Geogr. Fis. Dinam. Quat.
33 (2010), 155-164, 10 figg.

CORRADO CIMARELLI (*) & DONATELLA DE RITA (*)

DEEP-SEATED GRAVITATIONAL SLOPE DEFORMATIONS IN VOLCANIC SETTINGS: EXAMPLES FROM ITALIAN VOLCANOES

ABSTRACT: CIMARELLI C. & DE RITA D., *Deep-seated Gravitational Slope Deformations in volcanic settings: examples from Italian volcanoes*. (IT ISSN 0391-9838, 2010).

Volcanic areas are characterized by slow and rapid vertical ground deformations due to deep thermal instabilities or the resurgence of magma bodies in delimited sectors of a volcanic edifice. Moreover volcanic areas are often the loci of both tectonic and volcanic seismicity. For these reasons, in active or quiescent volcanoes, slope instability is common and may occur as sector or flank collapses gravitationally controlled, involving large rock volumes. Volcanoes experience this type of failure when they reach high relief and oversteepening in a relatively rapid period of activity. Many morphological and structural features affecting unstable volcanic edifices subjected to instability are similar to those described as associated to DGSD (Deep-Seated Gravitational Deformation). The most common features include horseshoe-shaped craters or calderas and associated large debris avalanche deposits.

Most of the Italian volcanoes, active, quiescent or dormant, show distinctive horseshoe-shaped craters opened at one end. Some of them are well known and studied features, some others have received less attention due to their state of preservation. For most cases of both categories triggers and favourable factors are still debated.

This paper presents case studies of slope deformations that may potentially be classified as DGSD affecting different types of volcanoes and volcanic islands in Italy.

KEY WORDS: DGSD, Volcano Instability, Italian Volcanoes, Volcanic Islands.

RIASSUNTO: CIMARELLI C. & DE RITA D., *Deformazioni gravitative profonde in ambiente vulcanico: esempi in vulcani italiani*. (IT ISSN 0391-9838, 2010).

Le aree vulcaniche sono soggette a deformazione verticale lenta o rapida dovuta ad una instabilità indotta da processi idrotermali o dalla risorgenza di corpi intrusivi in specifici settori dell'area vulcanica o di edifici vulcanici. Per di più le aree vulcaniche sono spesso interessate da sismicità sia a scala regionale che locale. L'instabilità degli edifici vulcanici si traduce spesso in collassi guidati dalla gravità di parti o dell'intero fianco dell'edificio vulcanico a cui si associano depositi di frana di volume considerevole. I processi di collasso si verificano quando l'edificio vulcanico raggiunge altezze considerevoli, rispetto al suo diametro di base, e l'accumulo dei materiali prodotti dalle eruzioni causa un sovraccarico di peso sia sull'edifico stesso che sul substrato su cui poggia l'edificio. Molti degli aspetti morfologici e strutturali che si sviluppano come conseguenza dell'instabilità di un vulcano sono simili a quelli osservati in ambiente sedimentario e generalmente classificati come DGPV (Deformazioni Gravitative Profonde di Versante). Le strutture più comunemente associate alla deformazione dell'edificio sono aperture del cratere o delle caldere a forma di ferro di cavallo a cui spesso sono associati depositi di colate detritiche di volume significativo.

Molti vulcani italiani, sia attivi che spenti o quiescenti, mostrano crateri e caldere a forma di ferro di cavallo. Alcune di queste strutture sono ormai note e ben studiate, mentre altre, per lo più relative ai vulcani più antichi, sono ancora poco conosciute e in molti casi la loro origine è ancora dibattuta.

In questo lavoro, dopo un breve excursus sulle strutture di deformazione più note dei vulcani attivi italiani, come quelle della Sciara del Fuoco di Stromboli, della Valle del Bove dell'Etna, del Vesuvio e di Ischia, vengono presentate alcune strutture deformative che mostrano aspetti comparabili con le DGPV dei vulcani spenti e sottomarini delle Isole Pontine, del vulcano di Roccamonfina e del vulcano di Panarea.

Nelle Isole Pontine di Ponza e Zannone, le deformazioni gravitative si sviluppano lungo piani estensionali a basso angolo che, per gli aspetti morfologici e strutturali osservati, possono essere interpretati come dovuti a stress locale indotto dall'intrusione del magma che alimentava la crescita di domi acidi sottomarini. A Ponza, questi piani, lungo cui si realizzava lo scivolamento gravitativo di masse di ialoclastiti dai fianchi dei domi in accrescimento, possono essere dovuti alla necessità di creare un equilibrio tra la progressiva iniezione del magma nella ialoclstite già depositata e lo stress gravitazionale. A Zannone, la crescita di un criptodomo portò al basculamento delle unità del basamento sedimentario che iniziarono a slittare lungo i piani di stratificazione raggiungendo le attuali posizioni stratigrafiche anomale lungo piani a basso angolo.

A Roccamonfina, nell'Italia meridionale, la presenza della struttura sommitale calderica aperta verso est a forma di ferro di cavallo può essere interpretata come dovuta all'instabilità del fianco orientale del vulcano, sviluppatosi in corrispondenza di un importante elemento strutturale a carattere regionale (faglia del Monte Massico). Gli aspetti morfologici e l'entità dei volumi coinvolti nel processo di scivolamento gravitativo, sono compatibili con quelli delle DGPV.

Infine, a Panarea, nell' arcipelago delle Isole Eolie, lungo la falesia occidentale dell'isola, è visibile il nucleo interno del domo lavico. L'esposizione del cuore del domo suggerisce che il vulcano sia stato soggetto a una o più fasi di collasso del fianco occidentale. L'analisi dettagliata della falesia ha evidenziato molti aspetti morfologici generalmente associati alle deformazioni gravitative profonde di versante (DGPV) ed in particolare a quelle definite sackungs.

TERMINI CHIAVE: DGPV, Instabilità dei Vulcani, Vulcani Italiani, Isole Vulcaniche.

(*) *Università degli Studi RomaTre, Dipartimento di Scienze Geologiche, L.go S.L. Murialdo 1 - 00146 Roma* - (derita@uniroma3.it)

INTRODUCTION

Deep-seated gravitational slope deformations (DGSD) usually refer to gravitational movements involving large rock volumes in high-relief mountain areas. They typically affect the whole hill-slope for thicknesses larger than several tens of metres and lengths of some kilometres (Zischinsky, 1966; 1966; Radbruch-Hall & *alii*, 1976; 1977; Agnesi & *alii*, 1978; Savage & Varnes, 1987). Although a definition of DGSD has not been clearly achieved yet, deep-seated gravitational slope deformations are commonly characterised by the following general features (Dramis & Sorriso-Valvo, 1994; Onida, 2001):

- The deforming mass may or may not be bounded by a continuous yielding surface; however, the continuity of such surface is not indispensable to explain the deformations at the surface.
- The volume of masses involved is of the order of several hundred thousands of cubic metres or more, the thickness is several tens of metres or more.
- Scale factors may influence the mechanical properties of the rock and, consequently, the deformation mechanism.
- The total displacement is small in comparison to the magnitude of the mass involved.

Peculiar morphological and structural features connected to DGSD are: double crests, sets of downhill and uphill facing scarps and counter-slope scarps, slope-parallel trenches, tension cracks in the upper slopes, and bulging lower slopes not necessarily associated with a continuous slip surface; also small-scale landslides, debris flows, and talus slope deposits are commonly associated with DGSD (Ter Stepanian, 1966; Radbruch-Hall & *alii*, 1977; Varnes & *alii*, 1989; Agliardi & *alii*, 2001; Tibaldi & *alii*, 2004).

