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Two Tectonic Geomorphology Studies on the Landscape and Drainage Network of Chain and Piedmont Areas of the Abruzzi Region (Central Apennines, Italy)

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1. Introduction

"Landscapes in tectonically active areas result from a complex integration of the effects of vertical and horizontal motions of crustal rocks and erosion or deposition by surface processes. In a sense, many landscapes can be thought of as resulting from competition among those processes acting to elevate the Earth's surface and those that tend to lower it" (Burbank and Anderson, 2001). Extracting information from deforming landscapes with an integrative approach is the main subject of tectonic geomorphology.

The landscape features have different dimensional scales that correspond to different tectonic implications. The major landforms (from continent scale to orogen scale; 10^7-10^4 km) and the intermediate ones (from mountain belt scale to ridge and valley scale; 10^4-10 km) result from the interaction of both endogenic and exogenic processes, with a dominancy of one over the other at different places and times, while the minor ones (at single landform scale; 10-10^{-2} km) are related to tectonics (tectonic landforms) or to erosion processes (i.e. fluvial, slope, glacial landforms) as defined since the beginning of the history of tectonic geomorphology (Gerasimov, 1946; Cailleux and Tricart, 1956; Mescerjakov, 1968; Ollier, 1981, 1999; Morisawa and Hack, 1985; Panizza and Castaldini, 1987; Ascione and Cinque, 1999; Burbank and Pinter, 1999; Burbank and Anderson, 2001; Peulvast and Vanney, 2001; Scheidegger, 2004). At intermediate to small scale, mountain belts, and related piedmont, are one of the main subjects of tectonic geomorphology. At this scale, drainage basins are the key features in the landscape. Basins consist of river channels, hill slopes, crests of interfluves and drainage divides that define the shape of the catchment. Some of these elements will respond more rapidly to changes imposed on them than others, according to the combination of many factors such as lithology, local tectonics, rock uplift/subsidence and climate changes (Morisawa and Hack, 1985; Kühni and Pfiffner, 2001; Twidale, 2004).

In tectonically active landscapes, changes in the incision/aggradation behaviour of the rivers are associated with the variations in climate and tectonics (Schumm, 1969; Bull, 1991; Merrits et al., 1994; Ascione and Cinque, 1999; Burbank and Pinter, 1999; Pazzaglia and

Brandon, 2001; D'Agostino et al., 2001; Pazzaglia, in press). Such changes occur following a specific sequence involving incision, valley widening and aggradation, and tend to form a series of fluvial terraces. Otherwise, local tectonics tend to shape certain landforms such as river bends, linear valleys, beheaded and hanging valleys, knick points, counterflow confluences of streams and alluvial fans (Miccadei et al., 2004; D'Alessandro et al., 2008; Della Seta et al., 2008 and references therein). The analysis and correlation of these features within the drainage basins allows for the discovery and definition of geomorphic markers of tectonics, as well as its timing. A major influence in landscape is certainly due to rock material properties, although at different scales there are different influences of rock material properties on landscape evolution. The geomorphological features of mountain areas shaped on hard rocks are well recorded in the general configuration of topography and in well preserved tectonic landforms. In piedmont areas, or in general in areas developed on soft rocks, the evidence of tectonics in the landscape is less clear. In these contexts only integrative studies based on (a) terrain analysis, (b) morphostructural analysis of the relief, (c) analysis of geomorphic markers such as certain landforms (geomorphological evidence of tectonics) and deposits (developed in continental environment), (d) drainage basins' analysis and morphometry, and (e) dating of deposits and landforms, provide clear indications concerning the role of tectonics in the landscape evolution.

Central Italy is characterized by a recent (Pliocene to present) geomorphological history and in this area several studies have been carried out at both local and regional scale, based on the integrative approach, by means of tectonic geomorphology methods (D'Alessandro et al., 2003; Miccadei et al., 2004; Ascione et al., 2008; D'Alessandro et al., 2008; Della Seta et al., 2008). In this paper two studies are presented on chain areas and piedmont areas in order to outline the methodological approach focused to decipher the role of morphotectonics and selective erosion in the landscape evolution (Fig. 1):

- chain area – escarpment between the Montagna del Morrone ridge and the Sulmona tectonic basin (central Abruzzi);
- piedmont area – dip stream valley (Sangro river valley, south-eastern Abruzzi)

These studies allow for the characteristics of the main morphostructural domains of central Italy (chain area and piedmont area) to be outlined and suggest, in general, the use of a similar methodological approach, but focused also on different geomorphological landscapes.

2. Study area

The Abruzzi region is located on the eastern slope of the central Apennine (central Italy). The geomorphological evolution of the region is related to a complex geological and structural framework developed since the Late Miocene with the formation of the Apennine thrust belt as part of the Mediterranean mountain system. The whole region has been affected since the Pliocene by extensional tectonics, uplift processes and strong morphostructural processes that have induced very active geomorphological processes. These processes have outlined and shaped the major morphostructural domain in the Abruzzi area: Apennine chain, Adriatic piedmont and Adriatic coastal plain (Fig. 1) (Patacca and Scandone, 2007).

At regional scale, the geomorphological analysis and the correlation to geological and structural characteristics allowed the identification, and the morphostructural characterisation, of the major landforms (Fig. 2; D'Alessandro et al., 2003). The results point out the clear coherence of present landforms with the tectonic framework in the Abruzzi area. In the chain area, exhumed thrust ridges and faulted homocline ridges are present (generally NW–SE, NNW–SSE, N–S), separated by tectonic valleys, fault line valleys, tectonic basins and tectonic-karstic basins, partially filled up with continental deposits. In the piedmont periadriatic area the most important morphological elements are represented by homocline relief (gently NE dipping), mesa relief, dip-stream valleys (SW–NE) and alluvial plains. The latter grade eastwards towards the coastal plain.

a)

b)

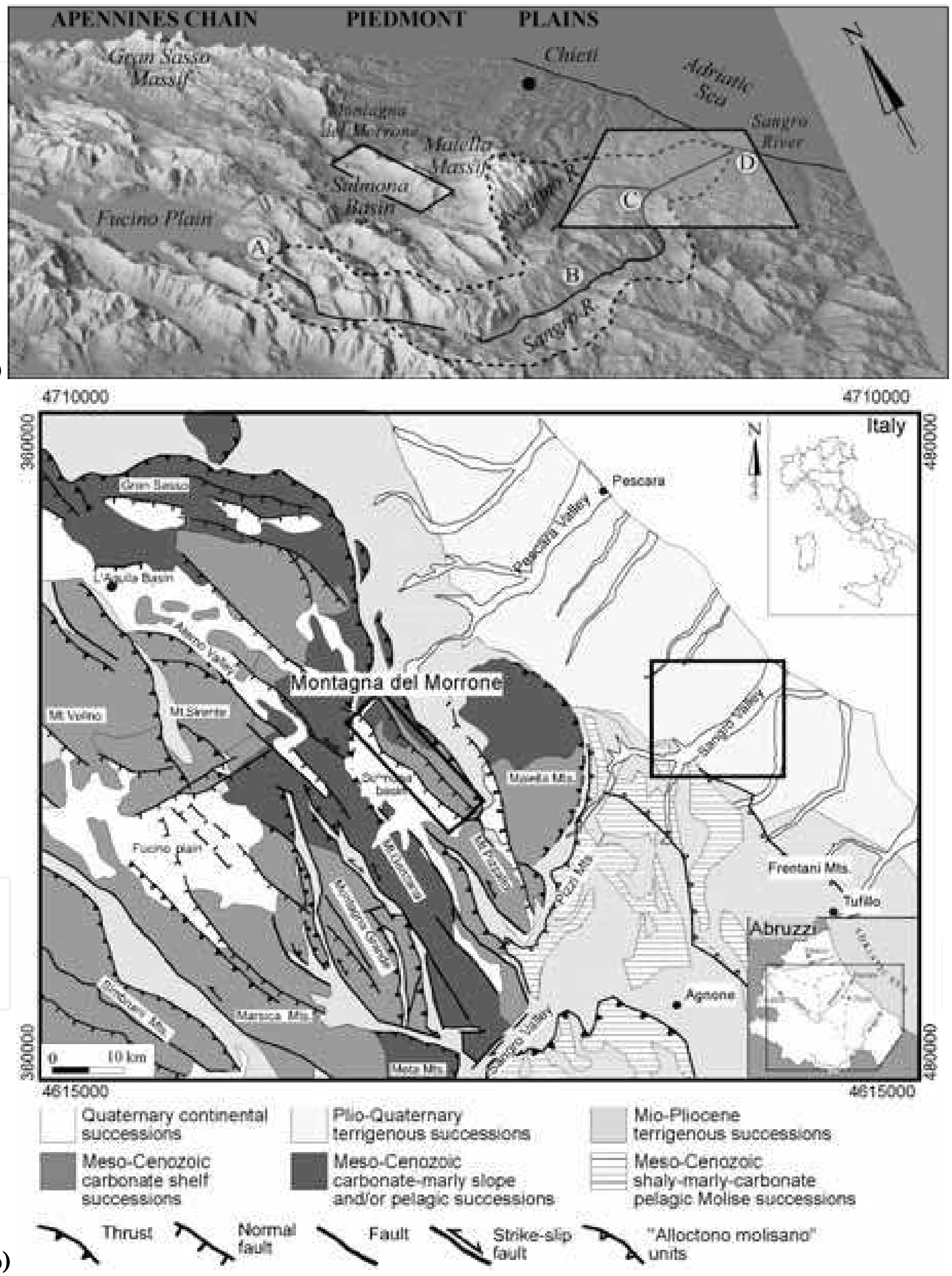

Fig. 1. Shaded relief image (a) and geological (b) map of the Abruzzi area (central Italy). Black boxes indicate the study areas

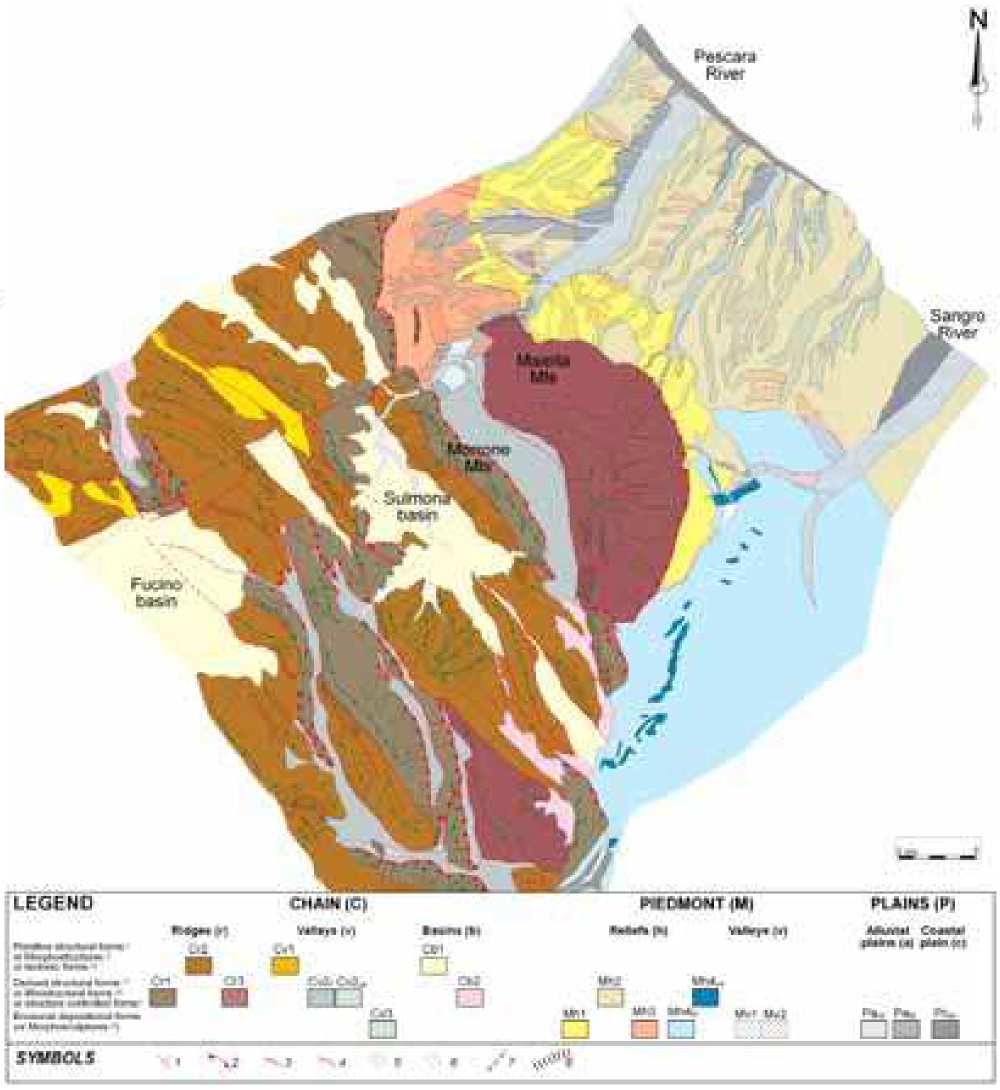

Fig. 2. Map of the morphostructural elements of central-eastern Abruzzi (modified from D'Alessandro et al., 2003).

LEGEND: CHAIN (C). Ridges: Cr1) *Exhumed thrust ridges*; Cr2) *Faulted homoclinal ridges*; Cr3) *Exhumed anticline ridges*. Valleys: Cv1) *Tectonic valleys*; Cv2) *Fault line valley* ($_{f}$ Neogene arenaceous-clayey foredeep sequences; $_{ca}$ Mezo-Cenozoic carbonate sequences); Cv3) *Transversal and Radial valleys*. Basins: Cb1) *Tectonic basin*; Cb2) *Karst-tectonic basin*. – PIEDMONT (M). Relief: Mh1) *Homoclinal relief* (Plio-Quaternary clayey-sandy sequences); Mh2) *Mesa relief* (Plio-Quaternary clayey-sandy-conglomeratic sequences); Mh3) *Eroded thrust relief* (Neogene arenaceous-clayey foredeep sequences); Mh4) *Hills on a chaotic and folded clayey-calcareous assemblage* ($_{cl}$ *"Argille varicolori"* auctorum complex and Cenozoic marly sequences; $_{ca}$ Meso-Cenozoic carbonate sequences); Mv1) *Dip-stream valleys*; Mv2) *Strike-stream valleys*. – PLAINS (P). Pa) Alluvial plains ($_{ra}$ recent alluvial deposits; $_{ta}$ Pleistocene terraced alluvial deposits); Pc) Coastal plain ($_{sc}$ recent sandy and conglomeratic deposits)

SYMBOLS: *1)* Regional attitude; *2)* Thrust (Miocene-Pliocene activity); *3)* Strike-slip fault (?Pliocene activity); *4)* Normal fault (Upper Pliocene - Quaternary activity); *5)* Major fault scarp; *6)* Major fault related scarp; *7)* Major crest; *8)* Primary drainage divide

[I]) Ascione and Cinque, 1999; Peulvast and Vanney, 2001. [II]) Gerasimov, 1946; Mescerjakov, 1968; Panizza, 1997. [III]) Bartolini, 2002. [IV]) Peulvast and Vanney, 2001. [V]) Ascione and Cinque, 1999

The piedmont of Abruzzi region is characterized by a low relief hill landscape (i.e. cuesta, mesa, plateau reliefs) on Mio-Plio-Quaternary terrigenous deposits, related to sin-, late-orogenic phases of the Apennines, by post-orogenic Quaternary marine regressive deposits and fluvial continental deposits. The transition from marine to continental deposits dates the emersion of the area and the starting point of the drainage evolution at the late Lower Pleistocene – early Middle Pleistocene. The Pleistocene fluvial landscape evolution of the piedmont area and the comprehension of the role of tectonics is an intriguing issue, being a key area for the Apennines' geodynamics, at the transition between compressional active tectonic areas, towards the east (Adriatic) and extensional active tectonic areas towards the west (Apennines chain).

3. Methods

The tectonic geomorphology studies presented in this work are carried out at drainage basin scale by means of: cartographic analysis and morphometry of orography and hydrography (map- and DEM-based), photogeology analysis, Quaternary continental deposits, fluvial terraces and morphotectonic detail field mapping, and morphotectonic cross section drawing. The topographic data in vector and in raster format were provided by Struttura Speciale di Supporto Sistema Informativo Regionale of Abruzzi Region (http://www.regione.abruzzo.it/xcartografia/).

