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THE SW ESCARPMENT OF MONTAGNA DEL MORRONE (ABRUZZI, CENTRAL ITALY): GEOMORPHOLOGY OF A FAULT-GENERATED MOUNTAIN FRONT

Abstract: Miccadei E., Paron P. & Piacentini T., *The SW escarpment of Montagna del Morrone (Abruzzi, Central Italy): geomorphology of a fault-generated mountain front*. (IT ISSN 1724-4757, 2004).

The relief features of the Central Apennines are formed by carbonate ridges, separated one from the other by narrow valleys, parallel to the ridges, cut in terrigenous sediments, or by wide intermontane depressions. The ridges have N-S, NW-SE or E-W orientations and steep slopes and they are broken by deep cuts and gorges. The landscape of the ridges is related to the morphostructural and morphosculptural evolution of fault scarps and fault line scarps.

The purpose of this study is the analysis of the geomorphological characteristics of the SW escarpment of Montagna del Morrone (2061 m a.s.l.), one of the main Central Apennine ridges.

The study investigated the geomorphology of the escarpment, focusing on the interaction between extensional tectonics, drainage evolution and the distribution of morphogenetic processes. Particular attention was devoted to the morphometry of the slope, of the drainage pattern, of the drainage basins and of the alluvial fan/catchment systems. Working from geomorphological and morphometric data we defined the processes that have generated and shaped the escarpment, and established the timing of its morphogenetic evolution.

Various types of analysis were combined: basic geological analysis, geomorphological survey, morphometric and slope analysis, morphometric analysis of drainage basins and drainage network, and morphometric analysis of alluvial fan/catchment systems. Topographic data, surface hydrology, and geomorphological data were geo-referenced and processed in a GIS.

The results indicate that the SW escarpment of the Montagna del Morrone ridge has the geomorphological features of high activity fault generated mountain fronts. This fault generated mountain front, however, shows a peculiar morphostructural setting variable both longitudinally and transversally. This led us to define a partition into three distinct sectors made up of adjoining relatively downfaulted and uplifted blocks: northern sector, central sector and southern sector.

In order to summarize the features characterising the three sectors, six morphostructural sections were drawn (three on straight transversal profiles and three on stream channel and interfluve profiles).

The geomorphological analysis highlighted a complex growth evolution, rapid in the earlier stages and continuing in succeeding stages with the dominance either of morphostructural factors, linked to the conflicting fault activity and regional uplift, or of morphosculptural processes, controlled by the litho-structural setting and by climatic change, particularly during the cold stages.

In a general balance, due to the local subsidence of the Sulmona basin relative to the Montagna del Morrone blocks along two major normal fault systems in a general uplift of the chain, the growth of the escarpment has strongly exceeded the effect of denudation. The morphogenetic processes are mostly due to drainage network linear down-cutting in the mid and lower parts of the northern and central sectors, while slope gravity areal denudation is prevailing in the upper part of the northern and central sectors and in the southern sector.

Finally, an attempt was made to summarise the main stages of the morphostructural evolution from Early Pleistocene to Holocene.

Key Words: Structural geomorphology, Fault related slope, Central Apennines, Abruzzi (Italy).

Riassunto: Miccadei E., Paron P. & Piacentini T., *Il versante SW della Montagna del Morrone (Abruzzi, Italia centrale): geomorfologia di un versante su faglia*. (IT ISSN 1724-4757, 2004).

Oggetto del presente studio è l'analisi delle caratteristiche geomorfologiche del versante SW della dorsale della Montagna del Morrone, nell'ambito di un programma di ricerca finalizzato allo studio dell'evoluzione morfostrutturale del territorio abruzzese. La Montagna del Morrone (2061 m s.l.m.), infatti, è una delle principali dorsali appenniniche posta nella porzione centro-orientale dell'Appennino abruzzese a ridosso della Montagna della Maiella.

Lo studio è stato rivolto alla caratterizzazione geomorfologica del versante SW, all'analisi dell'interazione tra tettonica estensionale, sviluppo del drenaggio e distribuzione dei processi morfoselettivi. Particolare attenzione è stata posta nell'analisi morfometrica del versante, del reticolo e dei bacini idrografici su di esso impostati, e dei sistemi conoide allu-

vionale/bacino. Sulla base degli elementi geomorfologici e morfometrici si è cercato infine di definire i processi che hanno determinato l'evoluzione morfogenetica del versante e di arrivare a una sua scansione temporale. A tal fine sono stati integrati diversi tipi di analisi e metodologie di studio, da rilievi di terreno, a interpretazione fotogeologica, a elaborazioni GIS sul reticolo idrografico e su DEM.

Il versante oggetto dello studio presenta, in sintesi, le caratteristiche di un *fault-generated mountain front*; tuttavia l'assetto morfostrutturale è del tutto peculiare nonché eterogeneo sia in senso longitudinale sia in senso trasversale e ciò ha portato a una distinzione in sue settori: settentrionale, centrale, meridionale. Per descrivere le caratteristiche dei tre settori sono stati realizzati sei profili morfostrutturali (tre su profili trasversali e tre su profili di aste principali e interfluvi dei bacini idrografici). Il settore settentrionale con profilo a gradinata è definito da una dorsale principale stretta e affilata e da una dorsale secondaria ampia e stondata nella parte mediana del versante. Nel settore meridionale la dorsale è più ampia e massiccia con un unico ripido gradino morfologico tra la sommità e la base. Il settore centrale, di transizione, è segmentato in tratti a diversa acclività ma, soprattutto, presenta marcati lineamenti perpendicolari al versante; esso può rappresentare a nostro avviso un settore di svincolo tra la parte nord e la parte sud.

L'analisi geomorfologica ha messo in luce un complesso modellamento sviluppatosi ciclicamente in più fasi successive con prevalenza ora della morfotettonica, in relazione all'intensità dell'attività delle faglie, ora dell'azione morfosculturale, in funzione dell'alternarsi delle fasi climatiche calde e fredde. In un bilancio complessivo la prima risulta sicuramente prevalente essendo stata capace di creare dislivelli fino a 1700 m solo parzialmente degradati dall'azione morfosculturale. È stata, infine, delineata una possibile scansione dell'evoluzione del versante.

TERMINI CHIAVE: Geomorfologia strutturale, Versante di faglia, Appennino centrale, Abruzzo (Italia).

INTRODUCTION

The purpose of this study is the analysis of the geomorphological characteristics of the SW escarpment of the Montagna del Morrone ridge. This is part of a research project focused on the study of the morphostructural evolution of the Abruzzi region.

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 well defined from a geological-structural point of view. 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 limb is broken by several normal fault systems, NW-SE striking and SW dipping, which separate the ridge from the Sulmona basin (fig. 1; Beneo, 1939; Vittori & *alii*, 1995; Vezzani & Ghisetti, 1997).

The SW slope has a varied physiography, both longitudinal and transversal, shaped by several scarps broken by gentle slopes or, at certain points, counter slopes. 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 junction with the neighbouring plain (Sulmona basin) corresponds with one of the main normal fault lines. Many ephemeral streams drain the slope down to the basal break. Here they have deposited many alluvial fans.

The study investigated the geomorphology of the escarpment, focusing on the interaction between extensional tectonics, drainage evolution and the distribution of morphogenetic processes.

Working from geomorphological and morphometric data, we defined the processes that have generated and shaped the escarpment and in this way established the timing of its morphogenetic evolution.

With this aim various types of analysis were used together: basic geological analysis, geomorphological survey, morphometric and slope analysis, morphometric analysis of drainage basins and drainage network, and morphometric analysis of alluvial fan/catchment systems. Topographic data, surface hydrology, and geomorphological data were geo-referenced in a GIS ArcView 3.2a® (ESRI®) and processed further with the appropriate extensions (Spatial Analyst® and 3D Analyst®, ESRI®) and spreadsheets.

The geological analysis was centred on a survey of the surface Quaternary deposits, with the geomorphological processes that formed them, and on the morpho-lithostratigraphic correlation with the neighbouring Sulmona basin previously studied in detail (Miccadei & *alii*, 1999).

The morphometric analysis and the slope analysis were carried out in a GIS, using a DEM processed from vector orographic data (25 m contour lines from IGM, authorization n°4961 date 10/03/99) and the DEM of the «Quote Medie d'Italia» archive (230x230 m grid), data provided by courtesy of S.G.N. (National Geological Survey). A net of topographic profiles, a slope map, and hypsometric integrals were created and some of the main morphometric properties used in relevant literature for the morphological analysis of fault related slopes and their level of activity were calculated (such as slope, sinuosity, and faceting; Bull & McFadden, 1977; Mayer, 1986; Stewart & Hancock, 1994; Keller & Pinter, 1996).

Morphometric analysis, processed in the GIS, was carried out on the drainage system of the slope, as a key to understand the morpho-evolutionary conditions of the slope, the role of structural factors in its evolution, and the relationship between drainage and extensional tectonics (Summerfield, 1991; Ciccacci & *alii*, 1992, 1995; Leeder & Jackson, 1993; Keller & Pinter, 1996; Hovius 2000; Lupia Palmieri & *alii*, 2001). The 3D processing of the drainage system on the DEM allowed us to calculate, through automatic or semi-automatic procedures (Evans, 1972; Pike, 2002), the main 2D and 3D morphometric parameters according to the most relevant literature. These included the definition of drainage basins and the calculation of the relative areal and relief properties (Schumm, 1956; Mayer, 1986; Leeder & Jackson, 1993; Keller & Pinter, 1996; Hovius 2000); the long profiles of stream channel and interfluves (Shepard, 1979; Kirby & Whipple, 2001; and in a large scale context Hovius, 2000); the stream ordering of the drainage network, the calculation of the principal morphometric properties and the curves and values of the hypsometric integrals of the basins (Horton, 1945; Strahler, 1952, 1957; Schumm, 1956; Avena & *alii*, 1967; Ciccacci & *alii*, 1992, 1995; Keller & Pinter, 1996; Lupia Palmieri & *alii*, 2001; Spagnolo, 2001).

Geomorphological and geological surveys were carried out at 1:10000 and 1:5000 scale, integrated by multi-scale aerial photo interpretation and by DEM analysis. The surveys were based on the guidelines proposed by the Grup-

po Nazionale Geografia Fisica e Geomorfologia (1994) and on those issued by the Servizio Geologico Nazionale (1994).

The surveys focused on the distribution of landforms present on the slope and their relationship with the slope architecture. A detailed analysis was carried out not only of structural landforms, slope gravity landforms and complex origin landforms, but also of alluvial fans present at the base of the slope. These are of great importance because they represent the morphological join between the slope and the plain and because they contain stratigraphic levels dated in previous work (Miccadei & *alii*, 1999).

The morphometic analysis of alluvial fans and alluvial fan/catchment systems, was carried out (through GIS and processing in DEM), referring to works of various authors, among these Bull (1964), Saito (1982), Blair & McPherson (1994), Oguchi & Ohmori (1994); Allen & Hovius (1998), and working from numerical models, Allen & Densmore (2000). Bull (1964) first, and then the others, bring to light the power law relationship between the different morphometric parameters, such as $A_f = k A_b^x$ (A_f = fan area, A_b = basin area, k and x = constant and exponent linked to the rock resistance, tectonic activity and climate conditions). In this case it is possible to regard some parameters as homogeneous (lithology, climatic conditions), so this analysis contributes to the study of the arrangement and morphostructural evolution of the whole slope and individual hydrographic basins.

GEOLOGICAL AND GEOMORPHOLOGICAL OUTLINE OF THE STUDY AREA

The relief features of the Central Apennines are formed by carbonate ridges, separated one from the other either by narrow valleys, parallel to the ridges and cut in terrigenous sediments, or by wide intermontane depressions. These depressions have a tectonic or karst origin and, in several cases, they are filled with continental Quaternary deposits (fig. 1).

The development and deepening of the drainage system in opposition to the tectonic activity and regional uplift has meant that processes due to running waters and gravity have dominated the erosion and shaping of the chain landscape. However, according to many authors writing on the Apennine chain, there has been a tight passive structural control on the distribution and extent of erosion (Mazzanti & Trevisan, 1978; Cinque, 1993; Dramis, 1993; Bigi & *alii*, 1996; Ascione & Cinque, 1999; Bartolini, 1999; Ollier, 1999; D'Alessandro & *alii*, 2003; Mayer & *alii*, 2003).

In the Central Apennines the ridges generally have N-S, NW-SE or E-W orientations, in relation to the principal tectonic axis. They have steep slopes and are broken longitudinally by deep cuts and gorges (fig. 1). The maximum heights vary, whether in a longitudinal or in a transversal way, from west to east. On the western side, they range between 1500-2000 m, while on the eastern side, there are heights of 2000-2500 which reach their highest point in the outermost part of the mountain chain with Corno Grande (2912 m, massif of the Gran Sasso) and Mt. Amaro (2793 m, Montagna della Maiella).

The landscape of the mountain chain, characterised by great variations in height and by a high amplitude of relief, is related to the morphostructural and morphosculptural evolution of fault scarps and fault line scarps that border the major and minor ridges. These scarps are generally found on the western and/or southern slopes and are characterised by strong Quaternary extensional tectonics (Demangeot, 1965; Brancaccio & *alii*, 1978; Blumetti & *alii*, 1993; Bosi & *alii*, 1993; Dramis, 1993; Calamita & *alii*, 2000; Ascione & Cinque, 1997, 1999; Ghisetti & Vezzani, 1997; Morewood & Roberts, 2000; Pizzi & Scisciani, 2000; D'Alessandro & *alii*, 2003). The slope development is generally due to the combination of denudation and linear downcutting. As suggested for the southern Apennines, the replacement processes and the sediment removal processes have led to slopes that can often assume the characteristics of a *Lehmann* or *Richter* slope (Brancaccio & *alii*, 1978; Ascione & Cinque, 1997). The landforms are generally well preserved because of recent tectonic activity and resistivity of carbonate rocks that form the spine of the chain.

The Montagna del Morrone is one of the most eastern peaks of the Central Appennines and is positioned immediately to the W of Montagna della Maiella (fig. 1). In the E it lies next to the Caramanico valley, which in the south reaches a height of 1282 m a.s.l.. This valley, N-S striking, separates the ridge of Montagna del Morrone from that of Montagna della Maiella (fig. 2). In the SW the Montagna del Morrone is enclosed by the almost triangular-shaped Sulmona basin which is crossed by numerous water courses: F. Vella, F. Gizio, F. Sagittario, F. Aterno; downstream these become the River Pescara, which takes its name from the homonymous springs in the northern part of the basin (fig. 2).

