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A PHYSICALLY-BASED SCALE APPROACH TO THE ANALYSIS OF THE CREEP PROCESS INVOLVING MT. GRANIERI (SOUTHERN ITALY)

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ABSTRACT

In January 1972, a rock slide of more than 2 million m^3 moved along the north-eastern slope of Mt. Granieri (900 m above sea level), in the Allaro River basin, close to Salincriti village (Calabria region, southern Italy). Subsequent field investigations (geomechanical surveys and laboratory creep tests on rock samples) validated the initially assumed ongoing "retrogressive" evolution of the phenomenon, which is mobilising a rock mass volume of about one million m^3. Data from a remote monitoring system (2 stationary inclinometers at different depths + 1 piezometer) and topographic surveys helped improve the understanding of these slope instabilities. Collected data were used to test a physically-based spatio-temporal approach permitting to scale up laboratory creep test results to the deformational processes of natural slopes. The study assessed whether a time-dependent phenomenon, already at a tertiary-creep stage, was responsible for the deformational processes observed at Mt. Granieri, whose morphological evidence was both reported in the literature about its historical landslides and visible in the topmost portions of the slope. Quantitative analysis of laboratory curves, scaled up to the natural process, made it possible to: i) confine tertiary-creep deformations to the topslope and to the first 300 m from the surface; ii) ascribe tertiary-creep deformations at Mt. Granieri to a highly altered portion of granites and to an underlying poorly altered one, and iii) demonstrate that deformations of the portion of the slope located a few hundreds of metres from the valley floor were dependent on a stationary (secondary-stage) creep process.

Key word: *rock mass creep, physic-analogical modelling, gravitational deformations*

INTRODUCTION

Deep-seated gravitational slope deformations (DSGSDs), associated with time-dependent rock mass behaviours, are widely documented in the Apennine chain, where rigid and ductile materials having a different rheological behaviour are juxtaposed (Nemcok & Baliak, 1977; Canuti *et alii*, 1990; Conti & Tosatti, 1993; Esposito *et alii*, 2007; Bozzano *et alii*, 2008; Bozzano *et alii*, 2013). The southern Calabria Apennines have still active tectonic uplifts of Pleistocene-Holocene age; in this sector, DSGSDs are the result of both an intense morphological evolution, due to subaerial erosion, and of geomechanical conditions with slope-scale effects, e.g. advanced alteration of rocks making up the local crystalline-metamorphic bedrock. Numerous studies have stressed the role of altered granitic rocks as a triggering factor for gravity-induced slope deformations, which can evolve into large landslides (Genevois & Prestininzi, 1979a; Genevois & Prestininzi, 1979b; Prestininzi, 1984; Pel-

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legrino, 2000; Martino *et alii,* 2004; Barrese *et alii* 2006; Pellegrino & Prestininzi, 2006; Pellegrino, *et alii,* 2008). Understanding the processes governing the evolution of slopes is crucial to investigating their stability and DSGSDs acting over a wide spatio-temporal scale (Maffei *et alii*, 2005). These deformations are generally supposed to obey time-dependent deformation laws and to undergo different evolutionary stages, expressed by continuous creep-induced deformations. A geological-evolutionary model of the slope, combined with targeted studies (e.g. lab tests and modelling), may help gather quantitative data on geomorphology and stress-strain behaviour of the affected materials (Maffei *et alii*, 2005).

The analysis described in this paper was carried out on the Mt. Granieri slope (southern Calabria, Italy), which is involved in a large-scale deformational process affecting considerable volumes of the Palaeozoic crystalline-metamorphic bedrock. The main objective of the study was to analyse and gain more insight into the time-dependent behaviour of rock masses and, under an experimental approach, to scale up the results of creep tests carried out on specimens from the investigated area to the overall slope. A physically-based spatio-temporal scale approach was thus developed and applied to laboratory data, with a view to determining the creep stages that the rock mass had reached in different sectors of the slope.

