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DEEP-SEATED GRAVITATIONAL SLOPE DEFORMATIONS IN ACTIVE TECTONICS AREAS OF THE UMBRIA-MARCHE APENNINE (CENTRAL ITALY)

ABSTRACT: ARINGOLI D., GENTILI B., MATERAZZI M. & PAMBIANCHI G., *Deep-seated gravitational slope deformations in active tectonics areas of the Umbria-Marche Apennine (Central Italy)*. (IT ISSN 0391-9838, 2010).

The present work illustrates three cases of deep-seated gravitational slope deformation (DSGSD) in an active tectonic area in the Umbro-Marchean Apennines. The area was affected by an intense seismic crisis that lasted eight months in 1997-98. The correct genetic attribution of the studied phenomena was possible only through the geomorphologic interpretation of numerous data acquired through geotechnical and geophysical surveys and instrumental monitoring. Two phenomena are found along the edge of the tectonic basin of Colfiorito, and the third is situated along the Chienti valley, at the foot of a wide versant on the left bank of the river. The studied phenomena involve the calcareous-marly and marly lithotypes of the «Umbria-Marche Sequence», affected by relevant tectonic dislocations: thrusts and normal and reverse faults. The epicentres of major earthquakes were aligned along the direct and reverse faults which are considered «capable».

KEY WORDS: Deep-seated gravitational slope deformation; Geomorphology; Monitoring; Active tectonics; Central Apennines.

RIASSUNTO: ARINGOLI D., GENTILI B., MATERAZZI M. & PAMBIANCHI G., *Deformazioni gravitative profonde di versante in un settore a tettonica attiva dell'Appennino umbro-marchigiano (Italia centrale)*. (IT ISSN 0391-9838, 2010).

Vengono illustrati nel presente lavoro alcuni casi di deformazione gravitativa profonda di versante (DGPV) in un settore tettonicamente attivo dell'Appennino umbro-marchigiano interessato di recente (1997-98) da un'intensa crisi sismica. La corretta attribuzione genetica dei fenomeni studiati è stata possibile attraverso l'interpretazione geomorfologica di numerosi dati acquisiti mediante indagini geologico-tecniche, geofisiche e monitoraggi strumentali. Il presente studio illustra tre fenomeni di DGPV ubicati sui versanti dell'Appennino umbro-marchigiano: Monte Pennino, Costa e Borgiano. I primi due casi sono posti rispettivamente sui bordi settentrionale ed orientale della conca tettonica di Colfiorito; mentre Borgiano è situato al piede del versante sinistro della valle del fiume Chienti. I fenomeni coinvolgono i litotipi calcareo-marnosi e marnosi della successione sedimentaria umbro-marchigiana, interessati da importanti dislocazioni tettoniche: sovrascorrimenti, faglie inverse e dirette; lungo quest'ultime, considerate «capaci», sono allineati gli epicentri dei recenti terremoti.

Il rilievo di Monte Pennino (1571 m s.l.m.) è costituito da un alto strutturale di Calcare massiccio, in facies di piattaforma carbonatica, a cui seguono sedimenti prevalentemente calcarei e marnosi di mare via via più profondo. L'assetto di queste ultime formazioni risulta predisponente a fenomenologie gravitative. Il settore sud-occidentale del rilievo è caratterizzato da un esteso versante strutturale, dove terreni rigidi (Scaglia rosata) risultano sovrapposti a litologie più duttili (Marne a Fucoidi basali) dando origine a fenomeni di tipo block-slide con evidenze geomorfologiche di un versante convesso interessato localmente da diverse fratture di trazione e da una trincea superiore che ne testimoniano l'attività. Ulteriori ricerche sono state estese nell'area sommitale del rilievo dove misure satellitari relative ad un caposaldo IGM hanno dato anomalie rispetto ai modelli deformativi elaborati che configurano spostamenti generali verso la depressione tettonica. Qui sono state evidenziati elementi litostratigrafico-strutturali ed elementi geomorfologici tali da giustificare una possibile deformazione gravitativa profonda del settore sommitale, congruente con quanto rilevato dalle misure satellitari. Il possibile livello di deformazione duttile è stato riconosciuto nella facies marnosa dei Calcari nodulari del Bugarone, con il coinvolgimento della massa rigida superiore costituita dai calcari micritici della Maiolica. L'evidenza geomorfologica principale è rappresentata da una trincea sommitale che provoca lo sdoppiamento di cresta, probabilmente impostata lungo le discontinuità tettoniche circa N-S. La trincea si presenta non molto profonda, dai margini smussati, con all'interno fratture di trazione e prosegue lungo versante meridionale consentendo l'impostazione di una vallecola di forma arcuata che si chiude bruscamente in corrispondenza dai Calcari nodulari del Bugarone.

Nell'area di Costa, settore sud-orientale della conca di Colfiorito, si individua una morfologia convessa che interrompe vistosamente la regolarità del versante di faglia. Numerose in questo settore sono le evidenze geomorfologiche riconducibili ad un fenomeno gravitativo esteso e complesso, tuttavia, per l'interpretazione dello stesso, sono state di fondamentale importanza alcune indagini geofisiche che hanno consentito di avallare detta ipotesi. In quest'area, dove è situato uno dei maggiori epicentri della sequenza sismica del 1997-1998, si sono verificati evidenti effetti co-sismici di superficie, quali fratture beanti e gradini. Le evidenze geomorfologiche, indizi di attività gravitativa, sono rappresentate in que-

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st'area da accumuli di crollo, fasci di fratture e fessure beanti, trincee, contropendenze e rigonfiamenti. A monte dell'abitato, localmente mascherato da una significativa copertura detritica, affiora il piano di faglia principale (70°/230°), che a luoghi disloca vistosamente i calcari della Maiolica. Lungo questo piano, a seguito del terremoto del 1997 si è formata una *free face*, con rigetto apparente variabile da 2 a 25 cm, associabile a rigetto tettonico secondo alcuni autori oppure prevalentemente a fenomeni gravitativi. A valle di Costa, al piede del versante, il substrato calcareo affiora in placche separate dalla coltre detritica, con giaciture localmente incongruenti con l'assetto generale limitrofo.

La corrispondenza tra le evidenze morfologiche profonde, evidenziate dalle geofisica, e quelle superficiali ha permesso di elaborare un modello geomorfologico della DGPV riconducibile a un fenomeno di *deep-seated block slide*, la cui evoluzione è dettata principalmente dall'input sismico e dalla possibile interconnessione con l'antico bacino lacustre pleistocenico.

Ad Est della conca tettonica di Colfiorito, in sinistra idrografica del Fiume Chienti e al bordo del Lago di Borgiano, un particolare fenomeno di DGPV è stato evidenziato attraverso le osservazioni geologiche consentite dalle attività estrattive e mediante monitoraggi ed indagini geofisiche. Gli elementi geologici caratterizzanti sono costituiti da discontinuità aperte recanti indicatori cinematici; da vistosi assottigliamenti di un livello guida di scisti bituminosi; da discontinuità sub-verticali con rigetti complessi. Gli elementi descritti sono tutti compatibili con un movimento di tipo gravitativo. L'elevata vulnerabilità dell'area ha spinto a mettere in opera un sistema di monitoraggio GPS, che ha confermato l'evoluzione gravitativa del versante. La sismica a riflessione, inoltre, ha evidenziato l'andamento profondo delle numerose fratture subverticali, che vanno a listricarsi nel livello duttile delle Marne a Fucoidi che giace sotto al fondo del lago, dove sono state individuate anche zone di taglio, con faglie e fratture a basso angolo disposte contromonte. In questo settore, che costituisce il piede del paleo versante, la deformazione ha determinato un rigonfiamento del substrato roccioso (*bulging*), sepolto dai depositi fluvio-lacustri. Il fenomeno gravitativo è ascrivibile ad un classico *deep-seated block slide*, con zona di deformazione duttile rappresentata dal livello marnoso-argilloso delle Marne a Fucoidi, mentre la zona di corona corrisponde ad un evidente rottura morfologica del versante ed è impostata su discontinuità tettoniche riprese dalla gravità.

