Geogr. Fis. Dinam. Quat.
32 (2009), 73-82, 11 figg.

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A DEEP-SEATED GRAVITATIONAL SLOPE DEFORMATION IN THE UPPER BARGONASCO VALLEY (LIGURIAN APENNINES) (****)

ABSTRACT: FACCINI F., PICCAZZO M. & ROBBIANO A., *A deep-seated gravitational slope deformation in the Upper Bargonasco Valley (Ligurian Apennines)*. (IT ISSN 0391-9838, 2009).

Deep-seated gravitational slope deformations (DSGSD) represent an important geomorphological feature of the Ligurian landscape, and have drawn scientific attention for the past several decades. Lithological characteristics of rock masses, tectonic movements, geomorphic and climatic factors are among the key processes generally recognized.

Along the slope, which spreads between a ridge at 880 m and the Bargonasco River at 220 m a.s.l., where serpentinites and basalt outcrops connect with cherts and other sedimentary rocks along tectonic lineations, typical geomorphological evidence of DSGSD are observed, including grabens, trenches, double ridges, depressions, troughs, and counterslopes scarplets, all of which may reactivate pre-existing structural discontinuities.

Within a UE program aimed at assessing the *Pian del Lago* wetland, which represent the top side of the DSGSD and correspond to a trench filled with lacustrine sediment, a drilling program was carried out and the stratigraphy of the area was defined.

Several radiometric analyses conducted on samples of core peat demonstrated that the most ancient phase of this lacustrine basin dates from the Upper Pleistocene, featuring major climate changes. As such, it is possible that the beginning of the DSGSD occurred earlier than this, and that its formation is correlated to the various stadial-interstadial transitions that characterized the last 100 ky BP.

KEY WORDS: Deep-Seated Gravitational Slope Deformation, Landslides, Ophiolites, Climatic changes, Ligurian Apennines.

INTRODUCTION

The deep seated gravitational slope deformations (DSGSD) were first identified in the 1960s and 1970s (Terzaghi, 1962; Jahn, 1964; Zischinsky 1966; 1969; Nemcok, 1972), even though accurate and systematic studies were carried out only over the past 20 years (Dramis, 1984; Savage & Varnes, 1987; Crescenti & *alii*, 1994; Dramis & Sorriso-Valvo, 1994; Crosta, 1996; Agliardi & *alii*, 2001; Saroli & *alii*, 2005). Specifically, deep-seated gravitational movements were fully acknowledged in the full Alpine and Apennine area (including Sicily) and were the subject of international scientific conferences (Crescenti & *alii*, 1994).

In Ligurian Apennines, the DSGSD represent an important geomorphic landscape feature, both along the coast and in the mountains. Only recently have they been identified and accurately studied scientifically, however often in a manner not suitable to their extension and complexity. In Liguria country, where the Alps and the Apennines meet, and where wide ophiolite masses outcrops with various metamorphic degrees and palaeo-geographic domains, different lithologies are frequently found adjacent to one another, in geomechanical and hydrological terms, often highly deformed, fractured, and altered. Furthermore, in Ligurian Apennines, Plio-Pleistocene tectonic movements are particularly active, the seismic activity remains significant, and marked climate changes feature all the Quaternary.

The present case study is focused on a DSGSD related to the built-up area of Bargone, in the Ligurian Apennines, East of the Genoa Province. The mass movement, located within the ophiolite bedrock of the Internal Ligurides, has been studied by various scientific and technical investigations, which have proven ineffective in identifying an origin correlated to a Sackung that involves the entire system ridge, slope, and valley. The examples mentioned in the present work often regard lithological conditions caused by the overlapping of hard over weak formations.

The area belongs to the European ecological network *Natura* 2000, designed to protect the most endangered habitats and species into the optimal wildlife areas, including the *Siti di Interesse Comunitario (S.I.C., i.e. Sites of*

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(****) *12th Belgium-France-Italy-Romania Geomorphological Meeting - IAG - «Climatic Change and Related Landscapees» (Savona 26-29 September 2007).*

This work were conducted with the assistance of D. Coniglio (Ph.D.), Comunità Montana Val Petronio (Liguria).

UE Interest). This area belongs to the S.I.C. 96 Mt. Verruga - Mt. Zenone - Mt. Roccagrande - Mt. Pu, which was recently botanically and environmentally enhanced. Within the context of a U.E. program aimed at better protecting the Pian del Lago wet land that make up the upper side of the DSGSD and corresponds to a trench filled with lacustrine sediment, a detailed site investigation was carried out, and the stratigraphy, structural settings, and hydrologic settings of the area were defined by borehole analyses and detailed geophysical surveys.

On the basis of available radiometric analyses, the most ancient stage of this endoreic basin can be dated, and thus the first possible time dating of one of these major mass movements, primarily featuring the Ligurian landscape, can be provided within a period characterized by frequent climate changes.

GEOGRAPHICAL AND GEOLOGICAL SETTINGS

The Bargonasco valley is located on the orographic right of the middle Petronio valley, less than 3 km from the coast, which stretches from Sestri Levante to Moneglia (fig. 1). The Bargonasco River, between the confluence with the Petronio River 46 m a.s.l. and at about 900 m altitude close to the Pass of Bocco, shows an average SSW-NNE course, with the east side more developed relative to the west. The watershed ridge marking the boundary of the catchment features mountain tops that reach fairly high altitudes, considering the proximity of the sea: these include mounts Roccagrande (971 m) and Tregin on the west side, the mounts Alpe (1093 m), Zenone (1055 m), and Pu (1001 m) on the east side.

