Weathering and erosion

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Denudation processes: weathering and erosion

Geomorphologists and physical geographers used many words to define the physical and chemical degradation of landscape. Weathering indicates the chemical and physical breakdown of rock materials in response to environmental conditions, while erosion defines the loss of material from its pre-existing position and its transport to other locations (Trudgill, 1983). Erosion acts both on unaltered rocks and weathered materials. Sometimes the terms are confused: for example, (1) mechanical weathering can be referred to erosion processes, or (2) corrosion is confused with processes related to metal alteration. The term corrosion identifies the dissolution and biochemical weathering of carbonate rocks.

Gregory (1911), in an excellent bibliographical work, provided a comprehensive overview of the terms used so far. As highlighted by himself, the use of words with different meanings represented a handicap in geomorphology and the studies of geomorphological agents, such as ice and water, and of their relative importance.

In this paragraph, the ways of using the terms degradation, erosion, corrosion, denudation, etc. in the international geomorphological literature will be analyzed. A separate section is reserved specifically to dissolution and biodegradation processes, whereas most of the sites and measuring stations of the erosion rates are located on carbonate rocks, both bare or colonized by endolithic lichens.

![Fig. 1: Relation between geomorphological processes (from Fairbridge, 1965)](image-url)
Weathering + erosion = denudation

Mechanical weathering

Chemical weathering

Biological weathering

Frost shattering
Insolation
Salt weathering
Pressure release

Solution and Carbonation
Hydrolysis
Hydration
Oxidation

Biomechanical
Biochemical

Weathering is influenced by

Soil

Climate

Landscape

Depth
Chemistry

Slope
 Aspect

Petier curves

Tropical weathering

Arid weathering

Periglacial weathering

Fig. 2: Sketch of weathering and erosion processes (from Atkinson, 2004).
Weathering

Weathering includes the processes of disintegration of the rocks "in situ", without movement. It should not be confused with erosion, which involves movement of water, wind or ice. Weathering involves a modification in the chemical, mineralogical, and physical properties of the rock, in response to the environmental conditions in which the rock is located. However, unlike the metamorphic processes, it takes place in the range of the Earth's surface temperatures. Some authors use also the term meteoric degradation instead of weathering.

Trudgill (1983) stated that the degradation systems are multifactorial and dynamic, and they are subject to experimentation in terms of inputs, outputs and internal processes. Moreover, the initial state, available energy and residual state can be defined.

Weathering processes can be divided into chemical weathering and physical weathering, although in nature it is impossible to distinguish chemical and physical processes, since they usually occur simultaneously (Fairbridge, 1968). For example, the crushing of rocks due to mechanical weathering increases the surface area exposed to chemical processes, while the chemical processes on crushed minerals are able to accelerate the mechanical process. As suggested by Atkinson (2004), it is often difficult to separate the processes also because, as in the case of salt weathering, the crystallization processes involving salt are chemical, but the forces involved in increasing the volume area are mainly mechanical.

Some authors distinguish the biological weathering (or bioweathering), due to the action of living organisms, from the aforementioned weathering processes. Organisms, in fact, may alter the rock starting from the abovementioned processes, in particular chemically, such as cyanobacteria, or physically, as some benthic organisms, or both, as endolithic lichens.

The intensity of physical and chemical degradation processes is indicated quantitatively as weathering index. Chemical weathering is expressed as the ratio of more stable and less stable materials, or also as the ratio of non-degraded and degraded minerals in a given volume. Physical weathering is expressed as the change in hardness and strength of materials, or as the ratio of the absorption capacity of the non-degraded and degraded materials (Whittow, 1984).

The intensity of weathering differs from the rate of degradation since the first refers to the degree of decomposition in a given time, while the rate is related to the amount of variation per unit time (Blend & Rolls, 1998).

Physical weathering

Physical and/or mechanical weathering include those processes that disintegrate without chemical alteration of the rock forming minerals (Blend & Rolls, 1998).
These processes, as indicated by Summerfield (1991), are related to a range of mechanisms whose effectiveness is not totally known, but clearly vary significantly as a function of environmental conditions.

The physical weathering processes are the following:

- wetting and drying cycles;
- thermal expansion (or spheroidal weathering), also known as onion skin;
- release of pressure, when superimposed materials are removed,
- haloclasty (Fig. 4) due to the presence of salts (or salt weathering),
- the weathering due to the presence of water (water-based weathering);
- freeze-thaw cycles (freeze-thaw weathering), which is related to the pressure exerted by the presence of water which leaches into the joints (Blend & Rolls, 1998);
- hydration, that occurs because of the increase of the temperature and evaporation of water,
- crystal growth, which produce stresses causing a bulge in the rock and consequently hydraulic weathering.

