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# Weathering grade of rock masses as a predisposing factor to slope instabilities: Reconnaissance and control procedures

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**Abstract**

Weathering of rock masses often assumes importance as a predisposing factor to slope instability and it is possible to map it at various scales depending on the different purposes. The effects of weathering processes are particularly intense on crystalline rocks (plutonic and metamorphic). These rocks are present in large areas of the globe and widespread in Calabria. The relationships between rock mass weathering grades and slope instabilities are analysed, with reference to sectors (1:50,000 scale) and areas (1:10,000 scale) where crystalline rocks are strongly affected by weathering. To this aim a reconnaissance procedure has been proposed to delimitate the zones with different weathering condition, three macro-classes at average scale (1:50,000) and six classes at detail scale (1:10,000). In this procedure first analysis of aerial photos and then field observations of representative situations have been used. The reconnaissance procedure has been verified in a selected study area (Acri), whose geological features are provided, by the comparison with weathering maps obtained by means of a control procedure. This last procedure consists of observations and index tests carried out in check points located in representative check sites (discolouration, sound when struck by geological hammer, effect of the point of geological pick, breaking with the hands, rebound of Schmidt Hammer, grain-size analysis). The results obtained confirm through quantitative data that the weathering of a rock mass can be assumed as a predisposing factor to slope instability. At average scale (1:50,000) the reconnaissance procedure is able to give weathering maps representative for this type of evaluation (the ratio between the landslides area in each weathering macro-class and the whole landslide area goes from 67% to 14% for the macro-class A and from 24% to 9% for the macro-class B); at detail scale (1:10,000) it is necessary to use a control procedure to obtain weathering maps indicative of predisposition to slope instabilities.


*Keywords:* Weathering; Slope instability; Reconnaissance procedure; Control procedure

## 1. Introduction

Lithologic maps, even though they describe thoroughly the characteristics of outcropping rocks, provide only general information about the weathering grade of rock masses. This assumes particular relevance for crystalline rocks, because the weathering processes they undergo could present heterogeneous characteristics in outcrop and in depth, from a mineralogical, physical and mechanical point of view. The lack of information on weathering conditions could strongly limit the value of lithologic maps.

Rock weathering takes on great importance for many aspects: the evolution and development of landforms (Modenesi and Paulo, 1983; Ollier, 1984; Migon and Lindmar-Bergstrom, 2001; Pain et al., 2001); the possible presence in rock masses of parts with both hard-rock and

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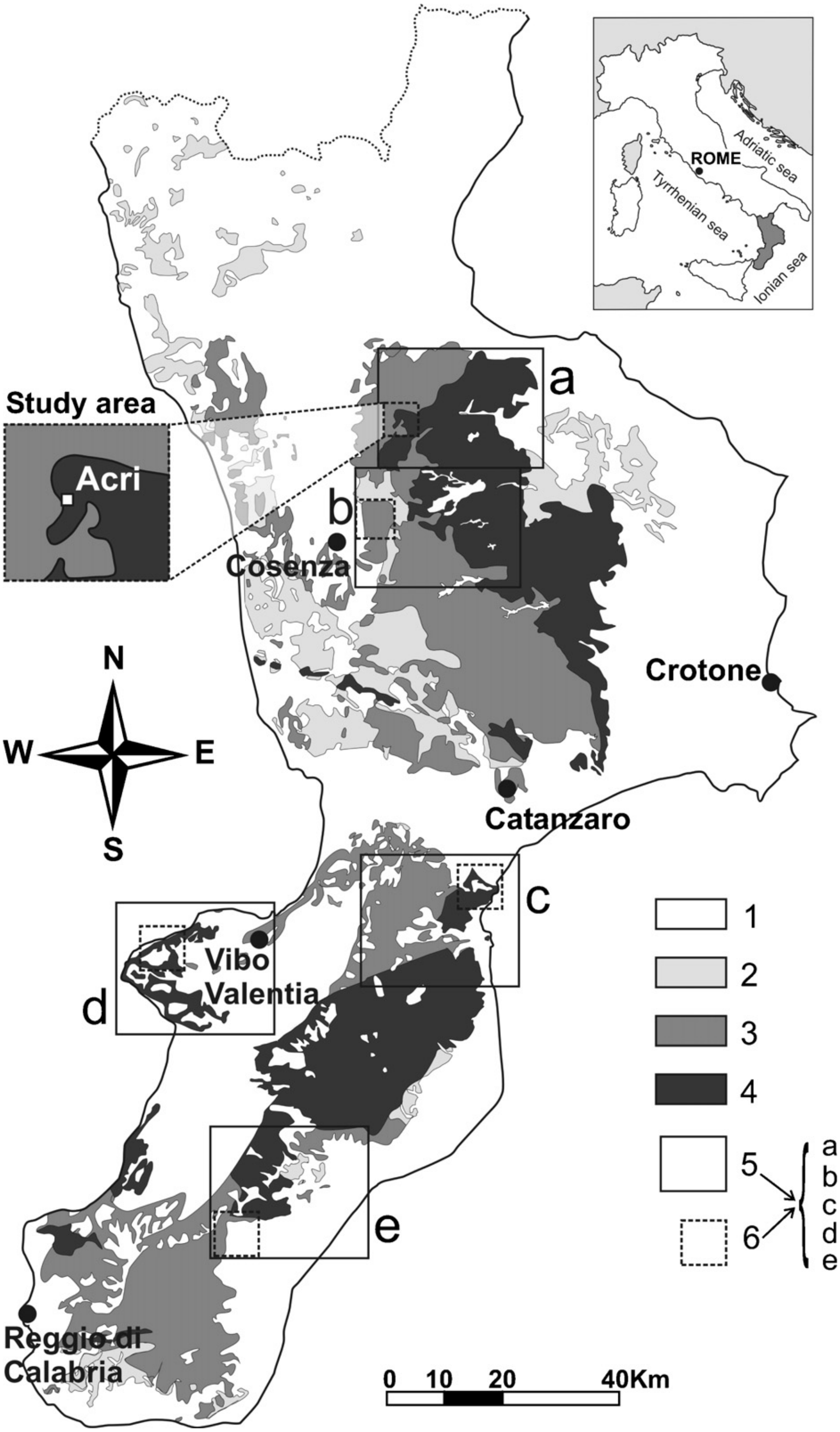


Fig. 1. Outcropping rocks at regional scale (1:250,000): 1) sedimentary deposits; 2) middle-low grade metamorphic rocks; 3) middle-high grade metamorphic rocks; 4) plutonic rocks; 5) sectors studied at average scale (1:50,000): a=Northern Sila, b=Central Sila, c=North-Eastern Serre, d=Capo Vaticano, e=North-Eastern Aspromonte; 6) areas studied at detail scale (1:10,000): a=Acri, b=San Pietro in Guarano, c=Squillace, d=Tropea, e=Platì.

soil-like behaviour (Dearman, 1976; I.S.R.M., 1978; Dearman and Irfan, 1978; I.A.E.G., 1981; G.C.O., 1984, 1988; Gullà and Matano, 1997); the relevance for the slope instabilities (Deere and Patton, 1971; Hencher et al., 1984; Brand, 1985; Nishida and Aoyama, 1985; Cascini et al., 1992, 1994; Gullà and Nicoletti, 1996; Lacerda and Santos, 2000; Calcaterra et al., 2004; Gullà et al., 2004a; Lacerda, 2004; Terranova et al., 2004; Valley et al., 2004). Therefore, weathering survey can be useful for different purposes.

In the present paper weathering survey is aimed to individuate the relationships between rock weathering grade and slope instabilities. In particular, the reliability of a reconnaissance procedure of rock mass weathering grade (Gullà et al., 2004b) is tested at 1:50,000 and 1:10,000 scales. To this purpose, the methodology and the results of reconnaissance procedure are synthesized; geological features of the selected study area are provided to verify the reconnaissance procedure; the methodology and the results of the control procedure are illustrated; relationships between rock weathering grade and slope instabilities are analysed; the reconnaissance procedure map and the control procedure map are compared.

## 2. Weathering grade maps from reconnaissance procedure

In order to verify if the weathering grade can be assumed as a predisposing factor of rock masses to slope instability, weathering maps for large areas are necessary at different scales. To this aim a reconnaissance procedure has been pointed out by Gullà et al. (2004b) and Borrelli et al. (2004). In the present paper this reconnaissance procedure has been used at average scale (1:50,000) and at detail scale (1:10,000).