The climate of the area is defined by the parameters recorded by the weather station of Castiglione Chiavarese (300 m), in the Upper Petronio Valley. The geographic setting and the main slope aspect of the valley create an air mass circulation featuring wet and warm winds blowing from the sea and entering the valley through the Petronio River axis.

Due to these conditions, relatively mild temperatures are generally observed, with an average of 13°-14°C, with frequent rainfall, with average annual rainfall of 1300 mm. The mean monthly temperature distribution shows a maximum in the summer, at above 22°C, and a minimum in winter, with isotherms included between 6° and 8°C.

The average monthly rainfall distribution shows a maximum in November (160 mm) and a minimum in July (less than 50 mm); the prevailing climate is Mediterranean, even though different topoclimates can occur according to altitude and slope exposure. Heavy concentrated rainfalls are often observed during the Fall season, when they can reach values as high as half of the annual total over only a few days. In 1966, the weather station of Castiglione Chiavarese recorded 510 mm of rainfall in October, and a year total of more than 3000 mm. This is a major instability factor causing wide landslide movements, which are observed primarily in the Upper Bargonasco catchment. Water supply significantly increases due to condensation

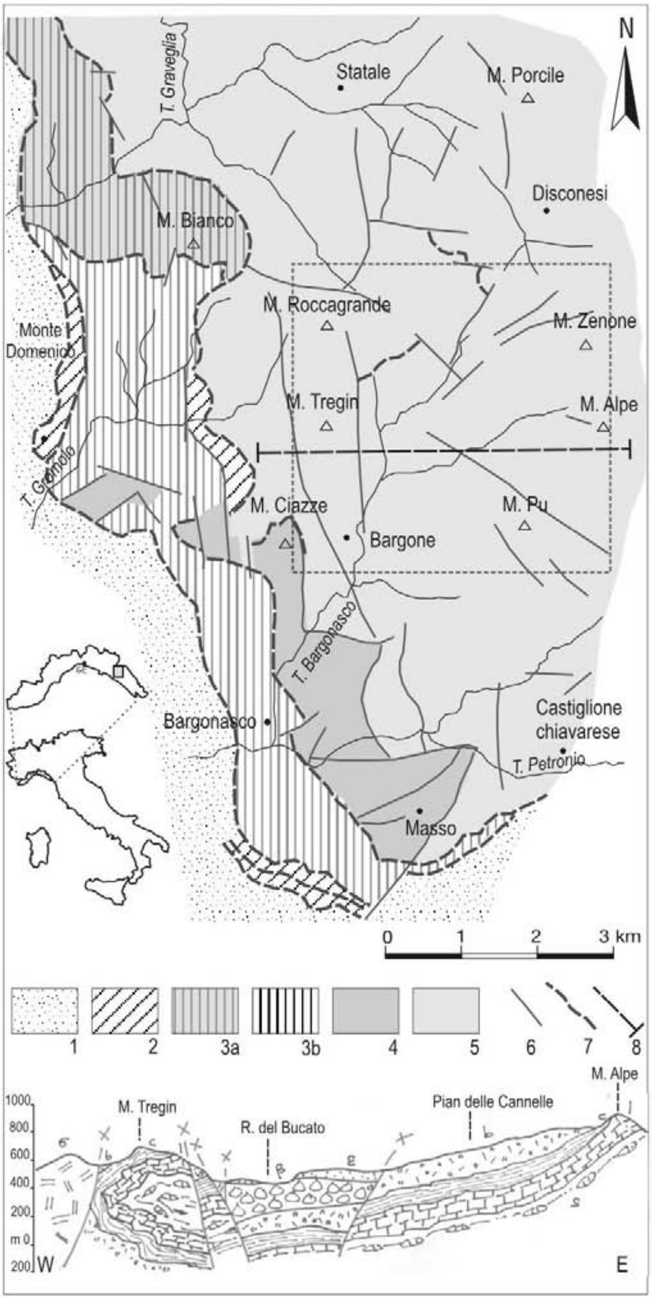


FIG. 1 - Geological units sketch map. Legend: M. GOTTERO UNIT - 1. M. Zatta sandstones; M. PORCILE UNIT - 2. M. Domenico sub-unit; 3. Rio Gromolo sub-unit (a. M. Bianco element; b. S. Antonio element); 4. M. Ciazze sub-unit; 5. M. Bocco sub-unit; 6. Main fault; 7. Main thrust; 8. Geological trace section (legend: σ. serpentinites; β. ophiolitic breccias; ϵ. gabbro; c. cherts; l. limestones; s. shales with limestones interlayers).

occurring close to the main watershed, and caused by the temperature decrease of the vapour-saturated air in contact with the bedrock.

The geological setting and the stratigraphical sequence of the Bargonasco are now well understood, as they represent the typical ophiolite sequence of the ocean floor, with the corresponding sedimentary covers, which underwent a weak metamorphism (Società Geologica Italiana, 1994).

The unit existing in the valley, which can be ascribed to the Ligurian Domain, is the ophiolite Unit of Mt. Porcile (fig. 1). This represents the basal portion of the sequence with ophiolite rock-type, which often protrude at the core of big recumbent folds, overlapped by the sedimentary cover.