Montagna del Morrone is made up of several aligned peaks, the highest being Mt. Morrone (2061 m a.s.l.), in the middle of this group. Other peaks are, from NW to SE: Mt. Rotondo (1731 m a.s.l.), C.le Affogato (1783 m a.s.l.), C.le della Croce (1901 m a.s.l.), Mt. le Mucchia (1986 m a.s.l.), and Mt. Mileto (1920 m a.s.l.) (fig. 2a,b). The maximum heights are therefore in the south-eastern part and the lowest in the north-western part. This part ends abruptly with a relief of 1400 m in the NW, down to the Popoli gorges (River Pescara valley, 235 m a.s.l.). It also ends suddenly in the S with a relief of 1200 m in the area of the River Vella valley, positioned initially NE-SW then E-W near the village of Pacentro, with heights of between 1000 and 700 m a.s.l. (fig. 2c).

Montagna del Morrone is a ridge clearly lengthened in a NW-SE direction with markedly steep SW and NE slopes. The maximum heights vary from over 2000 m in the central-southern sector to c. 1700 m in the northern sector, while the lowest heights are as low as 250 m in the NW. The transversal profile is asymmetric. The steep eastern slope, with a planar and slightly convex profile, slopes down to the Caramanico Valley, broken by a clear break in
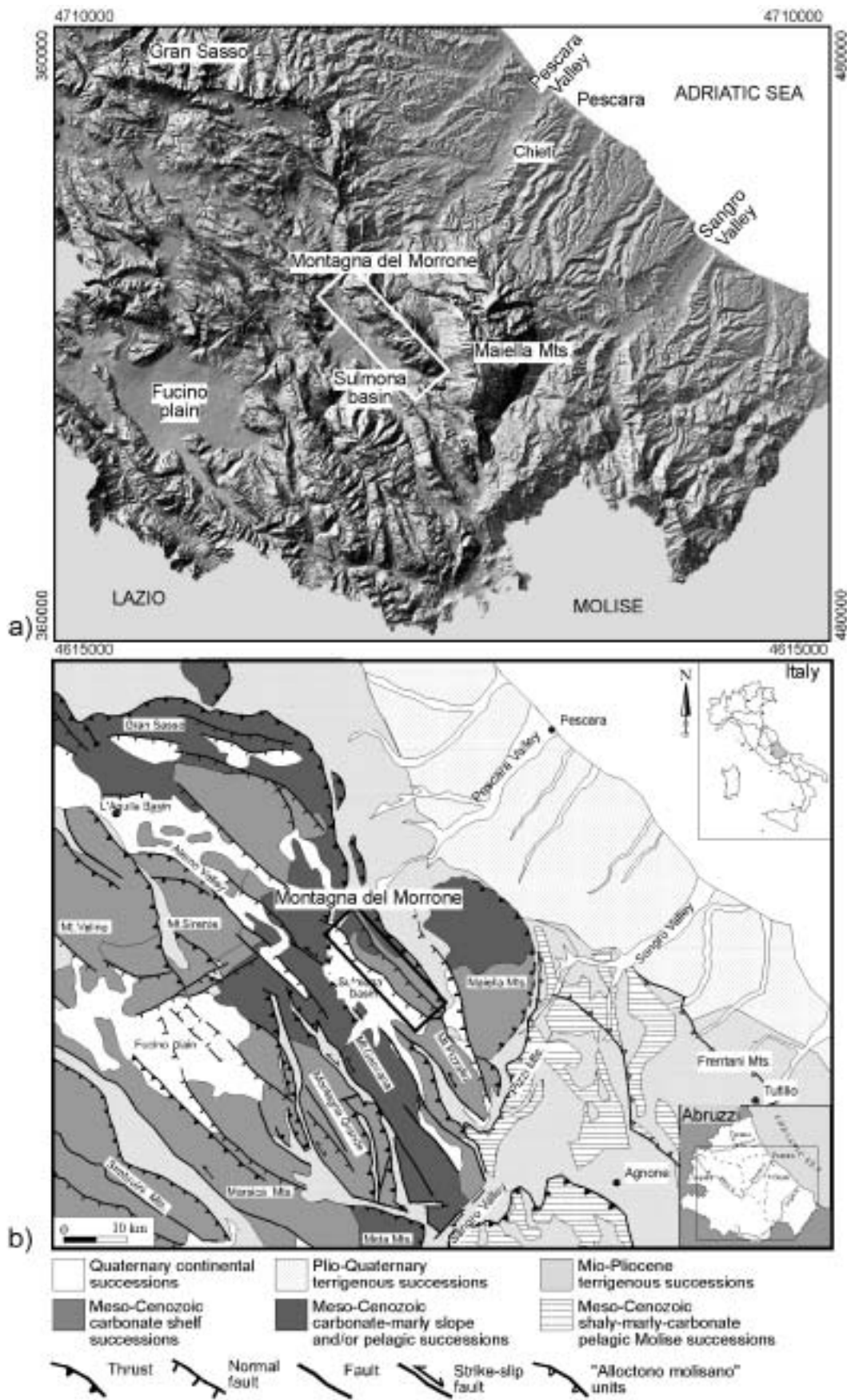
FIG. 1 - a) Shaded relief image of the Abruzzi area; the white box locates the Montagna del Morrone ridge. b) Schematic geological setting of the Abruzzi area.

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Fig. 2 - a) Topographic map of the Montagna del Morrone ridge; 25 m contour lines (IGM Authorization n° 4961, date 10/03/99). b) DEM of the Montagna del Morrone ridge, zenith view. c) Longitudinal topographic section along the crest of the Montagna del Morrone ridge (vertical exaggeration 2x).

the slope, which is followed by a lightly inclined slope. The summit gently undulates in the south, while it has a sharp crest to the north. The western slope, limited by a clear break at the base, presents an articulated morphology both in a longitudinal and transversal direction and is defined by several scarps broken up by areas of slight incline and locally by counter slopes.

The ridge is made up of thick marine Meso-Cenozoic carbonate successions, related to shelf, margin and slope-basin environments that differ in lithology and thickness (Raffi & Forti, 1959). These rock formations are found in an asymmetrical anticline fold, verging towards NE, with the axis striking in an Apennine direction (NW-SE). The SW side is cut by two main fault lines in a NW-SE direction, dipping SW. One fault line is located at the base of the slope, corresponding to the break in the slope that constitutes the junction to the Sulmona basin, while the other is located in the mid-slope. A series of secondary faults and transfer elements are linked to these two fault systems. Tectonic activity developing since at least the Early Pleistocene, has caused displacement of the bedrock in the order of thousands of metres (Vittori & *alii*, 1995; Vezzani & Ghisetti, 1997; Doglioni & *alii*, 1998; Miccadei & *alii*, 1999; Miccadei & *alii*, 2002). This occurs along the entire length of the ridge; towards the N it seems to connect with the faults that run along the Navelli Plain (Bagnaia & *alii*, 1989), while southwards it spreads into a series of smaller structures and it connects with the faults that run along the ridges of Mt. Porrara and Mt. Pizzalto.

On the slope there are continental Quaternary formations, deposited by alluvial and gravity processes, at different stages of evolution, and forming active, inactive and relict landforms sometimes visible in relief inversion. These are also cut by the extensional tectonics, with displacements that can reach 700-1000 m (Miccadei & *alii*, 2002).

Some of the points that have pushed this study forward can be summarised as follows: the representativity of the ridge in the context of the Central Apennines; its physiographic unity in contrast with the marked heterogeneity in the morphology of the SW escarpment, in the morphostructural architecture and in the geometry of the drainage basins; the clear evidence of structural landforms, slope gravity landforms and landforms due to running waters; finally, the possible correlation with the neighbouring Sulmona basin.

GEOLOGICAL DATA

The analysis of the structural characteristics of the ridge (lithologic and tectonic) constituted a basis for the study of landforms and geomorphological processes. The lithologic characteristics of the area studied were highlighted through the survey of carbonate bedrock formations and superficial deposits.

Bedrock formations

The bedrock formations are made up of carbonate rocks of Lias to Paleogene age divided into units accord-

ing to their resistance to weathering and erosive processes (fig. 3a).

In the northern area (from Schiena d'Asino to C.le Affogato), *bedded carbonate rocks* are present, made up of crystalline limestone, detritic limestone and micritic limestone with chert, in fine to medium thickness beds. The total thickness of the outcropping lithologic succession is about 1700 m (Lias-Palaeogene).

In the central area (between C.le Affogato and Mt. Morrone), *massive carbonate rocks* are present. They are rudist and orbitoline limestone and calcarenites with subordinate oolitic levels, in a massive setting or locally bedded. The total thickness of the rock formation is about 1800 m (Lias - Late Cretaceous).

Carbonate rocks in thick beds are present in the southern areas (from Mt. Morrone to the valley of the River Vella). These are made up of compact limestone and calcarenites with oolitic levels and rare marly levels; there are dolomites at the base. The total thickness of the outcropping rock formation is c. 2700 m (Lias-Early Cretaceous).

Dolomite rocks are present in the lower part of the slope in the northern and central sectors. They are made up of crystalline dolomites and dolomitic limestone (Lias).

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 (Raffi & Forti, 1959; Bellatalla & *alii*, 1992).

Superficial deposits

The superficial deposits are represented by Quaternary continental deposits (fig. 3b). From a lithological point of view, they are essentially breccias and conglomerates in lithofacies 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. It is hard to ascertain the date of these deposits, but based on comparisons with the sector of the Sulmona basin, they can be placed between the Early Pleistocene and the Holocene (Beneo, 1942, 1943; Sylos Labini & *alii*, 1993; Carrara, 1998; Miccadei & *alii*, 1999; Lombardo & *alii*, 2001). These deposits are distributed non-homogeneously along all of the slope, but have good continuity at the base and in the mid-slope.

There are *heterometric carbonate breccias* (up to boulder size) distributed non-homogeneously, in a chaotic setting with a large silt-clay matrix, forming thick bodies (from tens of metres to 200 m thick); these are paleo-landslide deposits. In some cases, substantial volumes of rock maintain the original bedrock-like lithostructural setting (SW of the Morrone di Pacentro, fig. 3b). They are located at heights from 500 m to 1300 m a.s.l. The most clearly seen deposits, characterised by the presence of boulders, vary in thickness from 100 to 200 m; they are found in the southern sectors corresponding to the village of Pacentro (fig. 4a). Other deposits of chaotic breccias, again characterised by high volumes of material, are found in the southern sector at the base of the slope and also in the

Fig. 3 - a) Geological-structural scheme of the Montagna del Morrone SW slope: 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) Superficial deposits scheme: 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.
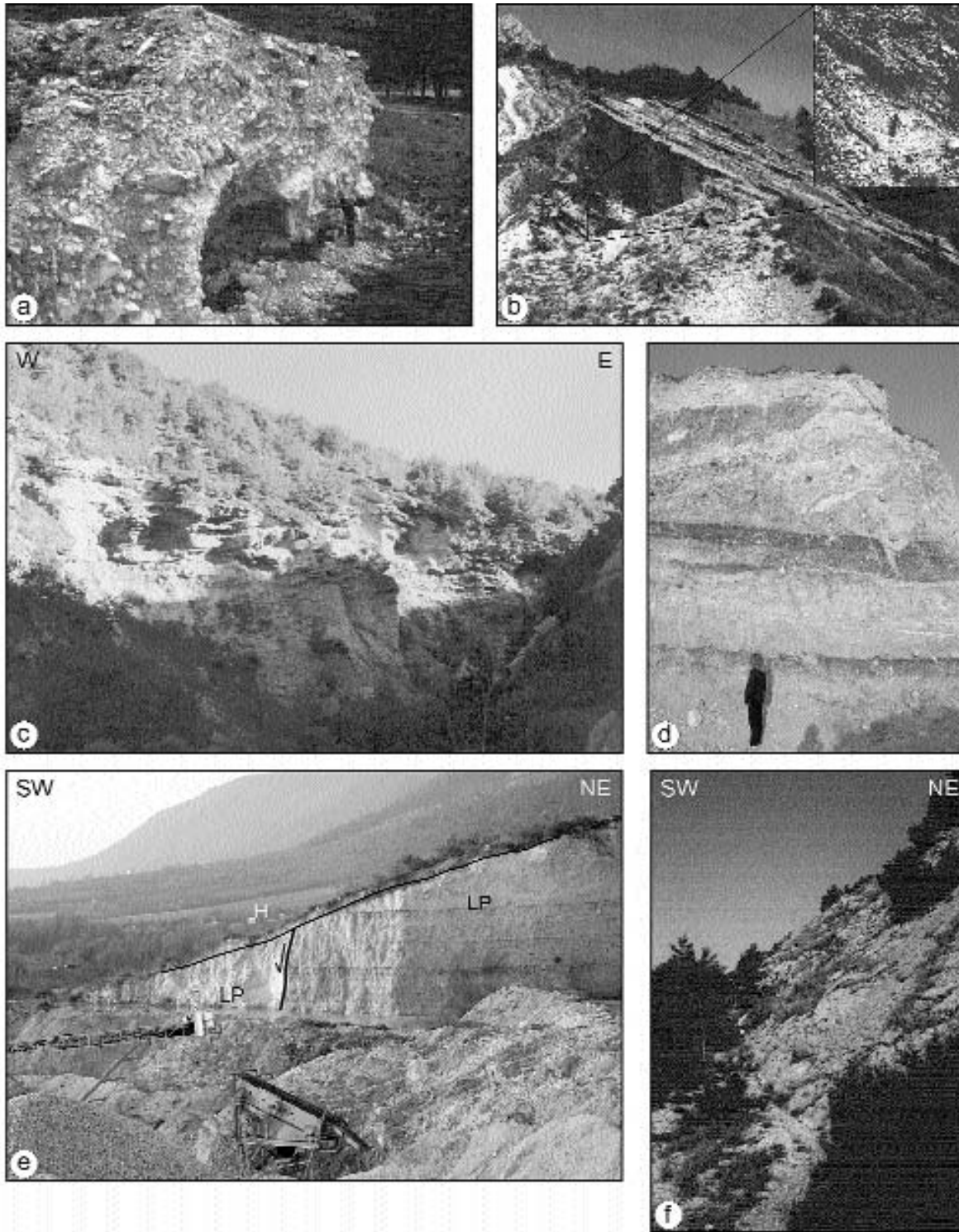
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FIG. 4 - Superficial deposits and tectonic elements outcropping on the SW escarpment of the Montagna del Morrone. a) Pacentro (southern sector): heterometric chaotic breccias (boulder up to 2-3 m), with carbonate angular clasts in a fine marly matrix, forming the body of the Pacentro paleo-landslide. b) Cima della Croce (central sector): heterometric carbonate breccias (from pebble to boulder size) in sorted fine and coarse layers, clast supported without matrix or with white sand matrix, cemented and bedded; these are related to slope facies. c) Pacentro - Mt. Mileto (southern sector): carbonate conglomerates and breccias, clast supported, cemented and bedded; these are related to alluvial fan facies. d) Bagnaturo (central sector): heterometric carbonate conglomerates, with sand matrix, arranged in lens or tabular layer, with soil levels interbedded; these are related to alluvial fan facies. e) Bagnaturo (central sector): secondary fault plane linked to the Basal Border Fault displacing by several tens of metres the Upper Pleistocene alluvial fan deposits (LP), while not affecting the overlying Holocene deposits (H). f) Schiena d'Asino (northern sector): scarplet corresponding to the major Schiena d'Asino fault plane.

central and northern sectors, along the mid-and upper-slope. These deposits can be dated to the Lower?-Middle Pleistocene because they underlie deposits of relict alluvial fans that have already been dated (Miccadei & *alii*, 1999).

