Chapter 10
Weathering of Rocks in Brazil

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10.1 Introduction

Weathering is an important aspect of rock behavior especially in tropical regions, where the process is accelerated by temperature variation over a year and the considerable amount of water (from rain). All types of rocks can present considerable change in their mechanical behavior due to physical and chemical weathering. It is therefore important to characterize the influence of weathering on the mechanical behavior of weathering materials, from fresh rock to soil, including its transitional material, to provide useful geotechnical data for design of civil and mining works.

Several authors working in various places worldwide have studied the effects of weathering on geomechanical properties of rocks under different climate conditions. On this context, the works by Ruxton and Berry (1957), Deere and Patton (1971), Dearman (1974, 1976), IAEG (1981), Beavis (1985), Lee and De Freitas (1988), Dobereiner and Porto (1990), Dobereiner et al. (1993), Gupta and Rao (2000), Arel and Önalp (2004), Basu and Aydin (2004), Marques et al. (2005, 2010), Marques and Williams (2015a, b), Marques et al. (2017), and Leão et al. (2016) can be cited as those which, by studying weathering profiles developed on various rock types, have tried to characterize the variations in mechanical properties (Marques et al. 2017).

The study of the influence of weathering and weatherability is closely related to the development of weathering profiles, characterized by several transitional materials between rock and soil, phenomena very common on humid tropical regions as those existing both in Brazil. The occurrence of weathering profiles on geotechnical works involving cut slopes, foundations, underground and open excavations on civil

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and mining works is of fundamental importance for its stability, as the weathering imposes different materials with different mechanical properties to the design (Marques 1998; Marques et al. 2010). In addition to that, the presence of structural discontinuities which, besides favoring water percolation and weathering, also induces variations on mechanical behavior and control stability because of its geometry and strength properties. Thus, a complex and important mechanism for rock and soil failure is provided and has commonly been responsible for several mass movements on roads, foundations and mining cut slopes.

Brazil has a very complex and diverse geology, as can be seen in the map shown on Fig. 10.1. The most common rock types are as follows:

- Sedimentary rock types, such as claystones, siltstones, shales, and limestones, on approximately 50% of the country's total area, on sedimentary basins, as shown on Fig. 10.1.

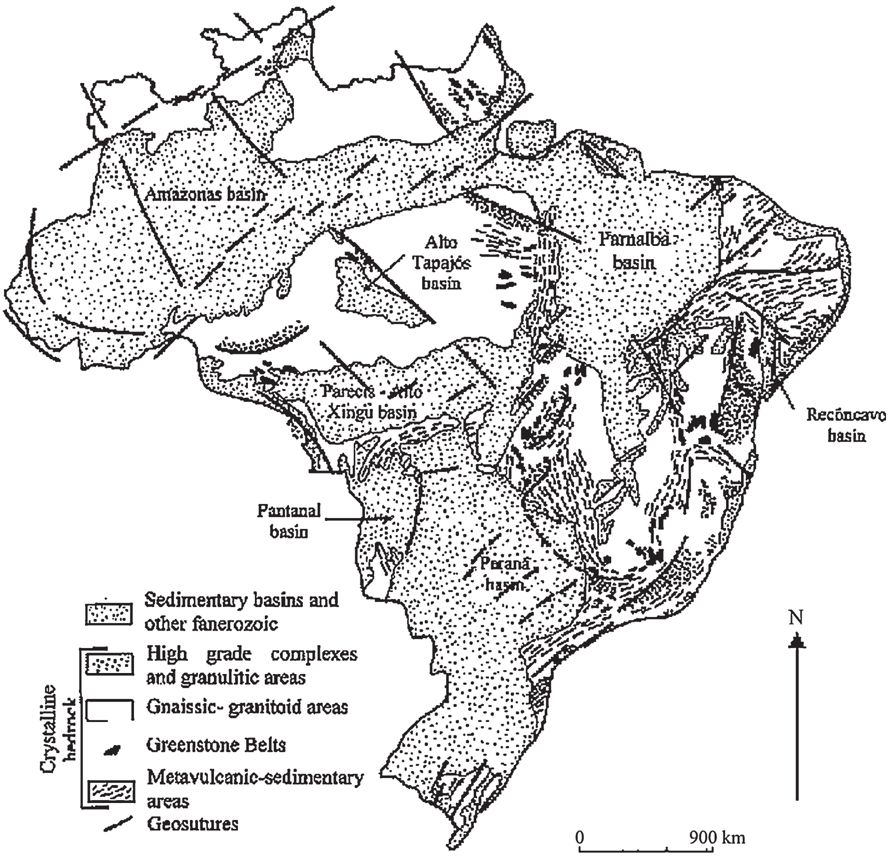

Fig. 10.1 Geological map of Brazil (Marques et al. 2005), showing its varied geology

- Metamorphic rocks, such as gneisses (several different types), amphibolites, migmatites, schists, phyllites, quartzites and marble, occupying gneissic-granitoid and high-grade granulitic complexes, and metavulcanic-sedimentary areas.
- Igneous rocks, such as basalts (Paraná basin), granites, diorites, and sienites occupying gneissic-granitoid areas and part of metavulcanic-sedimentary areas.

Weathering has been object of attention in more recent decades in Brazil, as this comprises an important mechanism controlling rock behavior on these areas. Presence of such profiles is a critical factor in the stability of cut slopes, foundations and underground excavations where the weathering produces materials with extremely variable behavior (reducing strength and increasing deformability and permeability). Further difficulty is provided by the presence of structural discontinuities that controls underground water movement and, hence, chemical weathering. The works by Menezes Filho (1993), Barroso (1993), Marques (1998), Marques et al. (2010), and Leão et al. (2016), should be pointed for metamorphic rocks. Regarding sedimentary rocks there are only few papers, the work of Marques et al. (2005) being one of the most recent. For igneous rock, Basu et al. (2009) have presented a study on evaluation of mechanical behavior on several weathering granite grades.

Another important aspect of considering weathering in design of civil and mining engineering in Brazil is that it can commonly reach several hundreds of meters in depth. Several engineering problems in Brazil are commonly related to weathering and among these problems the following deserves to be highlighted:

- Stability of mining and civil cut slopes (Fig. 10.2a, b).
- Instability of natural slopes (Fig. 10.2c).
- Underground excavation problems (Fig. 10.2c).

In the present chapter the main aspects that controls weathering in Brazil are presented, including their typical morphologies. The intention is to present general characteristics imposed by weathering on a tropical area and their influence on physical, chemical, mineralogical, and mechanical properties of the materials found in weathering profiles, focusing on sound rock to transitional rocky materials.

10.2 Main Aspects Controlling Weathering in Brazil

As already mentioned, weathering is a complex process. Many factors can control its development, but the most important ones are:

- *Rock type and presence of structures that can form discontinuities*—Each rock type has a typical mineralogy, which reacts differently to weathering and both macro and micromineralogy are important to the process. On Fig. 10.3a, b it is shown two different litotypes (phyllite and shale) presenting pyrites that can easily weather to secondary minerals, such as melanetrite and halotrichite. Fractures

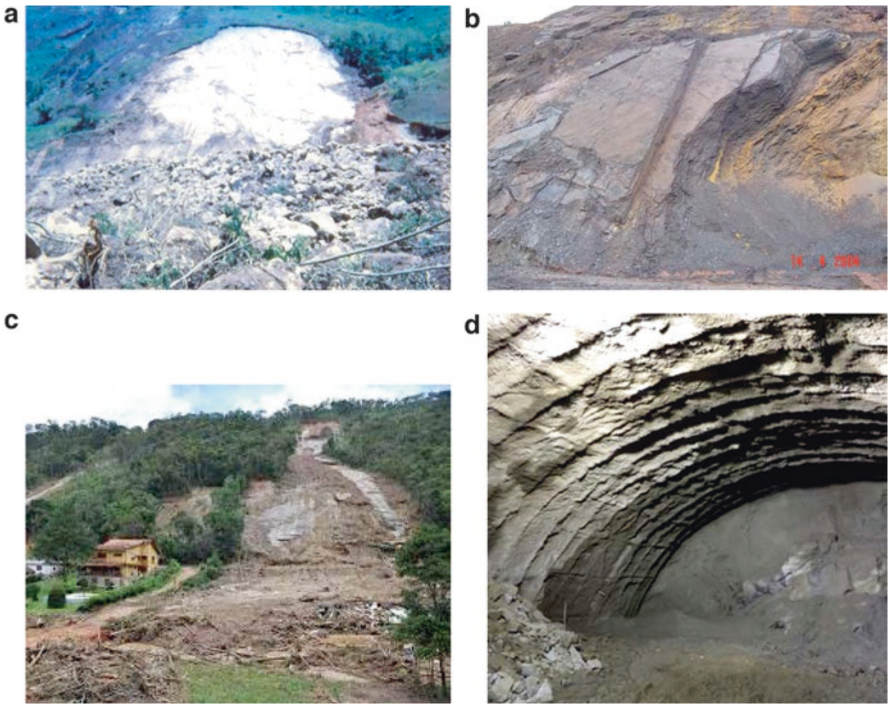

Fig. 10.2 Examples of weathering influence on civil and mining engineering: (**a**) An example of road slope failure along a stress relief joint (BR040 Highway, Rio de Janeiro state); (**b**) A weathered level developed along foliation in an itabirite from Alegria Mine (Ouro Preto, Minas Gerais state); (**c**) Failure in a natural slope over residential area during a major disaster on Rio de Janeiro state mountain region; (**d**) Weathering on a road tunnel at Petrópolis (Rio de Janeiro state) has imposed the need of extra support for tunnel excavation

(Fig. 10.3c, d), joints and faults can influence weathering, as these structures are preferential paths for water circulation. Directional structures and/or textures such as foliation, cleavage, and schistosity (Fig. 10.2b), can also influence weathering especially in the presence of discontinuities parallel to them.

