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GEOMORPHOLOGY, TECTONICS AND SEDIMENTOLOGY OF LATE QUATERNARY FANS BETWEEN GUARDIA PIEMONTESE AND PAOLA (TYRRHENIAN COAST OF CALABRIA, SOUTHERN ITALY)

Francesco Muto, Gaetano Robustelli (*), Fabio Scarciglia, Vincenzo Spina & Salvatore Critelli
Dipartimento di Scienze della Terra, Università della Calabria.
(*) Corresponding Author, e-mail robustelli@unical.it

ABSTRACT
An integrated geomorphological, preliminary structural and sedimentological study has been carried out, in order to investigate the role of tectonic and geological setting on the Late Quaternary evolution of the landscape.
The study area represents a portion of the onshore belt located on the eastern margin of the Tyrrhenian extensional basin (Coastal Range). This sector of Calabria consists of a thrust-pile (*Calabrian Arc Auct.*), including both metamorphic and non-metamorphic rocks.
Structural analysis evidences four sets of major fault systems; they affect a monocline consisting of a complex folded morphostructure. The NNW-SSE trending faults are dip-slip and oblique extensional faults, as suggested by superimposition of the striations. The relative chronology suggests that the youngest kinematics is represented by right-lateral normal faults. The NE-trending faults are oblique normal and dip-slip faults; the latter are compatible with the kinematics of the right-lateral NNW trend.
Geomorphological analysis allows three generations of alluvial-fans to be distinguished; furthermore, valley-side perched alluvial terraces occur in the lower reaches of the valley descending from the Coastal Range. The three generations of alluvial fans are telescopically arranged, and the apexes of the piedmont fans (1st generation) are entrenched in respect to perched alluvial terraces. The fans at issue derived from steep catchments, developed as consequent and/or subsequent river valleys debouching from the mountain front. The piedmont zone comprises the 1st generation of alluvial-fans, bordered to the West by a nearly N-S striking scarp commonly reaching up to 80 m in height to the South. The present-day coastal plain comprises the 2nd generation of alluvial-fans which lie upon and interfinger with Late Pleistocene coastal and eolian deposits; the latter sail the foot-zone scarp of piedmont fans. A tephra layer has been recognised within eolian deposits.
On the basis of preliminary structural and morphotectonic data, the last tectonic phase responsible for the latest landscape fragmentation, was probably characterised by a NW-SE trending extension direction. Moreover, morphometric measurements and pre-existing offshore data support the hypothesis that, since Middle-Late? Pleistocene time, weak tectonic subsidence, coupled with marine base level rise, constitute the main mechanisms promoting the creation of the accommodation space for fan aggradation.
The Quaternary alluvium is characterised by a variety of coarse-grained facies coming to be regarded as alluvial-fan facies. In particular, detailed facies analysis revealed the presence of 4 facies associations, mainly represented by debris flow, debris avalanche deposits and sheetflood facies; facies associations also allow different alluvial fan evolutionary stages to be outlined. In addition, the lithology of the bedrock outcropping within fan catchments, have been also identified as the main factors which played important roles in controlling the different depositional processes and consequently facies assemblages.

RIASSUNTO
*È stato condotto uno studio integrato di carattere geomorfologico, strutturale e sedimentologico al fine di investigare il ruolo svolto dalla tettonica e dall'assetto geologico sull'evoluzione tardo-quaternaria di una porzione della Catena Costiera. Essa rappresenta il margine orientale del bacino estensionale tirrenico. Questo settore della Calabria consiste in una struttura a falde (*Arco Calabro Auct.*), comprendente rocce sia metamorfiche sia non metamorfiche.*
L'analisi strutturale evidenzia quattro principali sistemi di faglie, che interessano una complessa morfostruttura. Le faglie NNW-SSE presentano cinematismi di tipo diretto ed estensionali obliqui, come suggerisce la sovrapposizione delle strie sui piani di faglia. La loro cronologia relativa mostra che la cinematica più recente è rappresentata dalle faglie normali a componente destra. Le faglie NE-SW risultano normal trascorrenti e dirette; le ultime sono compatibili con la cinematica dei sistemi NNW-SSE a componente destra.
L'analisi geomorfologica permette di distinguere tre generazioni di conoidi alluvionali. Inoltre, terrazzi fluviali sospesi si rinvengono incastrati morfologicamente nelle porzioni più basse e più distali (verso la costa) delle valli che dissecano la Catena Costiera. Le due generazioni di conoidi sono incastrate a cannocchiale l'una nell'altra, e gli apici dei quelle di prima generazione si incastrano tra i lembi dei terrazzi sospesi. I bacini di drenaggio che alimentano i conoidi, derivanti da un sistema di corsi d'acqua conseguenti e/o susseguenti che sboccano dal fronte montuoso, sono piuttosto acclivi. La zona pedemontana comprende le conoidi di prima generazione ed è limitata ad ovest da una scarpata a direzione circa N-S che verso sud raggiunge anche gli 80 m di altezza. La piana costiera attuale comprende le conoidi di seconda generazione, che si sovrappongono e si interdigitano con i depositi costieri ed eolici tardo-pleistocenici; questi ultimi, nei quali è intercalato un livello vulcanoclastico, suturano la scarpata che limita, verso mare, i conoidi della zona pedemontana.
Sulla base di dati strutturali preliminari e morfotettonici è stato possibile individuare l'ultima fase tettonica responsabile della frammentazione del paesaggio nell'area indagata, caratterizzata probabilmente da una direzione di estensione NW-SE. Inoltre, la misura di alcuni parametri morfometrici e la rilettura di dati sismici relativi alla piattaforma continentale sommersa consentono di ipotizzare che, a partire dal Pleistocene Medio-Superiore?, una debole subsidenza, accompagnata dalla risalita eustatica del livello del mare, doveva costituire il principale meccanismo per la creazione dello spazio di accomodamento utile alla crescita dei conoidi.
I depositi quaternari affioranti nell'area sono rappresentativi di sistemi deposizionali di conoide alluvionale. In particolare sono state distinte 4 associazioni di facies, tra cui le principali sono rappresentate da conglomerati massivi (debris-flow e debris-avalanche) e da depositi di lame di piena (sheetflood); le associazioni di facies hanno consentito, inoltre, di definire differenti stadi evolutivi nella crescita dei conoidi alluvionali. Inoltre, la litologia del substrato, sottesa ai vari bacini idrografici, rappresenta un'ulteriore fattore di controllo nello sviluppo dei differenti processi deposizionali.

Key words: Geomorphology, tectonics, sedimentology, coastal alluvial-fans, Tyrrhenian coast, Calabria, southern Italy

Parole chiave: Geomorfologia, tettonica, sedimentologia, conoidi alluvionali costieri, costa tirrenica, Calabria, Italia meridionale.

1. INTRODUCTION

The study area is located along the western coast of Calabria, on the eastern margin of the Tyrrhenian basin (Fig. 1A). This basin developed since late Tortonian times (Kastens *et al.*, 1990) as back-arc basin of the Southern Apennine thrust and fold belts (Patacca & Scandone, 1989; Patacca *et al.*, 1990). Since Middle-Late Pliocene the Tyrrhenian basin was affected by extensional tectonics, responsible for the formation of perityrrhenian depressions, such as the Paola slope basin (Barone *et al.*, 1982; Fabbri *et al.*, 1981; Rehault *et al.*, 1987), and the uplift of the Coastal Range (Sorriso-Valvo & Sylvester, 1993). The Plio-Quaternary evolution of the Paola slope basin has been investigated in detail by analysis of offshore data (Barone *et al.*, 1982; Gallignani, 1982; Argnani & Trincardi, 1988; 1993; Chiocci et al., 1989; Chiocci, 1995; Chiocci & Orlando 1995). Conversely, few studies have been carried out on the reconstruction of the onshore basin margin, due to the dearth of geomorphological and stratigraphical data. Robustelli *et al.* (2002) represent the first attempt to reconstruct a Middle-Late Pleistocene geomorphological evolution. Furthermore, the only available literature on the geomorphological features of the Coastal Range has focused on the assessment and estimation of uplift rates (Verstappen 1977; Carobene *et al.*, 1986; Carobene, 1987; Carobene & Ferrini, 1993; Bordoni & Valensise, 1998) and of hillslope degradation processes (Sorriso-Valvo & Sylvester, 1993; Sorriso-Valvo *et al.*, 1998).