Orography analysis is based on the 40m DEM. Within GIS software slope maps, energy of relief maps and hypsometry maps were realized. Hydrography analysis is based on 40m DEM and scale 1:25,000 topographic maps. Longitudinal profile, drainage density, azimuth of the drainage network, patterns and hydrography parameters were mapped (bifurcation parameters, hierarchic parameters, areal parameters etc.) in order to define the drainage development, to outline the control of morphological alignments and to suggest the tectonic control on basin arrangements (Horton, 1945; Miller, 1953; Schumm, 1956; Strahler, 1957; Avena et al., 1967; Avena and Lupia Palmieri, 1969; Ciccacci et al., 1992, 1995; Keller and Printer, 1996).

Photogeology analysis is performed on scale 1:33,000 aerial photos (Abruzzi Region Flight, 1982-1987) for the preliminarily mapping of main landforms (tectonic and structural landforms, fluvial landforms, slope landforms etc.). Structural geomorphology field mapping is carried out on 1:10.000 scale investigating bedrock geology, Quaternary continental deposits (fluvial, alluvial fan, slope deposits), main tectonic elements and morphotectonic evidence (ridges, slopes, valleys, hydrography forms and fluvial terraces) according to main national guidelines and national and international literature (Ambrosetti et al., 1976; ENEL, 1981; Panizza and Castaldini, 1987; Ciccacci et al., 1986; SGN, 1992, 1994; Leeder and Jakson, 1993; GNGFG, 1994; Centamore et al., 1996; Lupia Palmieri et al., 1996; Molin et al., 2004; Frenkel and Pazzaglia, 2005; APAT, 2007; Bull, 2007; D'Alessandro et al., 2008; Della Seta et al., 2008; ISPRA, 2009; Picotti et al., 2009; Miccadei et al., 2011; Pazzaglia, in press). The coupling of Quaternary continental deposits, fluvial terraces and morphotectonic evidence by means of morphotectonic profiles allowed finally to outline the relationships between forms and deposits.

These methods, taking into account the relationship between forms and deposits, outlined by morphotectonic mapping and morphotectonic profiles, can contribute to defining the main steps of landscape evolution and the major control on it (tectonics, rock properties, climate change etc.), and to estimate the timing of landscape development.

4. Case studies - chain area: tectonic basin and fault escarpment (Montagna del Morrone ridge)

4.1 Introduction

Montagna del Morrone (2061 m a.s.l.) is one of the main central Apennine ridges (central-eastern part of the Abruzzi Apennines; Fig. 1). It is made up of marine Meso-Cenozoic carbonate rocks, forming an asymmetrical anticline fold with a NW-SE axis, NE verging and overthrust onto Neogene terrigenous deposits. The SW slope is broken by several normal fault systems, NW-SE striking and SW dipping, which separate the ridge from the Sulmona tectonic basin (Fig. 1, 2; Miccadei et al., 1999; Doglioni et al., 1998; Miccadei et al., 2004). This slope shows a complex physiography, both longitudinal and transversal, with secondary ridges, scarps, gentle slopes or counter slopes (Fig. 3). The summit is gently undulating in the southern part, while the northern part is a narrow crest. At the base of the slope a sharp slope change joins the wide plain of the Sulmona tectonic basin and corresponds with one of the main normal fault lines of the Abruzzi area. Many ephemeral streams drain the slope down to the basal break forming alluvial fans.

The Sulmona tectonic basin is a half graben with a NW-SE master fault forming its eastern boundary along the Mt. Morrone slope and is filled by a thick sequence of lacustrine, fluvial and slope Middle-Upper Pleistocene deposits (Miccadei et al., 1999; 2002). It shows a peculiar physiographic setting: the lowest mean topographic height (300 m) in central Apennines intramontane basins, a strong relief (2000 m) up to the eastern ridge (Mt. Morrone) and an anomalous triangular shape. Here, a complex fluvial drainage system converges (Aterno River from NW, Sagittario River from SW and S, Gizio River from S, Vella River and Velletta River from SE) and flow into Pescara River.

The collected data (orography, hydrography, Quaternary continental deposits, morphotectonic evidence) allow us to define geomorphic markers of tectonics and to outline Quaternary landscape evolution of the escarpment between the Sulmona basin and Montagna del Morrone. In order to couple deposits and landforms, six morphotectonic sections are presented (three ridge transversal profiles representative of the northern, central and southern sectors; three stream channel and interfluve profiles representative of the drainage basins).

Fig. 3. Panoramic view (from SW) of the Monte Morrone SW escarpment

4.2 Results

The analysis of the morphotectonic features of the area is based on the investigation of geology (bedrock units, superficial deposits, tectonics and neotectonics) and geomorphology (structural, slope, karst and fluvial landforms, and alluvial fans).

4.2.1 Geology

Bedrock units are made up of carbonate rocks of Lias to Paleogene age divided into units according to their resistance to weathering and erosive processes (Fig. 4a): *bedded carbonate rocks* (outcropping in the northern area), *massive carbonate rocks* (outcropping in the central area), *carbonate rocks in thick beds* (outcropping in the southern areas), *dolomite rocks* (outcropping in the lower part of the slope in the northern and central sectors).
Such rock formations, as documented in the relevant literature, can be referred to various Meso-Cenozoic palaeogeographic domains: slope-basin in the northern sector, margin in the central sector and carbonate shelf in the southern sector (APAT, 2006).
Quaternary continental deposits (Fig. 4b) are essentially breccias and conglomerates that can be referred to talus slope and debris cones, to alluvial fans and to eluvial and colluvial covers. There are also chaotic breccias that can be accounted for by paleo-landslide. Based on comparisons with the sector of the Sulmona basin, these deposits can be placed between the Early Pleistocene and the Holocene (Sylos Labini et al., 1993; Carrara, 1998; Miccadei et al., 1999; Lombardo et al., 2001). These deposits are distributed non-homogeneously along all of the slope, but have good continuity at the base and in the mid-slope.
The SW escarpment of Montagna del Morrone is formed by the limb of the anticline structure disarticulated by systems of normal faults, known in the literature as the Monte Morrone fault zone (Vittori et al., 1995; Ciccacci et al., 1999; Miccadei et al., 2002, 2004). The bedrock formations are generally in counter-slope dipping strata, with NW- SE attitude and dipping from 20°NE (in the low part of the slope) to 70°NE (in the high part). Locally, at the base of the slope, there are also SW dipping strata (Fig. 4a).
There are two main normal fault systems with a predominantly N40°-50°W orientation (Fig. 4). These displace the bedrock formations and superficial deposits, and clearly display morphological evidence at different heights on the slope, corresponding to sharp slope breaks or clear fault scarps as described in the following paragraphs.
From the base upwards the main fault systems are as follows:
Basal border fault: this is a system of normal faults with Apennine orientation and SW dip which affect the bedrock formations (displacement higher than 1000 m), as well as the superficial deposits (estimated displacement of 700 m in the breccias of the Lower?-Middle Pleistocene [Miccadei et al., 2002] and up to several tens of metres in the alluvial fans of the Upper Pleistocene). Towards the north, it is made up of fault plains with N20÷30W orientation, 60SW dip and located at heights from 550 m to 650 m a.s.l. (Popoli, Roccacasale). Towards the south, it is made up of faults with attitude of N50÷60/50SW placed at heights between 750 and 800 m a.s.l. (Eremo di Celestino V, Pacentro).
The Schiena d'Asino fault: this is a system of normal faults with a N20÷30W strike and 60°÷50° SW dip (displacement in the bedrock formations over 1000 m) located at heights between 1100 and 1400 m a.s.l.. These fault plains, in the northern and central parts, are characterised by large rock fault scarps. The system continues southwards, but with a clear reduction of displacement and morphological evidence.
In the middle part of the slope, there is a secondary fault system with a N30÷50W orientation, widely covered by surface deposits. Minor faults with a NE-SW orientation and

limited extension are also present transversal to the slope, but mostly in the central sector; they are characterized by thick cataclasite strata. In general they correspond to small valleys, mostly covered by surface deposits. They can be interpreted as transfer elements between the Schiena d'Asino fault and the Basal border fault.

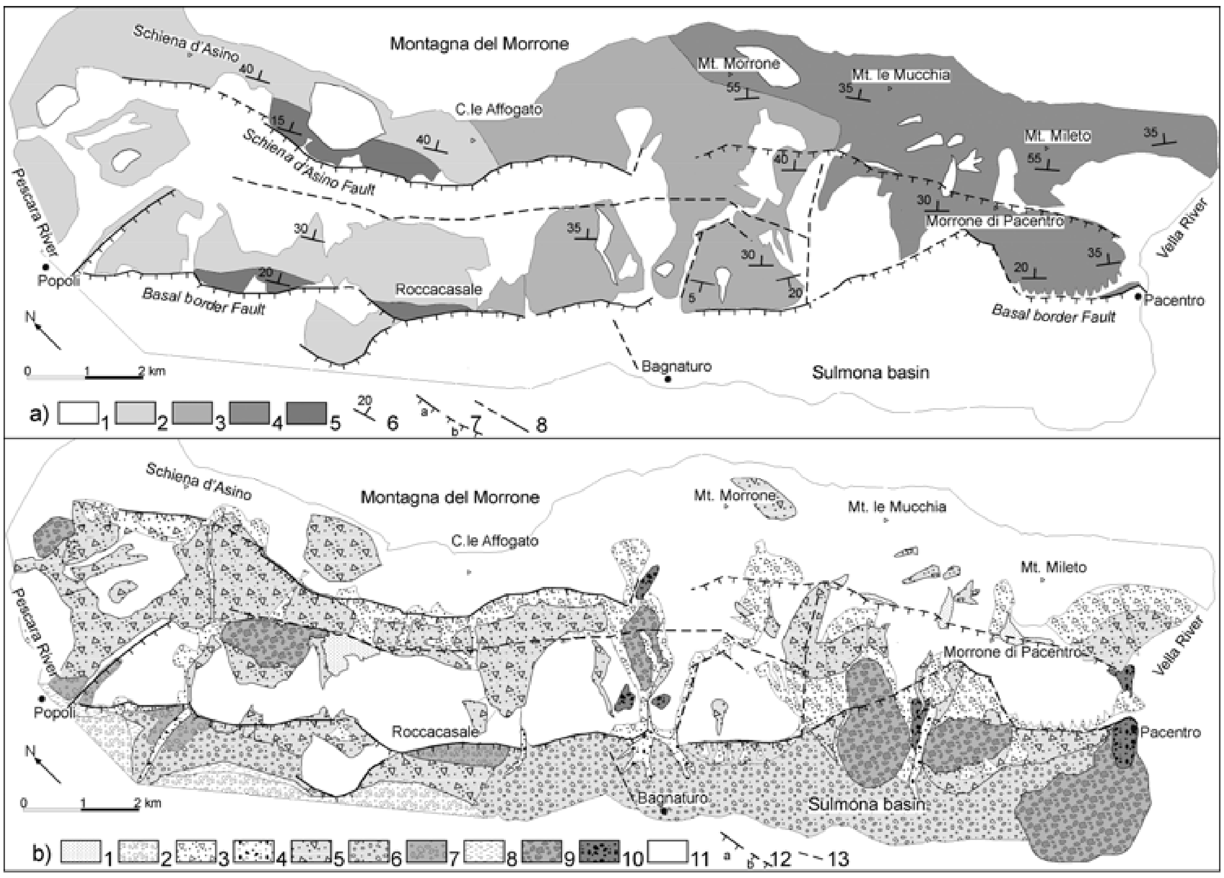

Fig. 4. Geological-structural scheme of the Montagna del Morrone SW slope (Miccadei et al., 2004). a) Bedrock units: 1) Superficial deposits; 2) bedded carbonate rocks; 3) massive carbonate rocks; 4) carbonate rocks in thick beds; 5) dolomite rocks; 6) attitude of strata and dip angle; 7) normal faults (a: visible slickenside; b: invisible slickenside); 8) faults. b) Quaternary continental deposits: 1) eluvial and colluvial deposits (Holocene); 2) sands and gravels, fluvial (Holocene); 3) loose stratified carbonate breccias, slope (Holocene); 4) loose carbonate gravel and breccias, alluvial fan (Holocene); 5) stratified carbonate breccias loose or poorly cemented, slope (Upper Pleistocene); 6) heterometric carbonate gravel and breccias loose or poorly cemented, alluvial fan (Upper Pleistocene); 7) heterometric carbonate gravel and breccias loose or poorly cemented, alluvial fan (late Middle Pleistocene); 8) limestone and clayey-silt, lacustrine (Middle Pleistocene); 9) heterometric and chaotic breccias, paleo landslide (Lower?-Middle Pleistocene); 10) cemented carbonate gravel and breccias, alluvial fan (Lower?-Middle Pleistocene); 11) bedrock formations (Meso-Cenozoic); 12) normal fault (a: visible slickenside; b: invisible slickenside); 13) fault

4.2.2 Geomorphology

This section includes results from orography and hydrography analysis and from geomorphological field mapping. Particular attention has been devoted to the morphometric analysis of the slope, of the drainage network and basins and of the alluvial fan/catchment systems. The main landforms mapped on the slope, both erosional and depositional, have been defined along with their relative morphogenetic agents. These data are described and discussed in the following paragraphs.

4.2.2.1 Orography

The analysis of orography and slope has outlined a NW-SE straight slope 20 km long and up to 1700 m high (Fig. 5) connecting the Sulmona basin (~350 m a.s.l.) and the Morrone ridge (2061 m a.s.l.). The planar and profile form of the slope consists of concave and convex elements, but mostly of planar segments and sharp breaks (Fig. 5). The orography analysis brought to light a strong longitudinal and transversal heterogeneity, and enables us to distinguish three sectors:

- northern sector, a double-ridged slope formed by two relatively down-faulted and uplifted blocks along the two major normal faults. It is made up of two rectilinear steep free faces, gently undulated (concave and convex) in plan, separated by an undulated horizontal or counter slope element.
- central sector, made up of three main units, a rectilinear steep free face upslope, a gently sloping midslope, undulated in plan, and then again a steep lower slope.
- southern sector, a single major uplifted block. The toe-slope is always marked by a sharp junction passing to the alluvial fan area with a high piedmont angle and it is broken by the mouths of narrow transversal valleys.

The Sulmona basin is a wide plain at 350-400 m a.s.l. partly dissected by the main river valleys (Aterno river, Sagittario river) with abrupt 50-100 m high terrace scarps.

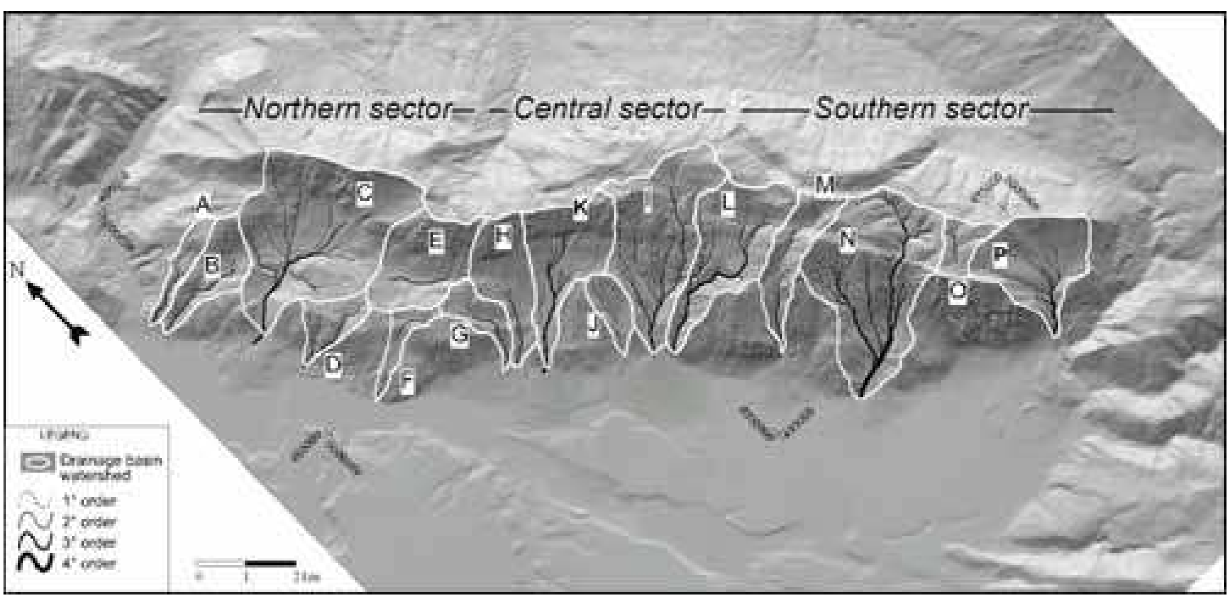

Fig. 5. Orography, drainage basins and network (ordered according to Strahler, 1957) of the Montagna del Morrone SW slope (Miccadei et al., 2004)

4.2.2.2 Hydrography

The drainage network on the steep and heterogeneous escarpment is made up of ephemeral stream channels and the toe-slope break, these stream channels become less defined, forming wide alluvial fans. The slope was subdivided into 16 basins (A-P; Fig. 5; Tab. 1, 2). Of these 16 basins, eight are spread from the line of the crest right to the base of the slope (C, H, I, K, L, M, N and P). Two are endoreic (E and O) on the upstream half of the slope and six develop on the downstream half of the slope (A, B, D, F, G and J). The relief of these basins varies from a minimum of 266 m at the endoreic Basin O, to a maximum of 1510 m at Basin I which extends down from the highest peak (2061 m a.s.l., Mt. Morrone) right to 551 m a.s.l. The total planimetric area of the 16 basins is about 50,0 km², while the total area of the slope is 74,3 km²: the slope is organised into drainage basins over 67% of its planimetric area, while the remaining 33% is made up of areas of interfluve.

