

Geological Society Engineering Geology Special Publication No. 23

# Weathering as a Predisposing Factor to Slope Movements

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Published by The Geological Society

# Weathering as a predisposing factor to slope movements: an introduction

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Recognition of weathering as a primary process in the development of landforms dates back at least to the late 19th and early 20th century, as indicated by several contributions from various countries (e.g. Cortese 1895; Branner 1896; Falconer 1911; Jutson 1914; Walther 1915); nevertheless, it was only in the second half of the last century that systematic studies on weathering and related topics such as geomorphology, engineering geology and petrography were carried out. In a recent review paper Ehlen (2005) found through an on-line search more than 9000 hits where the term 'weathering' was used, dating from the mid-1950s to the beginning of the 21st century. Such a huge number of citations clearly demonstrates the attention that the scientific community has dedicated to the in-place breakdown of rocks by chemical, physical and biological processes. However, despite the high frequency of landslides and erosional phenomena in weathered materials, and the damage and casualties they repeatedly cause, not very much is known about the direct and indirect relationships between weathering and slope movements. The matter is further complicated by the high variability of landslide features (Working Party on World Landslide Inventory 1993). According to the local conditions, a variety of slope movements may take place in the weathered rock masses. Shallow soil slips evolving to rapid and catastrophic debris flows are probably the most common type in steep residual soil slopes, whereas thicker failures, also including deep-seated complex movements, can affect large volumes of weathered rocks.

Following the first, simplified attempts to classify slides in natural slopes of residual soils (e.g. Morgenstern & de Matos 1975; Vargas & Pichler 1975), Durgin (1977) provided a comprehensive scheme of the relationships existing between landslides and weathering (Table 1). In general terms, studies on weathering-related landslides showed that in the less weathered rock volumes joints preferentially control the occurrence of instability phenomena such as rock falls and toppling failures, whereas in soil-like terrains failures are generally controlled by the interactions between the constituent elements (e.g. grains, clasts, blocks).

Although the fundamental geological and geomorphological features of weathering-related slope movements have been recognized with respect to both soil-like and rock-like materials, little attention has been paid to the mechanics and kinematics of the most important instability typologies in weathered materials. In this respect, in recent times, matric suction has been usefully considered in some studies dealing with the weathered cover, following the basic assumptions of the unsaturated soil theory (Fredlund & Morgenstern 1977). Matric suction, or negative pore pressure, increases the apparent strength of a soil; its role in controlling the stability of steep residual soil slopes after heavy and prolonged rainfall has been analysed in regional settings worldwide (e.g. Rahardjo *et al.* 2004; Cascini *et al.* 2006; and papers in this volume by **Alonso *et al.*** and **Picarelli & Di Maio**), thus representing a promising direction toward a better comprehension of the behaviour of weathered slopes and the occurrence and development of the related instabilities.

This Special Publication brings together papers presented at the Fourth General Assembly of the European Geosciences Union in Vienna, 15–20 April 2007, together with invited contributions. In this volume, following previous work (see Parise *et al.* 2004; Ollier *et al.* 2007), geomorphologists, engineering geologists and geotechnical engineers contribute to an up-to-date overview of approaches, methods and techniques devoted to better understanding the weathering conditions of rock masses on slopes.

The book includes worldwide case-studies, in which a variety of geological and geomorphological settings are treated, and is divided into three main sections, dealing with broad aspects of the weathering–landslides issue, and the analysis of slope movements in igneous or metamorphic and sedimentary weathered rocks.

The intention of the editors was to consider the subject from a different point of view than the usual climatic perspective in which the response to weathering agents is related to the specific environmental conditions typical of low, intermediate and high latitudes, respectively; such a

From: CALCATERRA, D. & PARISE, M. (eds) *Weathering as a Predisposing Factor to Slope Movements*.

Geological Society, London, Engineering Geology Special Publications, **23**, 1–4.

DOI: 10.1144/EGSP23.1 0267-9914/10/\$15.00 © The Geological Society of London 2010.