Quaternary continental and marine deposits associated with erosional landforms coexist in the study area. An integrated structural, stratigraphical and geomorphological study has been carried out in order to reconstruct the Late Quaternary evolution, and to state the role of tectonic and geological setting which, coupled with eustacy (Robustelli *et al.*, 2002), influenced alluvial fan development. These Authors have proposed a model of evolution, according to which Quaternary fan development was mainly related to phases of climate amelioration following glacial periods, but just before interglacial highstands were approached; progressively increasing moisture and temperatures allowed bio-chemical rock degradation, and consequent increased run-off favoured removal of slope-waste materials, which promoted alluvial-fan development, mainly by gravity processes. Sea level highstand induced coastal erosion of fan toes, resulting in foreshortened longitudinal profiles and fan dissection (*e.g.* Harvey *et al.*, 1999); sediment input was probably channelled away from subaerial basins, enabling progradation over the shelf. The subsequent lowering of sea level promoted fan-trenches lowering and the progressive emergence and dissection of the Paola Basin shelf; products of slope degradation during glacial periods, probably, had to be conveyed from the mountain catchments to fill paleovalleys, detected by means of seismic profiles analysis (Chiocci *et alii,* 1989; Chiocci, 1995; Chiocci & Orlando, 1995), thus disabling fan-development.

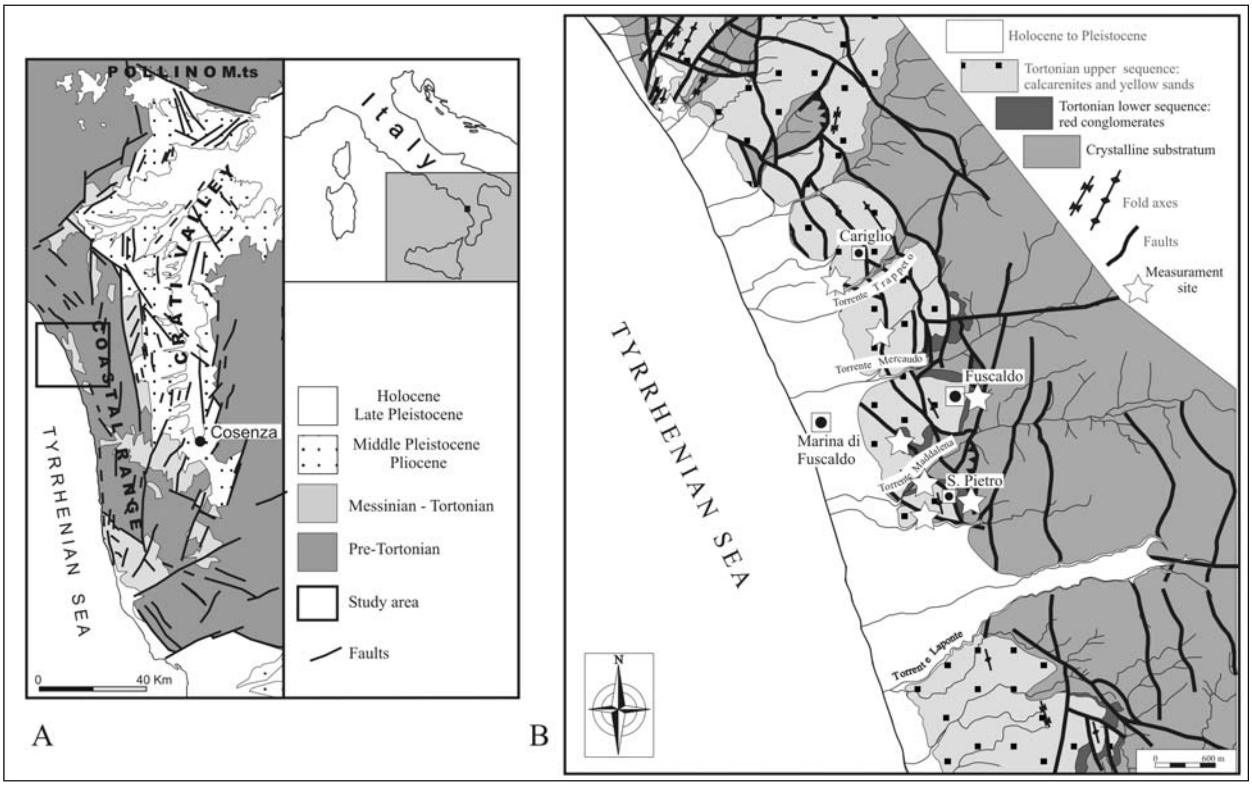

Fig. 1 - A - Northwestern sector of the Calabrian Arc (after Tortorici et. al., 1982, modified) with the location of the study area; B - Geological sketch map of the study area.

A - Settore nord-occidentale dell'Arco Calabro, (da Tortorici et al., 1982, modificato) ed ubicazione dell'area di studio; B - Carta geologica dell'area di studio.

2. GEOLOGICAL SETTING

The northwestern sector of the Calabrian chain consists of a flat-lying nappe (*Calabrian Arc Auct.*) which constitutes the morphostructural height of the Coastal Range (Fig. 1A); in particular it consists of high-grade metamorphic rocks of the *Polia Copanello Unit*, tectonically overlapping low-grade metamorphic rocks of the *Castagna Unit* and *Bagni Formation* (Amodio Morelli *et al.*, 1976; Dietrich, 1976; Colonna & Compagnoni, 1982); these units overlapped the *Ophiolitic Complex* (*Liguride Complex*, Ogniben, 1973; Messina *et al.*, 1981, Boullin, 1984; Knott, 1987; Dewey *et al.*, 1989), and the Carbonatic Units (Amodio Morelli *et al.*, 1976). Thrust-sheets were cut by four sets of major faults, the relative ages of which have been determined by Sylvester *et al.* (1987).

In the study area, a Miocene sedimentary sequence rests on the crystalline-metamorphic basement of the Coastal Range; it constitutes the sedimentary infilling of the correlative Amantea basin, dated to upper Tortonian by Di Nocera *et al.* (1974), outcropping to the South (Mattei *et al.*, 2002; Muto & Perri, 2002). In the study area, the Miocene deposits consist (Fig. 1B) of two unconformable sequences. The first one is characterised by conglomerates and sandstones, underlying the 2nd sequence constituted by yellow calcarenites and grey-blue clays; the latter have been recognised in boreholes along the coastline. This succession exhibits a general monoclinalic attitude, with a growing dip towards West. Late Quaternary continental deposits rest unconformably on the basement and the Miocene sedimentary sequence.

The Coastal Range is a *horst* which started to uplift since Plio-Pleistocene time (Tortorici, 1982a; 1982b), and produced the progressive isolation of the Crati Valley from the Tyrrhenian Sea, accompanied by the formation of the Paola Basin. This basin extends along the N-S direction, on the west side of the study area, from the Sangineto zone to the Capo Vaticano zone. The Paola basin has an architecture controlled by extensional tectonic phases and contractional events (Canu & Trincardi, 1989); moreover, it exhibits a depocenter localised immediately behind the continental slope, and is characterised by high depositional gradients (Fabbri *et al.*, 1981; Gallignani 1982; Barone *et al.*, 1982; Finetti & Del Ben, 1986; Chiocci, 1995).

3. PRELIMINARY STRUCTURAL ANALYSIS

The northwestern sector of the Tyrrhenian margin is characterised by a complex structural arrangement which is limited by the Falconara fault zone (Turco *et al.*, 1990) to the South and the Guardia Piemontese morphostructure to the North.