- *Natural slope (topography)*—On more inclined slopes, run off transport or landslides (Fig. 10.2a, d) of weathered material downhill, continuously exposes sound rock to weathering attack, in a way that weathered material has low thickness. On less inclined slopes, infiltration prevails over run off and so there is more water to attack rocks and weathering thickness can reach hundreds of meters.
- *Climate (weather)*—Weathering is climate-dependent process as the amount of water and daily and seasonal differences on temperature act as a catalyst for chemical reactions that can affect mineral changes. So on tropical and subtropical climates, commonly found in Brazil, the weathering process is accelerated and this is the main reason for the high weathering thicknesses found in the

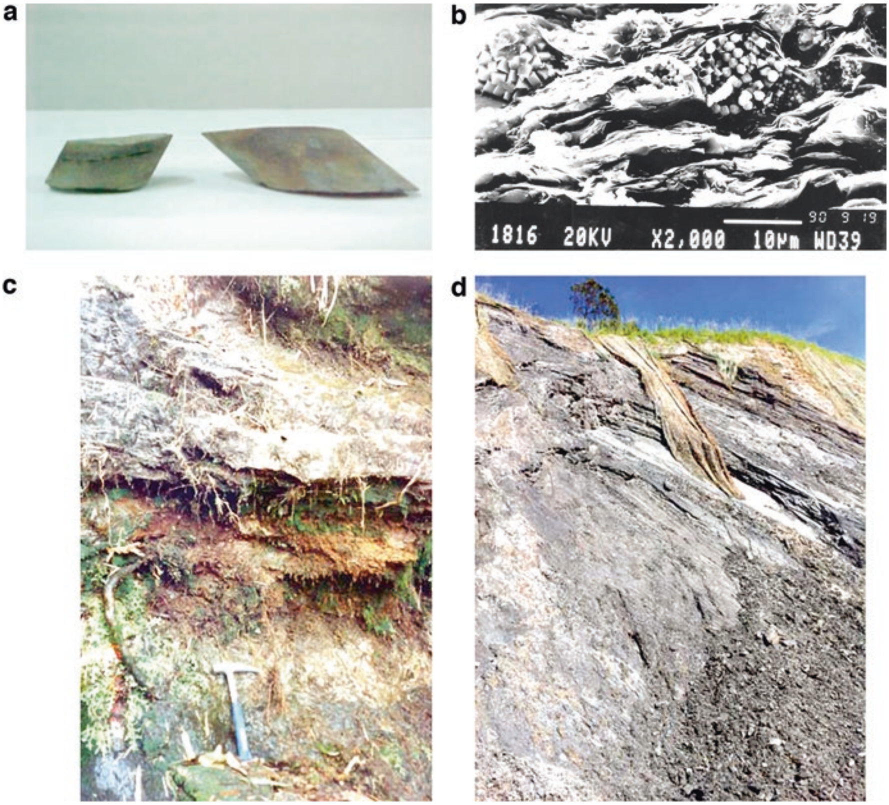

Fig. 10.3 Examples of influence of rock mineralogy and rock structures on its weathering. On (**a**) weathering of pyrite in a basic intrusive rock (Santiago et al. 2005) and on (**b**) pyrite crystals on a shale from Amazon River basin (Marques et al. 2005). On (**c**) is shown a residual soil filling a stress relief joint at a cut slope on gneiss. On (**d**) weathering along foliation in a phyllite of iron Quadrangle, Brazil

country. On more dry and cold climates, weathering is mainly due to physical weathering with lower mineral (chemical) change.

- *Extent of weathering process*—Time necessary for chemical decomposition of sound rock considerably varies due to climate type, topography and rock composition and structure. The longer the process can act, the higher will be weathering. So it can be thousand of years for the development of residual soils in dry and cold regions, while in humid and hot regions this process can occur in an engineering time.

Based, on that, the main particularity that makes the development of weathering in Brazil different from other countries, especially those on northern region of the planet, is climate. Similar climate conditions can be found in all southern hemisphere countries—Brazil, South Africa, Angola, Indonesia, Vietnam, Malaysia, some parts of Australia, and so on, and weathering results on similar weathering profiles for similar controlling factors and for the same lithotypes.

Depending on the rock genetic type, some structures can give rise to discontinuities and so control water flow. Sedimentary rocks can present sedimentary structures such as bedding and lamination, while metamorphic rocks can present foliation and cleavage. All rock types can present joints and faults. As all these structures, if defining discontinuities, increase specific surface exposed to water attack, its presence is also an important weathering control, as it controls the amount of chemical weathering. Other physical processes are very important for the development of weathering, such as:

- *Stress relief*—This process is common to all genetic rock types and result in joints with high aperture and with lower spacing closer to surface (Fig. 10.2a).
- *Wetting and drying cycling*—Occurs on both sedimentary rocks and metamorphic rocks of sedimentary origin mainly, due to the presence of clay minerals. It can cause disaggregation of rocks because of the expansion of clay minerals and mixed-layers due to water adsorption (Fig. 10.4).
- *Heating and cooling*—Another process that is common to all kinds of rocks. As some regions in Brazil can present very high daily and seasonal temperature variation, causing rocks to expand and shrink, resulting in rock fatigue, so creating and propaganting existing discontinuities.
- *Erosion effect of water and wind*—Erosion is more efficient on sedimentary rocks, but not exclusively. The effect of water and wind erosion can create different types of discontinuities such as fractures and joints.

Fig. 10.4 Black shale from Ilhas Group and undifferentiated Candeias Formation, from Recôncavo sedimentary basin, Bahia state, Northeast Brazil. It can be seen the effects of disaggregation (slaking) of rock, due to its explosion to weathering in a cut-slope

- *Mechanical excavation effect*—This is a much more localized process when compared to the other previously shown but it can be very important mainly in underground excavations (deep wells, tunneling, and mining). The higher the residual stresses within a rock mass the higher is the stress relief effect. So this type of effect is much more noticeable on igneous (plutonic) and metamorphic rocks, but also occurs on sedimentary rocks.

Many rock-forming minerals are relatively stable under surface conditions, but some can be particularly reactive, such as pyrite, marcasite, pyrrhotite, calcite, dolomite, biotite, garnet (group), olivine, halite, anorthite (calcium feldspar), and others. So in the engineering time scale, the most important chemical weathering processes, as suggested by Taylor (1988), and confirmed for weathering of rocks in Brazil are:

- *Oxidation* of sulphide minerals resulting in new formed minerals and (Fig. 10.5a).
- *Dissolution* of carbonaceous cements and salt minerals.
- *Hydration and other water-dependent effects* such as clay mineral and anhydrite hydration (Fig. 10.5b), ionic sorption, ion exchange, osmosis, and water adsorption.

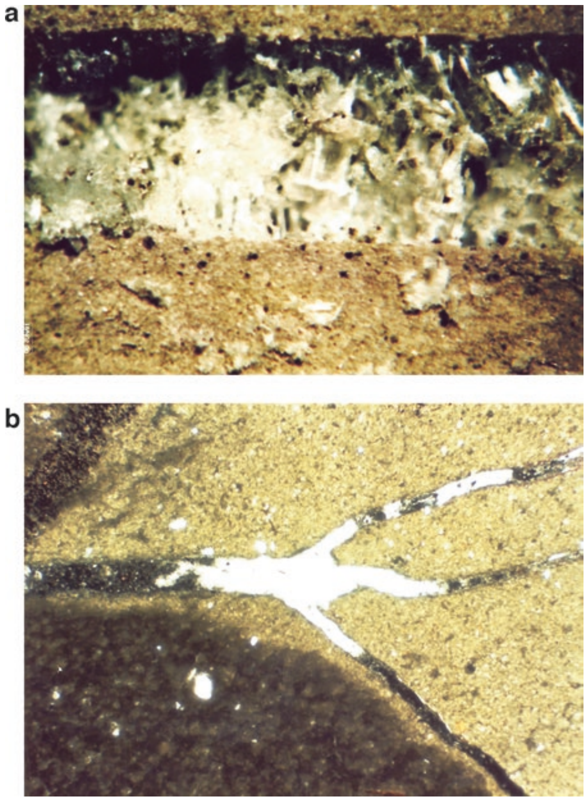

Fig. 10.5 On (**a**) new minerals crystals (Melanterite) formed due to weathering of pyrite in Amazon shale (Marques et al. 2005). On (**b**) the dark green area is an expanded (higher relief) clay mineral area due to its humidification by water, observed in a thin section (Marques et al. 2005) from the shale shown in Fig. 10.4

Table 10.1 Secondary minerals formed by some mineralogical change due to chemical weathering (Taylor 1988)

Original mineral	Secondary (new formed) mineral	Volume increase (%)
Pyrite (FeS_2)	Jarosite [$KFe^{3+}_3(OH)_6(SO_4)_2$]	115
	Melanterite ($FeSO_4{\cdot}7H_2O$)	536
	Ferrous Sulfate Anhydrous [FeO_4S]	350
Calcite ($CaCO_3$)	Gypso [$Ca(SO_4){\cdot}2H_2O$]	103
	Bassanite [$2Ca(SO_4){\cdot}H_2O$]	189
Illite [$KAl_2Si_3O_8(OH)_2$]	Jarosite [$KFe^{3+}_3(OH)_6(SO_4)_2$]	10
	Alunite [$KAl_3(SO_4)_2(OH)_6$]	8

In the sequence, some specific aspects of weathering of sedimentary and metamorphic rocks are presented. Studies on igneous rocks are current under development for the authors in Brazil but no data is presently available.

10.2.1 *Weathering of Sedimentary Rocks*

On the weathering of sedimentary rocks all three chemical processes described previously—oxidation, dissolution and hydration, and other water-dependent effects can occur, but the last two are the most common, as clay minerals and carbonatic rocks are more common than rocks with sulphide minerals. In Table 10.1, the main mineralogical changes on sedimentary rocks are presented. The same reactions can be easily found in weathering of these rocks in Brazil.