**Table 1.** *Weathering–mass movement relationships according to Durgin (1977) as reported by Migoñ*

| <i>Stage of weathering</i>                           | <i>Mass movements</i>  |
|--|--|
| Saprolite (thoroughly decomposed rock)               | Rotational slides, slumps  |
| Decomposed granite (<15% of fresh rock left)         | Debris flows, debris avalanches, debris slides   |
| Corestone stage (15–85% of fresh rock left)          | Rock fall avalanches, rolling rocks  |
| Fresh rock (<15% of weathered material along joints) | Rock falls, rock slides, block glides; debris avalanches and slides over sheeting surfaces |

scheme is based on studies such as that by Peltier (1950), where, starting from nine morphogenetic regions, eight weathering regions were set up, obtained by adding the intensity of both chemical and frost weathering in relation to rainfall and temperature.

At the same time, the nature of bedrock is commonly recognized as one of the main factors controlling the formation of weathered mantles and related landforms. However, although the main weathering-affected regions of the world have been adequately studied from the morphogenetic standpoint, rock weathering research has been mainly focused on granites and limestones, neglecting other rock types (e.g. marls, sandstones, low-grade metamorphic rocks), which are only occasionally dealt with from a weathering perspective.

In this Special Publication, the first, introductory section is opened by **Ollier** with a paper concerned with the principles of deep weathering. The author, claiming that ‘perhaps the greatest hazard in deep weathering is the failure to recognize it’, highlights that most geologists and engineers do not appreciate the great depths that weathering can attain. Further attention is paid to the current terminology, which, after more than 50 years of studies on weathering, is far from being unanimously shared; in this respect, the terminological confusion between soil, saprolite and regolith, discussed, among others, by Ehlen (2005) and Ollier *et al.* (2007), is typical.

The famous Po Shan landslide (which caused 67 fatalities) that occurred in 1972 in Hong Kong is used by **Ollier** as an example of the relationships between deep weathering and mass movements. This landslide induced the Hong Kong Government to systematically tackle the landslide hazard through a specific department, previously known as the Geotechnical Control Office, at present the Geotechnical Engineering Office (GEO). Hong Kong is also the focus of the paper by **Hencher & Lee**, who review the nature and mechanics of landslides in the weathered terrain there. In this paper, the authors present a relationship that links intensity of landsliding to the 24 h rainfall. The gradual deterioration

and internal erosion of slopes prior to detachment is discussed, with emphasis on the growth of natural piping systems and infilling of dilated fracture networks, which are recommended as important indicators of landslide development. The conclusions are supported by case examples of slope failures, the study of some of which has been taken to a forensic level.

A wide review dealing with the contribution of mass movement to the development of landforms in weathered granite and gneiss terrains is offered by **Migoñ**, using examples from SE Brazil, southern Mexico, SE China and elsewhere. A summary relationship is discussed, related to the weathering classification scheme by Ruxton & Berry (1957) and the Geological Society Engineering Group Working Party (1990). As described by **Migoñ**, the style of slope failures varies depending on the local relief and the grade of weathering (Fig. 1). Shallow debris slides and boulder falls are common in less weathered rock and steep terrains, whereas rotational slides appear to dominate in highly weathered rock and in more subdued topography. In certain topographic circumstances, slides may turn into debris flows or earthflows.

Two contributions in the first section have the theme of the behaviour of fissured, weathered clayey rocks.

**Alonso *et al.*** analyse the strength degradation of two marl formations from the Iberian peninsula, which show similar responses as a consequence of physical weathering processes (sucation changes and stress changes). According to **Alonso *et al.***, unloading changes effective stresses and leads to swelling of rocks if active minerals are present, whereas water content changes (sucation changes) induce plastic deformations producing fissuring of the rock. Through an extensive laboratory test campaign, partly related to a foundation–rock interface of a gravity dam and to a tunnel, the evolution in behaviour of the studied formations is demonstrated along with implications for weathering-related slope instability. The paper by **Picarelli & Di Maio**, based upon laboratory testing, field observations and ‘pure speculation’ (the authors’ own words), examines some processes of deterioration of stiff overconsolidated clays and clay shales, which, in turn, are considered among the main causes of landslides in fine-grained soils. In particular, deterioration localized within soil bands or involving large soil masses is described, with reference to its mechanical or physico-chemical causes. Again, confusion in terminology is highlighted: softening and strain-softening are frequently mentioned as the main causes of deterioration, as well as other phenomena, such as slaking, destructuring or fatigue.

