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The Crati River Basin: geomorphological and stratigraphical data for the Plio–Quaternary evolution of northern Calabria, South Apennines, Italy

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Abstract: In this paper, we present the results of an integrated geomorphological and stratigraphical study carried out in the eastern side of the Crati River valley (northern Calabria, South Italy). This area is characterized by the occurrence of three order palaeosurfaces that, along with low-sloping palaeovalleys and structural landforms, are striking features of the landscape. The relationships between morpho-tectonic and sedimentary evolution of the Crati Basin has been assessed through sandstone detrital modes, morphostratigraphy and geomorphological correlation with adjacent areas. The two main unconformity surfaces that typify the Quaternary fill were correlated to different steps of landscape evolution. The presence of both erosional and depositional palaeosurfaces has been a useful marker for reconstructing sedimentary and morphogenetic events, and hence to detect drainage network evolution and changes in source sediment area. In particular, we recognized that the study area experienced, during the late Pliocene–Early Pleistocene a period of subaerial landscape modelling as suggested by low-sloping palaeovalleys and related fluvial deposits (1st Order Palaeosurface). At that time, the source of the detrital constituents of the PPS Unit sandstones was mainly from the Sila Massif. The onset of Coastal Range identification and uplift (Early Pleistocene) marks a change in the geomorphic scenario with tectonic driven stream incision and valley development along the eastern side of Coastal Range, along with the occurrence of depositional and erosional landsurfaces (2nd Order Palaeosurface) at footslopes. During this period, the Coastal Range and Sila Massif were the sources for the detrital constituents of the PlS Unit sandstones. The progressive uplift of Coastal Range during late Early Pleistocene and the marked backstepping of the depositional systems along the Sila footslope was accompanied by alternating phases of down-cutting and base-level stability resulting in the development of a step-like distributed 3rd Order Palaeosurface. The presence of dolostone in detrital modes is clear evidence of stream piracy phenomena of ancient palaeovalleys by the Crati valley-facing drainage network.

Keywords: geomorphology, Plio–Quaternary, Calabria, southern Apennines, Italy.

Introduction

Calabria hosts a series of marine Plio–Quaternary basins, which developed during the late stage of continental collision (Patacca & Scandone 2001). Their evolution has been controlled by a series of roughly NW- and WNW- trending strike-slip fault zones formed during the Neogene. They controlled the migration of the Calabrian Arc and experienced episodes of extension (Van Dijk et al. 2000), responsible for the dissection of the Calabrian Arc (Lanzafame & Zuffa 1976; Lanzafame & Tortorici 1981; Tortorici 1981; Knott & Turco 1988; Turco et al. 1990; Tortorici et al. 1995; Schiattarella 1998; Cifelli et al. 2006; Tansi et al. 2007). This resulted in an alternation of morphostructural ridges and Plio–Quaternary tectonic depressions bounded by high-angle fault scarps (Fabbri et al. 1981; Barone et al. 1982; Argani & Trincardi 1993; De Rosa et al. 2002; Milia et al. 2008; Filocamo et al. 2009; Robustelli et al. 2005, 2009; Pepe et al. 2010; Spina et al. 2011; Tripodi et al. 2013; Longhitano et al. 2014; Robustelli et al. 2014; Zecchin et al. 2015). In particular, the Crati Basin (Fig. 1) developed in the subsiding hangingwall of the Crati fault system (*sensu* Spina et al. 2011), one of the active and segmented normal fault systems of Calabria (Tortorici et al. 1995; Galli & Bosi 2003; Tansi et al. 2005; Spina et al. 2009).

The Crati Basin is bounded by N-trending fault systems, and the relative tectonic landforms are morphologically well apparent. Its boundary faults related to regional strike-slip tectonics, but the structural evolution of the depression has long been debated (Turco et al. 1990; Tortorici et al. 1995; Tansi et al. 2007; Spina et al. 2011).

Anyway, the aforementioned studies focused their efforts on clarifying the stratigraphical, structural and seismotectonic framework of the Crati Basin, unfortunately their relationships to geomorphological settings were not considered. We lack studies of the geomorphological evolution of the Crati Basin through the analysis of the landscape characterized by hanging remnants of gentle erosional landsurfaces. Furthermore, very little is known about correlations between the landscape and marine morphostratigraphic records (Muto 2006), which could be very helpful for the reconstruction and interpretation of morphoevolutionary history.

These issues are addressed in our study of the left side of the Crati River valley, where much evidence of ancient landscapes can be found.

This paper aims to contribute to these issues, focusing on (i) description and correlation of gently erosional/deposition landsurfaces; (ii) characterization of the different stages of landscape evolution and their relationships to sedimentation. Furthermore, this paper also represents the first attempt to evaluate the relationships between landscape evolution and sandstone detrital modes, through the correlation of landscape and the composition and provenance of the sandstone strata of the Plio–Pleistocene sedimentary record.

Geological setting

The Crati Basin is an intra-arc tectonic depression located in the north-western part of the Calabrian Arc (Fig. 1), which is an arc-shaped continental fragment interposed between Sicilian Maghrebide belts, to the south, and the Apennine edifice, to the north (Amodio Morelli et al. 1976; Bonardi et al. 2001, and references therein). It is mostly made up of a series of thrust crystalline and metamorphic nappes overthrusted,