Another important process related to the weathering of sedimentary rocks is the influence of hydration due to penetration of water front into rock matrix, driven by capillarity forces or gas condensation. This process can cause entrapment and pressurization of air in pores, which can be sufficient to promote microfracturing, causing physical disintegration.

Marques et al. (2005) have developed studies on the durability of rocks (shales, mudrocks, and siltstones) from Recôncavo and Amazon River sedimentary basins. All those rocks, when exposed on cut slopes present a rapid disintegration, which commonly causes many geotechnical problems. The weathering mechanisms involved into its degradation where hydration of clay minerals and air entrapment into pores, caused by wetting-drying cycles. These processes have lead to the development of microfracturing and expansion causing loss of strength and high deformability of the weathered material.

10.2.2 *Weathering of Metamorphic Rocks*

Garnets, biotite, and feldspars are common minerals in Brazilian metamorphic rocks. Garnet and biotite can release considerable amounts of iron due to its weathering, which is leached through microfractures and micropores and deposits on those voids, acting like a cement and so resulting in an increase in strength on moderately weathered (W3 and W3/W4 classes, according to ISRM, 2015) layers of rock mass. Anorthite, on the other hand, rapidly weather to kaolin, reducing rock strength and increasing its deformability.

Works by Barroso (1993), Menezes Filho (1993) and Marques (1998) present detailed studied the influence of weathering on physical and geomechanical properties of three high grade metamorphic rocks (different type of gneisses—Leptinite, Augen gneiss, and Kinzigite, respectively). Both rock matrix and rock masses characteristics were described to form a complete picture of weathering influence on those rocks. By analyzing hand samples and thin sections those authors have determined that fracturing and microfracturing (especially transgranular fractures) present a substantial increase due to weathering. This physical process increases porosity and influence its mechanical behavior. Also, it allows water to access inner portions of rock matrix, leading to an increase in chemical weathering. Figure 10.6 shows some aspects of those studies and weathering influence on physical and mechanical properties (Marques et al. 2010). Table 10.2 presents a detailed description of microscopic (both mineralogical and structural) changes observed on those gneisses due to weathering.

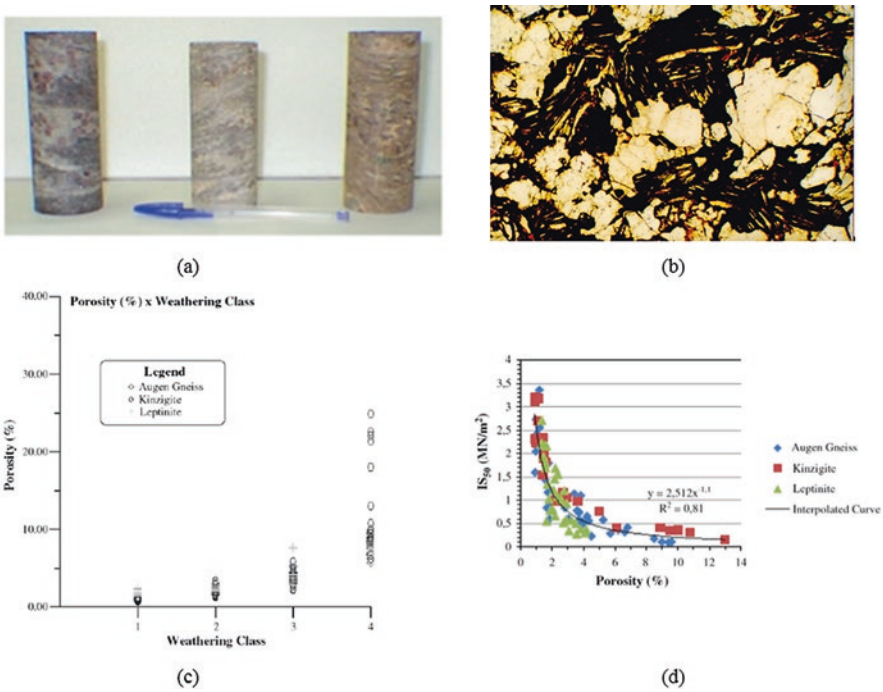

Fig. 10.6 (**a**) Effects of weathering on rock matrix of kinzigite from Rio de Janeiro (Marques et al. 2010). (**b**) Example of weathering effects on micro scale (Marques 1998). Influence of weathering on porosity (**c**) and relation between porosity and point load strength (**d**) for gneisses from Rio de Janeiro (Marques et al. 2010)

Table 10.2 Main mineralogical and microfracturing changes on gneisses from Rio de Janeiro due to weathering (Marques et al. 2010)

Weathering class	Augen Gneiss	Leptinite	Kinzigite
Sound rock (Class 1)	Plagioclases are sound—no signs of alteration—presenting typical white color. Quartz crystals are fractured and elongated. Biotites show a sound aspect, but few are slightly altered.	All minerals are sound. Only few biotite grains show more pale colors at its boundaries.	Plagioclases are lightly transformed into sericite and with few fractures open and oxidized. Biotites show a light discoloration on grain edges. Garnets and Sillimanite have sealed fractures without any oxidation sign. Cordierite presents few open fractures.
Slightly weathered (Class 2)	Great part of plagioclases are still sound. However, some of them show incipient alteration. Quartz is very fractured and elongated. Biotites are slightly discolored.	Plagioclases are lightly transformed into sericite. Biotites with discolored edges are oxidized along cleavage planes. Garnet with intergranular fractures is lightly weathered.	Some plagioclase crystals were transformed into sericite. Several open transgranular fractures are oxidized or filled with argillaceous material. Biotites with discolored edges and a few oxidized cleavage planes. Garnet with trans and intergranular fractures, lightly weathered. Cordierite with fractures filled with iron oxides.
Moderately weathered rock (Class 3)	Plagioclase crystals are opaque, showing evident caulinization. Quartz is very fractured, elongated and contouring phacoidal grains. Biotites are mainly oxidized, showing incipient exfoliation and iron deposit on their cleavage.	Sericite formation from plagioclase and feldspar surfaces is intensified at this stage. Biotites undergo an exfoliation process related to the opening of their cleavage. Garnet grains show a conspicuous of iron oxide along its internal fractures. There is a predominance of transgranular microfractures.	Plagioclase transformed into sericite is surrounded by argillaceous material and present several open, oxidized, trans and intragranular fractures. Biotites presents discolored edges, incipient exfoliation and oxidized cleavage. Garnet with transgranular open fractures and intragranular fractures filled with iron oxide. Cordierite with edges and fractures very oxidized. Argillaceous material more common than in Level W2.
Highly weathered rock (Class 4)	Plagioclases are mostly opaque and caulinized. Quartz are intensely fractured and oxidized. Biotites are oxidized and highly exfoliated.	At this weathering stage almost all plagioclase grains are transformed into clay minerals, especially kaolinite. Biotites are completely exfoliated. Garnets are oxidized.	Plagioclase occurs as rare, very fractured and oxidized crystals. Biotite occurs as a few sound, very fractured and oxidized crystals. Quartz presents oxidized fractures. Garnets crystals are intensely fractured. Argillaceous material occupies great portions of thin sections.

Santiago (2008), by studying laboratory weatherability of metabasic intrusive rocks (amphibolites) for Iron Quadrangle (Minas Gerais state), have also determined the influence of weathering on physical properties and parameters by using cycling tests such as natural cycling and water-oven cycling. Also, the author has analyzed mineralogical changes along the process.

10.3 Typical Morphology of Brazilian Weathering Profiles

Morphology of weathering profiles is an important aspect of weathering because it has a direct relation to geotechnical behavior of rock masses.

In the early stages of weathering studies, several authors (Moye 1955; Ruxton and Berry 1957; Dearman 1976; Dearman et al. 1978; IAEG 1981) divided noticeably different zones into the rock mass, based on three parameters: soil/rock ratio, rock discoloration degree, and presence of original structures, with no or few attention to rock matrix changes. However, because the created models did not completely express field behavior and of some confusion in the use of the method, the philosophy of the study changed and more attention to rock matrix was introduced (Beavis 1985; Barroso 1993; Menezes Filho 1993; Marques 1998; Gupta and Rao 2000; Arel and Önalp 2004; Marques et al. 2010). Recent studies have proved that a complete understand of weathering effects on rock masses can only be accessed if both approaches are used (Fig. 10.7).

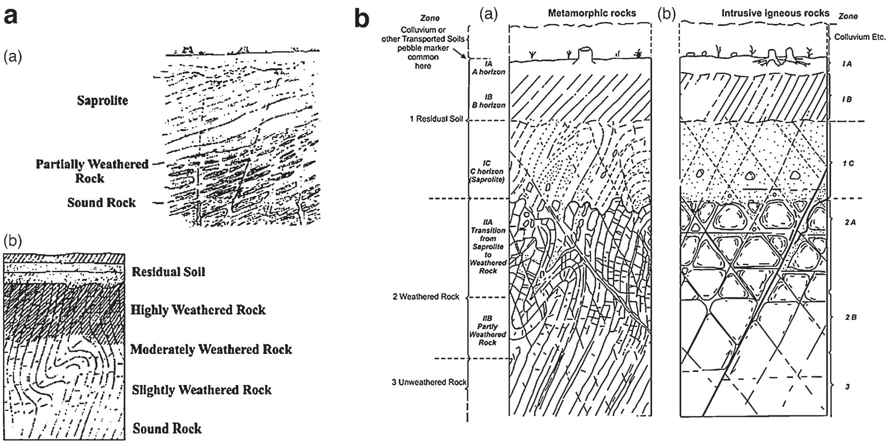

Fig. 10.7 Typical weathering profiles. (**a**) Profiles morphology proposed by Somers (1988) and Dobereiner and Porto (1989). On (**b**), weathering profiles for metamorphic (left) and igneous (right) rocks (Deere and Patton 1971)

According to Price (2009) four basic types of mass weathering (weathering profiles) can be identified:

- *Uniform weathering*—its also called sequential weathering profile, as a gradual and sequential decrease of weathering grade can be observed with depth (Fig. 10.8a).
- *Corestone weathering*—it is characterized by the presence of rounded and almost fresh rock blocks surrounded by decomposed rock or soil. It is typical of igneous rocks, both plutonic and volcanic (Fig. 10.8b).
- *Complex weathering*—an irregular profile due to contrasting layers weatherability and the structural complexity (presence of several geological structures such as joints, fractures, faults and folds). It is very common in metamorphic rocks such as schists and gneisses. Commonly stress relief joints also plays an important role in the morphology as these structures commonly present higher apertures, so allowing water to flow (Fig. 10.8c).
- *Solution weathering*—a specific weathering pattern related to carbonatic rocks, where fractures and bedding planes become open by dissolution and can evolve to karstic forms. This process can also occur on saline rocks (Fig. 10.8d).

