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# Quaternary alluvial fan systems of the Agri intermontane basin (southern Italy): tectonic and climatic controls

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**Abstract:** The Agri River high valley is a Quaternary intermontane basin located in southern Italy. The tectonic evolution of this basin was controlled by Lower Pleistocene strike-slip master faults, subsequently reactivated as normal faults until the Middle Pleistocene. The Quaternary sediments of the basin infill are mainly constituted of continental clastics, represented by coarse-grained alluvial deposits divided by unconformities. The arrangement of clastic deposits suggests that the Pleistocene to Holocene alluvial fan system developed along the eastern margin of the valley. Five generations of slope and alluvial fan systems have been recognized in the Agri basin. The oldest fans have formed on both slope and alluvial deposits. The younger alluvial fans are located along the entire valley floor and arose upon the earlier fan apexes originating in these valleys. The youngest fans are arranged in two different generations and show proximal facies distributed along the foot slopes. Plan view morphology, fan slope profiles, and sedimentary features of the fan system have been used here to determine the magnitude of the tectonic deformation episode affecting the faulted mountainous front of the Agri basin eastern margin. Both fast and slow tectonic episodes occurred during the different regional Quaternary tectonic stages that affected the southern Apennine chain. These tectonic episodes have therefore been analysed in relation to climatic conditions in order to determine their contributions to the evolution of the Pleistocene to Holocene fan systems.

**Key words:** Quaternary, Italy, southern Apennines, tectonics and climate, geomorphology, alluvial fans.

## Introduction

There are many studies regarding the role of tectonics and climate control on both the origins and the development of Quaternary alluvial fans in the literature (Bull 1967; Silva et al. 1992; Ritter et al. 1995; Frostick & Reid 1999; Viseras et al. 2003; Harvey 2004; Harvey et al. 2005; Robustelli et al. 2009). These elements are commonly considered to be very important in understanding the recent evolution of young orogens.

It has long been realized that the controlling factors of drainage basin properties influence the supply of water and sediment to the fan, and therefore the sedimentary processes and the resulting fan morphology. However, tectonic control may influence sediment production in the source area, and, together with gross topography, appears to primarily influence fan location, fan setting and gross fan geometry (Harvey et al. 2005). Furthermore, it has been demonstrated that fan morphology and fan sediment sequences are dependent on tectonics and the amount of accommodation space (Silva et al. 1992; Viseras et al. 2003). Recently, Robustelli et al. (2009) observed that tectonic and sea-level changes rather than climate conditions were the main factors in controlling the sediment/discharge ratio of alluvial fans.

After the Early Pleistocene, the axial zone of the southern Apennine chain was affected by strike-slip faulting, followed in Early–Middle Pleistocene by normal faulting. Large intermontane basins, including the Agri, Diano, Pergola-Melandro, Mercure, Sanza, and Noce basins (Schiattarella et al. 2003), were produced by active extensional tectonics of the axial zone of the southern Apennine chain. These basins were filled by coarse to fine continental deposits represented by different generations of Quaternary alluvial deposits and fan-related landforms. Differences in basin shape and size were strongly controlled by the activity of the faulted mountain front and the transverse drainage.

In order to understand the roles played by short-term tectonic episodes, punctuating longer term tectonic events, and climatic stages on Quaternary fan system evolution, stratigraphic and morphological analyses have been carried out, focusing on the eastern side of the Agri intermontane basin. In this area several generations of slope and alluvial fan systems, Early–Middle to Late Pleistocene in age, are located at the foot of a tectonically active mountain front (Di Niro & Giano 1995; Giano et al. 2000).

## Geological and geomorphological setting

### *Regional framework*

The southern Apennines (Fig. 1a) are a NE-verging orogenic wedge accreted from Late Oligocene–Early Miocene to Pleistocene. The chain is composed of Mesozoic-Cenozoic sedimentary cover arising from the deformation of several paleogeographic domains (i.e. the Ligurian oceanic crust and the western passive margin of the Adriatic plate) and of the Neogene-Pleistocene piggy-back basin, and foredeep deposits of the active margin. Recent shortening has occurred on the belt front deforming Pleistocene sediments and volcanics (Pieri et al. 1997; Beneduce & Schiattarella 1997) whereas widely documented extension is still active along the Apennines axis (Ortolani et al. 1992; Amato & Montone 1997). The average direction of the chain axis is about N150°, cor-

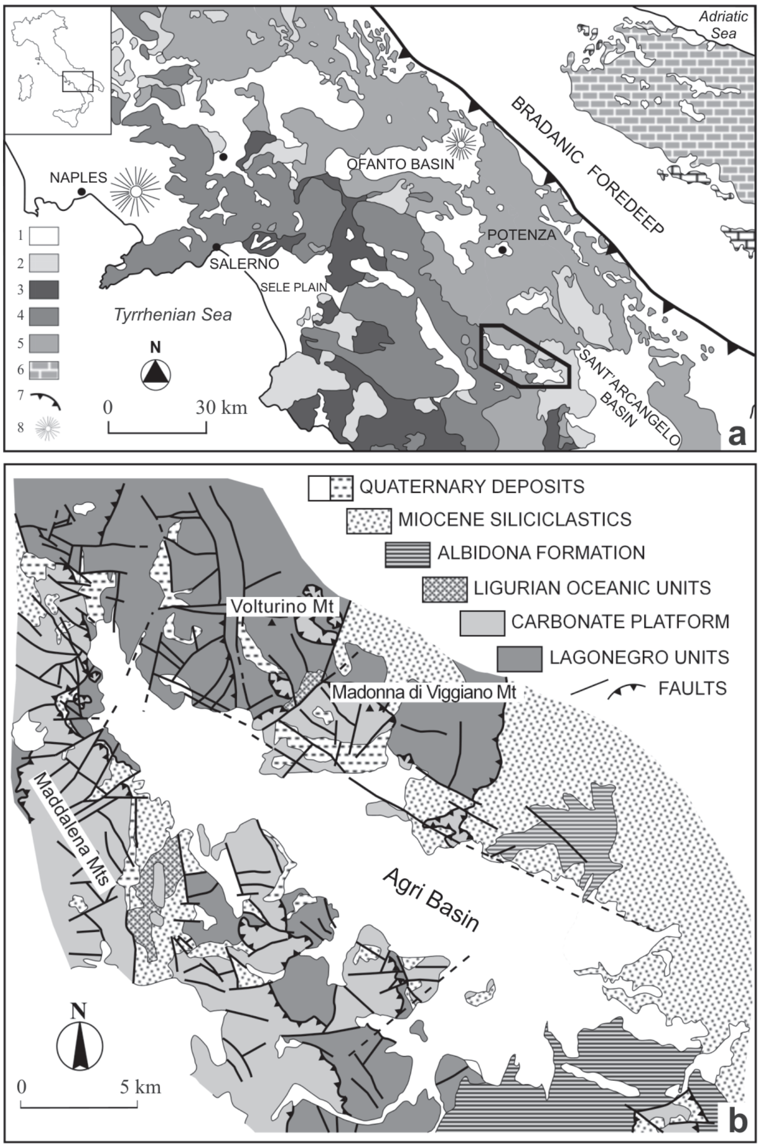

**Fig. 1. a** — Geological sketch map of the southern Apennines (the study area is reported in the frame). Legend: 1 — Plio-Quaternary clastics and volcanics deposits; 2 — Miocene syntectonic deposits; 3 — Cretaceous to Oligocene ophiolite-bearing internal units; 4 — Meso-Cenozoic shallow-water carbonates of the Apennine platform; 5 — Lower–Middle Triassic to Miocene shallow-water and deep-sea successions of the Lagonegro units; 6 — Meso-Cenozoic shallow-water carbonates of the Apulian platform; 7 — thrust front of the chain; 8 — volcanoes. **b** — Geological sketch map of the Agri basin.

responding to the strike of the main thrusts and coaxial normal faults. The axial zone of the belt was also affected by strike-slip faults trending, mainly N120° ± 10° and N50°–60° and by low-angle normal faults (Schiattarella 1998; Schiattarella et al. 2003, and references therein) during Pliocene–Pleistocene times, extensional tectonics characterized the Middle Pleistocene to Present time interval (Schiattarella 1998; Giano et al. 2000).

In the area from the Tyrrhenian Sea to the Adriatic (Apulian) foreland (i.e. from the top to the bottom of the tectonic stack) the following main tectonic units can be seen (Pescatore et al. 1999): (1) Jurassic to Oligocene polydeformed ophiolitic units, unconformably covered by syntectonic deposits, Early Miocene in age (Liguride units); (2) a carbonate platform unit (Campania-Lucania platform), whose age ranges from Late Triassic to Early Miocene; (3) several units mainly composed of deep-sea sediments, ranging from Lower Triassic to Lower–Middle Miocene (Lagonegro units); (4) a frontal imbricate fan made up of Cretaceous to Lower Miocene deep-sea marls, shales and sandstones covered by Middle to Upper Miocene flysch deposits; (5) Pliocene to Pleistocene foredeep clastic deposits; (6) the Apulian carbonate platform, which has been partly incorporated at the base of the accretionary wedge, forming in an easterly direction the least deformed foreland area.