The primary tectonic lineations, where the hydrographic network of the Bargonasco River and of its tributaries are clearly conditioned, are represented by two main systems, and by several other minor systems. One such system is oriented between NW-SE and WNW-ESE, and another is oriented between ENE-WSW. This tectonic system decisively affects the valley geomorphic aspects, causing forms such as steep rocky walls (west slopes of Mt. Tregin) and significant landslide areas (built-up area of Bargone), which is often the cause of deep-seated gravitational deformations as that discussed in the present study.

METHODS

In the present case study, the adopted methods are numerous and complex, and various analysis techniques are employed, both direct and indirect, with the purpose of permitting for comparison of the collected data, as well as subsequent interpretation and processing. The first stage of the study incorporates accurate reference research carried out both in the local historical archives, through interviews with the population, and by study of the AVI project landslide catalogue and on-line data banks (Consiglio Nazionale delle Ricerche, 1994).

The geomorphic studies carried out on this area were also considered and critically analysed. They often recognized the presence of forms, processes, and deposits of the gravitational type (Decandia & Elter, 1972; Abbate & *alii*, 1980; Pappalardo, 1994). However, they did not place the landslide events into a wider context, such as a model including the full ridge-slope-valley floor system (Dramis & Sorriso Valvo, 1994; Sorriso Valvo, 1995). Pappalardo (1994) recognized two main landforms: a tongue shaped debris body and a small hollow filled with peat sediments. The debris tongue is classified as rock fall due to the collapse of the upper part of the slope, comprised of soil and rock. The elongated deposits isolated in a small part of the slope, which had been lowered by a fault, resulting in the formation of a small lake.

Specific attention was focused on the hydrological aspects, by processing temperature and rainfall data, and through the census of springs, in order to identify the causes of the exceptional affluence of water reserves in the Bargonasco valley. As such, a geological and geomorphic survey of the entire sector was conducted. This included comparison of aerial photos taken over the past few decades, as well as comparison with historical maps dating as far back as the first half of the 19th century.

Additionally, geomorphic observations were carried out. Detailed field surveys were conducted *in situ*, taken from geo-panoramic points of view, such as the mounts Roccagrande, Tregin, and Pu, which, according to the specific valley morphological setting, effectively allowed us to understand the geomorphic model proposed in this work.

By the above described process, all the land elements were collected. These can be connected to the gravitational morphogenesis, with specific attention to the morphoneotectonic evidences, directly connected to the instability processes which were observed.

To this end, the data collected through the drilling activities carried out by the Comunità Montana Val Petronio were employed. The campaign was held on the occasion of the botanical and environmental enhance of the S.I.C. n° 96, and consisted of three borehole drillings carried out in the wet land of Pian del Lago (Subsoil, 2005). The drillings, each between 15 and 25 m deep, were equipped with piezometers, allowing for the measurement of pore pressure over time. Further, within this research project, some analyses were carried out in the laboratory using the radiocarbon techniques, which allowed for the assessment of the deposit age. Some samples underwent laboratory geotechnical tests as well, with the purpose of identifying and classifying the soils.

In order to link the punctual data obtained through the drilling surveys carried out at Pian del Lago, which represents an altitude flat area and which is located only dozen meters from the watershed ridge (fig. 2), two refraction seismic surveys were conducted over a length of 370 m. These allowed for the three-dimensional reconstruction of the wet land bottom as well as the collection of additional information regarding the bedrock fracture condition.

RESULTS

The geological and tectonic setting of the Bargonasco Valley is complex and difficult to interpret, because reasonably extended outcrops are observed along the ridge, particularly where the eastern and western watersheds are located (fig. 3).

All formations can be ascribed to the Mt. Porcile Unit, although they are tectonically separated by slip-off planes that identify various subunits. These formations can be recomposed into a short series of folds and into a megascale with a main element that is an anticline, and with a reverse side that is represented by the cherts and limestones of Mt. Tregin (Abbate & *alii*, 1980).

The western sides of mounts Pu, Alpe, and Zenone are formed by breccia and basalts in reverse series, whereas on the tops of mounts Alpe and Pu, cherts and limestones form complex structures.

The normal fault system determining the horst of Mt. Tregin - Mt. Roccagrande is well indicated on site by the contact of serpentinites featuring the full northern basin ridge and the top of Mt. Bocco.

The outcrops that can be seen inside the valley, which are represented by a limited lens of pillow basalts at Groppaggi, and by ophiolite breccia on the left bank of the Bargonasco River between Pian del Madico and Mt. Zeno-

FIG. 2 - Panoramic view of Pian del Lago.