Geological contexts, that are representative of outcropping rocks, have been selected to carry out the study as they have experienced the effects of intense weathering processes (Guzzetta, 1974; Ietto, 1975; Cascini et al., 1992, 1994; Calcaterra et al., 1996; Gullà and Nicoletti, 1996; Borrelli and Gullà, 2002; Gullà et al., 2004a). At an average scale (1:50,000) a reconnaissance survey of the weathering grade at outcrop has been carried out in the five sectors shown in Fig. 1: Northern Sila, Central Sila, North-Eastern Serre, Capo Vaticano, North-Eastern Aspromonte. At an average scale the reconnaissance procedure considers, for the plutonic and metamorphic rocks of medium-high grade, three weathering macro-classes. They are defined referring to the engineering behaviour of the rock mass: macro-class A, soil-like behaviour; macro-class B, weak rock behaviour; macro-class C, hard-rock behaviour. We analysed aerial photos (1:33,000 scale) and made field observations of representative situations to delimitate the zones with rock masses included in the three macro-classes. The main elements used for the weathering classification, through the interpretation of the aerial photos, were slope angle, relief contour and land use. The selected representative

| CLASS | TERM | DESCRIPTION |
|---|---|---|
| VI | RESIDUAL AND COLLUVIAL SOILS | All rock material is converted to soil. The original rock structure is completely destroyed. The point of geological pick easily indents in depth. When the rock material is struck by the hammer don't emits sound. |
| V | COMPLETELY WEATHERED ROCK | All rock material is completely discoloured and converted to soil, but the original mass structure is still visible. The point of geological pick easily indents. When the rock material is struck by hammer emits a dull sound. |
| IV | HIGHLY WEATHERED ROCK | All rock material is discoloured. The original mass structure is still present and largely intact. The point of geological pick not easily indents. The rock material make a dull sound when is struck by hammer. |
| III | MODERATELY WEATHERED ROCK | The rock material is discoloured, but locally the original colour is present. The original mass structure is well preserved. The point of geological pick produce a scratch on the surface. The rock material make a intermediate sound when is struck by hammer. |
| II | SLIGTLY WEATHERED ROCK | Discolouration is present only near joint surface. The original mass structure is perfectely preserved. The point of geological pick scratch the surface with difficulty. The rock material make a ringing sound when is struck by hammer. |
| I | FRESH ROCK | The rock material isn't discoloured and has it's original aspect. The point of geological pick scratch the surface with many difficulty. The rock material make a ringing sound when is struck by hammer. |

Fig. 2. Descriptions assumed as reference for the weathering classes (from Brand, 1990; GSE-GWPR, 1990; Cascini et al., 1992 modified).

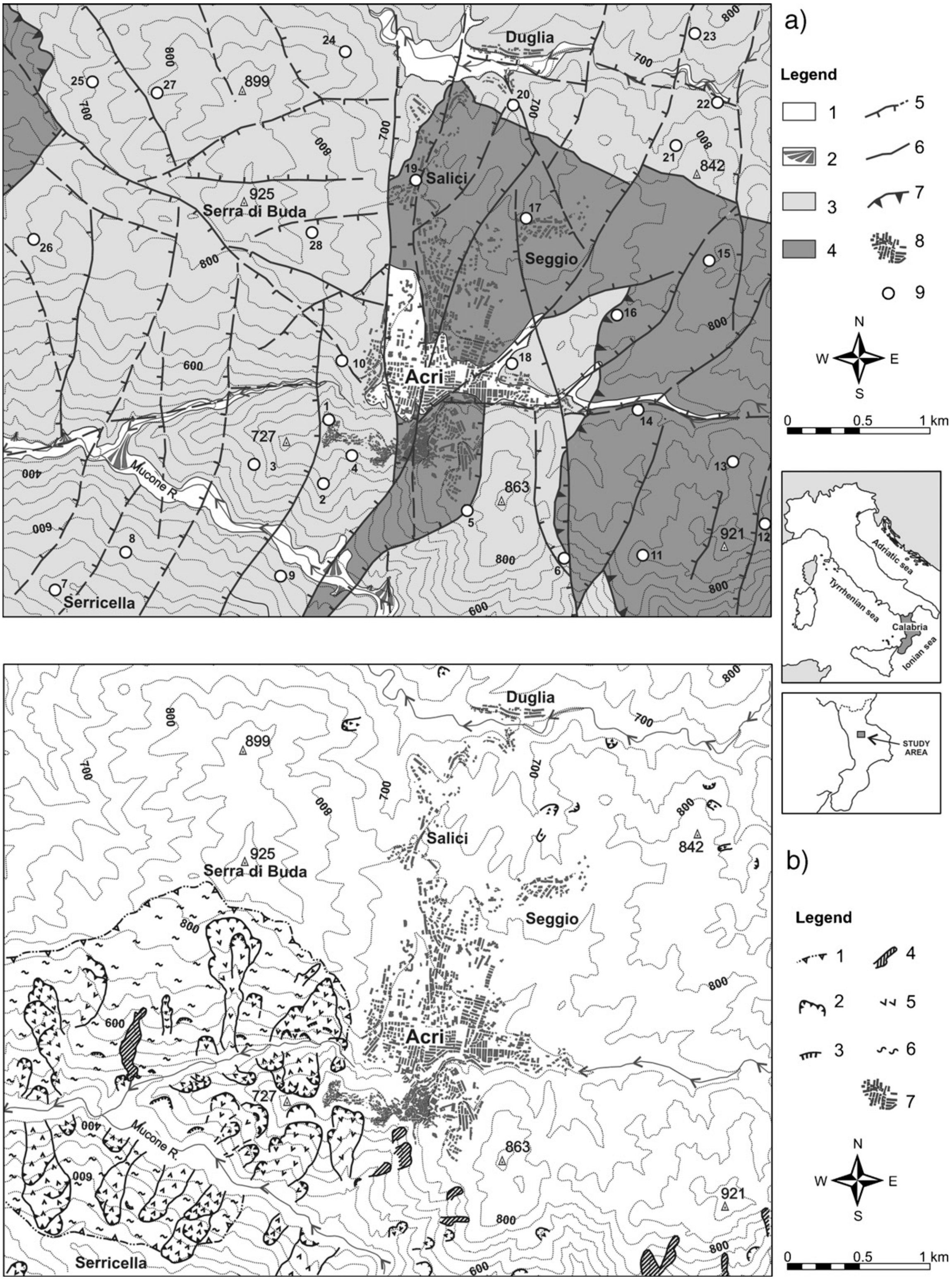


Fig. 3. Acri study area: a) simplified geological–structural map; legend: 1) sedimentary deposits; 2) alluvial fan; 3) gneissic complex; 4) granitic complex; 5) normal fault; 6) tectonic boundary; 7) thrust fault; 8) town; 9) check sites. b) simplified landslide map; legend: 1) Sackung boundary; 2) landslide scarp; 3) secondary landslide scarp; 4) debris flow; 5) slide; 6) Sackung; 7) town.

situations have been used to verify the correspondence between the distinguishing elements on the aerial photos and the weathering macro-classes observed in the field. Independent of the weathering reconnaissance, a survey of the slope instability has been carried out through the interpretation of aerial photos.

Every study sector is characterised by a percentage between 79% and 15% of the whole area of outcropping plutonic and medium-high grade metamorphic rocks. In each sector the ratio between the area of the landslides surveyed in each weathering macro-class and the whole landslide area is always between 82% and 32%. In particular the percentage of the macro-class A is generally higher, from 67% to 14%, compared to macro-class B, from 24% to 9%. Then, at an average scale, the weathering grade of rock mass can be assumed as a possible predisposing factor to slope instability (Borrelli et al., 2004; Gullà et al., 2004b).

At the scale 1:10,000 a reconnaissance survey of the weathering grade on outcrops was carried out in the five areas, located in the sectors considered at average scale, shown in Fig. 1: Acri area; San Pietro in Guarano area; Squillace area; Tropea area; Platì area. In the reconnaissance procedure defined at a scale of 1:10,000 six weathering grades have been considered: class VI (residual and colluvial soils), class V (completely weathered rock), class IV (highly weathered rock), class III (moderately weathered rock), class II (slightly weathered rock) and class I (fresh rock) (G.C.O., 1984; Cascini et al., 1992, 1994; GSE-GWPR, 1995; Gullà and Matano, 1997). Also at 1:10,000 scale the zones with different weathering grade have been delimitated through an analysis of aerial photos (in this case taken at 1:10,000 scale) and field observations in representative sites of each area. The descriptions used as reference for the field observations are reported in Fig. 2. The criteria, simplified for wide areas, are coherent with those used by Cascini et al. (1992) and Gullà and Matano (1997). Particular attention has been given to the field recognition of discolouration, textural and structural characters of the rock. Again independent of the weathering reconnaissance, slope instability has been surveyed at 1:10,000 scale through the analysis of aerial photos.

The comparison between the zones classified with different weathering grade and slope instability, referred to plutonic and metamorphic rocks of medium-high grade, points out that the percentage of landslide area included in classes III and II is small (about 1%), and that the percentage of landslide areas in class VI (38%) and class V (37%) is always higher than that in class IV (24%) (Borrelli et al., 2004; Gullà et al., 2004b). Then it is confirmed at a detailed scale (1:10,000) that the rock mass weathering grade is an indicator of slope instability predisposition (Borrelli et al., 2004; Gullà et al., 2004b).