GEOLOGICAL AND GEOMORPHOLOGICAL FEATURES

Mt. Granieri is located on the Ionian side of the Serre Calabresi massif, in the middle-upper portion of the Allaro River basin (Figs 1 and 2), extending for about 130 km^2. The slope is roughly NW-SE-trending, with elevations of up to 1,000 m above sea level (asl) and a height from the valley floor, where the Allaro River flows, of about 800 m (Fig. 2). The slope is made up of crystalline lithotypes, forming a granitic intrusive complex (Permian-Carboniferous, Bonardi *et alii*, 1984) in its middle-lower portion and a metamorphic one (Carboniferous?-Devonian-Silurian?) in its upper part. Granites and granodiorites outcrop at an average elevation of 215 to 700 m asl. The remaining 300 m consist of: i) a metamorphic transitional belt, which represents a contact zone, with a thickness of 20 to 50 m (heat-metamorphosed biotitic schists) and contact metamorphism of medium-low grade, and ii) biotitic schists, exposed in the topmost portions of the slope (Pellegrino, 2000; Barrese *et alii,* 2006; Pellegrino & Prestininzi, 2006; Pellegrino *et alii*, 2008). The heat-metamorphic contact and the overlying biotitic schists accommodate pegmatitic and/or hydrothermal intrusions, associated with sulphide mineralisations (Bonardi *et alii*, 1982). Stratigraphic relations between crystalline-metamorphic units are highly disturbed by some NW-SE-trending tectonic lines having a dominantly left-lateral strike-slip movement and a weak extensional component (Pellegrino, 2000; Pellegrino *et alii*, 2008). All of the above crystalline-metamorphic lithotypes have been experiencing diffuse and intense physico-chemical alteration processes. The latter processes are concentrated along metamorphic-aureole belts, as highlighted by multiple studies conducted in the Mt. Granieri area (Genevois & Prestininzi, 1979a; Genevois & Prestininzi, 1979b; Prestininzi, 1984; Pellegrino, 2000; Martino *et alii*, 2004; Barrese *et alii* 2006; Pellegrino & Prestininzi, 2006; Pellegrino *et alii,* 2008; Raman Y.V & Gogte B.S., 1982). Four different stages of alteration were identified for the above lithotypes. Genevois & Prestininzi (1979b) characterised the different states of alteration of the Mt. Granieri

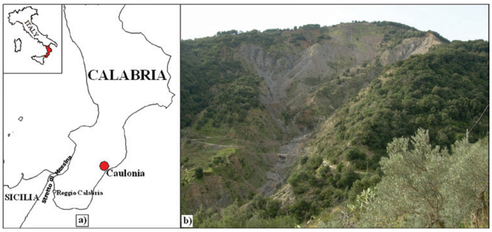

Fig. 1 - a) location of the study area and b) north-eastern slope of Mt. Granieri, where the area of detachment of the 1972 landslide at the top of the slope is visible

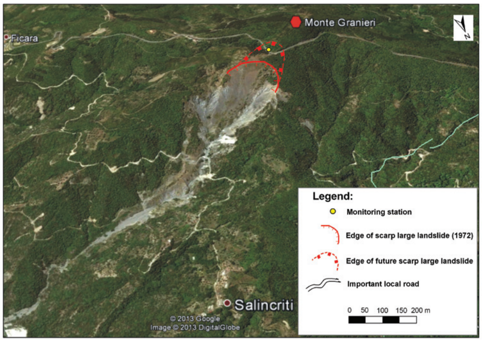

Fig. 2 - Upslope evolution of the large 1972 landslide, with the position of the future scarp

granites by using an alteration index (Ia%), i.e. the ratio of altered feldspars to total feldspars. Moreover, a flow of hydrothermal water with very low pH was observed to control the distribution of Ia% (PRESTININZI, 1984, BARRESE *et alii,* 2006). This control is witnessed by plenty of surface features, such as a number of acidic-pH (4.5<pH<5) springs located at the contact between the basal crystalline terms and the overlying metamorphic ones (PELLEGRINO & PRESTININZI; 2006). The sectors of the granitic mass most affected by alteration lie close to the heat-metamorphic contact aureole, where highly or completely altered materials are found.

The predisposing factors for the DSGSD of Mt. Granieri are: geological setting of the slope, occurrence of a rock mass at different stages of physico-chemical alteration, regional uplift and incision by the Allaro stream, which took place in successive steps. The DSGSD may be attributed to a sackung process (ZISCHINSKY *sensu*, 1969) associated with large landslides (e.g. the one of 1972 at the topslope) (PRESTININZI, 1984; PELLEGRINO, 2000), which accompanied the more extensive deformational phenomenon (GENEVOIS & PRESTININZI, 1979a). Kinematic indicators are distributed along the different sectors of the slope. The top of the slope is potentially unstable. It has a marked sackung (ZISCHINSKY, 1969) and consequent double crest, i.e. the edge of the potential landslide scarp (Fig. 3). The middle portion shows, instead, reverse slope conditions (Piana di Monte Granieri plain), intensely fractured areas due to concentration of shearing stresses, concave-convex morphologies not related to landslide debris (PELLEGRINO, 2000; MARTINO *et alii,* 2004; PELLEGRINO & PRESTININZI, 2006) (Fig. 2b)

Fig. 3 - a) Top of the Mt. Granieri slope. The arrow points to the double crest, visible in the upper part of the relief, where the future landslide scarp will be located; b) Rupture surface (and related detail) along the internal Caulonia-Nardo di Pace provincial road. On the right-hand side, the monitoring station whose location is shown in Fig. 2