Heterometric carbonate conglomerates and breccias (from pebble to boulder size), cemented and bedded, with a white-pink silt-sand matrix, accountable to alluvial fan facies and slope facies (at the highest altitudes), are present in isolated clusters at heights that range from 600 to 1700 m a.s.l.. The most easily discernable outcrops are found on Mt. Orsa and on the Cima della Croce (fig. 4b). Additionally, a strip lies on the deposits formed by the Pacentro paleo-landslide and is probably linked to those deposits found upstream in the Vallone di Mileto (fig. 4c). They are dateable to the Lower?-Middle Pleistocene.

Carbonate conglomerates and breccias varying in size (from pebble to boulder), from loose to poorly cemented and mostly stratified, with reddish silt-sand inter-bed, and paleosoil and volcanoclastic layers are accounted for by alluvial fan facies (fig. 4d). The presence of the volcanoclastic layers allowed these deposits to be dated to the late Middle Pleistocene and Upper Pleistocene (Miccadei & *alii*, 1999). They are most common around the morphological junction with the Sulmona basin (from 250 to 600 m a.s.l.). Layers of loose conglomerates, at the outlet of the main catchments, make up the active Holocene fans.

Stratified carbonate breccias, cemented in parts, and generally clast-supported, are most evident at heights ranging from 700 to 1800 m a.s.l and form talus slopes. It is hard to date them, due to the absence of certain stratigraphic elements, but they can be attributed to the Upper Pleistocene and in some areas to the Holocene.

Eluvial and colluvial deposits are most evident in the southern and northern sectors of the slope, in correspondence with the undulated upper zone and with the low incline mid-slope.

Tectonics and neotectonics

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 & *alii*, 1995; Ciccacci & *alii*, 1999; Miccadei & *alii*, 2002). 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.

There are two main normal fault systems with a predominantly N40°-50°W orientation (fig. 3). 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 affects 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 & *alii*, 2002, and up to several tens of metres in the alluvial fans of the Upper Pleistocene; fig. 4e). Towards the north, it is made up of fault planes 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 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 planes, in the northern and central parts, are characterised by large rock fault scarps (fig. 4f). 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 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.

GEOMORPHOLOGICAL DATA

The analysis of orography and drainage system, and the geomorphological survey were directed towards the study of the interaction between extensional tectonics, development of drainage, and distribution of denudation processes.

The landforms, both erosional and depositional, have been defined along with their relative morphogenetic agents. Particular attention has been devoted to the morphometric analysis of the slope, of the drainage network and basins developed on it and of the alluvial fan/catchment systems. These data are described and discussed in the following paragraphs, which illustrate topography and slope (figg. 5, 6), drainage system (figg. 7, 8, 9), structural landforms, slope gravity landforms, landforms due to running waters, and karst landforms (figg. 10, 11). Active, inactive and relict landforms are distinguished in order to better identify the evolution of the processes that have shaped the landscape of the various areas of the escarpment. Landform mapping and morphometric data processing were developed through automatic and semiautomatic procedures within the GIS supported by spreadsheets.

Orography

The SW side of Montagna del Morrone is a slope of considerable length (c. 20 km) and relief (1500-1700 m), even in comparison with other more important ridges of the Central Appenines. It is bound downslope by a sharp

junction with the Sulmona basin and upslope by a clear NW-SE crest. The total planimetric area covers about 74 km^2. The overall relief is 1480 m towards the north and 1660 m towards the south. Longitudinally it is markedly straight, with low values of sinuosity (S = 1.1) and faceting (F = 0,88) (Bull & McFadden, 1977; Mayer, 1986; Stewart & Hancock, 1994; Keller & Pinter, 1996). Transversally, on the contrary, it shows more irregularity. It is characterised by the development of morphological alignments, both transversal and parallel to the structure (fig. 5a). The first ones give rise above all to preferential run-off routes, the second ones define marked scarps and breaks in the slope.

In order to define in detail the physiographic characteristics of the slope, both a slope map (fig. 5a) and a grid of transversal topographic profiles (fig. 6) were automatically drawn by processing a DEM in the GIS software. The comparison of this data with the shaded relief image (fig. 5b, 2b) brought to light a strong longitudinal and transversal heterogeneity, and enabled us to distinguish three areas of differing morphology:
– the northern sector,
– the central sector,
– the southern sector.

The northern sector (from Schiena d'Asino to C.le Affogato) is characterised by a clear double step. Close to the straight and sharp principal crest there is a minor crest, lower and rounded, in the mid-slope. At the base of the slope, starting from the junction with the Sulmona basin, there is a slope segment with an average dip angle of 28° (from a height of 350 m a.s.l. to a height of 650 m a.s.l.). Upslope there is a gently sloping and undulated area (from 0° to 16°), transversally about 1500 m wide, which from a height of about 650 m reaches 950 m and includes an alignment of moderate isolated peaks. Further upslope, a slope with an average dip angle of 41° (at some points exceeding
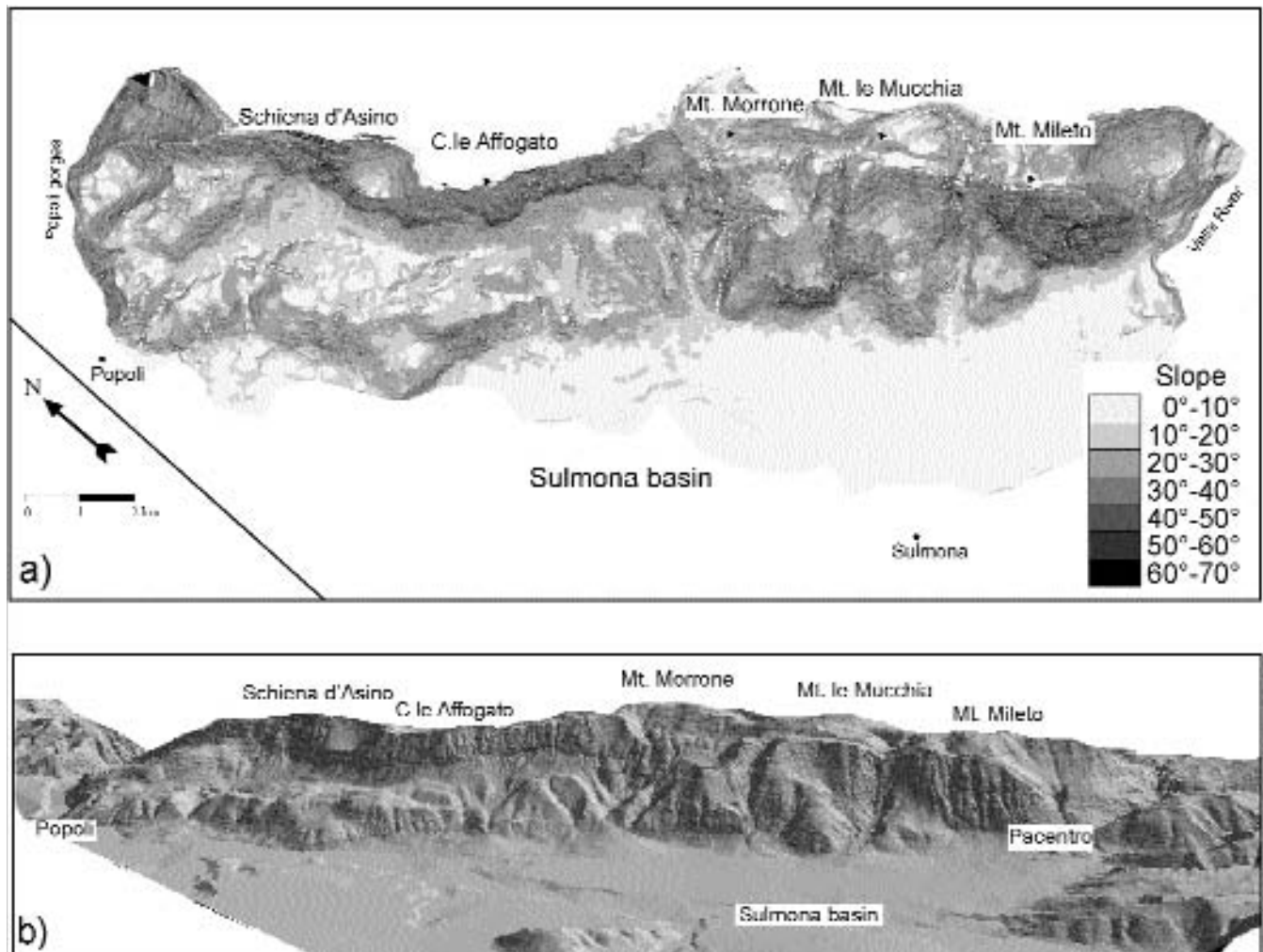

FIG. 5 - a) Slope map of the Montagna del Morrone ridge, derived from the DEM (Arc View 3.2a® and Spatial Analist® elaboration). b) 3D view from SW of a DEM of the Montagna del Morrone.
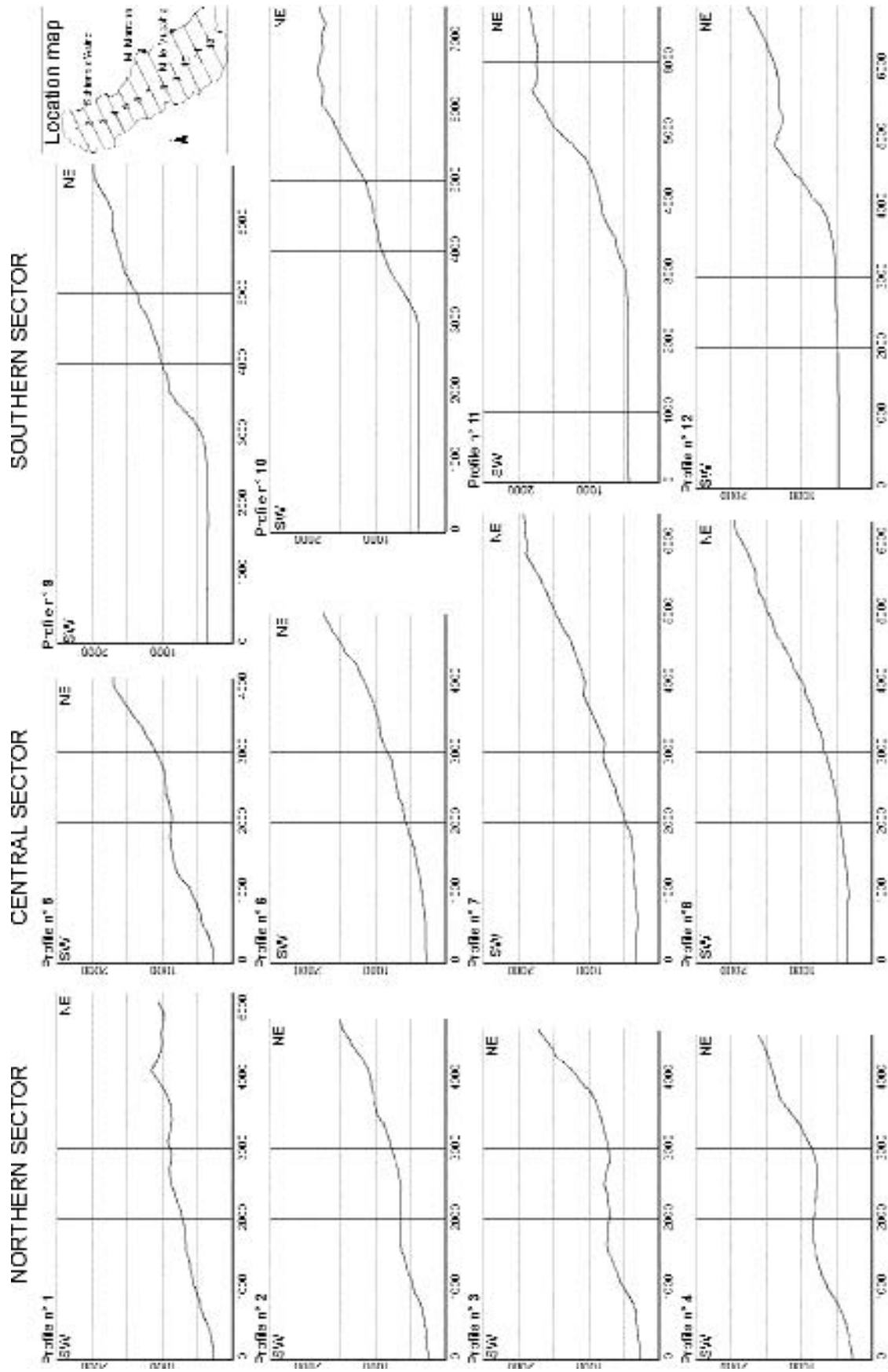
FIG. 6 - Transversal topographic profiles of the SW slope of the Montagna del Morrone.

60°) is present. From a height of 1100 m it reaches right up to the principal crest (Schiena d'Asino 1498 m a.s.l., C.le Affogato 1783 m a.s.l.) (fig. 5; fig. 6, profiles 1-4).

In the central sector (from C.le Affogato to Mt. Morrone), the minor ridge links up with the principal one at mid-slope, close to Cima della Croce. Again in this case the slope is segmented into three zones of differing steepness. However, the mid-portion, compared with the northern sector, shows a greater gradient, has no counter-sloping segments and is at the most 700 m wide. The lower part of the slope has an average incline of 26° (seldom exceeding 40°), from about 475 m a.s.l. to 750 m a.s.l. The less inclined mid-slope (on average 19°) goes from a height of 750 m a.s.l. to 900 m a.s.l. The upper part, with an average incline of 37° (locally reaching 50°) extends from a height of 900 m a.s.l. right up to the summit of Mt. Morrone (2061 m a.s.l.; fig. 5; fig. 6, profiles 5-8).