The study area of Acri has been chosen to verify the results obtained through the proposed reconnaissance procedure (Fig. 1), because it is in a part of Calabria where the presence of plutonic and metamorphic rocks is particularly relevant. Moreover, in the same area, there are other studies dealing with slope instability phenomena

**WEATHERING FEATURES IN THE CHECK SITE:**

| Point | Colour | Discolouration | | | | Indent | | | Sound | | | By hands | | | Weathering grade | Schmidt Hammer test | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A | B | C | D | A | B | C | A | B | C | A | B | C | | Rebound values | | | | | | | | | |
| | | Complete | Partial | Along discontinuities | None | Deep | Superficial | Scratch | Dull | Intermediate | Ringing | Crumble | Break | None | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Mean value |
| | | | | | | | | | | | | | | | | | | | | | | | | | |
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Notes: ……………………………………………………………………………………….
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Fig. 4. Storage form to collect observations and measures relative to weathering conditions (from Gullà and Matano, 1997 modified).

Table 1
Summarizing table of data collected in each check site

| Check site | Lithology | Point | Observations | | | | | PW | | SH | AW |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 | Point | Site | | Site |
| Acri 1 | Gneiss | 1 | b-r | A | B | B | B | IV | IV | 20 | IV |
| | | 2 | b-r | A | A–B | B | B | IV | | 15 | |
| | | 3 | b | A | B | C | C | III | | 27 | |
| | | 4 | b-g | A–B | A–B | B | B | IV | | 24 | |
| | | 5 | b-r | A | B | C | C | III | | 25 | |
| Acri 2 | Gneiss | 1 | b-r | A | A | B | B | IV | IV | 17 | IV |
| | | 2 | b-r | A | A | B | B | IV | | 19 | |
| | | 3 | b-r | A | A | B | B | IV | | 20 | |
| | | 4 | b-r | A | A | B | B | IV | | 12 | |
| | | 5 | b-r | A | A | B | B | IV | | 18 | |
| Acri 3 | Gneiss | 1 | b-r | A | A | A | A | V | V | 10 | V |
| | | 2 | b-r | A | A | A | A | V | | 10 | |
| | | 3 | b-r | A | A | B | B | IV | | 10 | |
| | | 4 | b-r | A | A | A | A | V | | 10 | |
| | | 5 | b-r | A | A | B | A | V | | 11 | |
| Acri 4 | Gneiss | 1 | g-w | B | B | C | C | III | III | 24 | III |
| | | 2 | g-w | B | B–C | C | C | III | | 25 | |
| | | 3 | g-w | B | B–C | C | C | III | | 31 | |
| | | 4 | g-w | B | B–C | C | C | III | | 41 | |
| | | 5 | g-w | B | B–C | C | C | III | | 38 | |
| Acri 5a | Granites | 1 | p | A | A | A–B | A | V | V | 6 | V |
| | | 2 | p | A | A | A–B | A | V | | 3 | |
| | | 3 | p | A | A | A–B | A | V | | 7 | |
| | | 4 | p | A | A | A–B | A | V | | 6 | |
| Acri 5b | Gneiss | 1 | b-r | A | A | A–B | A–B | V–IV | V–IV | 4 | V |
| | | 2 | b-r | A | A | A–B | A–B | V–IV | | 4 | |
| | | 3 | b-r | A | A | A–B | A–B | V–IV | | 3 | |
| | | 4 | b-r | A | A | A–B | A–B | V–IV | | 3 | |
| Acri 6 | Gneiss | 1 | g-b | A | A–B | B | B | IV | IV | 14 | IV |
| | | 2 | g-b | A | A–B | B | B | IV | | 10 | |
| | | 3 | g-b | A | A–B | B | B | IV | | 22 | |
| | | 4 | g-b | A | A–B | B | B | IV | | 26 | |
| | | 5 | g-b | A | A–B | B | B | IV | | 21 | |
| Acri 7 | Gneiss | 1 | r-b | A | A | A | A | V | V | 4 | V |
| | | 2 | r-b | A | A | B | A–B | IV | | 6 | |
| | | 3 | r-b | A | A | A | A | V | | 6 | |
| | | 4 | r-b | A | A | A | A | V | | 5 | |
| | | 5 | r-b | A | A | A | A | V | | 5 | |
| Acri 8 | Gneiss | 1 | r-b | A | B | B | B–C | IV–III | IV–III | 20 | IV |
| | | 2 | r-b | A | B | B | B–C | IV–III | | 22 | |
| | | 3 | r-b | A | B | B | B–C | IV–III | | 26 | |
| | | 4 | r-b | A | B | B | B–C | IV–III | | 19 | |
| | | 5 | r-b | A | B | B | B–C | IV–III | | 27 | |
| Acri 9 | Gneiss | 1 | b-r | A | B | B | B–C | IV | IV | 23 | IV |
| | | 2 | b-r | A | A–B | B | B | IV | | 19 | |
| | | 3 | b-r | A | B | B | B–C | IV | | 23 | |
| | | 4 | b-r | A | B | B | B–C | IV | | 24 | |
| | | 5 | b-r | A–B | B–C | B–C | B–C | III | | 28 | |
| Acri 10 | Gneiss | 1 | g-gr | B | B | B | C | III | III | 27 | III |
| | | 2 | g-gr | B | C | C | C | III | | 41 | |
| | | 3 | g-gr | B | C | C | C | III | | 40 | |
| | | 4 | g-gr | B | B | B | C | III | | 28 | |
| | | 5 | g-gr | B | C | C | C | III | | 36 | |
| Acri 11 | Granites | 1 | p-o | A | A | A | A | V–VI | V–VI | 3 | V |
| | | 2 | p-o | A | A | A | A | V–VI | | 4 | |

(continued on next page)

Table 1 (*continued*)

| Check site | Lithology | Point | Observations | | | | | PW | | SH | AW |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 | Point | Site | | Site |
| Acri 11 | Granites | 3 | p-o | A | A | A | A | V–VI | | 6 | |
| | | 4 | p-o | A | A | A | A | V–VI | | 7 | |
| | | 5 | p-o | A | A | A | A | V–VI | | 5 | |
| Acri 12 | Granites | 1 | p-o | A | A | A | A | V–VI | V–VI | 1 | V |
| | | 2 | p-o | A | A | A | A | V–VI | | 3 | |
| | | 3 | p-o | A | A | A | A | V–VI | | 5 | |
| | | 4 | p-o | A | A | A | A | V–VI | | 6 | |
| | | 5 | p-o | A | A | A | A | V–VI | | 6 | |
| Acri 13 | Granites | 1 | r–o | A | A | A | A | VI–V | VI–V | 0 | VI |
| | | 2 | r–o | A | A | A | A | VI–V | | 0 | |
| | | 3 | r–o | A | A | A | A | VI–V | | 0 | |
| | | 4 | r–o | A | A | A | A | VI–V | | 0 | |
| | | 5 | r–o | A | A | A | A | VI–V | | 0 | |
| Acri 14 | Granites | 1 | w-p-o | A | A | A | A–B | V | V | 7 | V |
| | | 2 | w-p-o | A | A | A | A–B | V | | 4 | |
| | | 3 | w-p-o | A | A | A | A–B | V | | 6 | |
| | | 4 | w-p-o | A | A | A | A–B | V | | 5 | |
| | | 5 | w-p-o | A | A | A | A–B | V | | 6 | |
| Acri 15 | Granites | 1 | w-o | A | A | A–B | A | V | V | 9 | V |
| | | 2 | w-o | A | A | A–B | A | V | | 6 | |
| | | 3 | w-o | A | A | A–B | A | V | | 8 | |
| | | 4 | w-o | A | A | A–B | A | V | | 9 | |
| | | 5 | w-o | A | A | A–B | A | V | | 6 | |
| Acri 16 | Granites | 1 | o | A | A | A | A | V–VI | V–VI | 5 | V |
| | | 2 | o | A | A | A | A | V–VI | | 6 | |
| | | 3 | o | A | A | A | A | V–VI | | 6 | |
| | | 4 | o | A | A | A | A | V–VI | | 5 | |
| | | 5 | o | A | A | A | A | V–VI | | 6 | |
| Acri 17 | Granites | 1 | p-o | A | A | A | A | V–VI | V–VI | 5 | V |
| | | 2 | p-o | A | A | A | A | V–VI | | 8 | |
| | | 3 | p-o | A | A | A | A | V–VI | | 7 | |
| | | 4 | p-o | A | A | A | A | V–VI | | 5 | |
| | | 5 | p-o | A | A | A | A | V–VI | | 7 | |
| Acri 18 | Gneiss | 1 | r-b | A | A | A | A | V–VI | V–VI | 1 | V |
| | | 2 | r-b | A | A | A | A | V–VI | | 4 | |
| | | 3 | r-b | A | A | A | A | V–VI | | 3 | |
| | | 4 | r-b | A | A | A | A | V–VI | | 5 | |
| | | 5 | r-b | A | A | A | A | V–VI | | 6 | |
| Acri 19 | Granites | 1 | w-p | A | A | A | A | V–VI | V–VI | 4 | V |
| | | 2 | w-p | A | A | A | A | V–VI | | 5 | |
| | | 3 | w-p | A | A | A | A | V–VI | | 3 | |
| | | 4 | w-p | A | A | A | A | V–VI | | 5 | |
| | | 5 | w-p | A | A | A | A | V–VI | | 5 | |
| Acri 20 | Gneiss | 1 | b-r | A | A–B | A | B | IV | IV | 14 | IV |
| | | 2 | b-r | A | A–B | A | B | IV | | 16 | |
| | | 3 | b-r | A | A–B | A | B | IV | | 17 | |
| | | 4 | b-r | A | A–B | A | B | IV | | 19 | |
| | | 5 | b-r | A | A–B | A | B | IV | | 17 | |
| Acri 21 | Gneiss | 1 | r-b | A | A | A | A | V–VI | V–VI | 3 | V |
| | | 2 | r-b | A | A | A | A | V–VI | | 3 | |
| | | 3 | r-b | A | A | A | A | V–VI | | 3 | |
| | | 4 | r-b | A | A | A | A | V–VI | | 5 | |
| | | 5 | r-b | A | A | A | A | V–VI | | 4 | |
| Acri 22 | Gneiss | 1 | r-b | A | A–B | B | B–C | IV–III | IV–III | 20 | IV |
| | | 2 | r-b | A | A–B | B | B–C | IV–III | | 19 | |
| | | 3 | r-b | A | A–B | B | B–C | IV–III | | 17 | |
| | | 4 | r-b | A | A–B | B | B–C | IV–III | | 12 | |
| | | 5 | r-b | A | A–B | B | B–C | IV–III | | 18 | |