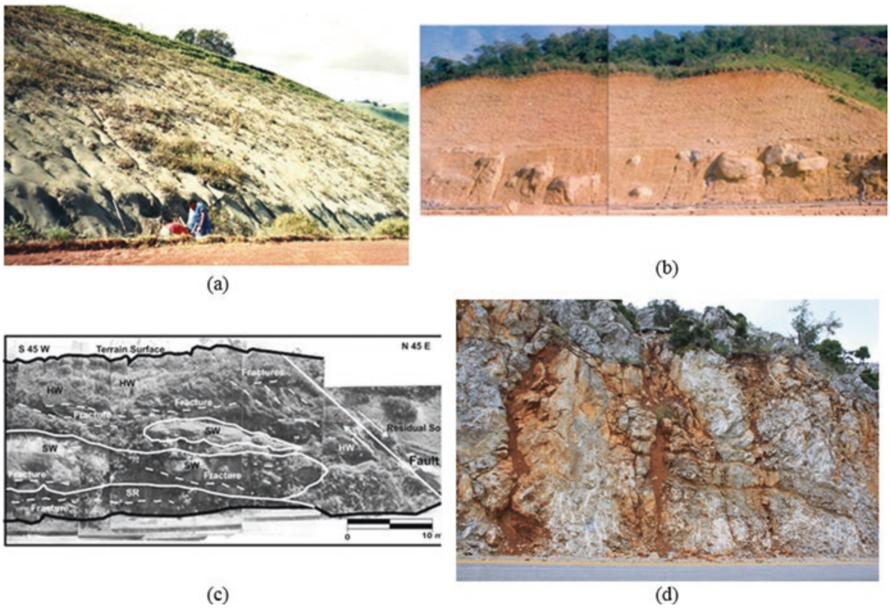

Fig. 10.8 Examples of typical weathering profiles (**a**) Marques (1992); (**b**, **c**) Marques et al. (2010)

10.3.1 Typical Weathering Profile Morphology for Brazilian Sedimentary Rocks

According to Dobereiner et al. (1993), typical morphology of weathering profiles for Brazilian sedimentary rocks can be divided in two types, as shown on Fig. 10.9a. Weathering profiles for clayey and silty rocks usually present a superficial layer of tablet-like material with variable (0.2–1.5 m) thickness. The presence of this layer is due to wetting and drying cycling caused by moisture variations related to water table fluctuation or rainfall. Also, changes in air humidity can cause the same process. In cut slopes where clay and silt-rich layers are exposed, this process is very common and occurs in a period of days to months. Whenever the thickness of the layer increases, it can result in landslides, which exposes sound rock and the processes is allowed to restart. This typical morphology can be modified by the presence of interbedded sandstone layers with argillaceous rocks (shales, claystones and siltstones), as shown on Fig. 10.9b. On theses profiles, the same tablet-like layer can occur on claystones and siltstones, letting sandstones layers in balance, which can break, originating rock-falls.

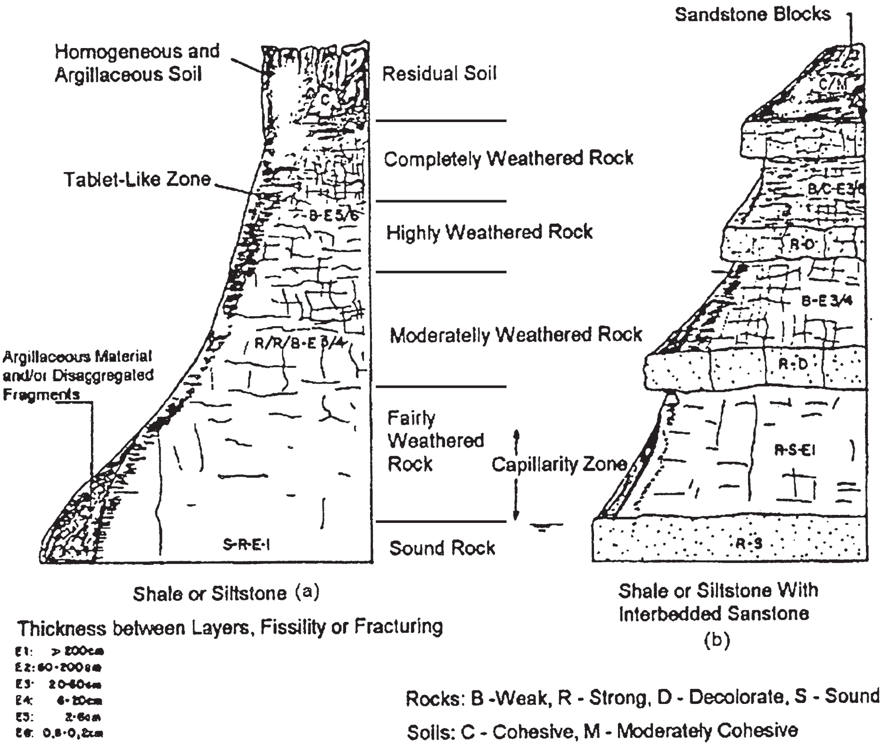

Fig. 10.9 Typical weathering profiles for sedimentary rocks (Dobereiner et al. 1993)

10.3.2 Typical Weathering Profile Morphology for Brazilian Metamorphic Rocks

The main geotechnical problems associated with metamorphic rocks weathering profiles are related to their structural complexity, to its irregular soil–rock contact surface and to their anisotropy (Dobereiner 1989). Some authors (Lee and Freitas 1988; Dobereiner and Porto 1990) have described difficulties when trying to fit the weathering profiles of metamorphic rocks studied by them into previous classifications. These structural complexities formed by the presence of several different types of tectonic structures—folds, foliation, faults, fractures, are fundamental for the weathering process of metamorphic rocks, as they can compose discontinuities through which water can flow and, therefore, promote chemical weathering and control the speed of weathering. Several heterogeneous morphological aspects such as sharp soil–rock contacts, the presence of a weathering front and the influence of subhorizontal stress-relief joints also contribute to make weathering profiles of metamorphic rocks even more complex.

On the weathering profiles of metamorphic rocks in Brazil, a remarkable observation is the importance of structures. Besides tectonic structures, which are important for all types of metamorphic rocks, stress relief joints play an especially role for the development of weathering profiles into high-grade metamorphic rocks, such as observed on Rio de Janeiro gneisses by Barroso (1993), Menezes Filho (1993), Marques (1998), and Marques et al. (2010) (Fig. 10.10d).

Another important aspect of weathering of these rocks is slope inclination, as observed by Marques (1998) for kinzigites from Rio de Janeiro. On more steep areas, stress relief joints mainly control weathering, promoting zoning with a clear tendency of reduction of weathering with depth. This behavior is influenced by fracture density and direction and is also important for the development and for the morphology of these profiles. On more fractured zones, weathering is much more complex, with several sharp and structurally controlled contacts between different weathering classes (Fig. 10.8c).

Some porphyroblastic gneisses can present a weathering profile showing blocks involved in a soil matrix, in a similar way of granites weathering profiles described for several authors, as Ruxton and Berry (1957). This, although, is not common in Brazil.

In a similar way, foliation also is important for the development of weathering, as it can have discontinuity planes parallel to it. If foliation is parallel or subparallel to surface, contacts are abrupt, as can be seen for phyllites from Iron Quadrangle (Minas Gerais state, Brazil) on Fig. 10.10a, b. When foliation is perpendicular to surface, the weathering profile is similar to the one presented on Fig. 10.10c. Weathering on discontinuities developed along foliation also creates sharp contacts between different weathering rock mass classes, as can be observed on Fig. 10.10b.