TERMINI CHIAVE: Deformazioni gravitative profonde di versante; Geomorfologia; Monitoraggio; Tettonica attiva; Appennino centrale.

INTRODUCTION AND PREVIOUS STUDIES

The landscape configuration of the central Apennine, analogous to most of the Italian landscape, strictly conforms to the composition of bedrock; the study area is only a limited sector that is highly representative of the whole area (fig. 1a). The main morpho-structures, composed of mountain ridges and intra-mountain tectonic depressions, are the result of deformation phenomena connected to the action of endogenous forces on a regional scale, that developed over a long period of time. Although it is difficult and uncertain, it is at times possible to identify deformations and dislocations of rocks that are relatively deep and widespread. They are driven by the geologic substratum and the local slope structure, but they originated from the sole action of gravity: the deep-seated gravitational slope deformations (DSGSDs).

In different parts of the world, since the first half of the XXth century, there has been a growing interest in the importance of the morphogenetic action carried out by DSGSDs in the evolution of reliefs. The hazard represented by these phenomena represent in civil engineering works have also been increasingly underlined (Harrison & Falcon, 1934; Jahn, 1964; Zischinsky, 1966; Nemčok, 1972; Radbruch-Hall & *alii*, 1976; Mahr & Nemčok, 1977; Varnes, 1978; Zaruba & Mencl, 1969; Savage & Swolfs, 1986; Hutchinson, 1995; Cruden & Varnes, 1996).

Analogous interest in such researches has also affected Italy, where these phenomena are particularly frequent throughout the territory, due to the country's complex geologic structure, the recent and present intense tectonic activity and the favorable morphostructural and morphoclimatic conditions (Guerricchio & Melidoro, 1981; Coltorti & *alii*, 1984; Mortara & Sorzana, 1987; Gentili & *alii*, 1992; Dramis & Sorriso-Valvo, 1994; Aringoli & *alii*, 1996; Agliardi & *alii*, 2001; Aringoli & *alii*, 2002; Crescenti & *alii*, 2002; Gentili, 2004; Ambrosi & Crosta, 2006; Aringoli & *alii*, in press).

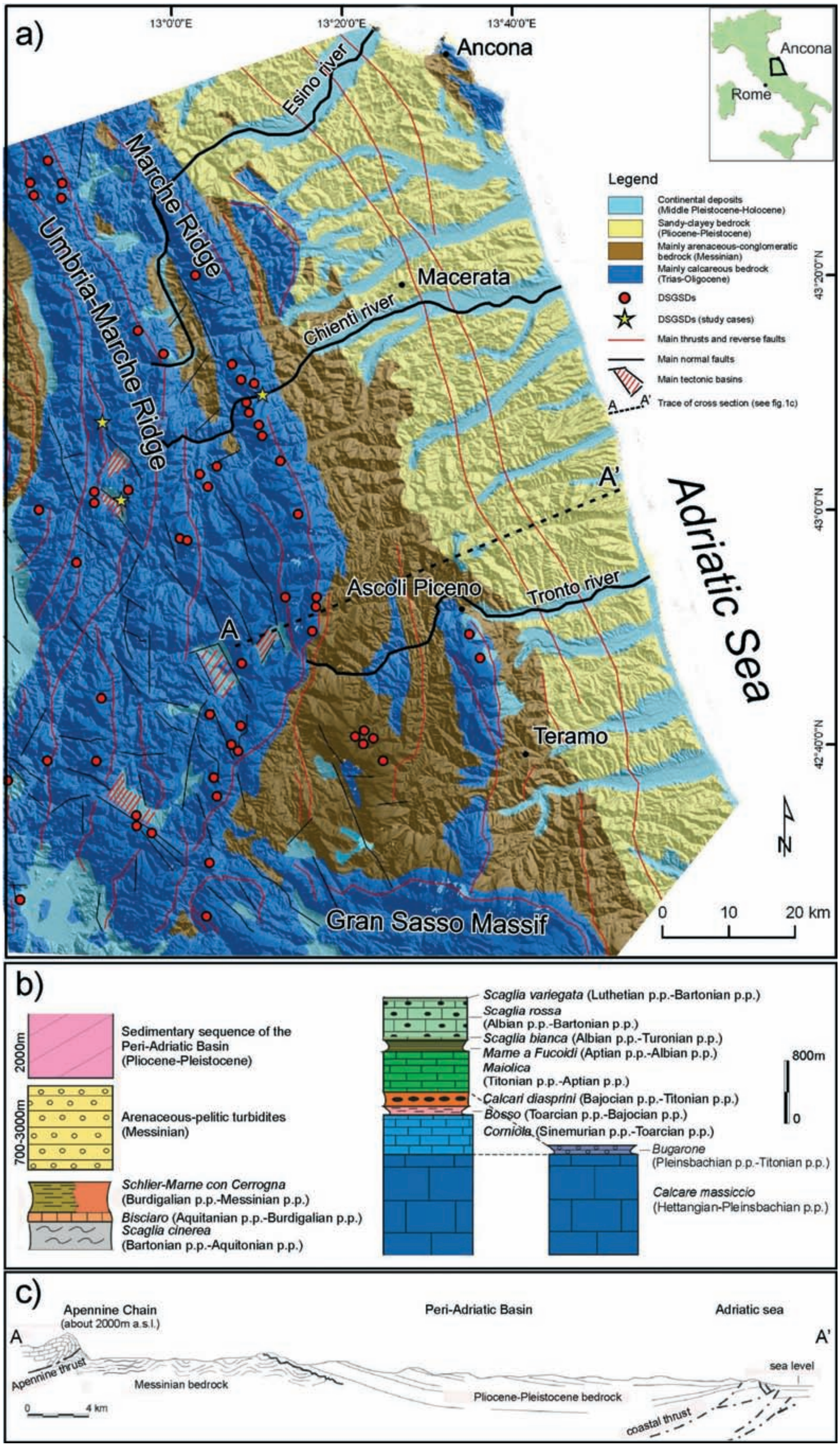
The numerous works mentioned above have recognised specific fundamental geological and distinctive geomorphologic elements. They also identified at macro and mesoscale the genetic factors and the most plausible evolutionary models on which the present nomenclature was based.

The geological and geomorphological analyses have been sometimes integrated with historical studies carried out for about thirty years on the lithoid formations, based in particular on a vast sector of the Central Apennine. (fig. 1a). These studies identified about 50 deep-seated gravitational slope deformations distributed along the chain flanks, on the slopes of the narrow valleys that cut the chain transversally, and on the slopes which border the tectonic basins. Their average extension is about 2 km^2; the estimated depth varies from several tens of metres to about 100 metres; lateral spreads and deep-seated block slide phenomena prevail upon those of sackung.

Fundamental genetic factors are identified in: overlaying process of rigid deformation rocky bodies upon ductile deformation layers; outcropping of thrusts, reverse or normal faults; tectonic fracturing, that sometimes generates cataclastic layers at low angles, often «altered» by karst phenomena; glacio-decompression in the higher sectors of the chain; shape variation of versants connected to the residual stresses of the various tectonic phases; intense seismic activity. It was possible to determine correlations with the fundamental morphometric parameters of the slope, as well as a good correspondence between tectonic alignments and the geomorphological elements typical of the DSGSDs (trenches, scarps, etc.); a careful analysis of the plano-altimetrical reports concerning these elements, their «freshness» and position with respect to the continental deposits, has at times made it possible to determine the chronological collocation of these phenomena and their evolutionary stages (Dramis & *alii*, 1987, 1995; Coppola & *alii*, 1978; Crescenti & *alii*, 1987; Blumetti & *alii*, 1990; Barchi & *alii*, 1993; Buccolini & Gentili, 1995; Farabollini & *alii*, 1995; Moro & *alii*, 2007; Galadini, 2006).