Table 1 (*continued*)

| Check site | Lithology | Point | Observations | | | | | PW | | SH | AW |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 | Point | Site | | Site |
| Acri 23 | Gneiss | 1 | r-b | A | A | A | A | V–VI | V–VI | 6 | V |
| | | 2 | r-b | A | A | B | B | V | | 17 | |
| | | 3 | r-b | A | A | A | A | V–VI | | 6 | |
| | | 4 | r-b | A | A | A | A | V–VI | | 6 | |
| | | 5 | r-b | A | A | A | A | V–VI | | 7 | |
| Acri 24 | Gneiss | 1 | b-r | A | A | A | A | V–VI | V–VI | 6 | V |
| | | 2 | b-r | A | A | A | A | V–VI | | 9 | |
| | | 3 | b-r | A | A | A | A | V–VI | | 8 | |
| | | 4 | b-r | A | A | A | A | V–VI | | 7 | |
| | | 5 | b-r | A | A | A | A | V–VI | | 5 | |
| Acri 25 | Gneiss | 1 | r-b | A | A | A | A | V–VI | V–VI | 8 | V |
| | | 2 | r-b | A | A | A | A | V–VI | | 8 | |
| | | 3 | r-b | A | A | A | A | V–VI | | 10 | |
| | | 4 | r-b | A | A | A | A | V–VI | | 8 | |
| | | 5 | r-b | A | A | A | A | V–VI | | 10 | |
| Acri 26 | Gneiss | 1 | r-b | A | A | A | A | V–VI | V | 6 | V |
| | | 2 | r-b | A | A | B | B | IV | | 17 | |
| | | 3 | r-b | A | A | B | B | IV | | 15 | |
| | | 4 | r-b | A | A | A | A | V–VI | | 4 | |
| | | 5 | r-b | A | A | A | A | V–VI | | 5 | |
| Acri 27 | Gneiss | 1 | r-b | A | A | A | A | V–VI | V–VI | 6 | V |
| | | 2 | r-b | A | A | A | A | V–VI | | 6 | |
| | | 3 | r-b | A | A | A | A | V–VI | | 6 | |
| | | 4 | r-b | A | A | A | A | V–VI | | 8 | |
| | | 5 | r-b | A | A | A | A | V–VI | | 8 | |
| Acri 28 | Gneiss | 1 | r-b | A | A | A | A | V–VI | V | 7 | V |
| | | 2 | r-b | A | A | B | B | IV | | 17 | |
| | | 3 | r-b | A | A | A | A | V–VI | | 8 | |
| | | 4 | r-b | A | A | A | A | V–VI | | 9 | |
| | | 5 | r-b | A | A | A | A | V–VI | | 11 | |

Observations: 1=colour (b=brown, r=reddish, g=grayish, w=white, o=orange, gr=greenish, p=pink); 2=discolouration (A=complete, B=partial, C=along discontinuities, D=none); 3=sound (A=dull, B=intermediate, C=ringing); 4=indent (A=deep, B=superficial, C=scratch); 5=by hands (A=crumble, B=break, C=none). PW=preliminarily weathering class; SH=mean value of the Schmidt Hammer rebound; AW=assigned weathering class.

(Parise and Calcaterra, 2000; Terranova et al., 2004; Gullà et al., 2004b).

## 3. Geology and slopes instability of the study area

The study area is located on the western side of the Sila Massif (Fig. 1) that, geologically, is composed of stacked nappes of several Paleozoic metamorphic and igneous terranes (Tortorici, 1982), emplaced during Oligocene–Lower Miocene time. Structurally the Sila Massif represents a horst bounded by Quaternary normal faults, having a N–S trend and forming fault steps declining to the W. Along this fault system the crystalline lithotypes are raised against the Plio-Pleistocene deposits filling the graben of the Crati Valley (Tortorici, 1981). The area examined corresponds to the western border of the Sila horst.

The Palaeozoic crystalline lithologies that outcrop in the study area, have been distinguished into a *gneissic complex* and a *granitoid complex* (Fig. 3a). The gneissic complex, *Polia-Copanello Unit* of Amodio-Morelli et al. (1976), is composed of an association of high-grade metamorphic rocks, represented by biotite-garnet gneiss, crossed by several quartz-feldspathic lenses and layers, and by biotite schists with garnet and sillimanite, often with fine-grained muscovite. The gneissic mass, locally intruded by pegmatitic dykes, is generally tectonized and weathered. The granitoid complex, *Monte Gariglione Unit* of Amodio-Morelli et al. (1976), outcrops almost exclusively in the eastern part of the study area. It is composed of granites and granodiorites characterised by quartz, plagioclase and biotite (Bertolani and Foggia, 1975). The granitoid complex is weathered and with a characteristic red-brown colour in outcrops.

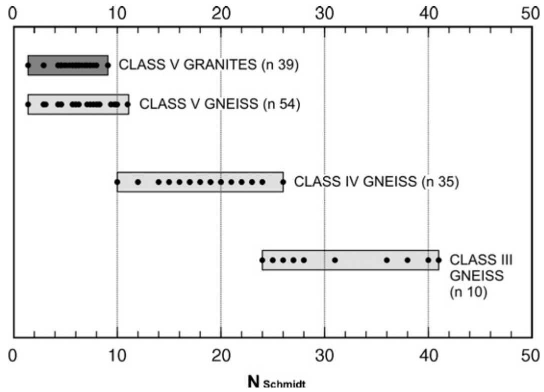


Fig. 5. Mean values and relative ranges of the Schmidt Hammer rebound referred to the weathering classes.

In the town of Acri there is a depression filled by Quaternary deposits made of sandy conglomerates of fluvial origin (Fig. 3a). Finally, along the main river, there are alluvial deposits of gravel of metamorphic clasts in a sandy matrix.

The principal tectonic elements in the study area, identified through the interpretation of aerial photos and then verified through field surveys, are reported in Fig. 3a.

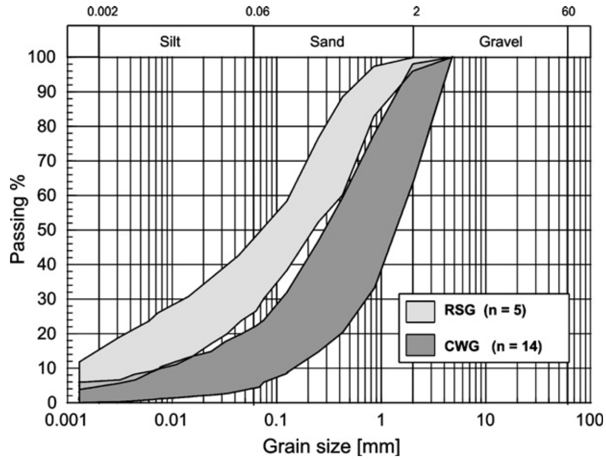


Fig. 7. Grain-size envelopes of residual soil from granite (RSG) and completely weathered granite (CWG) in Acri study area.