### *Geological and geomorphological background of the Agri basin*

The upper valley of the Agri River is a NW-SE oriented intermontane basin located in the Lucanian Apennine (Fig. 1a,b). This fault-bounded basin is about 30 km long and 12 km wide and it developed during Quaternary times in the axial zone of the fold-and-thrust belt.

The pre-Quaternary bedrock of the Agri basin (Fig. 1b) is constituted of Mesozoic to Cenozoic shallow-water and slope carbonates of the Campania-Lucania platform that thrusted on coeval pelagic successions (Lagonegro units) cropping out along the western and the eastern sides of the valley, respectively. Toward the East and South-East the bedrock is composed of Tertiary siliciclastic sediments (Albidona and Gorgoglione Formations), which occupy the southern part of the basin. During the Quaternary, the Neogene compressive structures were truncated by high-angle faults with different kinematics, which caused the development of the Agri valley, controlling depositional architecture and landscape evolution (Boenzi et al. 2004).

The Pleistocene Agri basin succession crops out in the southern sector of the basin, and it is overlain by Holocene deposits in the northern sector. The outcropping succession consists of continental clastic sediments, represented by Lower to Upper Pleistocene, coarse-grained talus, and by Middle Pleistocene alluvial deposits ("Complesso Val d'Agri", Di Niro et al. 1992). During the Early Pleistocene, the Agri basin developed in response to left-lateral strike-slip N120° trending master faults, reactivated as normal faults after the Middle Pleistocene (Giano et al. 1997; Schiattarella et al. 1998). This tectonic regime is also responsible for the development of many Quaternary intermontane basins of the southern Apennines, even though a more complex structural setting has been suggested for the Agri valley's evolution (Di Niro & Giano 1995; Giano et al. 1997; Schiattarella et al. 1998; Giano et al. 2000; Cello et al. 2000). Meso-structural analysis performed on fault planes indicates a recent regime with a NE-SW tensile axis. That such a tectonic regime is still active has been inferred from the regional seismicity and *in situ* stress measurements (Amato & Selvaggi 1993; Amato & Montone 1997) and proven by the occurrence of Upper Pleistocene paleosols involved in faulting (Giano et al. 2000).

Local uplift rates have been computed through the elevation of hanging relics of ancient landscape (Paleosurface Auctt.), whose age is considered to span from 1.8 to 0.125 Ma. (Brancaccio et al. 1991; Amato & Cinque 1999; Amato 2000; Schiattarella et al. 2003; Boenzi et al. 2004). The values of the Quaternary local uplift rates range from 0.4 mm/yr to about 0.7 mm/yr, compared to the regional uplift rate, equal or higher than 1 mm/yr in the last 1.2 Myr (Schiattarella et al. 2003, and references therein). Due to high slip rates on fault planes (0.5 to 0.8 mm/yr in the 1.2–0.73 Myr time span) the major portion of the amplitude of relief can be ascribed to the activity of basin-border faults. However, the local morphostructural offsets have to be coupled with regional uplift of the orogen to obtain the total amount of Quaternary uplift. It should be noted that during Late Pleistocene to Holocene times the same fault system was characterized by strongly decreased slip rates of up to 0.1 mm/yr (Schiattarella et al. 2003; Boenzi et al. 2004).

### *Stratigraphic setting of the Quaternary continental basin-fill*

The Agri intermontane basin (De Lorenzo 1898; Di Niro et al. 1992) is filled by Lower Pleistocene to Holocene continental clastic deposits (Fig. 2). During the Pleistocene, the depositional systems changed in time and space from fluvial

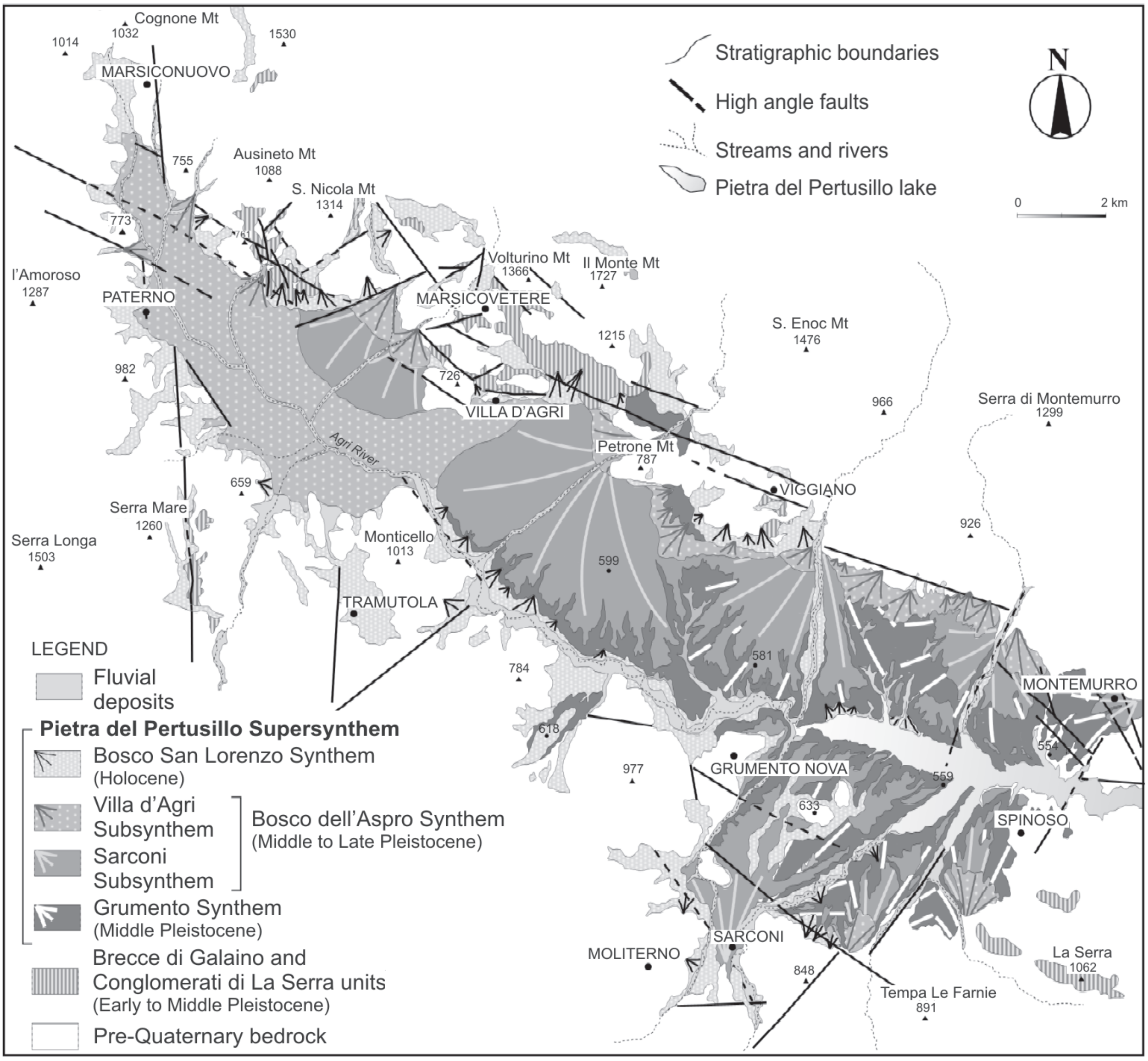

**Fig. 2.** Geological map of the Quaternary deposits crop out in the Agri intermontane basin. The Grumento Synthem is characterized by alluvial fan and coeval fluvial plain and lacustrine deposits; the Sarconi and the Villa d'Agri Subsynthems are constituted by coeval alluvial fan and fluvial plain deposits and by coeval alluvial fan and lacustrine deposits, respectively; the Bosco San Lorenzo Synthem is formed by coeval alluvial fan and fluvial deposits. The alluvial fan deposits of each synthem represent the fan systems discussed later in the text.

(alluvial fans and plain) to lacustrine (Di Niro et al. 1992; Zembo 2010). The stratigraphy of the southern sector of the Agri basin was first described by De Lorenzo (1898). Di Niro et al. (1992) informally called this Middle to Upper Pleistocene interval the "Complesso Val d'Agri" and divided it into three sedimentary units (lower, middle, and upper units), characterized by an overall coarsening-upward trend. Moreover, Di Niro & Giano (1995) improved the Agri basin stratigraphic resolution through the recognition of coarse-grained slope deposits, of Early to Late Pleistocene age, cropping out in the north-eastern and south-western basin margins ("Brecce di Galaino e Marsicovetere", Di Niro & Giano 1995; Giano et al. 1997; "Brecce di Serra Mare" Boenzi et al. 2004).

Recently, Zembo (2010) proposed an allostratigraphic model for the Agri basin infill introducing the "Agri Valley Allogroup". This allogroup cropping out in the southern sector of the basin, is constituted of four unconformity-bounded alloformations, and overlies the Lower Pleistocene deposits of the Spinoso Conglomerate Alloformation. Accordingly, the Agri Valley Allogroup is subdivided, from bottom to top, into the Pietra del Pertusillo, Valle del Nasillo, Vallone dell'Aspro and Torrente Casale Alloformations.