The present study wants to provide a further contribution to the knowledge of this subject matter, through the illustration and discussion of the geological and geomorphological models built for three DSGSDs case studies, that are difficult to identify (or susceptible to several interpretations) on the sole basis of geo-thematic surveys. A correct genetic attribution was only made possible by the

FIG. 1 - a) Litho-structural sketch of central Italy with location of main DSGSD phenomena; b) representative stratigraphic column of the Umbria-Marche Sequence; c) representative geological cross-section from the Apennine Chain to the Adriatic Sea.



geomorphologic interpretation of the rich data acquired through the geotechnical and geophysical surveys and monitoring operations at ground level and via GPS, carried out after the 1997-98 seismic crisis in Colfiorito, in view of the reconstruction and setting up of safety measures for the safeguard of structures and infrastructures.

The studied areas are located in the Umbro-Marchean Apennine (fig. 1a): Monte Pennino and Costa-Monte Tolagna, respectively placed along the southern and eastern borders of the tectonic basin of Colfiorito; Borgiano, at the foot of the slope on the left side of the Chienti river valley, transversal to the Marchean ridge.

REGIONAL SETTING

The Central Apennine (fig. 1a) is dominated by two vast palaeographical and structural units, whose evolution determined the current physical landscape: i) the «*Piattaforma carbonatica Laziale-Abruzzese*», where fine sedimentary sequences were deposited during the Late Trias p.p.-Miocene (marly-calcareous and dolomitic neritic sequence) and ii) the Umbria-Marche-Sabine basin, that bounds the former unit to the west, north and north-east, where open and deep sea sedimentary sequences occurred (marly calcareous and cherty pelagic sequences) during the mid-Lias - Miocene p.p., fig. 1b). The two areas were connected by a scarp (transition zone) where sedimentation was supplied partly by the materials eroded from the edge of the platform, and partly by the materials of the basin itself. Turbiditic silico-clastic associations developed along the east portion of the chain (Laga Formation, Tortonian-Messinian). They are superposed by a strong clayey body, mainly in discordance or by tectonic contact, containing different stratigraphic levels of sands and conglomerates of Plio-Pleistocene age.

The structural setting of the mentioned geologic substratum is rather complex (figs. 1a, c). It is in fact characterized by an association of folds, with a marked eastward vergence in the Umbria-Marche Apennine and to the north-east in the Gran Sasso d'Italia massif, dislocated by successive faults and thrusts. These elements represent the most important tectonic phenomena and create structures that extend on a regional scale in a arc-geometry. Normal Quaternary faults, with a prevalent westward dip, characterise the Umbria-Marche chain and are genetically linked to the grabens of Colfiorito, Castelluccio and Norcia, located on blocks that have been sagged by faults. Many of these tectonic elements show important signs of recent activity witnessed by frequent associated seismicity. The corresponding peri-Adriatic belt is characterised by an eastward verging monocline with a regular surface, that becomes more complex in depth (Calamita & Deiana, 1988).

The Umbria-Marche Apennine has revealed in time a frequent and diffused seismicity, alternating intense seismic sequences lasting weeks or months and relatively quiescent periods. There were about 60 intense earthquakes in the area between 1000 and 1984 (VIII-IX MCS), particularly frequent in the last 150 years. Historical surveys give evidence of strong earthquakes in ancient times: 102 A.C. in Valnerina; 217 A.C. in Val Tiberina; 446 e 801 A.C. in Spoleto, which caused the destruction of the town. The strongest earthquakes (X MCS) occurred in central Italy in the XIVth and XVIIIth centuries, some of which had a devastating effect and caused thousands of victims.

The most intense seismic event (XI MCS), occurred in 1703. The epicentre was in the Norcia-Leonessa area, and it was characterised by numerous *main shocks*. The southward propagation of multiple ruptures involved a widespread area including the basin of L'Aquila. Among the most recent destructive events we must point out the «earthquake of Norcia» in 1979 (Mw = 5.9, IX-X MCS). Comparable events affected the area between Serravalle di Chienti and Nocera Umbra in 1279 (IX MCS); the Alto Esino area (IX MCS), was struck by the «earthquake of Fabriano» in 1741; the Camerino area in 1799 (X MCS). This last event was characterised by numerous shocks of increasing intensity, a feature it shared with other sequences occurred in the area in 1781 (X MCS) and 1785 (IX MCS) and recently in 1997-1998, when the highest magnitude (Mw 5.8-6.0, IX-X MCS) was reached at 11,40 on 26th September 1997 (Baratta, 1901; Postpischl, 1985; Amato & *alii*, 1998; Cello & *alii*, 1998; Calamita & *alii*, 2000).

The offset of the geomorphological evolution, which occurred after the emersion of the farthest western zones, dates back to the early Messinian. It then proceeded towards the east and completed during the mid-Pleistocene. The low uplift rates and the diffused areal erosion phenomena connected to dry or damp subtropical climatic conditions up to the early Pleistocene, favoured the genesis of a paleo-landscape characterised by smooth shapes and different layers of flattening surfaces separated by modest depressions. The tectonic uplift probably began at the beginning of the Pleistocene epoch and was particularly intense at the end of the early-mid Pleistocene. It generated the numerous tectonic slopes that bound the mentioned grabens, favoured a rapid deepening of the hydrographic network often driven by tectonic displacements and caused the genesis of deep narrow valleys and steep slopes (Calamita & *alii*, 1999; D'Agostino & *alii*, 2001). The high levels of relief associated to this new geomorphologic context together with the succession of climatic phases in the area, favoured intense fluvial and versant dynamics that are still active.

Glacial and peri-glacial morphogenetic processes were also important. Specific morphologic evidence can be observed on the highest peaks (Sibillini Mountains, Laga Mountains, Gran Sasso d'Italia massif), and associated to the pleniglacial phases of the late Pleistocene and mid-late Pleistocene. There are still visible well-defined cirques and morainic sediments, as well as more important and widespread peri-glacial processes that are responsible for the deposition of thick and extensive stratified screes in the mid sectors or at the foot of the slopes (Castiglioni & *alii*, 1979; Coltorti & Dramis, 1995). The interaction of the mentioned valley deepening and the biostasy and rexistasy conditions linked to the Pleistocenic climatic changes, also generated three layers of terraced alluvial sediments that developed particularly in the mid stretches of the main valleys. It is also possible to identify a Holocene depositional phase, that was not as forceful as the others. It associated with the converging effects of anthropization in the area and the climatic oscillations of that period, which resulted in a significant increase in global rainfall at Mediterranean latitudes.

DATA AND DISCUSSION

The Colfiorito basin, where the three studied areas are located, is one of the several grabens that characterise the Central Apennine chain. It extends for about 92 km^2 and elevation ranges from 750 and 1571 m a.s.l.; its shape is elongated in a circa Apennine direction and is divided into several sub-basins whose depths range from 750 to 900 m a.s.l. (fig. 2).

The depression is circumscribed by arched fault versants, generated by the combination of the tectonic displacements that were responsible for the genesis of the above mentioned earthquake. They are oriented in three main directions (NW-SE, N-S e NE-SW). The bottom is regularised by fluvial-lacustrine deposits (end of the early Pleistocene-beginning of mid-Pleistocene), 30-60 m thick, that reach 120 m in the southern portion: conglomeratic horizons at the base that alternate with muddy-sandy layers towards the top; along the edges they interlock with slope deposits that prevail on the surface. Bedrock outcrops are numerous along the border slopes and are composed of limy-loamy lithotypes of the Umbro-Marchean sequence, dating back to the interval between the early-Lias and the Oligocene (fig. 1b).