In the second section, devoted to landslides in igneous and/or metamorphic rocks, four papers are dedicated to weathered magmatic rocks and related slope movements, treating case studies from Italy, Ethiopia, the USA and Brazil.

**Calcaterra & Parise** review about 40 years of studies focused on landslides in weathered plutonic and metamorphic rocks of the Calabria region in southern Italy. There, some researchers have recognized an ancient

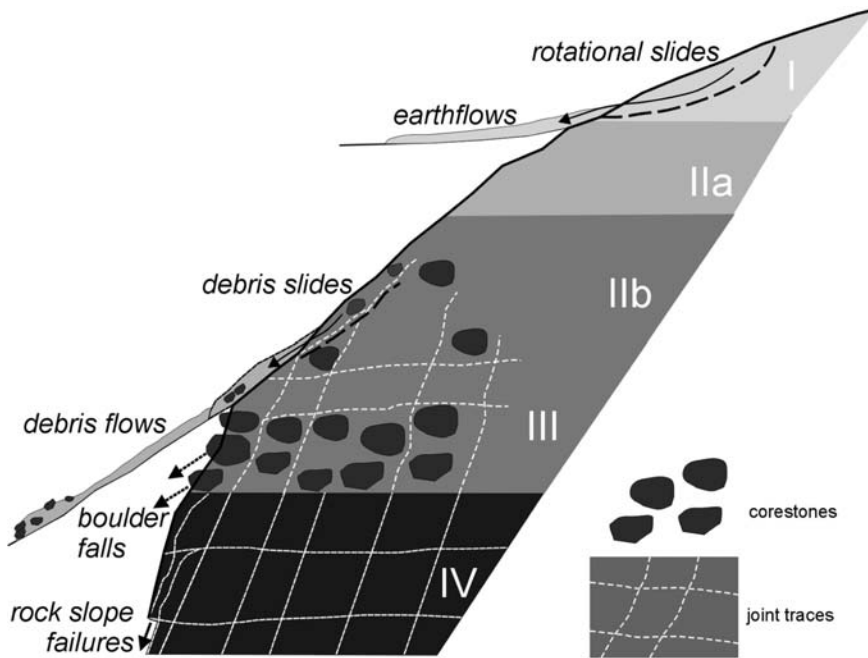


Fig. 1. Weathering grade-mass movement relationships in basement rocks, as described by Migoñ.

(Tertiary) weathering, which could be regarded as one of the main reasons for the depth of the weathered mantle: in some districts, the depth to unweathered rocks is as great as 150–200 m, displaying a complex profile. On the Calabrian slopes almost all the main typologies of mass movements have been recognized, ranging from shallow soil slips to extremely rapid debris flows and to slow-moving deep-seated gravitational slope deformations. In many cases, development of landslides has to be related to the availability of weathered materials on the slopes, and landslides are triggered by the main factors active in that region, from seismic shocks to intense and clustered rainfall events and, last but not least, anthropogenic actions.

**Delmonaco et al.** consider the weathering processes that affect the stability of the rock-hewn Orthodox churches of Lalibela, in Ethiopia, cut out of weathered basalts and volcanic tuffs some 800 years ago. Field surveys, *in situ* geotechnical analyses and laboratory tests have revealed that water represents the main causative factor of damage, in terms of direct rainfall, soil infiltration, capillarity and diffuse humidity; an important role is played by the presence of montmorillonite in the weathered volcanic materials. Major consequences are the alveolar weathering of the churches' façade, the degradation of the roofs, a reduction in the rock strength and sliding of façades along bedding joints.