Moreover, also the fundamental process of mechanical action exerted by the waves on the cliffs along the coast.

![Physical weathering on granitic rocks (California).](image)

**Fig. 3:** Physical weathering on granitic rocks (California).
The order in which these processes occur and their intensity is very difficult to evaluate and quantify. Furthermore, since the mechanical degradation implies the movement, even if modest, it is often confused with erosion.

Fig. 4: Haloclasty on coastal sandstones (Island of Pag, Croatia)

**Chemical weathering**

Chemical weathering produces modifications in the chemical composition of the minerals causing the breakup of the rocks. Chemical reactions do not necessarily include all the minerals. Unlike the mechanical weathering, which leads to break the former materials, chemical weathering involves their decomposition.

The processes included in this category are:

- dissolution, which is the most important type of weathering in carbonate rocks (a separate paragraph is dedicated to this process);
- hydration, the saturation, due to the fact that some minerals are able to absorb water in their structure increasing their volume, and then causing an increase in the stress within the rock;
- hydrolysis, which is related to the presence of silicates, such as feldspar and granite. It occurs when water reacts with the minerals in the rocks and decomposes them;
- oxidation, which involves metals and is a process of degradation and recomposition with other elements to which pure metals are affected;
- corrosion, geomorphologists use this term or as a synonym of chemical degradation or to indicate limestone dissolution.
Solution and corrosion

Dissolution, or solution covers all so-called soluble minerals. Soluble rocks are also those which contain salt and gypsum rocks, less wide than the carbonate rocks, but equally important from the point of view of the dissolution. In the case of the carbonates dissolution processes, the solution of the rock occurs in the presence of carbon dioxide; This is referred to corrosion. The calcium carbonate, in fact, is not soluble in pure water, however, the presence of weak acids favors the solubility. The addition of CO₂ to the water the rainwater into carbonic acid. The calcium carbonate thus becomes soluble in carbonic so that the limestones are subject to a higher solubility.

The complex chemical interactions that affect the dissolution of limestone processes take place according to the known formula:

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\text{CO}_2 + \text{H}_2\text{O} + \text{CaCO}_3 = \text{Ca}^{2+} + 2\text{HCO}_3^-
\]
As said, the dissolution process is rather complex and takes place according to several stages. It can also go from left to right, if the temperature is low and the high CO₂ partial pressure, giving rise to corrosion and from right to left, as occurs inside the cavities, where they form the calcite concretions. The calcium carbonate (CaCO₃) in the rock is transformed by rainwater (with H₂CO₃) and produces calcium ions (Ca²⁺) and bicarbonate ions (2HCO₃⁻), both soluble in water. The amount of CO₂ or other acids determines the water aggressiveness, or the ability to dissolve the calcium carbonate contained in the rock. Although limestone is an impermeable rock, the presence of a dense network of fractures makes the rock mass particularly vulnerable to chemical degradation. The dissolution can be greatly accelerated by the presence of acids from industrial pollution (Atkinson, 2004).

Also the sulfur dioxide produced by volcanic eruptions, from fossil fuels or from the decomposition of organic material, is able to transform in sulfuric acid and lead to the solution of rock minerals, such as atmospheric nitrogen which, turning into nitric acid, may cause disintegration in solution of the rocks. Anyway, in a nutshell, by studies and research in situ it can be stated that micritic carbonate rocks are more susceptible to corrosion than sparites; a heterogeneous texture promotes corrosion; the corrosion develops preferentially at the level of the planes of discontinuity. These results show that there is a relationship between petrography and corrosion.

Fig. 6: Karst landforms along a limestone coast (Ahrax Point, Malta)
Fig. 7: Small pits in the mid-tidal zone (Pisulj island, Croatia)

Fig. 8: Microrills at Krk island (Punat, Croatia)
Bioweathering

Biodegradation is caused by the demolition of plants and animals on the rock. It can be both chemical and physical. Trudgill (1976) includes the biological degradation in the chemical degradation, but recognizes the difficulty of distinguishing the two processes: for example, a mineral can be degraded by an acid, but the acid can derive from the physiological processes of organisms. Other bodies such as the Patella coerulea, especially in the littoral zone, can scrape or dig (grazing) the surface layer of rock weakly weathered by the action of purely chemical endolithic organisms, as cianofiti, lichens and mushrooms (Schneider, 1976). The contribution of all these bodies is sufficiently identified to recognize it as a separate category, divided in turn into degradation biophysical and biochemical degradation (Blend & Rolls, 1998).