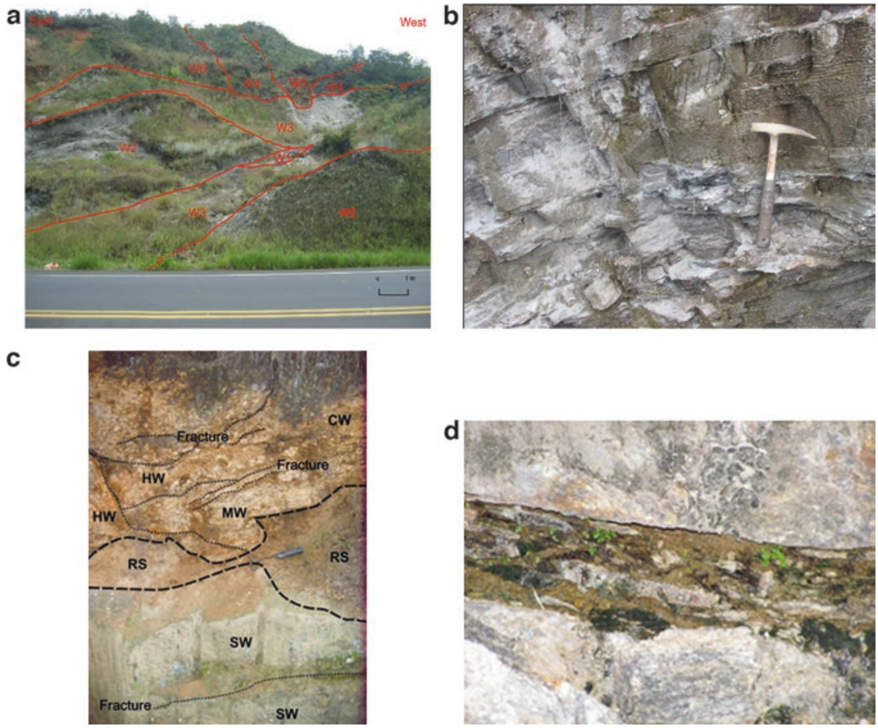

Fig. 10.10 Different aspects of weathering profiles of metamorphic rocks from Brazil. In (**a**) (from Leão et al. 2016) and (**b**) (from Carvalho et al. 2017) influence of penetrative foliation on weathering of phyllites from Iron Quadrangle, Minas Gerais state. On (**c**) a sequential weathering profile described by Marques et al. (2010); and on (**d**) aspects of weathering of gneisses from Rio de Janeiro (Marques et al. 2010)

10.4 Physical Parameters

Physical parameters of the sedimentary, igneous and metamorphic rocks can basically be evaluated by means of the specific density and the porosity. These two physical properties, especifically, are very important in the verification of the processes of weather degradation that the rocks can suffer. When unweathered, the rocks present ranges of typical values according to their origin.

In sedimentary rocks, the specific density may vary depending on the rock being clayey, the presence and proportion of clasts, existence of heavy minerals in their composition, besides the degree of lithification and cementation and type of cement. When these rocks are of chemical origin there is a greater influence of the presence of clay minerals, iron hydroxide, and bituminous substances.

In general, the geological characteristics directly influence the physical properties, where rocks with equal absolute porosity values may have different permeability, strength, and deformability values. Thus, density and porosity are directly related to the mineral composition of the rock, interstitial structure, silica content of the rock, and the presence of lamellar minerals (mica).

In metamorphic rocks, the factors that can influence the physical properties are fewer, however, they are of complex prediction if compared the sedimentary and igneous rocks. Basically, these properties vary according to the mineral composition, metamorphism class, and tectonic activity in the region, resulting in broad bands of specific density, in which the ones of sedimentary origin present smaller specific mass when compared to those of igneous origin. The porosity in these rocks is practically of fissural origin and rarely exceeds 1–2%. When porosity tends to higher values there is almost always a relationship with microcracking, reaching 10% in serpentinites. The formation of discontinuities in these rocks is dependent on the depth and conditions of deformation (stiffness, hardness) of the nesting rocks, besides the weathering action, for example.

The effect of weathering on sedimentary, igneous, and metamorphic rocks is distinct due to the intrinsic characteristics of these rocks. However, in general, weathering promotes the degradation of the physical properties, with reduction of the specific densities and increase of the porosity and capacity of water absorption as the class of rock weathering advances.

For this reason, the effect of weathering on physical characteristics of rocks can be evaluated through its index properties, in order to correspond to physical peculiarities that directly reflect the mineralogical composition and the voids present in the rock, in order to discern and quantify the rocky matrix (Leão et al. 2016). The index properties are obtained in samples of intact rock which, although not representing the properties of the rock mass, can help to classify it primarily (Azevedo and Marques 2002). Among them, specific mass and porosity are the most representative of the effects of weathering onto geotechnical parameters of altered rocks, considering that the increase of the specific mass and the reduction of porosity correspond, as a rule, to an increase of the resistance and a decrease of the deformability of rocks (Pinheiro 2002).

Not only, but mainly, in rock masses composed by soft foliated rocks, it is common the presence of discontinuities that develop parallel to the foliation. These interruptions of the continuity of the mineral formation and, as a result, of the rock matrix generate voids related to the deformation and rupture of the rocks. The amount of voids can be evaluated by porosity, that is, the ratio between the void volume of a rock sample and its total volume. These voids, pores or fissures, are not necessarily interconnected and may be completely closed (Hawkes and Mellor 1970), making it difficult to be measured. Moreover, primary porosity (pore volume between rock fragments) and secondary porosity (fracture and subsequent alteration of the rock) of the massif can be defined. In high grade metamorphic rocks (such as gneisses), porosity is a good property to evaluate the effects of weathering (Barroso 1993). Other important index properties, in soft silty-clayey rocks (Lashkaripour and Passaris 1995), are water absorption capacity and moisture content. According to Dobereiner (1984), the increase of these parameters represents a significant decrease on rock strength. The absorption of water, obtained by the "Quick absorption technique" (ISRM), makes it possible to evaluate the voids index and the altered state (Martin 1986). In rocks of a soft nature, disintegration may occur during the saturation process, requiring the use of the durability test (Pinho 2003) or different test procedures (Marques et al. 2017).

Figure 10.11 shows typical dry density values for sedimentary rocks (a), igneous (b) and metamorphic (c) and saturated specific mass for metamorphic rocks (d) from several countries, including Brazil (identified as BR in the rocks, according to the classes of change (ISRM 2015). In general, weathering promotes the reduction of the specific dry mass for all the rocks presented.

Brazilian shales and siltstones show, in general, lower values of dry density compared to other sedimentary rocks, probably due to the meteoric conditions to which these rocks were exposed. Comparing the sedimentary rocks (Fig. 10.11a), sandstones present greater dispersion for values of specific dry mass for the same class of alteration when compared to tuffs, limestones, and greywackes. In general, sandstones present good resistance to weathering, due to the high amount of quartz and other resistant minerals, but in clastic sandstones a differential alteration can occur due to the origin of the clast, the structural arrangement of the grains and to the presence and type of cement in the rock. It is also worth noting that the selection of suitable methods for extraction, preparation and decision on representative tests of

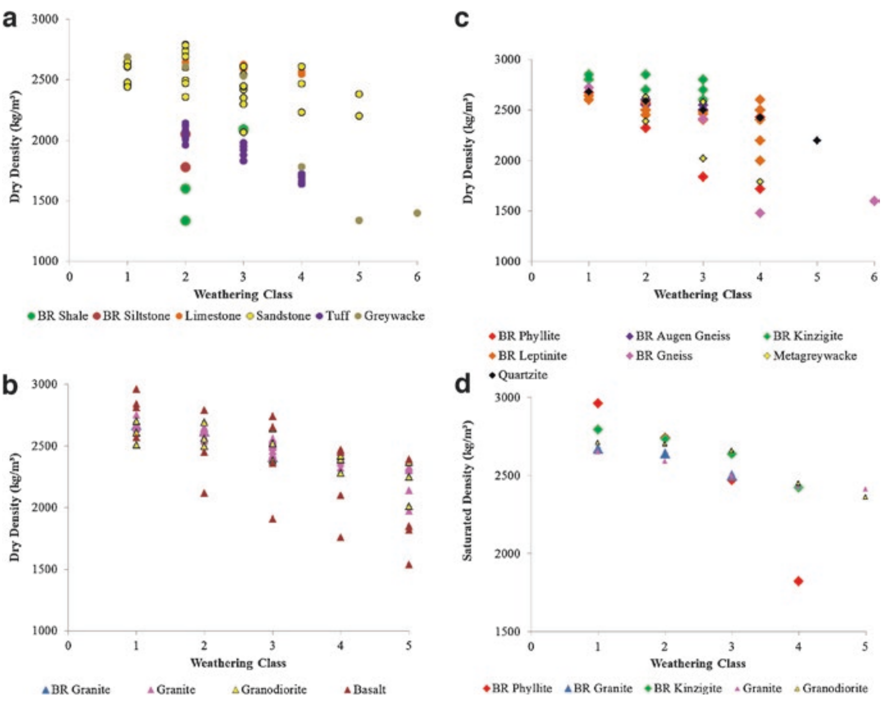

Fig. 10.11 Variation of dry density by weathering in sedimentary rocks (**a**), igneous (**b**) and metamorphic (**c**) and, of the specific mass saturated in metamorphic rocks (**d**). Brazilian rocks are identified by BR and are highlighted in the charts

the physical properties of sedimentary rocks can directly influence the results obtained (Kanji 2014) because these rocks are naturally soft when sound.

However, for the igneous lithotypes (Fig. 10.11b), there is a lower dispersion of the dry density values, with an evident tendency of reduction of this property values with weathering, both for Brazilian granites and for other igneous rocks. In general, there is a reduction of 10% of the dry density for granites when rock changes from class 2 to 3.

In coarser metamorphic rocks (Fig. 10.11c) dry density values are higher when compared to finer rocks (quartzite and phyllite). Despite of an evident tendency of reduction of dry density with weathering, there is a certain dispersion of the results for rocks of lower metamorphic grade as phyllite. For higher-grade metamorphic rocks, as in the case of augen gneisses and leptinites, this behavior can be observed mainly from weathering class 3, probably due to their intrinsic characteristics, such as mineralogy and texture.

In the case of saturated density, the trend is similar, both for Brazilian metamorphic rocks and others from different countries (Anagnostopoulos et al. 1993). It is worth noting the abrupt reduction of saturated density values for phyllites from classes 3 to 4, with a reduction of about 73%, since these rocks are easily disaggregated during the saturation process.

The effect of weathering on porosity promotes changes in the pore size distribution, geometry, connectivity, filling and formation of new pores, and can create systems of great complexity, depending on the rock, leading to variations in permeability and other mechanical properties (Tugrul 2014). Together with mineralogical composition and texture, porosity controls susceptibility of rocks to physical weathering (Hudec 1998).

By analyzing Fig. 10.12 it is possible to note that the porosity and the water absorption capacity increase with the advancement of weathering, but not to the same extent, since the water absorption capacity is dependent on the connectivity of the pores, for example. As weathering progresses, there is an increase in microcracks and voids in the rock.