Dramis & Sorriso-Valvo (1994) distinguish three basic types of DGSD: i) sackungs, ii) lateral spread of ridges and iii) lateral spread of thrust fronts. These types of mass-movements can be strongly conditioned by the present or recent tectonic history of the relief forms that they affect. Tectonics is thus one of the relevant factors for the development of such DGSD, especially when lateral-spread types and sackungs are concerned.The origin and evolution of DGSD are influenced by the local structural setting and the presence of rheological contrasts. In tectonically active areas, one of the most invoked, but seldom observed, triggering factors is seismic shaking (Saroli & *alii*, 2005). As concerns the activity of these phenomena, they can be in a dormant stage, but they can also display a surging-and-stopping behavior or a constant rate of deformation. Constant building-up of the relief, complex fracture patterns, and the height of a slope above a threshold value depending on the mechanical characteristics of the parent rocks, are favourable conditions for the development of DGSD (Dramis & Sorriso-Valvo, 1994). Such conditions are typical of currently orogenic chains and uplifted areas, but also areas of accumulation of material where rapid changing in relief energy is achieved.

Volcanic areas match these two last characteristics: slow and rapid vertical ground deformations are common in volcanic areas due to deep thermal instabilities over broad regions or the resurgence of magma bodies (dykes, sub-intrusive bodies) in very well defined sectors of a volcanic edifice. Moreover volcanic areas are often the loci of both tectonic and volcanic seismicity.

Morphological and structural features similar to those described as associated to DGSD may affect volcanic edifices. In fact, sector or flank collapses in active or quiescent volcanoes are gravitationally controlled and usually involve large rock volumes. Furthermore, volcanoes experience this type of failure when they reach high relief and oversteepening in a relatively rapid period of activity.

The paper presents case studies of slope deformations that may be classified as DGSD affecting different types of volcanoes and volcanic islands in Italy.

INSTABILITY OF VOLCANOES

Volcanic edifices are unstable structures due to their structure made of alternating strong (lavas) and weak (pyroclastics) rocks in many cases interbedded with sub-intrusive bodies such as dykes and sills. Overall the rock mass strength is low and volcanic materials subjected to the effects of fumaroles, further reduce the already low rocks strength by the production of hydrothermal and altered clay. For this reason, they may experience repeated structural failures during their evolution. Failure may occur suddenly in response to active deformation or may result over a long period of time due to oversteepening, overloading, or selective erosion. Common failures of active volcanoes appear to be dominated by vertical movements; their morphological expressions are pits and calderas. In large poligenetic volcanoes and volcanic islands, mass failure may incorporate horizontal vector as in the case of dome disintegration, sector collapse or lateral spreading (Mc Guire, 1996). In these last cases, giant mega-slides with volumes of cubic kilometres may occur, even involving the entire flank of the volcano usually leading to the emplacement of debris avalanches

The most common causes of instability of active volcanoes are the oversteepening and overloading of the edifice due to the continuous addition of exogenetic and endogenetic material (MC Guire, 1996); lithology and structural setting of the basement may also be important factors (Van Wyk De Vries & Borgia, 1996). Volcanic failure may be also related to rock strength anisotropy, internal structure, the in-situ stress field, fluid pressure distribution, lava injection and earthquake loading.

Even if the role of the magma may not be ignored, gravity is the most important contributory factor in the development of volcanoes instability and their failure. In volcanoes the morphologically relevant feature produced by failure is a distinctive horseshoe-shaped crater open at one end. The largest of the catastrophic collapses are one to two orders of magnitude greater in volume than for other landslides in non-volcanic terrains with bottom failure surfaces generally flatter than that for non-volcanic failures and reminiscent of detachment surfaces. Although these events are relatively rare, with recurrence-time of tens to hundreds of thousands years, they are recognised as a relatively common feature in volcanoes and volcanic islands. Moreover several studies have shown the importance of volcano instability for the study of tsunami generation and propagation (Chiocci & *alii*, 1998).

INSTABILITY OF ITALIAN VOLCANOES

Most of the Italian volcanoes, active, quiescent or dormant, show distinctive horseshoe-shaped craters opened at one end. Some of them are well known and studied features, some others have received less attention due to their state of preservation. For most cases of both categories triggers and favourable factors are still debated.

The most famous instability structures are those of Valle del Bove at Mt. Etna and Sciara del Fuoco at Stromboli. Valle del Bove depression is 7 km long, 5 km wide and more than 1 km deep, and it has been interpreted as due to a catastrophic gravitational collapse of the eastern flank of the modern Mongibello edifice (fig. 1a). The event(s) probably occurred less than 10.000 years ago (Guest & *alii*, 1984; Calvari & *alii*,1998) in a way similar to that which occurred at Mt St Helens in 1980 (Lipman & Mullineaux, 1981). Large submarine landslide deposits reported in the Ionian Sea offshore Mt. Etna have been recently correlated to the eastern flank collapse of the volcano (Pareschi & *alii*, 2006; Chiocci & *alii*, 1998).

The Sciara del Fuoco is a significant horseshoe-shaped depression affecting the northwestern side of Stromboli (fig. 1b). It was generated in the last 13,000 years by several collapses with volumes in the order of 1-2 km^3 (Kokelaar & Romagnoli, 1995; Tibaldi, 2001). The last one of these events occurred on 30th December 2002, the Sciara del Fuoco, oversteepened by the unceasing erupting activity, suddenly failed and a small avalanche (<0.01 km^3) caused a tsunami a few metres high that reached Sicilian and Calabrian coasts without deadly consequences.

Besides the well-known horseshoe-shaped structures of Etna and Stromboli volcanoes, we can remember the horse-shaped open structure of the Somma caldera rim within which the Vesuvius cone developed, recently related to off-shore debris flow deposits. The present Somma caldera (fig. 1c) has been interpreted as due mainly to W-SW directed sector collapse of the Somma cone, caused by excess vapour pressure generated during the Avellino eruption (3.5 ka; Rolandi & *alii*, 2004). The Authors