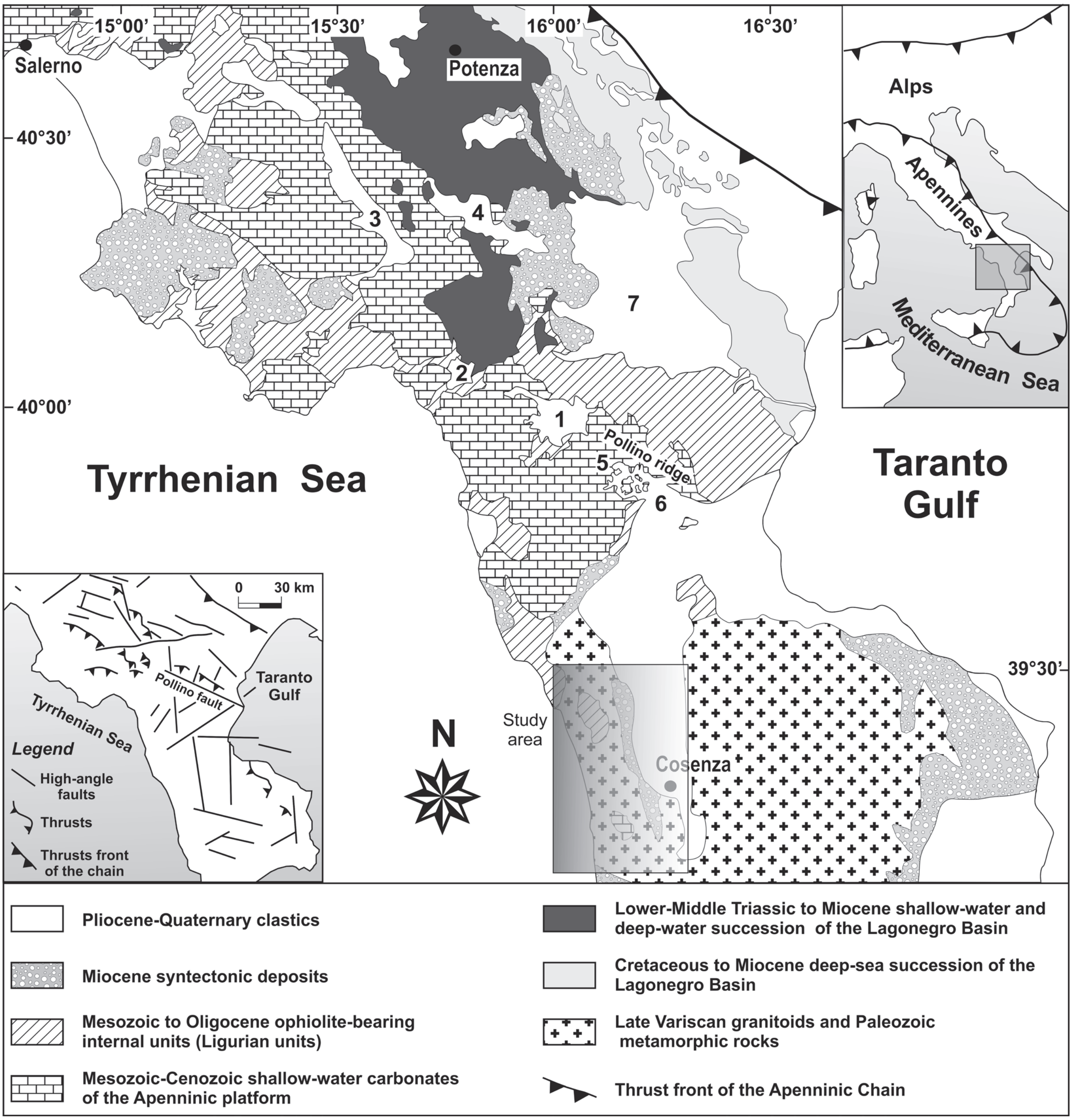

Fig. 1. Geological sketch map of southern Italy and its location in the central Mediterranean framework (top inset). The tectonic sketch map reporting the main tectonic features is shown in the inset on the bottom left. The study area (Crati Basin) is indicated by the inset on the bottom centre (modified after Robustelli et al. 2014).

starting in the Early Miocene, onto the carbonate platform rocks of the Apulian continental margin (Van Dijk et al. 2000; Bonardi et al. 2001; Butler et al. 2004; Iannace et al. 2007).

Neogene thrusting and the progressive southeastward migration of Calabrian Arc are closely related to the opening of the Tyrrhenian back-arc Basin (Kastens et al. 1988; Patacca & Scandone 1989), and was associated with NW- and WNW trending strike-slip fault zones. These controlled the migration of the Calabrian Arc along its borders, and were responsible for extrusion of the deep-seated units of the Calabrian Arc and of the underlying Mesozoic carbonate units (Tansi et al. 2007).

Strike slip faults were also important features as they were characterized by episodes of transtension (Van Dijk et al. 2000), responsible for the Crati Basin development (Knott & Turco 1988; Turco et al. 1990; Tortorici et al. 1995; Tansi et al. 2007).

Since the Middle Pleistocene, the Calabrian Arc has experienced a strong regional uplift, still active, resulting from the detachment of the Ionian subducted slab (Westaway 1993; Wortel & Spackman 1993; Tortorici et al. 1995; Van Dijk et al. 2000). This regional tectonic event led to the formation of a series of grabens along the entire western sector of the Calabrian Arc (the so-called Siculo-Calabrian Rift Zone, *sensu* Monaco & Tortorici 2000)

The Crati Basin, forming part of this zone, is bounded by the Coastal Range to the west, by the Sila Massif to the east, by the Pollino Ridge to the north and by a NW-trending ridge to the south (Fig. 1). The basin is L-shaped and can be divided into two sub-basins: the N–S oriented Crati and the E–W oriented Sibari sub-basins (Colella et al. 1987).

The N–S elongated Crati sub-basin (hereinafter called Crati Basin), which includes the study area (Figs. 1, 2), is morphologically asymmetric with a steeper and shorter fluvial drainage along its eastern side. Its shape is strongly controlled by an array of normal faults ("Crati Fault System" in Spina et al. 2009). The sedimentary infill derives from footwall uplifted areas exposed to extensive erosion (Molin et al. 2004; Olivetti et al. 2012), and overlies the Palaeozoic crystalline-metamorphic bedrock of the Calabrian Block and its Miocene sedimentary cover (Fig. 2).