Carbone et al. (2010) recognized a number of sedimentary units in the basin infill, by means of the lithostratigraphy and unconformity bounded stratigraphic unit approach (*sensu* Salvador 1987), including the Brecce di Galaino and the Conglomerati di La Serra lithostratigraphic units, and the Pietra del Pertusillo Supersynthem. This latter was itself divided, from bottom to top, into the Grumento, the Bosco dell'Aspro, and the Bosco San Lorenzo Synthems (Fig. 2). A correlation between the sedimentary units recognized by these different authors and the present is reported in Table1.

## The Agri basin alluvial fan systems

### *Depositional setting*

The Agri intermontane basin is characterized by Pleistocene to Holocene slope and alluvial fan deposits, all included in the Pietra del Pertusillo Supersynthem and in the Conglomerati di La Serra and Brecce di Galaino Units (Di Niro et al. 1992; Di Niro & Giano 1995; Giano et al. 2000; Zembo 2010; Carbone et al. 2010). These fan systems crop out mainly along the eastern basin margin, even though smaller fan bodies occur in the southern margin (Fig. 2).

The basin-wide unconformities recognized in the Quaternary clastic succession of the basin (Di Niro et al. 1992; Zembo 2010; Carbone et al. 2010) have been partially used to define alluvial fan sedimentary sequences from coeval fluvial and lacustrine deposits. Five Pleistocene to Holocene fan systems have been recognized within the sedimentary infilling of the Agri basin (Figs. 2 and 3).

The Lower to Middle Pleistocene fan sequence (fan system I) consists of about 20–30 m thick (Fig. 4), coarse-grained breccias and conglomerates pertaining to the Conglomerati di La Serra and Brecce di Galaino Units (Carbone et al. 2010; Fig. 2 and Table 1). The deposits of fan system I are mainly composed of two lithofacies. The first one consists of clast- to matrix-supported, coarse-grained breccias with in-

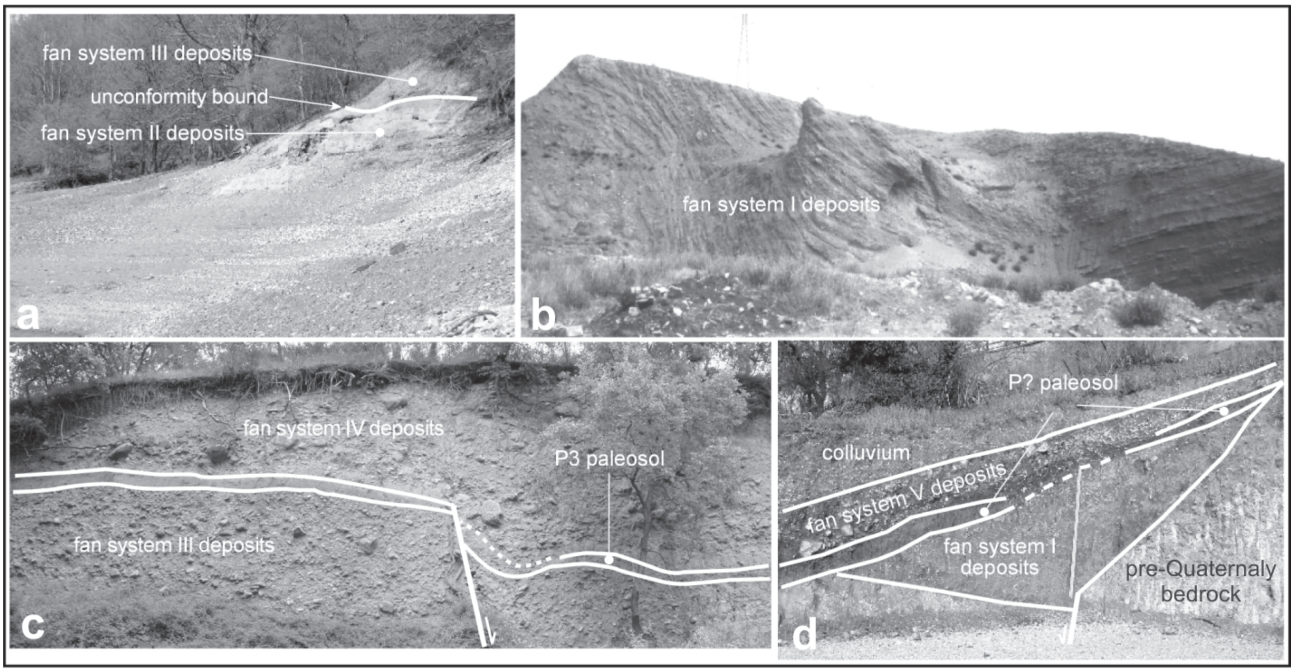

**Fig. 3.** Details of the fan deposits crop out in the faulted mountain front of the Agri eastern basin. Fan systems II and III deposits are divided by an unconformity that crops out between the Casale and Rifreddo Stream mouths (**a**); faulted coarse-grained deposits of the fan systems I coming from the Galaino village, note the syntectonic architecture of the breccia deposits and the erosion top surface (**b**); fan systems III and IV deposits are divided by a P3 paleosol in the Alli Stream (**c**); fan systems I and IV deposits are separated by a paleosol of uncertain attribution near Marsicovetere town (**d**).

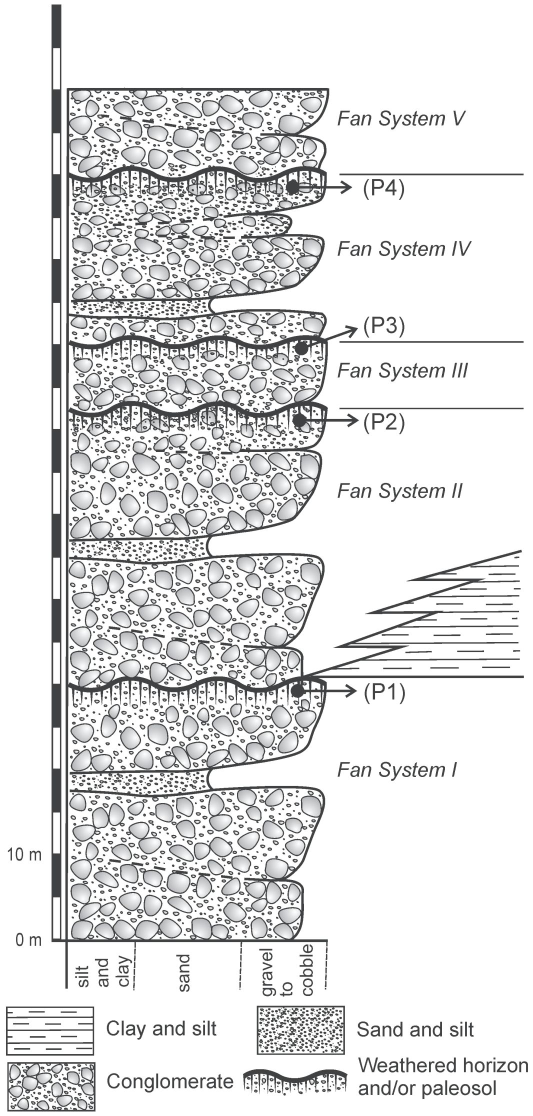

**Fig. 4.** Stratigraphic log of Agri basin fan systems and relationships among the fan deposits.

terbedded reddish paleosols; this lithofacies merges laterally into roughly stratified fine-grained breccias containing a reddish sand or clay matrix. Coarse-grained breccias have sharp and slightly irregular contacts. Clast shape ranges from angular to sub-angular, whilst matrix is a mixture of fine to coarse sands, containing terra rossa-type, reddish-brown mud and scattered pebbles. Breccias are stratified and locally massive (Fig. 3b,d). The second lithofacies consists of polymictic, generally massive conglomerates containing a reddish-brown clayey matrix. Clast shape ranges from rounded to sub-rounded, and the matrix is composed of fine-grained sand, silt and terra rossa-type reddish-brown clay. Fine-grained lenses, interbedded with conglomerates, randomly occur.

As a whole, the deposits of fan system I form coarse-grained slope to alluvial depositional systems (Di Niro et al. 1992). Fans were most likely delivered from bedload-dominated, braided channels (Zembo 2010), whereas slope deposits resulted from: (i) sediment-gravity flows produced both by bedrock cliff and colluvial slope failures, or (ii) fluid-gravity flows due to colluvial slope failures (Blair & McPherson 1994). These deposits can be interpreted as debris flows, and colluvial slides (Type I fan, *sensu* Blair & McPherson 1994). A reddish paleosol (P1, Fig. 4) developed on the top of fan system I indicates biostasy conditions and a locally non-depositional statement in the fan.