PLIO-PLEISTOCENE EVOLUTION OF THE MT. GRANIERI SLOPE

The evolutionary model of the north-eastern slope of Mt. Granieri was reconstructed via geomorphological analysis of different topographic sections transversal to the Allaro River valley. Records of subhorizontal flat surfaces, located at comparable elevations on the slopes of both the left and right banks of the stream, were interpreted as river strath terraces (*sensu* GARCIA, 2006). These terraces may have been built during different phases of standstill in the Allaro River erosional activity. Given their topographic elevations, the Allaro River strath terraces correlate with multiple orders of marine terraces along the Ionian coast of Calabria and on the Aspromonte massif (MIYAUCHI *et alii*, 1994). In more detail, the strath Allaro River terrace at an elevation of about 620 m asl correlates with the 3rd-order marine terrace (estimated date: 1000 ka). The strath Allaro River terrace at about 510 m asl correlates with the 4th-order marine terrace (estimated date: 950 ka). This surface may also correlate with the terrace underlying the small town of Gerace (Calabria), about 20 km south of the investigated area, and consisting of calcarenites, sandstones and sands supposedly belonging to the Mt. Narbone formation (BOZZANO *et alii,* 2010). The strath Allaro River terrace at about 450 m asl correlates with the 5th-order marine terrace (estimated date: 900 ka). The strath Allaro River terrace at about 380 m asl correlates with the 6th-order marine terrace (estimated date: 400 ka). Finally, the strath Allaro River terrace at about 300 m asl correlates with the 7th-order marine terrace (estimated date: 300 ka). This surface can thus be correlated with the Caulonia terrace, a transgressive conglomeratic body resting on the complex Argille Varicolori formation (PRESTININZI, 1995).

Based on the above data, the following assumption about the evolution of the slope was formulated. In the time interval from 1000 to 950 ka, the Allaro River must have incised the valley floor by about 100 m. Subsequently, a hiatus in the erosional process gave rise to the surface lying at roughly 510 m asl. In this stage, stream deepening is likely to have involved also the terms of the metamorphic aureole, which are now exposed on the slope at an elevation of 640 to 600 m asl. The process of incision of the valley resumed in the time interval from 950 to 900 ka, causing a further deepening of about 60 m. A new break in the erosional process thus formed the surface located at 450 m a.s.l. The erosional activity of the stream resumed in the time interval from 900 to 400 ka, when a new deepening (of about 70 m) occurred. This long timespan of about 500 ka must have been associated with other erosional and depositional cycles, whose morphological records were subsequently obliterated. A further standstill must have caused the formation of the surface located at 380 m asl, which was subsequently incised in a period of at least 300 ka, giving rise to the surface at about 300 m asl. In the period elapsed from 300 ka to the present, the Allaro River further downcut its bed, reaching its current elevations (about 210 m asl in the investigated sector). Figure 4 graphically depicts the reconstructed evolutionary model. The figure shows the breaks in stream incision, correlating with the terrace orders reported by MIYAUCHI *et alii* (1994) for the Serre Calabresi area.

METHODS

LABORATORY CREEP TESTS

Previous studies on the deep-seated gravitational deformation of Mt. Granieri (GENEVOIS & PRESTININZI, 1979b) stressed the role of mass rock creep affecting the slope. More specifically, the above-cited study was focused on the interaction between extent of alteration and visco-plastic behaviour of the deformed granitic mass. The study relied on a set of creep tests on granitic rock specimens collected from the slope; the specimens had different states of alteration, expressed by the alteration index, i.e. the ratio of altered feldspars to total feldspars (Ia%). The sampled alteration classes were considered to represent the different states of alteration of granite and the curves were built under different constant stresses σ_{app}, applied as a percentage of the UCS σ_0 on the related specimen. The laboratory-scale curves built by GENEVOIS & PRESTININZI (1979b) are reported in Figure 5. The time-dependent behaviour of the specimens shows an instantaneous elastic deformation, a primary-creep portion with a decrease of the strain rate vs. time, a secondary-creep portion with an almost constant strain rate and, depending on the percentage of stress applied, a tertiary-creep portion with an accelerated strain rate, especially under stresses close to the UCS. Tab. 1 summarises the main physical and mechanical properties of the tested specimens.