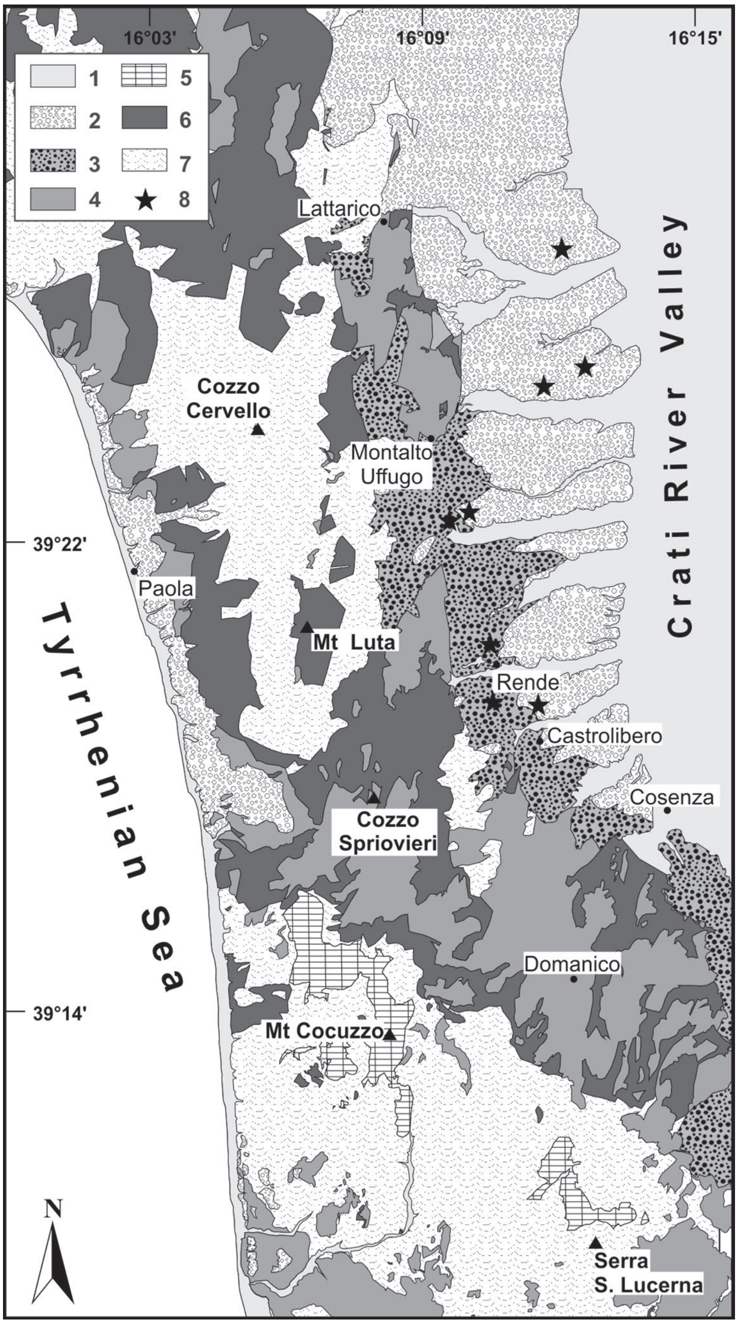

Fig. 2. Lithological map of the left side of the Crati Basin: (1) Fluvial deposits (Middle Pleistocene–Holocene); (2) Clay, sandstone and conglomerate (PlS Unit in Fig. 3A) (Early–Middle? Pleistocene); (3) Complex clastic wedge (PPS Unit in Fig. 3A) (Pliocene–Early Pleistocene). (4) Clay, sandstone and conglomerate (Miocene); (5) Dolostone and limestone(Mesozoic); (6) Calabride Complex (Paleozoic); (7) Liguride Complex (Mesozoic); (8) Sampled section for petrographic analyses.

Stratigraphy of the Crati Basin

The Crati Basin is filled by Plio–Pleistocene deposits that can be divided into two (Lanzafame & Tortorici 1981; Fabbricatore et al. 2014) or three main depositional sequences (Spina et al. 2011; Zecchin et al. 2015) bounded by a regional angular unconformity.

Regardless of the number of sequences, the key question manly concerns the age of the base of the Crati Basin infilling and, hence, the presence/absence of the "mid-Pliocene unconformity" of Zecchin et al. (2015). In this regard, geological data (Lanzafame & Tortorici 1981; Barone et al. 2008; Robustelli et al. 2009) and palaeontological analysis (Lanzafame & Tortorici 1981; Corbi et al. 2009; Fabbricatore 2011; Spina et al. 2011) provided conflicting age constraints on this issue. Anyway, subsurface data available for the Crati Basin, also reported in Spina et al. (2011), along with high resolution seismic reflection profiles (Milia et al. 2009) suggest that the Sibari Plain *(i.e.* the northernmost part of the L-shaped Crati Trough) appears to be developed and widened during the Upper-Pliocene–Lower Pleistocene time span.

Based on the foregoing survey, along with geological and lithostratigraphic survey, the Crati Basin infill was sub-divided into two major sedimentary units bounded by an angular unconformity, corresponding locally to an erosional surface (Fig. 3A). Moreover, the base of the lower unit is likely to correlate with the "mid-Pliocene unconformity" of Zecchin et al. (2015).

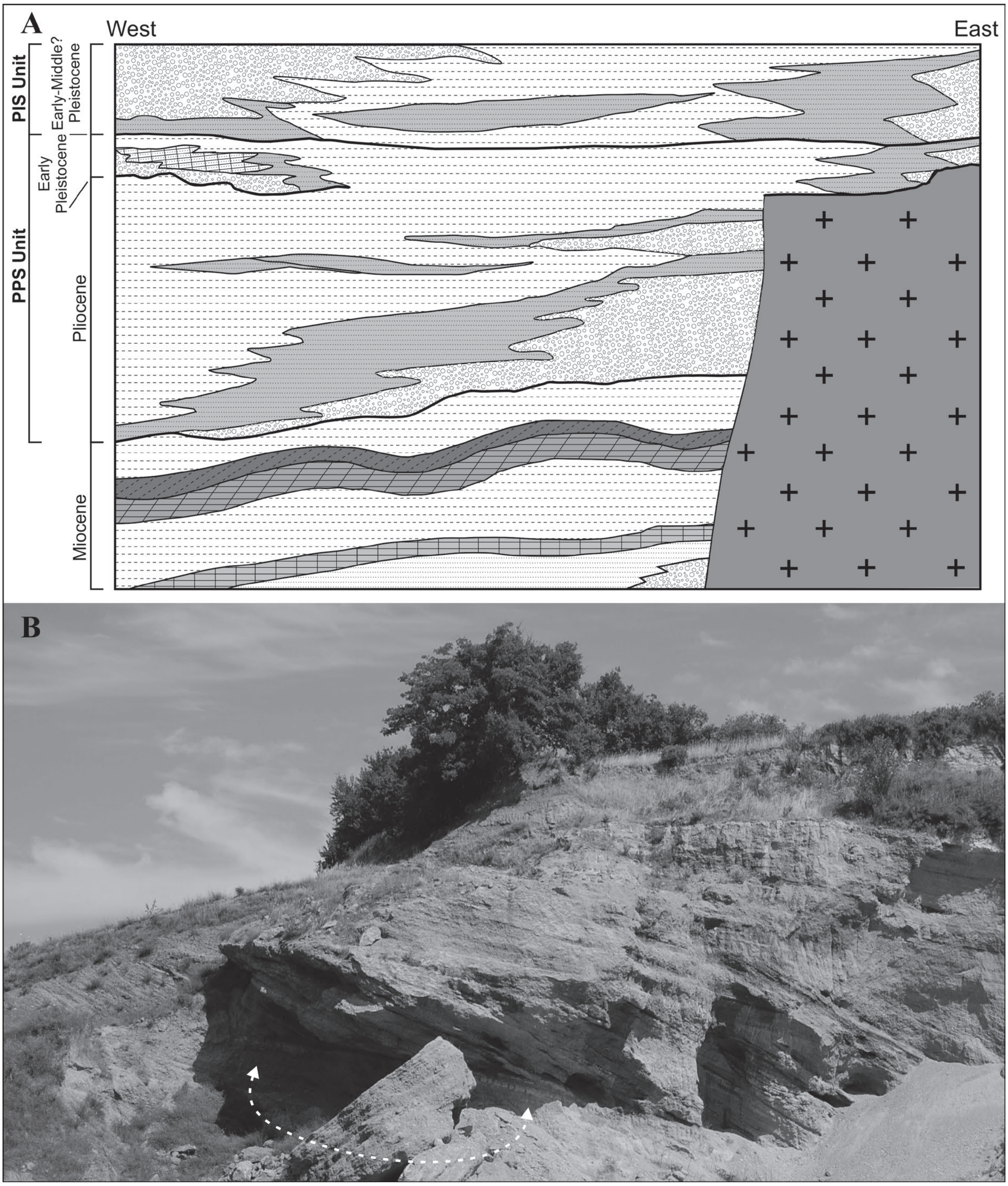

Fig. 3. **A** — Stratigraphic scheme of the Plio–Pleistocene deposits cropping out in the southern part of the Crati River valley. **B** — PlS Unit; detail view of Gilbert-type deltas showing aggradation/progradation style. The clinoform wedge is composed of a stack of two unconformity-bounded shingles.