Middle Pleistocene alluvial fan deposits (fan systems II), corresponding to the coarse-grained deposits of the Grumento Synthem of Carbone et al. (2010) crop out extensively in the Agri valley axis (Fig. 2, Table 1). Fan system II deposits, about 30 m thick (Fig. 4), consist of well to poorly sorted conglomerates with pebble- to boulder-sized clasts in the fan apex. In this area, sediments are polymictic, texturally immature and form normal to inverse grading beds that are locally massive. Reddish to brown sandy-clayey matrix is also present. Fan toe deposits are formed by gravels alternating with sandy, trough cross-laminated beds. Silty to sandy lenses also occur, locally showing soft-sediment deformation structures and plant fragments. These deposits are interpreted as the result of colluvial slope failure processes. Sediment-gravity flows, such as debris flows dominate the deposits of the fan apex (proximal fan), whereas fluid-gravity flows, such as sheetfloods, characterize the fan toe (distal fan) (Type II fan, *sensu* Blair & McPherson 1994). Progradation of fan system II toward coeval lacustrine successions of the Agri basin occurred during the Middle Pleistocene (Di Niro et al. 1992). During the Quaternary, recurrent subaerial exposures affected the top of fan system II, causing the development of paleosols and/or erosion surfaces (P2, Fig. 4). In particular, Zembo (2010) indicates a well-developed pedogenic calcrete horizon at the top of these fans which indicates a lack of sediment input for a prolonged period and semi-arid to arid climatic conditions.

After the late Middle to Late Pleistocene a new fan growth episode occurred, producing the alluvial fan sequences of fan system III. This system consists of coarse-grained deposits of the Sarconi Subsynthem (Bosco dell'Aspro Synthem of Carbone et al. 2010; Fig. 2, Table 1). Alluvial fans are located at the eastern and southern basin margins. Fan deposits are about 5–10 m thick (Fig. 4) and consist of monomictic, massive or crudely stratified conglomerates in the fan head. The clasts are of cobble to boulder size, and are sub-angular to rounded with low sphericity in shape. In the fan toe, massive or normally-graded silty to sandy lenses are interbedded with gravels, beds are plain parallel and imbricated clasts are present. Normal graded layers of massive silty sands alternating with sandy silts also occur (Fig. 3a,d), showing local low- to high-angle cross-stratification. The fan head succession suggests the occurrence of sediment gravity flows, such as debris flows, whereas the coeval fan toe deposits represent the results of fluid-gravity flows, such as sheetfloods and incised channels. They are diagnostic of sheetflood-dominated fans (Type II fan, *sensu* Blair & McPherson 1994). A paleosol several meters thick (P3, Fig. 4) developed at the top of fan system III, suggesting biostasy conditions and low sedimentation rates over a long time span. Paleosol P3 corresponds to a mature fersiallitic weathering profile bright brown to reddish-brown in colour. Pedological features have suggested to Zembo

**Table 1:** Comparison among this and previous studies on the valley fill deposits of the Agri basin.

| Fan Systems | from Carbone et al. in print | | | from Zembo 2009 | | from Di Niro et al. 1992 Di Niro & Giano 1995 Boenzi et al. 2004 | | Relative and absolute Ages | Fan deposits thickness |
|---|---|---|---|---|---|---|---|---|---|
| V | Pietra del Pertusillo Supersynthem | Bosco San Lorenzo Synthem | | Agri Valley Allogroup | Torrente Casale Alloformation<br>+<br>Holocene fluvial deposits<br>**MIS 3** | Complesso Val d'Agri | upper Interval | Holocene<br>5.2 ± 0.5 ka<br>3.3 ± 0.45 ka B.P. | ~ 10 m |
| IV | | Bosco dell'Aspro Synthem | *Villa d'Agri Subsynthem* | | Vallone dell'Aspro Alloformation<br>**MIS 5 - 125 ka** | | middle Interval p.p. | Late Pleistocene<br>from 56 ± 4 ka<br>to ~ 32 ka | ~ 20 m |
| III | | | *Sarconi Subsynthem* | | Valle del Nasillo Alloformation | | middle Interval p.p. | late Middle to Late Pleistocene | 5–10 m |
| II | | Grumento Synthem | | | Pietra del Pertusillo Alloformation | | lower Interval | Middle Pleistocene | ~ 30 m |
| I | | Brecce di Galaino unit<br>Conglomerati di La Serra unit | | | Conglomerati di Spinoso Alloformation | Brecce di Galaino and Marsicovetere<br>Brecce di Serra Mare<br>Conglomerati di Spinoso | | Early to Middle Pleistocene | ~ 30 m<br>~ 20 m |

(2010) a high degree of pedogenetic evolution in a warm-humid "Mediterranean-like" climate corresponding to a Late Pleistocene interglacial phase (Tyrrhenian, MIS 5; Martinson et al. 1987; Shackleton et al. 2003).

An erosion surface affected the paleosol P3 and was overlain by a new alluvial fan sequence that produced the Upper Pleistocene fan system IV (Fig. 3c). This alluvial fan system is closely adjacent to the north-eastern Agri basin margin (Fig. 2). Deposits consist of coarse-grained conglomerates corresponding to the Upper Pleistocene Villa d'Agri Subsynthem (Bosco dell'Aspro Synthem of Carbone et al. 2010; Fig. 2, Table 1). The succession, about 20 m thick (Fig. 4), is composed of coarse-grained, massive conglomerates, that are polymictic, poorly sorted and clast-supported with reddish-brown clayey sand matrix. Interbedded, massive gravelly to fine-grained sand lenses rarely occur. Depositional features indicate sediment-gravity flows produced by colluvial slope failure processes, feeding debris-flow-dominated fans (Type I fan, *sensu* Blair & McPherson 1994). A deep weathered profile, developed at the top of fan system IV (P4, Fig. 4), consists of a thick reddish-brown pedological complex. These paleosols, classified as two transitional brunified-fersiallitic paleosols by Zembo (2010), may suggest a transition from dry-cold to humid-warm climate during the MIS3 interglacial.

The most recent fan growth, Holocene in age, led to fan system V. Fan deposits, about 10 m thick (Fig. 4), consist of matrix- to clast-supported cobble to boulder sized conglomerates. Clast shape ranges from angular to sub-rounded. Sand lenses and organic-rich horizons are also interbedded (Fig. 3d). Fan system V is the uppermost interval of the Bosco San Lorenzo Synthem of the Carbone et al. (2010) (Fig. 2, Table 1). It crops out close to the faulted basin margin and at the base of the oldest incised fan system, forming coalescent fans (Fig. 5). Coarse-grained deposits indicate sediment-gravity flows produced by bedrock cliff failures and are diagnostic of debris-flow-dominated fans (Type I fan, *sensu* Blair & McPherson 1994). Fan sedimentation occurred in the deepened valleys incised by fluvial network during the Late Pleistocene tectonic stage. Both OSL and AMS $^{14}$C dating on fan deposits fix the absolute age between 5.2 ± 0.5 ka and 3.3 ± 0.45 ka BP (data from Zembo 2010).

### *Geomorphological features*

The eastern Agri basin is characterized by a faulted mountain front that has controlled the shape, morphology and sedimentary evolution of the basin from Early–Middle Pleistocene up to the present (Di Niro & Giano 1995; Giano et al. 2000). Moreover, historical seismicity shows that the study area has been affected by recurrent and large earthquakes such as the 1857 Basilicata Earthquake. Several superimposed alluvial fans (*sensu* Blissenbach 1954) with different morphological features and ages (Fig. 5a,b) were produced during the Quaternary evolution of the Agri basin. All the fans have been dissected, partially dissected or not incised by fluvial networks at the Present-day (Fig. 6), and the amount of fluvial deepening varies from about 43 m in the Rifreddo Stream Valley to a few meters in the Molinara Stream Valley (Fig. 7). A comparison of both slope and incised channel fan profiles of the Casale, Rifreddo, Alli, and Molinara Streams (Fig. 7) reveals that fluvial deepening has only occurred in the Rifreddo and Casale Streams and not in the Alli and Molinara Streams. With regard to fan toe, the amount of dissection of the Rifreddo and Casale Streams