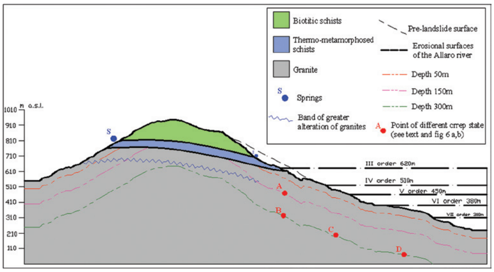

Fig. 4 - *Evolutionary-geological model of the Mt. Granieri slope, highlighting the elevations of the strath Allaro River terraces, which can be correlated with the marine terrace reported by* MIYAUCHI *et alii., 1994 for the Serre Calabresi area*

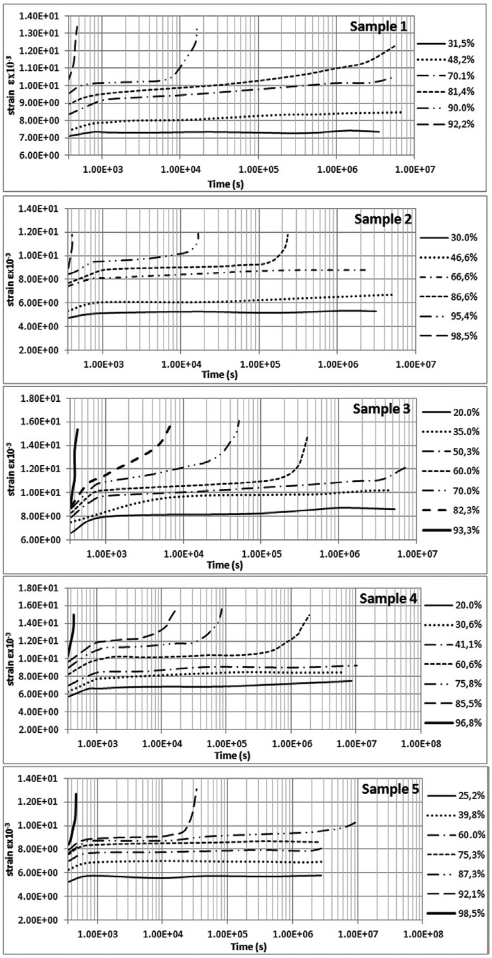

Fig. 5 - *Laboratory creep curves for different states of alteration at different percentages of UCS. As shown in Table 2, the most altered classes are those of specimens 3 and 4; specimens 5, 2 and 1 have gradually lower states of alteration (*GENEVOIS *&* PRESTININZI*, 1979b)*

SCALING OF CREEP CURVES

The study experimented the scaling up of laboratory results to the actual slope, by transposing the creep tests conducted by Genevois & Prestininzi, 1979b to a spatio-temporal scale comparable to the one of the actual slope.

The scaling approach resorted to the same relations as those used for small-scale physico-analogical models of geological processes (Hubbert, 1937; Ramberg, 1981; Middleton & Wilcock, 1994; Bretschneider, 2010; Bozzano *et ali*i, 2013). Creep curves were thus scaled by using dimensional equations based on the relations between the scaled system and the real prototype. In particular, the scaling consisted of two steps: step 1 - spatial upscaling (scaling of geometric dimensions) to define the stress scale ratio; step 2 - temporal upscaling through the stress scale ratio and the viscosity scale ratio.

Stress scaling was derived from the following dimensional relation:

$$\sigma^* = \rho^* \cdot g^* \cdot l^*$$

where: σ* is the stress ratio, g* is the gravity ratio (g=1), l* is the length ratio (ratios of scaled system to real prototype).

Additionally, laboratory curves were scaled by assuming three different geometric scale factors, in order to take into account the involvement of a rock mass within 300 m of depth (kinematically consistent with ongoing deformations with respect to the geometry of the present slope). The original length of the specimen (5.4 cm on average) was scaled up to three different rock mass thicknesses (50, 150 and 300 m, respectively) (Fig. 3), resulting into three scaled-up geometric dimensions, varying with the depth and thickness of the rock masses considered. These dimensions made it possible to apply the laboratory-tested rheological behaviour to portions of the slope with different dimensions.

Sample	γ_n (kN/m^3)	σ_c (MPa)	η (Pa·s)	Ia (%)
1	26.2	119.2	1.7×10^{11}	13
2	26.7	123.5	1.4×10^{11}	25
3	25.6	66.8	6.3×10^{10}	55
4	25.4	56.5	8.2×10^{10}	44
5	26.1	92.1	1.1×10^{11}	36.9

Tab.1 - Main physical and mechanical properties of samples with different states of alteration analysed by Genevois & Prestininzi (1979b)

	Laboratory specimens	Natural slope	Ratio
ρ* (kg/m^3)	2610	2665	0.98
g* (m/s^2)	9.81	9.81	1
L* (m)	0.054	50	1.08×10^{-3}
σ* (Pa)			1.06×10^{-3}
η* (Pa·s)	1.11×10^{11}	2.68×10^{21}	4.14×10^{-11}
ε* (1/s)			3.91×10^{-8}
t* (s)			2.55×10^{7}

Tab. 2 - Example of computation of the scale ratios for alteration class 5 at a depth of 50 m

The subsequent processes were the temporal upscaling of laboratory creep tests on granite specimens with different extent of alteration, and the viscosity scaling.