Analysis of the distribution of slope instabilities in the study area has been performed both through the interpretation of air photos (IGM flights 1:33,000 and 1:10,000 scales) and field surveys. The surveyed slope instabilities cover an area of about 4.4 $km^2$ (19% of whole study area).

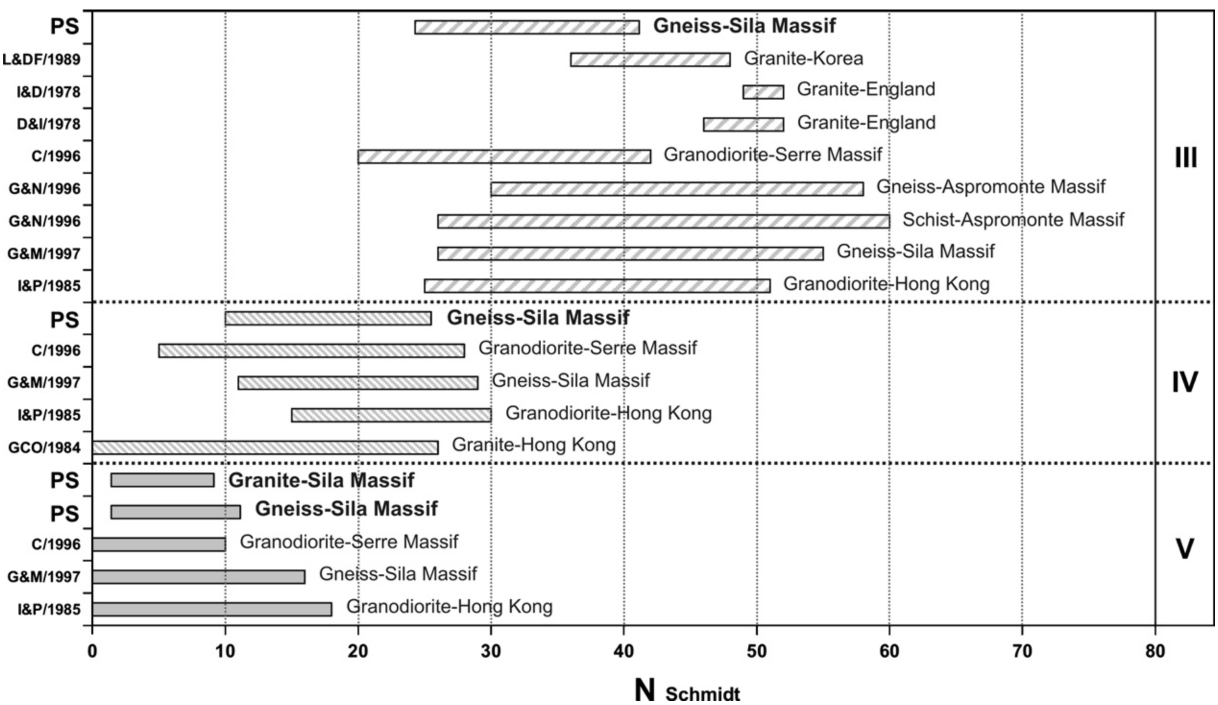


Fig. 6. Comparison between the ranges of Schmidt Hammer rebound obtained in the present study (PS) and other studies: L and DF/1989=Lee and De Freitas (1989); I and D/1978=Irfan and Dearman (1978); D and I/1978=Dearman and Irfan (1978); C/1996=Calcaterra et al. (1996); G and N/1996=Gullà and Nicoletti (1996); G and M/1997=Gullà and Matano (1997); I and P/1985=Irfan and Powell (1985); GCO/1984=Geotechnical Control Office (1984).

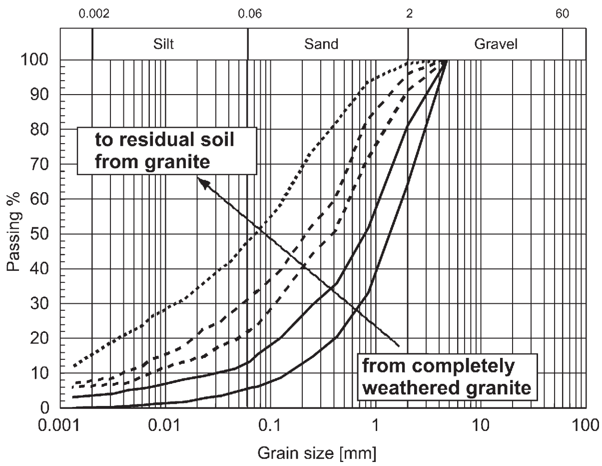


Fig. 8. Transformation of the grain-size curve with the progressive increase of weathering in the granites of Acri study area.

In the study area several mass movements types, located mainly on Mucone river valleysides, have been observed. Three types of mass movement according to Varnes (1978) have been identified and mapped: sackung, slide and debris flow (Fig. 3b).

The sackung type movements (Sorriso-Valvo and Tansi, 1996) are located on the northern side of Serricella and on the southern side of Serra di Buda, and they involve only metamorphic rocks (Fig. 3b). Slides are widespread both on the sackung area and on other slopes of the Mucone valley (Fig. 3b). Debris flows are located mainly on steep granite slopes and involve superficial weathered materials (Parise and Calcaterra, 2000).

## 4. Control procedure

### 4.1. Methodology

A control procedure has been defined at a scale of 1:10,000 in order to verify the results obtained from the reconnaissance. The control procedure was divided in two stages.

In the first stage the main and secondary roads of the study area were traversed. Along these roads observations of the distinctive characters of rock mass, such as colour and presence of relict structures, were made. Photographic documentation of the weathering conditions was acquired, and possible representative check sites were identified. These sites are mostly cutslopes, natural or man-made, where it has been possible to get information about the development of weathering profiles. The exposure of the rock mass at the check sites is at least 20 m in length and 3–4 m in height. For the study area 28 check sites were chosen, with an average density of one site for every 0.8 $km^2$. Some check sites were located where the weathering class was uncertain.

In the second stage we selected the check points where observations and tests were going to be carried out

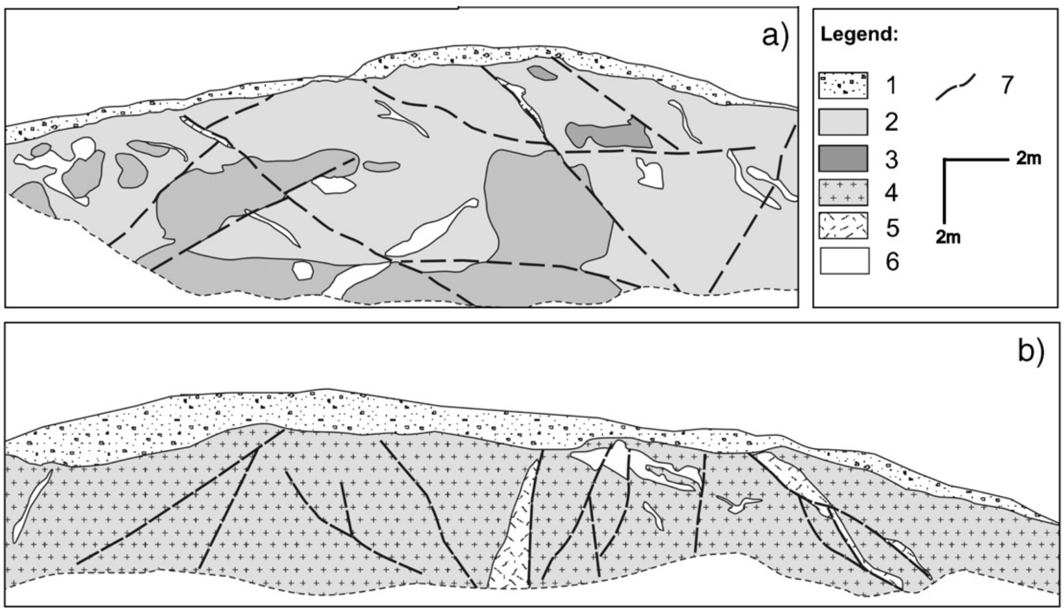


Fig. 9. Weathering profiles of two representative cutslopes: a) gneiss; b) granite. Legend: 1) residual and colluvial soils (class VI) from granite or gneiss; 2) completely weathered gneiss (class V); 3) highly weathered gneiss (class IV); 4) completely weathered granite (class V); 5) fault gouge; 6) pegmatite; 7) tectonic structure.