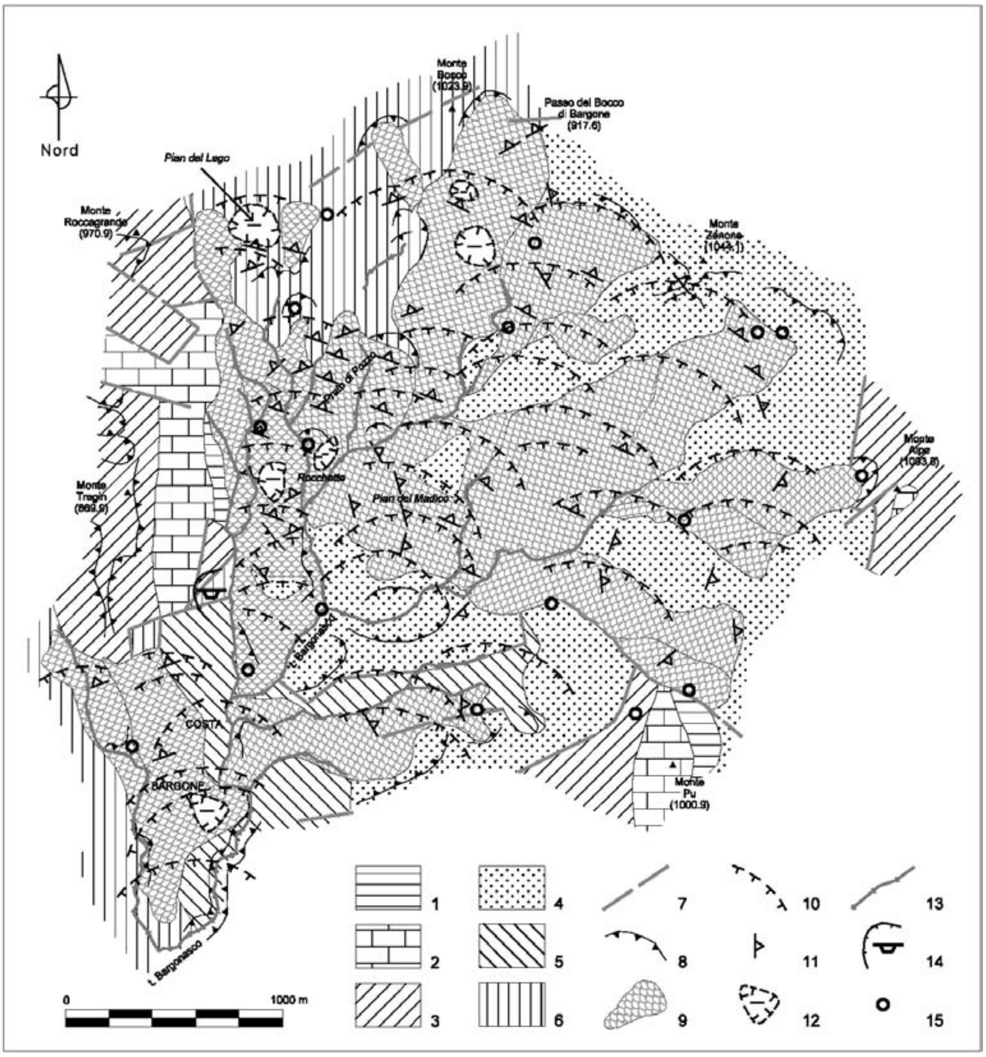


FIG. 3 - Geomorphological sketch map. Legend: 1. shales with limestones interlayers; 2. limestones; 3. cherts; 4. ophiolitic breccias; 5. gabbro; 6. serpentinites; 7. main fault; 8. edge of degradational and/or landslides scarp; 9. landslide; 10. edge of scarp due to DSGSD; 11. reverse slope; 12. close depression with swampy deposit; 13. riverbed with trend to down-cutting; 14. abandoned quarry with anthropogenic edge scarp; 15. perennial spring.

ne, can all be ascribed to displaced rock masses, isolated by extended ancient and relict landslides.

The catchment is characterized by landslides of different sizes, genesys, and activity stages. Among these, the most significant include (a) the south of Mt. Tregin, longer than 1 km, regarding the built-up area of Bargone, and (b); the east of Mt. Tregin, which reaches the river bed of the Bargonasco River, and bears an elongated shape and N-S oriented and spreading for more than 2 km, from Pian del Lago. The landslides, which are located in the eastern catchment area, including those from the southern and western slopes of the Pass of Bocco, Mt. Zenone and Mt. Alpe, as indicated by the wide landslide scarplets, reach the left bank of the Bargonasco River. In the areas where these landslides are located, a number of reverse slopes are observed. These cause a general terraced slope setting and form closed depressions comprise of wet lands containing lacustrine deposits.

A number of morphoneotectonic evidence was identified along the ridge and inside the Bargonasco River basin located close to the built-up area of Bargone (fig. 4). In particular, on the northern and eastern ridge a number of saddles were observed, while on the western watershed, the tectonic scarplet marking the boundary with the eastern area of Mt. Tregin and Roccagrande can be seen. Furthermore rectilinear crests and planimetric offsets were identified, while the hydrographical network shows, which a rectangular pattern with frequent diversion elbows, together with the rectilinear development of some valley, suggest strong tectonic control. Some triangular and trapezoidal facets were found on the northern slope of Mt. Pu, at Pian del Madico and on the right bank of the Bargonasco River.

Due to the high relief energy, the water supply, and the type of landslide bodies, all the primary and secondary hydrographic network appears to be in marked deepening.

Over a total surface area of 10 km^2, a census of more than twenty springs was taken, half of which supply waterworks, as in the case we are examining. These springs were located at an altitude as well, as in the case of mounts Alpe and Zenone, inside wide landslide bodies, as at Bargone and Prato di Pozzo, or along the contact area between the landslide bodies and huge olistolithes.