Figure 10.12a, e shows naturally lower porosity and water absorption capacity for igneous (Fig. 10.12b, e) and metamorphic rocks (Fig. 10.12c, f) when compared to sedimentary rocks, even when undergoing weathering. More significant variations in porosity can be observed in samples of greywacke, due to the alteration of the clasts of the rock.

In low porosity rocks, this characteristic is due to cracking and, to a lesser degree, to intergranular cracking. Igneous rocks present a difference on porosity and water absorption capacity due to the type of magmatic rock. On effusive rocks, such as basalts, porosity is mainly related to gas and water vapor bubbles created during the cooling of the lava. In the cataclastic and weathered zones magmatic rocks develop higher porosity from fracturing, reaching between 10% and 20%, while on massive rock matrix porosity does not exceed 1–3%. Brazilian granites show an increase of up to 8% and 4% for porosity and water absorption capacity, respectively, from Class 2 to 3. Granodiorites show a larger increase in porosity than granites, with less than 1% for class 1, reaching up to 15% for class IV; similar behavior is observed in

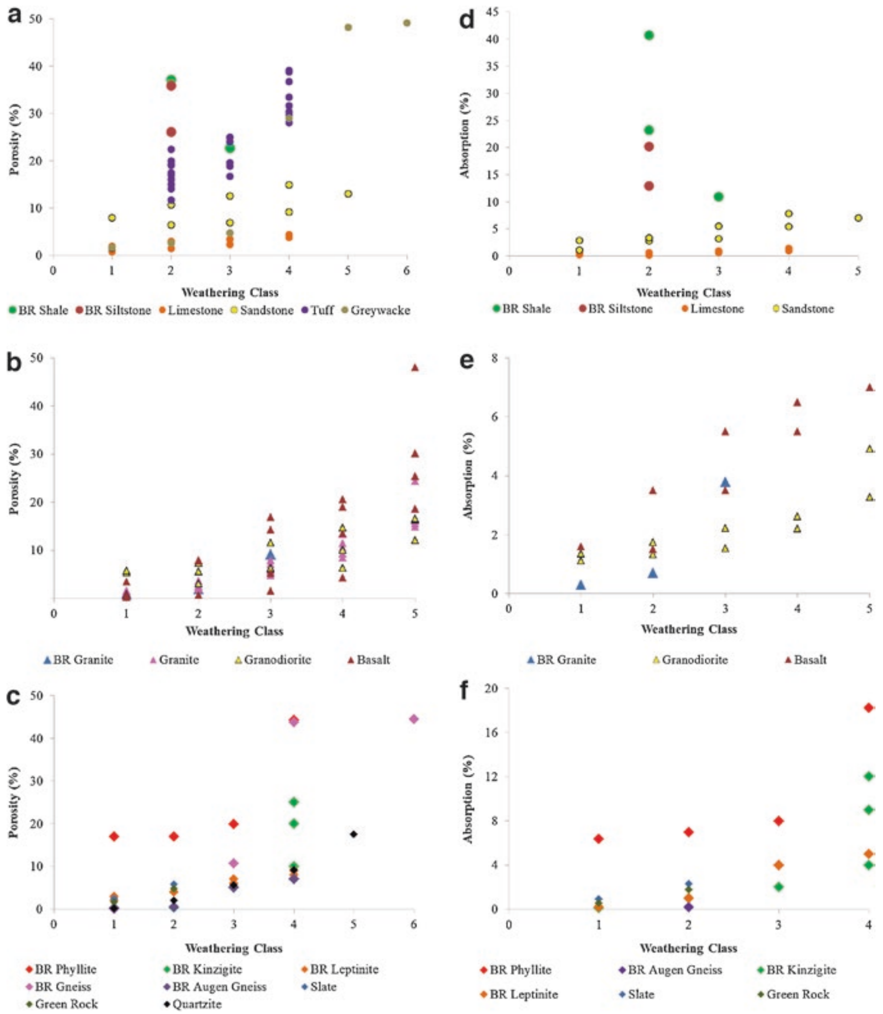

Fig. 10.12 Variation of porosity and water absorption capacity with weathering in sedimentary rocks (**a** and **d**), igneous (**b** and **e**), and metamorphic (**c** and **f**). Brazilian rocks are identified by BR and highlighted in the charts

the water absorption capacity (Heidari et al. 2013). Note that the porosity of the basalts is less than 1% for class 1 reaching almost 50% for class 5, due to the increase in microcracks within the grains and matrix due to the weathering (Tugrul 2014).

It is observed that metamorphic rocks present a similar behavior to the one described for igneous rocks, whose porosity and water absorption capacity is mainly function of the increase of rock fracturing, facilitated by the existence of structures such as bundles, lineaments, and foliations that, due to the advance of weathering, tend to propagate along discontinuity planes. In naturally soft and clayey rocks,

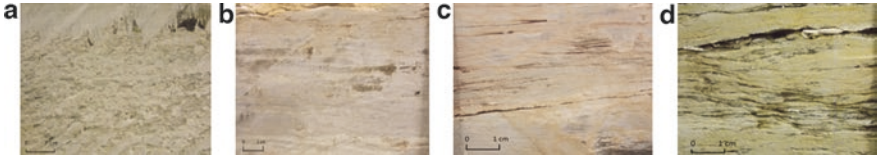

Fig. 10.13 Orthogonal foliations for the weathering classes 1 (**a**), 2 (**b**), 3 (**c**), and 4 (**d**). Aperture and persistence increase with weathering (Leão et al. 2016)

such as phyllites, these values tend to be higher when the rock is sound, compared to other coarse-grained and even some fine-grained metamorphic rocks, such as slates, due to the existence of penetrative foliation planes that facilitate the process of change, as shown in Fig. 10.13.

Values of microfracturing index (I_{fr}) on a Brazilian phyllite studied by Leão et al. (2016) have increased considerably from class 2 to class 4, but decreases from Class 4 to Class 4/5. This result is attributed to physical weathering because this process occurs primarily in rock layers (up to Class 4) of the weathering profile. Additionally, in more weathered zones (Classes 4/5 and 5), chemical weathering frees more iron oxide, which then precipitates along preexisting fractures, commonly sealing them. The micropetrographic index (I_{mp}) for these rocks showed an increase from Class 3 to Class 4/5 and little differentiation between Classes 4 and 4/5 indicates that chemical weathering occurred primarily during weathering of rock material and that almost none occurred during soil formation. These results are similar to the ones found for Australian phyllites.

10.5 Chemical and Mineralogical Characteristics

Amongst the endogenous factors, mineralogical composition of the rock is considered as the main conditioning factor, since each mineral presents a distinct response to alteration (Goldich 1938). Another condition refers to the granulometry, which influences the resistance of rock to alteration due to the mineral specific surface. Aspects such as parent rock texture, recrystallization of grains, presence of geological structures and directional textures (foliation, cleavage, etc.) also facilitate weathering.

Petrographic analysis is a widely used method to evaluate and quantify, microscopically, the presence of (1) microstructures; (2) mineralogy composition, which influences the roughness surface (Barton 1973); and (3) texture. It can also provide useful estimation of porosity of the rocks (Goodman 1989). It should be noted that the first three factors are the main characteristics controlling the intensity of weathering (Hudec 1998), with reverse changes in the crystallization of rock minerals (Goodman 1993). In some of the results presented on this chapter, the use of quantitative indices can be correlated with physical and mechanical characteristics (Ceryan et al. 1998). This method has the advantage of being a direct analysis, with some precision in the identification of important aspects of the rock matrix and the influence of weathering, with limitations on the identification of clay minerals, and have been widely used by several authors (Rodrigues et al. 1978; Russel 1982; Marques and Vargas Jr. 1994).

In rocks as thin as phyllites, in which mineralogy cannot be determined by macroscopic evaluations, the petrographic analysis allows the identification of the effects of weathering in the rock. In samples of seritic phyllites from Batatal Formation (Minas Gerais, Brazil), as the rock changes from class 1 to class 4, the percentage of muscovite (high birefringence) decreases, and the percentage of sericite increases. The distinction between these two minerals occurs on the altered edges (sericita) of the muscovite, where the birefringence colors are noticeably lower than those of the muscovite. In smaller quantities, there is a relative increase of quartz grains in the most altered classes, as this mineral is resistant to chemical intemperism processes. Due to the opening of the foliation plans with the progression of weathering, the percolation of mineralized fluids occurs, filling the discontinuities with minerals, as observed in Fig. 10.14.

In the weathering of igneous rocks, kaolinization is very common, especially in granitic rocks. Minerals like quartz, tourmaline, and muscovite remain almost unchanged. However, feldspars are easily dissolved by the presence of water, which percolates throughout fractures and micro-fractures. The effect of chemical weathering promotes the dissolution of feldspar, creating cavities and forming kaolin and smectite, among other clay minerals. Thus, X-ray diffraction (XRD) techniques can be used, and present advantages in relation to usual petrography descriptions for rocks with very fine granulometry. This technique is very useful for the estimation of clay minerals and mineralogy formation due to weathering (Gidigasu 1971, 1974). This can influence the degree of leaching and laterization, cation exchange, and hygroscopic moisture, as shown in Fig. 10.15. It can be noted that peaks of muscovite occur at all levels and it is worth noting that sericite shows similar signs, which would mark the mineral alteration. However it is not possible to distinguish the proportion between these two minerals. The kaolinite occurs at peaks of 12.2° and is more evident in the alteration classes 3 and 4, indicating that the intemperic processes are more active at these levels. 2:1 clay minerals appear in discrete peaks around 6° from class 1 to class 4, in small proportions (Leão et al. 2016).