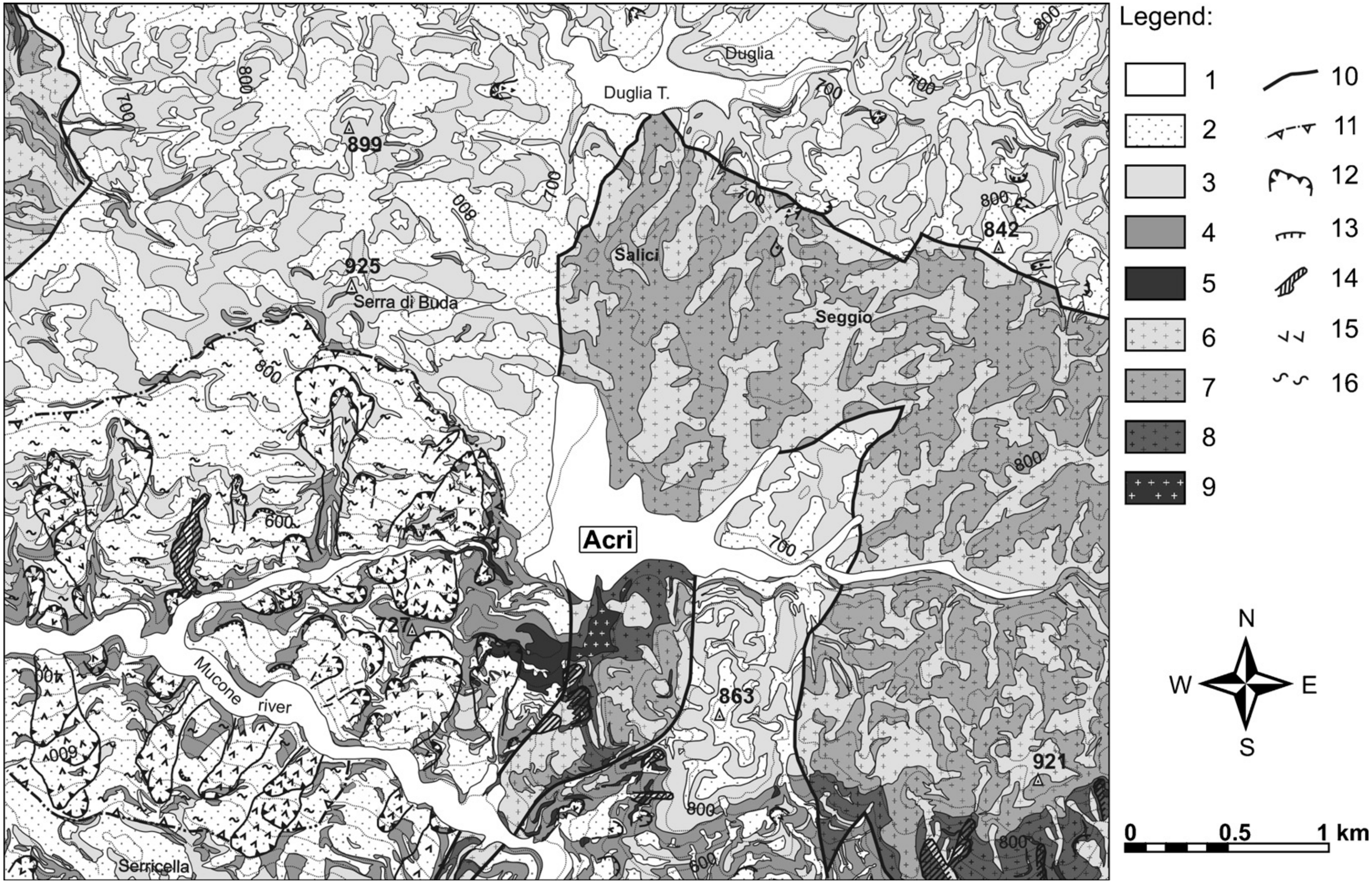


Fig. 10. Weathering grade and landslide map of the study area from control procedure (1:10,000 scale): 1) sedimentary deposits; 2) class VI gneiss; 3) class V gneiss; 4) class IV gneiss; 5) class III gneiss; 6) class VI granites; 7) class V granites; 8) class IV granites; 9) class III granites; 10) tectonic boundary; 11) Sackung boundary; 12) landslide scarp; 13) secondary landslide scarp; 14) debris flow; 15) slide; 16) Sackung.

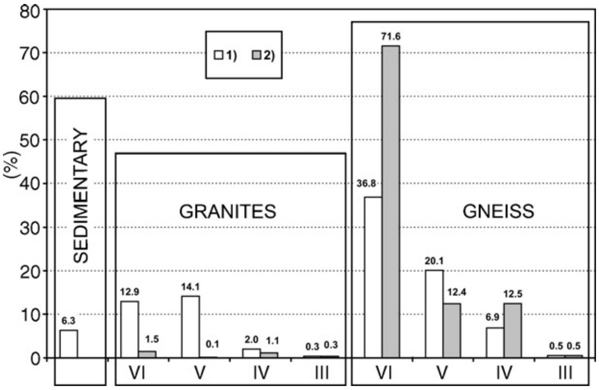


Fig. 11. Distribution percentage from control procedure map (1:10,000 scale): 1) ratio between cropping rock area (sedimentary; granite and gneiss in weathering classes) and total study area; 2) ratio between landslide area of each lithology and total landslide area.

at each check site. The number of the check points has been established following the extent and complexity of the site compared to the weathering conditions. In the present study five check points were sufficient to obtain a suitable characterisation of the weathering at each check site. The observations and the measures carried out to define the weathering grade are reported on a storage form (Fig. 4).

At the check points we collected qualitative data such as: discolouration, sound when struck by a geological hammer, the effect of the point of geological pick, breaking by hand. In addition for each point the Schmidt Hammer test was carried out; in particular nine rebounds were made for each point. From these nine tests it is possible to get the average value referred to the point itself. The collected data allowed us to assign a weathering class to each check point and, according to the analysis of weathering class in the five check points, to each check site. At the check sites where the attribution to the weathering classes VI or V is uncertain, samples have been taken and grain-size characteristics have been used to better distinguish residual and colluvial soils from completely weathered rock. In the study area this condition is present at some check sites located in granites.

To get preliminary indications about weathering profiles, for each check site, delimitation of the zones with different weathering grades was carried out using the methodology proposed by Gullà and Matano (1997).

### 4.2. Results

The 28 check sites in the study area relate to the different lithologies (Fig. 3), with 8 sites on granites, 19 on gneiss, and one site on the tectonic contact between granite and gneiss. The analysis of observations collected at the 143 check points allowed us to establish preliminarily weathering grades for each site (Table 1). For the sites on granites, 6 belong to class V–VI and 3 to class V; for the sites on gneiss, 6 cases belong to class V–VI, 4 to class V, one to class V–IV, 5 to class IV, 2 to class IV–III, and finally 2 to class III (Table 1).

The average values of the Schmidt Hammer rebounds measured at each check point are shown in Table 1. These values have a general coherence with the weathering grade preliminarily defined (Fig. 5), with values from 24 to 41 (mean 33.1) for class III gneiss, from 10 to 28 (mean 19.7) for class IV gneiss, from 1 to 17 (mean 7.1) for class V gneiss, from 1 to 9 (mean 5.5) for class V granites.

This coherence is confirmed in Fig. 6 where the data are compared with those relative to the different lithologies present in various geo-environmental contexts. For the same weathering classes, apart from the kind of lithology, the ranges of variability are quite comparable, with a limited overlap in the ranges of variation of the different weathering classes (Fig. 6).

The ranges shown in Fig. 5 can be assumed as representative of the weathering classes present in the Acri study area and are utilised for the assignment of the weathering class to each check point and site (Table 1). For the sites on granites one case belongs to class VI and 8 to class V; for the sites on gneiss 11 cases belong to class V, 7 to class IV, and 2 to class III (Table 1).

The grain-size envelopes of the collected samples are illustrated in Fig. 7. The samples were located in zones representing residual soils from granites and completely weathered granites. The samples collected in residual

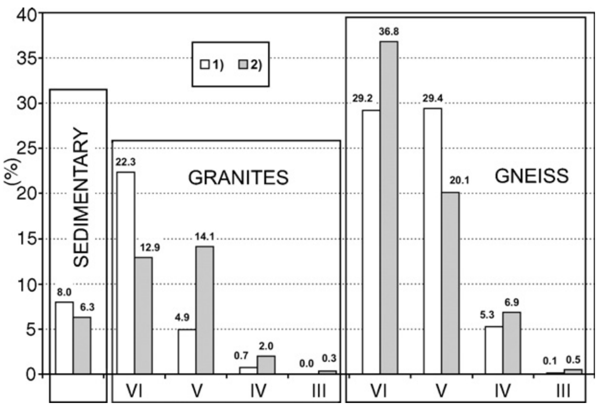


Fig. 12. Comparison at detail scale between the ratio percentage of cropping rock area (sedimentary; granites and gneiss in weathering classes) and total study area obtained by: 1) reconnaissance procedure map; 2) control procedure map.