Basin	Area (Km²)	Perim. (Km)	H (m)	L (Km)	Re	Rc	Rh	∫ ips	ΣNu	ΣL (Km)	D	F
A	0,85	5,60	809	2,59	0,40	0,34	0,31	0,49	3	2,46	2,88	3,51
B	1,92	6,70	792	2,87	0,54	0,54	0,28	0,47	3	3,75	1,96	1,57
C	9,03	13,25	1335	3,85	0,88	0,65	0,35	0,41	20	15,71	1,74	2,21
D	1,15	5,21	533	2,04	0,59	0,53	0,26	0,68	7	3,77	3,27	6,07
E	3,36	7,88	1021	2,83	0,73	0,68	0,36	0,27	4	4,17	1,24	1,19
F	0,76	5,65	667	2,37	0,42	0,3	0,28	0,65	1	2,64	3,45	1,31
Average Northern sect.	*2,85*						*0,31*	*0,50*			*2,42*	*2,64*
G	1,11	5,58	596	2,08	0,57	0,45	0,29	0,67	4	3,26	2,92	3,59
H	2,62	8,20	1360	3,22	0,57	0,49	0,42	0,47	4	2,85	1,09	1,53
I	5,78	12,22	1510	4,50	0,60	0,49	0,34	0,56	16	13,93	2,41	2,77
J	0,93	4,23	588	1,81	0,60	0,65	0,32	0,59	1	1,83	1,97	1,08
K	3,57	9,73	1425	3,84	0,56	0,47	0,37	0,52	14	6,58	1,84	3,92
Average Central sect.	*2,80*						*0,35*	*0,56*			*2,05*	*2,58*
L	4,38	10,85	1464	4,25	0,56	0,47	0,34	0,60	13	9,81	2,24	2,97
M	2,05	8,62	1420	3,45	0,47	0,35	0,41	0,67	3	4,39	2,14	1,46
N	7,75	12,01	1436	4,44	0,71	0,68	0,32	0,64	47	22,67	2,93	6,06
O	0,91	4,68	266	*1,15*	0,94	0,52	0,23	0,45	5	1,93	2,11	5,47
P	3,72	8,43	1230	2,61	0,83	0,66	0,47	0,62	13	6,46	1,74	3,49
Average Southern sect.	*3,76*						*0,35*	*0,60*			*2,23*	*3,89*
Average all basins	*3,12*				*0,62*	*0,52*	*0,33*				*2,25*	*3,01*
Total	*49,89*											

Table 1. Main area and relief geomorphic indices of the basins: H) maximum relief; L) longitudinal length; Re) elongation ratio; Rc) circularity ratio; Rh) relief ratio; ∫ips) hypsometric integral; ΣNu) number of stream segments; ΣL) total stream segment length; D) drainage density; F) drainage frequency

The areal and relief properties of the basins (Tab. 1: Re, elongation ratio; Rc, circularity ratio; Rh, relief ratio; Schumm, 1956; Mayer, 1986; Keller and Pinter, 1996) were analysed, together with the hypsometric data (Tab. 1: ∫ips; Strahler, 1952), not simply to give an indication of the morpho-evolutionary stage, but also to identify the principal situations of disequilibrium and structural control.

Basin	Nu (1°)	Nu (2°)	Nu (3°)	Nu (4°)	ΣNu	Rb (1°-2°)	Rb (2°-3°)	Rb (3°-4°)	Rb aver.	Nd (1°)	Nd (2°)	Nd (3°)	Rbd (1°-2°)	Rbd (2°-3°)	Rbd (3°-4°)	Rbd aver.	R aver.
A	2	1	0	0	3	2,0				2	1	0	2,0				
B	2	1	0	0	3	2,0				2	1	0	2,0				
C	14	5	1	0	20	2,8	5,0		3,9	13	5	1	2,6	5,0		3,8	0,1
D	4	2	1	0	7	2,0	2,0		2,0	4	2	1	2,0	2,0		2,0	0,0
E	3	1	0	0	4	3,0				3	1	0	3,0				
F	1	0	0	0	1	0,0				1	0	0	0,0				
G	3	1	0	0	4	3,0				3	1	0	3,0				
H	3	1	0	0	4	3,0				3	1	0	3,0				
I	12	3	1	0	16	4,0	3,0		3,5	11	3	1	3,7	3,0		3,3	0,2
J	1	0	0	0	1	0,0				1	0	0	0,0				
K	10	3	1	0	14	3,3	3,0		3,2	8	3	1	2,7	3,0		2,8	0,3
L	9	3	1	0	13	3,0	3,0		3,0	6	3	1	2,0	3,0		2,5	0,5
M	2	1	0	0	3	2,0				2	1	0	2,0				
N	34	9	3	1	47	3,8	3,0	3,0	3,3	28	8	3	3,5	2,7		3,1	0,2
O	4	1	0	0	5	4,0				4	1	0	4,0				
P	10	2	1	0	13	5,0	2,0		3,5	7	2	1	3,5	2,0		2,8	0,8
Total	115	35	9	1	160					98	33	9					
Average									3,2							2,9	0,3

Table 2. Geomorphic indices of the drainage network of the 16 basins present on the SW escarpment of Montagna del Morrone. Nu) stream number; Rb) bifurcation ratio; Nd) number of streams flowing into higher order streams; Rbd) direct bifurcation ratio; R) bifurcation index

The northern sector shows elongated (Re=0,4-0,5) and irregular (Re=0,7-0,9) drainage basins with moderately high relief ratios (Rh=0,26-0,36; Tab. 1). The drainage pattern is heterogeneous, sub-dendritic in the upper part and parallel in the lower part. Only Basin C is extended across the whole escarpment, but it shows a clear downstream narrowing (Fig. 5). The downslope interfluves are made of triangular-shaped fault related slopes passing upslope to moderate transversal spur ridges and then to the horizontal undulated mid-slope. In the upper part the valleys are just notched into the uplifted block of the Schiena d'Asino fault. The stream channels have concave-convex profiles with moderate knick points. The hypsometric integrals have values lower than in the southern sector (0,5-0,3) and show concave-convex curves (Fig. 6, Tab. 1).

The southern sector shows elongated (Re=~0,5) and irregular (Re=0,7-0,9) drainage basins with high relief ratios (Rh=0,23-0,47; Tab. 1), separated in the interfluves by wide straight rectilinear slopes (Fig. 5). The drainage patterns are parallel in the lower part of the slope and rectangular on the summit, the drainage density is moderate (1,74-2,93), intermediate between central and southern sectors, the stream channel profiles are convex with sharp knick points, the stream channel/interfluve relief is low, the ipsometric integral show high values (>0,6) and convex curves (Fig. 6, Tab. 1),.

The central sector is in an intermediate situation: the catchments are developed all along the slope, except for a single case (Basin J), but they show a strong downstream narrowing (Re=~0,5; Rh=0,29-0,42). The drainage pattern is parallel, transversal to the slope (Fig. 5), and characterised by the lowest drainage density (1,09-2,92). The stream channel profiles are mostly planar with moderate knick points and the hypsometric integral values are intermediate (0,4-0,6) with moderately convex curves (Fig. 5, Tab. 1).

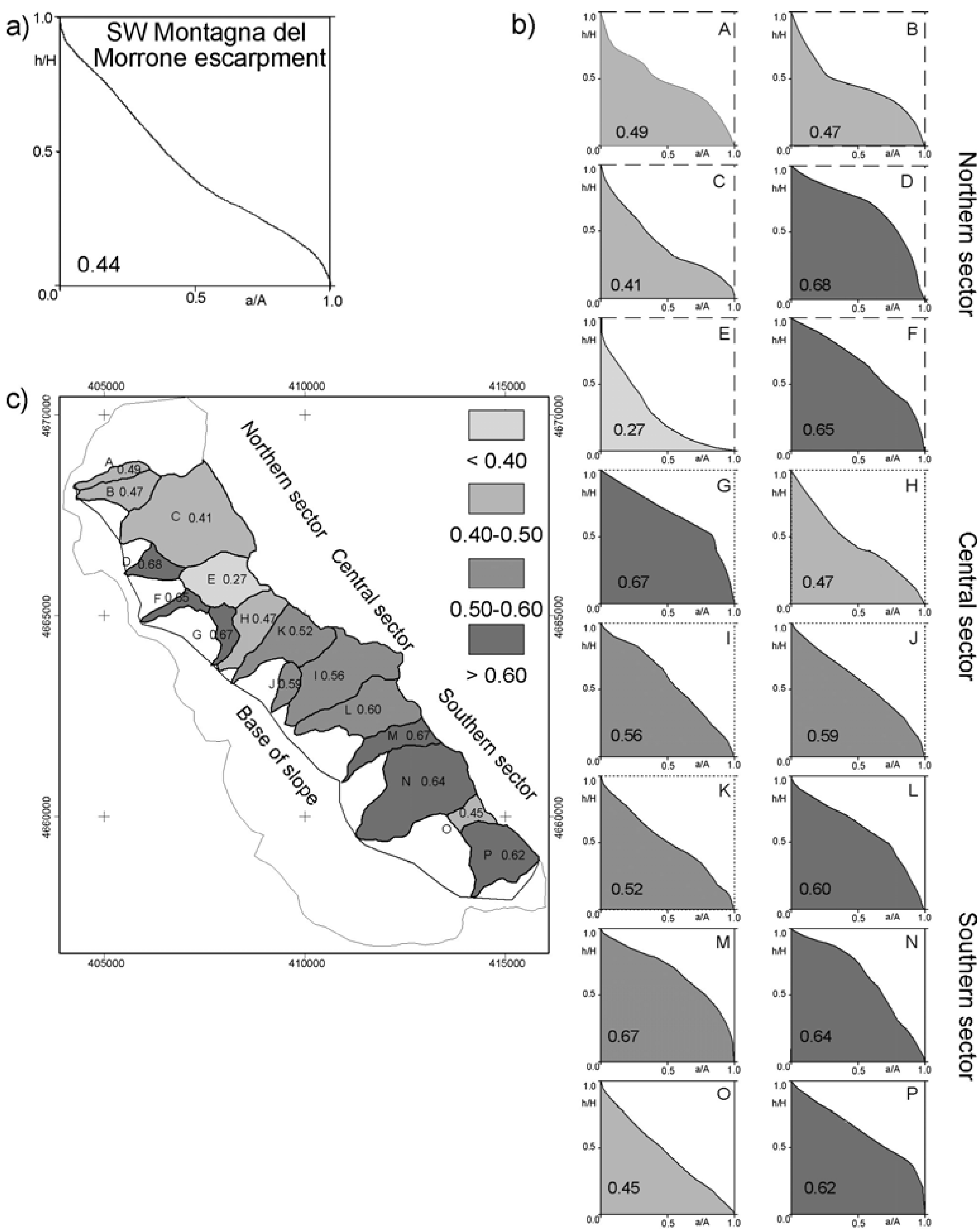

Fig. 6. Ipsometric analysis of the SW escarpment of Montagna del Morrone (Miccadei et al., 2004). a) Ipsometric curves and ipsometric integral value of the whole escarpment.
b) Ipsometric curves and ipsometric integral values of the 16 drainage basins.
c) Planimetric distribution of the ipsometric integral values

4.2.2.3 Structural landforms

The geomorphological surveys allow for the mapping of landforms such as fault scarps, fault related slopes and crests (Fig. 7), essentially controlled by the normal fault systems on the slopes.

Fault scarps are located on the slope, at various heights corresponding to the main fault lines. Three subtypes were distinguished: fault scarps, partly retreated and weathered fault scarps, retreated and weathered fault scarps (Demangeot, 1965; Wallace, 1977; Brancaccio et al., 1978; Bosi et al., 1993; Stewart and Hancock, 1994; Ascione and Cinque, 1997; Peulvast and Vanney, 2001).

The *fault scarps* are made up of rock scarps from some tens of metres to 100 m high, markedly straight, with a basal and a summit part. The basal part is made up of well smoothed scarplets, from a few decimetres to some metres high, 45° - 70° dipping. This typology occurs mainly in the northern sector of the ridge and in the upper parts of the slope. Along the basal fault line these can be identified between Popoli and Roccocasale, at heights from 400 m to 600 m.

The *partly retreated and weathered fault scarps* are rock scarps up to 100 m high, sinuous, 60°-35° dipping. The basal smoothed scarplets corresponding to the fault plain are only locally preserved and partially covered by scree slopes. Upslope the free faces have, to some extent, retreated from the fault line. Inactive talus deposits, and at certain points the apex of inactive alluvial fans, can show evidence of displacement. These features were identified at the base of the slope above all in the southern sector (Pacentro).

The *retreated and weathered fault scarps* can be identified as weak breaks in the slope, often discontinuous and partially or completely covered by surface deposits (talus debris and alluvial fans). These landforms are linked upslope to moderate and weathered rock scarps, which result from retreat of the fault scarps.

Fault related slopes: are made up of generally straight and rectilinear high angle slopes (30° - 60°), in limestone from stratified to massive, generally counter-slope plunging or sub-horizontal, bordered at the base by the different kinds of fault scarps described above. They are present particularly in the upper part of the slope, in the northern sector (Schiena d'Asino, C.le Affogato) and in the lower part (Popoli, Roccacasale, Pacentro) (Fig. 7). Especially in the central and southern sectors, they are incised by gullies and affected by slope processes that have formed talus slopes and debris cones, both inactive and active, at the base. In the lower part of the escarpment the fault related slopes, dissected by the outlets of the drainage basins, have a sub-triangular shape.

Crest lines: develop in a clear, sharp and slightly asymmetrical shape in the northern sector, while in the central and southern sectors they are more discontinuous, set upslope from a less inclined and gently undulating slope unit.

4.2.2.4 Slope landforms

Several slope landforms are mapped in the study area, even though non-homogeneously distributed: landslide scarps, rock slide bodies, talus slopes and debris cones and also evidence of deep seated gravitational slope deformations (Fig. 7).

Landslide scarps: are made up of arched or semi-circular rock scarps on limestone bedrock formations. They show a marked concave profile, but are generally very weathered. These forms are located on the higher parts of the slope, in the northern, central and southern sectors of the ridge.