In this case, the dimensional relations were as follows:

$$\sigma^* = \eta^*/\varepsilon^* \text{ and } t^* = 1/\varepsilon^*$$

where σ* is the stress ratio, η* is the viscosity ratio, ε* is the strain rate ratio, t* is the temporal ratio (ratios of scaled system to real prototype). Table 2 gives an example of the temporal upscaling of creep tests, in this specific case on a specimen with alteration class 5 and a geometric scale ratio whereby the length of the specimen corresponds to a rock thickness of 50 m. The stress ratio was obtained via dimensional upscaling; the viscosity ratio compared the viscosity values of granite (measured by Genevois & Prestininzi, 1979b in their creep tests) with the viscosity values of granite under normal in-situ conditions. In the same material, viscosity depends on its strain rate, which depends in turn on the applied stress. In the creep tests, given the applied stress and the unconfined condition of the specimen, the measured viscosities proved to be much lower than those of in-situ granitic rocks. The viscosity ratio may be obtained by comparing these values. Strain rates and thus temporal scale ratios may be compared by using the viscosity ratio together with the stress ratio.

With the above-described approach, the experimental creep curves built by Genevois & Prestininzi, 1979b were scaled up, considering for each specimen: i) the different extent of alteration, and ii) the different depths of interest (Figs 5a, b, c). Table 3 summarises the scaling factors. Figures 5a, b, c provide the experimental curves of specimens with different extent of al-

Sample	t* for 50 m depth	t* for 150 m depth	t* for 300 m depth
1	3.35×10^{7}	1.12×10^{7}	5.58×10^{7}
2	4.15×10^{7}	1.38×10^{7}	6.91×10^{7}
3	8.83×10^{7}	2.94×10^{7}	1.47×10^{7}
4	6.73×10^{7}	2.24×10^{7}	1.12×10^{7}
5	2.55×10^{7}	1.72×10^{7}	8.60×10^{6}

Tab. 3 - Temporal upscaling factor for different samples at different depth intervals teration: specimen 2 (unaltered – Ia=25%), specimen 5 (averagely altered – Ia=37%) and specimen 4 (highly altered – Ia=44%) scaled up to thicknesses of 50, 150 and 300 m. The upscaling of these curves yielded particularly significant results for better understanding and describing the ongoing deformation of the Mt. Granieri slope.

DISCUSSION

Results from the physically-based spatio-temporal upscaling of laboratory creep tests made it possible to determine the creep deformation stage that the granites involved in the Mt. Granieri deformation had reached at different depths and in the different stages of the geomorphological evolution associated with the deepening of the valley by the Allaro River.

Based on the reconstructed evolutionary model, the gravitational deformations of Mt. Granieri originated during a standstill in the erosional activity of the stream, corresponding to the strath surface which correlates with 4th-order terraces (estimated date: about 950 ka), i.e. after incision of the contact between heat-metamorphosed schists and underlying granites. The aforesaid sector was affected by the 1972 rock avalanche. Taking into account the alteration profiles proposed for the slope by various authors (Barrese *et alii,* 2006; Pellegrino & Prestininzi, 2006; Pellegrino, *et alii* 2008), the granites occurring in the topmost portions of the Mt. Granieri slope are more altered, as their measured Ia% values are higher (sample 4, Table 2). The investigated sector of the slope is roughly 150 m-thick and the acting vertical stress is estimated at roughly 3 MPa, corresponding to about 57% of the tensile strength determined for the samples of the higher alteration class (sample 4, Tab. 2). This condition coincides with the scaled-up creep curve of Fig. 5a; therefore, the slope sector under review is at a tertiary-creep stage (point A of Fig. 4 and 6a). Hence, this condition is conducive to rupture phenomena, including past landslides and evidence of ongoing fracturing and surface mobility, as previously observed by various authors (Prestininzi, 1984; Martino *et alii,* 2004; Pellegrino & Prestininzi, 2006; Pellegrino *et alii* 2008). At greater depth, the less altered granites have better mechanical properties (passage from the alteration class of sample 4 to the alteration class of samples 5 and/or 3). In this case, the scaled-up reference curves are as shown in Fig. 5b. The stresses acting in situ at these depths are equal to approximately 5.5 MPa, equal to about 60% of the UCS determined for the samples of alteration class 5. Hence, also in this case, considering an evolution time of about 500 ka, or starting from the formation of the strath surface corresponding to the 4th-order marine terrace, granites are at an incipient stage of deformation due to tertiary creep (point B of Fig. 6b). This condition applies to