The oldest structures are represented by thrust faults and by two generations of folds, with axes oriented roughly from NNW-SSE to NNE-SSW. These folds, which involve all the Tortonian deposits, are asymmetric and verging to the East.

These structures are cut by transtensive fault systems, that represent the result of the latest tectonic phases related to the Tyrrhenian basin Quaternary spreading. Fault-slip data were collected in 8 measurement sites, for a total amount of 120 measures. Measurement sites were positioned in Miocene deposits, whereas Quaternary deposits do not display any signs of deformation. Nevertheless, Quaternary tectonics is clearly demonstrated by evidence of uplifted Tyrrhenian strandlines (sea caves at about 12 m a.s.l. located near to Cetraro, close to the North of the study area, Carobene et al., 1986; Carobene, 1987; Bordoni & Valensise, 1998), and by cross-cut relationships between marine terraced deposits and fault systems (Tortoricil *et al.*, 2002); furthermore, from a geomorphological point of view, the fact that remnants of perched alluvial terraces are not related to any present-day or past landform and are located close to the escarpment bounding the mountain front support the Quaternary tectonic activity.

Literature data (Tortorici *et al.*, 2002; Muto & Perri, 2002; Tortorici *et al.*, 1995) were used to constrain the chronology and the stress field of the last fault activity.

A strong fit exists between the orientation of the main meso-faults and macro-fault systems, plotted in

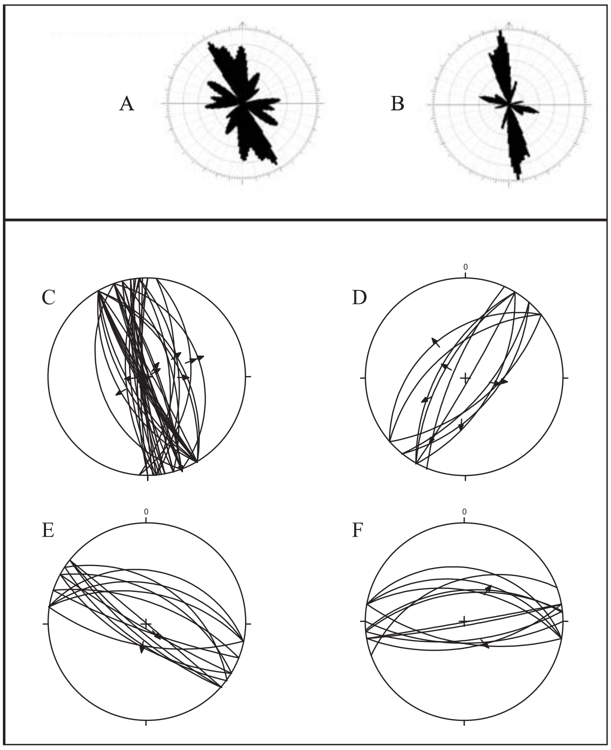

Fig. 2 - Structural data collected in the Miocene deposits.
A - Rose diagram of the main meso-faults collected; B - Rose diagram of the macro-fault systems mapped in the study area; C - Lower hemisphere stereographic projection of the NNW trending fault system with the latest kinematic indicators on the planes; D - Lower hemisphere stereographic projection of the NE trending fault system with the latest kinematic indicators on the planes; E, F - Lower hemisphere stereographic projection of the NW-SE and E-W trending fault systems.

Dati strutturali rilevati nei depositi miocenici.
A - Rose diagram relativo alle principali mesofaglie misurate. B - Rose diagram relativo alle macro strutture cartografate; C - Proiezione stereografica, emisfero inferiore, del sistema di mesofaglie NNW-SSE con gli ultimi indicatori cinematici rilevati sui piani; D - Proiezione stereografica, emisfero inferiore, del sistema di mesofaglie NE-SW con gli ultimi indicatori cinematici rilevati sui piani; E, F - Proiezione stereografica, emisfero inferiore, del sistema di mesofaglie NW-SE e E-W.

rose diagrams (Figs. 2A and 2B), suggesting that fault slip data well clarify the last kinematics of macro-faults.

The main system faults are NNW-, NE-, NW- and E-trending. The occurrence of overlapping kinematic indicators on the same fault plane, along with the presence of different slip directions on fault planes having the same strike and dip, allow multiphase tectonics to be outlined. The latest fault kinematics is showed in Figs. 2C-F. In particular, fault slip data of the NE-trending systems suggest that their kinematic chronology shifts from left-lateral normal to normal dip-slip faults. The NNW-trending system faults show dip-slip and oblique normal movements; the superimposition of the striations allows a relative chronology of their movement to be fixed, *i.e.* from dip-slip to right-lateral normal faults. The left lateral NE-trending faults system, compatible with the NNW-trending dip-slip system, is older than the latest phase of movement characterised by dip-slip NE-trending normal faults and relative NNW-trending right lateral normal faults. The E- and NW-trending fault system are oblique normal faults and are characterised by a kinematics which is locally superimposed to left strike-slip ones.

The latest kinematic indicators are consistent with an ESE-WNW extension interpretation, which represents the main mode of deformation of the Calabrian Arc since Middle Pleistocene times (e.g. Tortorici *et al.*, 1995).

4. GEOMORPHOLOGY

Quaternary deposits of the study area, representing mainly marine and alluvial environments (Argnani & Trincardi, 1993; Sorriso-Valvo & Sylvester, 1993; Sorriso-Valvo *et al.*, 1998; Robustelli *et al.*, 2002), are hosted in a narrow coastal strip, which can be considered the onshore counterpart of the Paola Basin infilling. These deposits are limited inland by the Coastal Range, essentially evolved by slope replacement mechanisms and river dissection. As a consequence of this evolution the west-facing slope of this mountain ridge shows well-defined triangular facets as isolated remnants of the N-S trending fault scarp, partly dismantled.

The hydrographic network formed as a response to the Coastal Range uplift, producing steep catchments debouching seaward from the mountain front, which led to the emplacement of three generations of alluvial fans. As a general rule the drainage pattern follows the main fault system (Sylvester *et al.*, 1987; Sorriso-Valvo & Sylvester 1993) and shows several asymmetric valleys. Geomorphic evidence suggest that the E-W consequent streams were interrupted and deflected by NE- and N-S trending subsequent streams, at least in the northern sector of the study area. Some morphometric data of the main stream catchments have been calculated, such as the mean drainage basin slope (Ds) and the drainage basin area (Da), the sweep angle, As (*sensu* Viseras *et al.*, 2003) and the mean slope (Fs) of the fans. From these data it can be observed that the source catchments of the major rivers are very steep: the mean slope of the drainage basins, in fact, ranges from 31.43 to 40.65%. On the contrary, the fans are gentler, with mean slopes approximately around 10-14% or lower, except in the case of the T. Laponte (Fs = 15.48%).

On the basis of data provided by Robustelli *et al.* (2002), three generations of alluvial-fans, telescopically arranged, have been distinguished. From a geomorphological point of view, the study area consists of different, narrow geomorphological zones, parallel to the coast and limited by approximately N-S trending scarps probably not related to faults (Fig. 3). The piedmont zone comprises the 1st generation of alluvial-fans which are telescopically inset in respect to remnants of perched alluvial terraces (Fig. 4A), gently sloping seaward but apparently not related to any present-day or past landform, which hang in some of the main river valleys dissecting the Coastal Range. A nearly N-S striking scarp borders the piedmont zone; local remnants of eolian deposits, with continental fauna, are well preserved on the basal portion of the foot-zone scarp. Quite a similar stratigraphic situation characterises the piedmont zone of the central Coastal Range (Sorriso-Valvo & Sylvester, 1993), where sandy eolian deposits outcrop along the foot-zone scarp and underlie the youngest alluvial fans. Amino-acid racemization dating on *Helix sp.* fix the emplacement of eolian sands at about 70 kyr B.P. (Sorriso-Valvo, pers. comm.). Furthermore, they rest on buried gravel deposits that constitute the bulk on which post-eolian sedimentation took place, as inferred by boreholes data, and are commonly capped by thin layers of slope deposits produced by scarp retreat. Hence these eolian sands clearly postdate the 1st generation of alluvial fans (Middle-Late? Pleistocene) and predate the 2nd one (Upper Pleistocene-Holocene) (Fig. 4B). The most recent alluvial-fans, Late Holocene to recent in age, develop close to the present-day coastline, and are substantially inactive and subject to very slight river dissection. They lie upon and are entrenched within Late Pleistocene–Holocene coastal deposits, consisting of beach sands and gravels as well as eolian sands (Fig. 3).