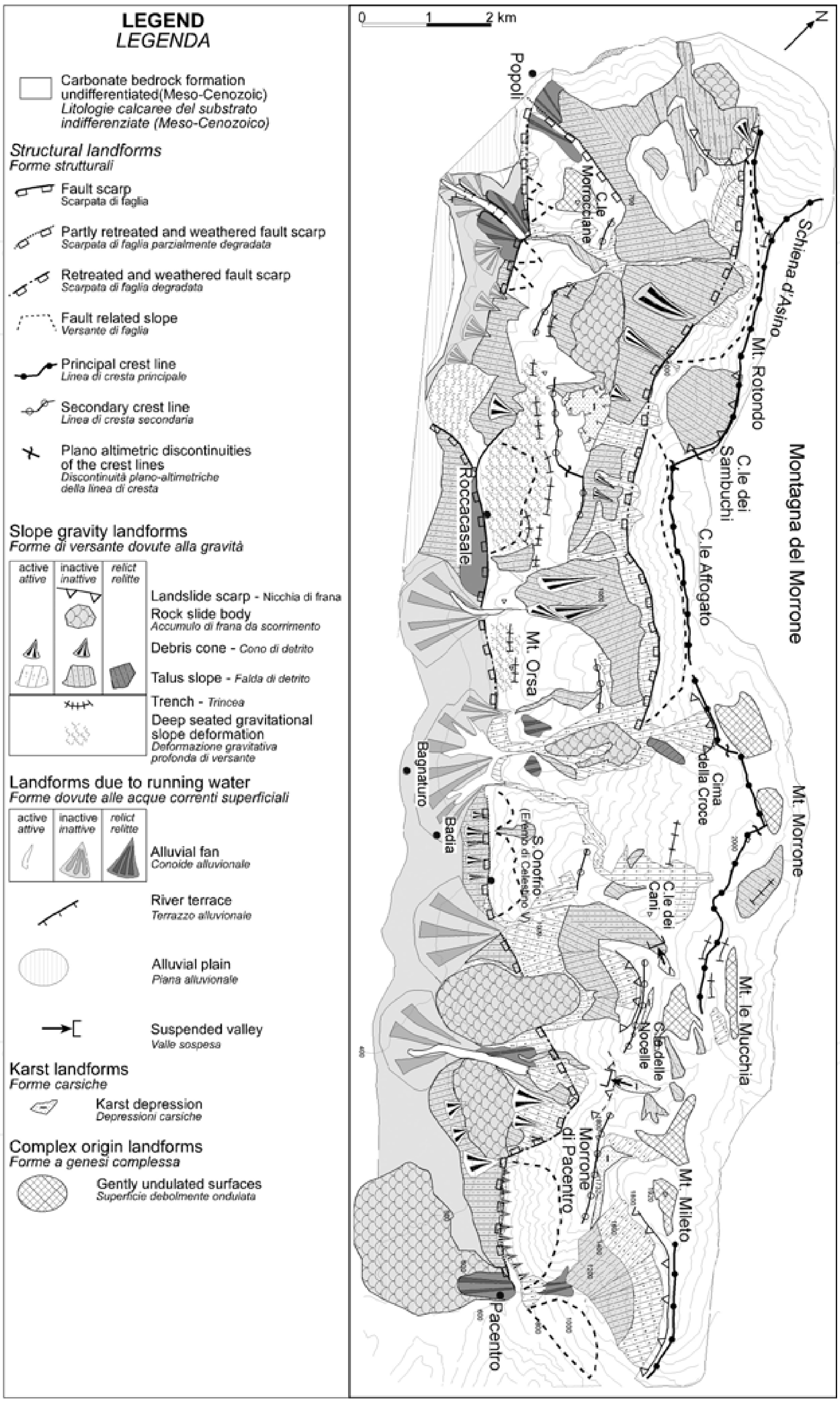

Fig. 7. Geomorphological map of the SW escarpment of Montagna del Morrone (Miccadei et al., 2004)

Rock slide bodies: are made up of limestone in large blocks and of heterometric carbonate breccias (up to boulder size) in a chaotic arrangement with abundant clay-silt matrix, or, in some cases, of considerable volumes of limestone stratified rock that still maintains the original lithostructural arrangement. They show with a surface up to 3 km² (length/width ratio of 2:1 to 1:2) and thickness up to hundreds of metres. The longitudinal profile of the slip surface and landslide body is always markedly concave-convex. The movement from the slip surfaces is variable from several hundred metres to several km. The movement is generally complex, however, it is principally attributable to translational and rotational rock slide mechanisms. Similarly to the slip surfaces, the landslide accumulation is also partially covered by talus slopes and debris cones, by active and inactive alluvial fans (Late Pleistocene – Holocene) and by some relict parts, which have been attributed to the Mid-Pleistocene (Miccadei et al., 1999). This suggests an Early?-Mid Pleistocene age for the landslides identified on the slope. They are therefore entirely inactive paleo-landslides; only a few minor ones can be attributed to more recent ages.
Talus slope and debris cones: are formed by bodies of heterometric carbonate breccias. Various inactive forms can be identified from the characteristics of the material, the abundance or absence of matrix, soil and vegetation or from the characteristics of overlooking rock slopes. They are present along the whole escarpment of Montagna del Morrone.
Deep seated gravity slope deformations (D.S.G.S.D.): some areas of the slope are interrupted by elongated trenches and sackung-like features running parallel to the slope itself (NW-SE to NNW-SSE orientation), which are some tens of metres wide and some hundreds of metres long (up to 1000 m). These depressions are in general partly filled with debris and colluvial deposits. These features bring to light the presence of D.S.G.S.D. (Cavallin et al., 1987; Crescenti et al., 1989; Dramis and Sorriso-Valvo, 1994). They are especially evident in the central-northern part of the slope at heights from 1200 m to 500 m, upslope from the principal fault slopes along the Basal border fault (between Popoli and Roccacasale). In some cases they can be identified also upslope from the fault slope of Schiena d'Asino. In the summit area of the southern sector the arrangement of the trenches and karst depressions lead to an elongated NW-SE oriented depression from several tens to hundreds of metres wide and several kilometres. These forms do not display signs of recent movement, but they are very evident indeed and have not be shaped or filled by the geomorphological processes.

4.2.2.5 Karst landforms and complex origin landforms

Mapped landforms are gently undulated surfaces, small karst depressions and suspended valleys (Fig. 7).
Gently undulated surfaces: are areas with gently undulating morphology shaped in the bedrock formation, at a height that ranges from 1800 m to 2000 m, close to the top of the ridge in the central and southern sectors. The occurrence of small dolines and karst valleys suggests that the karst weathering is an important morphogenetic factor.
Karst depressions: are closed depressions with irregular shapes, elongated with a NW-SE or SW-NE orientation, medium in size (length ranging from 500 to 1000 m, width ranging from some tens of metres to 200 m) and filled with residual soils and colluvium. They are located between Mt. Morrone and Morrone di Pacentro at heights of 1500 - 1750 m. Being suspended at these heights, some of these features have been preserved, while others were broken by the incision of the streams along the slope and, also in this case, by intersection with the slip plain of some of the major landslides (Fig. 7).

Suspended valleys: are small valleys, with a flat or concave floor, located in the upper part of the slope (central and southern sectors). They have a very gentle stream channel gradient, abruptly passing downstream to a high stream channel gradient. This creates knick points and strongly convex channel profiles.

4.2.2.6 Fluvial and water erosion landforms

Fluvial and water erosion landforms are mostly present in the lower part of the SW Morrone slope. Major landforms mapped are: fluvial terraces, alluvial plains, alluvial fans (Fig. 7). Alluvial fans are active, inactive or relict and were the subject of morphometric analysis of the fan/catchment systems.

Alluvial fans: all along the join between the slope and the plain several fans are present, ranging in size from several ha to 2,20 km^2 and with slope angles of up to more than 17°. The apex is located close to the Basal border fault, slightly upslope, entrenched in the fault related slopes and in the lower part of the catchments. Only the apex of Basin N is deeply entrenched, possibly because it is located between two wide landslide bodies (Fig. 7). The landforms are mostly inactive. The geometry and the spatial relationship between active and inactive forms indicate a general fan aggradation, except in the northern sector. Basin C, in particular, shows a clear entrenching of three subsequent fans and the formation of two orders of terraces.

Morphometric analysis of fan/catchment systems: the morphometric analysis on the main fan/catchment systems was processed in a GIS and on the DEM, following the most relevant literature (Bull, 1964; Saito, 1982; Blair and McPherson, 1994; Oguchi and Ohmori, 1994; Allen and Hovius, 1998; Allen and Densmore, 2000) and it is summarized in Tab. 3. The relationship between the main parameters and the interpolated functions are shown in Fig. 8. The first graph shows the relationship *fan area vs. catchment area* (Fig. 8a), defined by one of the most widely accepted functions ($A_f = k\ A_b^x$, where A_f = fan area , A_b = basin area, k and x = constant; Allen and Densmore, 2000), also defined by the ϕ ratio (fan area/catchment area; Allen and Hovius, 1998). Note the good alignment of most of the data except for a few anomalies (Basin C and N; triangular symbol in Fig. 8a).

The fan area was compared to the volume eroded from the catchments (EVc, Tab. 3, Fig. 8b), estimated as follows:

EVc = Vmax-Vc-TLVc (*Vmax* = volume of a prism with base corresponding to the catchment area and height to the catchment relief; *Vc* = volume between the catchment surface and a horizontal surface at the minimum height of the catchment; *TLVc* = estimated volume lacking because of the tectonic displacement along the Schiena d'Asino fault). In the third graph the relationship between the estimated fan volume (Vf) and the estimated volume eroded from the catchments (EVc) is shown (Fig. 8c). In both graphs the data distribution is similar to the first graph (Fig. 8a), but much more scattered; the anomalous data of Basin C and N is confirmed. The fourth graph (Fig. 8d) is similar to the first (Fig. 8a), but we must also consider the relief ratio (Rh) of the catchment in order to verify whether not only the dimension, but also the steepness could be an important factor in the geometry of the fans.

So the fan/catchment systems that seem to be anomalous in the previous graphs (Basin C and Basin N, triangular symbol in Fig. 8a,b,c,d) have been considered in detail. They both have a small alluvial fan, compared to the catchment area, and they have a low ϕ ratio value (fan area/catchment area) with respect to the other basins (Tab. 3). In the first case (Basin C) the deeply entrenched fans indicate the occurrence of deposition and erosion pulse, which led to the fan being undersize due to sediment removal. The geometry of the catchment and

the distribution of surface deposits in it, indicate the presence of possible internal storage points that could have contributed to the undersizing of the fans, preventing the sediment supply. In the second case (Basin N) the geometry of the drainage pattern, the basin, the stream channel profile and the ipsometric integral (Fig. 6,7) suggest that the upper part of the catchment underwent a capture during the evolution of the slope. Therefore, the morphometric ratios were recalculated eliminating the supposed captured part (N* in Tab. 3).
The four graphs of Fig. 8a',b',c',d' were reprocessed eliminating the anomalous data (Basin C, Basin N) and considering the recalculated data (N*): note the clear increase in the R^2 value of the regression line calculated. Particularly the approximation of the N* value to the tendency line could be an indirect confirmation of the capture process in the upper part of Basin N: the fan morphometry is still in equilibrium with the pre-capture catchment morphometry. Furthermore, note the increase of R^2 in the graph of Fig. 8d' in relation to the value in the graph of Fig. 8a' which suggests the influence of catchment steepness in defining the fan area.

Basin	Af (km^2)	Hf (km)	Lf (km)	Sf Hf/Lf	Vf (km^3)	Ac (km^2)	Rc (m)	Lc (km)	Rh c	LVc (km^3)	TLVc (km^3)	EVc (km^3)	∫ ips	ϕ
C (Tot)	1,64	0,160	1,64	0,10	43,7E-3	9,03	1335	3,850	0,35	7,05	2,00	5,05	0,41	0,18
C (pars)	0,46	0,070	0,85	0,08	5,4E-3	9,03	1335	3,850	0,35	7,05	2,00	5,05	0,41	0,05
K	1,44	0,200	1,44	0,14	47,9E-3	3,57	1425	3,836	0,37	2,48	0,30	2,18	0,52	0,40
I+L	2,20	0,320	1,95	0,16	117,3E-3	10,16	1510	4,500	0,34	6,23	1,60	4,63	0,58	0,22
J	0,46	0,225	1,17	0,19	17,1E-3	0,93	588	1,811	0,32	0,23	x	0,23	0,59	0,49
J+I+L	2,66	0,320	1,95	0,16	141,7E-3	11,09	1510	4,500	0,34	6,45	1,60	4,85	0,59	0,24
M	1,17	0,255	1,28	0,20	49,8E-3	2,05	1420	3,448	0,41	0,94	x	0,94	0,67	0,57
N	1,39	0,100	1,16	0,09	23,2E-3	7,75	1436	4,440	0,32	4,12	x	4,12	0,64	0,18
N*	1,39	0,100	1,16	0,09	23,2E-3	4,75	1360	2,950	0,46	2,58	x	2,58	0,60	0,29
N**	1,74	0,350	2,16	0,16	33,7E-3	4,75	1360	2,950	0,46	2,58	x	2,58	0,60	0,37

Table 3. Morphometric parameters of the main alluvial fan and related source catchments (C, northern sector; K, J, I, L, central sector; M, N, southern sector). Af) Fan area; Hf) Fan relief; Lf) Fan length; Sf) Average fan slope; Vf) Estimated fan volume; Ac) Catchment area; Rc) Catchment relief; Lc) Catchment length; Rh c) Catchment relief ratio; LVc) Catchment lacking volume; TLVc) Tectonic lacking volume; EVc) Estimated eroded volume; ∫ ips) Hypsometric integral; ϕ) Fan area/Catchment area; x) negligible; N*) without possible captured upper part of the catchment; N**) considering the entrenched apex

4.3 Discussion
4.3.1 Orography and hydrography
The distribution of slope and relief is irregular in relation to the tectonic setting (Fig. 9): in the southern sector, slope and relief are mostly in the lower part along the wide free face; in the central and particularly in the northern sector, slope and relief are mostly in the upslope, low in the midslope and increase again in the lower part down to the toe-slope break.
The hydrography analysis outlines a poorly developed drainage system with slow denudation processes and strongly controlled by extensional tectonics. The southern sector of the ridge is characterized by a poorly dissected morphology and a clear stage of inequilibrium. This is due to a strong lithological and tectonic control: a single block of resistant rocks relatively uplifted by the activity of the Basal border fault and poorly incised by the drainage network.

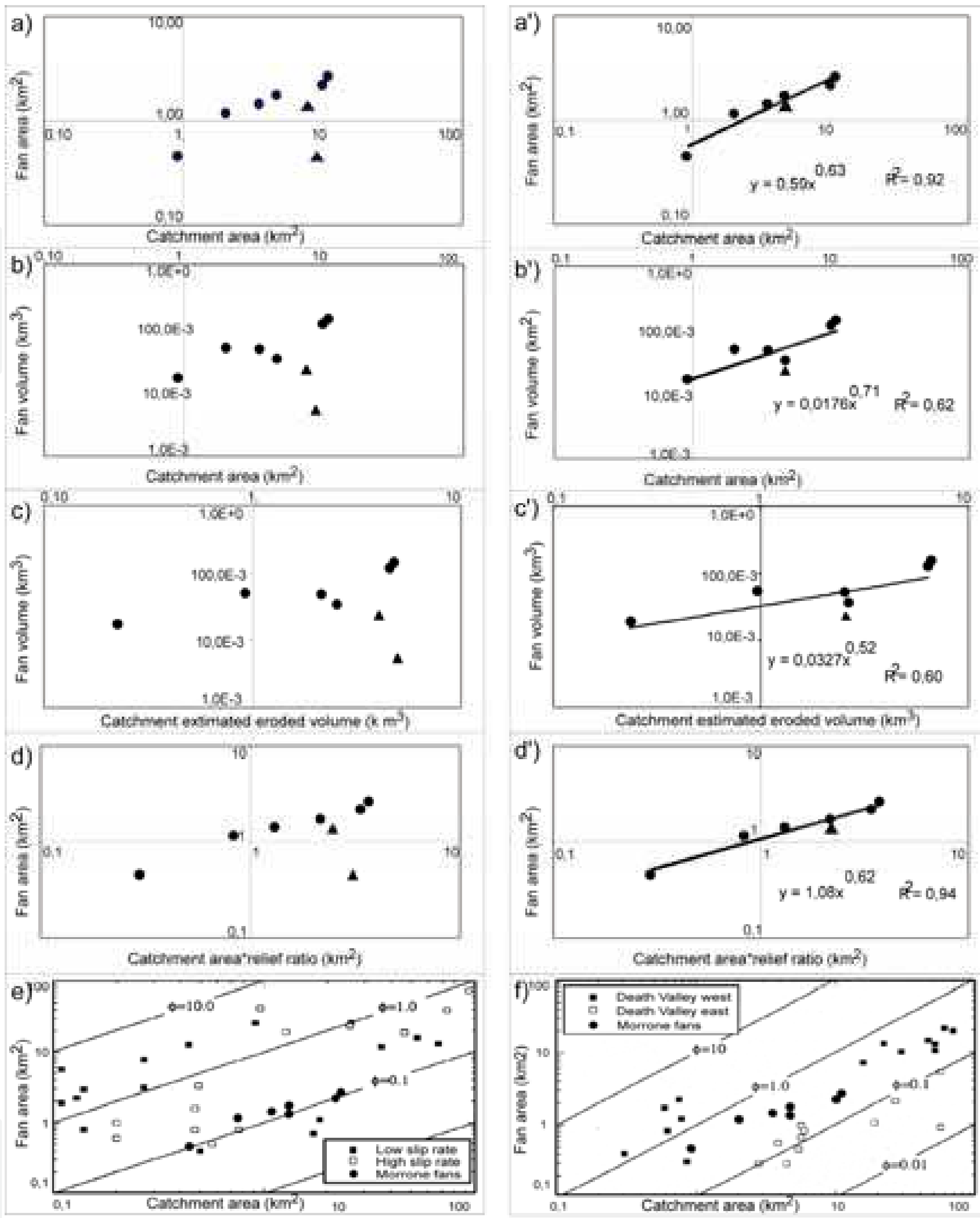

Fig. 8. Graphics illustrating the relationships between some of the main morphometric parameters of alluvial fan/catchment systems (refer to Tab. 3). Note the logarithmic axes; each symbol represents a single fan/catchment pair (Circle: normally developed fan/catchment systems; Triangle: anomalous developed fan/catchment systems; see text for detail).
a) Fan area vs. catchment area. b) Fan volume vs. catchment area. c) Fan volume vs. catchment estimated eroded volume. d) Fan area vs. catchment area x relief ratio. a') b') c') d') are the same graphics of a, b, c, d, reprocessed eliminating and recalculating the anomalous data (see text for detail). e) comparison of values of ϕ ratio (fan area/catchment area) calculated on the Montagna del Morrone with value obtained from numerical modelling (Allen and Densmore, 2000). f) comparison of values of ϕ ratio (fan area/catchment area) calculated on the Montagna del Morrone with value calculated in different structural context (Death Valley, Nevada U.S., Allen and Densmore, 2000)