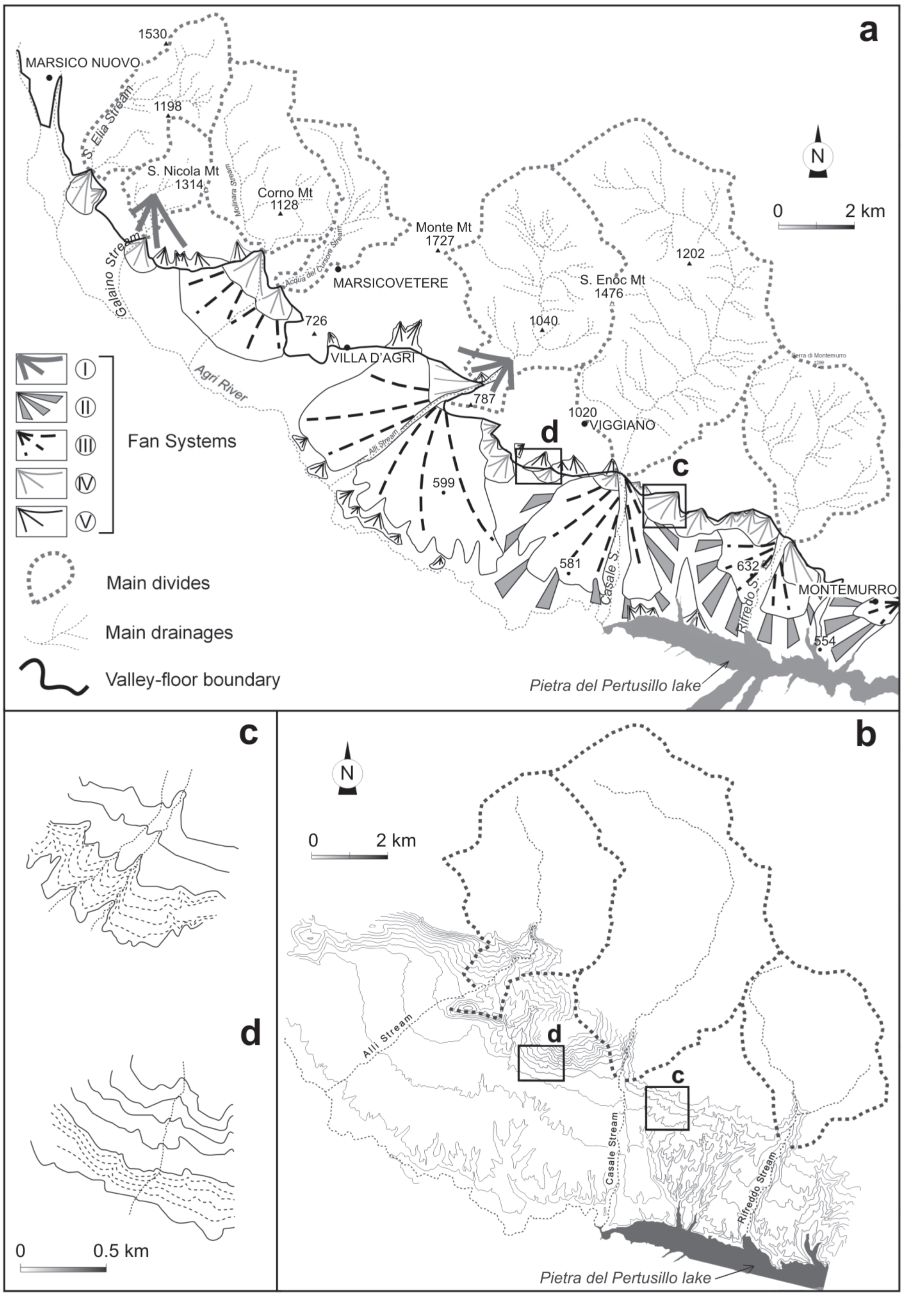

**Fig. 5.** Plan view distribution and drainage basins of the fan systems (**a**); topographic contour-lines with 25 m of equidistance of the Alli, Casale, and Rifreddo fan systems; in the foreground fan system III is shown (**b**); example of a fan with non concentric and evenly spaced contour-lines coming from fan system IV (**c**) and fan system V (**d**), respectively. The undashed lines in the frame (b), (c), and (d) indicate a contour-line interval with 25 m of equidistance; the dashed line in the frame (c) and (d) indicate a contour-line interval with 5 m of equidistance. The location of the (c) and (d) sites are reported in the (a) and (b) frames.

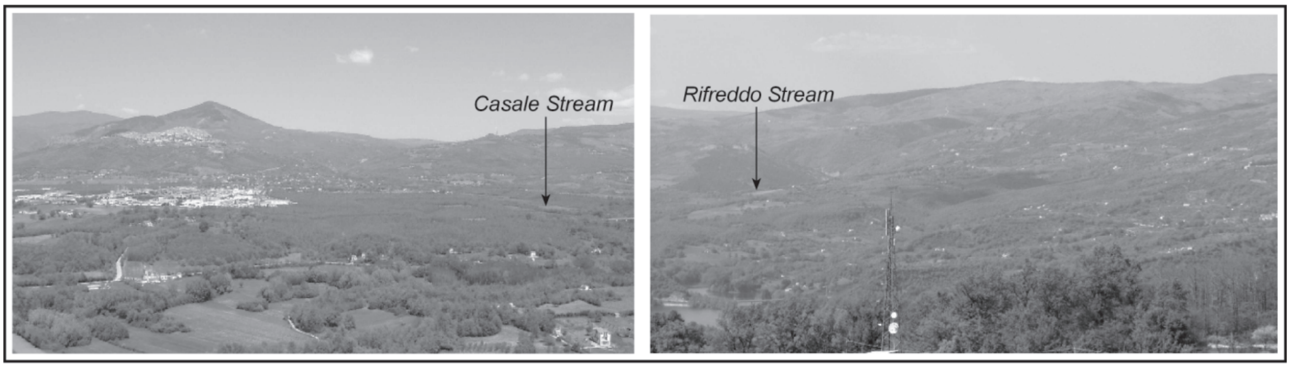

**Fig. 6.** Fan surfaces and vertical incision of the Casale (**a**) and Rifreddo (**b**) Streams.

ranges from about 43 to 50 m and from about 30 to 45 m, respectively. The shifting of the vertical deepening in these streams was produced by an incomplete backwearing of the stream channel network of the Agri basin.

In order to differentiate between the various generations of the fan systems of the Agri basin, plan view topographic contour and radial slope profile analyses have been carried out. Plan view extension of the eastern basin margin shows an irregular distribution of fan systems, coalescing to form a narrow bajadas (Fig. 5a,b).

As suggested by Keller & Pinter (1996), alluvial fans are conical in shape under geometrically-simple and tectonically-stable conditions. Topographic contours across a cone-shaped fan are similar to segments of evenly spaced concentric circles. It has also been recognized that if a conical fan is tilted, contour lines across the fans form segments of ellipses and not of circles. Plan view extension of the Agri basin fan systems shows that the topographic contour-lines across fan systems III, IV, and V do not correspond to segments of concentric and evenly spaced circles, but rather to ellipses (Fig. 5b). Therefore, it is possible to surmise that the evolution of these fan systems was controlled by the tectonic activity of the mountain front during the late Middle Pleistocene to Holocene time span. Moreover, the development of fan system I was also controlled by the Early Pleistocene tectonic activity (Figs. 3b, 5a) and its first plan view contour-line has not been preserved in the present-day landscape. Unfortunately, no data on tectonic rates (fast or slow tectonic episodes) can be provided from topographic contour-lines of the fan systems I, III, IV, and V. On the other hand, no morphological features have been obtained from fan system II plan view analysis, because it has been almost entirely buried by the younger fan system III deposits (Fig. 5a,b).

Topographical surveys indicate that the fan system areas are clearly superimposed and show a decrease in area from fan system II to fan system V. On the other hand, an increase of plan view area can be seen moving from fan system I to fan system II (Fig. 5a,b). Furthermore, fan systems II and III have large plan view areas and show a low fan slope gradient (Fig. 8). On the contrary fan systems I, IV, and V have small plan view areas and exhibit an high fan slope gradient (Figs. 5a,b,c,d and 8). In a faulted mountain front, rapid hanging wall subsidence and footwall uplift produce small piedmont fans and proximal axial rivers, whereas a slower deformation leads to large, low-gradient fans and distal axial rivers (Burbank & Anderson 2001). Accordingly, during each of the several Quaternary long-term tectonic stages of the southern Apennines which have affected the Agri basin, a short-term fast tectonic episode of the mountain front could have controlled the development of the smaller fan systems I, IV, and V. On the contrary, a short-term slow tectonic episode of the mountain front could have occurred during the evolution of the larger fan systems II and III (Fig. 5a,b).

Alluvial fans of the Agri basin are characterized by a slightly concave-upward slope profile divided by several clear break-in-slopes that permit the detection of different radial segments (Fig. 8). Concave-upward slope profiles of the Galaino, Molinara, Alli, Casale, and Rifreddo fans (Fig. 8)