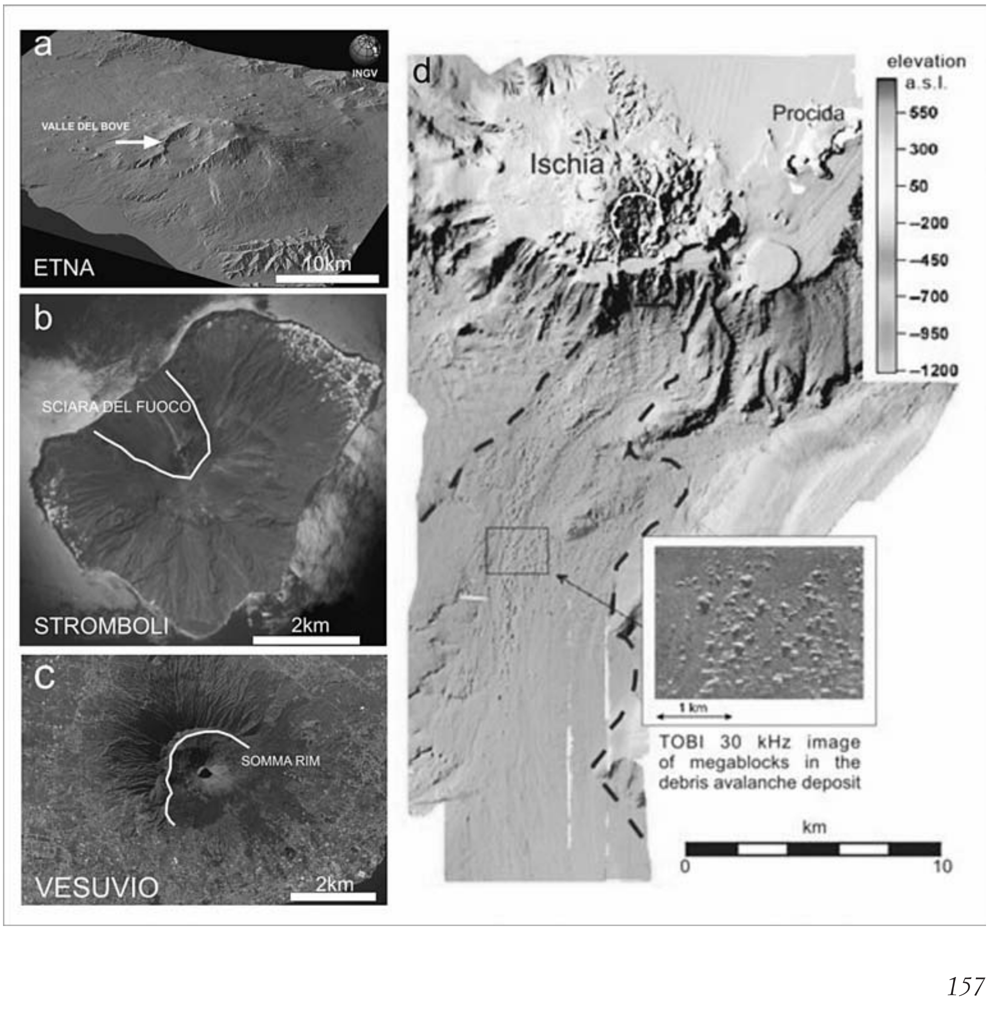

FIG. 1 - Horseshoe-shaped structures of Italian volcanoes. a) Valle del Bove, Etna (Sicily, southern Italy) interpreted as due to catastrophic collapse of the western flank of the volcano. b) Sciara del Fuoco, Stromboli (Aeolian Archipelago, southern Italy); horseshoe-shaped depression affecting the northwestern side of Stromboli. c) The open caldera of the Somma-Vesuvio volcano (sourthern Italy) interpreted as due to W-SW directed sector collapse of the Somma cone. d) Ischia, offshore of the Bay of Naples (southern Italy). The submarine landslide starts from the horseshoe scar on the southern flank of the island and extends for several kilometres on the seafloor (modified after Chiocci & De Alteriis, 2006).

(Rolandi & *alii*, 2004) speculate that, during the 79 A.D. and 472 A.D. eruptions, the flank failure processes were extended to the S-SE sector of the Somma edifice.

In the Mediterranean Sea, sector collapses, first proposed for Stromboli Island, have been claimed to occur during the Holocene and Recent at Somma-Vesuvius (Milia & *alii*, 2003) even though in both cases direct evidence of the genetically related underwater debris avalanche is lacking. Geomorphological evidences of a major collapse event have been reported also at Ischia (Chiocci & De Alteriis, 2006).

At Ischia (fig. 1d), the collapse left a subaerial to submarine horseshoe scar on the southern flank of the island and generated a debris avalanche incorporating thousands of giant blocks dispersed as far as 50 km from the island and covering an area of 250-300 km^2 as testified by seismic profiles. The major collapse was followed, and probably also preceded, by recurrent, less catastrophic terrestrial and underwater failures. Such volcanic collapse, may have triggered tsunami waves over the entire Bay of Naples during prehistorical/ historical times.

Even dormant volcanoes such as Vulture in southern Italy, Roccamonfina at the border between Campania and Lazio and the polygenetic volcanoes of the Latian Volcanic Districts (Central Italy) show morphological evidences of instability events testified by open craters or caldera rims.

The open summit caldera rim of the Vulture volcano has been interpreted (Guest & *alii*, 1988) to have a sector collapse origin. Similar morphological structures shown by the major polygenetic central volcanoes of the Latian Districts (Latera volcano in the Vulsini Volcanic District; Sacrofano in the Sabatini Volcanic District, the Tuscolano-Artemiso rim in the Colli Albani Volcanic District) do not have a clear origin. In all cases, the horse shaped opened caldera rims have been explained as due to successive caldera collapses related to major explosive events producing huge ignimbrites. However, it is interesting to note that the rims are interrupted where, below the volcano, a structural high of the sedimentary basement is truncated by a regional fault. Thus, it is possible to speculate that the instability of the volcanoes could have been related to tectonic processes and possibly triggered by seismic shaking (Moro & *alii*, 2007). Unfortunately, younger volcanic deposits mask the possible presence of debris flow or avalanche deposits related to the sector collapse event(s) and the interpretation of the morphological shape remains speculative.

Anyway, among these horseshoe-shaped morphological features, there are some that show significant geological evidences of being due to DGSD. In the next section we present examples related to the Ponza dome complex, to the Roccamonfina volcano and to the Panarea dome complex.

Ponza dome complex

Ponza dome complex is part of the Pontine archipelago that is located almost 30 km offshore the central Tyrrhenian coast of Italy, between Rome and Naples (fig. 2). The northern islands of the Archipelago, Ponza, Zannone and Palmarola, are predominantly characterized by Upper Pliocene high-K calc-alkaline rhyolite lavas issued from submarine vents (Conte & Savelli, 1994; de Rita & *alii*, 2001). The islands lie on the continental Tyrrhenian shelf constituted of Miocene-Pliocene thrust units affected by the extensional tectonics related to the Pliocene-Pleistocene evolution of the Tyrrhenian basin. The extensional tectonics dissected the thrust units in a series of structural highs and lows filled up by the Pliocene-Pleistocene clay sediments.

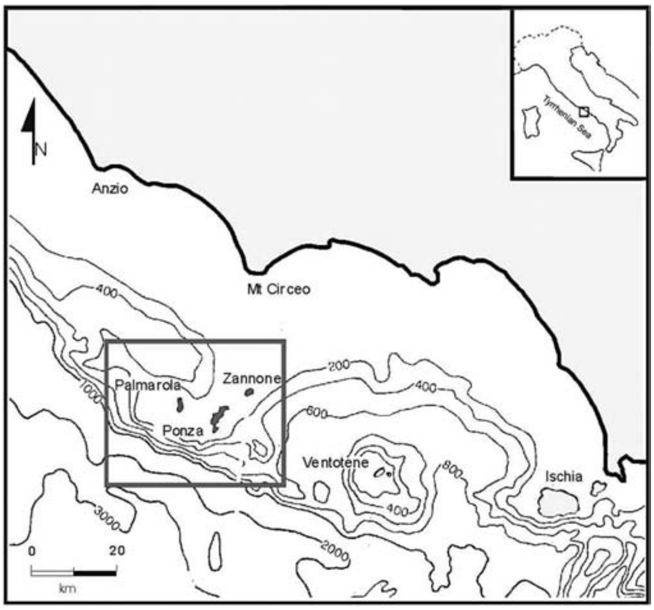

FIG. 2 - Location of the Pontine archipelago and of the Ponza, Zannone and Palmarola islands in the northern part of the archipelago.