Pliocene–Early Pleistocene sedimentary unit (PPS)

This unit rests erosively and unconformably on Miocene deposits as well as pre-Neogene crystalline and metamorphic bedrock. Its thickness increases towards the Sibari Plain, as shown also by deep wells for hydrocarbon exploration.

Based on lateral and vertical sedimentary wedge arrangement, this unit forms a complex assemblage of clastic wedges up to 250 m-thick in the North of the study area. Its basal part consists of superimposed and juxtaposed deltaic depositional systems grading laterally and vertically into marine sandstone and silty clay. This portion of the succession pinches out to the South, where this unit is only characterized by its uppermost part consisting in clayey sediments passing upward to mixed silici/bioarenites strata and, again, to clay (Fig. 3A). Based on the occurrence of *Hyalinea balthica*, the uppermost part of the succession is considered not older than Calabrian (older Emilian).

Early–Middle? Pleistocene sedimentary unit (PlS)

The second unit rests erosively and/or unconformably on the PPS unit, and locally directly onto the bedrock and the Miocene sediments along the southern portion of the basin. It consists of continental to marine stacking depositional systems deposited in response to tectonic-induced basin subsidence; it started in the west and proceeded eastwards, causing a diachronous transgression (Lanzafame & Zuffa 1976; Lanzafame & Tortorici 1981; Tortorici 1981; Spina et al. 2009; Fabbricatore et al. 2014). According to data provided by Lanzafame & Tortorici (1981) and by Young & Colella (1988), this unit can be considered younger than 1.2 M.y. (late Early Pleistocene).

In particular, moving to the East the related deposits consist of massive to crudely stratified, locally amalgamated, pebble-to-cobble alluvial-fan conglomerates grading basinward into fine to coarse-grained deltaic and beach deposits. The succession is more than 100 m thick and consists mainly of shoreface and offshore sands and clays, and shoal-water deltaic clinostratified gravels. To the South, they form alternating clastic wedges, locally telescopically arranged. To the North, the deltas are organized into vertically-stacked sequences that display internal depositional architectures consisting of alternating progradational and aggradational geometries, developing a basinward offset delta sequences of Gilbert-type deltas (Fig. 3B) very rich in dolomitic gravel. This arrangement can be interpreted as a result of tectonic control of the basin margin (*e.g.* Longhitano 2008).

Morphotectonic data

The oldest geomorphological elements in the area are hanging relics of a low-relief landscape (hereinafter named the 1st Order Palaeosurface) occurring on the uplifted mountain ridge (Figs. 4, 5A) ranging in elevation between 1000m and 1200 m a.s.l., and cutting crystalline and Miocene sedimentary bedrock.

Its formation can be related to relief smoothing processes — fluvio-denudational — acting during periods of relative stability of erosional base-levels. In particular, this landscape includes highly eroded fault scarps, with cross profiles locally declined at 20°, and low-sloping palaeovalleys, hanging and beheaded valleys, none of them linked to the present-day drainage network. Scattered patches of fluvial conglomerates characterize this gently rolling landscape, but no chronological constraint is available. Therefore, the development of the 1st Order Palaeosurface can be ascribed to the Pliocene on the basis of cross-cutting relationships with bedrock, and geological and geomorphological data provided (Tortorici et al. 1995; Robustelli et al. 2005; Milia et al. 2009, Olivetti et al. 2012)

Moving downslope towards the Crati Trough, the apparent N-trending fault scarps correlated with a new generation of low relief landscape (2nd Order Palaeosurface). Remnants of the 2nd Order Palaeosurface, occurring between 400 and 600 m a.s.l. (Fig. 4), are widespread throughout the study area; at the footslope of Mt. Luta and Cozzo Sprovieri (Figs. 4, 5A), they are locally associated with slope and alluvial sediments (Fig. 5B). Elsewhere, they form gentle footslopes carved into hard rock, showing similar degree of maturity and concave slope breaks at comparable elevation. Because this landscape seals PPS unit, its development occurred during the late Early Pleistocene.

Downslope of the previous landscape (Figs. 4, 5C), it is important to note much steeper elements of hanging relics of the 2nd Order Palaeosurface, outlining the latest phases of basin infilling. These fault scarps are related to a block faulting episode that caused the uplifting of the 2nd Order Palaeosurface and the development of the recent Crati Basin; its depositional top surface, representing the 3rd Order Palaeosurface, occur as stepped sequences in which vertical spacing varies from metres to tens of metres. The surfaces show an uneven spatial and altimetric distribution across stepped, inclined planes that are separated by scarps not related to tectonic structures, as they largely match with top depositional surfaces of basinward offset Gilbert-type deltas.

According to stratigraphic data, these step-like distributed surfaces indicate that the final stages of basin infilling were accompanied by progressive and continuous dissection of ancient landscapes where alternating phases of down-cutting and of base-level stability occurred fairly quickly.

Petrographic signature of Plio–Pleistocene deposits

Eighty arenite samples representing the Crati Basin infilling were collected along the south-western part of the Crati Trough between Rende and Lattarico. They were analysed according to the Gazzi-Dickinson method (Gazzi 1966; Dickinson 1970; Ingersoll et al. 1984; Zuffa 1985; Critelli & Le Pera 1994).