Finally, the southern sector (Mt. Le Mucchia, Mt. Mileto) is a wide and massive ridge. In this sector the slope profile is made up of two main segments: a high and steep segment with an average incline of 34° (wide areas exceed 50° or even 60°), which goes from the basal junction (550-600 m a.s.l.) to 1700 m a.s.l. and a zone with a low and irregular incline, 1000 m wide up to the crest, which has a height of 1800-1900 m a.s.l. In this last slope unit there are nearly flat or slightly undulating zones (fig. 5; fig. 6, sections 9-12).

In short, the analysis shows the irregular distribution of slope and local relief. In the southern sector they are concentrated in the lower part, along the basal escarpment, and diminish towards the summit. In the central and above all in the northern areas, they are concentrated in the upper part, are reduced in the mid-slope and moderately increase again towards the base. As we shall discuss in great detail below, this all plays an important role in the distribution of the morphogenetic processes which have shaped the slope.

Drainage system

The analysis of drainage networks and of the geometry of the related basins, particularly of their morphometric properties, is acknowledged to be one of the essential elements in the study of the relationship between erosional processes and morphostructural processes. Our investigation integrates the approaches proposed by various authors for the definition of the morpho-evolutionary stages, of the structural conditioning in the shaping of the SW escarpment of Montagna del Morrone (Horton, 1945; Strahler, 1952, 1957; Avena & *alii*, 1967; Avena & Lupia Palmieri, 1969; Ciccacci & *alii*, 1992, 1995; Lupia Palmieri & *alii*, 2001) and for the understanding of the relationships between extensional tectonics and the evolution of the drainage system (Summerfield, 1991; Leeder & Jackson, 1993; Keller & Pinter, 1996; Hovius, 2000).

The drainage network on the steep and heterogeneous escarpment is made up of ephemeral stream channels. Corresponding to the toe-slope break, along the Basal border Fault, these stream channels give rise to alluvial fans and become less defined (only a few clearly carve out the alluvial fans).

The slope was subdivided into 16 basins (A-P; fig. 7; tab. 1). 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,
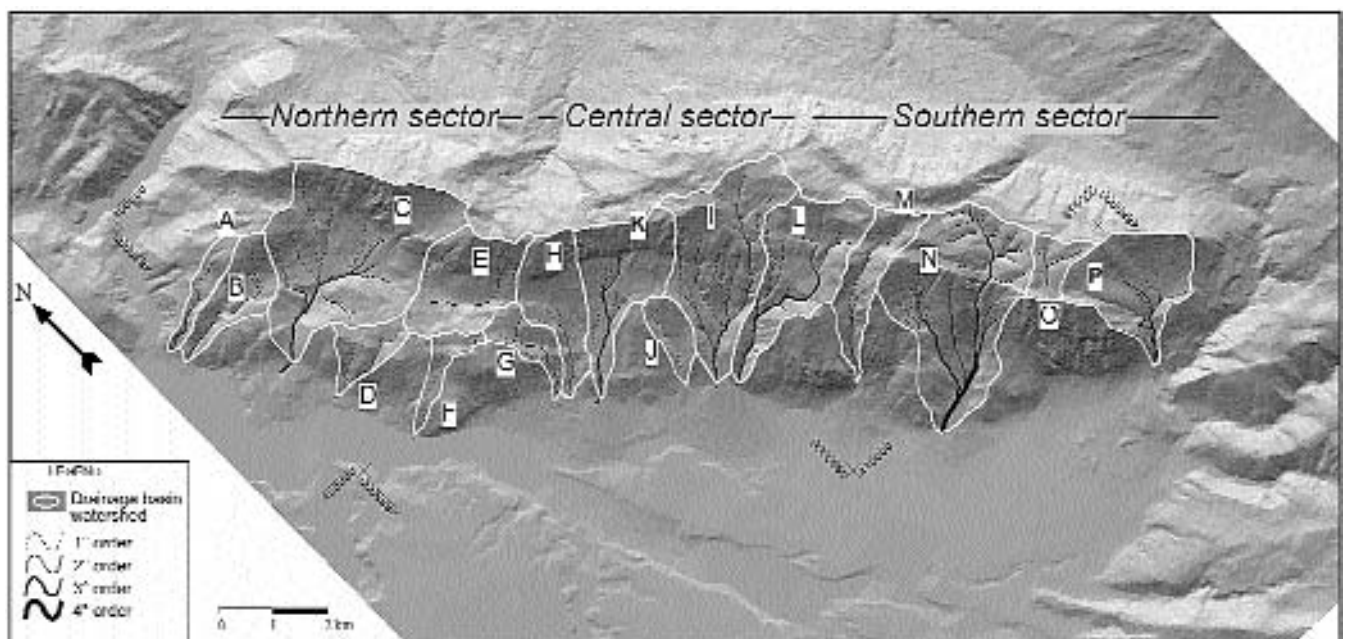

FIG. 7 - Drainage basins and ordered drainage network (according to STRAHLER, 1952) on the Montagna del Morrone SW slope.

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

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											

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.

The defined basins show a complex organisation and a variable geometry, from elongated to squared off or subcircular. With the three distinct sectors of the slope, it is also possible to note distinct characteristics of basins and patterns.

In the northern part the development of the basins along the slope is blocked by the minor ridge; an endoreic basin develops from the principal crest line to the mid-slope (E, fig. 7 and tab. 1) while others go from this point right to the base of the slope (A, B, D, F, of fig. 7 and tab. 1). Only basin C covers the whole slope. In this sector the basins have a strongly asymmetric geometry: sub-trapezoidal on the upper part of the slope, and very nar-

row and triangular on the lower part. The drainage pattern is heterogeneous, with parts upslope being sub-dendritic, while down-stream it appears to be parallel. In the central sector, the basins develop all along the slope, except for two cases (G, J), but have a pear-like shape and clear downstream narrowing (H, K, J, I of fig. 7 and tab. 1); the drainage pattern is clearly of a parallel type, transversal to the slope. In the southern sector the basins go from the summit down to the base of the slope and present a symmetrical shape, triangular or pear-like (L, M, N, O, P of fig. 7 and tab. 1), apart from in the case of Basin O, rectangular and isolated. In this case the network is rectangular in the summit area of the ridge and becomes sub-parallel in the lower part. The area of the basins is variable (from 0.75 to 9 km²) and differing between N (average area 2.85 km²) and S (average area 3.76 km², tab. 1).

The areal and relief properties of the basins (tab. 1: Re, elongation ratio; Rc, circularity ratio; Rh, relief ratio; Schumm, 1956; Mayer, 1986; Keller & Pinter, 1996) were analysed, together with the main stream channel long profiles (fig. 8; Shepard, 1979; and in a large scale context Hovius, 2000) and the hypsometric data (tab. 1: ∫ ips; Strahler, 1952), not simply to give an indication
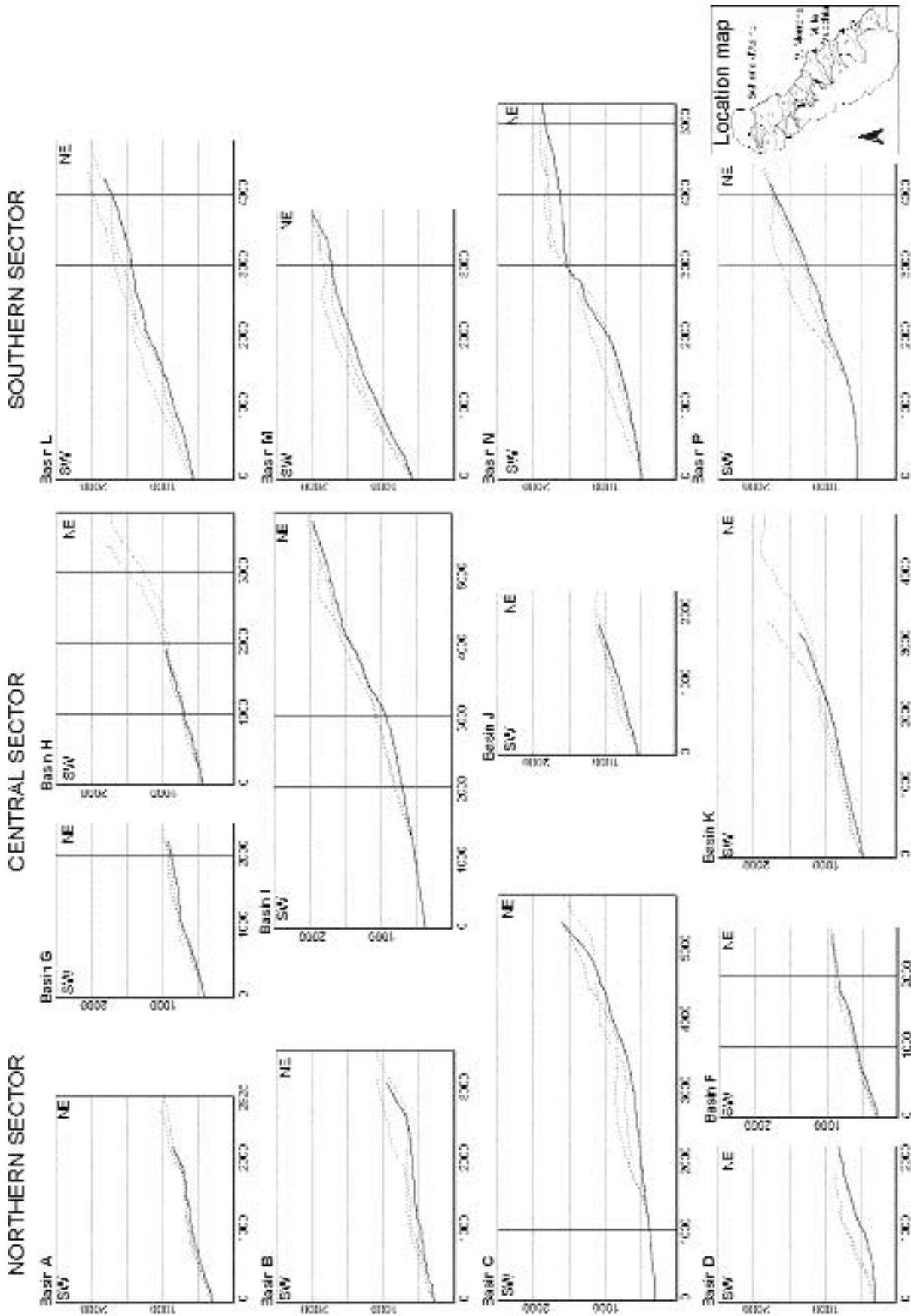
FIG. 8 - Stream channels (continuous line) and interfluves (dashed line) long profiles of the drainage basins of the SW escarpment of Montagna del Morrone.

of the morpho-evolutionary stage, but also to identify the principal situations of disequilibrium and structural control.

The elongation ratio shows mainly low values (0.4-0.6; tab. 1) for most of the basins (A, B, D, F, G, H, I, J, K, L, M), indicating strong control of the relative tectonic uplift of the slope, and of the resulting high gradient. Only in a few cases are there values higher than 0.7 (C, E, N, O, P). These indications are further strengthened in comparison with the drainage patterns, which characterise the various basins: the basins with a lower elongation ratio are the ones characterised by a parallel pattern.

Similar consideration can be given to the circularity ratio (Rc), which has an average value of 0.52, with strong variability from 0.30 to 0.68 (tab. 1). These values are from medium-low to medium-high amongst those noted in the relevant literature in similar lithostructural contexts (Avena & Lupia Palmieri, 1969). It is possible to note a slight increase with the basin size increase, suggesting a progressive regularisation with the widening of the basin.

In both cases the highest values can be found in basins C, E, N, O, and P; basins E and O are endoreic, while the others are influenced in their general geometry, as we shall see, by the development of large rock landslides or by capture phenomena.

The relief ratio (Rh) is recognized as a sound indicator of the morpho-evolutionary stage (Schumm, 1956), both in wide and small basins in particular when compared to the analysis of stream gradients and hypsometric data. The average value found of 0,33 (tab. 1), with a maximum of 0,47, indicates a clearly young morpho-evolutionary stage over the whole slope, influenced by tectonic activity and resulting relative uplift.

For each basin, the main stream channel long profile and the profiles of the left and right interfluves were drawn using the GIS (fig. 8). In this case again, it is evident how in the northern sector the long profiles present a concave-convex shape with moderate knick points in the mid part of the slope. In the central and southern sectors, one can respectively identify profiles which are irregular but tend towards being rectilinear with moderate knick points, and profiles that present clear convexity and marked knick points in the summit area where there are localised segments of low gradient (basins I, L, M, N). This suggests a strong disequilibrium of the upper part of these basins. It is also interesting to note the low relief between the stream channel profile and interfluve profiles (mostly in the central and southern sectors), which indicates a moderate dissection of the drainage system and suggests a poor development of the downcutting processes. On the other hand, in the northern sector the relief is relatively higher, thus suggesting more developed downcutting.

In order to further explore the morphometric analysis, so as to proceed to a comparison with the field data, the hypsometric curves of the individual basins and of the whole slope were drawn, again by DEM processing in the GIS. In this way the hypsometric integral was calculated (fig. 9; tab. 1; according to Strahler, 1952).

The hypsometric curve of the whole slope appears in general to be regular and concave (hypsometric integral 0,44). In detail, the curve is characterised by a clear double convexity, with a concave intermediate part.

The curves and values of the integrals calculated for the individual basins are certainly significant. The values of the hypsometric integrals vary from 0,27 to 0,68 (fig. 9; tab. 1), covering almost the entire range of values characteristic of various morpho-evolutionary stages of a drainage basin of moderate dimensions (Ciccacci & alii, 1992, 1995). The lower values concern the endoreic basins E and O, and Basin C, the only one in the northern sector that stretches all along the slope. Note the decrease in values from the southern sector towards the central and northern sectors (as illustrated graphically in fig. 9) especially if the small basins on the lower part of the slope are not considered. In the same way, the hypsometric curves also differ. In the southern sector, they are characterised by a marked convexity (L, M, N, P; fig. 9). In the central, they are irregular, generally convex with knick points and slightly concave parts (G, H, I, J, K, fig. 9). In the northern, the curves (A, B, C, D, fig. 9) present a clear concave-convex trend with clear knick points, which suggest a strong state of disequilibrium.

This distribution, together with the narrowing shapes of the basins, the gradients of the stream channel profiles and the parameters already discussed, is thought to be the result of the morphostructural effects of the normal fault system (Schiena d'Asino Fault, fig. 5) in the mid-slope and in the middle part of the major basins, more than of a different morpho-evolutionary stage related to slope denudation or downcutting.