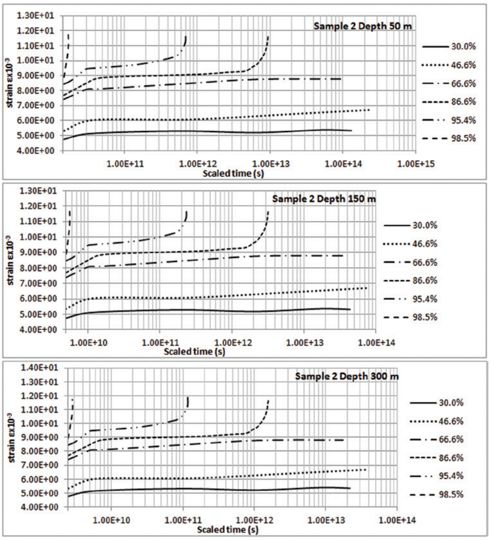

Fig. 5a - Creep curves for sample 2 (unaltered) of Tab. 2 (three depth intervals) scaled down to the dimension of the slope

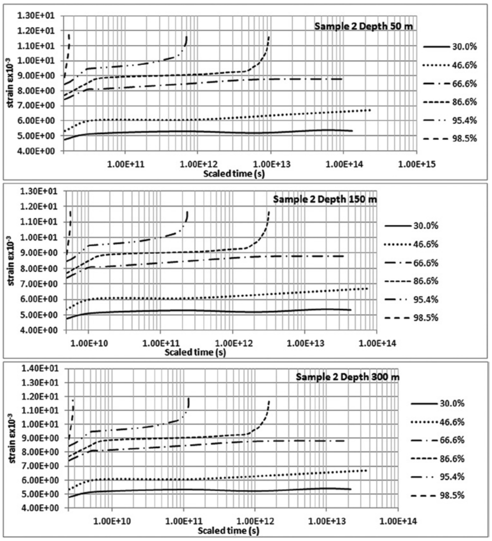

Fig. 5b - Creep curves for sample 5 (averagely altered) of Tab. 2 (three depth intervals), scaled down to the dimension of the slope both altered and unaltered granites at the top of the Mt Granieri slope. In more detail, this tertiary creep is already at an advanced stage in the first 150 m of thickness, where it mostly involves altered granites, whilst it is incipient within 300 m of thickness, where it involves poorly altered granites.

It is worth emphasising that a monitoring survey of the investigated slope is still under way. The survey is based on data recorded by inclinometer probes installed at different depths (down to 35 m from ground level) in the top part of the investigated slope, at the Piana di Monte Granieri plain (Fig. 2). The strain rates measured so far during the survey (Pellegrino, 2000; Pellegrino *et alii,* 2008) are about two orders of magnitude higher than those obtained from creep curves. This finding infers a deformational process that has already exceeded rupture conditions and the fact that the shallowest portions of the landsliding slope are subject to rainfall-induced accelerations, as highlighted by previous studies (Pellegrino *et alii,* 2008).

In the intermediate sector of the slope, whose morphological evolution started not before 400 ka, the situation is as shown in point C of Figs 4 and 6b. In this instance, even considering conditions more conducive to creep and thus the worst alteration class (class 5) for these sectors and a depth of 300 m, the crystalline rock is at a secondary-creep stage and its strain rate is constant over time.

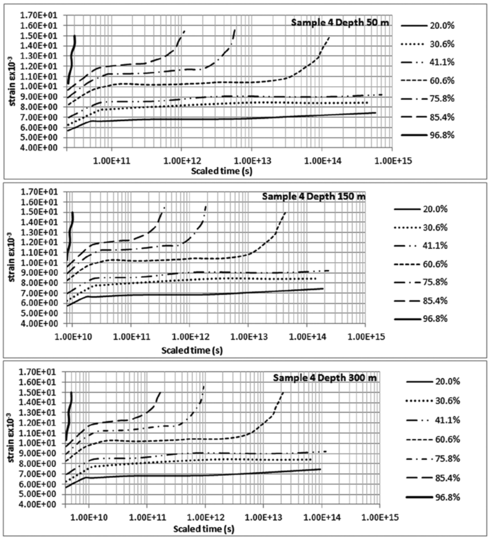

Fig. 5c - Creep curves for sample 4 (highly altered) of Table 2 (three depth intervals) scaled down to the dimension of the slope

Likewise, in the more downhill sector of the slope, deformation must have started not before the formation of the strath surface correlating with the 7th-order marine terrace (Fig. 4), i.e. about 300 ka. Even the assumption of the worst granite alteration conditions for this sector (alteration class 5) and of a depth of 300 m from ground level (consistent with the kinematics of the deformational process) cannot justify a tertiary-creep stage for the rock mass under review. In fact, as shown in Figs 4 and 6b (point D), the granitic rock in this sector of the slope is at a secondary-creep stage.