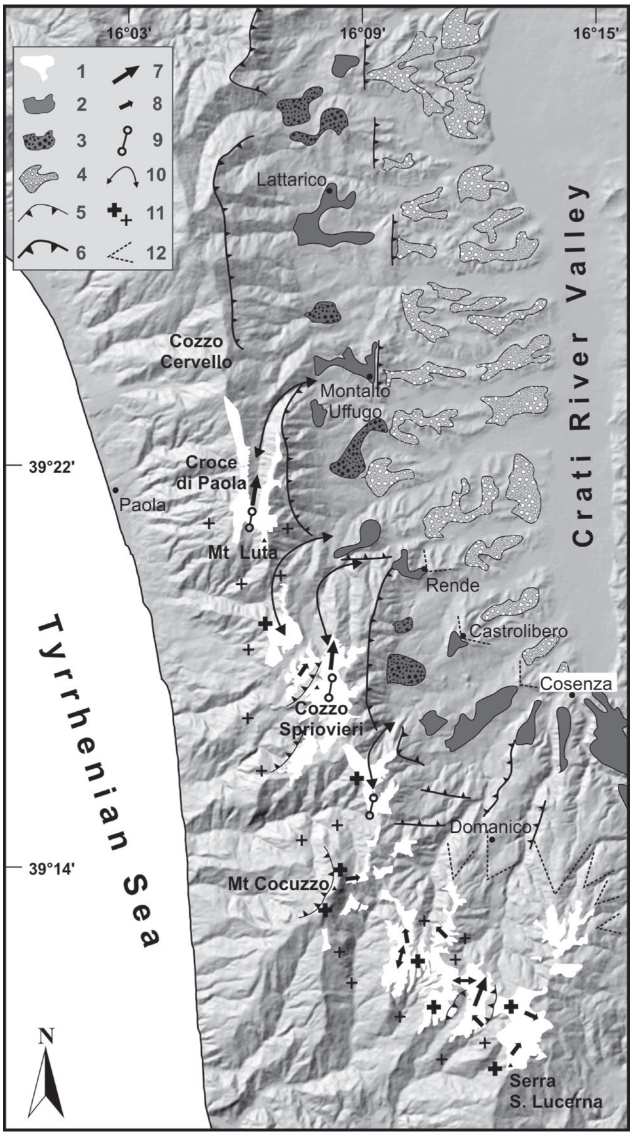

Fig. 4. Morphostructural sketch map of the left side of Crati Basin showing the main recognized landforms and the distribution of the three orders of Palaeosurfaces: (1) 1st Order Palaeosurface; (2) 2nd Order Palaeosurface (erosional); (3) 2nd Order Palaeosurface (depositional); (4) 3rd Order Palaeosurface; (4) Eroded fault scarp; (5) Fault scarp; (6) Direction of the main low-gradient paleovalleys; (7) Direction of the secondary low-gradient paleovalleys; (9) Wind gap; (10) River capture; (11) Main tops (thick cross) rising above the 1st Order Paleosurface, along with hypothesized ones (thin cross) should form part of the ancient watershed of N- NE-directed paleodrainage; (12) Homoclinal ridge.

Petrographic analyses of the Plio–Pleistocene sandstones of the Crati Basin determines petrofacies characterizing each lithostratigraphic unit (Fig. 6A), hence petrofacies get the same names as sedimentary units.

The PPS unit sandstones show different composition moving upward in the succession, and to the South.

In the area of Montalto Uffugo, the lower porzion is quartzofeldspathic ($NCE_{99}CE_{1}CI_{0}$–$Qt_{40}F_{45}L+CE_{15}$) (Fig. 6). Low-grade to medium-grade metamorphic lithic grains (Lm) are the dominant lithic population and include phyllites and fine-grained schist fragments (mean value of lithics $Lm_{95}\,Lv_{0}\,Ls_{5}$). Minor carbonate sedimentary lithic fragments consist of micritic and sparitic limestones while siliciclastic sedimentary lithic fragments do not occur.

The upper portion ($NCE_{65}CE_{18}CI_{17}$–$Qt_{30}F_{39}L+CE_{31}$) tends toward a feldspatholithic composition (Fig. 6) rich in sedimentary lithic grains ($Lm_{14}\,Lv_{0}\,Ls_{86}$), mainly carbonate grains (micritic and sparitic limestones). The intrabasinal carbonate (CI) component, made up of bioclasts, increases upward.

To the south, in the area of Rende, the detrital-mode of the PPS Unit sandstones shows a similar trend (from quartzofeldspathic — $NCE_{87}CE_{10}CI_{13}$–$Qt_{48}F_{28}L+CE_{24}$ — to feldspatholithic — $NCE_{41}CE_{15}CI_{44}$–$Qt_{26}F_{31}L+CE_{43}$ — composition), even though compositional data reveals a higher increase in sedimentary detritus. Carbonate sedimentary lithic fragments consist of micritic and sparitic limestones, whereas the intrabasinal carbonate component increases upward, where bioclasts are very abundant.

The lower part of the PlS Unit sandstones (Fig. 6) are quartzofeldspathic ($NCE_{89}CE_{10}CI_{1}$–$Qt_{40}F_{42}L+CE_{18}$), with a composition comparable to the lower portion of the PPS Unit, but richer in sedimentary lithic grains. The upper portion of the PlS sandstones tends to have a more feldspatholithic ($NCE_{79}CE_{21}CI_{0}$–$Qt_{28}F_{39}L+CE_{33}$) composition. These sediments contain carbonate sedimentary lithic grains (mean value of lithics $Lm_{36}Lv_{0}Ls_{64}$), but it is worth noting the progressive increase, and then the decrease of dolostone moving to the younger portion (uppermost in Fig. 6), also characterized by a trend again toward a quartzofeldspathic composition.

The Early Pleistocene sandstones cropping out along the right side of the Crati (Fig. 4) River valley are quartzofeldspathic ($NCE_{100}CE_{0}CI_{0}$–$Qt_{46}F_{32}L+CE_{22}$), with abundant feldspar grains. Low-grade to medium-grade metamorphic lithic grains (Lm) are the dominant lithic population and include phyllites and fine-grained schist fragments (mean value of lithics $Lm_{98}Lv_{0}Ls_{2}$).

Quaternary basin evolution

The Crati Basin is one of the main basins in the Calabrian Arc where landscapes and stratigraphic architecture are useful tools for the reconstruction of the main stages of landscape, tectonic and stratigraphic evolution during the Quaternary in the northern Calabria.

The integrated analyses performed here highlight that tectonics played a key role in the basin's genesis and evolution (Turco et al. 1991; Cifelli et al. 2007; Tansi et al. 2007). The reconstructed geomorphological and sedimentary history shows that the study area experienced a number of morphogenetic cycles since the Pliocene (Piacenzian?) and during the Early–Middle? Pleistocene.

The main evolutionary steps of the Crati Basin are summarized in the following morpho-evolutionary stages.