The drainage density shows, according to the relevant literature (Avena & alii, 1967; Lupia Palmieri & alii, 2001), values which are never very high (D average = 2,25) and which have an irregular distribution (tab. 1). This could support, in our opinion, the indication of a poor down-cutting of the drainage network. A slight increase in D values also confirms the greater development of these processes in the northern sector (tab. 1).

For each basin, the drainage network was ordered (according to Strahler, 1957) and the principal morphometric properties were calculated, using automatic and semi-automatic procedures (tab. 2, tab. 3).

The stream ordering (fig. 7) shows a poorly developed network (it exceeds the 3rd order only for one basin), which is mainly irregular and characterised by great variability in length in the streams of different orders (standard deviation in tab. 2).

The differences in frequency of the segments of successive order (tab. 2) and the values of bifurcation ratio and bifurcation index (tab. 3), were compared with the results also obtained in similar areas from a lithostructural point of view (Avena & Lupia Palmieri, 1969; Lupia Palmieri & alii, 2001). The data show values which are never high (average Rb = 3,19, average Rbd = 2,90, average R = 0,29). This indicates good organisation of the network, which results, we believe, mainly from the moderate development of the drainage system.
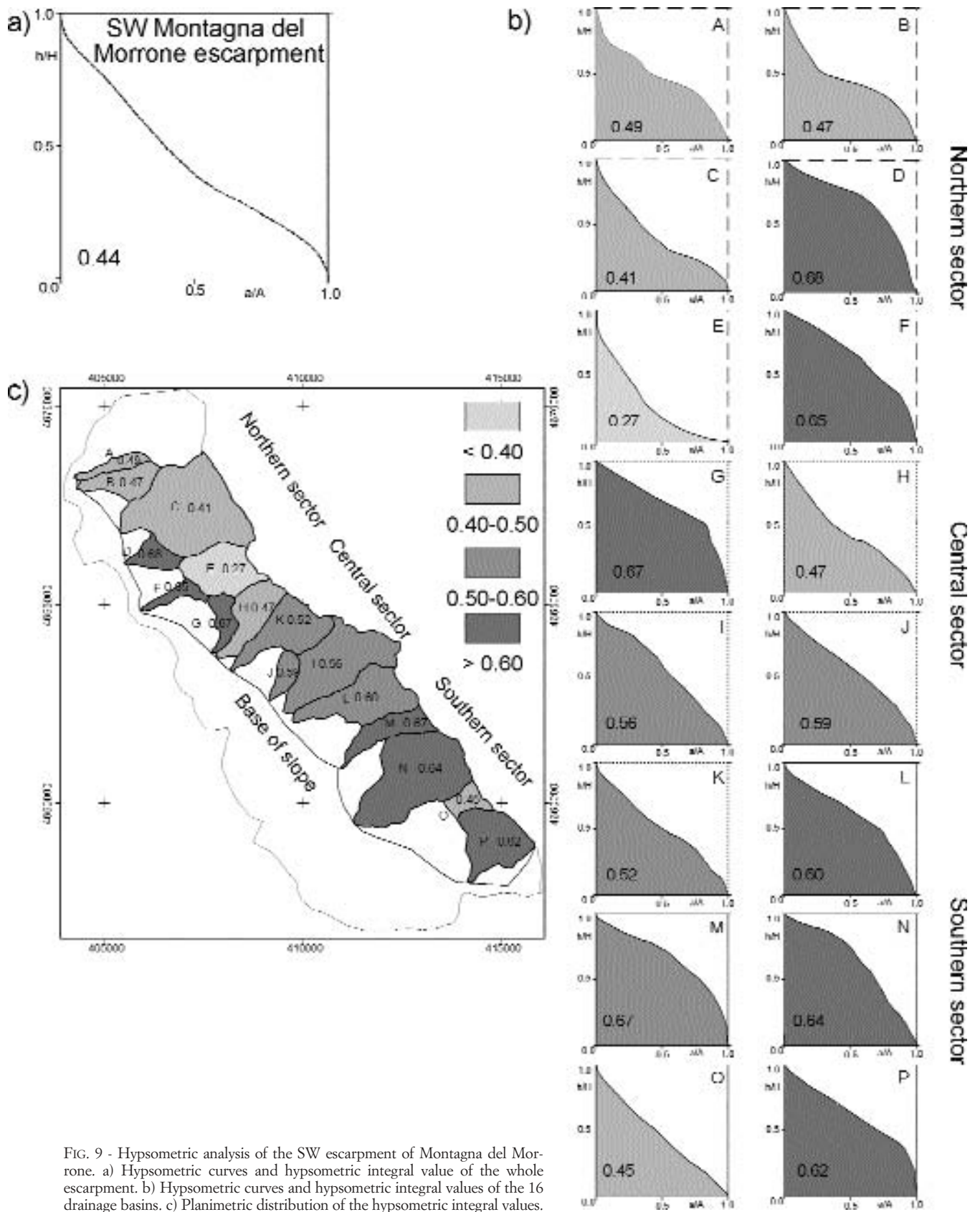
FIG. 9 - Hypsometric analysis of the SW escarpment of Montagna del Morrone. a) Hypsometric curves and hypsometric integral value of the whole escarpment. b) Hypsometric curves and hypsometric integral values of the 16 drainage basins. c) Planimetric distribution of the hypsometric integral values.

TABLE 2 - Stream ordering of the slope's drainage system

Stream order (u)	ΣNu	L max (m)	L min (m)	Average L (m)	Stand. Dev. L (m)
1	115	2642	67	530	464
2	35	2445	84	807	588
3	9	3375	534	1966	1165
4	1	1551	1551	—	—

Structural landforms

The geomorphological surveys brought to light the presence of forms such as fault scarps, fault related slopes and crests (fig. 10). These landforms are essentially controlled by the presence of important normal fault systems.

Fault scarps: These landforms are located on the slope, at various heights corresponding to the main fault lines. Taking into account the outcropping of the fault planes, the profile of the scarps, the occurrence of basal scarplets and the reciprocal relationships between bedrock and debris deposits, three subtypes were distinguished: fault scarps, partly retreated and weathered fault scarps, retreated and weathered fault scarps (Demangeot, 1965; Wallace, 1977; Brancaccio & *alii*, 1978; Bosi & *alii* 1993; Stewart & Hancock, 1994; Ascione & Cinque, 1997; Peulvast & 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 generally well smoothed scarplets, from a few decimetres to some metres high, with inclinations of 45°-70°; it corresponds to the surface expression of fault planes. Against the base of the scarps there are mostly inactive debris deposits. The summit area is made up of free faces, with evidence of slope gravity denudation, locally combined with the action of channel flow and nivation. This typology occurs mainly in the northern sector of the ridge and in the upper parts of the slope (Schiena d'Asino, C.le Affogato, fig. 11a) at heights of roughly 1100 m and 1200 m a.s.l. under the peaks of Mt Rotondo, C.le dei Sambuchi, C.le Affogato e C.ma della Croce. Along the basal fault line these can be identified between Popoli and Roccocasale, at heights from 400 m to 600 m (tab. 4).

The *partly retreated and weathered fault scarps* are rock scarps from a few tens of metres to 100 m high, slightly sinuous, with slope angle generally from 60° to 35°. The basal smoothed scarplets corresponding to the fault plane are only locally preserved, partially covered by scree slopes. Upslope the free faces have to some extent retreated from the fault line; the free face is clearly preserved but much more weathered than in the previous case. 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, Eremo di Celestino V, fig. 11b).

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). They develop particularly where the bedrock is made up of highly jointed limestone and cataclasite (along the basal fault line between Roccacasale and Popoli at heights of 500-1300 m), because these structural conditions favour weathering processes. These features are linked upslope to moderate and weathered rock scarps, which result from retreat of the fault scarps. Based on the analysis of the transversal profile, the evolution of the fault scarp can be referred to a model of slope replacement, as already well described in similar contexts in the

TABLE 3 - Geomorphic indices of the drainage network of the 16 basins present on the SW escarpment of the Montagna del Morrone. Nu) stream number; Rb) bifurcation ratio; Nd) number of stream flowing into higher order streams; Rbd) direct bifurcation ratio; R) bifurcation index

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
Average									3,2							2,9	0,3
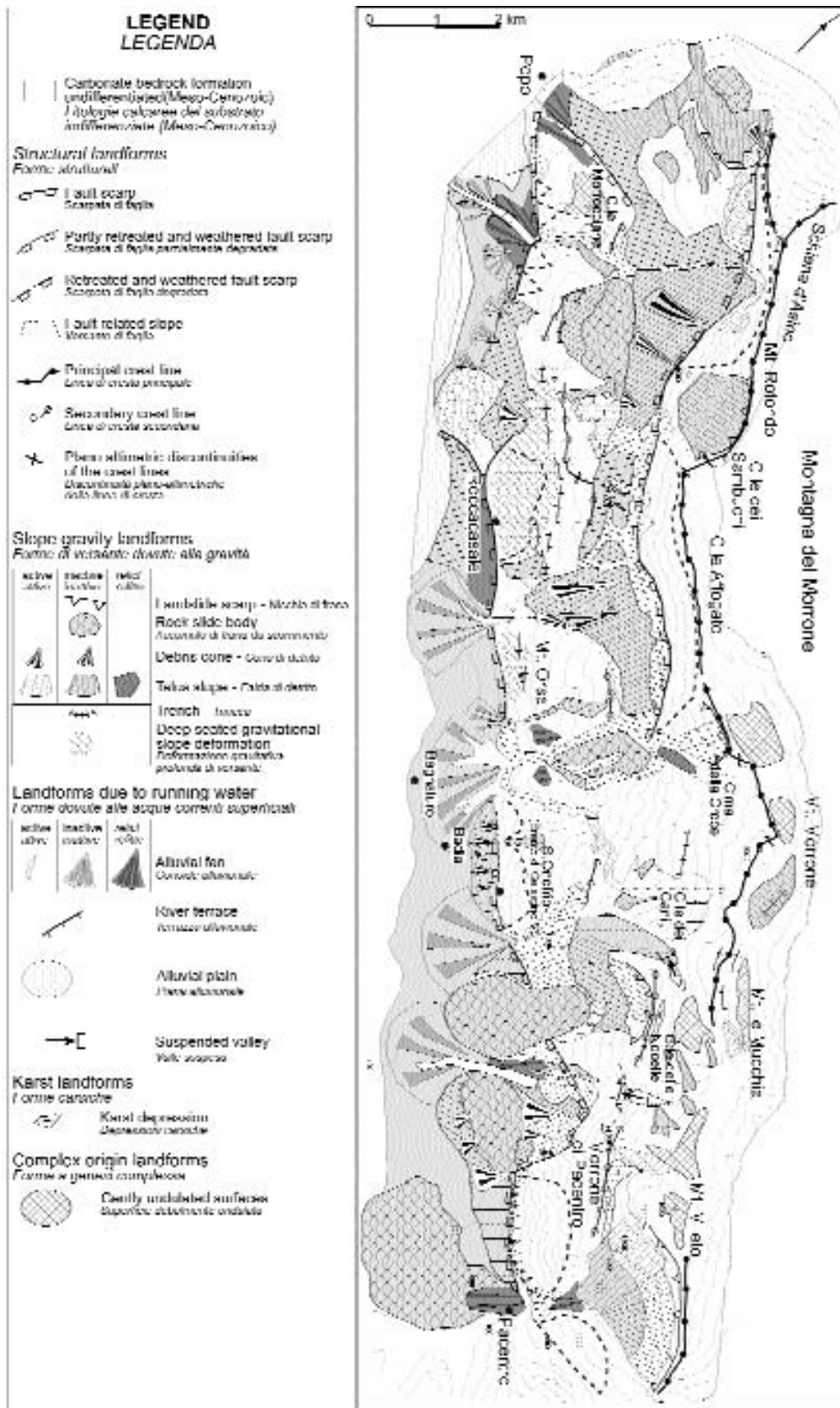
FIG. 10 - Geomorphological scheme of the SW escarpment of Montagna del Morrone.

FAULT SCARPS					
Località	Schiena d'Asino	C.le Affogato	Iaccio Rosso - valle di Mileto	Mass. Muzzi - C.le dei Cani	
H1	900 m	900 m	1100 m	700 m	
H2	1300 m	1400 m	1700 m	1400 m	
L	3500 m	7700 m	400 m	9900 m	

FAULT SLOPES					
Località	C.le Morrocciane	C.le Novelluccio	Roccacasale	M. Orsa	Sant'Onofrio	Morrone di Pacentro
H1	400 m	400 m	500 m	500 m	500 m	700 m
H2	600 m	700 m	1000 m	1000 m	1300 m	1200 m

southern Appenines (Brancaccio & *alii*, 1978; Ascione & Cinque, 1997).

Fault related slopes: These 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, frequently studded with rocky cliffs and bordered at the base by the different kind 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; fig. 11a), and in the lower part (Popoli, Roccacasale, Pacentro) (fig. 10). Especially in the central and southern sectors, they are incised by gullies and affected by slope gravity 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 (fig. 11c).

Crest lines: They 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. The main crest is aligned along an Apennine orientation (NW-SE) and can be traced very clearly from Schiena d'Asino up to Mt. Mileto. It presents, particularly in the central area, some important planimetric discontinuities that develop in an E-W to NE-SW direction and which cause it to deviate slightly from the general Apennine orientation, with displacements in the order of 500-1000 m. Such discontinuities can be identified in particular in the central sector (fig. 10).

Secondary crest lines, moderately defined and made up of alignments of isolated peaks, are present in the northern sector (the mid-part of the slope). In the southern sector they are clearer and sharper (the upper part of the slope). In the first case (Cle Novelluccio, Mt. Capo d'Acero, Monti della Rocca) the crests have an orientation of N40W; they are about 2000 m SW from the principal crest line and 1000 m lower. In the southern sector (Cimerone, C.le delle Nocelle, Morrone di Pacentro) the secondary crests are close to the summit, with heights higher than the preceding ones; they are about 1000 m away and 100 m lower from the principal crest line. As regards the morphology of the secondary crest, the longitudinal disconnection between the northern and southern sectors develops in the central

sector, just as occurs with the main crest. This can be attributed to transversal tectonic features on the ridge (fig. 10).

Slope gravity forms

The processes and the relative forms linked to the action of gravity are well represented, even though they are distributed non-homogeneously. There are landslide scarps, rock slide bodies, talus slopes and debris cones and also evidence of deep seated gravitational slope deformations, which will be described below, referring to fig. 10. and tab. 5.