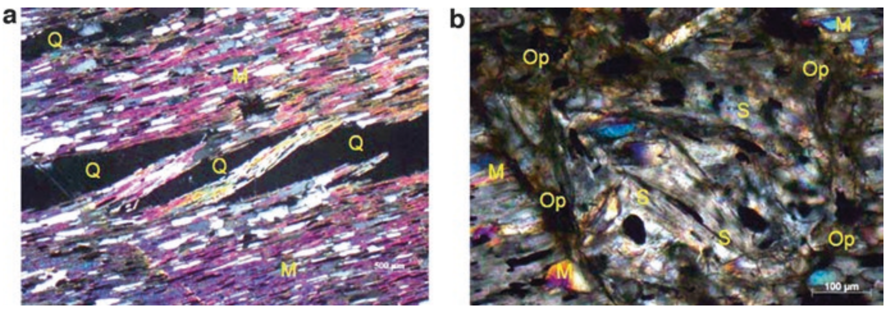

Fig. 10.14 Muscovite bands (M) interspersed with quartz grains (Q) in phyllite class 1 (**a**). In (**b**) sericite formation process (low birefringence) in the muscovite bands, with filling of micro-cracks by oxides and opaque (Op) (Leão et al. 2016)

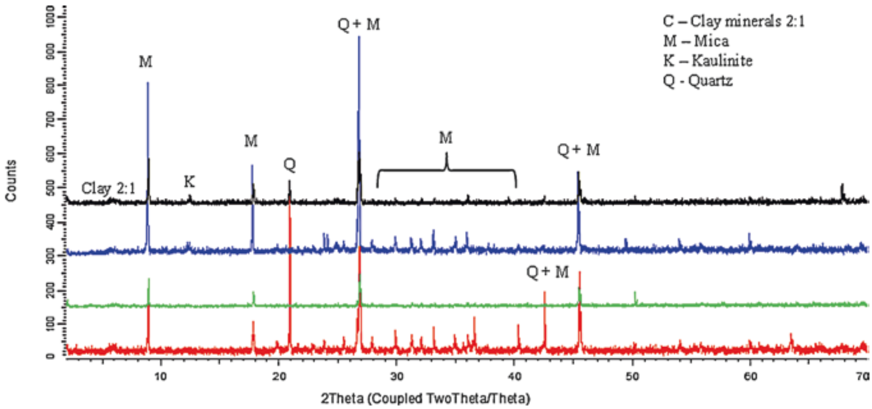

Fig. 10.15 XRD analysis in phytochemical samples of class 1 (red), 2 (green), 3 (blue) and 4 (black). It is possible to observe that the progression of weathering leads to the development of 2:1 expansive minerals (Leão et al. 2016)

The identification of the presence of expansive clay minerals, especially in rocks that have foliation planes and low mechanical resistance, facilitates the understanding of compression and relaxation effects of these planes (Bhasin et al. 1995). It is also worth mentioning that clay minerals associated to discontinuities and moisture variation are also responsible for chemical weathering of rocks (Taylor and Smith 1986; Gökçeoglu and Aksoy 2000).

Geochemical analysis methods seek to quantitatively estimate the mobility/immobility of elements by the action of weathering, leaching, as well as loss/gain of source material (Chadwick et al. 1990). Among the major intemporal processes responsible for the loss/redistribution of these elements are (1) the dissolution of primary minerals, (2) the formation of secondary minerals, and (3) the reduction, transport and exchange of ions (Thanachit et al. 2005).

Analyses by X-ray fluorescence (FRX) allow a qualitative and quantitative evaluation of the concentration of chemical elements present in rock samples. The use of this technique for the understanding of alteration processes is very valid, since intemperic processes denote the mobility of certain chemical elements, especially in supergenic environments (Licht 1998). The behavior of the chemical elements in supergenic conditions, as in the QF, is governed by the pH, oxidation potential (Eh), granulometry, mineral dissolution, hydrological regime, and chemical properties of the elements (Van Der Weijden and Van Der Weijden 1995). Some elements such as titanium and iron present low mobility and great possibility of reprecipitation (motivated by processes of dissolution of primary minerals). Aluminum also obeys this principle, forming secondary minerals such as kaolinite and gibbsite (Holanda and Bueno 2010).

It is common to use mineralogical indexes to characterize stages of evolution of weathering, to quantify matrix weathering and to serve as a guide or reference for geomechanical properties of rocks (Brimhall and Dietrich 1986). Initially, mineralogical indexes were proposed for granites based on the relationships between stable and unstable minerals (Lumb 1962; Dearman and Irfan 1978), later applied to other genetic types. More recently, proposals for mineral alteration indices based on more sophisticated laboratory techniques have been presented, such as electron microscopy (Hu et al. 2014).

Considering the geochemical changes in the protoliths and their products of weathering, especially in climates with water surplus and high annual average temperatures, several researchers proposed chemical indices based on molecular relations of the major elements, very useful to discuss the evolution of a profile of weathering. It is worth noting that the use of these indices differs in the treatment of homogeneous weathering profiles (Sutton and Maynard 1992) and heterogeneous weathering profiles (Ciampone et al. 1992), in which, in the latter case, the presence of discontinuities can generate levels of chemical composition and mineralogical properties.

In some of these indices, presented in Table 10.3, relationships between immobile (slightly soluble) and mobile elements (concentration reduces as weathering and leaching advance) are assumed. (a) There are indices that are based on the percentage of total silica; (b) however, they can be very questionable, as they consider silica in the form of quartz. Indexes based on chemical change consider certain elements as immobilized; (c) aluminum is of low mobility and remains constant during weathering in the weathering-potential index (WPI) and product index (PI) cases, both proposed by Reiche (1943). The chemical index alteration (CIA) is currently one of the most used chemical indices for evaluating weathering. Proposed by Nesbitt and Young (1982), the CIA uses the molecular ratio between larger mobile and immobile elements and functions as an index of the intensity of weathering. There are still indices that consider the relationships previously commented, but relate their concentration when healthy and weathered (d). It is worth noting that aluminum, abundant in the composition of many minerals, can be representative as an evaluation element in chemical indices, as it presents greater mobility, as a result of environments with pH below 4.5 and in the presence of organic acids (Gardner 1980, 1992).

The use of these indices may be interesting to evaluate the effect of chemical weathering on physical weathering. Figure 10.16 presents results of chemical indices in four classes of alteration of a phyllite (W1—Class 1 to W4—Class 4) of the Quadrilátero Ferrífero (QF, southeast Brazil).

The chemical indices ba, ba1, ba2, and ba3 showed reduction of values with the evolution of weathering. In terms of silica content, the indices (Silica/R_2O_3 and R) showed a variation and progression according to the more subtle weathering, showing (Silica/R_2O_3, PI, R, and STI) the non-chemical alteration of quartz in this intemperic evolution. Based on these results it was concluded that a SiO_2 concentration occurs in class 4 materials, reflecting the formation of clay minerals. The R index itself, which is highly recommended for the evaluation of silica loss with alumina, in igneous and metamorphic rocks, due to the increase in weathering, was not very significant for the phyllites studied. Considering the indices that evaluate the chemical alteration of the rock (CIA and CIW), the representativity was low, which was already expected as these indexes are mostly used for evaluating alteration in rocks

Table 10.3 Chemical indexes based on molecular relations of mobilizable/immobilizable elements (a), based on silicon content (b), based on chemical change (c), and based onnormalized indices (d)

Chemical index	Author
(a)	
$\text{ba} = \frac{K_2O + Na_2O + CaO}{Al_2O_3}$ $\text{ba1} = \frac{K_2O + Na_2O}{Al_2O_3}$ $\text{ba2} = \frac{CaO + MgO}{Al_2O_3}$ $\text{ba3} = \frac{K_2O + Na_2O + MgO}{Al_2O_3}$	Harrassowitz (1926)
$\text{Base}: Al = \frac{K_2O + Na_2O + CaO + MgO}{Al_2O_3}$ $\text{Base}: R_2O_3 = \frac{K_2O + Na_2O + CaO + MgO}{Al_2O_3 + Fe_2O_3 + TiO_2}$	Colman (1982)
$\text{b1} = \frac{Al_2O_3}{TiO_2}$	Rocha Filho et al. (1985)
$WR = \frac{CaO + MgO + Na_2O}{ZrO_2}$	Chittleborough (1991)
(b)	
$SF = \frac{SiO_2}{Fe_2O_3}$ $\frac{\text{Silicium}}{R_2O_3} = \frac{SiO_2}{Al_2O_3 + Fe_2O_3 + TiO_2}$	Jenny (1941)
$\text{PI} = \frac{SiO_2}{SiO_2 + Al_2O_3 + Fe_2O_3 + FeO + TiO_2}$	Reiche (1943)
$\text{R} = \frac{SiO_2}{Al_2O_3}$	Ruxton (1986)
$STI = \frac{\frac{SiO_2}{TiO_2}}{\frac{SiO_2}{TiO_2} + \frac{SiO_2}{Al_2O_3} + \frac{Al_2O_3}{TiO_2}}$	De Jayawardena and Izawa (1994)

(continued)