The organisms may exert efforts of physical type, such as the expansion and contraction of the plant tissues in alternating phases of dry\wet or chemical degradation actions, such as lichens, emitting carbon dioxide can increase the dissolution of carbonates. The wide distribution of biological agents, the Antarctic dry areas, it is particularly important as degradation agents.

![Bioweathering by cyanobacteria (Premantura, Croatia).](image-url)
Bioweathering by endolithic lichens

Lichens are organisms formed by a fungus (mycobiont), dependent trophically from primary producers (fotobionti) (Honneger, 1998, 2001).

They are able to develop both physical and chemical degradation. The evidence of these actions are in the observation of the areas surrounding the lichen, which shows a superficial part of fragmented rock and a lower zone where the hyphae penetrate the rock sound.

The biophysical degradation is performed both due to the penetration of the hyphae, usually for depth of 1-3 mm, which create tensional efforts in most rocks, both due to the expansion of the thalli of the hyphae and due to the absorption of water (lichens increase the volume of water from 150% to 300%. According Blend & Rolls, 1998%).

The biochemical degradation is related to the production of organic acids, linked to the vital processes of these organisms. The effectiveness of an organic acid depends on its solubility in water. The oxalic acid, product from the fungal component, is soluble to the extent of 143 g/l (Blend & Rolls, 1998).

Particularly effective is the action of biological degradation in the so-called "endolithic environment", that is, under the stone surface, which represents an ecological niche for a range of microorganisms, said endolithic (Pohl & Schneider,
2002). On the rocks carbonate penetration within the substrate can be particularly massive as much as the mycobiont the fotobionte are able to actively dissolve the carbonate matrix, which is thus colonized for some millimeters thick, up to over one centimeter (Pinna et al., 1998). The surface alteration comes in the form of deposits, spots and pitting (hollows).

The presence of carbonic anhydrase (CAs), ie the enzymes that contain Zn$^{2+}$, catalyze the interconversion of carbon dioxide and bicarbonate ion. Their activity accelerates the dissolution of carbonates and is present, for example in the thallus of *Petractis Clausa*, in particular at the level of lithocortex, that is, the outermost layer of the lichen thalli and the hyphae, which determine the formation of cavities in the pseudomedulla. As demonstrated by Mathieu et al. (1973), the carbonic anhydrase have different roles, even in mycobiont, being involved in glaucogenesi in lipogenesis and in the dissolution of the substrate.

![Fig. 11: Lichen weathering (Photo Prof. Mauro Tretiach).](image)

**Erosion**

The term comes from the Latin *ex* = out and *rodere* = gnaw. It is a purely mechanical process whose description appears for the first time in 1774, in Natural History, Oliver Goldsmith. The erosion, in the modern conception of the term, involves either removal, then the acquisition of material, from the point that the transport of the material in which it was produced. Originally the transport was not included in the
processes of erosion. This is an important distinction with the degradation, in which the transport is not involved. Huxley (1877) associates the erosion to chemical processes and suggest that "the power of water to dissolve the calcium carbonate and then" eat away at the limestone rock". Gilbert (1877) introduced the term erosion by including the degradation, transport and action of running water. Fairbridge (1968) adds that the erosion removes rock debris, so the detritus.

The erosive agents, e.g. those that cause erosion, have running water (including waves, currents and tides), which erodes traction, saltation, suspension, solution and flotation, the wind that erodes by deflation, corrosion and abrasion ice, digging for scouring, plucking and sapping. So that erosion occurs, it is necessary that the erosive agent exerts a greater force on the rock surface to resistant forces. Once past this force and exceeded the elastic limit of the material, the resulting material will be moved in the direction of the force and will be delivered at different speeds.

Fig. 12: Abrasion landforms along the Eastern Adriatic coast (Croatia)

Note that the degradation favors erosion, but cannot be considered a prerequisite (Trudgill, 1983) nor an erosive agent. The erosion also refers to those of denudation processes that wear out the Earth's surface due to mechanical action of the debris carried by erosive agents and cannot be considered a synonym of denudation, as it is part of it. Using the two terms interchangeably, is not distinct erosion results from the process. Penk (1894) clearly distinguished the two terms, confining the erosion processes and the end result to denudation. Some authors include gravity, and then the landslides, erosion, while others exclude it, because of the usual difficulty of
distinguishing the individual processes: the case of a degraded material on top of a coastal cliff, which collapses to the foot and is removed by abrasion marina.