The long seismic crisis that began in September 1997 and persisted until the first months of 1998, caused evident geomorphologic effects at ground level, both co-seismic and deferred, represented by widespread fracturing and the activation or reactivation of mass movements (Basili & *alii*, 1998; Cello & *alii*, 1998; Esposito & *alii*, 2000; Vittori & *alii,* 2000; Galadini & *alii*, 2003). Subsequent in-depth geologic, geomorphologic, geotechnical and geophysical surveys and instrumental monitoring provided new and important data that are later illustrated and explained in this study.

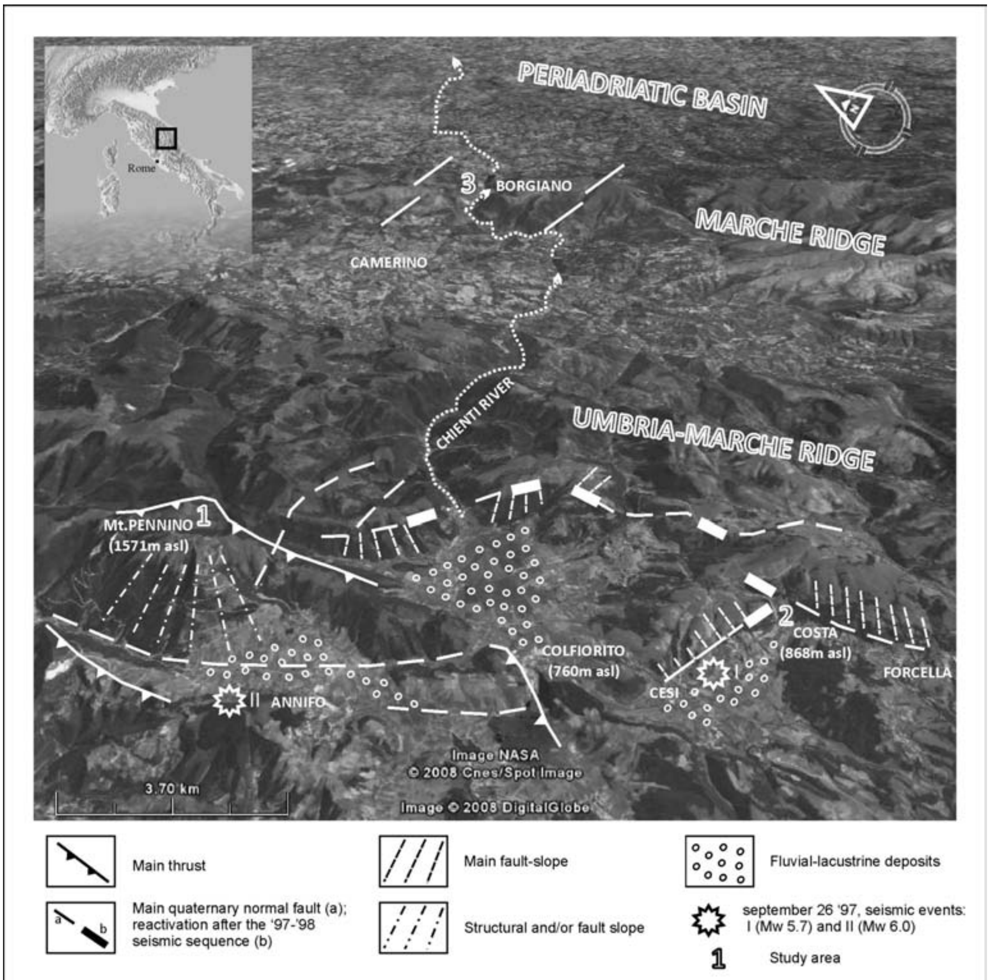


FIG. 2 - Morpho-tectonic sketch of the study area.

Monte Pennino Area

In the extreme northern portion of the basin there is a minor plane (Piano di Annifo), that closes to the north on the slopes of Monte Pennino (1.571 m a.s.l.) (figs. 1a, 2).

This relief geologically corresponds to the limestone massif of the Calcare massiccio formation, outlined by normal faults of Jurassic age. The Calcare massiccio is overlayed by the nodular limestones of the Bugarone formation, that forms a thin layer of marly limestone (<30m); this layer is followed up by the micritic limestone of the Maiolica formation extending up to the top of the structure. Marne a Fucoidi, Scaglia Rosata and Scaglia Cinerea formations outcrop laterally in stratigraphic sequence, and form a vast anticline fold with a N-S axis and overturned eastern flank (figs. 1b, 3a, b). The lying positions of the formation strata vary between sub-horizontal (on the top of Mount Pennino), inclined at 50°-60° to the SW (western flank of the relief) and upturned near the thrust that cuts the western slope. Measurements carried out in several stations made it possible to define the shape of the tectonic and stratigraphic discontinuities suitably represented in stratigraphic stereo-plots (fig. 3a). The main tectonic elements are represented by normal faults (Mt. Prefoglio - Mt. Pennino, Annifo), thrusts (to the east of Mt. Pennino) and numerous minor faults with different trends (fig. 3a).

Early geological and geomorphological studies underlined several predisposing structures that could be associated with gravitative phenomena in the complex of Mount Pennino: the south-western sector, characterised by a wide structural slope mainly modelled on the Scaglia rosata, with a slightly convex profile towards the base, where a progressive inclination increase and the jointing of the Scaglia rosata and Scaglia cinerea strata is evident; the outcrop of the Marne a Fucoidi formation on the summit sector of the same slope, a sub-flat morphology on which there stands out a vast bevelled trench; the intermediate area of the slope dissected by open fractures parallel to the slope, linked to present minor gravitative movements that can be ascribed to the deep incisions of the hydrographic network that characterises the relief; minor trenches, counter slopes and steps, that sometimes determine considerable deviations of the minor hydrographic network.

Taking into account the above described geological and geomorphological elements, it is possible to hypothesize the existence of a deep-seated gravitational slope (fig. 3b). The phenomenon lay down on the basal marly level of the Marne a Fucoidi formation that in the upper part of the slope outcrops and hosts a trench, whereas at the foot generates bulges and brittle deformation of the overlaying lithologies.