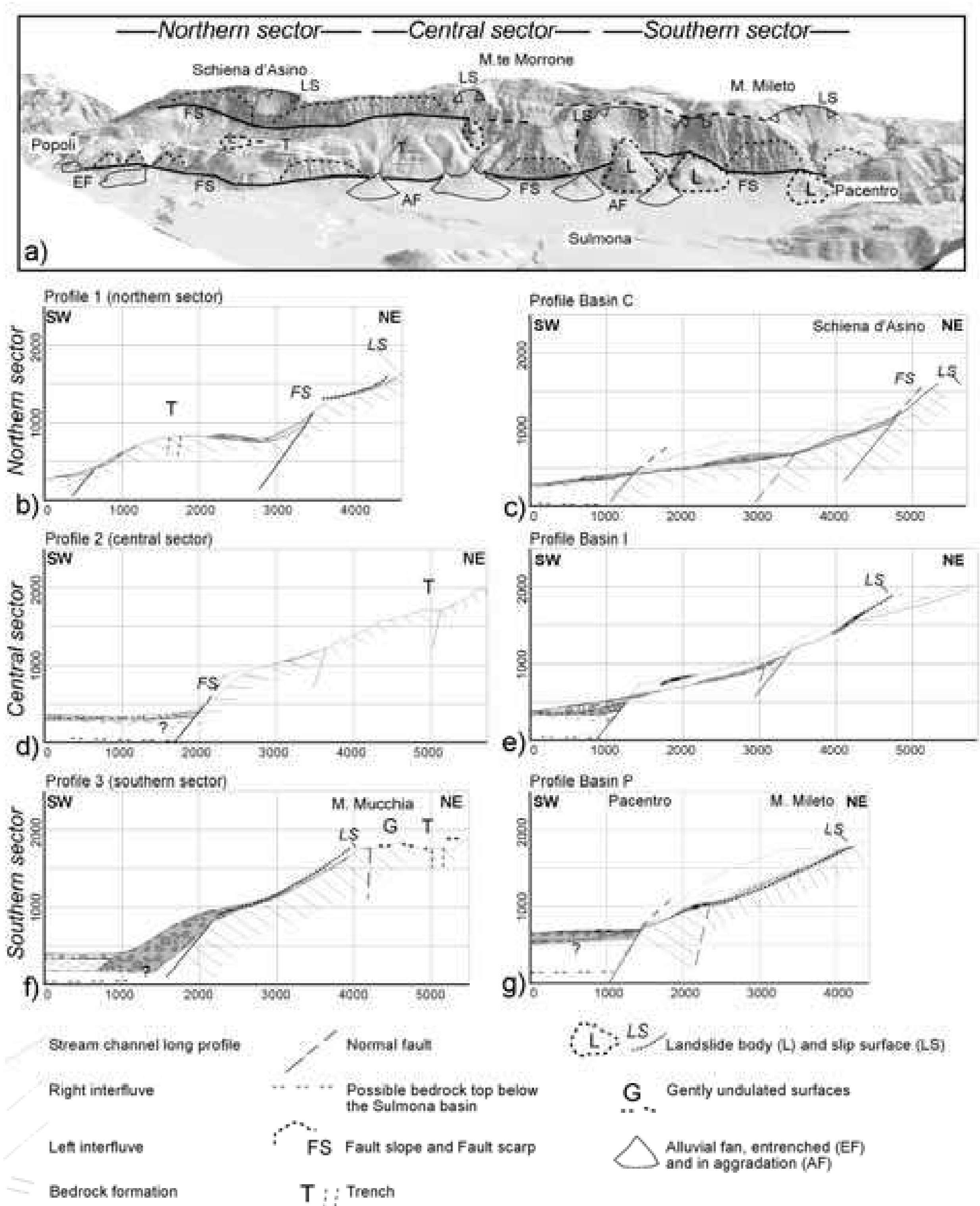

Fig. 9. a) Synthetic 3D morphostructural scheme profiles of the SW escarpment of the Montagna del Morrone (Miccadei et al., 2004). b, c) synthetic transversal and stream channel morphostructural profiles of the northern sector of the escarpment; d, e) synthetic transversal and stream channel morphostructural profiles of the central sector of the escarpment; b, c) synthetic transversal and stream channel morphostructural profiles of the southern sector of the escarpment (for the legend of the deposits see Fig. 4)

The different morphometry of the drainage of the northern sector is thought to be due not to a different development of the erosional processes, but to a different morphostructural setting of this sector of the escarpment. It consists of a double-ridge made up of two different blocks risen in parallel along the Basal border fault and the Schiena d'Asino fault, which have formed two separate fault related slopes with the slightly undulated area in between (Fig. 4, 9). This setting has led to the separation of the catchments between the upper and lower blocks of the slope and the concave-convex hypsometric curve of the basin developed throughout the escarpment (Basin C).

This setting of the central sector is controlled by the interplay of principal faults parallel to the ridge and secondary transversal faults (Fig. 4, 9): the southern termination of the Schiena d'Asino fault, with a reduced morphostructural role, has formed an upper fault related slope, but has not separated upper and lower catchments as in the northern sector. The relative uplift of the lower block along the Basal border fault and the conflicting drainage deepening brought about the downstream narrowing of the catchments. The secondary transversal faults control the development of the parallel drainage network.

4.3.2 Geomorphology

The geomorphological surveys allow for the mapping of structural landforms, slope landforms, karst landforms and fluvial and water erosion landforms.

The processes that have controlled the evolution of the escarpment are highlighted by the characteristics and degree of physical weathering, retreat of fault scarps and fault related slopes, and in particular by the analysis of transversal profiles (mostly rectilinear with more or less evident rock scarps, Fig 9) when compared to the distribution of slope depositional forms (rock landslides and talus slopes) (Fig. 7).

The variable degradation of the fault scarps and the morphology of the fault slopes (according to Brancaccio et al., 1978; Wallace, 1978; Blumetti et al., 1993; Bosi et al., 1993; Stewart and Hancock, 1994; Ascione and Cinque, 1997; Peulvast and Vanney, 2001), suggest a variable balance between the relative tectonic uplift, rejuvenating the fault scarps, and the slope denudation processes. Variability of rock resistance seems to have a control on the development of the geomorphic processes influencing the physical weathering because of the different type of stratification, degree of fracturing and local presence of cataclasite.

Moreover, it is worth noting that the upslope profile of several fault scarps is poliphasic (Fig. 9). This suggests again the cyclic alternation of relief building phases linked to tectonic activity and slope denudation events.

In the northern sector, the slope related to the Schiena d'Asino fault shows a profile made up of a clear fault scarp separating slope segments with different dip angles (Fig. 9b, c). Upslope there are many minor rock cliffs and secondary scarps, while downslope there is a talus slope. On the basis of the models proposed by the literature, particularly for the Apennine area (Demangeot, 1965; Brancaccio et al., 1978; Bosi et al., 1993; Ascione and Cinque, 1997), the slope is thought to be affected by a period of repeated tectonic activity with slope development by replacement with moderate sediment accumulation on the downfaulted block. A possible renewal of the tectonic activity would have formed the present basal fault scarp, which is only partly weathered. On the slope related to the Basal border fault, only triangular shaped fault related slopes, retreated and developed, are preserved (Fig. 9b,c; Brancaccio et al., 1978; Wallace, 1978). This clearly shows the role of drainage downcutting in the geomorphology of the lower part of the northern sector.

In the southern sector, the geomorphological characteristics of the escarpment indicate that the relative uplift has taken place mostly on the Basal border fault (Fig. 9f,g). The basal fault scarp has in many cases clearly retreated and the fault line is covered by scree (Demangeot, 1965; Ascione and Cinque, 1997). Furthermore, on the fault related slope, there are wide rock landslide bodies and remnants of relict alluvial fans, referable to Early?-Mid Pleistocene age. This suggests an early stage of strong activity on the Basal border fault, leading to slope development by wide and sudden mass movements together with early slope replacement processes on the resistant, but highly jointed rocks. This created a steep slope, mostly planar, and supplied slope deposits along the slope down to the base, which are now preserved in remnants. The continuation of the fault activity, possibly at a reduced rate, has brought about a gradual slope development, shaping the basal fault scarps with a high sediment supply that has partly covered the fault lines, the relative scarplets and the landslide bodies placed on them (Fig. 7, 9a,f,g).

Several slope landforms are mapped in the study area, even though non-homogeneously distributed: landslide scarps, rock slide bodies, talus slopes and debris cones, and also evidence of deep seated gravitational slope deformations (Fig. 7, 9). The most significant landforms are large rock landslides mapped on the escarpment. Based on the geomorphological analysis, these landforms are thought to have started as deep seated gravitational slide deformation (D.S.G.S.D.), then evolved as large landslides (Dramis and Sorriso-Valvo, 1994; Dramis et al., 1995).

The distribution of such landforms is linked to the distribution of slope and local relief. In the southern sector of the ridge, the slope and local relief is concentrated in the basal part of the slope, corresponding to the Basal border fault related slope, where the main landslide bodies are located. Poor evidence of D.S.G.S.D. is mostly located in the summit area of the ridge. In the northern sector, however, the distribution of the slope and local relief in two parallel belts seems to have partly prevented the evolution of D.S.G.S.D. into landslides. Evidence for the former is in fact distributed along the lower part of the slope, while landslides are found only on the upper part of the slope, where the gradient becomes steep again.

On the basis of morpho-lithostratigraphic correlations with the relict alluvial fan deposits, these landslides can be dated to the Early?-Mid Pleistocene. The preparatory morphostructural conditions, such as high steep slope on carbonate jointed rocks, and the trigger causes, possibly related to strong seismicity necessary for the occurrence of this type of landslide, could be linked to an important morphotectonic phase during this period. This would have had a great effect on the morphogenesis of the slope. This is confirmed by the intense tectonic activity that took place between the Early Pleistocene and the Mid-Pleistocene, highlighted by various authors in the chain and periadriatic piedmont (Dramis, 1993; Bigi et al., 1996; Centamore and Nisio, 2003). So, possibly a large part of the relief of the slope should have already been formed in the early stages of the slope evolution (Early?-Mid Pleistocene) and would have further growth in later times, as confirmed by the geometry of the foot of the slip surfaces now suspended hundreds of metres above the base of the slope (Fig. 9 b, f, g).

Karst landforms and complex origin landforms on Mt. Morrone are found in the summit areas, as well as on several ridges of the eastern-central Apennines (Montagna Grande, Mt. Godi, Mt. Sirente, Monti Peligni, Maiella). These features have been attributed by many authors to remnants of a summit paleo-landscape and to different periods of shaping from the Late Miocene (Demangeot, 1965) to Late Pliocene-Early Pleistocene (Dramis, 1993; Coltorti and Farabollini, 1995; Centamore and Nisio, 2003). When considering the surface of the mid-slope in the northern sector, it is possible to identify a displacement of the undulated surface brought about by the Schiena d'Asino fault.

In our case, the landform characteristics and the geomorphological correlations with slope forms seem to suggest that the shaping of undulated surfaces and karst depressions may have started before the activity of the landslides between C.le delle Nocelle and Pacentro. This would allow the dating of the first genesis of these forms to a period before the Early?-Mid Pleistocene.

Geomorphological analysis of the alluvial fans has provided a significant contribution to the understanding of the morphostructural evolution of the escarpment and of its base junction with the Sulmona basin. The fans have been useful in defining the morphostratigraphic relationships between the deposits on the slope and in the basin, and also because of the volcanoclastic levels and paleosoil inside them, which have allowed the deposits to be dated (Miccadei et al., 1999). The morphometric analysis of the main fan/catchment systems is summarized in Tab. 3 and Fig. 8. The law which governs the fan area/catchment area relationship (according to Oguchi and Ohmori; 1994; Oguchi, 1997; Allen and Hovius, 1998; Allen and Densmore, 2000) is: $A_f = 0{,}59\, A_b^{0{,}63}$. Note that the constant k (0,63 in this case) has a direct relationship with the erodibility of the materials, as already indicated in Bull (1964), and an inverse relationship with the rate of the movement of the faults at the apex of the fans (Oguchi and Ohmori, 1994).

The analysis of the results that were obtained on the Montagna del Morrone SW escarpment has very clearly demonstrated how the values, and especially the value of the constant k, are among the lowest known in the relevant literature and similar to values measured on fault related slopes with a fault slip rate documented at some mm/yr (Fig. 8e,f; Allen and Hovius, 1998; Allen and Densmore, 2000). This can be only partly due to higher resistance of the bedrock and must therefore also be accounted for by the high slip rate of the slope's basal fault. The relationships between the other morphometric parameters are also governed by a power law, as the graphs of Fig. 8b′, c′ show. The data are more scattered, but they confirm the morphostructural considerations.

Another important aspect relates to the values for the fan area/catchment relationship, which are markedly far from the gathered data in Fig 8a, as similarly occurs for the other parameters (Fig. 8b, c, d). These values are of fan/catchment systems which have undergone noteworthy perturbation in their geometry (Basin C - Mancini fan; Basin N - Marane fan). In the first case there are several generations of fans that are built up one upon the other. The positioning of the alluvial terraces and the correlation with the terraces of the Sulmona basin demonstrate how the development of the fan itself was affected by external elements, such as the process of regressive erosion from the Gole di Popoli in the Sulmona basin (Ciccacci et al., 1999). This has extended its action headward, leading to a re-cutting of the fan and limiting its growth. The overall catchment geometry and the surface sediment distribution suggest that internal factors such as the existence of sediment storage points in the catchment, which tend to prevent the sediment supply to the fan, have also led to the fan being undersize. In the second case (Basin N) the geometry of the network, of the basin and its hypsometry (Fig. 4,5) show how a large part of the summit area of the basin itself may have been 'captured' during one of the recent phases of the slope's development. This is confirmed by comparing the value of the relationships calculated and illustrated in the graphs of Fig. 8. If the area that is considered the object of capture is excluded from the calculation, the data (triangular dot) clearly approximates to the regression line (cfr. Fig. 8 a, b, c, d, e Fig. 8 a′, b′, c′, d′). Moreover, the anomalous value in the relationships studied shows that the phenomenon must have come about recently, as the re-equilibrium of the fan-basin system has not yet been achieved. Since Allen and Densmore (2000) point to re-equilibrium periods that are in fact rapid (to the order of tens of thousands of years), even considering the presence of resistant lithologies, it seems possible to date the capture to the Late-Pleistocene.

Therefore, it can be stated that the morphometric analysis of fan-basin systems can be exploited in morphostructural contexts such as the central Apennines, whether it be in morphotectonic analysis of fault related slopes or in the assessment of the conditions of equilibrium for single fan-catchment systems, which contributes to the study of local morphostructural evolution.

Finally, the geomorphological evolution of the alluvial fans in the central and southern sectors can be summarized. In the southern sector they are relatively small, with high dip angles, in clear aggradation, and are controlled by structural factors such as the resistant rocks of the catchment bedrock and the high slip rate on the Basal border fault. Considering the relationship between landslide scarps, catchments and alluvial fans, according to Blair (1999), it is possible to argue that the initiation of the catchments was due to the emplacement of the large landslide body.

In the northern sector, the alluvial fans are controlled more by interaction with the geomorphological evolution of the Popoli gorge, the northern outlet of the Sulmona basin, than by these same structural factors (Ciccacci et al., 1999). The regressive erosion due to the incision in the Popoli gorge deeply affected the alluvial fans of this sector, but only just touched those of the central sector, without reaching the southern sector.

4.4 Landscape evolution of the escarpment between the Montagna del Morrone ridge and the Sulmona tectonic basin

The integrated morphotectonic approach to the study of the mountain landscape of the central Apennine chain allows us to outline the main steps of the escarpment between Montagna del Morrone and the Sulmona basin (Fig. 10). The results clearly indicate that it is a high activity fault-generated mountain front according to Bull and McFadden (1977), Bull (1977), Wallace (1978), Bull (1987), Keller and Pinter (1996), and Allen and Densmore (2000). These features include low sinuosity and faceting, high slope and local relief, elongated and out of equilibrium drainage basins, convex and knick pointed stream channel profiles, prevailing areal denudation processes, general aggradation of the alluvial fans at the base of the slope and morphometry of the alluvial fan/catchment system.