**Denudation**

The sum of the weathering processes of rocks, erosion and transport, responsible for the lowering of the topographic surface, is defined by the term denudation (denudation), indicating the morphological result of all agents wear out the earth's surface.

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\text{DENUDATION} = \text{EROSION} + \text{WEATHERING}
\]

**Measuring erosion rates**

Erosion involves the removal and transport of material by different factors, such as the running water. Sometimes, erosion may be enhanced by prior weathering. The knowledge of erosion rates can be very useful to model the differential evolution of reliefs and landforms (Trudgill, 1983). Anyway, it is fundamental to remember that current erosion rates may not be simply used to extrapolate past erosion rates. In fact, past regimes of erosion could be very different from nowadays (Trudgill, 1983).

Accurate instruments, such as MEM’s, can be used to evaluate rates of erosion directly using repeated observations of surface lowering. Erosion rates can be assessed also using indirect techniques, such as the comparison of reliefs or measures of mass or volume losses.

**Micro erosion meters**

Rock lowering rates can be measured using both MEM, following High and Hanna's (1970) instructions, and analogic or digital TMEMs (aTMEM or dTMEM), as described by Trudgill et al. (1981). These instruments are equipped with three specially shaped supports that adhere to three titanium studs (two semi-spherical and one flat shaped) that were fixed into the limestone slab. The exact relocation of the fixed studs was derived from the configuration called the Kelvin clamp principle. The height of the surface is measured relative to the studs and this reading can be repeated at fixed intervals depending on the rock.

Usually, MEM are equipped with a centesimal-resolution dial gauge and are only capable of collecting few measures (from one to three) for each station. The dTMEM is equipped with a millesimal-resolution electronic dial gauge. Digital readings can be directly downloaded on to a laptop computer (Stephenson, 1997). Using this
configuration, a large dataset can be obtained, with up to 238 measurements at a bolt site. Due to the large number of sites actually monitored (more than 600 stations all over the Mediterranean area), Furlani et al. (2011) and Furlani and Cucchi (2013) decided to consider only 25 readings from each station. Even if the number of readings was near the minimum required for the measured erosion rates (10 readings), as suggested by Trenhaile and Lakhan (2011), sometimes there can be a need to measure very quickly. Sometimes the number of readings can be reduced because organisms covered the slab and prevent measurements. A calibration steel base is used to check the instruments before every measurement session. The electronic dial gauge had a resolution of 0.001 mm, while the error, determined by the manufacturer (Mitutoyo), was ±0.003 mm. Readings below 0.010 mm must be considered with caution (Stephenson et al., 2004). To reduce temperature-related errors, the instrument was set in equilibrium with air temperature before use.

Probe erosion due to measurements was estimated by Furlani et al. (2011) using two different methodologies: (1) repeated readings on a test block, which revealed a probe erosion of 0.003 mm after 100 measures; and (2) through visual microscopic analysis of 20 samples of rock touched by the probe and 20 others untouched by the probe (this was performed by Prof. Mauro Tretiach of the Department of Geobotany of the University of Trieste). The micro erosion meter has been widely used to study limestone erosion rates (Trudgill, 1983). Mean limestone erosion rates are of the order of about 0.01 mm/a to 0.04 mm/a. These rates are rapid enough to be assessed over years of measures. Gomez-Pujol et al. (2007) and Furlani and Cucchi (2007) reported significant diurnal surface variations. Furlani et al. (2009) reported one order of difference between subaerlial rates and coastal rates, the late up to 0.15 mm/a. At the same time, Furlani and Cucchi (2013) measured erosion rates in the mid-tidal zone in the Gulf of Trieste and reported erosion rates ranging from 0 to 0.3 mm/a.
Recently, erosion rates were measured also using laser scanners (Swantenson et al., 2006), although the resolution allow to use it only in rocks with high erosion rates, or to measure the surface roughness.
Coastal vs subaerial erosion rates

Rocks exposed on coasts are often eroded into notches, on vertical cliffs, or pinnacles and potholes, in sub-horizontal surfaces. They are well-carved in the mid-tide zone because here marine processes are mainly focused (Trudgill, 1985).

Fig. 15: Laser scanner survey at Qarraba (Malta)

Fig. 16: Coastal marine and subaerial processes (from De Waele & Furlani, 2013).
Fig. 17: Coastal vs inland surface lowering rates (from Furlani et al., 2009).

Fig. 18: Limestone lowering rates in the mid-tidal zone (from Furlani and Cucchi, 2013).
References


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