Drillings carried out at Pian del Lago, where the top bench is located at 830 m a.s.l. (fig. 5), allowed us to assess the thickness of the lacustrine deposit. This varied between 3 m and 14 m, and between the lithological type of the bedrock, which can always be ascribed to serpentinites (fig. 6). In all cases, a thick, highly altered and fractured rock level exists. Further, the ground thickness thins one proceeds downhill, indicating a basement counterslope. Consequently, the lacustrine sediment maximum thickness was identified at the morphological flat area base, and

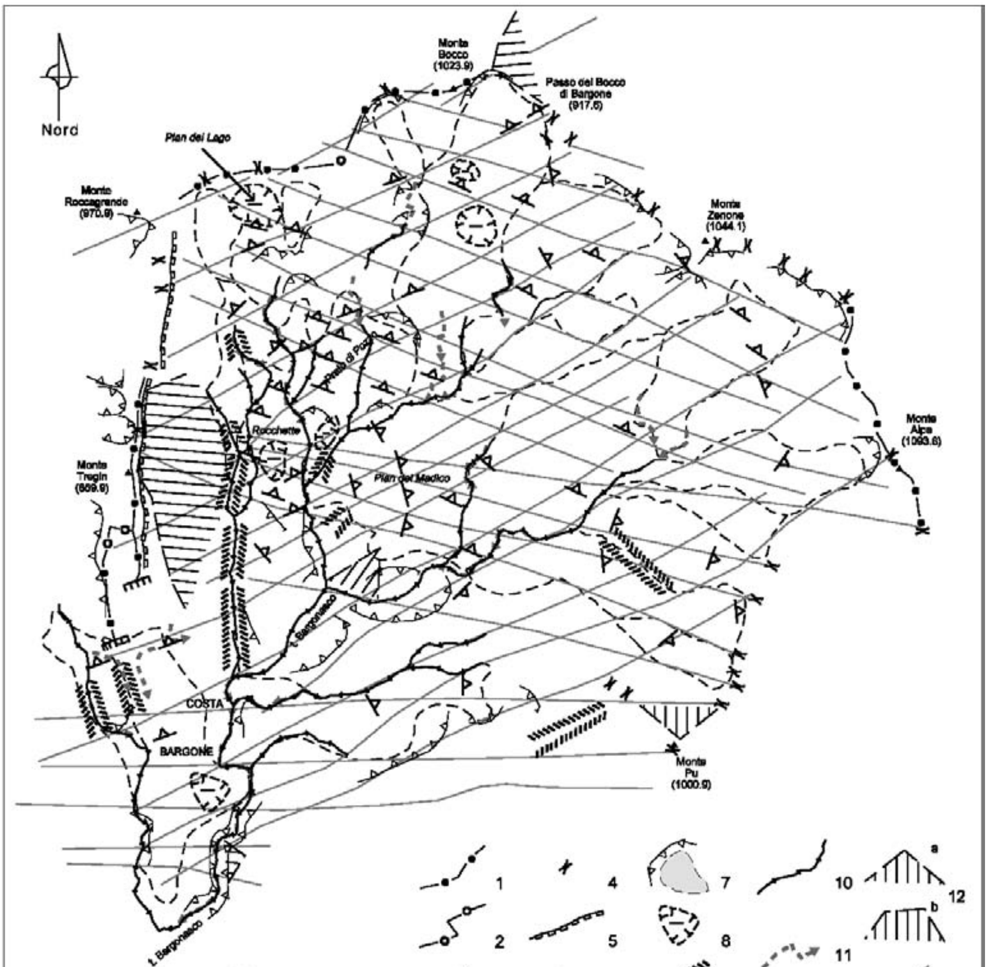


FIG. 4 - Morpho-neotectonic map. Legend: 1. linear ridge; 2. planimetric ridge discontinuities; 3. altimetric ridge discontinuities; 4. saddle; 5. edge of tectonic scarp; 6. reverse slope; 7. landslide; 8. close depression; 9. linear valley; 10. riverbed with trend to down-cutting; 11. diversion elbow; 12. triangular (a) or trapezoidal (b) facette; 13. tectonic line.

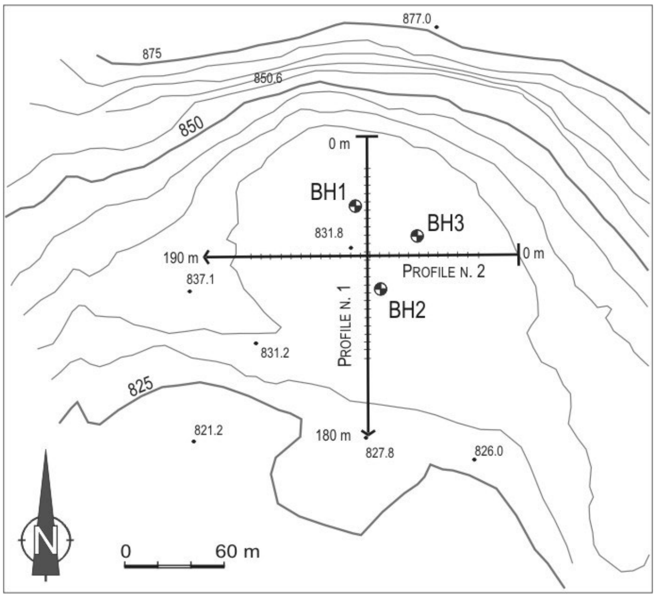


FIG. 5 - Pian del Lago prospecting map, with location of boreholes (BH) and seismic refraction surveys (Profile).