The bulk of the piedmont zone, reaching an elevation of about 130 m a.s.l., consists of the oldest generation of coalescent alluvial-fans, which show a sweep angle 60°. A particular attention must be given to a huge fan developed at the mouth of T. Laponte, which is entrenched in – and partly rests on – the dissected T. Maddalena alluvial fan. From the geomorphic relationships between the two alluvial bodies, the Laponte fan is obviously younger. Although its drainage basin is not the widest (Da = 6.32 Km^2), it is extremely large, with an As value close to a square angle and the feeder channel filled with great amounts of sediments (cf. Sorriso-Valvo *et al.*, 1998), assuming a typical “mushroom” shape (Viseras *et al.*, 2003) in plan view. In the sector between Valle Santa Maria and the T. Maddalena, at the toe of the piedmont zone, the lower and younger alluvial fans occur. Their sweep angles commonly vary from 30-40°, reaching higher values for the T. Mercaudo (60°) and the T. Trappeto (about 90°).

The above mentioned eolian sands, which taper upslope the nearly N-S striking scarp bordering the piedmont zone, are quartzolithic in composition; they have abundant lithic grains, and mostly equal amounts of quartz and feldspar (Qm_{20} F_{18} Lt_{62}). Feldspar is dominantly plagioclase. Aphanitic lithic fragments (Lm_{86} Lv_0 Ls_{14}) include abundant metamorphic lithic fragments, represented by phyllite, fine-grained schist and minor fine-grained gneiss and amphibolite; sedimentary

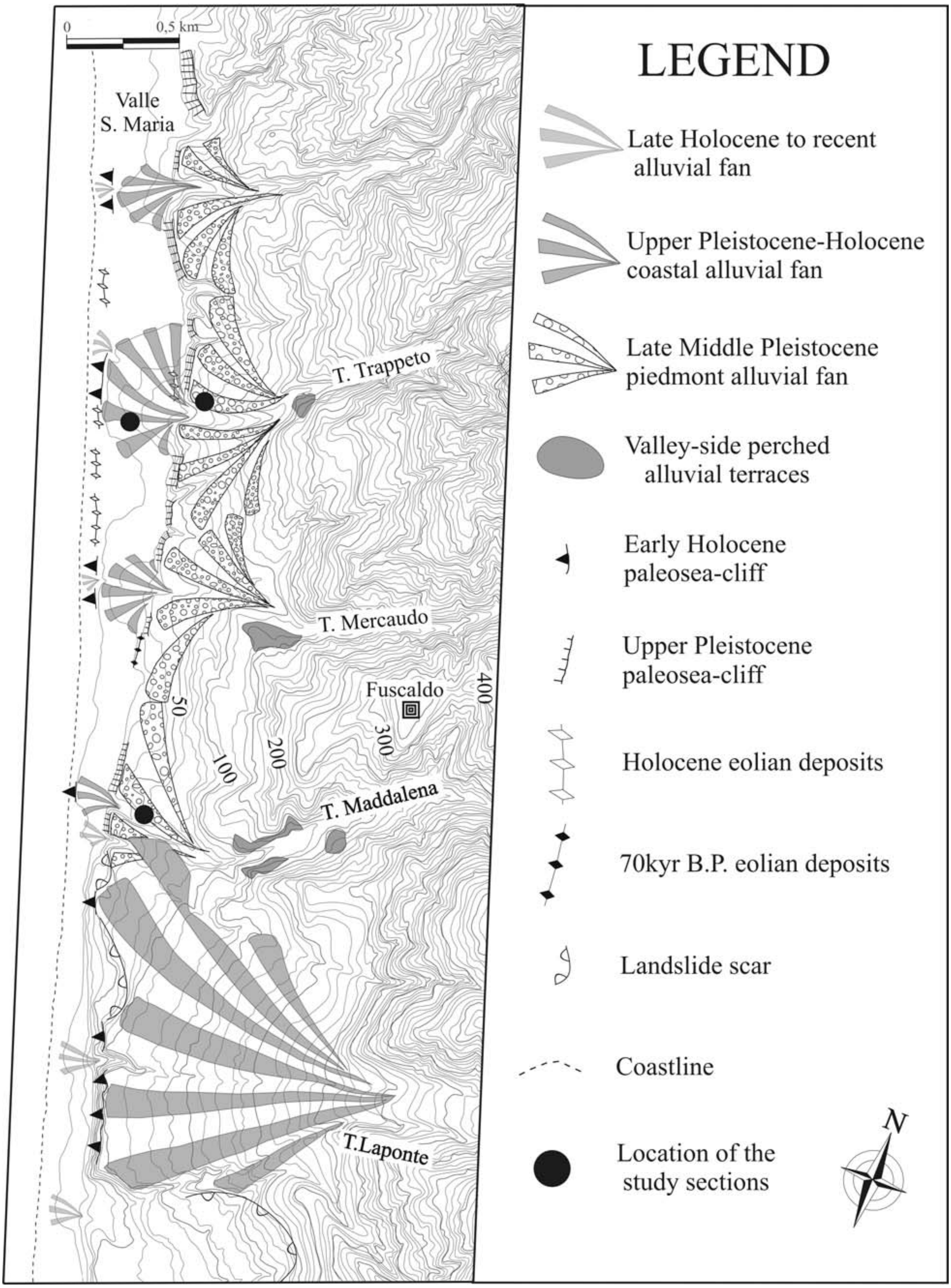

Fig. 3 Geomorphological sketch map of the study area.
Schema geomorfologico dell'area di studio.

lithic fragments are subordinate and include micritic and sparitic limestone, dolostone and metalimestone lithic fragments. Coarse–grained rock fragments include plutonic (mostly granodiorite and minor granite) and gneiss rock fragments. The abundant metamorphic detritus is derived from the diverse tectonostratigraphic units of the Coastal Range, *Bagni, Castagna* and *Polia Copanello Units* (Amodio Morelli *et al*., 1976; Dietrich, 1976; Colonna & Compagnoni, 1982), whereas the sedimentary detritus is derived from Mesozoic to Miocene sedimentary strata of the *San Donato* and *Verbicaro Units* (Amodio Morelli *et al*., 1976) and the Miocene sedimentary successions (Di Nocera *et al*., 1974; Mattei *et al*., 2002; Muto & Perri, 2002).

A fine-textured, greyish tephra layer, about 20 cm thick, is interbedded within their upper portion and consists of impure volcanoclastic sands. Volcanic detritus includes pumice fragments, having vitric texture, and sometimes including plagioclase, pyroxene and biotite crystals. Rare volcanic lithic fragments exhibiting microlitic texture consist of particles having plagioclase, biotite and pyroxene microlithes, and a vitric groundmass. In addition to volcanic detritus, the sample contains various non-volcanic detritus, which includes single quartz and feldspars, metamorphic and carbonate lithic fragments, and coarse-grained plutonic rock fragments. Micrite and microsparite interstitial component constitutes matrix and early cement of the sample.

5. ALLUVIAL-FAN STRATIGRAPHY

On the basis of geomorphic analysis, described in the previous section, the Quaternary alluvium consists of perched valley-side terraced deposits and alluvial fan deposits; the latter comprise two generations of alluvial fans, telescopically arranged. Alluvial-fan deposits are characterised by the dominance of conglomerates; fine-grained facies were not observed. The clast lithology slightly varies over the study area; dominant clasts include ophiolitic units, phyllites, gneiss, schists, granites and sedimentary rocks.