Landslide scarp: These are made up of arched or semi-circular rock scarps, mainly wide (1000-3000 m), placed on the limestone bedrock formations, generally plunging counterslope. The scarps and the relative slip surfaces are neoformation surfaces or possibly linked to major joints or faults affecting the bedrock formations. They show a marked concave profile (fig. 11d), but are generally very weathered and shaped by further slope gravity processes, which have created active and inactive scree slopes within them. This shows that the detachment of the landslide bodies is not recent. These forms are located on the higher parts of the slope: C.le dei Sambuchi-Montagnola, in the northern sector of the ridge, at a height of 1659-1700 m a.s.l.; Cima della Croce, in the central sector, at a height of 1850-1900 m a.s.l.; C.le delle Nocelle (fig. 11d), Mt. Mileto, in the south, at a height of 1700 m a.s.l. (tab. 5).

Rock slide body: They are made up of bodies 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 are distributed both at the base of the slope and in some points in its mid-part (fig. 10). They are large and lengthened perpendicularly or transversally to the slope: with a surface up to 3 km² (length/width ratio of 2:1 to 1:2) and thickness up to hundreds of metres (tab. 5). The longitudinal profile of the slip surface and landslide body is always markedly concave-convex (fig. 11d). The movement from the slip surfaces is variable from several hundred metres to several km. Especially in the cases with little movement, the accumulation is still partially superimposed onto the
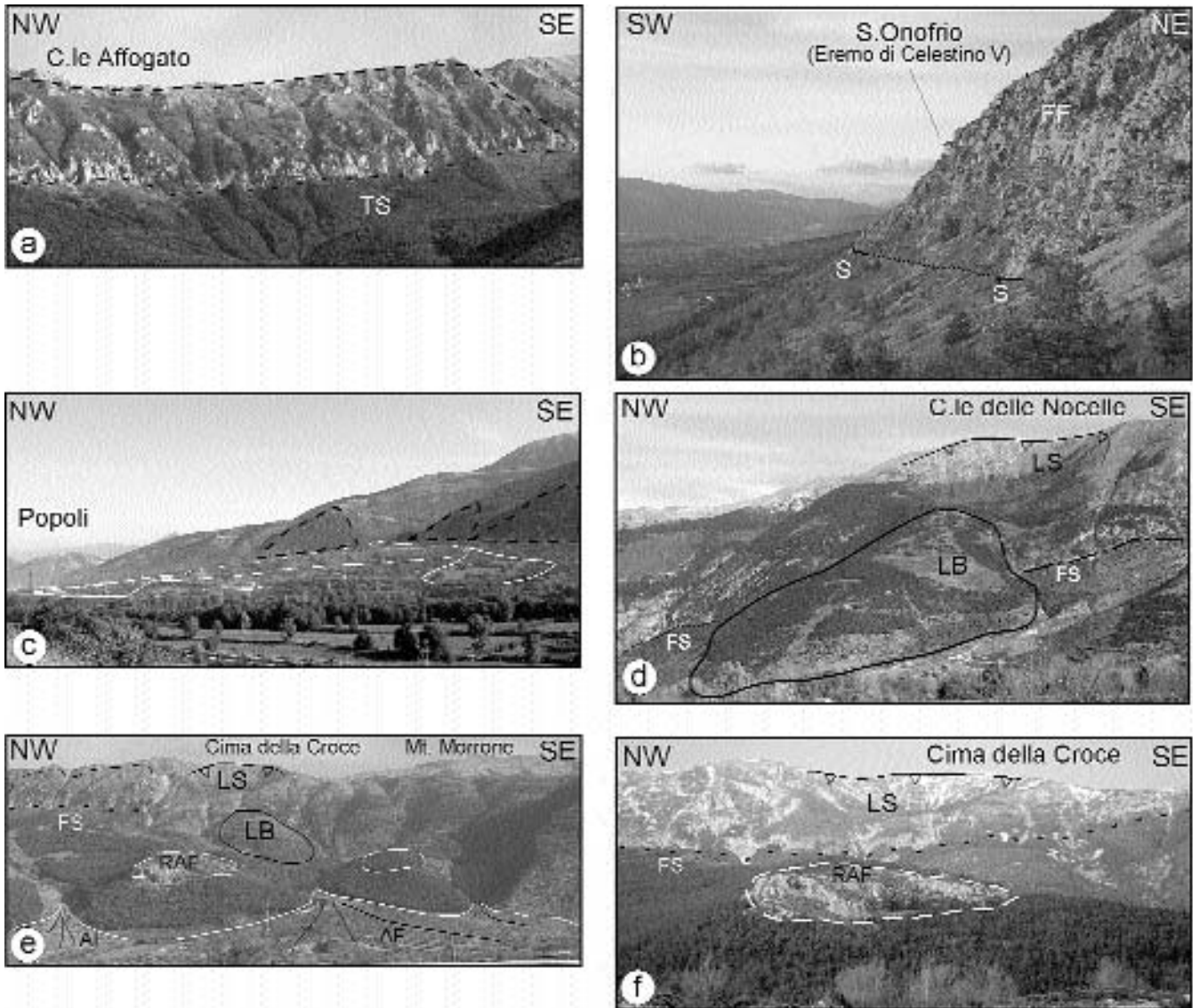
FIG. 11 - Main landforms on the SW escarpment of Montagna del Morrone. a) C.le Affogato (northern sector): fault scarp (basal scarplet and upper free face), related fault slope with several rock scarps remnants of the slope development, and talus slope at the base of the scarp (TS). b) S. Onofrio, Eremo di Celestino V (southern sector): partly retreated and weathered fault scarp, note the free face (FF) and the talus slope deposits covering the scarplet (S) corresponding to the fault line at the base. c) Popoli, Mancini fan (northern sector): entrenched alluvial fans at the outlet of Basin C; triangular facets in the interfluves. d) C.le delle Nocelle (southern sector): landslide scarp, related slip surface (LS) and landslide body (LB); note the clear concave convex-profile of the slope and the landslide body lying against the Basal border Fault, which fault scarps (retreated and weathered) are evident to the NW and to the SE (FS). e) Cima della Croce, Mt. Morrone (central sector); note the presence of structural and slope gravity landforms in the upper part of the slope: a fault scarp to the left (FS, just south from fig. 11a), the Cima della Croce landslide scarp (LS) and the landslide body (LB); landforms due to running water are present in the lower part of the slope: alluvial fans (AF) and remnants of relict alluvial fans (RAF) at present in relief inversion some hundreds of metres above the thalweg. f) Cima della Croce (central sector): in the foreground a close up of a remnant of relict alluvial fans (RAF); in the background the southern end of the Schiena d'Asino - C.le Affogato fault scarp (FS) and the landslide slip surface (LS) partially shaped also by nivation processes.

slip surface and maintains only a slightly deformed litho-structural arrangement similar to that of the bedrock formation (C.le delle Nocelle, fig. 11d).

The movement is generally complex, but however attributable principally to translational and rotational rock slide mechanisms. Similarly to the slip surfaces, also the landslide accumulation is 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 (fig. 5; Miccadei & *alii*, 1999). The geomorphological antecedent relationships between the various landforms suggest, there-

TABLE 5 - Main slope gravity landforms; morphometry:: H1) minimum height; H2) maximum height; S) area; L) length; l) width; Δo) horizontal movement; Δv) vertical movement

	LANDSLIDE SCARPS					
Località	Schiena d'Asino	C.le Sambuchi	Cima della Croce	C.le delle Nocelle	Morrone di Pacentro	Mt. Mileto
H1	800 m	1650 m	1850 m	1600 m	1500 m	1200 m
H2	1000 m	1700 m	1900 m	1700 m	1650 m	1700 m
L	1500 m	2300 m	1500 m	1500 m	1400 m	3300 m

	LANDSLIDE BODIES					
Località	Schiena d'Asino (Gole di Popoli)	C.le Novelluccio (C.le Sambuchi)	Cima della Croce	C.le delle Nocelle	Morrone di Pacentro	Pacentro
H1	450 m	600 m	700 m	500 m	600 m	400 m
H2	550 m	800 m	1300 m	1300 m	800 m	700 m
S	300 ha	1000 ha	650 ha	2350 ha	800 ha	2700 ha
L	700 m	900 m	1500 m	2200 m	900 m	2400 m
l	450 m	1800 m	700 m	1200 m	1600 m	2100 m
Δo	900 m	1900 m	1100 m	1000 m	1500 m	4000 m
Δv	400 m	700 m	600 m	500 m	800 m	1000 m

	D.S.G.S.D.		
Località	Roccacasale - Mt. Orsa	Cima del Mt. Morrone	Mt. Le Mucchia
H1	600 m	1600 m	1900 m
H2	900 m	1700 m	2000 m

fore, an Early?-Mid Pleistocene age for the principal landslides identified on the slope (Pacentro, Morrone di Pacentro, C.le delle Nocelle, Cima dei Sambuchi, tab. 5). They are therefore entirely inactive paleo-landslides; only a few minor ones can be attributed to more recent ages.

Talus slope and debris cone: These 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 (fig. 11b). The talus slopes and debris cones lie either on bedrock formations or on different Quaternary superficial deposits. Indeed, they are present along the whole escarpment of Montagna del Morrone with extensions that run for several kilometres longitudinally, up to over 1 km transversally and up to 600 m on relief. They are seen in several ravines, inside the large landslide slip surfaces and especially at the foot of fault scarps and fault slopes: Schiena d'Asino-Cima della Croce, at heights ranging from 1300 m to 700 m; S. Onofrio, at heights from 600 m to 400 m; Morrone di Pacentro, at heights from 600-800 m a.s.l. (tab. 5).

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 & *alii*, 1987; Crescenti & *alii*, 1989; Dramis & 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; fig. 10). In some cases, they can be identified also upslope from the fault slope of Schiena d'Asino (tab. 5). 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 long (this is clearly seen in fig. 2b and in fig. 6, profiles 9, 10, 11).

The spatial relationships between the presence of D.S.G.S.D. and the geometry of the faults suggest that the evolution of such deformations is due to the high local relief and the tension on the slope caused by tectonic displacement along the faults during stages of intense activity. The evolution of such deformations could be responsible for the movement of the main landslides present along the slope. They would, therefore, have characterised the shaping of the slope from the Early?-Mid Pleistocene up to more recent times. 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.

Landforms due to running waters

Landforms due to running waters are mostly present in the low part of the SW Morrone slope. There are alluvial fans which are active, inactive or exist as relict landforms. A morphometric analysis of the fan/catchment systems was carried out on the main landforms. Gullies are present on the slope and frequently on the fault related slopes together with slope deposits and forms (fig. 11a). River terraces are also present at the base of the slope.

Alluvial fans: All along the join between the slope and the plain there are several fans (tab. 6; fig. 10, fig. 11c, e, f), seldom coalescent, ranging in size from several ha to 2,20 km² 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. 10). The fans, as shown in the previous sections, are formed mostly of calcareous gravel deposits and they are cut internally by faults whose activity is documented up to the Late Pleistocene. The fault scarps that have displaced the fans' surface are mostly flattened by erosional and depositional processes (fig. 4e) (see also Miccadei & *alii*, 1999). In some cases also the apex of inactive fans is cut by normal faults.

The landforms are mostly inactive; only at certain points (upper part and apex) do they show evidence of active depositional processes (fig. 11e). The geometry and the spatial relationship between active and inactive forms indicates a general fan aggradation, except in the northern sector (Basin A,C). Particularly Basin C shows a clear entrenching of three subsequent fans and the formation of two orders of terraces (fig. 11c).

At certain points in the middle part of the slope and entrenched in the lower part of the catchments there are remnants of relict alluvial fans. Some of these are now at the catchment interfluves in relief inversion, suspended some hundreds of metres above the present stream channel (fig. 11f).

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; Blair & McPherson, 1994; Oguchi & Ohmori, 1994; Allen & Hovius, 1998; Allen & Densmore, 2000) and it is summarized in tab. 7. The relationship between the main parameters and the interpolated functions are shown in fig. 12.

TABLE 6 - Main alluvial fans morphometry: H1) minimum height; H2) maximum height; Af) fan area

Source catchment	Activity	type	H1 (m)	H2 (m)	Af (km²)
Basin A	relict	entrenched	400	500	0,35
Basin C	relict - inactive	entrenched	250	410	1,64
Basin K	active - inactive	in aggradation	330	530	1,44
Basin I+L	active - inactive	in aggradation	360	685	2,20
Basin J	inactive	in aggradation	360	585	0.46
Basin M	inactive	in aggradation	360	615	1,17
Basin N	active - inactive	in aggradation	400	650	1,39

The first graph shows the relationship *fan area vs. catchment area* (fig. 12a), 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 & Densmore, 2000), also defined by the ϕ ratio (fan area/catchment area; Allen & Hovius, 1998). Note the good alignment of most of the data except for a few anomalies (Basin C and N; triangular symbol in fig. 12a).

The fan area was compared to the volume eroded from the catchments (EVc, tab. 7, fig. 12b), 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. 12c).

In both graphs the data distribution is similar to the first graph (fig. 12a), but much more scattered; the anomalous data of Basin C and N is confirmed.