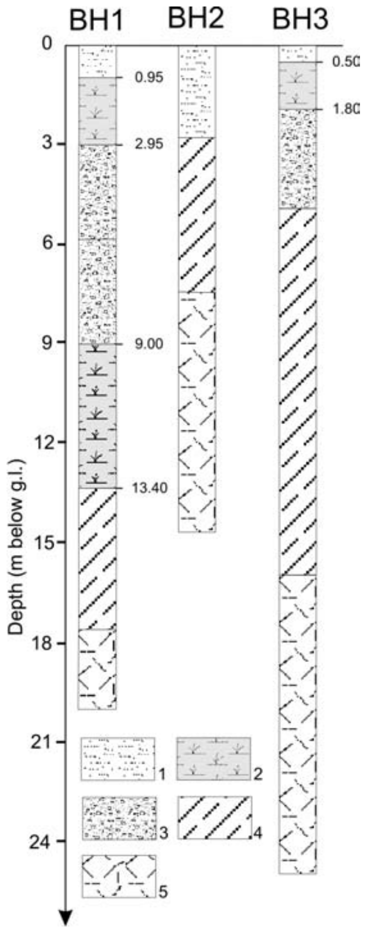


FIG. 6 - Boreholes stratigraphies. Legend: 1) Organic-earth cover; 2) Swampy deposit; 3) Colluvial and debris cover with thin swampy layers; 4) Very altered and fractured bedrock; 5) Fractured bedrock (serpentinite).

showed significant alternations of organic matter with sediments that could be ascribed to the slope debris. In particular, the organic level located between 11 and 12 m deep from the g.l. shows a predominant fine silt and clay fraction and a subordinate sand component. Further, the soil displays a high liquid limit.

Punctual knowledge of the stratigraphical setting was extended by means of seismic surveys, which provided a four-horizons model that was difficult to interpret when compared with the stratigraphical features derived from drillings (fig. 7). Two major aspects appear. First, the outstanding difference of seismic wave velocities of the second, third, and fourth layer along both profiles, particularly the profile uphill-downhill-oriented (profile 1), shows relatively low values. Second, in both cases, both surface levels, which have approximately the same thickness, can be ascribed to loose soil, while the third bed, which represents the highly fractured and altered bedrock, shows an increasing thickness going from W to E and from N towards S. This is, similar to conclusions drawn from the surface survey and from drillings (fig. 8). The fourth layer, based on its depth, can be ascribed to the bedrock, although the relatively lower velocity of profile 1 suggests diffuse fracture conditions.

A number of paleobotanical and archaeological studies carried out on Pian del Lago (MacPhail, 1988; Cruise & *alii*, 1998; Maggi, 1997; Campana & *alii*, 1998; Cruise & Maggi, 2000; Maggi, 2004; Università degli Studi di Genova, 2005) indicate a correlation between the depth and the age of soils, and vary up to 12 ky BP across the first 4-5 m below g.l. This provides indicates that the peat layers drilling in BH1, ranging from 9 m to 13.4 m below the g.l., are older than 30 ky BP (fig. 9).