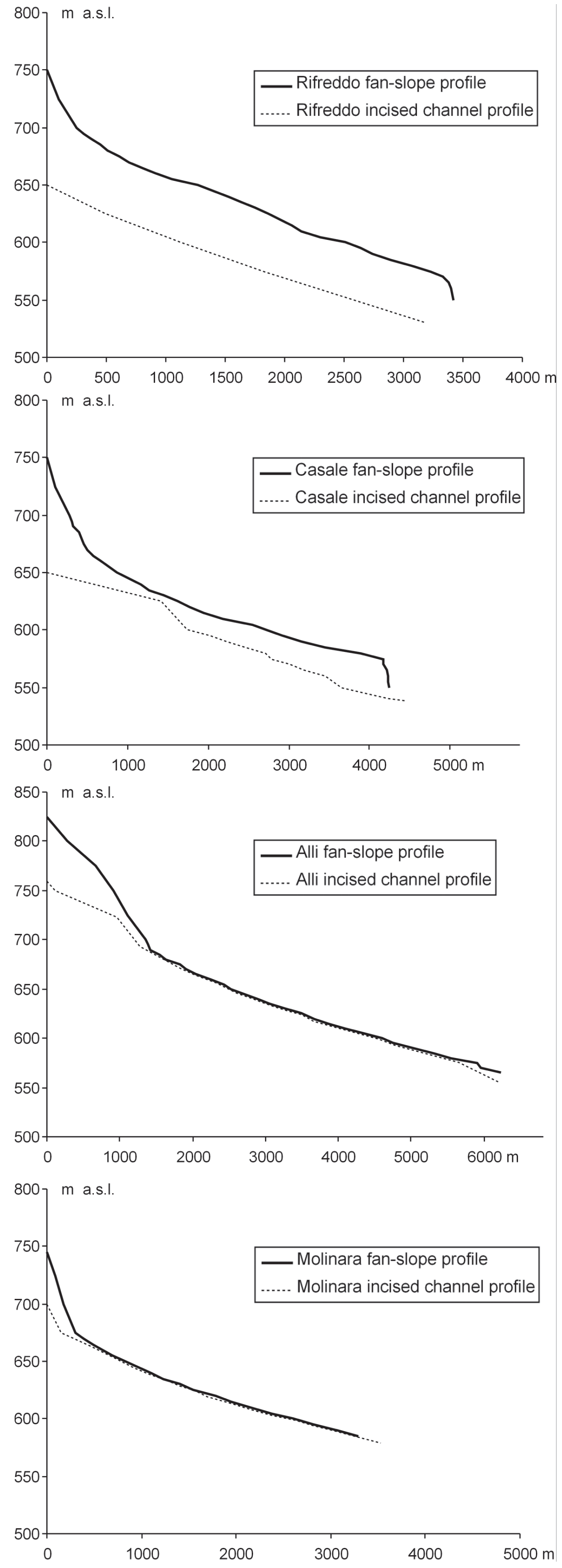

**Fig. 7.** Longitudinal fan slope profiles and incised channels of the Molinara, Alli, Casale, and Rifreddo Streams.

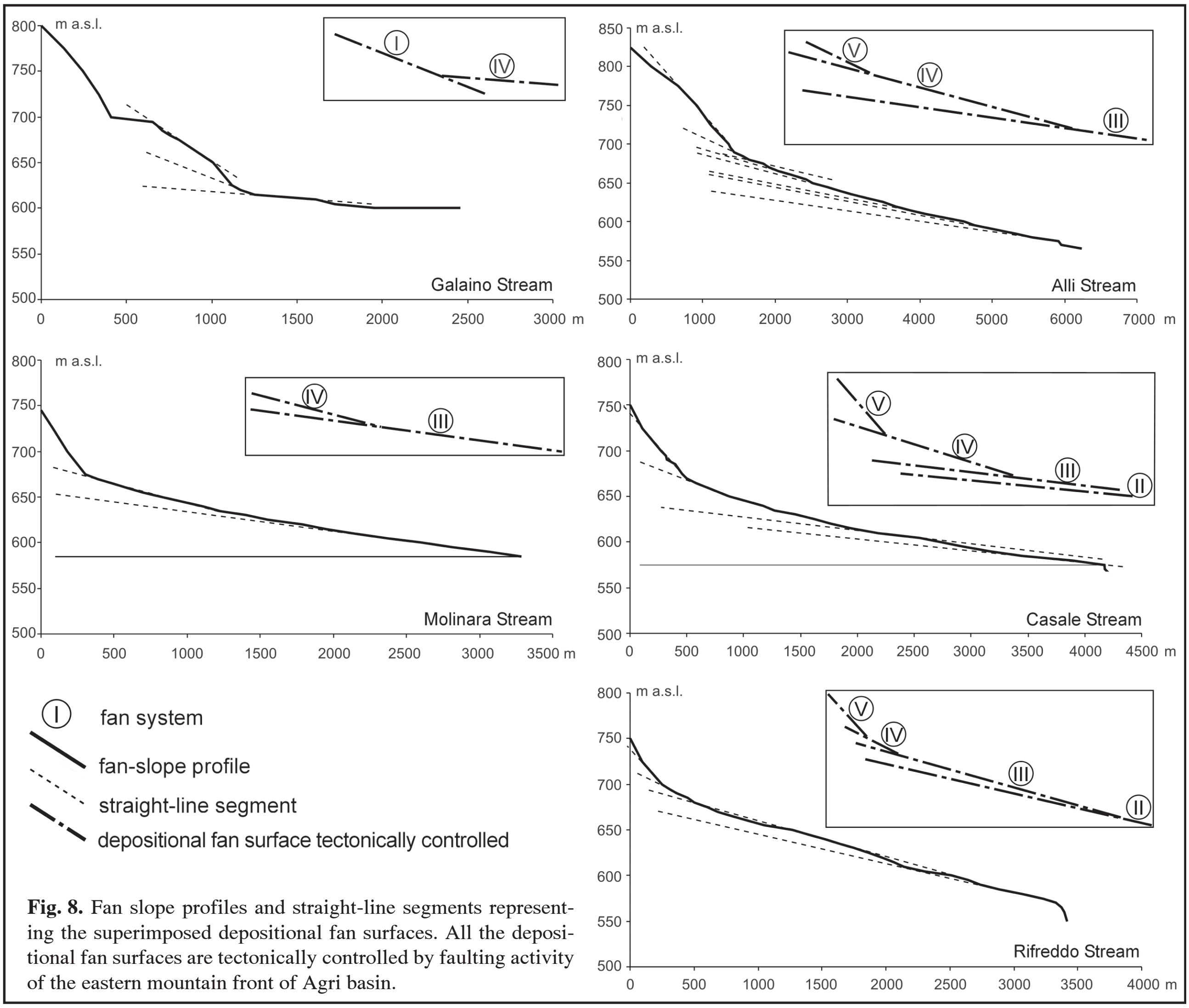

**Fig. 8.** Fan slope profiles and straight-line segments representing the superimposed depositional fan surfaces. All the depositional fan surfaces are tectonically controlled by faulting activity of the eastern mountain front of Agri basin.

have been divided into several straight-line segments (Bull 1977). Four straight-line segments have been inferred from the Casale and Rifreddo fans, three from the Alli one, and only two segments from the Molinara and Galaino fans (Fig. 8). There is a decrease in the slope angle between two adjacent segments of the fan profile in a downward direction. Moreover, this break-in-slope profile can also be drawn as a curve in plan view, along the topographic contour-line of fans (Fig. 5a,b), and may be interpreted as a depositional fan surface. The occurrence of stratigraphic markers (i.e. erosion surface, weathered profile and/or paleosols) on the top-surface of fans also suggests the interpretation of the straight-line segment as the top of the sedimentary fans.

Since similar coarse-grained sedimentation characterized fan systems I to V, a comparable angle of the straight-line segments forming the slope profile of the fan could be expected (Fig. 8). The discrepancy between the angles of the straight-line segments observed from the fan slope profile (Fig. 8) could be attributed to the rate of Quaternary uplift of the mountain front during the long-term tectonic stages (Schiattarella et al. 2003; Boenzi et al. 2004). In particular, a fast tectonic episode could be responsible for the high-gradient slope profiles of fan systems I, IV, and V (Fig. 8). Conversely, a slow tectonic episode could produce the low-gradient slope profiles of fan systems II and III (Fig. 8). Therefore, the straight-line segments observed from the fan slope profile can be interpreted as tectonically controlled depositional fan surfaces (Fig. 8).

## Discussion and conclusions

Although tectonics and climate are the primary factors in controlling alluvial fan evolution (Bull 1977; Frostick & Reid 1989; Silva et al. 1992; Ritter et al. 1995; Viseras et al. 2003; Harvey 2004; Robustelli et al. 2009), it is often more difficult to determine their relative roles. Harvey et al. (2005) suggest that fan evolution is controlled by both climatic change and tectonic processes over different timescales of $10^2$–$10^4$ years and in excess of $10^4$ years, respectively. However, it should also be considered that the magnitude of tectonic activity is not constant over time and

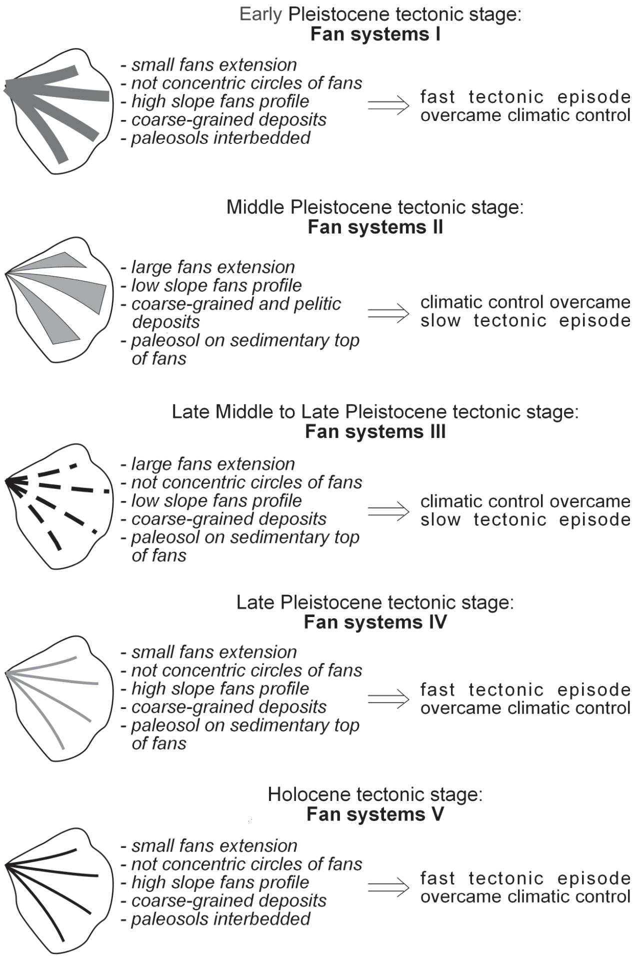

**Fig. 9.** Synoptical scheme showing the morpho-sedimentay features (on the left column) and the tectonic/climatic control (on the right column) of the development of the Agri basin fan systems.