Because of the dearth of exposures which affect valley-side terraced deposits, sedimentary facies analysis has concerned only alluvial-fan facies. In particular a number of stratigraphic sections have been measured in order to give the sedimentary logs of Fig. 4, because of the vertical cliffs which confine the piedmont zone allu-

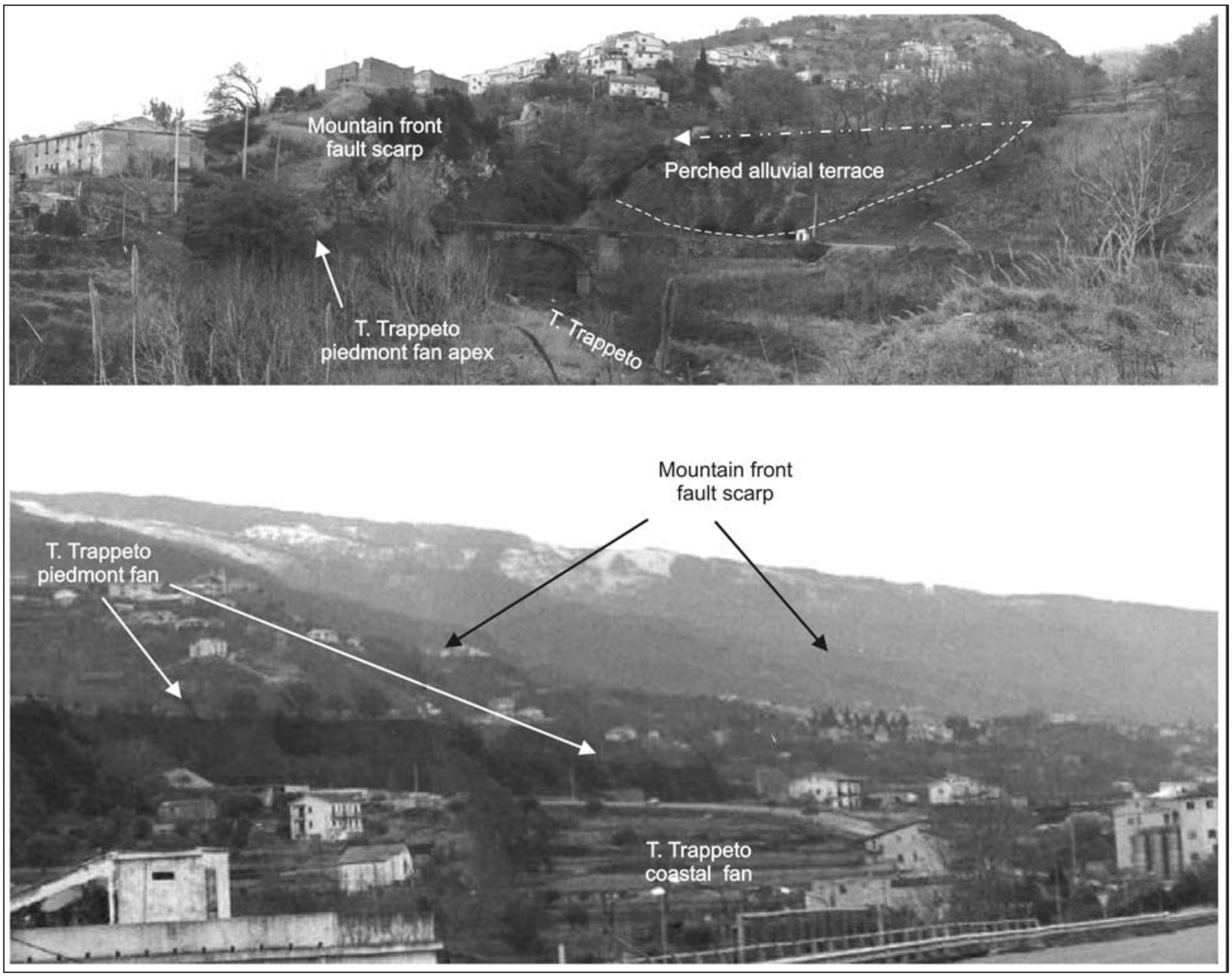

Fig. 4 - Overviews showing the morphologic relationships among the perched alluvial terraces, the mountain front and the piedmont alluvial fans (A) and between the piedmont and the coastal alluvial fans (B).

Foto panoramiche che illustrano i rapporti tra i terrazzi fluviali sospesi ed il fronte montuoso ed i conoidi pedemontani (A), e tra i conoidi pedemontani e costieri (B).

vial fan; therefore sections were obtained along river incision and road cuts and extend parallel to fan-slope up to 9 m in width, and are representative of the uppermost portion of alluvial fans.

As far as coastal-plain alluvial fans are concerned, thanks to excavations for the foundation of buildings located in the middle portion of T. Trappeto coastal fan, the relative sedimentary log (Fig. 4) is given; unfortunately no sections are available for T. Mercaudo and T. Maddalena Coastal fans, because of the lack of artificial and natural exposures, the latter owing to slight river dissection.

The base of both generations of alluvial fans is not exposed; the maximum thickness, provided by well log data, is 45 m and 35-40 m for the coastal and piedmont alluvial deposits, respectively.

According to Robustelli *et al*. (2002), the latest phases of fan development occurred during climate amelioration following glacial periods, when increasing moisture and temperatures, enabling bio-chemical rock degradation, and increasing run-off allow slope-waste materials to be removed, mainly by gravity and subordinately tractive processes.

5.1 FACIES ANALYSIS

The Quaternary alluvium is characterised by a variety of coarse-grained lithofacies coming to be regarded as alluvial-fan facies. In particular detailed facies analysis revealed the presence of 5 sedimentary facies, discussed below, which are described on the basis of clast-size, bedding, sedimentary structures and shape of the units.

Three sedimentary logs are given in Fig. 4; they are representative of the uppermost part of the T. Trappeto piedmont fan, T. Maddalena piedmont fan and T. Trappeto coastal fan.

Facies 1 - Structureless, cobble to boulder-size conglomerate

No good exposures of this facies occur in the study area; a number of very small outcrops occur along roads ascending T. Laponte alluvial-fan apex zone, and as subordinate facies alternating in T. Maddalena alluvial-fan deposits. The latter allows facies analysis to be made.

This facies consists of massive, monomictic, matrix to clast supported conglomerates of cobble to boulder grade. Basal surfaces of these beds, up to 1.8 m thick, are sharp and display fairly erosional features. Matrix content is locally abundant; it consists of a mixture ranging from silt to pebble, seemingly of the same composition as the largest clasts; the latter are angular to subangular in shape, and it is worth noting the presence of shattered ones. Fabric is disorganized, although uncommon, crudely coarse-tail inverse grading occurs.

Facies 2 - Structureless, clast-supported conglomerate

Massive, poorly sorted, sheet conglomerates comprise this facies. Bed thickness varies between 0.4 and 1.2 m. Basal bedding contacts are sharp and slightly irregular, with relief of up to 0.15 m; scour surfaces may be observed, but they are very uncommon. The debris consists of pebble to cobble-size clasts, ranging from angular to subrounded in shape. Matrix in an unsorted mixture varying between silt and fine-grained pebble, and is rarely sufficiently abundant to support clasts. Fabric is disorganized, although the longest a-axes of some elongate clasts may be seen parallel to paleoflow and imbricated a(p), a(p)a(i). Grading is absent or basal inverse grading locally occurs.

Facies 3 - Inversely graded, clast-supported conglomerate

Inversely graded, clast-supported, poorly to moderately sorted sheet conglomerates characterise this facies. Basal surfaces of the beds, up to 0.5 m in thickness, are sharp and non erosive. Pebble to cobble-size clasts comprise this facies, ranging from angular to subrounded in shape. Matrix, varying between sand to fine pebble, is never sufficiently abundant. Inverse-grading is well developed; inverse to normal grading is uncommon (Fig. 5A). Clast fabric locally displays a preferred a(p)a(i) clast orientation.