This fault-generated mountain front, however, shows a peculiar morphostructural setting, variable both longitudinally and transversally, which led us to define a partition in three distinct sectors: northern, central and southern (Fig. 9). This is closely associated with the morphotectonic evolution of the Montagna del Morrone ridge and the Sulmona basin, which is due to the contrast of local tectonic subsidence on the basin and regional uplift during the Pleistocene (Miccadei et al., 2002).

The geomorphological investigations highlight a complex cyclic evolution in succeeding stages with the dominance either of morphotectonics, linked to the conflicting fault activity and regional uplift, or of erosional processes, particularly during cold stages of Quaternary climate fluctuations (Miccadei et al., 2004).

In a general balance the growth of the escarpment has strongly exceeded and dominated the effect of denudation, due to the local subsidence of the Sulmona basin relative to the Montagna del Morrone blocks along the Basal border fault and the Schiena d'Asino fault and to the general uplift of the area,. This has created relief of up to 1700 m and enabled the maintenance of very steep slopes, on highly resistant rocks, which have been moderately weathered and incised by climate-controlled erosional processes. These processes are mostly due to drainage network linear down-cutting in the mid and lower part of the northern and central sectors, while slope areal denudation is prevailing in the upper part of the northern and central sectors and in the southern sector.

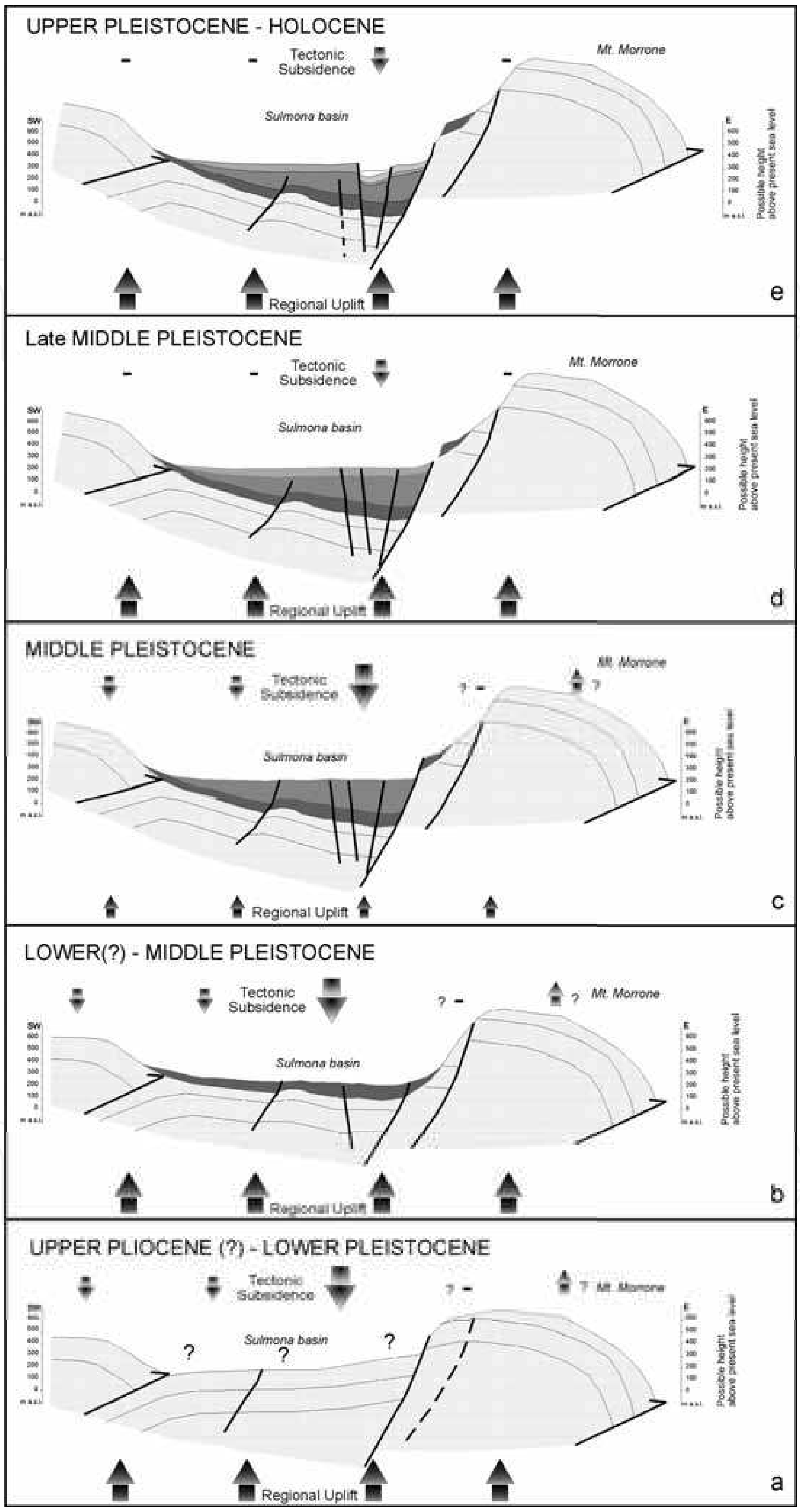

Fig. 10. Evolution of the escarpment between the Montagna del Morrone ridge and the Sulmona basin (Miccadei et al., 2002)

In conclusion, it is possible to define the evolution of the escarpment between the Montagna del Morrone ridge and the Sulmona basin as a growth evolution, rapid in the earlier stages and then continuing in the later phases. We can summarise the main stages of this morphotectonic evolution as follows (Fig. 10):

- Early moderately high relief incised by geomorphic processes, among which possibly karst weathering; remnants of this landscape, though reworked by karst processes and nivation, are preserved on the top of the ridge (Lower? Pleistocene);
- Growth of the slope due to the strong activity of the normal fault; earlier doubling of the ridge in the northern sector; the central sector begins to work as a structural transfer; the occurrence of fractured carbonate rocks, the high local relief and high slope, and eventually, the occurrence of earthquake-triggered landslides, led to the emplacement of large rock slides and to sediment accumulation along the slope (scree slope breccias, alluvial fan conglomerates) (Lower?-Mid Pleistocene);
- Development of drainage basins similar to the present ones (including Basin C, eventually after an early capture of the upper part) and incision of previous alluvial fans (Middle Pleistocene);
- Erosion of the escarpment, mostly due to slope denudation processes in the southern sector (and upper part of the central and northern sector) and to stream incision in the northern sector (Middle-Late Pleistocene);
- Morphotectonics, though possibly less intense than in the earlier stages, led to a progressive renewal with evidence of faulting, along the basal fault scarp of the southern sector and along both fault scarps of the central and northern sector (renewal mostly evident in the upper slope along the Schiena d'Asino fault scarp); a perturbation of some of the alluvial fan/catchment systems, caused in the northern sector by headward regressive erosion on the alluvial fans, controlled by the Sulmona basin outlet evolution and by upstream capture phenomena in the southern sector (Middle-Upper Pleistocene);
- The erosion processes are capable of only partly contrasting the morphotectonic processes (evidence of faulting occurs mostly on Late Pleistocene alluvial fans) and have led to partial reorganization of the drainage basin, still now clearly out of equilibrium, particularly in the southern sector. The present morphotectonic setting is acquired (Upper Pleistocene-Holocene).

5. Case studies - piedmont area: dip stream valley (Sangro river valley)

5.1 Introduction

The Sangro river is, at present, 107 km long and flows on the Adriatic side of central Italy from the inner part of the Apennines to the coast. The direction of the river is variable, from N-S in the upper reach, to WNW-ESE, to SW-NE, to S-N, and, finally, to SW-NE in the lower reach (Fig. 1). The main tributary is the Aventino river, which flows along the eastern side of the Maiella massif and then into the Sangro 20 km away from the coast. The present drainage basin area is about 1560 km^2 and its mean elevation is 970 m a.s.l.; about 70% of the basin lies within the range area; 30% within the piedmont one. The Sangro river's long profile consists of several segments, the highest long valley gradient being in the intermediate sector between the range and the piedmont. Its course and long profile show that the Sangro river can be divided into different reaches based on abrupt bends and/or long gradient variations (Fig. 1). The first part of the Sangro river flows within the range on clayey-arenaceous Miocene foredeep deposits and meso-cenozoic carbonate sequences, and shows a regular long profile with knick points corresponding to the occurrence of carbonate rocks and thrusts. The intermediate reaches carve into thrusted pre-orogenic clayey and carbonate Oligo-Miocene pelagic sequences, overlain by sinorogenic clayey arenaceous Miocene foredeep deposits. This reach shows a marked convex shape with sharp knick points related to the lithostructural control of alternating clayey and carbonate rocks. The abrupt long gradient decrease corresponds to the front of the range. The lower reach incises with a concave long profile the Plio-Pleistocene clayey-sandy marine sediments of the Adriatic basin (Fig. 11).

The study area, the lower part of the Sangro valley, is located in the Adriatic piedmont, in the south eastern Abruzzi area and lies in a complex geological framework between the central Apennines and the coast (Fig. 11). This area is characterised by a cuesta, mesa and plateau relief at a moderate elevation, sloping from SW to NE, from 500 m a.s.l. to sea level. The Sangro river flows, in this area, from 150 m a.s.l. to sea level.

The geological setting is characterized by late-orogenic Plio-Pleistocene Adriatic foredeep units that, in the SW sector, unconformably overlie pre-orogenic Molise pelagic units (Fig. 1). The Plio-Pleistocene units consist of Middle Pliocene to Early Pleistocene foredeep terrigenous clayey-sandy deposits, up to 2000 m thick, with interbedded conglomerates, coarsening upwards into a sandstone-conglomerate regressive sequence. The structural setting is defined by a regional homocline gently dipping north-east and locally affected by systems of low displacement faults (NW-SE, SW-NE). The Plio-Pleistocene foredeep sequence unconformably overlies folded and thrusted Miocene-Pliocene structures.

In the SW sector (Fig. 12) the pre-orogenic Molise pelagic units are made up of a clayey pelagic Oligocene-Miocene formation (argille varicolori formation) and of a limestone and marly-limestone pelagic Miocene formation, which is followed by a pelitic and arenaceous-pelitic sin-orogenic foredeep Late Miocene sequence. The above mentioned units were affected by fold and thrust Miocene-Pliocene deformations that involved a major NE transport.

Pre-, sin- and late-orogenic sequences are unconformably overlain by Middle-Late Pleistocene and Holocene continental conglomerates and subordinate sands, mainly related to fluvial and alluvial fan deposits.

In the study area, characterized by non-conservative lithology of the bedrock and by widespread superficial deposits, the analysis of geomorphological evidence of tectonics and its correlation with the Quaternary continental deposits and drainage network contribute to defining the role of tectonics in the landscape development (Castiglioni, 1935; Rapisardi, 1982; Ciccacci et al., 1986; Aucelli et al., 1996; Centamore et al., 1996; Del Monte et al., 1996; Bigi et al., 1996; Belisario et al., 1999; Currado and D'Ambrogi, 2002; Molin et al., 2004; Scheidegger, 2004).

The present drainage network and basin of the Sangro river, similarly to those of the main Adriatic rivers, are characterised by general and local geomorphic markers of tectonics and by different types of anomalies: basin asymmetry, irregular long profiles and statistical azimuthal distributions, drainage pattern types, main channel position in the present floodplain, asymmetric distribution of fluvial terraces (Coltorti et al., 1991; Elmi, 1991; Aucelli et al., 1996; Del Monte et al., 1996; Currado and D'Ambrogi, 2002; Molin and Fubelli, 2005; Spagnolo and Pazzaglia, 2005).

The geomorphological study performed in the area allowed us: i) to identify the fluvial and alluvial fan deposits and the transverse and longitudinal geometry of the related terraces; ii) to qualitatively and quantitatively analyse the geometry of the drainage network; and iii) to determine the distribution and geometry of significant morphotectonic evidence such as linear valleys and asymmetric valleys, hanging and beheaded valleys, counterflow streams and river bends.

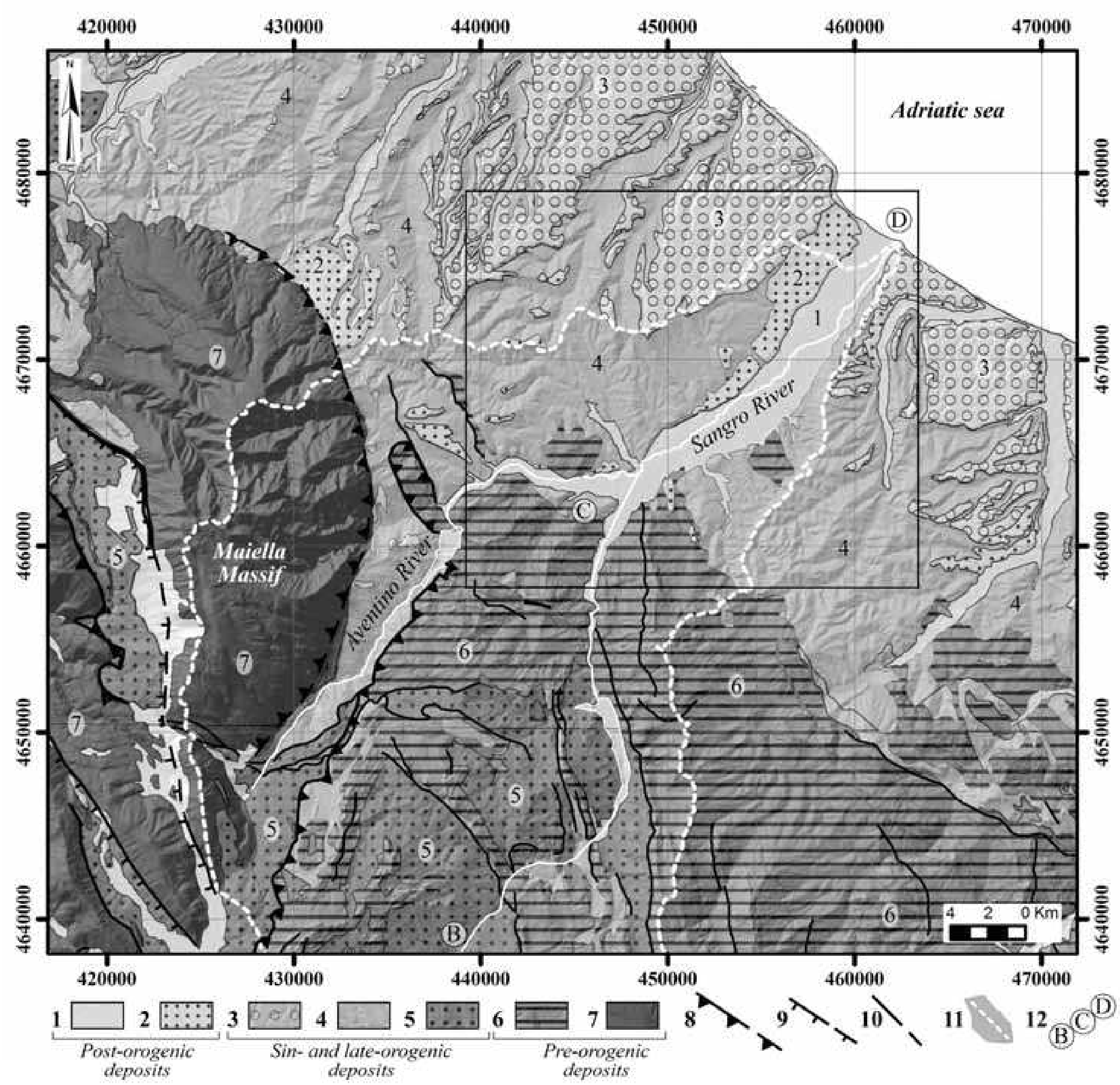

Fig. 11. Geological scheme of south-eastern Abruzzi and location of the study area (black box). Legend: *post-orogenic Quaternary continental deposits*, 1) fluvial deposits (Holocene), 2) terraced fluvial and alluvial fan deposits (Middle-Late Pleistocene); *sin- and late-orogenic terrigenous deposits*, 3) marine to continental transitional sequences (Early Pleistocene), 4) hemipelagic sequences with conglomerate levels (Late Pliocene-Early Pleistocene), 5) turbiditic foredeep sequences (Late Miocene-Early Pliocene); *pre-orogenic carbonate, marly and clayey deposits*, 6) Molise pelagic sequences (Oligocene-Miocene), 7) carbonate platform, slope and pelagic sequences (Jurassic - Miocene); 8) thrust (dashed if buried); 9) normal fault (dashed if buried); 10) fault with strike slip or reverse component (dashed if buried); 11) Sangro river drainage divide; 12) course of the Sangro river (Fig. 1)

5.2 Results

In the lower Sangro valley, five levels of terraced *fluvial and alluvial fan deposits* can be identified, at decreasing heights above the present alluvial plain. The terraces show a heterogeneous plano-altimetric distribution and different sedimentological characteristics, formed in both alluvial fan (T1, T2) and fluvial environments (T3-T5 and alluvial plain) (Fig. 12; Tab. 4).