TABLE 7 - 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) negligeble; N*) without possible captured upper part of the catchment; N**) considering the entrenched apex

| Basin	Af (km²)	Hf (km)	Lf (km)	Sf Hf/Lf	Vf (km³)	Ac (km²)	Rc (m)	Lc (km)	Rh c	LVc (km³)	TLVc (km³)	EVc (km³)	∫ 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
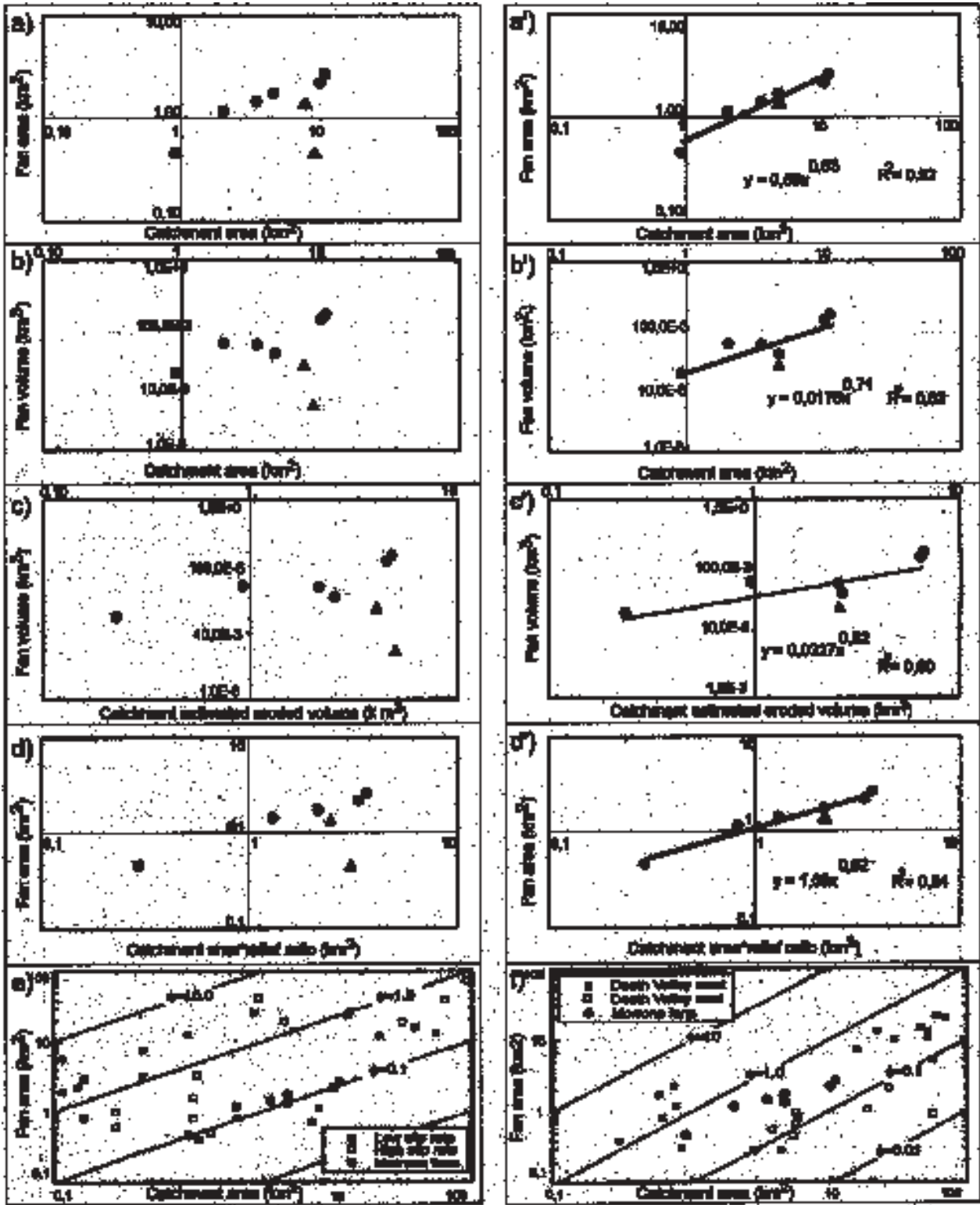
Fig. 12 - Graphics illustrating the relationships between some of the main morphometric parameters of alluvial fan/catchment systems (referred to Tab. 6). Note the logarithmic axes; each symbol represents a single fan/catchment pair (Circle: normally developed fan/catchment systems; Triangle: anomalous 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 extimated 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 & 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 & Densmore, 2000).

The fourth graph (fig. 12d) is similar to the first (fig. 12a) 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. 12 a, 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. 7).

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. 7, 8, 9) 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. 7).

The four graphs of fig. 12 a', 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 the 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. 12 d' in relation to the value in the graph of fig. 12 a' which suggests the influence of catchment steepness in defining the fan area.

River terraces: These are present only in the northern part of the slope, at its base, and they are evident in the alluvial fan of Basin C (Mancini fan; fig. 10, fig. 11c). The stream is now entrenched between two orders of terraces shaped in the alluvial fans of the late Middle Pleistocene and the Upper Pleistocene. A terrace continues toward SW and involves the lower parts of other fans.

Karst landforms

The karst weathering process has shaped, and still shapes, the limestone rocks of the bedrock of the Montagna del Morrone ridge, forming minor and major forms, both on the surface and underground. It is worth mentioning gently undulated surfaces, small karst depressions, and suspended valleys located in the upper gently sloping part of the ridge.

Gently undulated surfaces: These 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 (fig. 6, section 7, 10, 11). They are generally bounded by sharp breaks followed by steep slopes and seem to be intersected by the slip planes of some of the major landslides (Mt. Mileto; fig. 10). Some similar but less evident features are located mid-slope in the northern sector (fig. 6, section 2). The occurrence of small dolines and karst valleys suggests that the karst weathering is an important morphogenetic factor.

Karst depression: These 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 plane of some of the major landslides (fig. 10).

Suspended valleys: They 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 nick points and strongly convex channel profiles (fig. 8, Basin N, M). These features seem mostly to be related to the capture of the karst depressions in the upper part of the slope.

DATA DISCUSSION

The collected data allow us to outline some points about the Quaternary geomorphological evolution of the escarpment and the balance of the processes that have shaped the SW side of Montagna del Morrone.

In order to summarize the main morphostructural and morphosculptural features, six morphostructural sections are presented (fig. 13). Three of them are made on straight transversal profiles, chosen from fig. 6 (profile 4, 9, 10) as representative of the northern, central, and southern sectors (fig. 13 b, d, f). The others are made on stream channel and interfluve profiles chosen from fig. 8 (Basin C, I, P) as representative of the drainage basins of the slope's three sectors (fig. 13 c, e, g).

Orography and slope

The analysis of orography and slope has outlined a NW-SE straight slope 20 km long and up to 1700 m high (fig. 2, fig. 5b). In detail the slope is made up of several units that led to the division in three sectors. The planar and profile form, consisting of concave and convex elements but mostly of planar segments and sharp breaks (fig. 5a, fig. 6), is closely linked to the tectonic setting (fig. 3, fig. 13). The northern sector can be seen overall as a double-ridged slope formed by two relatively down-faulted and uplifted blocks along the two major normal faults.
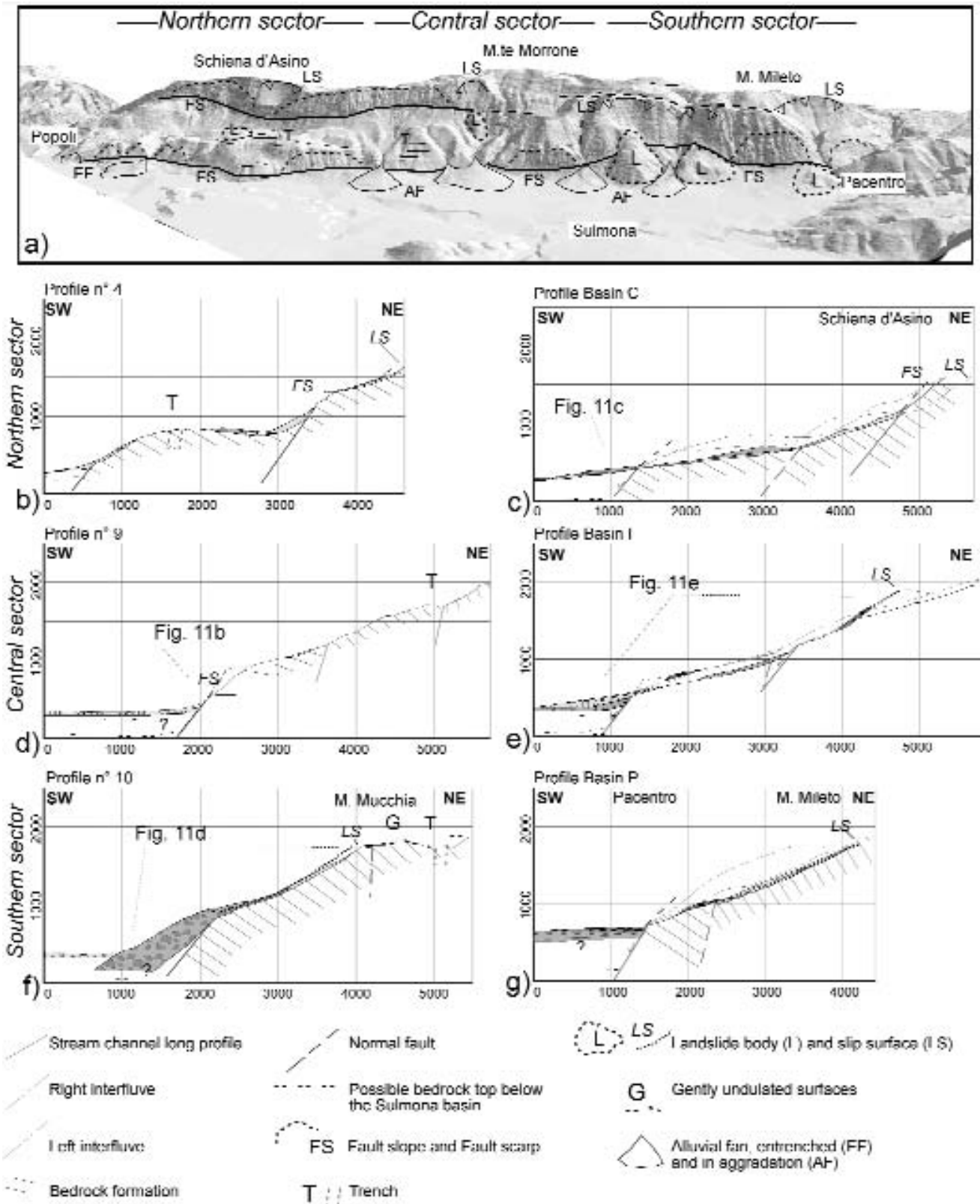
FIG. 13 - a) Synthetic 3D morphostructural scheme profiles of the SW escarpment of the Montagna del Morrone. b, c) synthetic transversal and stream channel morphostructural profiles of the northern sector of the escarpment; d, e) synthetic transversal and stream channel morphostructural profiles of the central sector of the escarpment; b, c) synthetic transversal and stream channel morphostructural profiles of the southern sector of the escarpment (the profiles are chosen from fig. 6 and fig. 8; for the legend of the deposits see fig. 3).

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. The central sector is 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. The southern sector can be seen as a single major uplifted block. The form of the escarpment is closely linked to the occurrence of a major fault at the base that led to most of the downfaulting of the piedmont and the relative uplift of the escarpment. The morphostructural effects of the secondary fault in the upper part are less evident (fig. 13). The escarpment shows a wide and steep free face in the lower part, generally rectilinear and straight, but with at least three concave-convex elements; the upper part and the summit area is gently sloping and undulated.

The toeslope 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.

In summary, the distribution of slope and relief is irregular in relation to the tectonic setting: 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 they are mostly in the upslope, they are low in the midslope and increase again in the lower part down to the toeslope break.

Drainage system

The drainage basin morphometry, applied to area and relief properties and to the stream network, then compared to the landforms distribution gives good indications concerning the balance of factors controlling the geomorphological evolution of the slope.

The morphometric parameters calculated in the previous section, according to a classic interpretation (Strahler, 1957; Avena & Lupia Palmieri, 1969; Lupia Palmieri & *alii*, 2001), outline a poorly developed drainage system with slow denudation processes and strongly controlled by extensional tectonics.

The southern sector shows elongated and irregular drainage basins with high relief ratios (tab. 7), separated in the interfluves by wide straight rectilinear fault related slopes (fig. 7, fig. 10). Many data, such as the drainage patterns, parallel in the lower part of the slope and rectangular on the summit, the convex stream channel profiles with sharp knick point, the low stream channel/interfluve relief (fig. 8), the high values of the ipsometric integral (>0,6) and their convex curves (fig. 9, tab. 1), indicate a low 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 shaped by the drainage network.

In the northern sector the drainage pattern is heterogeneous, sub-dendritic in the upper part and parallel in the lower part. The catchments are separated in the upper part from the lower part; only Basin C is extended across the whole relief area, but it shows a clear downstream nar-

rowing (fig. 7). 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 (fig. 10). The stream channels have concave-convex profiles with moderate knick points (fig. 8). The hypsometric integrals have values lower than in the southern sector (0,5-0,3) and show concave convex curves (fig. 9, tab. 1). This 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. 13 b,c). 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).

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. The drainage pattern is parallel, transversal to the slope (fig. 7), the stream channel profiles are mostly planar with moderate knick points (fig. 8) and the hypsometric integral values are intermediate (0,4-0,6) with moderately convex curves (fig. 9, tab. 1). This setting is controlled by the interplay of principal faults parallel to the ridge and secondary transversal faults (fig. 13 d,e): the southern end 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 controlled the development of the parallel drainage network.

The role of capture processes in the geomorphological evolution

Some drainage basins are a key to understanding the role of drainage capture processes in the evolution of the SW escarpment of Montagna del Morrone.

In Basin C a capture occurred in the early stage of escarpment evolution, followed by antecedence process in the drainage evolution. The threshold formed along the lower block, possibly increased by the fault activity, has been progressively incised by the linear deepening processes developing downstream (see the mostly concave stream channel profile in fig. 8). These processes have been strengthened because of the moderate debris supply in the lower part of the basin and the occurrence of storage points for the sediments supplied from upstream.

On the other hand, the downslope threshold that closes Basin E, not eroded in the early stage, has been preserved up to now because of the very slow linear deepening erosion in the small lower block catchments.

In Basin N, capture occurred but the basin is in strong disequilibirium. This is highlighted by the sharp knickpoint in the upstream channel profiles and by the junction of a rectangular upstream drainage pattern and parallel downstream pattern. As we shall see below, it is also supported by the morphometry of the alluvial fans/catchments.

Basin O is closed and suspended upslope; capture has not occurred, but is likely to occur in the future evolution of the escarpment.

The progress of these phenomena is due to different factors. In the northern sector it is thought to be due to the balance between tectonic activity along the fault systems on the slope (Basal border Fault and Schiena d'Asino Fault) and the linear down-cutting along the stream channels. In the southern sector it seems mostly linked to the development of the large landslide and to the following denudation and local moderate down-cutting of the stream channels.

The distribution of the landforms on the escarpment and the relationship between them allow us to support and better define the morphology and drainage evolution of the escarpment, both locally and generally, and evaluate the balance between morphostructural and denudation processes in the three sectors of the escarpment.

Structural landforms

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

The escarpment denudation caused by slope gravity processes, which are in opposition to the prevailing fault-related relief growth, is due to the combination of two main processes. Firstly, wide and sudden mass movement emplacement, whose intensity is controlled by fault activity and slope angle, and secondly gradual and slow slope development, which is weathering-dependent and linked to the resistance of the different type of carbonate bedrock and to the alternation of cold and warm climatic stages (several superimposed generations of talus slopes were formed; fig. 3b, fig. 10). The combination of the processes is variable in the three sectors of the escarpment. The general evolution is a complex type of slope replacement starting from a steep slope (60°-75°) in strong closely jointed rocks with a slope angle higher than the stability angle of the rock mass (Summerfield, 1991; Ascione & Cinque, 1997).