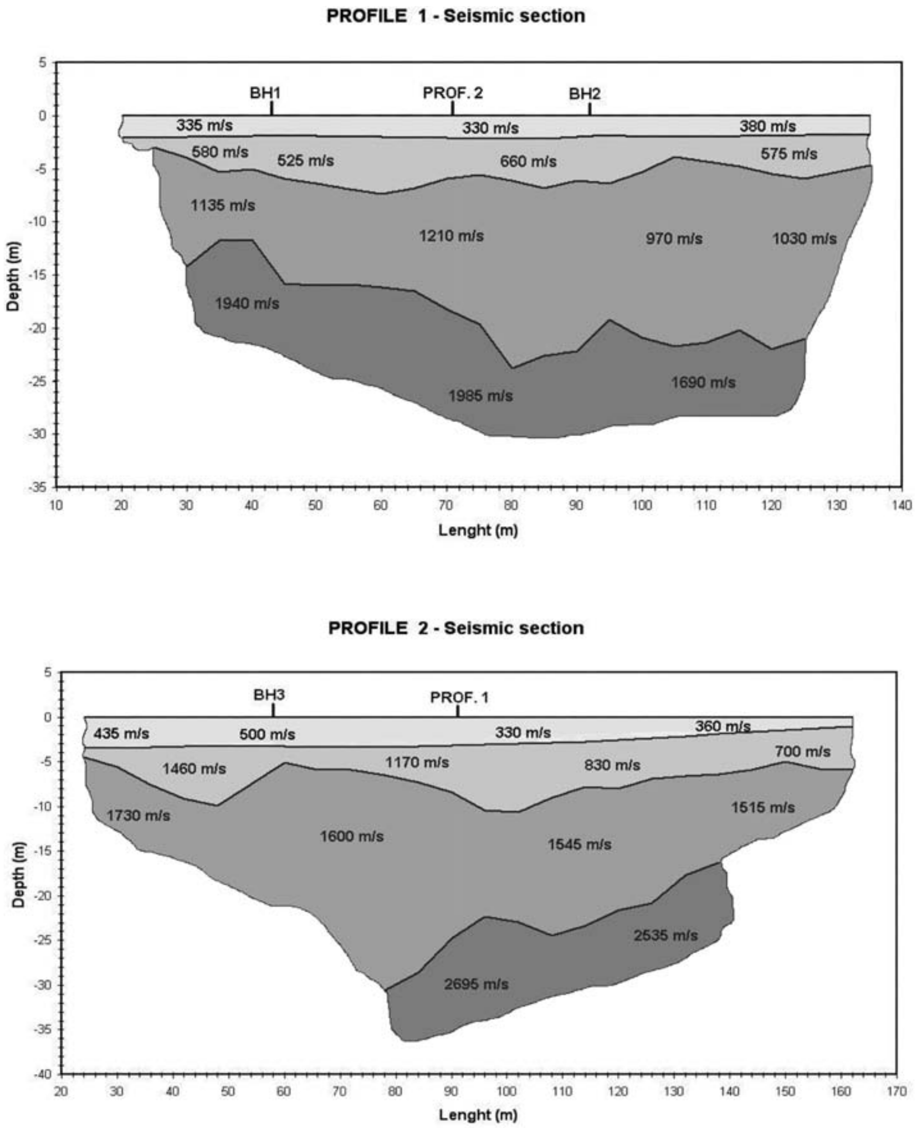
DISCUSSION

The results of the case study following data processing carried out during the interpretation and synthesis stage suggest a deep seated gravitational slope deformation at the base of the landforms in the upper Bargonasco Valley.

Along the slope, which runs from the ridge at 880 m and the Bargonasco River at 220 m a.s.l., characterized by serpentinites and basalt outcrops connected with cherts and other sedimentary rocks, along a tectonic lineation system, typical geomorphic evidence of DSGSD can be observed, including grabens, trenches, double ridges, depressions, troughs, and reverse slopes. These may reactivate pre-existing structural discontinuities. As such, the reference model can be considered similar to the rock flows or *Sackung* type (Bisci & *alii*, 1996; Dikau, 1999; Ambrosi & Crosta, 2006). In particular, the hydrographical network appears to be controlled by two principal tectonic lineation systems, located in NE-SW and NW-SE medium directions.

A rock microplate system can be recognized throughout the slope scale. The system sank down, forming a terraced slope profile, featuring a series of flat areas between 831 m (Pian del Lago) and 280 m (Bargone), alternating with uphill facing scarplets (fig. 10).

FIG. 7 - Seismic sections (Profile n. 1 and 2; see fig. 5 for location).



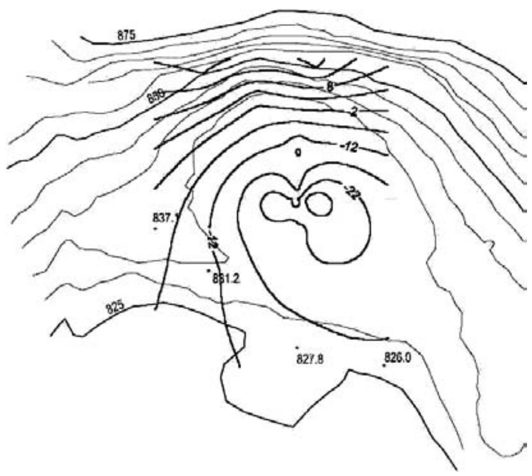


FIG. 8 - Contour lines on the top of fractured bedrock at Pian del Lago, (0 m elevation at ground level).

Although the surface geomorphic survey was applied to the full slope, only the top area of this terraced series was more accurately studied, as it represents the major area in terms of DGSGD evolutionary history. This flat area is the most ancient and exemplary relative to the morphological bench developments located downhill (fig. 11).

Based on our studies, the Pian del Lago can be recognized as a trench of tectonic-gravitational origin. It features a reverse slope, where lacustrine sediments were deposited, with a base age that dates to an earlier stage of the Last Glacial Maximum, coincident with the stadial-interstadial transitions of the Middle Pleniglacial, during the Upper Pleistocene (Orombelli & *alii*, 2005). It is consistent with other deep-seated deformations known in Italy (Crosta & *alii*, 2008).

Originally, this DSGSD likely displayed typical in stability factors (Dramis, 1984). Among these factors, the complex geological type of this field must be recognized.

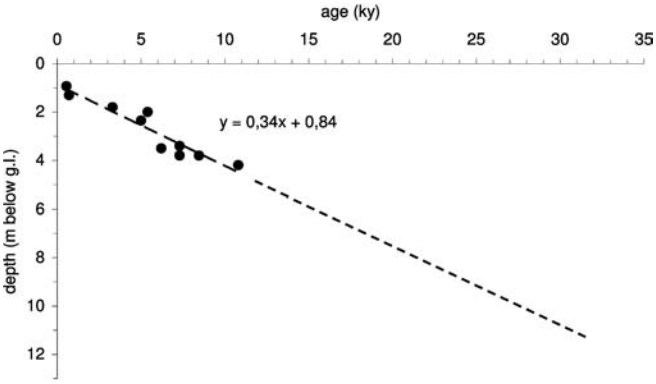


FIG. 9 - Correlation chart between depth and age of soils from radiometric analysis data on the Pian del Lago wet zone.