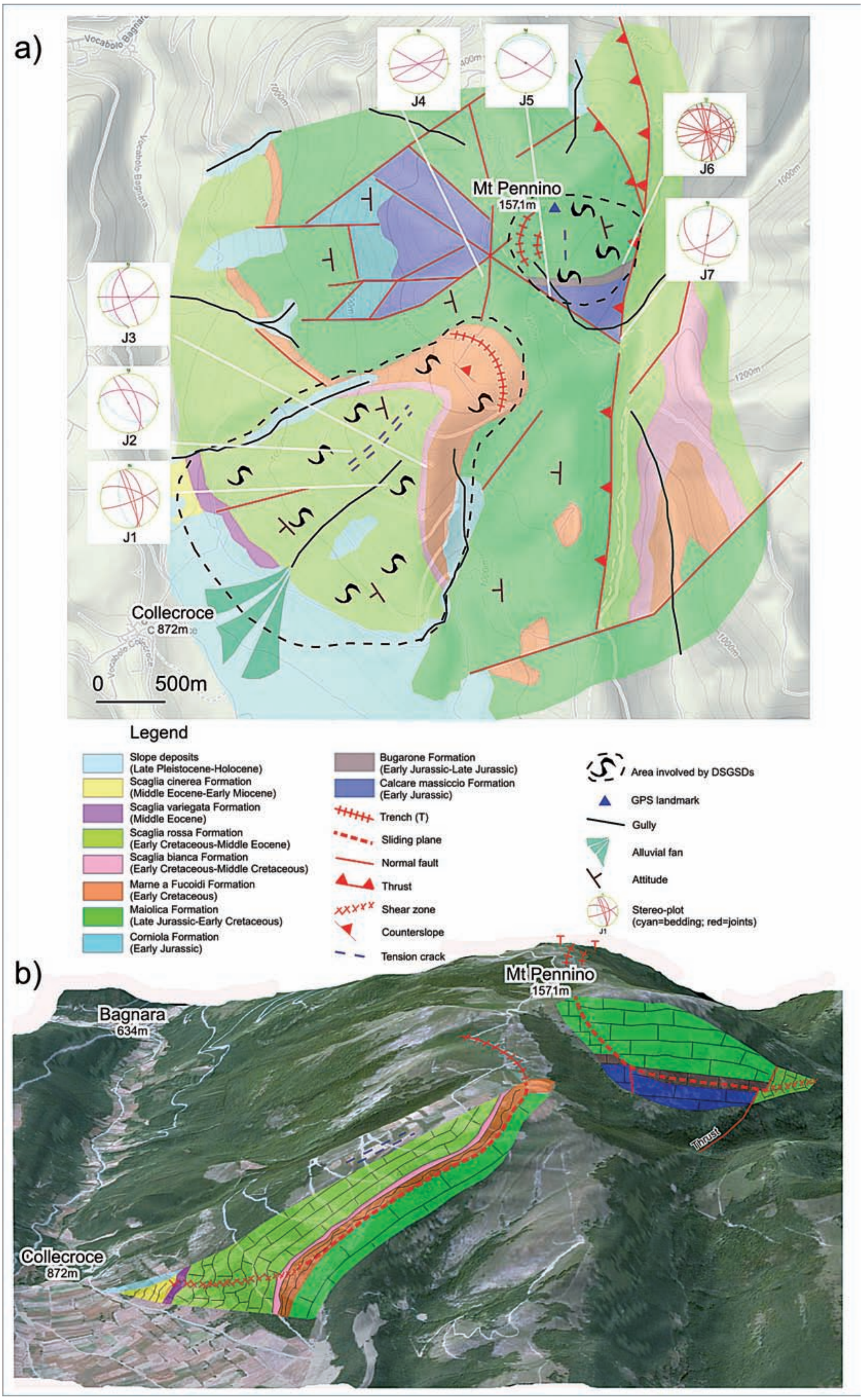
These data, however, were insufficient to define a reliable morphodynamic model. The trigonometric measurements carried out in the area of Colfiorito by the IGM «Istituto Geografico Militare», following the 1997 seismic crisis, were therefore fundamental. They clearly underline, in numerous instances, ground deformations that are often congruent with the tectonic stress fields and kinematics observed in direct faults. A stronghold of the national trigonometric network is also located on the summit of Mt. Pennino (1571 m a.s.l.), whose periodical measurements have, however, displayed movements that are clearly in contrast with the tectonic stress fields and coseismic deformation models elaborated by means of IGM 95 net (Anzidei & *alii*, 1999; Hunstad & *alii*, 1999). In particular, the measurements of the summit GPS landmark have provided horizontal movements of 82 mm towards the north-eastern quadrants, and vertical movements of –34.8 mm that testify subsidence. (Surace, 1997; Salvi & *alii*, 2000).

These anomalies led to a deeper survey of the lithostratigraphical setting of this area; this survey showed structural conditions and geomorphological elements that could justify a gravitative deformation of the summit, congruent with the data obtained from satellite surveys. A possible and probable ductile deformation level was recognized in the marly level of the nodular limestone of the Bugarone formation, which, in this context, is reduced to few metres with respect to the original 30-40 m. This reduction can be attribute both to the weathering by water circulation (upper fractured calcareous aquifer) and to squeezing phenomena due to the movement of the overlaying rigid mass. The rigid mass involved at higher levels is composed of micritic limestones of the Maiolica formation, that outcrop on the summit with a thickness of about 150 m. The present formation displays an inclined stratification at 20-30° to the NE and is affected by sub-vertical discontinuities mainly oriented roughly N-S and E-W. The main geomorphological evidence is represented by a trench that caused the formation of a double ridge, which probably follows the tectonic discontinuities in roughly N-S direction (fig. 4). The trench is not very deep, its borders are bevelled and it shows internal fractures with evident signs of progressive traction; it moves southward as a concentrated erosion trench that curves valley-ward and eventually blends within the clayey-marly layers of the Bugarone formation. The summit trench and the described erosion trench are, in our opinion, the superficial manifestation of a deep gravitational phenomenon whose geological and geomorphological characteristics allow it to be plausibly classified as a *deep-seated block slide* (Dramis & Sorriso-Valvo, 1994; Cruden & Varnes, 1996).

Costa Area

In the south-western sector of the Colfiorito basin, the fault slope lasts for several kilometres; among the built-up areas of Cesi and Forcella the dip-slip movement, following N-S and NW-SE directions, displays evident displacement of hundreds of meters (figs. 2 and 5a). The bedrock along these slopes is composed of limestone and marly limestone of the Meso-Cenozoic formations (Maiolica, Marne a Fucoidi, Scaglia bianca-rosata) of the

FIG. 3 - Mount Pennino area: a) geological and geomorphological sketch with stereo-plots of the main joint systems; b) block diagram and interpretative cross-sections.



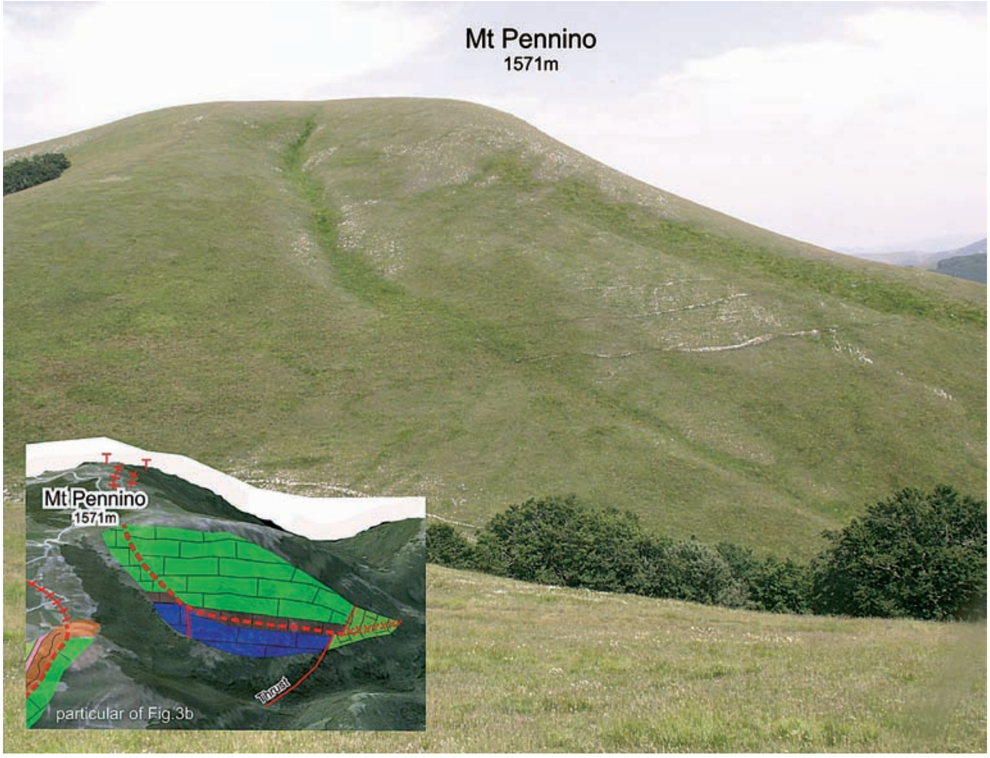


FIG. 4 - Top of Mount Pennino: gravitational trench on the southern side.