Facies 4 – Horizontally, crudely stratified clast-supported conglomerate

This facies is characterised by vertically alternating couplets of clast-supported sheet conglomerates (Fig. 5B); beds of this facies, up to 0.4 m thick, have sharp, non erosive basal bedding contacts. The debris consists of subangular to subrouded pebble to cobble grade and pebble to pebbly granule gravels.

The coarse gravel units, occasionally clast-thick, are massive and moderately sorted; crude normal gradind may occur. Imbrication, locally well developed, is variable, showing a(p)a(i) and a(t)b(i) fabric modes.

The finer grained beds seem to be more extensive than the coarse grained ones; they are moderately to well sorted and no grading has been observed. Pebble-size clasts show a local a(t) b(i) fabric mode. Outsized clasts, of coarse pebble to fine cobble grade, are sparsely present and their long axis are aligned both parallel and normal to bedding planes.

Facies 5 – Lenticular, clast-supported conglomerate

This facies rests on facies 2 and 3; it consists of moderately to well sorted, clast-supported, lenticular gravel units up to 0.2 m thick and varying between 0.6 and 1.1 m in width. Granule to fine pebble-size clasts comprise this facies. Grading is absent, although crudely normal grading locally occurs. Imbrication may be well developed, showing a(t)b(i) fabric mode.

5.2 INTERPRETATION AND FACIES ASSOCIATIONS

Detailed facies analysis revealed the presence of five facies, the interpretation of which has been described accordingly as follows. Lateral and vertical facies associations, coarse-grained texture, disorganized fabric, together with geomorphic analysis suggest that the depositional events were of very high-energy and consistent with an alluvial-fan depositional system.

Facies 1: Debris-avalanche deposits

The conglomerates of facies 1 are massive, monomictic, matrix to clast supported and cobble to boulder grade; these features suggest high-energy depositional events. Furthermore, the angular nature of the gravel clasts, locally shattered, their monomictic composition and their poor sorting are interpreted as deposition by debris-avalanche events (Sorriso-Valvo, 1988; Yarnold &

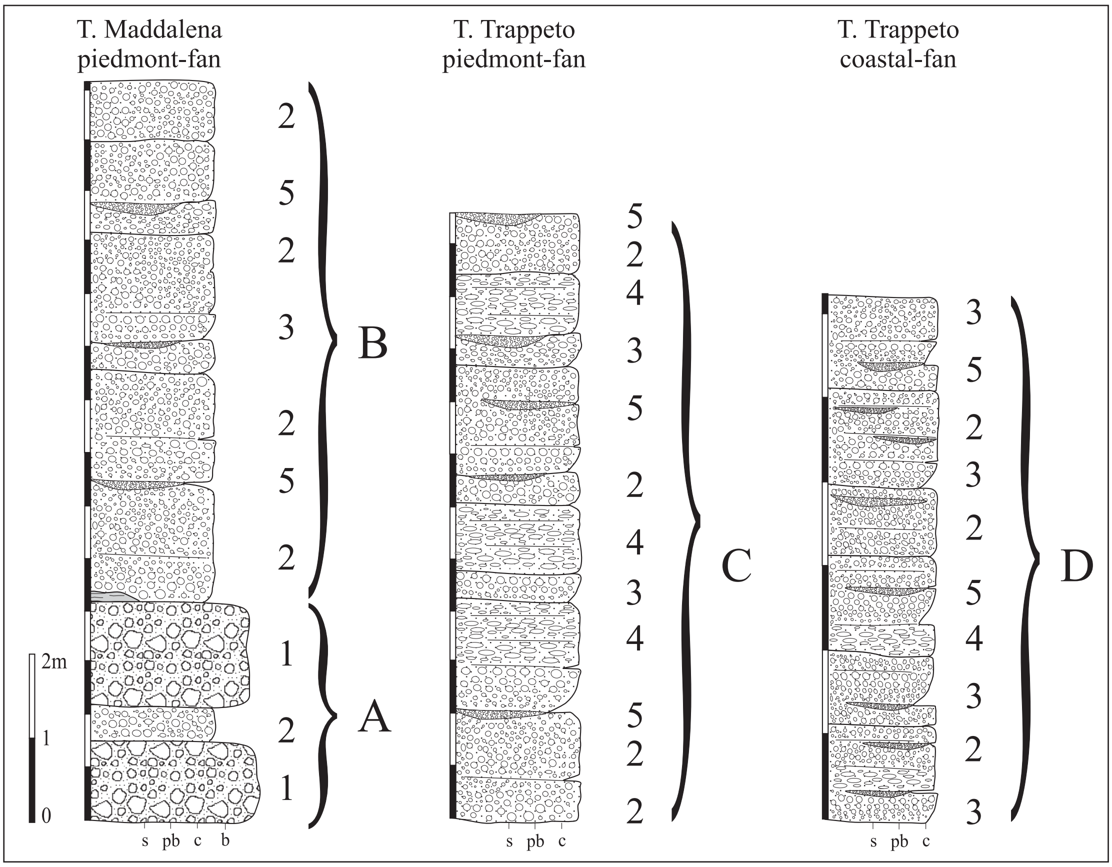

Fig. 5 - Logs of the alluvial fan conglomerates. Numbers refer to lithofacies. Letters refer to facies associations (see the text for details).

Sezioni stratigrafiche dei conglomerati alluvionali. Le lettere si riferiscono alle litofacies. Le sigle si riferiscono alle associazioni di facies (si veda il testo per i dettagli).

Lombard, 1989; Yarnold, 1993; Blair & McPherson, 1994).

This facies results from failure of a large fractured and weathered bedrock cliffs which, during downward fall was characterised by partial disintegration; in fact shattered boulders, but also very weathered angular clasts, may be observed.

A clayey reddish-brown paleosol layer, with wavy upper and lower boundaries, rests on this facies association (Robustelli *et al.*, 2002).

Facies 2: Debris-flow deposits

The massive, sheet-like, non erosive based, poorly sorted, clast-supported nature of this facies suggest that depositional events were of high-energy, *i.e.* unconfined debris-flow. According to Shultz (1984), this facies is interpreted as depositional evidence of pseudoplastic debris flow; in particular these units may represent the deposits of cohesionless debris-flow (Smith & Lowe, 1991; Sohn *et al.*, 1999) dominated by frictional grain interactions in which clast collision is hampered, resulting in the lack of inverse grading and clast imbrication. The local *a*(p)*a*(i) clast fabric indicates that brief or transient laminar shear affected debris flow (e.g. Nemec & Postma, 1993). Beds with coarse-tail basal inverse grading are indicative of non-shearing rigid plugs resting on the basal part of flows affected by intense laminar shear (Nemec & Postma, 1993; Johnson & Rodine, 1984; Sohn et al., 1999).

Facies 3: Clast-rich debris-flow deposits

Facies 3 is interpreted as the deposits of high-concentration flows. The low matrix content, the framework support, the *a*(p)*a*(i) clast imbrication and the upward coarsening trend are thought to be evidence of clast-rich debris flow (Shultz, 1984). Generally the above described features are consistent with deposition of unconfined, cohesionless debris flows (Nemec & SteelL, 1984; Shultz, 1984; Smith, 1986; Smith & Lowe, 1991), and the inverse grading being representative of granular flows in which a dispersive pressure dominates during motion (Lowe, 1982; Todd, 1989; Sohn *et al*, 1999). This facies may also be interpreted as representative of very high sediment-concentration dispersions, such as hyperconcentrated flood-flows, i.e. dilution of debris flows (Pierson, 1980; Pierson & Scott, 1985; Ridgway & DeCelles, 1993; Smith & Lowe, 1991 among others).

Facies 4: Sheetflood deposits

The dominance of horizontally stratified conglomerates, characterised by vertically alternating couplets of coarse and fine grained beds, indicates that high-energy tractional processes were involved. In particular, the tabular conglomerate sheets suggest that deposition was laterally extensive. As a whole this facies is interpreted as being formed by deposition of unconfined sheetflood pulses well testified by the alternating couplets of different clast-size (*e.g.* Blair & McPherson, 1994). High-density flood-flow interpretations, in particular hyperconcentrated flood flows (sensu Smith, 1986; Smith & Lowe, 1991), may also be suggested by the clast fabric, including the outsized ones within the finer-grained beds.

