due to the concentration of the accommodation space close to the main fault scarp.

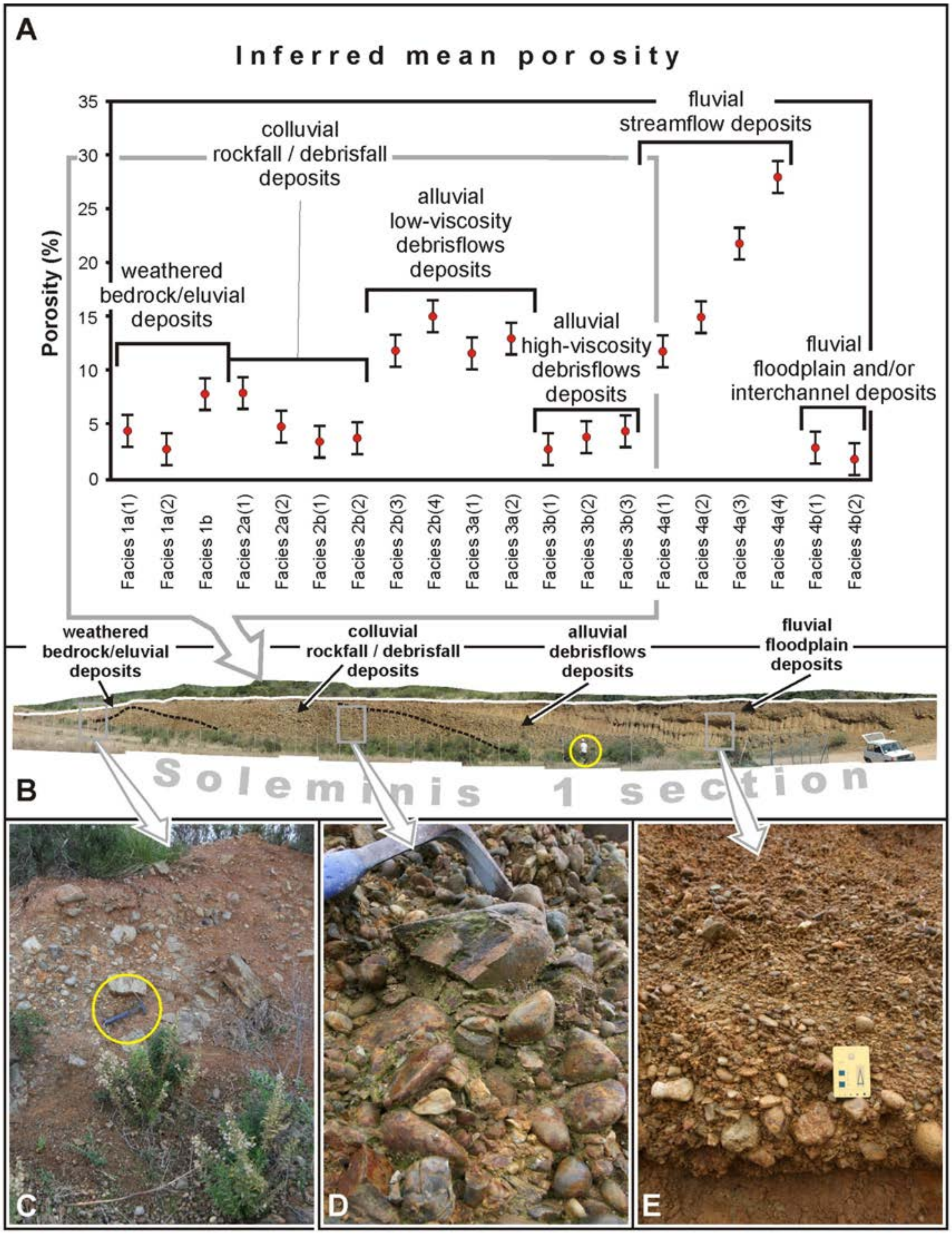

Fig. 22. Porosity values, as obtained from the image analysis of outcrop photographs, plotted against their relative position along a depositional profile (see panel B). (B) Transect of the Solemins 1 section, showing the lateral transition from eluvial/colluvial facies (left side), to alluvial (center) and to fluvial facies (rigth side). (C to E) Sedimentological details of the previous section.

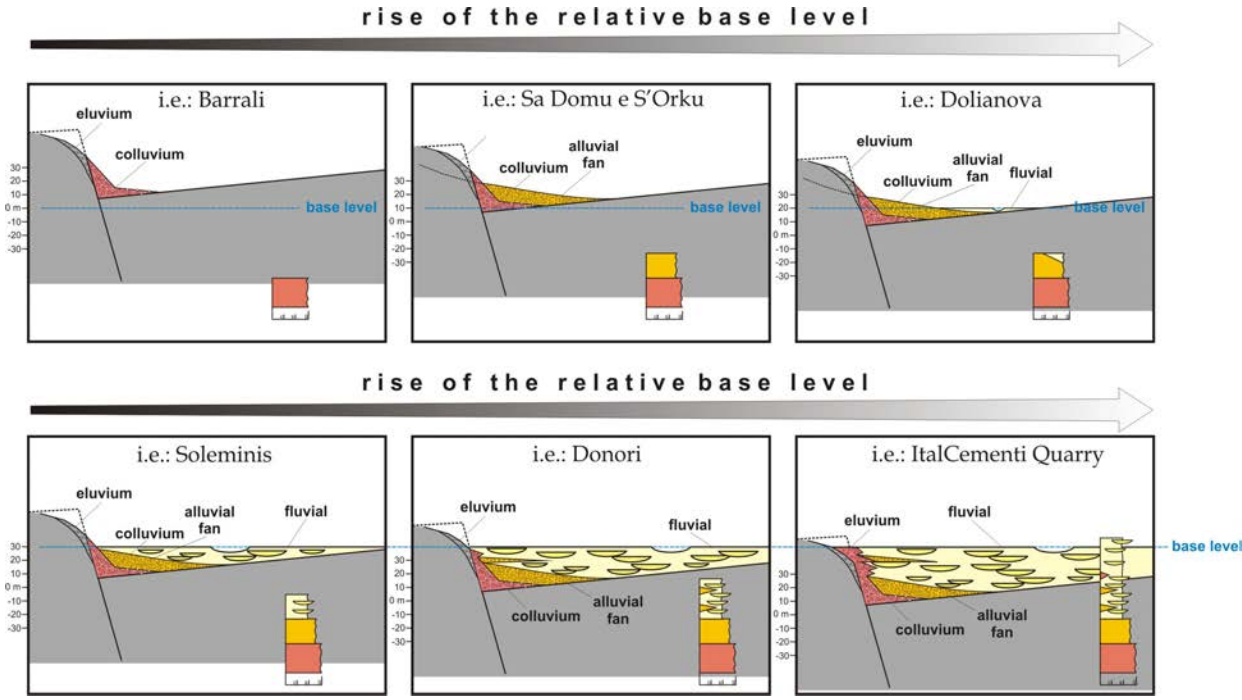

Fig. 23. Six types of bi-dimensional half-graben mini-basins explaining the highly varying thicknesses recognised among the studied deposits. Their 'dimensions' (thickness and lateral extension) depend on the accommodation space available for sediment accumulation. This 'capacity' is the result of the interplay between the elevation of the base level and the topographic profile. In areas where the base level is lower than the topography, sediments are very thin, immature and chaotic. Where the base level exceeds in elevation the topographic base, sediments form thicker accumulations, made up of mature and well organised alluvial to fluvial sequences.