Umbro-Marchean sequence (fig. 1b). In the study area, the lithotypes show a regular bedding, with slight dipping in the mid and higher portions of the slope, and variable in the lower portions, below the main normal fault (figs. 5a, b).

In this area we can find one of the main epicentres of the seismic sequence of 1997-1998, where evident co-seismic superficial effects occurred. In particular, around the village of Costa and especially in the mid-higher portion of the slope, there have been observed widespread breakdown phenomena, involving deposits and blocks of bedrock; fractures and open fissures also with displacements, which could reach 2-3 decimetres have been also observed. Their arrangement is partially compatible with the tectonic pattern and they are usually parallel to the direction of the slope.

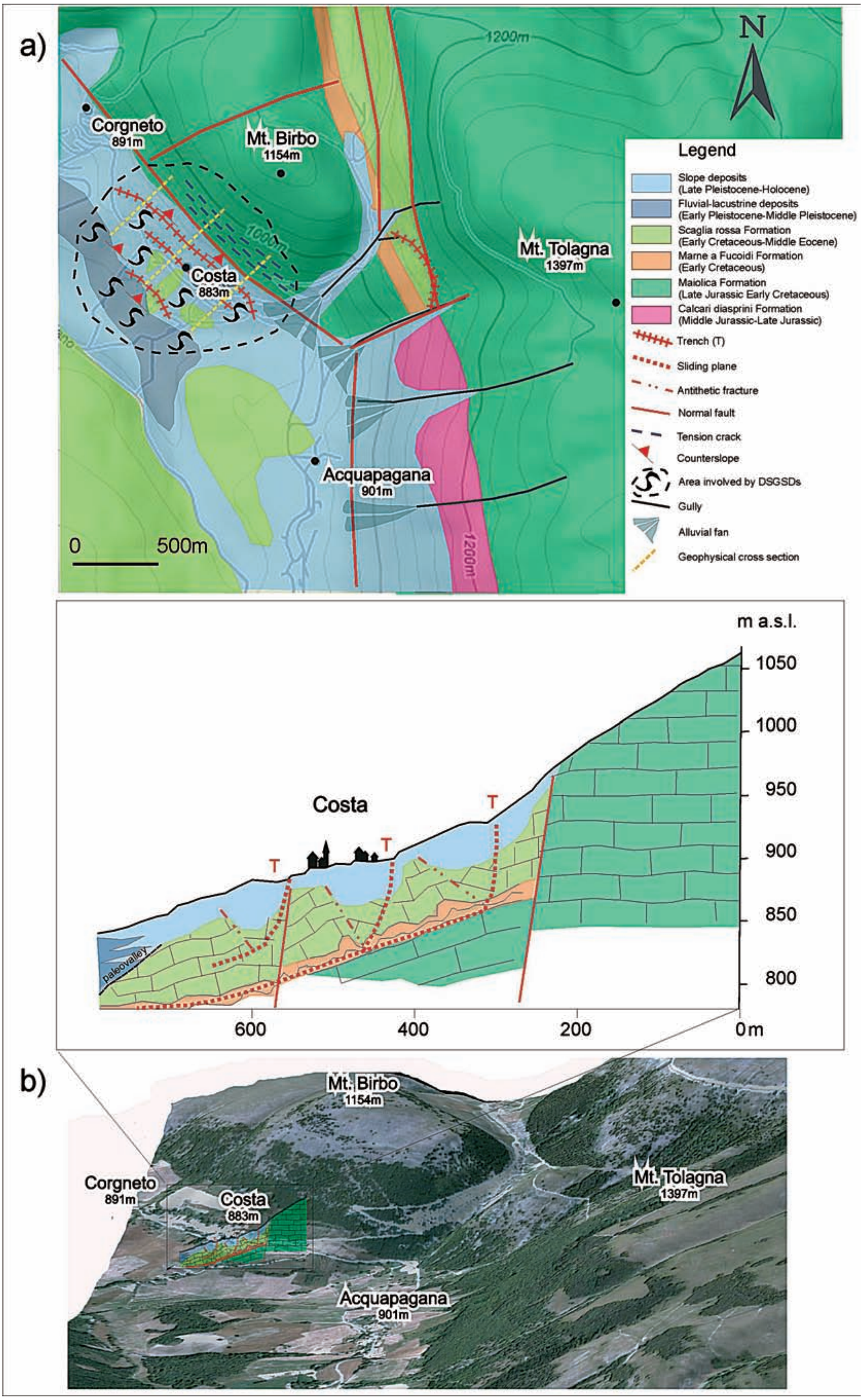
The main fault plain (70°/230°) outcrops immediately below these fractures; it is locally hidden by a thick slope deposits, and it clearly displaces the Maiolica limestone. A *free face,* formed along this plain as a consequence of the 1997 earthquake, shows a variable thickness that ranges between 2 and 25 cm; this element has been associated, with different interpretation to a tectonic displacement (Cello & *alii*, 1998) or to gravitational phenomena (Aringoli & *alii*, 2002).

Nearer the bottom, where the village lies, within the strong and widespread detritic cover (maximum thickness of 20m, fig. 5b), the slopes are characterised by counterslopes, bulges and noticeable scarps with a linear (the widest ones) or curving trend, that witness serious superficial gravitational events. The scarps often correspond to cemented gravel layers, sometimes sub-horizontal or dipping opposite with respect to the slope; this shape is associable with gravitative displacements. Below the village of Costa, in sub-plain or counter slope morphologies, there are found old colluviated paleosoils, and that settled along the counterslopes. They were preserved thanks to the rapid covering process carried out by landslide build-up material. At the foot of the slope the Scaglia rosata formation outcrops in plates that are separated by the detritic cover. These plates lie in a position dipping in the same direction as the slope, and although they often conform to the adjacent outcropping phenomena, they sometimes present local incongruent features such as an increased inclination towards the base.

From a morphologic point of view, the whole slope of the village of Costa shows an overall convex shape articulated with local bulges, trenches, counterslopes and steps; all these elements can be potentially associated to a deep gravitative deformation phenomena. The morphology in this sector visibly «disrupts» the regularity of the fault slope (fig. 5a, b).

The hypothesis concerning the above mentioned gravitational phenomenon were partly and locally verified by means of geophysical surveys and numerical models. Modelling results and surface evidences were in line. Further detailed geophysical surveys (seismic refraction and geo-electrical methods), extended to the whole slope, have recently allowed to improve the deformation model and confirmed the suggested deep gravitative deforma-

FIG. 5 - Costa area: a) geological and geomorphological sketch; b) block diagram and interpretative cross-section.