Ponza is the largest of the Pontine islands. It mainly consists of submarine volcanic rocks exposed largely in the central and northern parts of the island. Submarine volcanic rocks of Ponza are the result of hyaloclastic fragmentation that occurred during extrusion of rhyolitic lava domes when magma contacted with sea water. The submarine volcanic rocks include hyaloclastite and coherent dikes that were emplaced when the hyaloclastite carapace became thick enough to protect the melt from direct contact with the water. The hyaloclastite carapace was subjected to thermal contraction and fractured in radial and concentric patterns (de Rita & *alii*, 2001).

Besides hyaloclastite and dykes, at Ponza mass slide deposits are present, including both large volume of sub-horizontal bedded sandstones and smaller volume of thick, massive and chaotic deposits associated with U-shaped channels (fig. 3a). These reworked deposits are related to the growth rate of the domes, reflecting periodic collapses that maintained equilibrium between height and radius of each single dome (fig. 3b; de Rita & *alii*, 2001). The rapid quenching due to the contact between magma and sea-water favoured the rapid vertical growth of the domes, whereas, the particulate nature of the hyaloclastite cara-

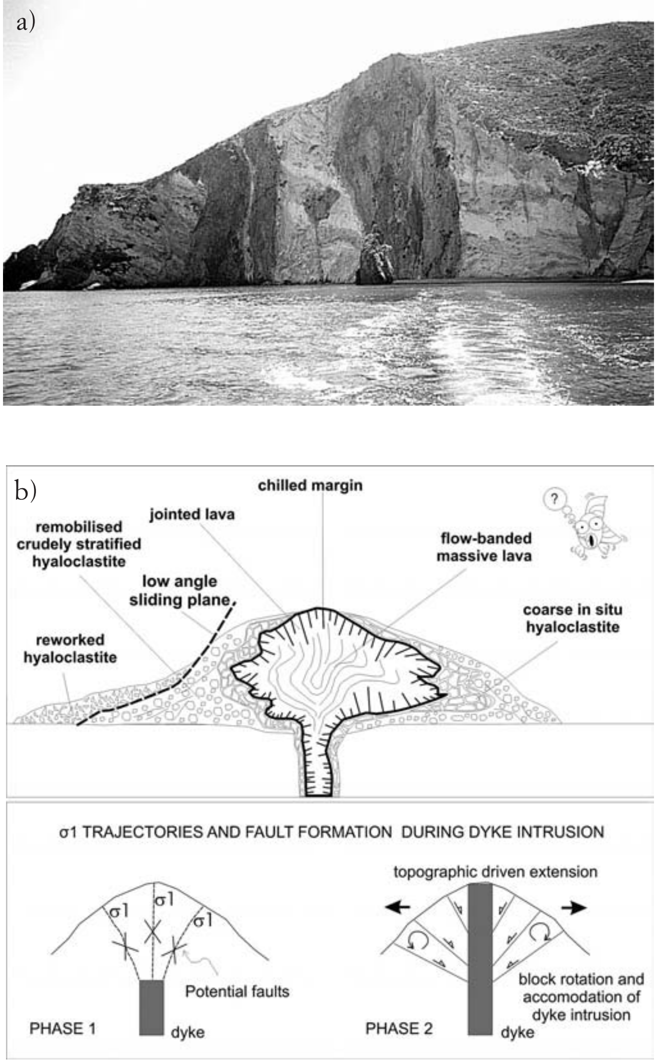

FIG. 3 - Volcano instability features in submarine domes. a) Ponza islands, Cala del Core locality. Along the cliff, hyalocalstites (white) and dykes (black) are exposed. In the hyaloclastite deposits, lenses of mass slide deposits are confined in small sized U-shaped channels. Reworking occurred during the growth of the domes, for remobilization of hyaloclastites during periodic collapses that maintained equilibrium between height and radius of each single dome. b) Schematic model illustrating the growth of submarine domes with relative hyaloclastite facies, and the orientation of local stresses during dyke intrusion.

FIG. 4 - Ponza, Cala dell'Acqua locality. Low-angle plane along which hyaloclastites gravitationally slid down.

pace, together with the submarine environment, prevented their excessive vertical growth: large slides of hyaloclastite moved along low angle planes (fig. 4) to restore morphological equilibrium of the dome, as soon as the vertical growth of the dome exceeded a gravity stability threshold depending on the thickness and coefficient of internal friction of the hyaloclastite carapace. This process might have lasted for hundreds to thousand of years according to observed dome-forming eruptions. Several features recognised recall those typical of DGSD: a) the large volume of rocks usually involved; b) the presence of small-scale landslides and debris flows; c) the deformational pattern deduced by the analysis of fracture and fault plane orientation that is mainly related to the local stress induced by magma intrusion and may be interpreted as the result of the interplay of progressive injection of magma into hyloclastite, and of gravitational stress (de Rita & *alii*, 2001).

North east of Ponza is Zannone island. The island represents a single submarine cryptodome that during its emplacement uplifted and tilted the sedimentary units of the basement (fig. 5). Evidences are the sub-vertical dip of the Triassic dolomites (Unità di Capo Negro, de Rita & *alii*, 2004), their basal contact with the underlying sedimentary Triassic units that is through a low angle extensional fault, the presence of slickensides due to gravitational interbed movements in the flysch units, in general the anomalous contact between sedimentary units that cannot be explained in term of structural deformational stress and finally the morphological features recognizable along the northern cliff of Zannone.

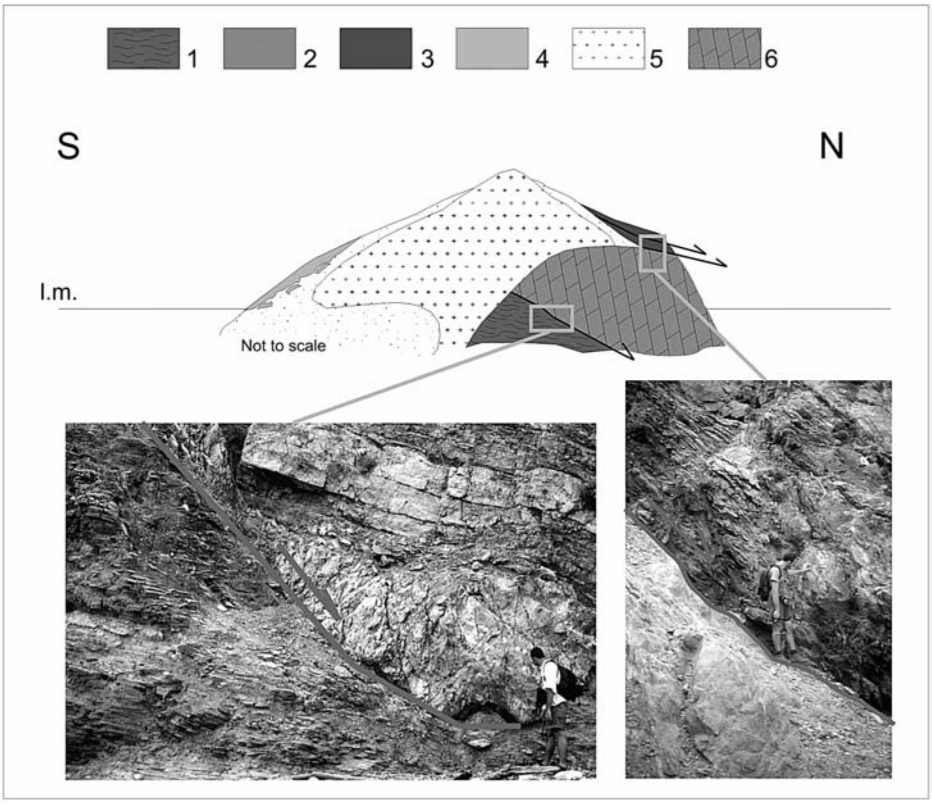

FIG. 5 - Schematic geological model of Zannone island. The two photos show the anomalous structural contacts along low-angle extensional planes (in red) between the units of the sedimentary basament. 1. Triassic dolomites and limestones. 2. Messinian or Pliocene clayey sediments. 3. Miocene siliciclastic units (flysch). 4. Massive clast supported hyaloclastites. 5. Aphanitic to porphric dyke. 6. Upper Cretaceous marls and limestones.