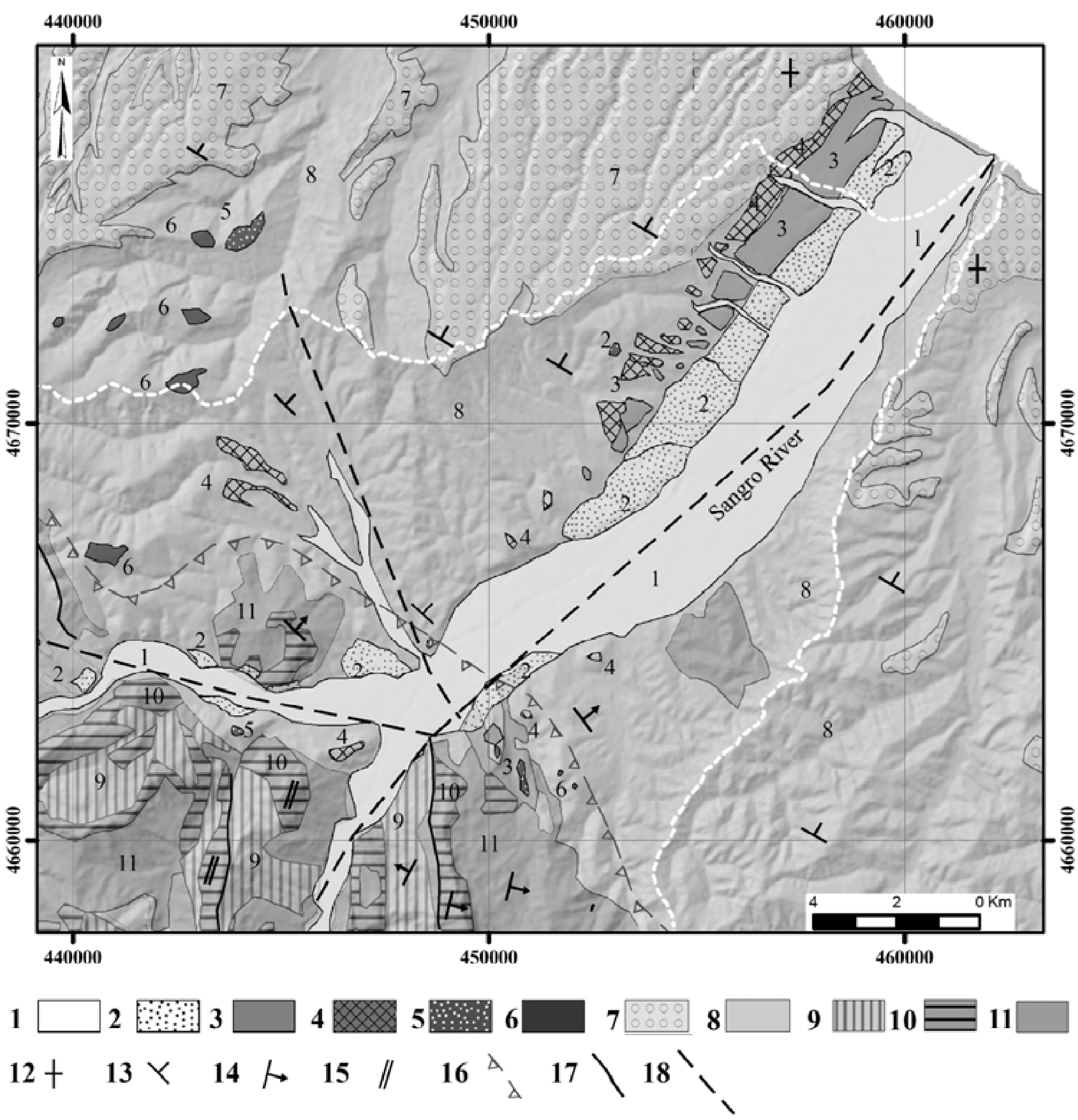

Fig. 12. Geologic and fluvial terraces map of the lower Sangro river valley (D'Alessandro et al., 2008). Legend: *post-orogenic Quaternary continental deposits*, 1) present alluvial plain deposits (Holocene), 2) fluvial terrace T5 deposits (Late Pleistocene), 3) fluvial terrace T4 deposits (late Middle Pleistocene), 4) fluvial terrace T3 deposits (Middle Pleistocene), 5) alluvial fan T2 deposits (Middle Pleistocene), 6) alluvial fan T1 deposits (Middle Pleistocene); *sin- and late-orogenic terrigenous deposits*, 7) conglomerates and sandstone of marine to continental transitional sequences (Early Pleistocene), 8) clays and sands of hemipelagic sequences with conglomerate levels (Late Pliocene-Early Pleistocene), 9) sandstone and siltstone of turbiditic sequences (Late Miocene-Early Pliocene); *pre-orogenic carbonate, marly and clayey deposits*, 10) limestone and marly-limestone of Molise pelagic sequences (Miocene), 11) clays of Molise pelagic sequences (Oligocene-Miocene); 12) 0-10° dipping strata; 13) 10-45° dipping strata; 14) 45-80° dipping strata; 15) 80-90° dipping strata; 16) buried thrust; 17) fault with strike slip or reverse component; 18) inferred neotectonic fault

The alluvial fan deposits (T1 and T2 in Fig. 12) are located at the summit of the hilly relief, at an elevation higher than 300 m a.s.l. and along the drainage divide between the Sangro basin and the surrounding ones. The fan deposits consist of heterometric, poorly sorted and sub-angular conglomerates (ϕ_{max}> 50 cm) with a matrix of fine gravel to sand. They show variable thicknesses up to 20 m and they are often deeply eroded or preserved only as gravel remnants on planar surfaces.

The fluvial deposits are distributed along the lower Sangro valley, more extensively on the NW side. On the SE side the deposits are rare and thinner. They are arranged in four levels, inset in the older alluvial fan terraces, at elevations decreasing from 280 m to the present valley floor (T3, T4, T5 and present alluvial plain, Fig. 12, Tab. 4). Along the NW valley side down to the river mouth, the terrace treads are at various heights above the present valley floor, decreasing from 150-100 m in the case of T3, to 120-60 m (T4), 50-30 m (T5), down to the present alluvial plain (Tab. 4).

Terrace	m *a.s.l.*	m *a.p.c.*	Deposit age
T6 (alluvial plain)	0-130	0	Holocene
T5	30-160	30-50	Late Pleistocene
T4	60-230	60-120	late Middle Pleistocene
T3	100-280	130-150	Middle Pleistocene
T2 (alluvial fan)	220-300	>160	Middle Pleistocene
T1 (alluvial fan)	330-350	>200	Middle Pleistocene

Table 4. The correlation of fluvial terraces, alluvial fan surfaces and related deposits is based on elevation (m a.s.l.) and height above the present channel (m a.p.c.); the age of the deposits is inferred from the correlation with surrounding basins in the Adriatic piedmont (Demangeot, 1965; Calderoni et al., 1991; Coltorti et al., 1991; Nesci et al., 1992, 1995; Fanucci et al., 1996; Di Celma et al., 2000)

The deposits of the four terrace levels are made up of heterometric, moderately-to-well sorted pebble-to-cobble conglomerates; they are generally clast-supported with sandy matrix. The thickness of fluvial deposits is moderate, up to 20 m in the lower part of the valley. The basal erosive unconformity on the Pleistocene clayey and sandy bedrock outcrops in several locations on the valley side, particularly in quarries located in the lower part of the valley.

The transverse profiles show the relative incision of the fluvial terraces in the alluvial fan terraces and of the different terrace levels one into the other. The valley long profile shows a general downstream convergent geometry of the terrace treads.

The age of fluvial and alluvial fan deposits is inferred from the correlation with the surrounding basins in the Adriatic piedmont, as indicated in the previous section. The alluvial fans and the highest fluvial terrace (T1, T2, T3) are ascribed to the Middle Pleistocene, the second fluvial terrace (T4) to the late Middle Pleistocene, the third (T5) is dated to the Late Pleistocene and the alluvial plain to Holocene.

The Sangro river shows a mainly sub-dendritic *drainage pattern* in the piedmont area and a generally angular or trellis one in the mountain zone, related, in general terms, to both lithological and structural control. In the lower Sangro valley (Fig. 13a) the total azimuthal stream analysis of the network confirms the general sub-dendritic pattern, showing a sub-elliptical shape, although E-W and NW-SE main orientations are present (Fig. 13b; Tab. 5).

However, considering only the main streams (3rd order or higher), a general angular pattern can be detected along SW-NE, WSW-ENE and NW-SE orientations, as shown by the azimuthal statistics of the main streams (Fig. 13c; Tab. 5).

Morphotectonic field mapping focused on valley features: linear and asymmetric valleys, hanging and beheaded valleys, river bends and counterflow confluences of streams (Fig. 14a). Planimetric distribution is seemingly non-uniform, however, the analysis of azimuthal distribution can highlight an alignment along preferential orientations (Fig. 14b; Tab. 6).

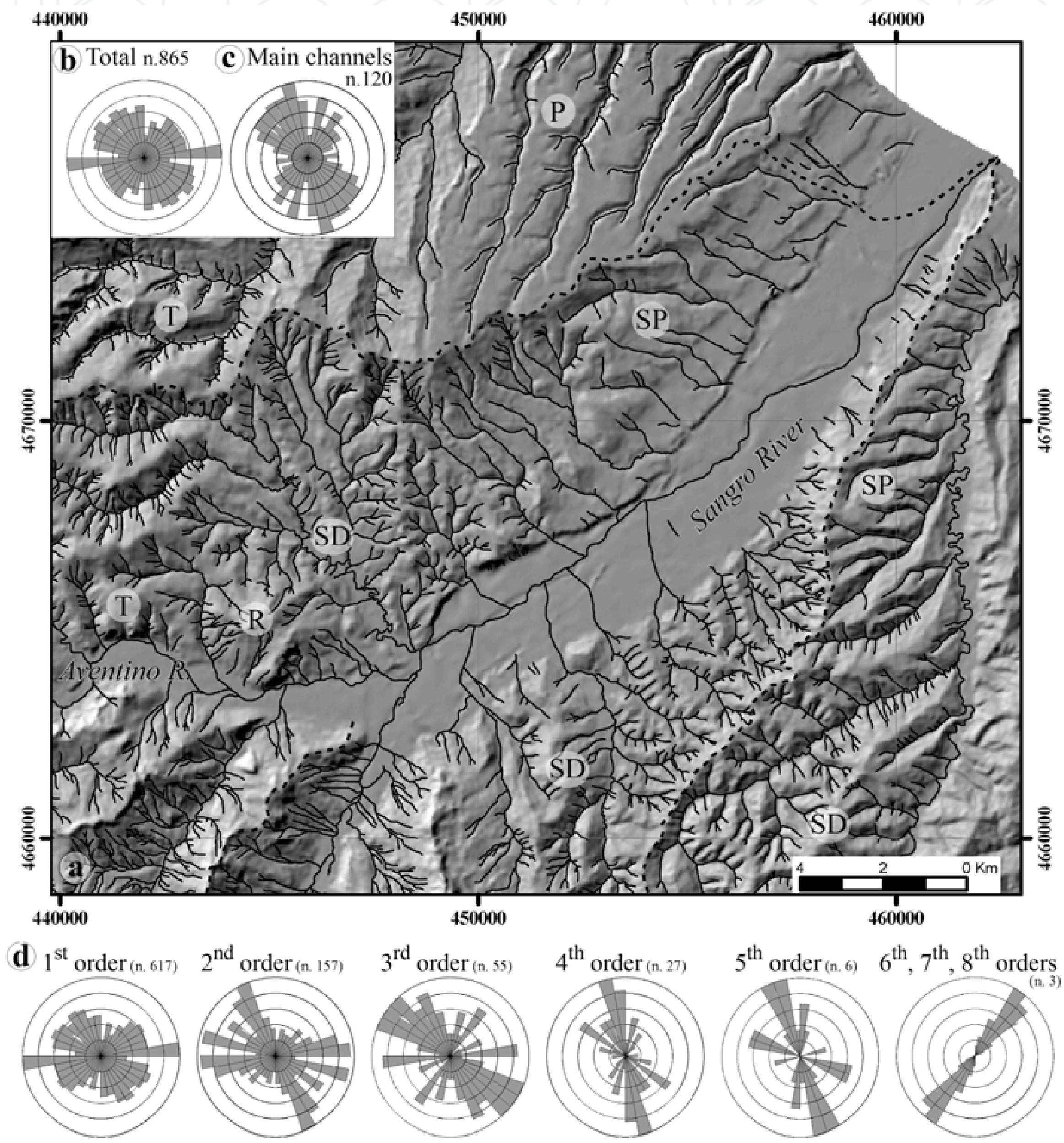

Fig. 13. a) Drainage network of the Sangro basin in the piedmont area and of the surrounding areas; the dashed line marks the drainage divide of the Sangro basin (D'Alessandro et al., 2008). Legend of local drainage patterns: SD) sub-dendritic; P) parallel; SP) sub-parallel; T) trellis; R) radial. b) Total stream azimuth rose diagram for the lower Sangro valley. c) Main stream azimuth rose diagram. d) Azimuth rose diagram of the streams ordered according to Strahler (1957)

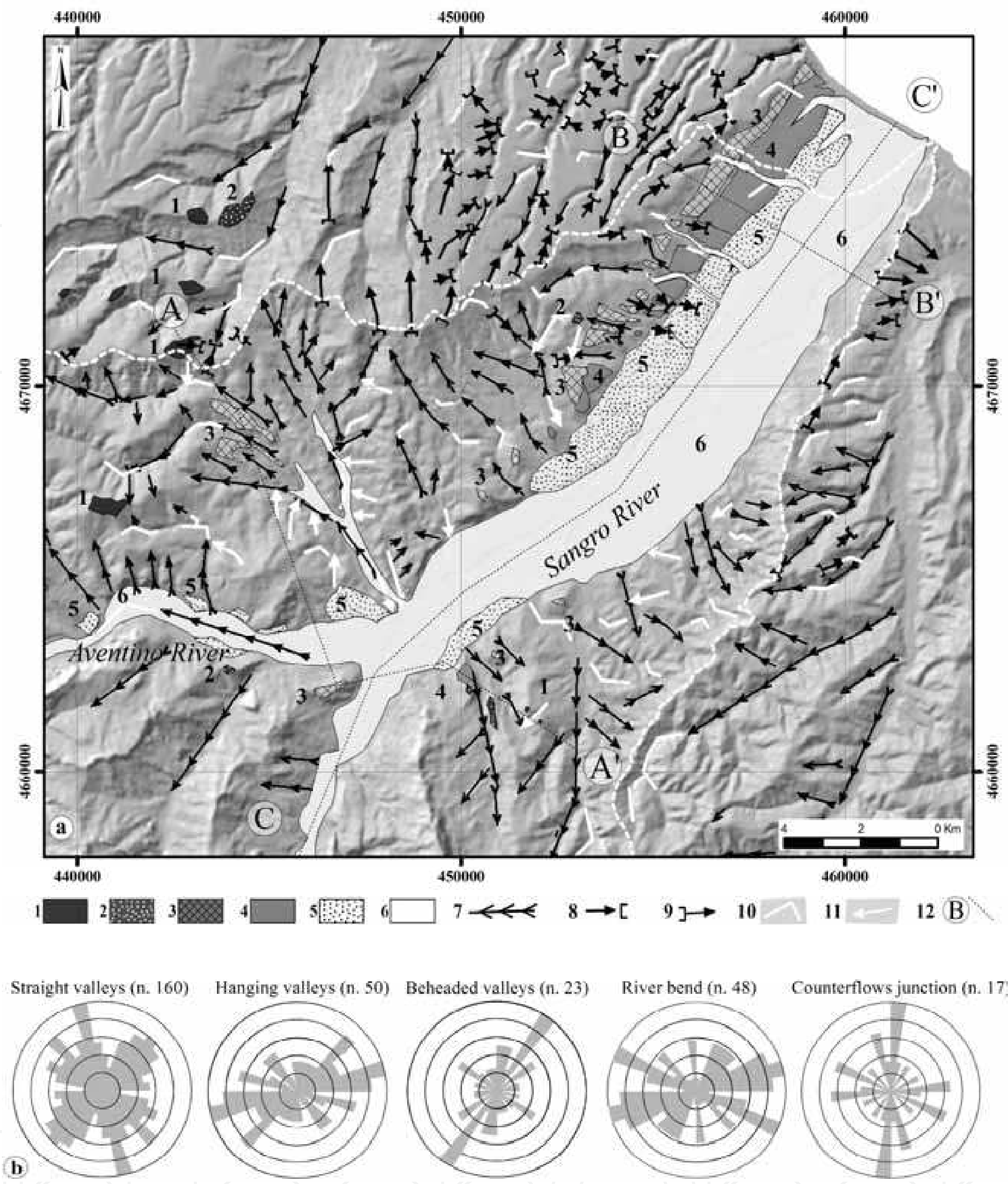

Fig. 14. a) Map of the morphological field evidence of tectonics (D'Alessandro et al., 2008). Legend: 1) alluvial fan surface T1; 2) alluvial fan surface T2; 3) fluvial terrace T3; 4) fluvial terrace T4; 5) fluvial terrace T5; 6) present alluvial plain; 7) linear and asymmetric valley; 8) hanging valley; 9) beheaded valley; 10) river bend; 11) counterflow confluence of streams; 7) profile locations (see Fig. 15). b) Azimuth rose diagram of morphological field evidence of tectonics