CONCLUSIONS

This study experimented a physically-based approach to scale up laboratory creep tests to the spatio-temporal evolution of a natural slope and thus to assess the different creep stages of its current deformations. The approach was tested on the case study of Mt. Granieri (Calabria, Italy). For this area, results from creep tests carried out on rock samples taken from the slope and with different states of alteration were available.

In spite of uncertainties associated with the above assessment, the results obtained with this approach proved to be consistent with the case study. The transposition of rock mass stresses to the scaled curves indicated tertiary creep-induced deformations; these deformations are demonstrated on site by monitoring surveys and by clear morphological evidence. The

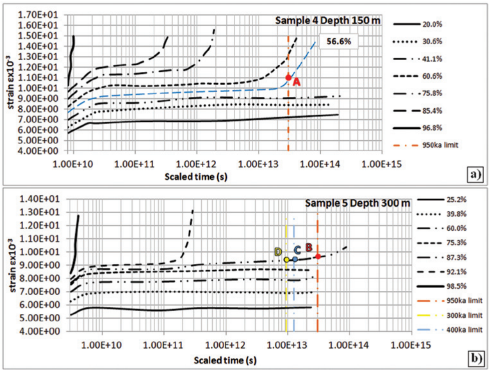

Fig. 6 - Plausible creep stages for granites outcropping at the top (points A and B of Figure 4) of the Mt. Granieri slope and in the valley floor (points C and D of Figure 4). The dashed line in blue in a) is the result of an interpolation made to obtain the values for a percentage of UCS of 57%.
Point A: creep stage at 950 ka and 50 m of depth.
Point B: creep stage at 950 ka and 300 m of depth.
Point C: creep stage at 400 ka and 300 m of depth.
Point D: creep stage at 300 ka and 300 m of depth

phenomenon started about 950 ka in the topmost portions of the slope down to depths of 150-300 m from the topographic surface, affecting highly to poorly altered granitic rocks underlying the contact with heat-metamorphosed schists. The scaled-up creep curves also infer that the temporal evolution of valley deepening by the Allaro River does not justify similar creep stages in the lower portion of the Mt. Granieri slope. Here, even on the assumption of the worst alteration conditions for granitic rocks and of the highest rock mass thicknesses (still consistent with the kinematics of slope deformations), only stationary-creep conditions are plausible.

The deformational scenario elucidated by this study may trigger a new large landslide (mobilising an estimated volume of 1 Mm^3), as an evolution of the phenomena that have historically affected the topslope and, in particular, as a retrogression of the 1972 rock avalanche (mobilising a volume of rock mass estimated at about $2Mm^3$).

REFERENCES

Barrese E., Pellegrino A., Prestininzi A. (2006) – *Analisi dei processi di alterazione delle rocce cristallino-metamorfiche del bacino delle Fiumare Allaro e Amusa (Massiccio delle Serre, Calabria, Italia): aspetti generali ed effetti legati alle fasce di aureola metamorfica.* Italian Journal of Engineering and Enviroment, **1**: 51-74.

Bonardi G., De Vivo B., Giunta G., Lima A., Perrone V. & Zuppetta A. (1982) - *Mineralizzazioni dell'Arco Calabro Peloritano. Ipotesi genetiche e quadro evolutivo.* Boll. Soc. Geol. It., **101**: 141-155.

Bonardi G., Messina A., Perrone V., Russo S. & Zuppetta A. (1984) - *L'unità di Stilo nel settore meridionale dell'Arco Calabro-Peloritano*. Boll. Soc. Geol. It., **103**: 279-309.

Bozzano F., Bretschneider A. & Martino S. (2008) - *Stress-strain history from the geological evolution of the Orvieto and Radicofani cliff slopes (Italy)*. Landslides, **5** (4): 351-366.

Bozzano F., Martino S. & Prestininzi A. (2010) - *Ruolo dell'assetto geologico sulle condizioni di stabilità della collina di Gerace (Reggio Calabria, Italia).* Ital. J. Geosci. (Boll. Soc. Geol. It.), **129** (2): 280-296.

Bozzano F., Bretschneider A., Esposito C., Martino S., Prestininzi A., Scarascia Mugnozza G. (2013) - *Lateral spreading processes in mountain ranges: insights from an analogue modelling experiment.* Tectonophysics. http://dx.doi.org/10.101 06.j.tecto.2013.05.006

Bretschneider A. (2010) - *The role of the geological contact in lateral spreading processes.* Ph.D. Thesis. Department of Earth Sciences, Sapienza University of Rome.

Canuti P., Casagli N., Garzonio C.A. & Vannocci P. (1990) - *Lateral spreads and landslide hazards to the Northern Apennine; the example of Mt. Fumaiolo (Emilia Romagna) and Chiusi della Verna (Tuscany).* 6th International Congress - International Association of Engineering Geology: 1525-1533.