Even in the Zannone case, due to the old age of the island, the morphological features usually related to the DGSD are not easily recognizable. Nevertheless, the role played by gravity, the large rock volume involved in the slides, the fact that the deformation affected large thickness and length of the northern hill slope may all be considered elements indicative of DGSD.

The Roccamonfina volcano

Roccamonfina volcano is located at the northern margin of the NE-trending Garigliano graben (fig. 6). De Rita & Giordano (1996) suggest that the most important episodes in the volcano's history (630-50 ka) have been controlled by tectonic activity associated with the graben's master-faults. Roccamonfina volcano comprises two main parts: a strato-volcano developed inside the graben, and a complex of centres developed on the south-eastern horst. The summit of the strato-volcano is truncated by a horseshoe shaped caldera (dimensions 6.5 km by 5.5 km) with the longest axis trending NW. The caldera opens towards the SE along NE-trending faults, which belong to the same system as the graben faults. Some authors (Chiesa & *alii*, 1985; Cole & *alii*, 1992) related the caldera to ignimbrite eruptions (Brown Leucititic Tuff [BLT] or Campagnola Tuff ignimbrites), even if Chiesa & *alii*, (1985) suggested that the shape of the caldera could be caused by the mechanism of lateral sector collapse toward the east. They supported the hypothesis with data from a deep borehole (Watts 1987; Ballini & *alii*, 1989) drilled at the geometrical centre of the caldera, which encountered the base of the volcanic products at the same depth as in the surroundings, indicating no subsidence. The borehole encountered a layer of juvenile-free breccia (Ballini & *alii*, 1989) that was interpreted as the co-ignimbrite breccia of the BLT (Watts, 1987). De Rita & Giordano, (1996) demonstrated that caldera collapse was not related to explosive eruptive events emplacing ignimbrites but it probably occurred as a mechanical re-adjustment to the high extension rate of the Garigliano graben

FIG. 6 - Location of the Roccamonfina volcano in the Garigliano Graben (Southern Italy). The horseshoe-shaped caldera of the volcano, opened toward West, is visible.

during a climax of the regional tectonism at around 400 ka. The present elliptical shape of the collapsed area is due to the superposition of a linear NE-trending graben structure to the east, and a sector collapse toward the west. The breccia is interpreted in this case as the expression of the lateral collapse of the volcano caused by tectonic activity (fig. 7). Also in this case we may recognize many aspects related to the DGSD. The morphological horse-shoe shaped feature, the presence of the related chaotic breccia, the volume of failed material, estimated to be in the range of 17-20 km^3 (De Rita & Giordano, 1996) suggest that Roccamonfina volcano was subjected to gravitational instability and that the summit of the volcano slid along pre-existing volcano-tectonic tangential discontinuities.

Panarea volcanic complex

Panarea Volcanic Complex (PVC) is part of the Aeolian volcanic arc (Southern Italy) and is located 20 km southwest of Stromboli and 25 km northeast of Lipari and Vulcano islands (fig. 8). The subaerial portion of the PVC is constituted by the island of Panarea (the smallest of the Aeolian Archipelago: 3.3 km^2) and a group of minor islets: Basiluzzo, Lisca Bianca, Dattilo, Bottaro, Lisca Nera, Panarelli and Le Formiche. The islands rise from a flat shallow submarine platform that constitutes the top of a huge cone-shaped volcanic edifice whose basal diameter reaches 20 km at a depth of 1500 m below sea level (Gabbianelli & *alii*, 1990; Romagnoli, 1990).

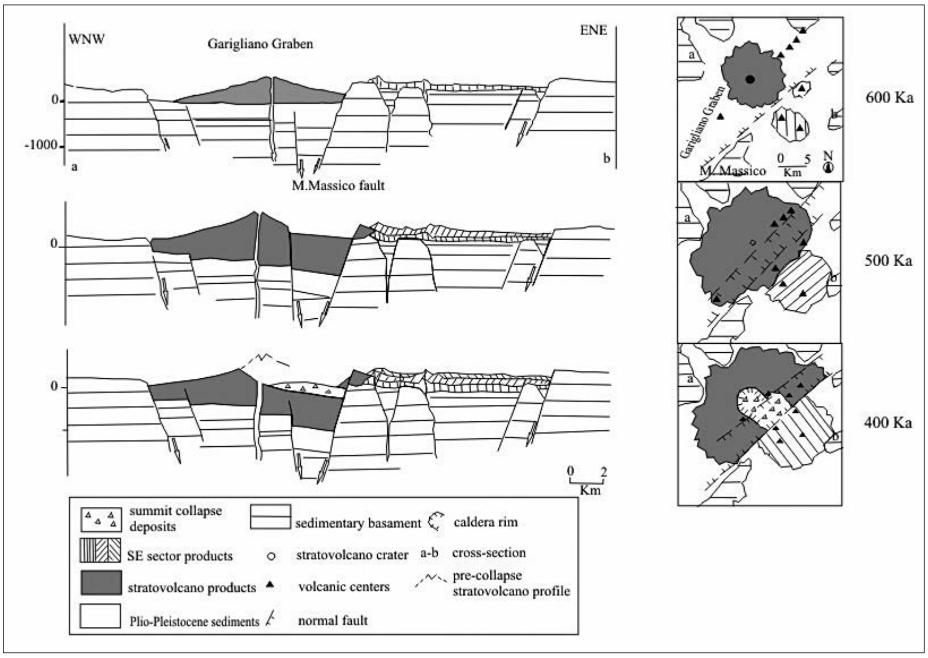

FIG. 7 - Schematic model of the Roccamonfina volcano evolution (after de Rita & Giordano, 1996, modified). 600 ka: growing of the strato volcano inside the Garigliano graben. 500 ka: the eastern flank of the volcano is continuously downthrown by activity of the Mount Massico and associated antithetic faults. 400 ka: gravitationally controlled flank collapses of the volcano at the climax of regional extension.