Linear valleys and asymmetric valleys show a main NNW-SSE orientation and secondary NW-SE and SW-NE orientations. These features - which are linked to the Late Pleistocene terrace (T5) - incise the Middle Pleistocene alluvial fan surfaces and the later fluvial terraces (T1 to T4) on the NW side of the Sangro valley, whereas they incise the Early Pleistocene clayey bedrock on the SE side.
The hanging valleys are located particularly on the northern and eastern sectors of the area, with WSW-ENE and SW-NE dominant orientations. River bends are frequent all over the

study area and particularly on the NW side of the Sangro valley (Fig. 14). The azimuthal analysis shows two prevailing orientations: WSW-ENE and NW-SE (Fig. 14b).
The planimetric distribution of the beheaded valleys indicates a dominant SW-NE orientation (Fig. 14). In particular, they are located along the present northern and southern drainage divide of the Sangro basin, and drain into the adjacent basins (Fig. 14).
Finally, the counterflow confluences are mainly on the NW side of the Sangro valley (Fig. 14), they show a prevailing N-S direction and are connected to NNW-SSE linear valleys. These elements are located in an area characterised by beheaded valleys.
The morphological evidence of tectonics allows us to detect morphotectonic lineaments, mainly SW-NE, along the main valley, on its right side and in the northern area outside the Sangro basin. These lineament are intersected by NNW-SSE and WNW-ESE ones, particularly in the SW sector of the study area (Fig. 14, Tab. 6). On the NW side of the valley the correlation between terraces and morphotectonic elements indicates that the SW-NE elongated beheaded valleys are intersected by NNW-SSE and WNW-ESE linear valleys and river bends. The beheaded SW-NE valleys lie on, or slightly incise, the sandy-conglomeratic regressive sequence on top of the marine Pleistocene succession; locally, they are correlated with T1 terraces. The linear valleys incise the Middle Pleistocene fluvial and alluvial fan terraces (T1-T4) and are correlated with the Late Pleistocene terrace (T5). On the right (SE) valley side, it is possible to detect the intersection of NE-SW minor elements (counterflow confluences, linear valleys) with major NNW-SSE and WNW-ESE linear valleys, as already suggested by the drainage pattern.

order	orientation
1st	E-W NW-SE
2nd	NNW-SSE E-W
3rd	NW-SE
4th	NNW-SSE
5th	NNW-SSE
6th 7th 8th	SW-NE

Table 5. Dominant azimuthal distribution of the ordered streams (Strahler, 1957)

elements	orientation
Linear valleys	NNW-SSE SW-NE
Asymmetric valleys	NNW-SSE E-W
Hanging valleys	SW-NW WSW-ENE
Beheaded valleys	SW-NE
River bends	WSW-ENE WNW-ENE
Counterflow confluences	N-S

Table 6. Dominant azimuthal distribution of the morphotectonic evidence

5.3 Discussion

The analysis and the correlation of fluvial terraces and alluvial fan surfaces, drainage patterns and morphotectonic evidence provide several indications concerning drainage development in the piedmont area of the Sangro valley since the Middle Pleistocene. Moreover, they allow us to evaluate the role and timing of tectonics in the development of the piedmont area of the Sangro valley.

The remnants of alluvial fan surfaces (T1 and T2; Fig. 12, 15), on top of the hilly relief and along the present drainage divide, outline a landscape completely different from the present one: a Middle Pleistocene wide piedmont plain on which - after the emergence and, more specifically, during early continental morphogenesis - large alluvial fans formed, as already observed in the northern sector of the Adriatic piedmont (Nesci and Savelli, 2003).

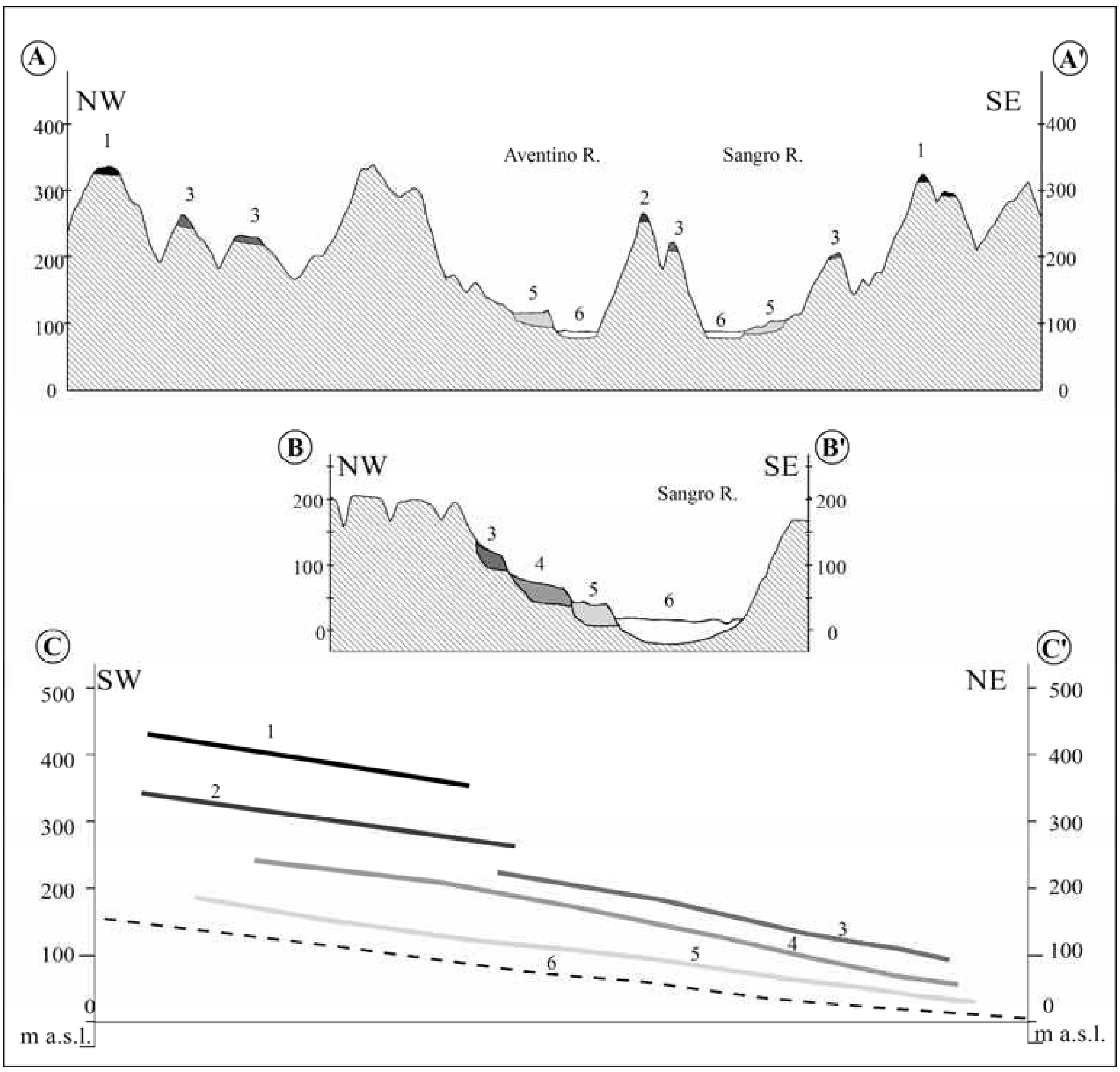

Fig. 15. Cross-valley and long profiles showing the relation of the terrace deposits with the local valley geometry (A-A', B-B') and the relations among the terrace tread levels (C-C') (D'Alessandro et al., 2008). Location and numbers legend are referred to Fig. 14

The plano-altimetric distribution of T3 and T4 fluvial terraces (Fig. 14, 15), elongated in the SW-NE direction and entrenched into the ancient fan surfaces and along both margins of the present valley, indicates the development of a subsequent SW-NE consequent drainage starting in the Middle Pleistocene (Coltorti et al., 1991; Nesci et al., 1992; Fanucci et al., 1996). This is confirmed by the SW-NE parallel pattern with marked SW-NE linear valleys, preserved in the northern area outside the drainage divide of the Sangro basin (Fig. 13).

On the NW side of the Sangro valley, a sub-parallel drainage is present along the NNW-SSE direction. Moreover, the sub-dendritic drainage shows NW-SE to NNW-SSE elongated main streams on both valley sides (3rd, 4th, 5th order, Fig. 13). These streams are marked by linear valleys that cut Middle Pleistocene fluvial terraces (T3 and T4) and are connected to the Late Pleistocene terrace (T5) (Fig. 14). This configuration indicates the control of local tectonics on drainage development along NNW-SSE faults and fractures, and suggests that the age of these elements can be ascribed to the late Middle Pleistocene (Fig. 12). The analysed counterflow junction of streams confirms tectonic control along the NNW-SSE orientation (Fig. 14). In the lower part of the valley, along the coastal area, the occurrence of SW-NE, NW-SE river bends and the anomaly in the path of the drainage divide can be related to the role of gravity deformation parallel to the coast.

On the SE side of the Sangro valley, SW-NE counterflow confluences and linear valleys carved on the clayey bedrock are aligned to the straight flank of the main valley and intersect NNW-SSE and WSW-ENE linear valleys. In this case, local tectonic control on the drainage is exerted also along SW-NE lineaments (Fig. 14).

Hence, a rectangular drainage network (*sensu* Zernitz, 1932) developed during the late Middle Pleistocene, as a result of the junction of previous SW-NE streams' directions - controlled by differential uplift and tilting - and new NNW-SSE, WNW-ESE and SW-NE streams' directions, controlled by local tectonics along faults and fracture systems (Figs. 12, 14). The development of the NNW-SSE streams, on the NW side of the Sangro valley, beheaded the previous SW-NE drainage, as highlighted along the present divide. A major rearrangement of the drainage widened the basin towards the left (NW) side. In this scenario local tectonics could be an additional explanation of the drainage basin asymmetry in the Adriatic piedmont.

Finally, the development of a sub-dendritic drainage pattern on the clayey Plio-Pleistocene bedrock in the peripheral parts of the basin, together with a local radial pattern on the clayey-calcareous Miocene sequence, indicates a prevailing lithostructural control in the last phase of drainage incision and in the definition of the present fluvial landscape.

5.4 Sangro dip-stream valley landscape evolution

The integrated morphotectonic approach to the study of the fluvial landscape of the Adriatic piedmont allows us to outline the main steps of the lower Sangro river valley evolution:

- alluvial fan development in a wide piedmont plain (Middle Pleistocene), following the emergence of the Adriatic basin, which progressively occurred during the Early Pleistocene due to regional uplift, as already observed in the northern Abruzzi and Marche area (Nesci and Savelli, 2003; Cantalamessa and Di Celma 2004);
- consequent SW-NE parallel drainage controlled by a regional topographic gradient, due to regional differential uplift with NE tilting and by SW-NE tectonic structures (Middle Pleistocene);
- superimposition of the SW-NE drainage on the uplifting piedmont and development of fluvial terraces (Middle Pleistocene – late Middle Pleistocene);

- development of NNW-SSE, WNW-ESE and SW-NE faults with low displacements and fractures (late Middle Pleistocene);
- adaptation of the drainage network to fault and fracture systems, and development of a rectangular pattern (late Middle Pleistocene – Late Pleistocene);
- rearrangement of the drainage network due to lithology-controlled morphoselective processes (Late Pleistocene – Holocene).

The role of regional uplift with NE tilting in the development of the piedmont consequent valleys is confirmed in the case of the Sangro river valley. Local tectonics, mainly along NNW-SSE, WNW-ESE and SW-NE faults and fractures (Fig. 10), played a crucial role in the rearrangement and configuration of the drainage network during the late Middle Pleistocene.

6. Conclusion

This chapter provides examples of morphotectonic studies undertaken in Abruzzi (central Italy) within chain and piedmont areas:
- chain area – escarpment between the Montagna del Morrone ridge and the Sulmona tectonic basin (central Abruzzi);
- piedmont area – dip stream valley (Sangro river valley, south-eastern Abruzzi)

These areas are characterized by different geomorphological features: 1) bedrock lithologies (conservative carbonate bedrock in the montane area, not conservative clayey-arenaceous-conglomeratic bedrock in the piedmont area), 2) surface deposits (slope and alluvial fan deposits in the montane area, fluvial and alluvial fan deposits in the piedmont area), 3) landforms (slope landforms and fluvial, and water erosion landforms in the montane area, fluvial and water erosion landforms in the piedmont area), and 4) tectonic framework (strong Pleistocene-Holocene extensional tectonics and uplift in the montane area, Pleistocene-Holocene uplift with poor local tectonics in the piedmont area).

The studies suggest that different features of morphostructural domains require similar approaches and methods with suitable adaptation, based on (a) terrain analysis, (b) morphostructural analysis of the relief, (c) analysis of geomorphic markers such as certain landforms (geomorphological evidence of tectonics) and deposits (developed in a continental environment), (d) analysis and morphometry of drainage basins, (e) dating of deposits and landforms.

These studies are focused on deciphering the role of morphotectonics and selective erosion in the landscape's evolution, incorporating regional morphostructural analysis (based on DEM analysis), Quaternary fluvial deposits mapping, local morphostructural analysis (based on field mapping and aerial photo interpretation), drainage network analysis and orography and hydrography morphometry. The key point is the integration of field geomorphological methods and modern morphotectonic analysis (including drainage network and terrain analysis). Only the correlation of these methods of analysis at drainage basin scale allow us to find out and define geomorphic markers of tectonics and landscape evolution, suggesting also its timing.

The results allow us to outline the main morphostructural features of central Italy (chain area and piedmont area) and to suggest the use of a similar methodological approach, but focused also on different geomorphological landscapes. In addition, discussion and conclusions of the studies show how integrative morphotectonic studies allow for the description of drainage network and landscape evolution driven by the alternating action of tectonic forces and geomorphic processes due to orography and Pleistocene climate fluctuations. It is possible also to define the role of morphotectonics and selective erosion in the landscape evolution and suggest the relative timing of this evolution, while only incorporating specific geochronology studies enables us to define the absolute timing of tectonics and landscape evolution.

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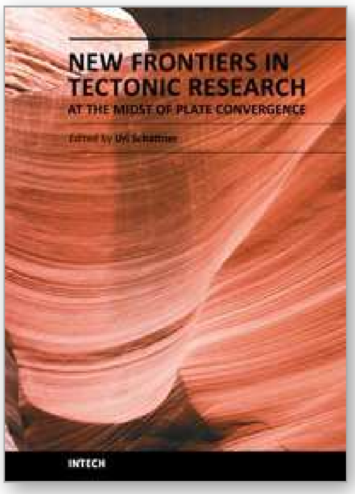

New Frontiers in Tectonic Research - At the Midst of Plate Convergence
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Ocean closure involves a variety of converging tectonic processes that reshape shrinking basins, their adjacent margins and the entire earth underneath. Following continental breakup, margin formation and sediment accumulation, tectonics normally relaxes and the margins become passive for millions of years. However, when final convergence is at the gate, the passive days of any ocean and its margins are over or soon will be. The fate of the Mediterranean and Persian Gulf is seemingly known beforehand, as they are nestled in the midst of Africa-Arabia plate convergence with Eurasia. Over millions of years through the Cenozoic era they progressively shriveled, leaving only a glimpse of the Tethys Ocean. Eventually, the basins will adhere to the Alpine-Himalaya orogen and dissipate. This book focuses on a unique stage in the ocean closure process, when significant convergence already induced major deformations, yet the inter-plate basins and margins still record the geological history.