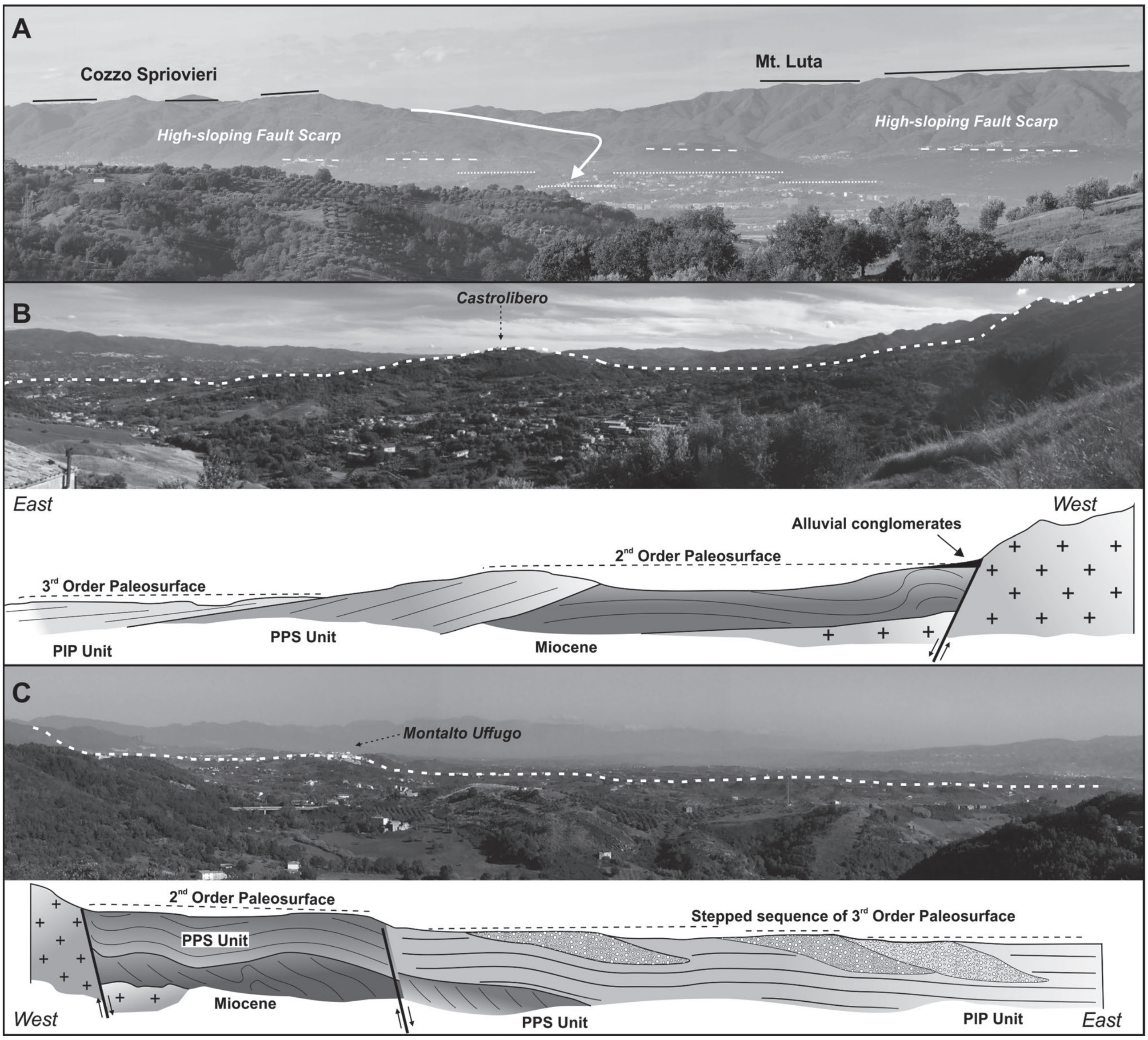

Fig. 5. Overview of landscapes noticeable in the study area and morphostratigraphic section of the Crati Basin showing the distribution of the three orders of Palaeosurfaces. **A** — View from the East of Cozzo Spriovieri-Mt. Luta ridge; white arrow indicates stream piracy evidence responsible for feeding dolomitic clasts into delta wedges during the Early–Middle? Pleistocene; 1st Order Palaeosurface=solid line; 2nd Order Palaeosurface=dashed line; 3rd Order Palaeosurface=dotted line. **B** — View from the North of Castrolibero rigde accompanied by a morphostratigraphic section; **C** — View from the South of Montalto Uffugo area characterized by a stepped sequence of 3rd Order Palaeosurface related to stratigraphic architecture (see text for detail).

Stage 1 (Pliocene)

The oldest stages of landscape evolution are represented by hanging remnants of the 1st Order Palaeosurface (Figs. 4, 5A), carved into crystalline and sedimentary bedrock of the Coastal Chain.

Although some surfaces presumably developed locally as a border polje through karst processes at the contact between limestones and crystalline rocks, this landscape is considered to result from fluvio-denudational relief smoothing processes acting during periods of relative stability of erosional base-levels, as much geomorphological evidence strongly indicates (e.g., concave-up, low gradient footslopes, low-sloping palaeovalleys, alluvial conglomerate).

The absence of clear step-like distributed surfaces indicates that the relief dismantling was quite continuous and characterized by a long-term phase of base-level stability or slow base level lowering. By considering geological and geomorphological data provided in northern Calabria (Robustelli et al. 2005; Barone et al. 2008; Robustelli et al. 2009; Spina et al. 2009; Pepe et al. 2010; Muto et al. 2015), the present upland developed mainly during the Lower Pliocene and partly correlates to the low-relief landscape characterizing the Sila Massif (Olivetti et al. 2012).