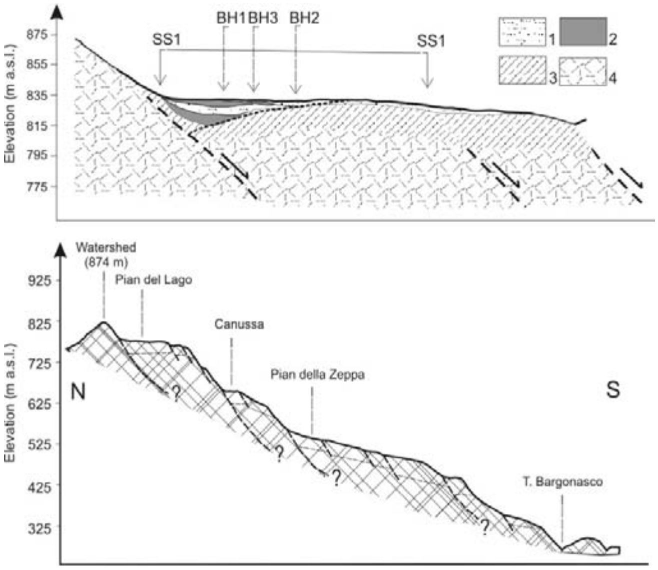


FIG. 10 - Schematic section from Pian del Lago to the Bargonasco river (downup, dashed line mean deformation surface, grid mean displaced rock masses) and Pian del Lago geologic section (updown). Legend: 1. Colluvial and debris cover with thin swampy layers, earth cover; 2. Swampy deposit; 3. Very altered and fractured bedrock; 4. Fractured bedrock (serpentinites).

It involves the widespread lithologies contact with a marked geomechanical and hydrological contrast, and tectonic development. Additionally, climate changes play an important role as the surface alteration processes and the erosion action by the running waters influence the slope stability conditions and the seismic stress.

The tectonic uplift of the Ligurian Apennine in the Plio-Pleistocene is likely the primary factor that caused the formation of a pervasive lineations system, with regard to the continental margin and the sea side; it formed a series of tectonic landforms leading to the formation of the present seashore. Among the most significant lineations related to the morphological and tectonic events, the lineation of the Petronio River E-W oriented must be acknowledged (Fanucci & Nosengo, 1979).

In such a morpho-structural situation, active exogenous processes developed, fuelled by the high energy relief. They are connected to bedrock alteration, to the running water, and to the action of gravity, as well as periglacial action (Pappalardo, 1994). Further, they caused major slope instability, primarily due to continuous alternations of climatic interglacial and glacial stages of the Quaternary. As such, deep-seated gravitational events were probably triggered (Dramis & *alii*, 1987).

At times, these were significantly large and likely reactivated many times, as valley systems evolved. The seismic conditions, which are presently of small intensity, but still significantly close to the study area, were stronger during the Plio-Pleistocene period owing to the neotectonic activity.

Events such as those discussed above, played a major role also in other Ligurian valleys, particularly in those adjacent to the study sites. Here, evidence of deep-seated gravitational movements have been described, frequently corroborated by continental river-lacustrine altitude deposits (Maifredi & Nosengo, 1975; Brancucci & *alii*, 1982; Federici & *alii*, 2004; Brandolini & *alii*, 2007).

CONCLUSIONS

Over the past decad, the DSGSD have been drawing scientific attention and were acknowledged in different geographical and environmental areas (Crescenti & *alii*, 1994). Their importance is evident in land planning, and in relation

FIG. 11 - Panoramic view of upper Bargonasco Valley from Mt. Tregin.

to the activity stage of some gravitational events, causing interferences with settlements and risk conditions for human.

Furthermore an accurate knowledge of these deep-seated deformations is essential in terms of water supply management, as they represent reservoirs with recharge mechanisms that must be ensured, not only by infiltration linked to rainfalls, but also by altitude condensation of air masses, fostered by the geographical and physical land settings. This is the case for the examined DSGSD with main slope aspects to the sea. It is therefore necessary to place surface landslides in a wider geomorphic context, on the scale of the full slope; these show themselves with various kinematic mechanisms and dynamics, and only represent the major morphological aspect of DSGSD.

In the Ligurian region, these deep-seated gravitational movements are prevalent. In particular, in the Ligurian Apennine we have investigated case histories for which the research methods used in this work can be properly validated and compared, in the light of different geological and geomorphological conditions which were observed. These include Santo Stefano d'Aveto and Alpepiana in the Upper Aveto Valley, Campegli in the Petronio Valley, Belpiano in the Sturla Valley, Lemeglio along the coast.

In Liguria, in a complex geological and tectonic context featuring continuous approaches of lithologies with different geomechanical and hydrological features, within the same formation high neotectonic activity can be found. This activity involved a differential uplift of whole land areas and the continuous development of fault scarplets. Quaternary climate changes, in particular those of the last glacial age, regulated the denudational processes to the slope scale, resulting in the depositions of large quantities of water and debris as a consequence of changes of the base level.

The observation scale of these DSGSD involves significant difficulties, during the study period the monitoring stage, and during possible actions for reducing geomorphological hazards. Therefore, it is essential to invoke differentiated survey and monitoring techniques, with a multiscalar approach, so as to allow a collected data comparison by means of different methods. Herein, this process was deemed useful. The integration of direct stratigraphical data with a new series of drillings and geophysical surveys allows us to reach a larger and wider depth over the full slope, providing a series of targets which can be monitored through Synthetic Aperture Radars (SAR) interferometry.

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(Ms. presented 30 September 2007; accepted 30 December 2008)