Facies 5: Stream-flow deposits

Facies 5 is thought to be deposited by low-energy stream flow. Evidence for stream-flow processes include framework-support, *a*(t)*b*(i) imbrication, sorting and the lenticular geometries of individual units. This facies is associated with beds of facies 2 and 3, on which it commonly rests, and are representative of deposition in small channels that developed over fan-slope after debris-flow deposition; in particular these lenticular gravel beds are thought to be produced by fine-fraction winnowing on the debris-flow by overland water flows (Blair & McPherson1994).

Facies associations

Lateral and vertical facies association, coarse-grained texture, disorganized fabric, together with geomorphic analysis suggest that the depositional events were of very high-energy and consistent with an alluvial-fan depositional system. Four facies associations have been distinguished and discussed below.

Facies association A is restricted to the base of the upper portion of T. Maddalena piedmont fan and T. Laponte fan; the few and scattered road-cut sections and observations of the cliffs from a distance indicate that this facies association consists of vertically alternating debris flow and, subordinately, debris avalanche deposits. Very uncommon beds of facies 5 may occur.

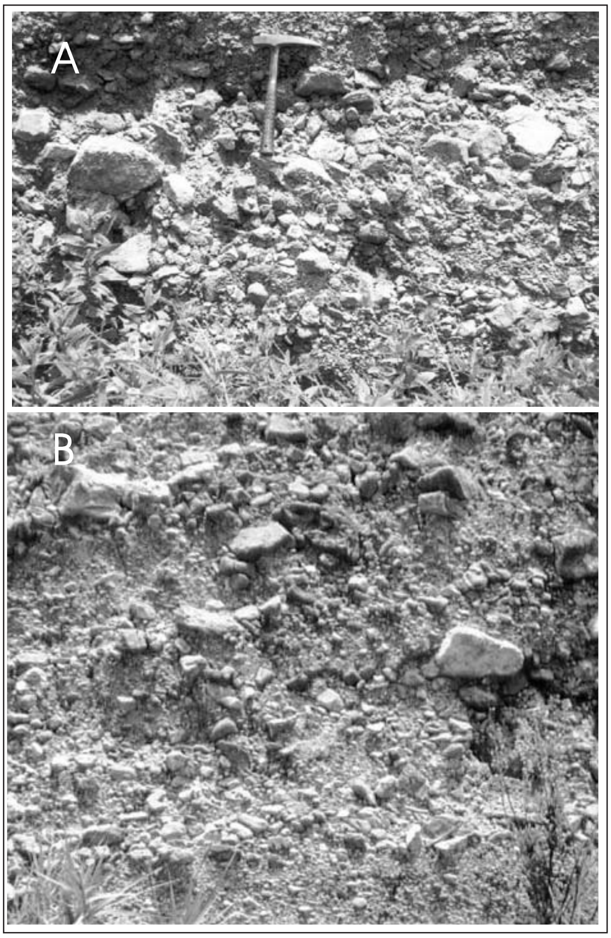

Fig. 6 Alluvial fan facies. A - Inverse grading sheet conglomerates interpreted as pseudoplastic debris flow (see the text for details); B - Alternating couplets of sheetflood facies; a(p) fabric mode is well noticeable.

Particolari delle facies che caratterizzano i conoidi alluvionali. A - Conglomerati a gradazione inversa interpretati come la deposizione ad opera di debris flow pseudoplastici; B - Alternanza di coppie di livelli conglomeratici a differente granulometria interpretati come depositi di lame di piena (sheetflood); risulta ben evidente la disposizione dell'asse maggiore dei clasti, parallela alla superficie di stratificazione (a(p)).

Facies association B characterised the upper portion of T. Maddalena piedmont fan. The most common facies is the massive, poorly sorted, clast-supported sheet conglomerates (Facies 2). Subordinate facies are represented by inversely graded conglomerates (Facies 3) and clast-supported, lenticular units (Facies 5) of granule-pebble grade.

Facies association C constitutes the bulk of the upper portion of T. Trappeto piedmont fan. It consists of alternating debris flow (Facies 2, 3) and sheetflood (4) facies; lenticular units (Facies 5) produced by fine-fraction winnowing on the debris-flow are also common.

Facies association D is restricted to the upper portion of T. Trappeto coastal fan and consists of debris flow deposit (Facies 2) usually capped by conglomerate lenses of facies 5. Sheetflood facies are uncommon. This facies association, though analogous to facies association C, is characterised by a decrease in clast-size. For instance debris-flow deposits of pebble to cobble grade and pebble to fine cobble grade characterised T. Trappeto piedmont and coastal fan, respectively (Robustelli *et al*., 2002).

6. DISCUSSION AND CONCLUSION

On the basis of all data collected by means of an integrated geomorphological, structural and sedimentological approach, interesting issues can be addressed to discuss the Late Quaternary fan evolution along the northwestern sector of the Coastal Range.

A strong structural control of drainage pattern is highlighted. To the North of the study area stream directions follow strikes and fold axes trends of the Miocene sedimentary cover. Moving southward the drainage network, although following faults pattern, is superimposed over the fold limb of the Miocene succession.

As resulting from structural and morphotectonic studies addressed to paleostress reconstruction in an area close to the South (Muto & Perri, 2002; Tortorici *et al*., 2002), the last tectonic phase was probably characterised by a NW-SE trending extension direction and was responsible for the creation and re-activation of NE-trending faults; furthermore, it caused the reactivation of the NNW-trending ones with right lateral transtensive kinematics. This tectonic phase can be ascribed to Middle-Late? Pleistocene on the basis of cross-cut relationships between marine terraced deposits and fault systems (Tortorici *et al*., 2002); it could have been the cause of landscape fragmentation, by interrupting the continuity of a possible pre-existing coastal plain and producing valley-side perched alluvial terraces, as also testified by the lack of landforms related to the perched terraces (Figs. 3 and 7A). The following development of the 1st generation of alluvial fans tapered upslope the triangular facets and sealed the fault scarps (Fig. 7B) created by the previous block-faulting. Since that time fan development was mainly related to eustacy, as suggested by Robustelli *et al*. (2002) and briefly reported in Section 1.

The bathymetric maps of the continental shelf (present seafloor isobaths; Argnani & Trincardi, 1988; Chiocci *et al.*, 1989), as well as the maps reporting the reconstruction of the last glacial erosional surface and the total thickness of Holocene deposits provided by Chiocci *et al.* (1989) and Chiocci & Orlando (1995), show patterns of seafloor dip and slope scarps orientation, which widely match with the strikes of the main fault system observed onshore, *i.e.* NE-, NNW-, NW- and E-trending faults - as the well-known Falconara fault (Turco *et al.*, 1990) - it may suggest that the above mentioned tectonic phase has lasted at least till late Upper Pleistocene.