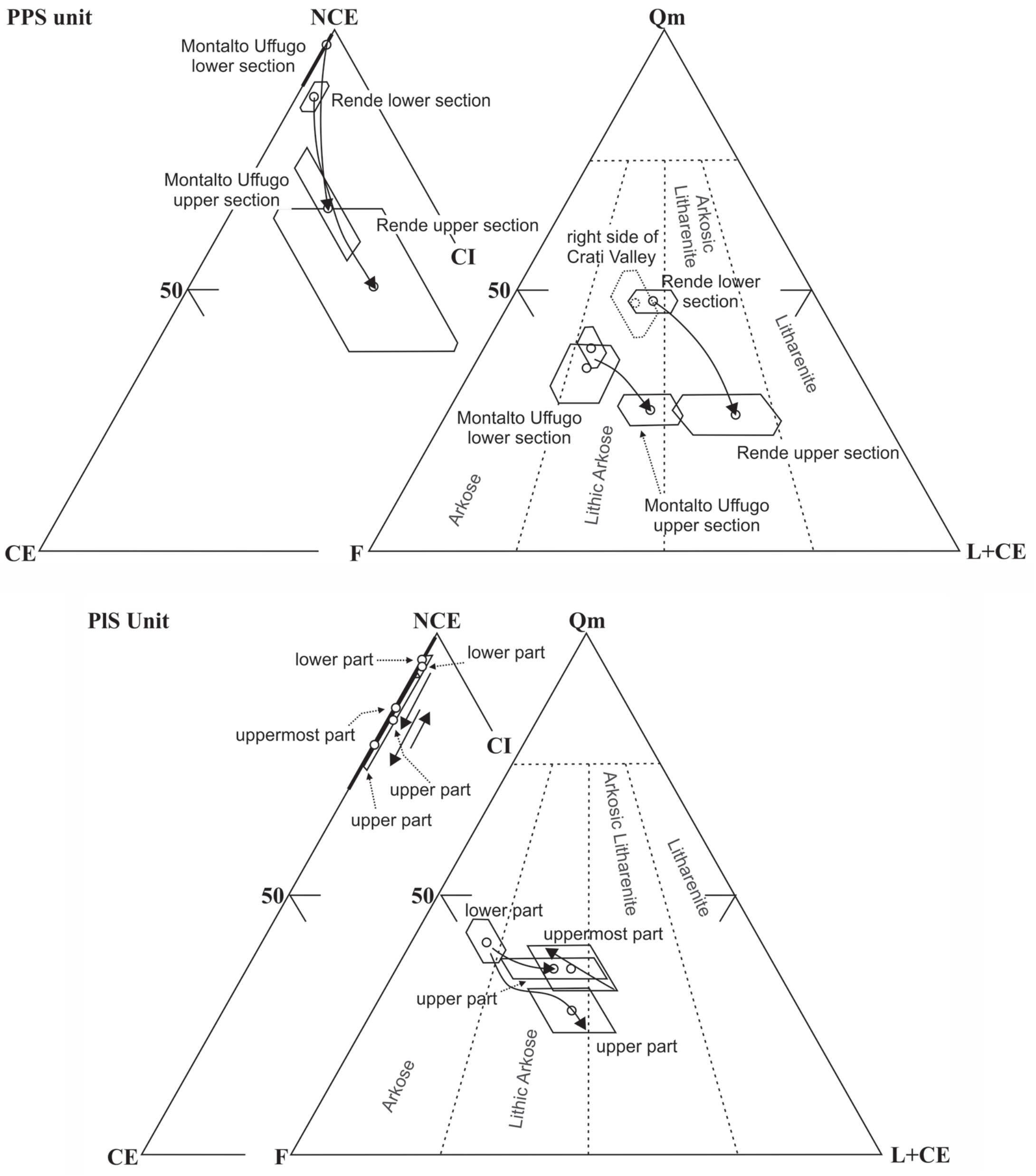

Fig. 6. Ternary diagrams showing sandstone composition of PPS and PlS 1 Units. Mean (symbols at the centre of polygons) and standard deviation (polygon); Qm (monocrystalline quartz), F (feldspars, K+P), and Lt (aphanitic lithic fragments and fine-grained polycrystalline quartz+CE). NCE (extrabasinal noncarbonate grains), CE (extrabasinal carbonate grains), CI (intrabasinal carbonate grains).

In particular, these gently rolling landscape relics (1000 to 1200 m elevated and Late Miocene to Pliocene in age) do not show clear evidence of being originally connected with the Tyrrhenian coast (Fig. 7A). On the contrary, the occurrence of some beheaded, low-sloping and dry river valleys that witness a north-northeastward direction of palaeo-drainage, along with the presence of fluvial conglomerates, made up of dolomitic clast fed by the Triassic dolostone cropping out to the South, strongly support the above hypothesis. Furthermore, the size of the main palaeo-valleys and the degree of rounding of fluvial gravel clasts strongly suggest that they were cut by high-order streams with catchment areas that had to cover much of the distance that nowadays separate them from the south-southwestern source area (Tyrrhenian area; Fig. 7A). Therefore, we might assume that the 1st Order Palaeosurface, nowadays found near the Coastal Range summit line, formed on the north-northeastern flank of the northern Calabrian chain.

Stage 2 (late Pliocene–Early Pleistocene)

The upper Pliocene–lower Pleistocene marks the first splitting of the previous Palaeolandscape and its lowering westward. This led to the development of a narrow trough bordered by N-trending faults, which records the onset of marine sedimentation (PPS Unit), and represents the early structural depression where the modern Crati Basin will develop later on (Fig. 7B). This period clearly marks the initial stretching of this portion of the southern Apennines,

Geological data suggests that tectonic subsidence provided the accommodation space for the deposition of the PPS Unit, for the progressive backstepping of the system, and for the progressive drowning of bedrock moving to the south

Furthermore, comparison between the quartzolithic/feldspatholithic detrital modes of Coastal Range littoral province (Le Pera & Critelli 1999) and quartzofeldspathic detrital modes of late Miocene wedge top basins (Barone et al. 2008), indicates a possible provenance of the lower portion of the PPS Unit from the Sila massif. Moreover, it is noteworthy the similar detrital modes between sandstones of the Rende lower section and Pleistocenic sandstones cropping out along the eastern side of the Crati Valley. Conversely, feldspathic lithic arenite strata of the upper part of the Late Pliocene–Early Pleistocene sediments indicate decreasing siliciclastic influx (NCE) into the basin (favouring intrabasinal carbonate productivity; e.g., Barone et al. 2008) as well as a possible new low-relief source area located to the South as the northward decrease in calcareous sedimentary detritus in the PPS Unit suggests.

From the foregoing considerations, we consider that the western part of the 1st Order Palaeosurface was poorly fragmented and lowered next to base level. As result, the landscape underwent slow dissection, which allowed reshaping of the 1st Order Palaeolandscape. Westward of the study area, Milia et al. (2009) also argued for the presence of southern sediment source areas.