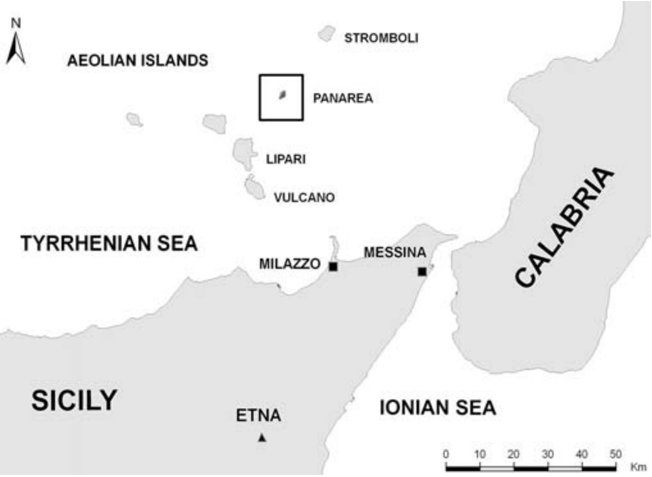

FIG. 8 - Location of the Panarea island in the Aeolian Archipelago, Southern Italy.

Panarea is formed by several wedge-shaped lava lobes, bounded by sub-radial fractures developed during the dome growth as consequence of relatively high effusion rate, low cooling rate and low yield strength (Fink & Griffith, 1998). The dome volume (0.46 km^3) is within the range of lava volumes emitted during relative long-lived domes eruptions (Cimarelli & *alii*, 2008). Despite its roughly circular symmetry, Panarea displays gentle sloping eastern flanks and a western steep cliff along which the inner core of the dome is exposed. This suggests that the dome could have experienced volcanic collapses along the western sector.

We have analyzed in detail the morphological features of the western cliff by obtaining a DTM from two pairs of overlapping vertical digital aerial photographs (Cimarelli, 2006, 2007)

The island of Panarea has a roughly elliptical shape whose major axis is NNE-SSW oriented. Along this direction runs the main water divide (Castello di Salvamento - Punta del Corvo - Costa del Capraio) which separates two morphologically distinct slopes. The western slope consists of a steep rocky cliff (slope range 50-87°) that is carved by numerous linear incisions that reach sea level. The evolution of this slope is mainly due to erosion by rock falls and in a minor way to deposition of blocks along the narrow erosive gullies. In the sector between Grotta del Tabacco and Punta Scritta, field analysis shows that main ridges along the slope coincide with dykes crosscutting most of the volcanic succession exposed along the cliff. From the DTM analysis is evident the concentration of ridges in the sector of Castello di Salvamento. Counter-sloping triangular facets perpendicular to the direction of the ridges break their continuity in the sector of Cala Bianca (fig. 9).

Triangular facets display NNW strike and a constant ENE plunge, isolating along the slope a set of trenches parallel to the ridge crest of Castello di Salvamento - Punta del Corvo. These lineaments tend to disappear further south along the slope of Costa del Capraio. There is a good correspondence between directions of these morpholineaments and directions of fractures measured along the coast at Cala Bianca. Most likely these lineaments correspond to a set of fractures contemporaneous with or later than the emplacement of the dykes. These kinds of morphological features resemble those usually associated in literature to Deep-seated Gravitational Slope Deformations (DGSD) and among them to those known as «sackungs» (Zischinsky, 1966).

Although several features along the western cliff of Panarea are similar to those observed in DSGD, we must remark that the mass of rock involved at Panarea is much smaller than that usually involved in DGSD. However the sector affected by the deformation along the cliff is about 1 km long and its surface covers 51.000 m^2. The total volume of involved rocks is of the order of·10^7 m^3 (10^{-2} km^3). This volume takes into account the portion of rocks outcropping above the sea level and limited to the east by the Punta del Corvo-Costa del Capraio summit ridge (fig. 10). We approximated the Punta del Corvo-Costa del Capraio ridge as a vertical plain, in order to obtain a rough esti-

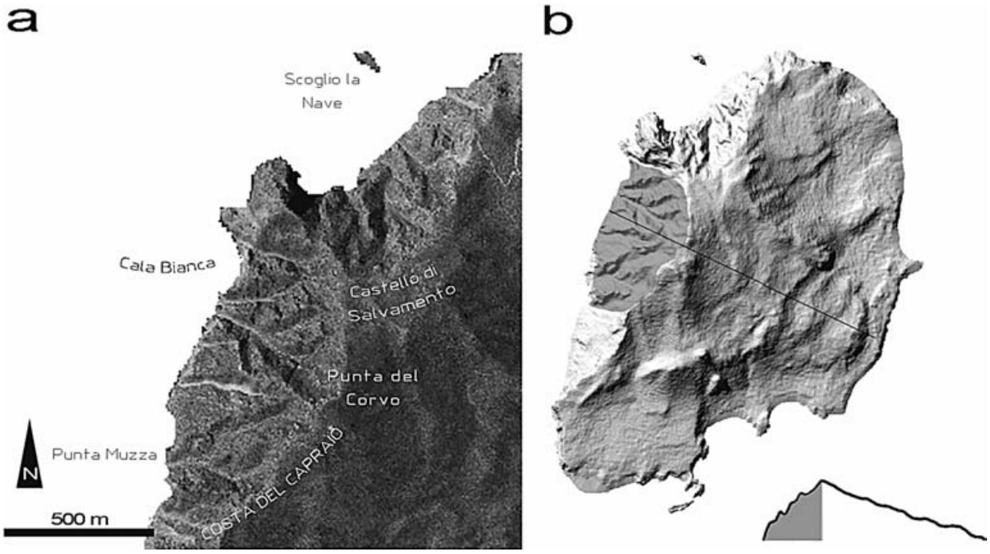

FIG. 9 - a) Dykes forming ridges along the western cliff of the Panarea island, at Castello di Salvamento locality. Parallel trenches on the slope at Cala Bianca are indicated by allignments of counter-sloping triangular facets; b) extension of rock mass involved in the slope deformation, shown in gray.

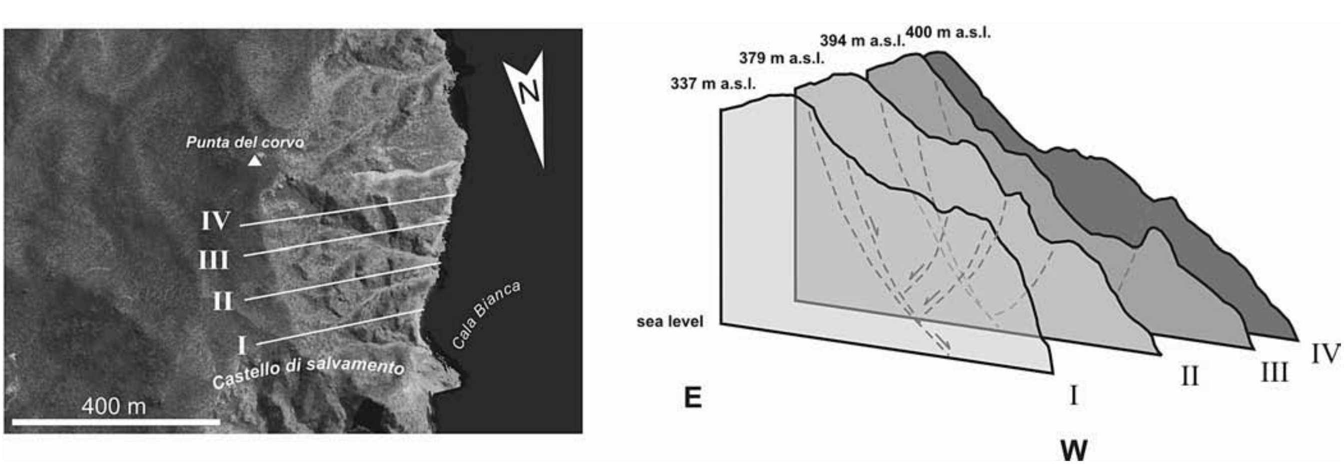

FIG. 10 - Topographic profiles of the western cliff and structural interpretation of counter-slope trenches.

mate of the total volume of rock involved in the deformation. Being the DGSD most likely to occur as creep movement or flow of material along a variably inclined zone of deformation (or along a discrete slip plane), the volume of rock calculated to be involved in the deformation at Panarea must be considered as an end-member overestimation.