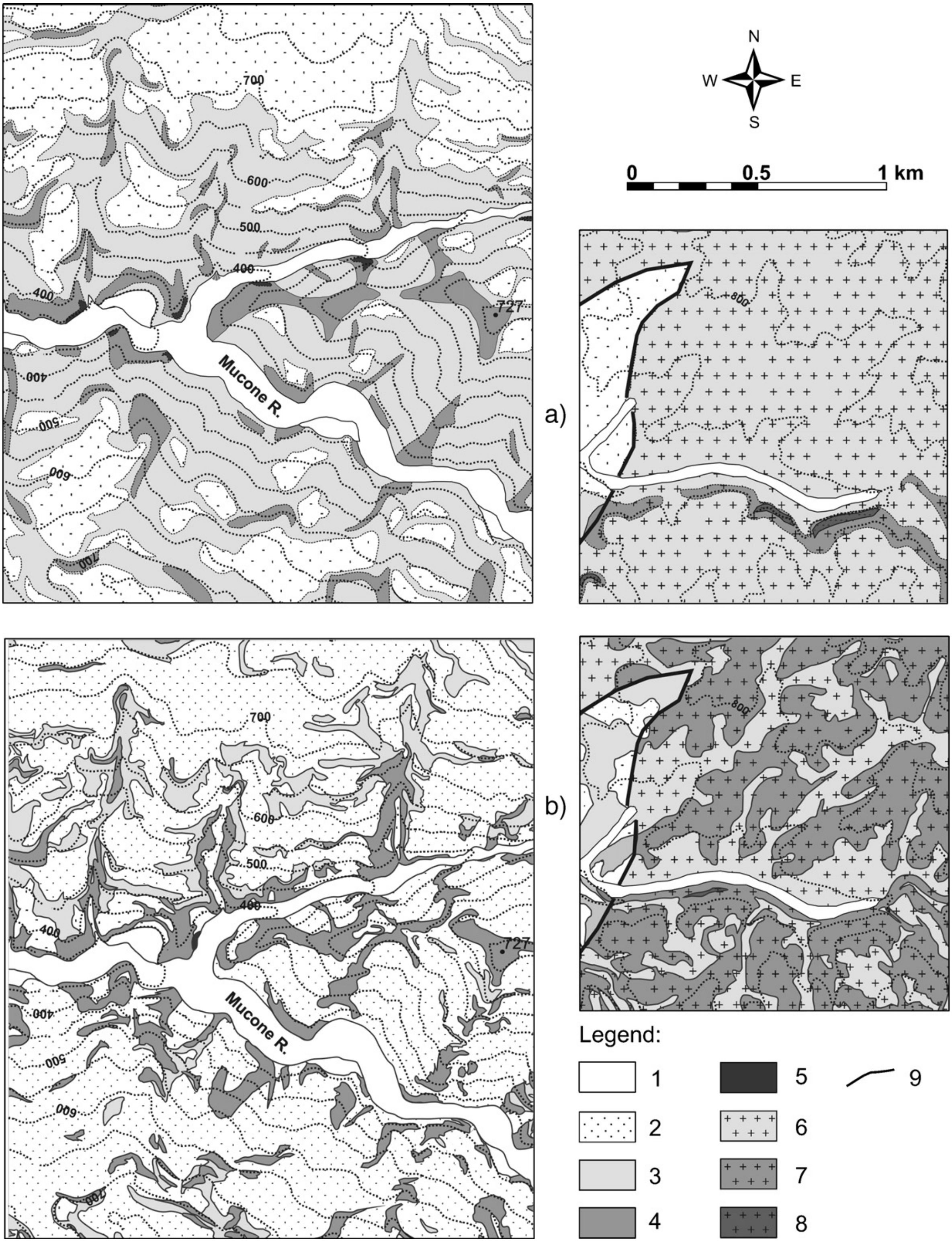


Fig. 13. Comparison at detail scale between two portions of weathering maps obtained by: a) reconnaissance procedure; b) control procedure. Legend: 1) sedimentary deposits; 2) class VI gneiss; 3) class V gneiss; 4) class IV gneiss; 5) class III gneiss; 6) class VI granites; 7) class V granites; 8) class IV granites; 9) tectonic boundary.

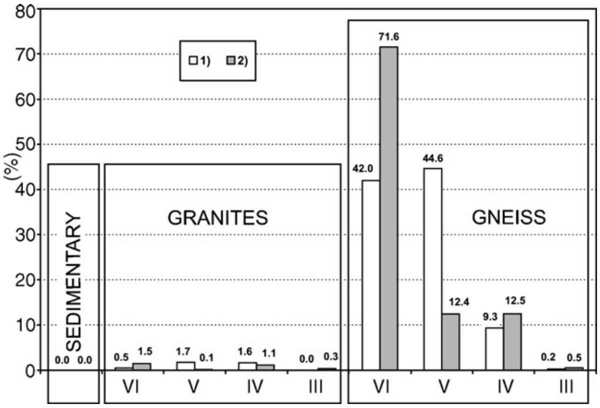


Fig. 14. Comparison at detail scale between the ratio percentage of landslide area of each lithology (sedimentary; granites and gneiss in weathering classes) and total landslide area obtained by: 1) reconnaissance procedure map; 2) control procedure map.

soils show a percentage of gravel and sand between 52% and 74%, while the samples in completely weathered granites have a percentage of gravel and sand between about 80% and 97%. A progressive increase in weathering produces a gradual transformation of the grain-size curve (Fig. 8), to accord with what is reported in literature for different geo-environmental contexts (Lumb, 1962; Cascini and Gullà, 1993). The results obtained allowed us to verify the preliminarily classification of weathering grade in the same check sites (Table 1), and indicate that this kind of analysis can be used as a tool to discriminate, in uncertain situations, residual soils from completely weathered rock.

Some cutslopes have been examined to get information about the thickness of weathering profiles (Fig. 9). The cutslope illustrated in Fig. 9a is an example of a complex weathering profile in the gneiss of the study area. It is noticeable that the effects of weathering are intense and complex. The transition between weathering classes can be either gradual or sharp. The highly weathered rock masses have a variable thickness from 0.5 m to about 4 m. Near the most important discontinuities, gneiss changes its texture and becomes soil-like in character (completely weathered rock); the thickness of these zones ranges from 2 m to 5 m, and the colour is prevalently dark brown and/or red-brown with yellow discolourations. The weathered rocks are intruded by pegmatitic dykes with a thickness of about 1 m. The weathering profile includes an upper zone, up to 0.5 m of thickness, constituted by residual and colluvial brown-coloured soils. The weathering condition is associated with an intense fracturing determined by joints, thrust faults and some normal fault planes. Moreover it is possible to observe fault gauge along some fault planes.

The cutslope reported in Fig. 9b is representative of the weathering profiles recognisable in outcropping granite. In this case it is possible to notice the heavier effects of weathering processes: completely weathered granites (class V) and residual and colluvial soils (class VI). The weathering profile is simple (Brand and Phillipson, 1985). The completely weathered rock zone has a variable thickness from 2 m to 5 m, with intrusions of pegmatitic dykes that show a weathering grade generally lower than the incorporating rock. The class VI zone, constituted by residual and colluvial dark-coloured soils, is continuous and with a limited thickness, about 1.5 m. This cutslope shows the same structural conditions described above for the gneiss cutslope.

### 4.3. Weathering map from the control procedure

The results obtained from the control procedure allowed us to review the weathering grade map resulting from the 1:10,000 reconnaissance procedure (Fig. 10). With regards to the spatial distribution of weathering grade: class VI is present as isolated outcrops both on top reliefs and in the mid-lower parts of the slope; class V is widespread on the right valleyside of the Mucone river, constantly present above an elevation of 750 m; class IV is widespread on the mid-lower parts of the western and eastern slopes above the Mucone river, and in isolated outcrops mainly in the zones of Serra di Buda and Duglia; class III, finally, is present above all on the hill occupied by the historical centre of Acri and in some isolated outcrops on the right slope of the Mucone river.

From the control procedure map the total surface of 23.3 km$^2$ is made of 94% crystalline rocks (granites and gneiss). The 21.8 km$^2$ of outcropping crystalline rocks are constituted of 69% gneiss and 31% granites. Weathering classes from VI to III are present in outcrops, for the whole study area: class VI accounts for 50% (13% granites and 37% gneiss), class V for about 34% (14% granites and 20% gneiss); class IV for 9% (2% granites and about 7% gneiss); finally class III is present with a percentage of about 1% (0.3% granites and 0.5% gneiss) (Fig. 11).

In relation to slope instability, whose location is reported in Fig. 10, the distribution of the total surface affected by landslides (4.4 km$^2$) is about 73% for weathering class VI (2% granites and 71% gneiss); about 13% for class V (0.1% granites and 12.4% gneiss); 14% for class IV (1% granites and 13% gneiss); finally about 1% for class III (0.3% granites and 0.5% gneiss) (Fig. 11). The percentage of landslide area in class VI is clearly greater than that in classes V and IV (almost equal) and is irrelevant in class III.