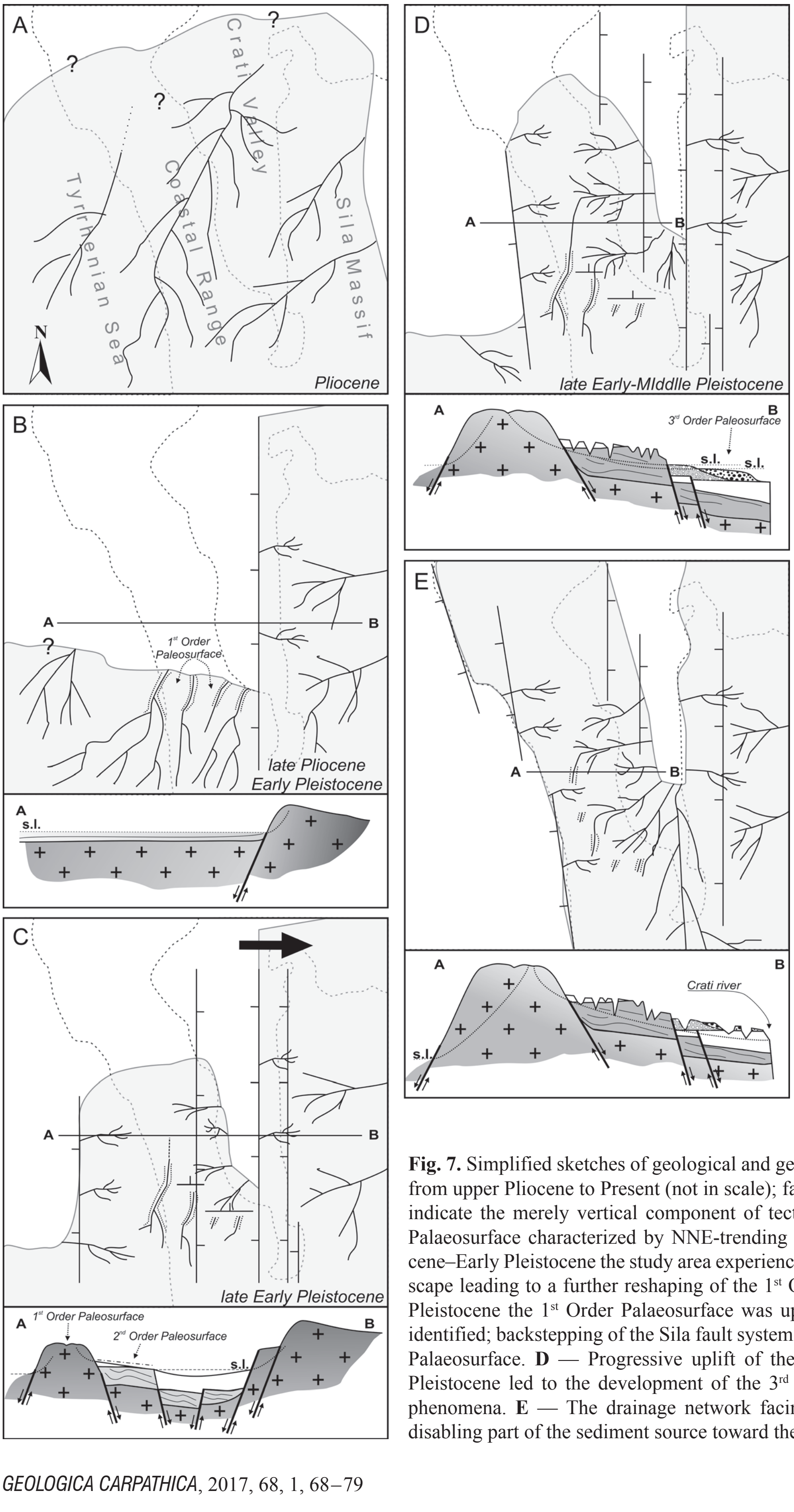

Fig. 7. Simplified sketches of geological and geomorphological evolution of the Crati Basin from upper Pliocene to Present (not in scale); faults shown in the following frames claim to indicate the merely vertical component of tectonics: **A** — Development of the 1st Order Palaeosurface characterized by NNE-trending palaeodrainage. **B** — During the late Pliocene–Early Pleistocene the study area experienced a first fragmentation of the previous landscape leading to a further reshaping of the 1st Order Palaeosurface. **C** — During the Early Pleistocene the 1st Order Palaeosurface was uplifted and the Coastal Range started to be identified; backstepping of the Sila fault system (black arrow); development of the 2nd Order Palaeosurface. **D** — Progressive uplift of the Coastal Range during the Early–Middle? Pleistocene led to the development of the 3rd Order Palaeosurface, and to stream piracy phenomena. **E** — The drainage network facing the Tyrrhenian Sea was responsible for disabling part of the sediment source toward the Crati valley.

Stage 3 (late Early Pleistocene)

The early Pleistocene marks a significant change in the geological and geomorphological scenario of the study area. A blockfaulting episode caused the fragmentation of the 1st Order Palaeosurface, the development of a depression bordered by high angle, NNE-trending faults, and an eastward migration of the fault system resulting in uplift and erosion of the Sila slope (Fig. 7C).

At the end of the Emilian the Coastal Range was likely wider than today toward the West, but afterwards it has progressively assumed its modern shape.

As a consequence, a new base-level became established and led to the development of the 2nd Order Palaeosurface. Remnants of this landscape occur at elevations between 400 and 600 m a.s.l. (Figs. 4, 5). They appear entrenched within remnants of the 1st Order Palaeosurface to the South, and they are very noticeable on the footslopes of the Coastal Range ridge (Fig. 4). Here the 2nd Order Palaeosurface relics are characterized by depositional and erosional landforms (Figs. 4, 5), the last ones carved into hard rocks and showing a similar degree of maturity at comparable elevation. The drainage network formed as a response to the uplift of the Coastal Range, producing steep catchments from which alluvial deposition prograded onto the piedmont zone (Fig. 5B).

A late Early Pleistocene age can be ascribed to the development of the 2nd Order Palaeosurface, as it rests erosively or seals *Hyalinea Balthica* bearing deposits.

Over the same time-span, the coastal area experienced subsidence, resulting in clastic sedimentary successions having first a quartzofeldspathic composition. Although detrital modes indicate a Sila Massif provenance, detrital components (richer in carbonate sedimentary lithic grains) and palaeocurrents also reflect provenance from the Coastal Range.

Stage 4 (late Early–Middle? Pleistocene)

After the development of the 2nd Order Palaeosurface, tectonics caused the formation of a depression bordered by high angle, NNE-trending faults that draw progressively the recent Crati valley profile (Fig. 7D, E).

Pulses of eastward migration of fault systems affected the Sila Massif (Lanzafame & Tortorici 1981; Fabbricatore et al. 2014) and caused the drowning of coastal slices and uplift of the Sila Massif. The presence of perched-fluvial terraces and hanging stream-dissected fans found at different elevations within the valleys of the Tyrrhenian slope of the Coastal Range (Robustelli et al. 2005; Muto 2006) further support the uplift affecting the ridge at issue. At the same time, the Crati Basin experienced an almost continuous and fragmentary uplift where gentle erosional landscapes did not form, but depositional landscapes still survive, though deeply dissected. The tectonic control of the eastern basin margin from which Gilbert-type deltas were sourced, forced an offset basinward arrangement. Similarly, the influence of tectonics is also strongly suggested by the marked backstepping of the depositional systems cropping out on the eastern side of the Crati Trough (Fabbricatore et al. 2014).

In this framework, more than one depositional surface developed. According to stratigraphical data and depositional system arrangement, these step-like distributed surfaces (3rd Order Palaeosurface) indicate that the final stages of basin infilling were accompanied by progressive and continuous dissection of ancient landscapes and characterized by alternating phases of down-cutting and of base-level stability that occurred fairly quickly through time (Figs. 4, 5).

It is also worth noting the difference in sediment detrital modes and partitioning in composition during this phase of landscape evolution. Although detrital modes indicate variable composition from quartzofeldspathic to feldspatholithic, the increase and decrease of dolostone in fine-grained deltaic sediments are clear evidence of stream capture phenomena and recycling processes. In fact, as the rivers flowing toward the Crati Basin had their longitudinal gradients increased due to uplift, headward propagation of incision tended to capture the NNE-directed palaeodrainage drainage (Fig. 7D) the watershed of which still had to include Triassic dolostone (M. Cocuzzo area; Figs. 2, 4).

Afterwards, river capture phenomena resulting from headward retreat of river valleys flowing toward the Tyrrhenian Sea were responsible for disabling the dolomitic sediment source area toward the Crati valley (Fig. 7E), outlining the current physiography of the study area.

Concluding remarks

The integrated geomorphological and stratigraphical approach adopted for the study of the Crati Basin represents another goal of improving our knowledge of the Plio–Quaternary landscape evolution of northern Calabria. The Crati Basin development and evolution was reconstructed through a model depicting the relationships between sedimentary units, bounding surfaces and landsurfaces. In this regard, the timing of the Crati landscape evolution was constrained between late Pliocene and Middle Pleistocene

On the basis of sandstone detrital and geomorphological evidences, we have better constrained the timing of landscape evolution and its relationships with basin sedimentary infilling.

The presence of *Hyalinea balthica* confirms the existing inferred age for the lower boundary of the PlS Unit, and reveals that the upper age limit of the 2nd Order Palaeosurface has to be younger than 1.2 M.y.

The depositional system arrangement of PlS Unit and the related step-like distributed 3rd Order Palaeosurface, result from alternating phases of down-cutting and base-level stability, and suggest the progressive and continuous dissection of ancient landscapes.

The roles of tectonics and river piracy are emphasized as control mechanisms for composition and provenance of the sandstone strata. Tectonics caused a change in fluvial connectivity and the re-arrangement of the formerly NNE-ward-draining river network during the late Early Pleistocene and then in more recent times.

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