space, and thus alternating periods of fast and slow short-term deformation occur during a longer term tectonic stage. In this way, the magnitude of the short-term tectonic deformation could interact with climate at the same timescale ($10^2$–$10^4$ years), and thus the interplay between climate and rapidity of deformations could be observed and compared by means of morphosedimentary analysis of fans.

In the Quaternary Agri basin (Di Niro et al. 1992; Di Niro & Giano 1995; Giano et al. 2000; Schiattarella et al. 2003; Boenzi et al. 2004; Zembo et al. 2009; Carbone et al. 2010), a comparison between slow/fast tectonic activity of a mountain front versus climatic control on the fan system development has been carried out (Fig. 9). All sedimentary fan bodies of the study area are characterized by coarse-grained deposits (Figs. 3 and 4) that seem to reflect a strong tectonic control on their evolution (Frostick & Steel 1993; Kumar et al. 2007). In particular, the debris-flow-dominated fans (Type I fan, *sensu* Blair & McPherson 1994) of fan systems I, IV, and V indicate rapid sedimentation, linked to a fast tectonic episode of the mountain front, whereas both the debris-flow- and sheetflood-dominated fans (Type II fan, *sensu* Blair & McPherson 1994) of fan systems II and III suggest lower sedimentation produced during a slow tectonic episode of the mountain front. On the contrary, unconformities within the fan systems suggest that sedimentation decreased and fan head entrenchment likely occurred. Moreover, weathered horizons and paleosols indicate a lack of sedimentation in the basin and different climatic conditions during their evolution. Morphological features (plan view extension and slope profile) of the alluvial fans indicate that a slow tectonic deformation was responsible for the growth of large fan systems, including II and III (Figs. 5a,b and 8), whereas a fast tectonic deformation controlled smaller systems, such as the I, IV, and V fans.

A first tectonic stage (Early Pleistocene) affected the study area, causing a regional uplift rate of about 0.8 mm/yr that was not constant over time (Schiattarella et al. 2003; Boenzi et al. 2004). In fact, within a regional tectonic stage, the magnitude of uplift varies from fast to slow tectonic episodes. This uplift marked both the initial asymmetrical basin opening and the creation of accommodation space for deposition of the coarse-grained fan system I (Di Niro & Giano 1995; Giano et al. 2000). Fans were deformed and uplifted by tectonic episodes (Giano et al. 1997), and consequently the present-day fan surface does not approximate classical concentric fan circles (Fig. 5a), and shows a high fan slope gradient (Fig. 8). A fast tectonic episode, included in the Early Pleistocene tectonic stage of the southern Apennines, directly controlled fan-shape, fan-slope profile, and sediment yield, having greater influence than climatic control during the same time interval (Fig. 9). In fact, coarse-grained deposits and a reduced fan extension show that fast deformation occurred during this tectonic stage. In contrast, a break in the tectonic uplift and a decrease in the sedimentation rate produced a development of a reddish paleosol (P1 in Fig. 4) on the top of the Brecce di Galaino Units. This paleosol could be indicative of the dominance of climatic factors in the tectonic deformation of fan system I.

Since the Middle Pleistocene, the regional uplift rate of the southern Apennine chain has been about 0.6 mm/yr on average (Amato 2000; Schiattarella et al. 2003). In the Agri basin, the long wavelength tectonics (i.e. regional uplift rate) punctuated by local, shorter-term faulting rates (about 0.5 mm/yr: Schiattarella et al. 2003; Boenzi et al. 2004), produced the accommodation space for the deposition of fan system II. Furthermore, the non-concentric and evenly spaced circles deduced from fan system IV (Fig. 5b,c) also indicate this tectonic activity, but they do not provide data about the tectonic rates. Very large cone-shaped fans with low-gradient slopes developed and coarse- to fine-grained deposition took place from the fan head to the fan toe. The fan deposits, interpreted as type II fans (*sensu* Blair & McPherson 1994), migrated downstream to the lacustrine and fluvial plain environments, testifying a good degree of organization of the paleo-depositional setting and steady tectonics. In contrast to the major uplift rate which occurred in the Agri basin during the Middle Pleistocene, the morphological and sedimentary features of the fans suggest that they were influenced by a slower tectonic episode, included in the Middle Pleistocene tectonic stage of the southern Apennines.

Moreover, the occurrence of lacustrine facies of the Grumento Synthem (Fig. 2) suggests the existence of climatic control in fan development which exceeded the influence of the tectonic episode (Fig. 9). The occurrence of a pedogenic calcrete horizon on the top surface of fan system II (P2 in Fig. 4) indicates the end of the fan system formation. A tectonic quiescence and a low sedimentation rate probably took place at this moment.

Active faulting during the late Middle to Late Pleistocene tectonic stage of the southern Apennine chain produced a local uplift rate of about 0.7 mm/yr (Boenzi et al. 2004), causing the widening of the Agri basin and, consequently, the development of fan system III. The Upper Pleistocene reddish paleosol which developed on the top surface of fan system III (P3 in Fig. 4) corresponds to the fersiallitic paleosol assigned to MIS5 from Zembo (2010). This dating leads to a consideration of these fan deposits as older than 125 kyr. Morphological (large cone-shaped fans in plan view and low fan slope profile) and sedimentary (Type II fans, *sensu* Blair & McPherson 1994) evidence suggests that a slow tectonic deformation episode took place during the development of fan system III. A good degree of internal organization of the proximal and distal sedimentary facies suggests significant climatic control in the development of fan system III. Therefore, morpho-sedimentary features indicate that climate is the primary controlling factor on fan evolution rather than tectonics (Fig. 9).

A Late Pleistocene tectonic stage produced a new uplift of the Agri basin's eastern margin (Giano et al. 2000) generating the development of fan system IV. Absolute dating of this system fixes between 56 ± 4 ka and ~ 32 ka (Zembo 2010) as the age of its development. Coarse-grained deposits, produced by colluvial slope failure processes, characterized the deposits of fan system IV, interpreted as debris-flow-dominated fans (Type I fan, *sensu* Blair & McPherson 1994). These fans are also characterized by a reduced plan view extension and a high-angle slope profile (Figs. 5a,b,c,d and 8). These morpho-sedimentary features are an indication of a fast tectonic episode which occurred during the Late Pleistocene tectonic activity (~ 24 kyr). Accordingly, it is suggested that a rapid tectonic episode had more significant consequences than climatic conditions in the evolution of fan system IV. The deepening of the Agri basin fluvial network and fluvial back wearing began at the end of the deposition of fan system IV.

Late Pleistocene to Holocene tectonic activity of the eastern Agri basin margin was characterized by a strongly decreasing fault slip rate down to 0.1 mm/yr (Schiattarella et al. 2003; Boenzi et al. 2004). Therefore, a lower and local rate of tectonic displacement controlled the development of fan system V during the Holocene. On the contrary, debris-flow-dominated fans (Type I, *sens*u Blair & McPherson 1994), associated with reduced plan view fan extension and not concentric circles with high-angle profiles indicate a quicker tectonic deformation episode. This apparent discrepancy between a low uplift rate and a fast tectonic deformation could be explained by a high sedimentation rate probably related to a momentary increase in the fluvial discharge produced by a strong sudden tectonic episode. Therefore, if this hypothesis is true then also in the case of fan system V, the tectonic signal has greater influence than that of climatic control.

In conclusion, within the framework of the Quaternary tectonic stages affecting the southern Apennines, both the magnitude (fast or slow rate) of the tectonic episodes and the climatic conditions were responsible for the development of the alluvial fan systems of the Agri basin (Fig. 9).

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## References

Amato A. 2000: Estimating Pleistocene tectonic uplift rates in the Southeastern Apennines (Italy) from erosional land surfaces and Marine Terraces. In: Slaymaker O. (Ed.): Geomorphology, human activity and global environmental change. *Wiley,* 67–87.

Amato A. & Cinque A. 1999: Erosional landsurfaces of the Campano-Lucano Apennines (S. Italy): genesis, evolution, and tectonic implication. *Tectonophysics* 315, 251–267.