**Latham et al.** discuss a case study from Haywood County, North Carolina, USA. The Hunters Crossing landslide, a slow-moving, weathered rock slide, involves a small community of condominiums in the town of

Waynesville, where a complex suite of metamorphic rocks (migmatitic metagreywacke, schist, gneiss) crops out. After a detailed site investigation campaign, it appeared that the failure surface was potentially located at about 11 m below the ground surface, possibly at the contact between saprolite or completely decomposed rock and partially decomposed rock. However, inclinometers installed at two locations on the slope have not detected enough movement to corroborate that assessment.

Based upon some decades of specific research, **Lacerda** reviews the main properties of the Brazilian saprolitic and lateritic soils, with special attention paid to shear strength parameters, a basic topic to better comprehend the mechanics of landslides. **Lacerda** concludes his paper by stating that many slides in residual soils are directly related to relict structures inherited from the parent rock, and the residual strength is relevant in these cases. Moreover, the existence of 'true' cohesion in lateritic soils is particularly important in the initiation of shallow slides.

Three case studies dealing with sedimentary weathered formations are presented in the third section of the book.

The interrelationship between slope deformation and fault-induced weathering as a preparatory factor for the development of sliding is analysed by **Pánek et al.** through several case studies from the Western Carpathians in the Czech Republic. The study area comprises flysch nappes with alternating sandstone and shale of different permeability. By means of geomorphological analyses, the authors demonstrate how weathered fault zones influenced

the development of some of the largest and most active slope failures in the study area, among which some deep-seated lateral spreading and complex movements in massive bedrocks are described.

To clarify the erosion processes on a marly bare slope in the southern French Alps, the erosion processes on a steep and erodible slope composed of Black Marls formations were observed by Yamakoshi *et al.* using a time-lapse video camera. The observations revealed that miniature debris flows occurred at the time of the rainfall–runoff event during which the most severe erosion took place over the 3 month observation period. With the term ‘miniature debris flows’, the authors define small-scale flows inside the slope rills, where sometimes intermittent surges form, identical to debris flow in natural torrents.

Meisina closes the volume with a contribution on a new correlation between the residual shear strength and the methylene blue value for weathered clay soils on argillaceous bedrock and on alluvial soils in the Oltrepo Pavese area of Northern Italy; shallow landslides occur periodically in these soils as a result of high-intensity rainfall. The method, although not an alternative to the classical laboratory tests, is considered helpful for a rapid assessment of residual shear strength for design purposes and hazard studies.

Following four years (2004–2007) of organization of a specific symposium on ‘Slope movements in weathered materials: recognition, analysis, and hazard assessment’, within the framework of the General Assembly of the European Geosciences Union, our hope is that the present volume might provide useful hints on this issue, and encourage further efforts at both the local and the international level to move in the direction of gaining a more thorough knowledge about the way weathering acts in predisposing natural slopes to the occurrence of mass movements, thus contributing to the process of mitigating the risks related to natural hazards.

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This volume is intended to provide an up-to-date overview of the approaches, methodologies and techniques devoted to better understanding of the weathering conditions of rock masses on slopes. According to the local conditions, a variety of slope movements may take place and involve weathered rock masses. Shallow and rapid soil slips evolving to debris flows are probably the most common type of slope movement. At the same time, deep-seated, intermittent landslides can also affect large volumes of weathered rocks and soils. Despite the high frequency of landslides in weathered materials, and the damage and casualties they repeatedly cause, little is known about the relationship between weathering and slope movements. This book presents worldwide case studies, where a variety of geological and geomorphological settings are discussed. The content is divided into three sections: the first is devoted to broad aspects of the weathering/landslide processes; the second and third sections include papers dealing with igneous/metamorphic and sedimentary weathered rocks, respectively.

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**Cover illustration:**

Landslide- and erosion-fed alluvial fan in the Assi river, Serre Massif.  
(Calcaterra & Parise)