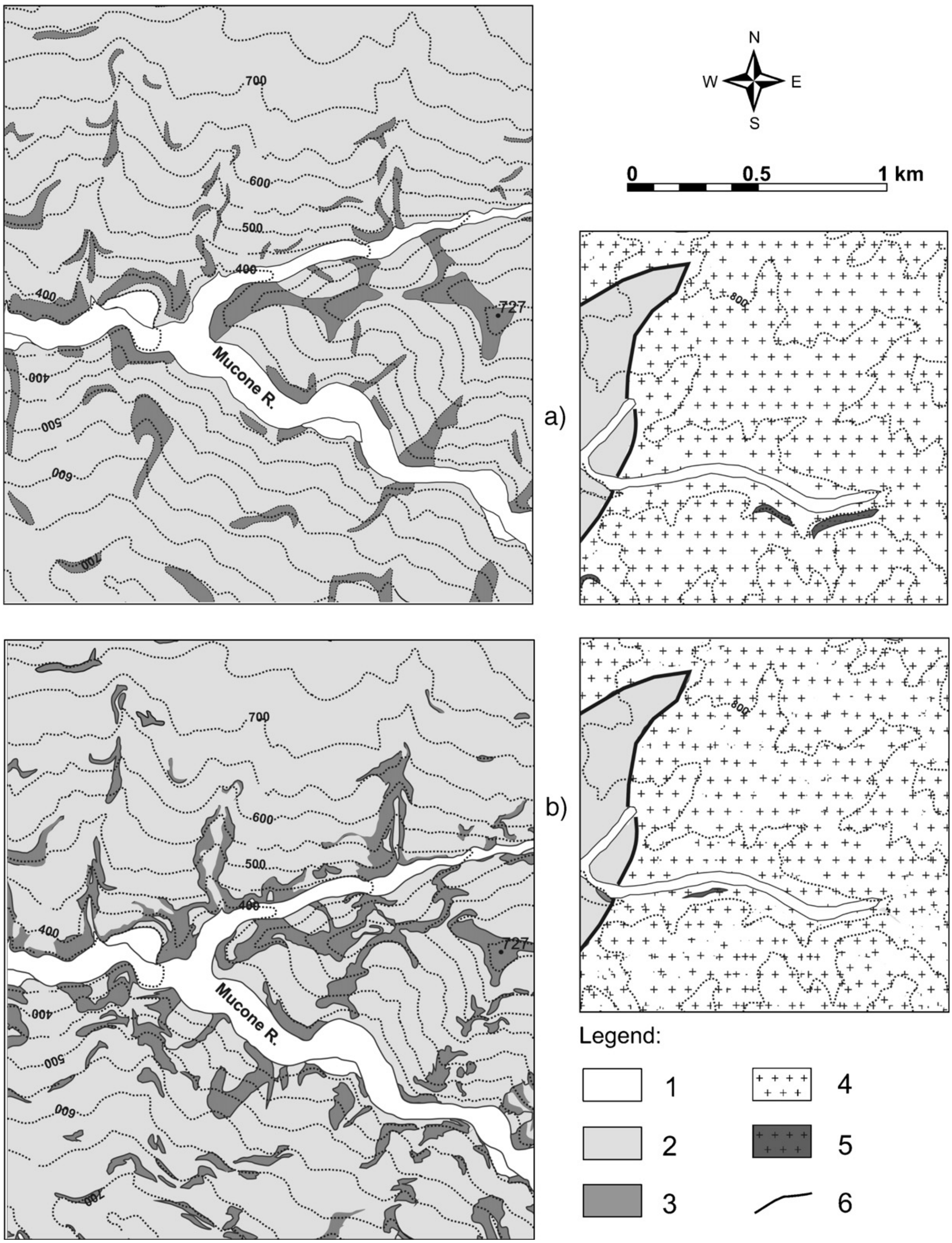


Fig. 15. Comparison at average scale between two portions of weathering maps obtained by: a) reconnaissance procedure; b) control procedure. Legend: 1) sedimentary deposits; 2) macro-class A gneiss; 3) macro-class B gneiss; 4) macro-class A granites; 5) macro-class B granites; 6) tectonic boundary.

### 4.4. Verification of reconnaissance procedure

With regards to the surfaces of the weathering classes at the detailed scale (1:10,000), from the comparison between the reconnaissance procedure map and control procedure map it appears that: in granites class VI reduces from 22.3% (reconnaissance procedure) to 12.9% (control procedure), class V increases from 4.9% to 14.1%, class IV increases from 0.7% to 2%, class III is present only with a percentage of 0.3% in control procedure map; in gneiss class VI increases from 29.9% to 36.8%, class V reduces from 29.4% to 20.1%, class IV increases from 5.3% to 6.9% and class III increases from 0.1% to 0.5% (Fig. 12). In Fig. 13 examples of these differences are shown for two representative portions of the study area, where gneiss and granites outcrop.

As a consequence there are also differences in the ratio between the landslide area of each weathering class and the whole landslide area. In particular for granites the differences are not so relevant, there is an increase in the landslide area in class VI (from 0.5% to 1.5%), a decrease in classes V (from 1.7% to 0.1%) and IV (from 1.6% to 1.1%). Class III, not present in the reconnaissance procedure map, presents a 0.3% of landslide area. For the gneiss there is a clear increase in the landslide area for what regards class VI (from 42% to 71.6%), a clear decrease for class V (from 44.6% to 12.4%), and a slight increase for classes IV (from 9.3% to 12.5%) and III (from 0.2% to 0.5%) (Fig. 14).

In Fig. 15, at average scale, the control procedure map has been compared with the reconnaissance procedure map for the same two representative portions. In Figs. 16 and 17 it is possible to observe that there are no relevant differences either in the weathering macro-class or in the landslide percentages.

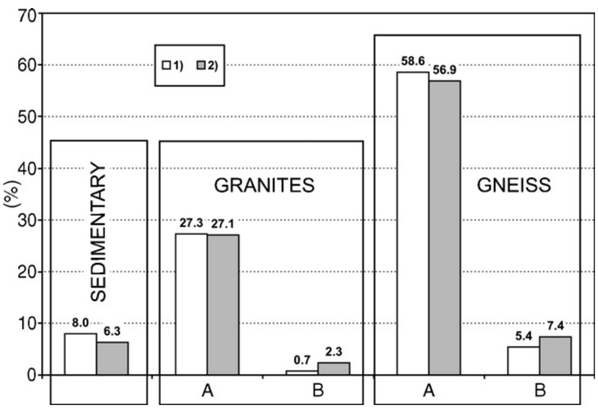


Fig. 16. Comparison at average scale between the ratio percentage of cropping rock area (sedimentary; granites and gneiss in weathering macro-classes) and total study area obtained by: 1) reconnaissance procedure map; 2) control procedure map.

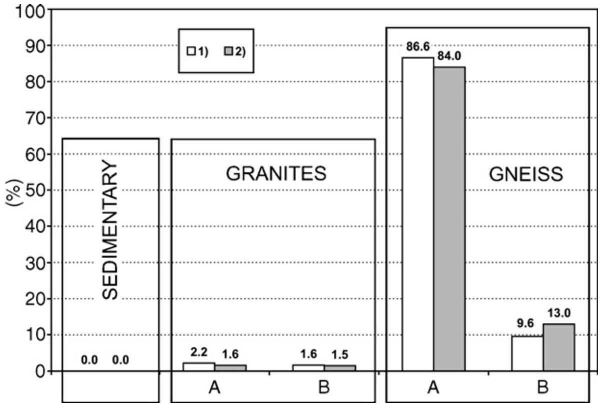


Fig. 17. Comparison at average scale between the ratio percentage landslide area of each lithology (sedimentary; granites and gneiss in weathering macro-classes) and total landslide area obtained by: 1) reconnaissance procedure map; 2) control procedure map.

## 5. Conclusions

The results obtained confirm through quantitative data that the weathering of rock masses can be assumed as a predisposing factor to slope instability. The verifications carried out through the control procedure show that at a scale of 1:50,000 the reconnaissance procedure is able to give representative weathering maps for this type of evaluation. In particular the ratio between the area of the landslides in each weathering macro-class and the whole landslide area is from 67% to 14% for the macro-class A and from 24% to 9% for the macro-class B. At a detailed scale of 1:10,000 reconnaissance procedure maps give preliminarily indications, but it is necessary to use a control procedure to obtain weathering maps that are indicative of a predisposition to slope instability.

The tests carried out with the Schmidt Hammer in more than 140 check points gave a useful indication of the relationships between weathering grade and mechanical strength index (Fig. 6).

A preliminary characterisation of the grain-size envelopes relative to classes VI and V granites is shown in Fig. 7. In the detailed survey, this feature has confirmed the possible use of grain-size curves as an analytical tool to distinguish residual soils from completely weathered rocks (Fig. 8).

For the observations carried out on the studied cut-slopes, the weathering profiles, both in gneissic and granitic rock masses, are particularly intense and only weathering classes IV, V and VI are present. In particular weathering profiles are generally complex in gneiss, while they are simple in granites (Fig. 9).

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