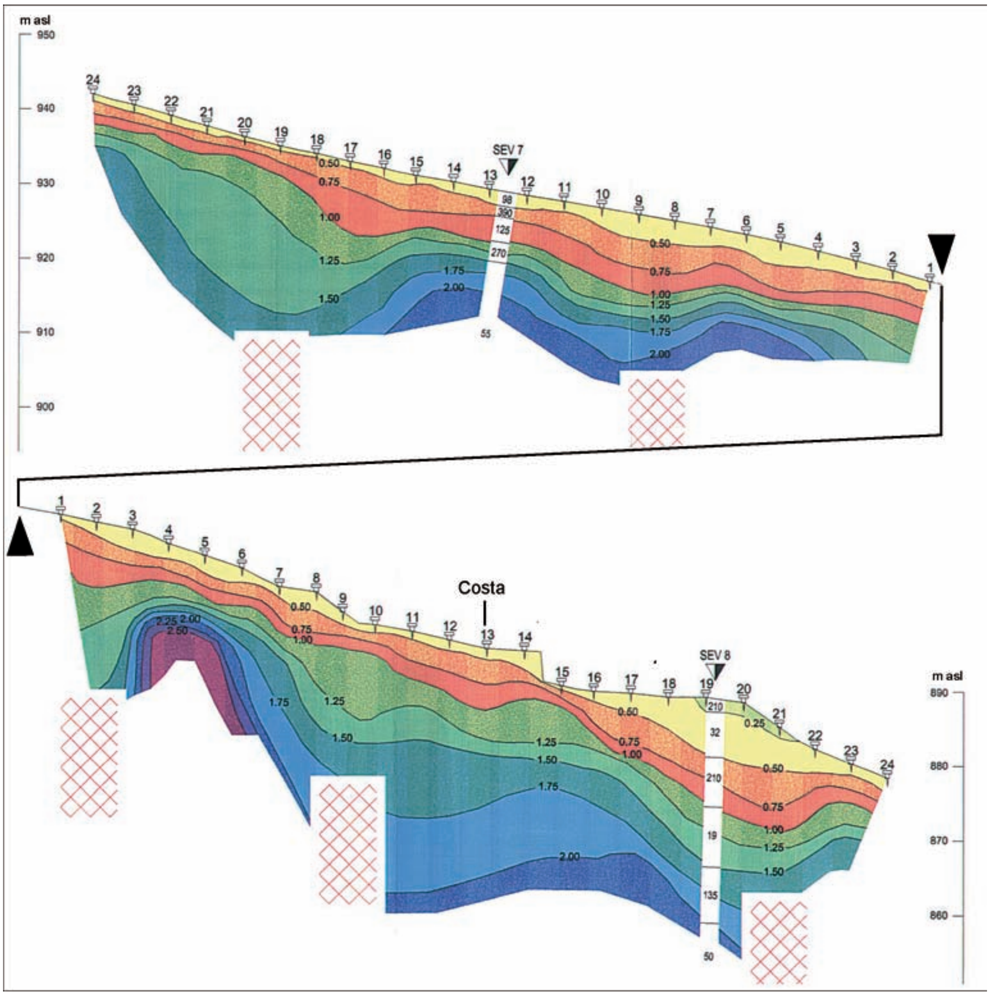


FIG. 6 - Example of seismic cross-section obtained from the geophysical survey; for the location see figure 5a.

tion theory. These surveys underlined the presence of a wide belt of chaotic materials and deep trenches that originate in the main fault and correspond to zones of intense bedrock fracturing (fig. 6). The correspondence between deep and superficial morphological evidences has made it possible to elaborate a geomorphological model of the DSGSD that is schematically represented in this section in figure 5b.

The typology of this phenomenon can be traced back to a *deep-seated block slide*, whose evolution is mainly dictated by seismic input, although a very important triggering element is given by the major deepening of the valley in the past, that lead to the marly levels outcropping. It is also possible to assign an important role to the persistence of widespread lacustrine basins, that characterised the Colfiorito basin during the early and mid-Pleistocene.

BORGIANO AREA

Slightly eastward of the tectonic basin of Colfiorito, along the Chienti river valley, where the river flows into the artificial inlet of the Borgiano lake, it is possible to recognise on the left bank, a particular phenomenon of deep-seated gravitational slope deformation (figs. 2, 7a).

Maiolica (micritic limestone), Marne a Fucoidi and Scaglia bianca-rosata (clayey-marly) formations outcrop in the examined area and form a narrow anticline fold with an axis oriented roughly N-S. The axial culmination of the fold shows a harsh knee-shaped flexure with the lower inflection point corresponding to the valley bottom, and the higher inflection point (knee) set in the mid portion of the left valley slope. The plicative structures are affected by fault and joint systems oriented roughly E-W and N-S (fig. 7a, b).

Quarrying activities carried out along the slope allowed to evidence in detail the geological and structural characteristics the study area; these latter underline the presence of numerous elements that clash with the average tectonic context of the area.

The E-W discontinuities in the higher sector of the quarry front are open (up to several decimetres; fig. 8) and characterised by the presence of cataclasytes with

FIG. 7 - Borgiano area: a) geological and geomorphological sketch; b) block diagram and interpretative cross-section (modified after Aringoli & *alii*, in press)

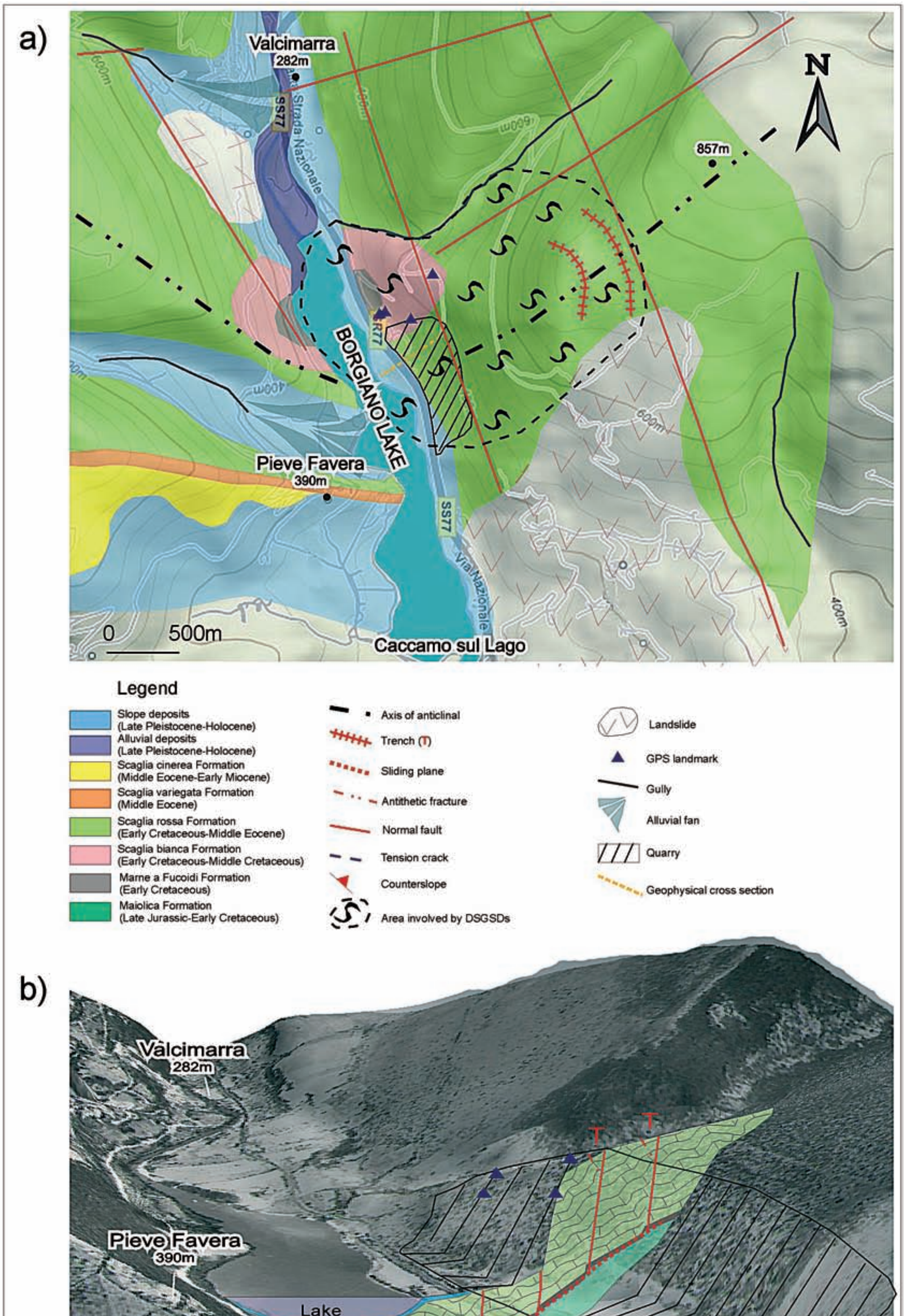


FIG. 8 - Borgiano area: E-W open fractures in the Scaglia rosata formation.