Other important features on the western cliff of Panarea fit the characteristics of «sackungs» structures: a) the morphological aspects of the cliff; b) the evident tectonic control; c) the vertical tectonic and volcano-tectonic mobility that characterizes the Aeolian archipelago and the Calabrian Arc in general; d) the state of alteration and fracturing of the rocks involved in the deformation in particular in the hyaloclastites outcropping at the base of the slope.

Concerning the existence of deposits related to the collapse, our information about the submerged platform is not detailed enough to either confirm or exclude the presence of hummocky morphologies. In fact, DEM of the submerged portions has a resolution of 30x30 metres/pixel, which means that blocks must exceed at least 60x60 metres in dimension to be detected. Moreover the debris could have overflowed the shelf-break, leaving no remarkable morphology on the platform. High-resolution seismic profiles don't cover the key sectors, but provide interesting data on the submerged marine terraces along the western coast of Panarea (Chiocci & Romagnoli, 2004). The presence of two orders of submerged marine terraces along the western sector testify to the huge amount of remobilised sediment available on this portion of the platform during relative vertical movement of the apparatus. Unfortunately we have no constraints on the age of these sedimentary cycles that are generally referred to the late Quaternary (Chiocci & Romagnoli, 2004). Another interesting feature of these terraces is the delta-shaped bulge just offshore of Cala Bianca. Such a morphology could be attributed to the presence of a buried fan-shaped deposit of collapsed material. Moreover a N-S oriented section of the seismic profile, acquired offshore the Cala Bianca sector, displays a series of diffraction hyperbolae. Deplus & *alii*, (2001) and Le Friant et alii, (2002) found similar seismic diffraction effects in the seismic profiles along the submarine debris avalanche deposits of Martinique and Dominique islands in the French Lesser Antilles. The Authors interpreted these seismic diffractions as due to the presence of lava mega-blocks in the debris avalanche deposits.

However, we cannot exclude the possibility that such seismic diffractions could have been caused by the presence of deep canyons along the PVC slope.

CONCLUSIONS

Most of the Italian volcanoes, active, quiescent or dormant, show distinctive horseshoe-shaped craters opened at one end that may be classified as DGSD. Some of them are well known, as in the case of the Sciara del Fuoco of Stromboli volcano or the Valle del Bove of Etna; some others have received less attention due to their state of preservation. In this paper we described different types of deformational features affecting some Italian volcanoes that show affinities with the DGSD. In the case of the Ponza and Zannone islands in the Pontine Archipelago, these features may be related to local stress induced by magma intrusion. At Ponza they may be interpreted as the result of the interplay of progressive injection of magma into hyaloclastite, during the growth of submarine domes, and gravitational stress. At Zannone, a submarine cryptodome during its emplacement uplifted and tilted the sedimentary units of the basement provoking the gravitational sliding of some sedimentary units that now appear in anomalous structural contact.

At Roccamonfina (Southern Italy), the summit of the strato-volcano is truncated by a horse-shoe shaped caldera. We suggest that the volcano was subjected to gravitational instability and that the summit of the volcano slid along pre-existing volcano-tectonic tangential discontinuities whose aspect are similar to those of DGSD.

Finally, at Panarea in the Aeolian archipelago, along the western steep cliff of the island, the inner core of the dome is exposed. This suggests that the dome could have experienced volcanic collapses along the western sector. The detailed analysis of the western cliff has evidenced morphological features resembling those usually associated in the literature with Deep-seated Gravitational Slope Deformations (DGSD) and among them to those known as «sackungs», even if the mass of rock involved at Panarea is much smaller than that usually involved in DGSD. Evidences of DGSD are considered to be: a) the morphological aspects of the cliff; b) the evident tectonic control; c) the vertical tectonic and volcano-tectonic mobility that characterizes the Aeolian archipelago and the Calabrian Arc in general; d) the state of alteration and shattering of the rocks involved in the deformation in particular in the hyaloclastites outcropping at the base of the slope.

The recognition of DGSD even in volcanic setting suggests that these morphological features are essentially due to gravity with less influence of the triggering causes. Essential element for DGSD development seems to be the high rate of uplift with respect to a threshold value determined by the equilibrium with the gravitational stress.

Dimensions of the deformational structures and the volume rock involved may depend on the rate of uplift and nature of the material.

REFERENCES

AGLIARDI F., CROSTA G. & ZANCHI A. (2001) - *Structural constraints on deep-seated slope deformation kinematics*. Engineering Geology, 59, 1, 83-102.

AGNESI V., MACALUSO T., MONTELEONE S., PIPITONE G. & SORRISO VALVO M. (1978) - *Tipi e dinamica delle deformazioni gravitative profonde in relazione alle strutture geologiche. I casi di Monte Genuardo e di Scodello (Sicilia occidentale)*. Bollettino della Società Geologica Italiana, 108, 379-389.

BALLINI A., BARBERI F., LAURENZI M.A., MEZZETTI F. & VILLA I.M. (1989) - *Nuovi dati sulla stratigrafia del vulcano di Roccamonfina*. Bollettino del Gruppo Nazionale di Vulcanologia, 2, 533-555.

Calvari S., Tanner L.H. & Groppelli G. (1998) - *Debris-avalanche deposits of the Milo Lahar sequence and the opening of the Valle del Bove on Etna volcano*. Journal of Volcanology and Geothermal Research, 87, 193-209.

Chiesa S., Cornette Y., Gillot P.Y. & Vezzoli L. (1985) - *New interpretation of Roccamonfina volcanic history*. International Associacion of Volcanology and Chemistry of the Earth Interior, Sicily (abstract).

Chiocci F.L., Budillon F., de Alteriis G., Marani M., Gamberi F., Romagnoli C., Martorelli E., Bosman A., Cammaroto S., Cammarano D., Celia Magno M., Falese F.G., Imbe' G., Jacobs J.L., Wallace R.F., Matthew D. & Flewellen C. (1998) - *Prime immagini TOBI nei mari italiani. Rilievo sonar ad alta definizione e grande copertura di elementi geologici primari del Tirreno meridionale.* Atti del 49° Congresso della Società Geologica Italiana, Palermo, Settembre 1998.

Chiocci F.L. & Romagnoli C. (2004) - *I terrazzi deposizionali sommersi nelle Isole Eolie (Sicilia)*. Memorie Descrittive della Carta Geologica Italiana, 58, 81-114.

Chiocci F.L. & De Alteriis G. (2006) - *The Ischia debris avalanche: first clear submarine evidence in the Mediterranean of a volcanic island prehistorical collapse*. Terra Nova, 18, 202-209.

Cimarelli C. (2006) - *New geo-volcanological data on the evolution of Panarea Volcanic Complex and their implicationon volcanic hazard.* PhD thesis (Geodinamica - XVIII Ciclo) Università degli Studi Roma Tre. Unpublished.