Amato A. & Montone P. 1997: Present-day field and active tectonics in southern peninsular Italy. *Geophys. J. Int.* 130, 519–534.

Amato A. & Selvaggi G. 1993: Aftershock location and P-velocity structure in the epicentral region of the 1980 Irpinia earthquake. *Ann. Geofisica* 36, 3–15.

Beneduce P. & Schiattarella M. 1997: Relationships between Quaternary tectonics and volcanogenic deformation in the Campi Flegrei, Ustica Island, and Vulture Mount areas (Southern Italy). *Quaternario* 10, 583–588 (in Italian).

Blair T.C. & Mcpherson J.G. 1994: Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes and facies assemblages. *J. Sed. Res.* A64, 450–489.

Blissenbach E. 1954: Geology of alluvial fans in semiarid regions. *Geol. Soc. Amer. Bull.* 65, 175–190.

Boenzi F., Capolongo D., Cecaro G., D'Andrea E., Giano S.I., Lazzari M. & Schiattarella M. 2004: Polyphase geomorphological evolution and uplift rates of the sout-western side of the Agri high Valley (southern Apennines). *Boll. Soc. Geol. Ital.* 123, 357–372 (in Italian).

Brancaccio L., Cinque A., Romano P., Rosskopf C., Russo F., Santangelo N. & Santo A. 1991: Geomorphology and neotectonic evolution of a sector of the Tyrrhenian flank of Southern Apennines (Region of Naples, Italy). *Z. Geomorph. N.F., Suppl.-Bd.* 82, 47–58.

Bull W.B. 1977: The alluvial-fan environment. *Progress in Physical Geography* 1, 222–270.

Burbank D.W. & Anderson R.S. 2001: Tectonic geomorphology. *Blackwell Science*, 1–274.

Carbone S., Giano S.I., Lentini F. & Tescione M. 2010: Expanatory notes of the Italian Geological Map to 1:50.000 map scale. Sheet 505 Moliterno. *ISPRA, Dipartimento Difesa del Suolo, Servizio Cartografico*, *Relazioni e Documentazione di base*, Roma, 1–107 (in Italian).

Cello G., Gambini R., Mazzoli S., Read A., Tondi E. & Zucconi V. 2000: Fault zone characteristics and scaling properties of the Val d'Agri Fault System (Southern Apennines, Italy). *J. Geodynamics* 29, 293–307.

De Lorenzo G. 1898: Relics of Pleistocene wide lakes from the Southern Italy. *Atti Reale Acc. Sc. Fis. Mat.* 17, 1–11 (in Italian).

Di Niro A. & Giano S.I. 1995: Geomorphological evolution of the eastern side of the Agri high Valley (Basilicata). *Studi Geologici Camerti, Spec. Vol.* 1995/2, 207–218 (in Italian).

Di Niro A., Giano S.I. & Santangelo N. 1992: Preliminary notes on the geomorphological and sedimentary evolutions of the Agri high basin (Basilicata)". *Studi Geologici Camerti, Spec. Vol.* 1992/1, 257–263.

Frostick L.E. & Reid I. 1989: Climatic versus tectonic controls of fan sequences: lessons from the Dead Sea, Israel. *J. Geol. Soc. London* 146, 527–538.

Frostick L.E. & Steel R.J. 1993: Tectonic signatures in sedimentary basin fill: an overview. *Int. Ass. Sed., Spec. Publ.* 20, 1–9.

Giano S.I., Lapenna V., Piscitelli S. & Schiattarella M. 1997: New geological and geophysical data on the structural setting of the Quaternary continental deposits of the Agri high Valley (Basilicata). *Quaternario* 10, 591–596.

Giano S.I., Maschio L., Alessio M., Ferranti L., Improta S. & Schiattarella M. 2000: Radiocarbon dating of active faulting in the Agri high Valley, Southern Italy. *J. Geodynamics* 29, 371–386.

Harvey A.M. 2004: The response of dry-region alluvial fans to late Quaternary climatic change. In: Alsharhan A.S., Wood W.W., Goudie A.S., Fowler A. & Abdellatie E.M. (Eds.): Desertification in the Third Millenium. *Balkema*, Rotterdam, 83–98.

Harvey A.M., Mather A.E. & Stokes M. 2005: Alluvial fans: geomorphology, sedimentology, dynamics — introduction. A review of alluvial-fan research. *Geol. Soc. London, Spec. Publ.* 251, 1–7.

Keller E.A. & Pinter N. 1996: Active tectonics. *Prentice Hall*, 1–338.

Kumar R., Suresh N., Sangode S.J. & Kumaravel R. 2007: Evolution of the Quaternary alluvial fan system in the Himalayan foreland basin: Implications for tectonic and climatic decoupling. *Quat. Int.* 159, 6–20.

Martinson D.G., Pisias N.G., Hays J.D., Imbrie J., Moore T.C. & Shackleton N.J. 1987: Age dating and the orbital theory of the ice ages: development of a high resolution 0–300,000 year chronostratigraphy. *Quat. Res.* 27, 1–29.

Ortolani F., Pagliuca S., Pepe E., Schiattarella M. & Toccaceli R.M. 1992: Active tectonics in the Southern Apennines: Relationships between cover geometries and basement structure. A hypothesis for a geodynamic model. *IGCP Nº 276, Newsletter* 5, 413–419.

Pescatore T., Renda P., Schiattarella M. & Tramutoli M. 1999: Stratigraphic and structural relationships between Meso-Cenozoic Lagonegro basin and coeval carbonate platforms in southern Apennines, Italy. *Tectonophysics* 315, 269–286.

Pieri P., Vitale G., Beneduce P., Doglioni C., Gallicchio S., Giano S.I., Loizzo R., Moretti M., Prosser G., Sabato L., Schiattarella M., Tramutoli M. & Tropeano M. 1997: Quaternary tectonics in the Bradano-Ionian area. *Quaternario* 10, 535–542.

Ritter J.B., Miller J.R., Enzel Y. & Wells S.G. 1995: Reconciling the roles of tectonism and climate in Quaternary alluvial fan evolution. *Geology* 23, 245–248.

Robustelli G., Lucà L., Corbi F., Pelle T., Dramis F., Fubelli G., Scarciglia F., Muto F. & Cugliari D. 2009: Alluvial terraces on the Ionian coast of northern Calabria, southern Italy: Implications for tectonic and sea level controls. *Geomorphology* 106, 165–179.

Salvador A. 1987: Unconformity-bounded stratigraphic units. *Geol. Soc. Amer. Bull.* 98, 232–237.

Schiattarella M. 1998: Quaternary tectonics of the Pollino Ridge, Calabria-Lucania boundary, southern Italy. In: Holdsworth R.E., Strachan R.A. & Dewey J.F. (Eds.): Continental transpressional and transtensional tectonics. *Geol. Soc. London, Spec. Publ.* 135, 341–354.

Schiattarella M., Ferranti L., Giano S.I. & Maschio L. 1998: Quaternary tectonic evolution of the Agri high Valley (southern Apennines). *Atti 79º Congr. Soc. Geol. Ital.,* Palermo, 21–23 Settembre.

Schiattarella M., Di Leo P., Beneduce P. & Giano S.I. 2003: Quaternary uplift vs tectonic loading: a case-study from the Lucanian Apennine, southern Italy. *Quat. Int.* 101–102, 239–251.

Schiattarella M., Di Leo P., Beneduce P., Giano S.I. & Martino C. 2006: Tectonically driven exhumation of a young orogen: an example from the southern Apennines, Italy. In: Willett S.D., Hovius N., Brandon M.T. & Fisher D.M. (Eds.): Tectonics, climate, and landscape evolution. *Geol. Soc. Amer.*, *Spec. Pap.*, 398, *Penrose Conference Series*, 371–385.

Shackleton N.J., Sánchez-Goñi M.F., Pailler D. & Lancelot Y. 2003: Marine isotope substage 5e and the Eemian interglacial. *Global and Planetary Change* 36, 151–155.

Silva P.G., Harvey A.M., Zazo C. & Goy J.L. 1992: Geomorphology, depositional style and morphometric relationships of Quaternary alluvial fans in the Guadalentin Depression (Murcia, Southeast Spain). *Z. Geomorphologie, N.F.* 36, 325–341.

Viseras C., Calvache M.L., Soria J.S. & Fernandez J. 2003: Differential features of alluvial fans controlled by tectonic or eustatic accommodation space. Examples from the Betic Cordillera, Spain. *Geomorphology* 50, 181–202.

Zembo I. 2009: Stratigraphic architecture and quaternary evolution of the Val d'Agri intermontane basin (Southern Apennines, Italy). *Sed. Geol.* 223, 206–234.

Zembo I., Panzeri L., Galli A., Bersezio R., Martini M. & Sibilia E. 2009: Quaternary evolution of the intermontane Val d'Agri Basin, Southern Apennines. *Quat. Res.*72, 431–442.

Wright V.P. 2007: Calcrete. In: Nash D.J. & McLaren S.J. (Eds.): Geochemical sediments and landscapes. *Blackwell Publishing,* 1–465.