The slope profile, either a Lehmann type or Richter type, does not have a clear and univocal distribution because of the variability of sediment removal at the base of the slopes. However, the Richter type is predominant, particularly in the northern sector, with the outcropping in many cases of the fault plain uncovered or only partially covered by sediment. A Lehmann type slope occurs only at a local scale where the fault is covered by sediments (Fig. 10).

The variable degradation of the fault scarps and the morphology of the fault slopes (according to Brancaccio & *alii*, 1978; Wallace, 1978; Bosi & *alii*, 1993; Stewart & Hancock, 1994; Ascione & Cinque, 1997; Peulvast & 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. 13d). 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. 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, case 2 in fig. 50; Brancaccio & *alii*, 1978, fig. 1f; Bosi & *alii*, 1993; Ascione & Cinque, 1997, fig. 2c) 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 (fig. 13b). On the slope related to the Basal border Fault, only triangular shaped fault related slopes, retreated and developed, are preserved (fig. 10, fig. 13b; Brancaccio & *alii*, 1978, fig. 1b; Wallace, 1978, fig. 4). 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. The basal fault scarp has in many cases clearly retreated and the fault line is covered by scree (Demangeot, 1965, 5 in fig. 50; Ascione & Cinque, 1997, fig. 2a). 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. 10, 13).

Taking into account the debated elements and considering the summarizing morphostructural sections (fig. 13), it is possible to come to certain conclusions about the slip rate of the faults.

For the northern sector, we have an average slip rate of c. 0,8-1,0 mm/yr on the Basal border Fault, during the period between the Early?-Mid Pleistocene and the Holocene, and c. 0,3 mm/yr on the Schiena d'Asino Fault during the same period (fig. 13 b, d). The proposed slip rate for the southern section (fig. 13f) is c. 1,2-1,4 mm/yr; in this case, the dating of the relict landforms on the slope is set by the morphological relationship with the relict alluvial fans located slightly to the north (Mt. Orsa; fig. 10, 13e). These data are consistent with the values previously obtained in the same area and in neighbouring areas (Miccadei & *alii*, 2002; Pizzi & *alii*, 2002).

Slope gravity landforms

As for slope gravity landforms, several conclusions can be made on the evolution of the large rock landslides present on the escarpment. These features are thought to have started as D.S.G.S.D., then evolved as large landslides (Dramis & Sorriso-Valvo, 1994; Dramis & *alii*, 1995). The morphology of the areas surrounding the slip surfaces has controlled the extent of movement affecting the landslide bodies (fig. 13 b, f, g) and, as a consequence, their lithostructural setting. In the case of little movement, the lithostructural setting is still similar to that of the stratified bedrock (fig. 13f), and in the case of more movement, it is completely chaotic (fig. 13b, g).

The distribution of such landforms and of the occurrence of D.S.G.S.D. 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. The evidence of D.S.G.S.D. is limited and 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 (Crescenti & *alii*, 1989; Dramis & Sorriso-Valvo, 1994; Dramis & *alii*, 1995). 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 & *alii*, 1996; Centamore & Nisio, 2003). It is therefore necessary to take note that a large part of the relief of the slope should have already been formed in the early stages of the slope evolution (Early?-Mid Pleis-

tocene) and would then have increased, as possibly confirmed by the geometry of the foot of the slip surfaces now suspended hundreds of metres above the base of the slope (fig. 13 b, f, g).

Karst landforms

The karst landforms and the complex origin landforms on Mt. Morrone are found in the summit areas, so corresponding to similar occurrences on several ridges of the eastern-central Appennines (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 & Farabollini, 1995; Centamore & Nisio, 2003). In our case the landform characteristics and the geomorphological correlations with slope gravity forms seem to suggest, therefore, 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, without excluding that further shaping followed. This would allow the dating of the first genesis of these forms to a period before the Early?-Mid Pleistocene.

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 (fig. 13 a).

Landforms due to running waters

Geomorphological analysis of the alluvial fans has made a significant contribution to the understanding of the morphostructural evolution of the escarpment and of its base junction with the Sulmona basin. Indeed the fans have been useful both 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 themselves to be dated (Miccadei & *alii*, 1999). The morphometric analysis of the main fan/catchment systems (fig. 12, working from Bull, 1964; Blair & McPherson, 1994; Oguchi & Ohmori; 1994; Oguchi, 1997; Allen & Hovius, 1998; Allen & Densmore, 2000) has brought to light important aspects.

As previously discussed, the high values of the regression lines' R2 values in the graphs, "purified" of the anomalous values (fig. 12 a', b', c', d'), confirms the validity of the power law that regulates the morphometry of the fan/catchment systems: $A_f = k \, A_b^x$ (A_f = fan size, A_b = catchment size, k and x = the constant and the variables due to the lithological and structural context). These laws, which have been widely accepted in works discussing different climatic and tectonic environments (Oguchi & Ohmori; 1994; Oguchi, 1997; Allen & Hovius, 1998; Allen & Densmore, 2000), can therefore also be applied in a climatic and morphostructural environment like that of the Central Appennines.

The law which governs the fan area/catchment area relationship 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 & 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 slope with a fault slip rate documented at some mm/yr (fig. 12e, f; Allen & Hovius, 1998; Allen & Densmore, 2000). This can be only partly due to a 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. 12b', c' show. The data are more scattered, but they confirm the morphostructural considerations.

Another important aspect regards the values for the fan area/catchment relationship, which are markedly far from the gathered data in fig 12a, as similarly occurs for the other parameters (fig. 12b, 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 & alii, 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. 7, fig. 8, fig. 9) 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. 12. If the area that is considered object of capture is excluded from the calculation, the data (triangular dot) clearly approximate to the regression line (cfr. fig. 12 a, b, c, d e fig. 12 a', b', c', d'). Moreover, the anomalous value in the relationships studied shows that the phenomenon must have come about at a recent moment, as the re-equilibrium of the fan-basin system has not yet been achieved. Since Allen & 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 & alii, 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 (fig. 10).

CONCLUSIONS

In this work we have described and discussed the geomorphological characteristics of the SW escarpment of Montagna del Morrone. The study focuses on the landform distribution and the morphometric analysis of topography, drainage system, and alluvial fan/catchment systems. The results clearly agree with the features recognized as indicators of high activity fault-generated mountain fronts by Bull & McFadden (1977), Bull (1977), Wallace (1978), Bull (1987), Keller & Pinter (1996), and Allen & 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. This is closely associated with the morphotectonic evolution of the Montagna del Morrone ridge and Sulmona basin, which is due to the contrast of local tectonic subsidence on the basin and regional uplift during the Pleistocene (Miccadei & alii, 2002). The three sectors of the es-

carpment are made up of adjoining relatively downfaulted and uplifted blocks. The geometry of the two faults located in the northern sector (Basal border Fault and Schiena d'Asino Fault) determines the doubling of the ridge (fig. 13 b, c). The presence of transversal faults on the slope and the interference with the Schiena d'Asino Fault determine the morphology of the central part, which is therefore an area of transition between the northern and southern sectors, both from a structural and geomorphological point of view (fig. 13 d,e). The presence of a principal fault at the base and one at the summit, which is clearly secondary, determine the form of the slope's southern part (fig. 13 f, g).

The slope architecture seems to have been formed during the earlier phases of its morphostructural evolution, between the Early and Mid-Pleistocene, due to a strong activity of the normal faults with uplift rates strongly exceeding denudation rates. Later the conflicting interplay of relative tectonic uplift and denudation due to climate-controlled geomorphic processes modified the architecture that had already formed.

The geomorphological analysis, thoroughly discussed in the previous section, has highlighted a complex cyclic evolution in succeeding stages with the dominance either of morphostructural factors, linked to the conflicting fault activity and regional uplift, or of morphosculptural processes, controlled by climatic change and particularly by the cold stages.

In a general balance the growth of the escarpment, 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 the general uplift of the chain, has strongly exceeded and dominated the effect of denudation. This has created relief of up to 1700 m and enabled the maintenance of very steep slopes, made possible by the resistant rocks, which have been moderately weathered and shaped by the climate-controlled morphosculptural 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 gravity areal denudation is prevailing in the upper part of the northern and central sectors and in the southern sector (fig. 14).

Slope evolution is related to a slope replacement process, controlled by physical weathering, together with large rock landslide development particularly in the early stages and mostly in the southern sector and in the upper part of the northern sector. The slope profile, either a Lehmann or Richter type, does not have a clear and univocal distribution because of the variability of sediment removal at the base of the slopes. However, the Richter type is predominant, particularly in the northern sector, with the outcropping in many cases of the fault plain uncovered or only partially covered by sediment.

Finally, it is possible to sum up the relationship between the morphostructural processes and the morphosculptural action of the different sectors of the slope.

In the northern sector the morphostructural construction processes have been distributed on a wide part of the slope and concentrated on the two parallel belts that correspond to the Basal border Fault and the Schiena d'Asino fault. The doubling of the ridge is the result of the Quaternary fault activity with differential down-faulting and uplifting along two parallel narrow zones on the slope (fig. 13a, b). The geomorphic processes have developed in relation to gravity denudation and running water downcutting. Detritic production and formation of landslides have occurred in the upper parts of the slope. Linear erosion down-cutting has been mostly active in the lower part.

In the southern sector the effects of the mophostructural processes have been concentrated in the basal part of the slope, so corresponding with the Basal border Fault, which has led to a strongly pronounced escarpment and the development of a wide belt of high local relief (fig. 13f, g). This has affected the marked development of slope gravity denudation, with the development of large landslides, especially during the initial stages of the escarpment evolution during the Early?-Mid Pleistocene, and more generally has led to strong degradation and erosion. The denudation process has been mostly areal. The large amount of sediment produced has been supplied directly to the base of the slope at the junction with the plain without any accumulation in storage points along the slope. Therefore the sediment has directly fed the talus slope, the debris cones (more frequent and widespread than in the northern sector) and the alluvial fans (more regularly developed than in the northern sector).

The central sector is in an intermediate condition. The fault's morphostructural effect is mostly on the lower part of the slope (Basal border Fault) but has developed also in the mid-slope (Schiena d'Asino Fault). Denudation due to slope gravity processes has developed all along the slope but mostly in the mid- and upper part, while the linear down-cutting due to running water processes has been mostly active in the mid-and lower parts, favoured by the presence of transversal faults. The morphoscultural processes result from a combination of both areal denudation and linear downcutting.

In conclusion, it is possible to define the evolution of the SW escarpment of the Montagna del Morrone ridge as a growth evolution, rapid in the earlier stages and then continuing in the later phases. We can summarise the main stages of this morphostructural evolution as follows:

– Early moderately high relief shaped by geomorphic processes, among which there was possibly karst weathering; remnants of this landscape, though reworked by karst processes and nivation, are preserved on the top of the ridge (Early? Pleistocene);

– Creation of the morphostructural architecture 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 with the early shaping of morphostructural alignment transversal to the ridge; the occurrence of joint-
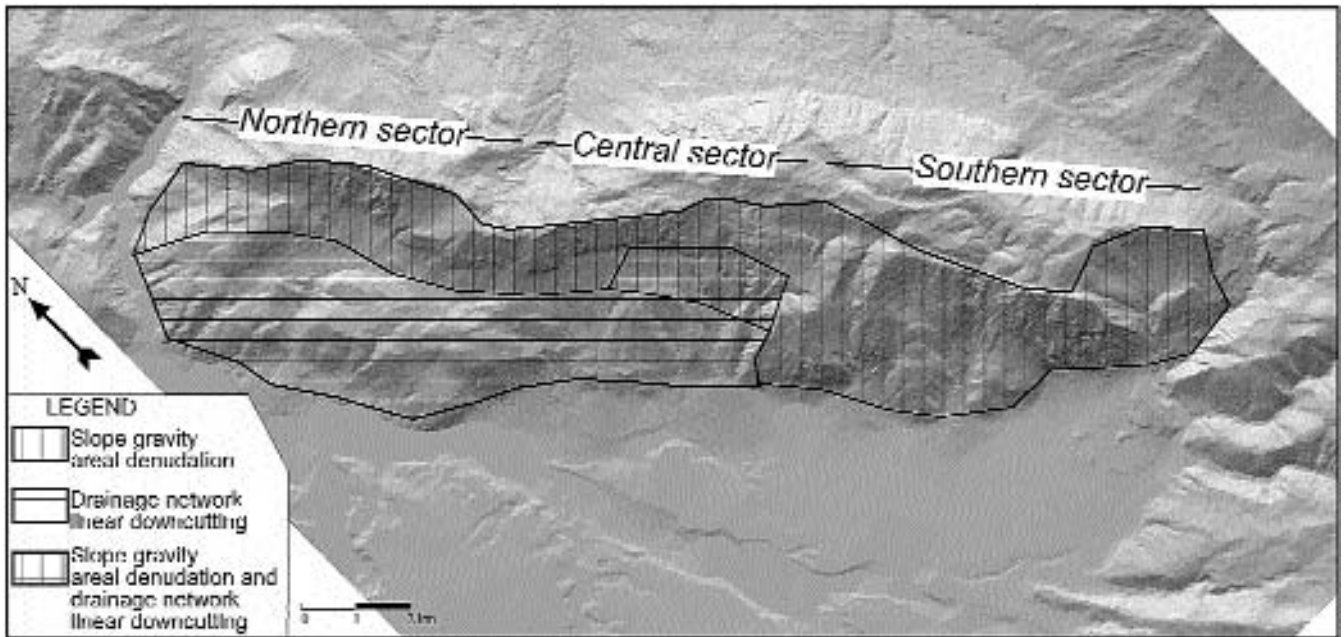
Fig. 14 - Different domains of the SW escarpment of the Montagna del Morrone ridge, on which different morphosculptural processes took place.

ed 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; sediment accumulation along the slope (scree slope breccias, alluvial fan conglomerates) (Early?-Mid Pleistocene);

– Development of drainage basins similar to the present ones (including Basin C, eventually after an early capture of the upper part) (Mid Pleistocene);

– Shaping of the escarpment, mostly due to slope gravity denudation processes in the southern sector (and upper part of the central and northern sector), and to running water linear down-cutting in the northern sector (Mid-Late Pleistocene);

– The morphostructural processes, though possibly less intense than in the earlier stages, led to a progressive renewal of the basal fault scarp of the southern sector and the couple of 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 (Mid-Late Pleistocene);

– The morphosculptural processes are capable of only partly contrasting the morphostructural processes and have led to partial reorganization of the drainage basin, still now clearly out of equilibrium, particularly in the southern sector. The present morphostructural setting is acquired (Late Pleistocene-Holocene).

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