Cimarelli C. (2007) - *New geo-volcanological data on the evolution of Panarea Volcanic Complex and their implicationon volcanic hazard.* Plinius, 33, 1-8.

Cimarelli C., de Rita D., Dolfi D. & Procesi M. (2008) - *Coeval strombolian and vulcanian-type explosive eruptions at Panarea (Aeolian Islands, Southern Italy)*. Journal of Volcanology and Geothermal Research, 177, 797-811.

Cole P.D., Guest J.E., Duncan A.M., Chester D.K. & Bianchi R. (1992) - *Post-collapse volcanic history of calderas on a composite volcano:an example from Roccamonfina, Southern Italy*. Bulletin of Volcanology, 54, 504-520.

Conte A.M. & Savelli C. (1994) - *Vulcanismo orogenico dell'isola di Ponza: rioliti calcalcaline ed evoluzione trachiti-comenditi di serie shoshonitica*. Memorie Descrittive della Carta Geologica d'Italia, 49, 333-346.

Deplus C., Le Friant A., Boudon G., Komorowski J.C., Villemant B., Harford C., Ségoufin J. & Cheminée J.-L. (2001) - *Submarine evidence for large-scale debris avalanches in the Lesser Antilles Arc.* Earth and Planetary Science Letters, 192, 145-157.

de Rita D. & Giordano G. (1996) - *Volcanological and structural evolution of Roccamonfina volcano (Italy): origin of the summit caldera.* In: McGuire W.J., Jones A.P. & Neuberg J. (Eds.), «Volcano Instability on Earth and other planets». Geological Society, special publications. 110, 209-224, London.

de Rita D., Giordano G. & Cecili A. (2001) - *A model for submarine rhyolite dome growth: Ponza Island (central Italy)*. Journal of Volcanology and Geothermal Research, 107, 221-239.

de Rita D., Fabbri M. & Cimarelli C. (2004) - *Evoluzione pleistocenica del margine tirrenico dell'Italia centrale tra eustatismo, vulcanismo e tettonica.* Il Quaternario, 17 (2/1), 523-536.

Dramis F. & Sorriso-Valvo M. (1994) - *Deep seated gravitational deformations, related landslides and tectonics*. Engineering Geology, 38, 231-243.

Fink J.H. & Griffiths R.W. (1998) - *Morphology, eruption rates, and rheology of lava domes: insights from laboratory models*. Journal of Geophysical Research, 103 B1, 527-545.

Gabbianelli G., Gillot P.Y., Lanzafame G., Romagnoli C. & Rossi P.L. (1990) - *Tectonic and volcanic evolution of Panarea (Aeolian Islands, Italy)*. Marine Geology, 92, 313-326.

Guest J.E., Chester D.K. & Duncan A.M. (1984) - *The Valle del Bove, Mount Etna: its origin and relation to the stratigraphy and structure of the Volcano.* Journal of Volcanology and Geothermal Research, 21, 1-23.

Guest J.E, Duncan A.M. & Chester D.K. (1988) - *Monte Vulture Volcano (Basilicata, Italy): an analysis of morphology and volcaniclastic facies.* Bulletin of Volcanology, 50, 244-257.

Le Friant A., Boudon G., Komorowski J.C. & Deplus C. (2002) - *L'île de la Dominique, à l'origine des avalanches de débris les plus volumineuses de l'arc des Petites Antilles* Geoscience 334, 235-243.

Lipman P.W. & Mullineaux D.R. [ed.] (1981) - *The 1980 Eruptions of Mount St. Helens: Washington, U.S.* Geological Survey Professional Paper 1250, Washington, D.C., 844 pp.

Kokeelar P. & Romagnoli C. (1995) - *Sector collapse, sedimentation and clast population evolution at an active island-arc volcano: Stromboli, Italy.* Bulletin of Volcanology, 57, 240-262.

McGuire W.J. (1996) - *Volcano instability: a review of contemporary themes*. In: W.J. McGuire, A.P. Jones & J. Neuberg (Eds.), «Volcanic Instability on Earth and Other Planets». Geological Society, London, Special Publications, 110, 1-23.

Moro M., Saroli M., Salvi S., Stramondo S. & Doumaz F. (2007) - *The relationship between seismic deformation and deep-seated gravitational movements during the 1997 Umbria-Marche (Central Italy) earthquakes*. Geomorphology, 89, 97-307.

Onida M. (2001) - *Deformazioni gravitative profonde di versante: stato delle conoscenze e progresso delle ricerche in Italia*. In: G. Pasquarè (Ed.), «Tettonica recente e instabilità di versante nelle Alpi Centrali». CNR - Istituto per la dinamica dei processi ambientali - Milano, 208, 35-73.

Pareschi M.T., Boschi E., Mazzarini F. & Favalli M. (2006) - *Large submarine landslides offshore Mt. Etna*. Geophysical Research Letters. 33, L13302, 5 pp.

Radbruch-Hall D., Varnes D.J. & Colton R.B. (1977) - *Gravitational spreading of steep-sided ridges («Sackung») in Colorado*. Journal of Research, U.S. Geol. Survey, 5, 359-363.

Radbruch-Hall D., Varnes D.J. & Savage W.Z. (1976) - *Gravitational spreading of steep-sides ridges («Sackung») in Western United States.* International Association for Engineering Geology Bulletin, 14, 23-35.

Rolandi G., Bellucci F. & Cortini M. (2004) - *A new model for the formation of the Somma Caldera*. Mineralogy and. Petrology, 80, 27-44.

Romagnoli C. (1990) - *Caratterizzazione morfostrutturale e vulcanologica sottomarina delle Isole Eolie (Tirreno Meridionale): ipotesi di stadi evolutivi dei complessi*. PhD Thesis Università di Bologna, 144 pp. Unpublished.

Saroli M., Stramondo S., Moro M. & Doumaz F. (2005) - *Combined techniques to detect large scale gravity-driven-phenomena movements: Northern Sicily case study*. Terra Nova, 17, 35-43.

Savage W.Z. & Varnes D.J. (1987) - *Mechanics of gravitational spreading of steep-sides ridges (sackung)*. International Association of Engineering Geology Bulletin, 35, 31-36.

Ter Stepanian G. (1966) - *Type of depth creep of slopes in rock masses*. Problem Geomeh, 3, 49-69.

Tibaldi A. (2001) - *Multiple sector collapses at Stromboli volcano, Italy: How they work.* Bulletin of Volcanology, 63, 112-125.

Tibaldi A., Rovida A. & Corazzato C. (2004) - *A giant deep-seated slope deformation in the Italian Alps studied by paleoseismological and morphometric techniques*. Geomorphology, 58, 27-47.

Van Wyk de Vries B. & Borgia A. (1996) - *The role of basament in volcano deformation*. In: McGuire W.J., Jones A.P. & Neuberg J. (edits), «Volcano Instability on Earth and other planets». Geological Society of London, Special Publications, 110, 95-110.

Varnes D.J,. Radbruch-Hall D. & Savage W.Z. (1989) - *Topographic and structural conditions in area of gravitational spreading of ridges in the western United States*. U.S. Geological Survey Professional Paper, 1496.

Watts M.D. (1987) - *Geothermal exploration of Roccamonfina volcano, Italy*. Geothermics 16, 517-528.

Zischinsky U. (1966). - *On the deformation of high slopes.* Proceedings of the first Conference International Society of Rock Mechanics, Lisbon, 2, 179-185.

(Ms. received 30 April 2010; accepted 30 October 2010)