Moreover, offshore from Capo Bonifati (just a few kilometres northwest of the study area) and from Guardia Piemontese, sharp breaks in slope approximately at depths of 75-90 m b.s.l. can be clearly recognised. These scarps border offshore two flat surfaces, which Chiocci *et al.* (1989) simply interpret as erosional terraces related to sea-level stillstands. The complete lack of Late Pleistocene marine terraces in the study

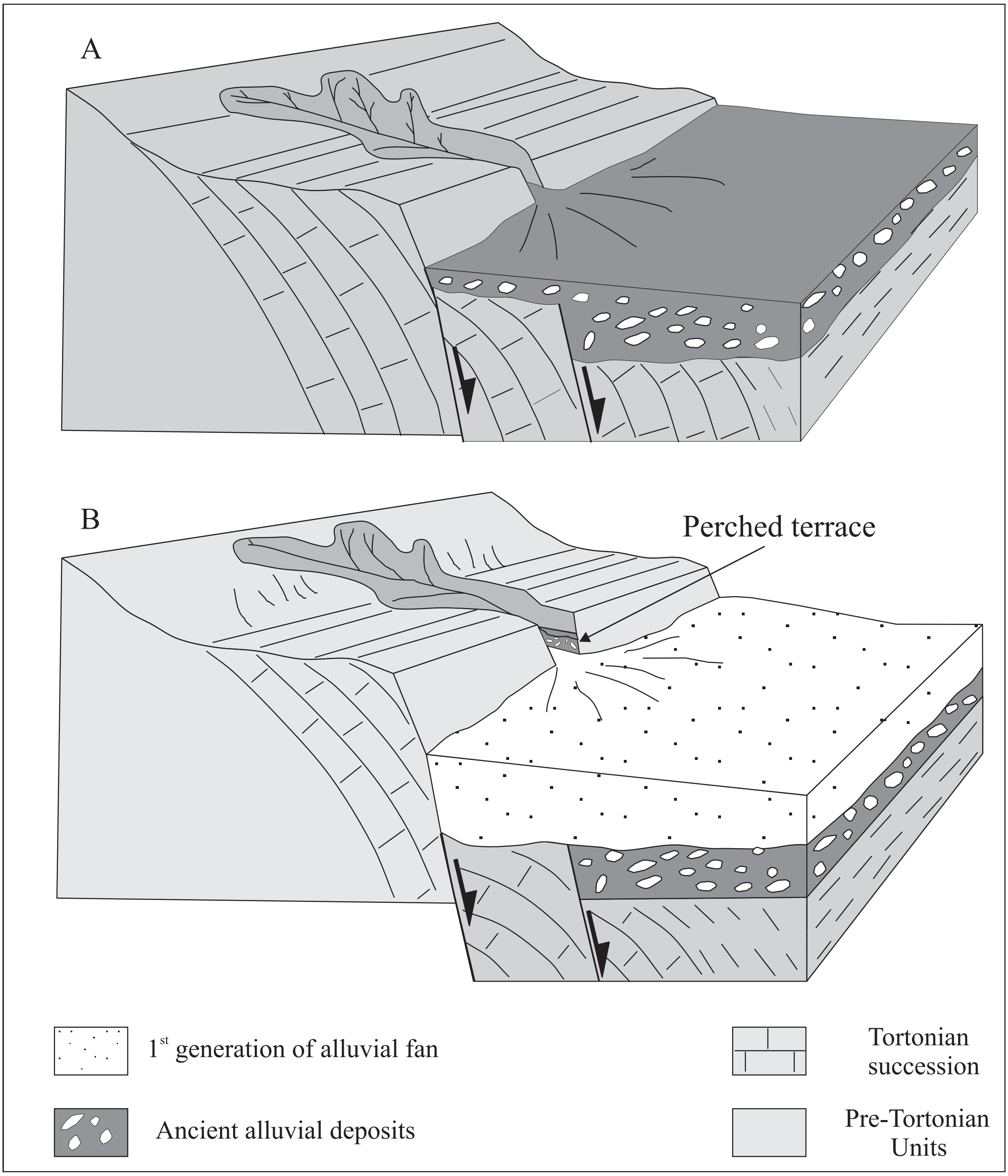

Fig. 7 - Main stages of Late Quaternary morphotectonic evolution of the study area (see the text for details).

Principali fasi dell'evoluzione morfotettonica tardo-quaternaria dell'area in esame (si veda il testo per i dettagli).

area, which, on the contrary, developed during Pleistocene times and were tectonically uplifted to different heights both in the northern and the southern sector of the Tyrrhenian coast of Calabria (Carobene & Dai Pra, 1990; Carobene & Ferrini, 1993; Tortorici *et al.*, 2002) could be explained in two different ways: (i) the rates of sea-level rise and tectonic uplifts were substantially equal in the study area, so that the terraces never formed (Cinque *et al.*, 1993); (ii) the terraces really did form indeed and were subsequently submerged for subsidence phenomena involving this onshore sector of the Paola Basin.

In the latter case, it could be hypothesised that the flat surfaces, occurred on continental shelf and identified from seismic data, would tentatively be related to the above mentioned wave-cut marine platforms (buried by Holocene deposits), and be the submerged counterpart of the adjacent, raised Late Pleistocene terraces. What is more, the presence of huge bioherm structures, up to several tens of metres high, just close to the slope break of these flat morphologies (Chiocci *et al.*, 1989) supports this idea: in addition, encrusting marine organisms of this kind usually develop in limpid and relatively shallow water (photic zone) and their relics often outcrop at the top of marine terraces of different ages all along the south Tyrrhenian Sea coast (e.g. Brancaccio *et al.*, 1990; Carobene & Dai Pra, 1990; Iannace *et al.*, 2001; Riccio *et al.*, 2001; Scarciglia *et al.*, 2003). Their extreme vertical extension could be related to their rapid growth upwards concurrently with the progressive land subsidence and relative sea-level rise, just to maintain their suitable life environment. Furthermore, the landward migration of Holocene depositional depocenters (Chiocci *et al.*, 1989; Chiocci, 1994) and their location at the mouth of the major streams dissecting the Coastal Range and debouching along the west coast (Argnani & Trincardi, 1988; 1993), which clearly indicate a strong control by sediment input from continental feeding sources, could have also been favoured by subsidence.

Some parameters used in the morphometric analysis of alluvial fans (*e.g.* Viseras *et al.*, 2003) may support this hypothesis; in fact weak tectonic subsidence, coupled with marine base level rise, may constitute the main mechanisms promoting the creation of the accommodation space for fan aggradation. In fact, it is worth noting that to the North of the study area uplift rates are very low (0.05 mm/yr, Carobene *et al.*, 1986; Bordoni & Valensise, 1998). In addition, Robustelli *et al.* (2002) already highlighted that important fan development occurred in the study area during transitions toward interglacial periods, characterised by climatic amelioration and significant sea-level rise.

Both the peculiar "mushroom" shape and the high sweep angle values measured for late Pleistocene-Holocene fans (Fig. 3), can be interpreted as due to low subsidence and sea-level rise, combined with high sediment input, which produce a retrograding stacking pattern, with a mountain embayment associated with an expansion of the fan (Viseras *et al.*, 2003).

Furthermore, the lack of fault evidence within the alluvial fan successions could be related just to the low rates of subsidence.

As far as facies analysis are concerned, factors that control alluvial fan facies assemblages have been identified.

Moving northward, T. Maddalena and T. Trappeto alluvial fan deposits consist of slightly different facies associations (Fig. 5). T. Maddalena piedmont fan was built solely by sediment gravity flows (debris avalanche and debris flow processes), whereas T. Trappeto piedmont fan deposits consist of alternating sediment gravity flows (debris flow processes) and fluid gravity flows (sheetflooding). In both cases, secondary processes, *i.e.* overland flows, caused locally winnowing of the top surfaces. Some features, such as climate, vegetation types, tectonic setting etc. are thought to have been approximately the same during fan construction. Even though the T. Maddalena catchment area is larger than the T. Trappeto one (12.02 km^2 vs. 6.26 km^2), this feature, as other fan and catchment morphometric data, are not prerequisites to promote different facies assemblages (*e.g.* Blair, 1999). According to Blair (1999) and Blair & McPherson (1994), lithology of the bedrock underlying fan catchments is thought to control the slight differences in depositional processes and relative facies associations, i.e. weathering caused differences in sediment particle-size, influencing permeability, which may promote sediment gravity flows vs. fluid gravity flows. Although the bulk of the bedrock underlying fan catchments at issue comprises quite similar lithologies, major exposures of schists and phyllites of the ophiolitic units in the T. Maddalena fan catchment (28% vs. 15%) may be considered as the main key factor in the differences among facies assemblages.

Furthermore, the finer-grained facies, characterising coastal fans in respect to piedmont ones (Robustelli *et al.*, 2002), may be interpreted as the sedimentary response to different alluvial fan evolutionary stages, reflecting the progressive increase of drainage basins size, coupled with the decrease of drainage basins slope (*e.g.* Blair & McPherson, 1994).

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