dip-slip bands that clash with the transverse kinematics usually observed along the faults in the analysed valley portion; these elements indicate, a probable gravitational relaxation of the masses valley-ward. Other cemented gravels in the bedrock have revealed an evident deeper thinning in a layer of oil shale (*Livello Bonarelli)* found at the base of the Scaglia rosata formation. The overlying limestone is so fractured and disjoined that it becomes impossible to distinguish its stratification. In the median area, in relation to the maximum inclination line, there were observed numerous sub-vertical discontinuities oriented roughly E-W, where dip-slip displacements occurr and locally form several geological *mini-graben* (fig. 9). Due to the mining activities in this sector and to the high vulnerability of the area (main road network and hydroelectric basin at the foot of the slope), a limited number of collapses occurred that lead to the setting up of a GPS monitoring system. According to the obtained results, in relation to the maximum inclination, the landmarks displacements (horizontal maximum = 83 cm; vertical maximum = –27.8 cm) are congruent with the observed extensive system and the geological *mini-graben*.

Geological, structural and geomorphological observations and instrumental measures of this sector of the slope are not easily traced back to superficial landslide phenomena, such as the limited fall phenomena and the translational slides. The suggested deep influence of deformation mechanisms in this portion of the slope was later supported by means of geophysical surveys that showed the in-depth development of discontinuities. The GPS landmarks, extended throughout the study area (from the bottom of the lake to half of the entire slope) revealed, both in the area affected by superficial mass movements and in the rest of the slope, the presence of numerous sub-vertical or valley-wards dipping fractures, many of which open on the surface and reaching depths of more than 80-100 m down to the Marne a Fucoidi formation (fig. 10, cross-section L1, L2, L3); underneath the bottom of the lake, however, shear zones have been found, with faults and low angle fractures in a counterslope direction, as well as bulging phenomena in the rocky bedrock covered by fluvial-lacustrine deposits (fig. 10, cross-section L4).

The totality of the geological and structural data indicates the presence of noticeable anomalies with respect to the neighbouring areas. The geomorphological setting is also anomalous, as it presents a convex slope, an evident trench in the higher portion, shelves, counterslopes and deviations of the hydrographic network.

The acquired data made it possible to define the geological and geomorphological model for this phenomenon that could be ascribed to a widespread deep seated slope deformation, in which the ductile deformation zone is represented by the marly-clayey basal member of the Marne a Fucoidi formation. The landslide crown, that is still subject to traction, corresponds to the E-W oriented discontinuities, affected by friction cemented gravels that has undergone local gravitative, but not tectonic, reactivation processes. The overlying limestone formations involved in the deformation belong to the upper portion of the Marne a Fucoidi (calcareous member) and Scaglia bianca-rosata formations, which are also compromised by active and recurrent superficial translational slides, fall and topple phenomena.

The results of the surveys above described allow us to ascribe the studied phenomenon to a deep-seated block slide (Dramis & Sorriso-Valvo, 1994; Cruden & Varnes, 1996), that will be the object of further study, for its particularly important location (primary road network and hydroelectric basin). Further researches will focus on the definition of appropriate monitoring devices (inclinometers, piezometers and GPS net) for the setting up of safeguarding measures for the area.

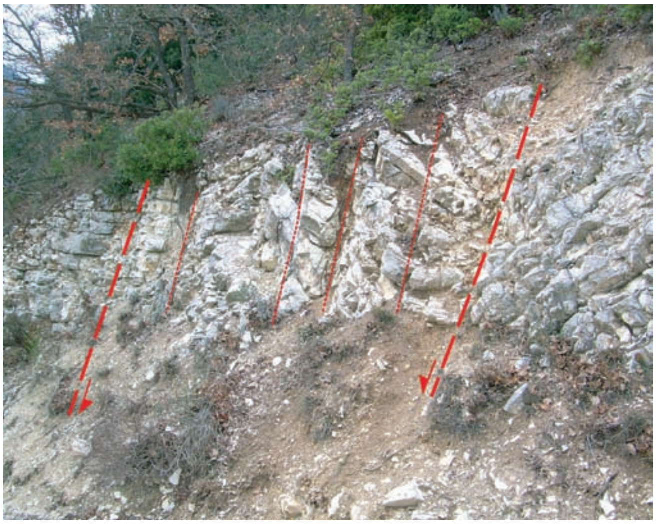


FIG. 9 - Borgiano area: E-W discontinuities forming a geological mini-graben in the middle portion of the slope.

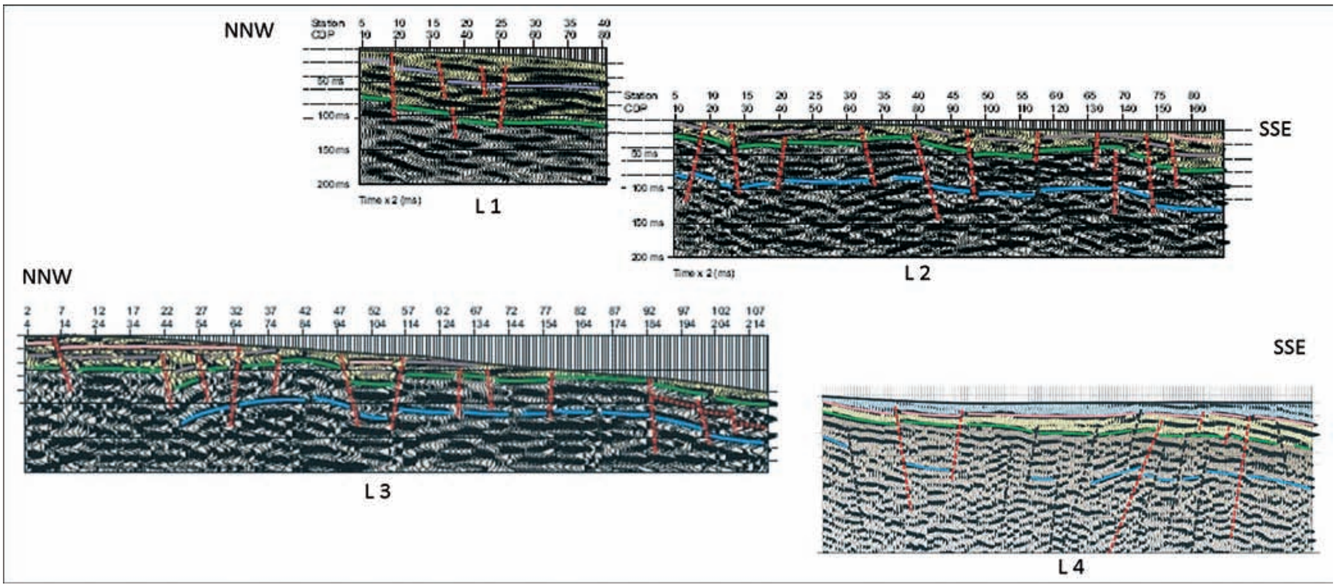


FIG. 10 - Borgiano area: geophysical cross-sections (L1, L2, L3, L4, after Aringoli & *alii*, in press); for the location of the seismic profiles see figure 7a.

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