Conti S. & Tosatti G. (1993) - *Landslides affecting tabular rocks in complex geological situations: the case of Sasso di Simone and Simoncello (Northern Apennines, Italy).* In: Novosad S. & Wagner P. (eds.). *Landslides*. Proc. 7th ICFL: 219-224, Prague and Bratislava, Balkema.

Esposito C., Martino S. & Scarascia Mugnozza G. (2007) - *Mountain slope deformations along thrust fronts in jointed limestone: an equivalent continuum modelling approach*. Geomorphology, **90**: 55-72.

Garcia A.F. (2006) - *Thresholds of strath genesis deduced from landscape response to stream piracy by Pancho Rico Creek in the Coast Ranges of central California.* American Journal of Science, **306**: 655-681.

Genevois R. & Prestininzi A. (1979a) - *Analisi tridimensionale della stabilità di versanti rocciosi: la frana di Salincriti.* Geol. Appl. Idrogeol., **24**: 367-387.

Genevois R. & Prestininzi A. (1979b) - *Time dipendent behaviour of granitic rocks related to their alteration grade.* Rock Mechanic, Proc. Int. Congr., Montreaux, 153-159.

Hubbert M.K. (1937) - *Theory of scale models as applied to the study of geologic structures.* Geol. Soc. Am. Bull., **48**: 1459-1520.

Maffei A., Martino S. & Prestininzi, A. (2005) - *From the geological to the numerical model in the analysis of gravity-induced slope deformations: an example from Central Apennines (Italy).* Engineering Geology, **78**: 215-236.

Martino S., Pellegrino A., Prestininzi A. & Scarascia Mugnozza G. (2004) - *The impact of alteration on DSGSD in cristalline-metamorphic rocks: the case of Mt. Granieri-Salincriti (Calabria-Italy).* Italian Journal of Engineering and Enviroment, **1**: 33-60.

Middleton G.V. & Wilcock P.R. (1994) - *Mechanics in the Earth and enviromental sciences.* Cambridge University Press, 439 pp.

Miyauchi T., Dai Pra G. & Sylos Labini S. (1994) - *Geochronology of Pleistocene marine terraces and regional tectonics in the Thyrrenian coast of south Calabria, Italy.* Il Quaternario, **7**: 17-34.

Nemcok A. & Baliak F. (1977) - *Gravitational deformation in mesozoic rocks of the Carpathian mountain range.* Bull. IAEG, **16**: 109-111.

Pellegrino A. (2000) - *Aspetti metodologici nella caratterizzazione geomeccanica degli ammassi costituiti da rocce cristalline vulnerabili ai processi di alterazione e possibili implicazioni nella genesi dei fenomeni franosi e delle Deformazioni Gravitative Profonde di Versante, applicazione in alcune aree situate all'interno dei bacini dei F. Amusa e Allaro (RC), Calabria.* Dottorato di Ricerca XIII Ciclo in Scienze della Terra. Università degli studi di Roma "La Sapienza".

Pellegrino A. & Prestininzi A. (2006) - *Impact of weathering geomechanical properties of rocks along thermal-metamorphic contact belts and morpho-evolutionary preocesses: the deep-seated gravitational slope deformations of Mt. Granieri-Salincriti (Calabria-Italy).* Geomorphology, **87**: 176-195.

Pellegrino A., Prestininzi A. & Scarascia Mugnozza G. (2008) - *Costruzione del modello geologico-tecnico in ammassi cristallino-metamorfici affetti da intensi processi di alterazione: un esempio di applicazione nei bacini delle F.re Allaro ed Amusa (Massiccio delle Serre, Calabria).* Proc. IX Int. Symp. Landslides, Balkema, Rotterdam.

Prestininzi A. (1984) - *Deformazioni gravitative profonde: aspetti cinematic ed analisi dei rapporti con alcuni processi alterativi.* Boll. Soc. Geol. It., **103**: 707-716.

Prestininzi A. (1995) - *Il ruolo degli eventi naturali sulla evoluzione urbana del centro abitato di Caulonia-Castelvetere (Reggio Calabria).* Primo Convegno del Gruppo Nazionale di Geologia Applicata, Giardini Naxos (ME), 11-15 giugno 1995. Estratto da: Geologia Applicata e Idrogeologia, **30** (1): 393-403.

Raman Y.V. & Gogte B.S. (1982) - *Quantitative studies of weathering in saprolitized charnockites associated with a landslide zone at the Porthimund Dam*, *India.* Eng. Geology, **19**: 29-46, Elsevier Scient. Pub. Amsterdam.

Ramberg, H. (1981) - *Gravity, deformation and the Earth's crust in theory, experiments and geological applications.* Academic Press, London.

Zischinsky U. (1969) – *Uber Sackungen*. Rock Mech., **1**: 30-52.