Chemical index	Author
$(WI-1/WI-2)=\dfrac{\dfrac{SiO_2+CaO}{Fe_2O_3+TiO_2}}{\dfrac{SiO_2+CaO}{Al_2O_3+Fe_2O_3+TiO_2}}$	Darmody et al. (2005)
(c)	
$SF=\dfrac{SiO_2}{Fe_2O_3}$ $\dfrac{\text{Silicio}}{R_2O_3}=\dfrac{SiO_2}{Al_2O_3+Fe_2O_3+TiO_2}$	Jenny (1941)
$PI=\dfrac{SiO_2}{SiO_2+Al_2O_3+Fe_2O_3+FeO+TiO_2}$	Reiche (1943)
$R=\dfrac{SiO_2}{Al_2O_3}$	Ruxton (1986)
$STI=\dfrac{\dfrac{SiO_2}{TiO_2}}{\dfrac{SiO_2}{TiO_2}+\dfrac{SiO_2}{Al_2O_3}+\dfrac{Al_2O_3}{TiO_2}}$	De Jayawardena and Izawa (1994)
$(WI-1/WI-2)=\dfrac{\dfrac{SiO_2+CaO}{Fe_2O_3+TiO_2}}{\dfrac{SiO_2+CaO}{Al_2O_3+Fe_2O_3+TiO_2}}$	Darmody et al. (2005)
(d)	
$B=\dfrac{b_{\text{weathered}}}{b_{\text{sound}}}$	Harrassowitz (1926)
$LCH\,\text{Factor}=\dfrac{I_{\text{weathered}}}{I_{\text{sound}}}$, when $I=\dfrac{K_2O+Na_2O}{SiO_2}$	Jenny (1941)
$WI=\dfrac{WPI_{\text{weathered}}}{WPI_{\text{sound}}}$, when $WPI=\dfrac{K_2O+Na_2O+CaO\cdot H_2O}{SiO_2+Al_2O_3+Fe_2O_3+TiO_2+CaO+MgO+Na_2O+K_2O}$	Short (1961) (WI), Reiche (1943) (WPI)
$K=\dfrac{I_{\text{weathered}}}{X_{\text{sound}}}$, where $I=\dfrac{SiO_2}{Al_2O_3}$ $X=\dfrac{K_2O+Na_2O+CaO}{Al_2O_3}$	Rocha Filho et al. (1985)
$\text{Imob}=\dfrac{I_{\text{sound}}-I_{\text{weathered}}}{I_{\text{sound}}}$, when $I=K_2O+Na_2O+CaO$	Irfan (1996)

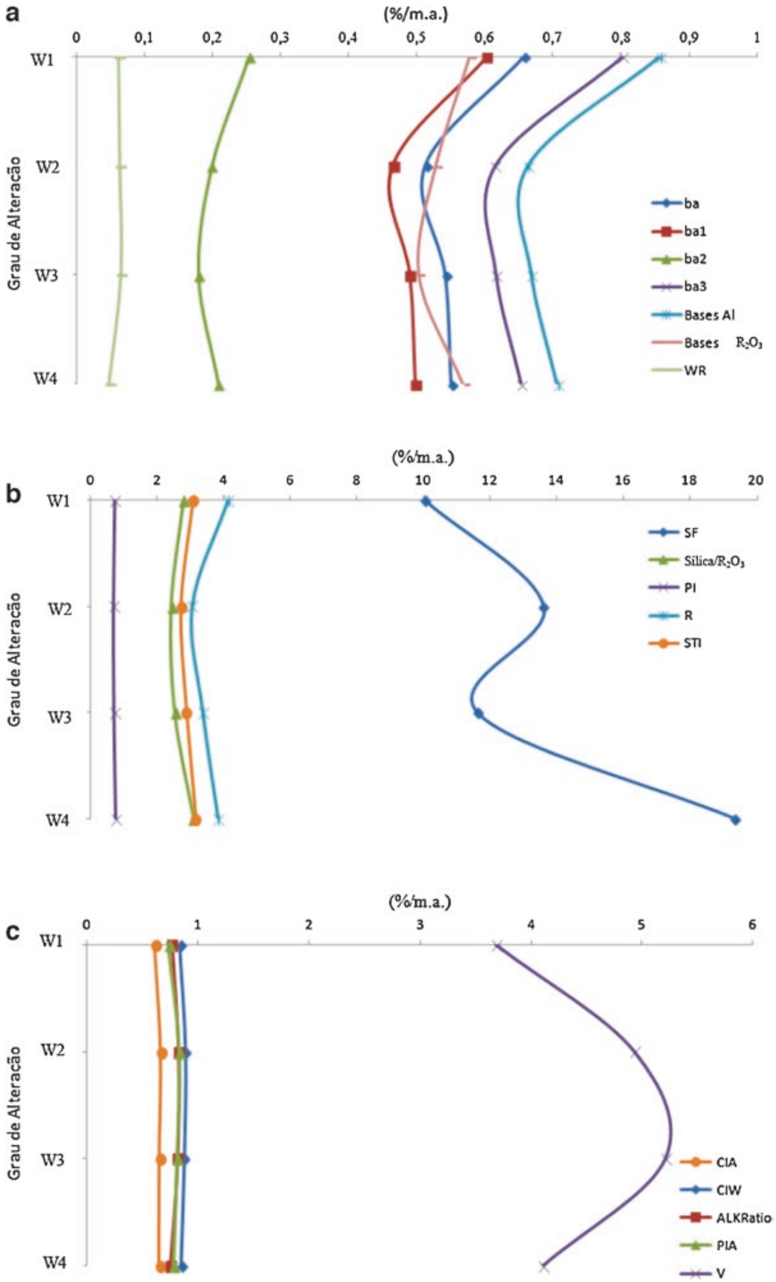

Fig. 10.16 In (**a**), chemical index mobilizable/immobilizable relation (ba, ba1, ba2, and ba3—Harrassowitz 1926; Bases R_2O_3 and Al—Colman 1982 and WR—Chittleborough 1991). In (**b**), silica contents (SF and Sílica/R_2O_3—Jenny 1941; PI—Reiche 1943; R—Ruxton 1986; STI—Jayawardena and Iazama 1994). In (**c**), indexes based on chemical change (CIA—Nesbitt and Young 1982; CIW—Harnois 1988; ALK Ratio—Harnois and Moore 1988; PIA—Fedo et al. 1995; V—Vogt 1972)

rich in feldspar, mineral that was not found in the phyllites under study. However, as these indices take into account elements such as Al and K, present in the chemical formulae of the main minerals of the rock (muscovite and sericite), a slight tendency is observed, originated from the alteration processes that occur in these minerals (Leão et al. 2016).

10.6 Mechanical Properties

In ideal elastic conditions, mechanical properties of geological materials, whether soils, rocks or their intermediate state (altered rocks), by static (stress–strain relations) and dynamic (elastic wave velocity) experiments should result in the same outcome. However, rock masses are not ideal elastic, mainly due to factors such as heterogeneity.

The study of the behavior of rock masses composed by soft rocks and the weathering action on them is still subject of discussion. Their weathered portions may present remnant aspects of the parent rock and the geotechnical-geomechanical parameters of these materials are difficult to obtain in situ (Leão 2015) and in the laboratory. Rocks, when weathered become soft and even when they are naturally soft, they may present problems related to sampling, preparation and selection of tests that can represent its properties variation (Kanji 2014); and representativity and extrapolation in numerical models (Agliardi et al. 2001). Due to their typical brittle behavior, equipment and samplers used for testing hard rocks are not adequate for use on soft rocks and, on the other hand, these rocks are too resistant when subjected to the conditions of ordinary experiments in soil mechanics (Kanji 2014).

There are no internationally accepted standards for the preparation of specimens in altered rocks. Some authors state that the existing standards for hard rocks are, in some ways, very strict (Pells and Ferry 1983; Chiu et al. 1983). In particular, in relation to the height–diameter ratio for uniaxial and triaxial compression tests, the 2:1 height–diameter ratio is acceptable for altered rocks (Chiu et al. 1983), although based on few data. For uniaxial compression, the ISRM (Brown 1981) recommends a ratio of 2.5:1, not excluding soft rocks. Another problem is the possibility that the materials contain expansive properties, compromising the specimens during drying processes. The re-saturation of the samples can generate desagregation and disintegration (Pinho 2003). Finally, in disaggregated rocks, such as sandstones with little cementing, total or partial disintegration of the sample during vacuum sealing may occur, and it may be necessary to adopt alternative saturation techniques, such as progressive saturation (Marques et al. 2017).

In fact, performing tests on weathered rocks, soft and weakly weathered rocks should follow certain precautions without neglecting the standards of execution, and each exception should be analyzed, discussed and included with common sense (Leão 2017).

10.6.1 Strength Characteristics

The point load test is a simple, fast and inexpensive test in which samples can be of different size and shape, as well as easy to reproduce due to equipment portability (ISRM 2015). This test is highly recommended for the characterization of the rocks and may be related to the uniaxial compression strength (ISRM 2015). In clayey rocks, such as claystones and siltstones, with a strength of less than 25 MPa, this test is not recommended due to the penetration of the conical tips in the sample (Hawkins and Pinches 1992). If to be used, a correction in the results will be necessary (ISRM 2015). Even so, the test is a commonly used for the determination of the compressive strength, due to the difficulties in the preparation/machining of the samples.

By comparing distinct rock groups, the strength values may also be very different. Igneous rocks and some varieties of quartzite and sandstones have the highest compressive strengths when compared to other rocks. Sound igneous rocks can reach compression strength of up to 414 MPa (basalts), also driven by the crystalline arrangement and presence of porphyries of reduced porosity. High-grade metamorphic rocks, such as amphibolites, are also included in this category.

The effect of weathering promotes a reduction in the resistance of the rocks, motivated by changes in their microfabric, which controls their resistance. This effect can be observed in Fig. 10.17 for sedimentary rocks (a and d), igneous rocks (b and e) and metamorphic rocks (c and f). In the case of metamorphic rocks in Brazil, results of tests in samples are presented in the orthogonal (O) and parallel (P) directions to the foliation of the rock.

In general it can be noted that the increase of weathering promotes the reduction of both the uniaxial compressive and the point load index strength. Comparing results obtained in tests carried out in samples oriented in the orthogonal direction to the rock foliation, one notices that the values are larger when compared to the ones obtained in tests of samples oriented in the parallel direction to foliation. The texture, mainly concerning the size of the grains and the presence of cementing substances, is the main responsible for the resistance. This can be observed when comparing igneous and high-grade metamorphic rocks to sedimentary and low-grade metamorphic rocks. However, for a specific weathering class, the values of uniaxial compressive strength are almost equivalent (classes 4 and 5). On sedimentary rocks, the presence and type of cementing materials can increase the mechanical strength of the rock and minimize the loss of resistance with weathering, as observed in limestones and sandstones (Fig. 10.17a). Compared with clayey rocks (mudstones and tuffs) or the one with clay-like materials between main minerals (as on marls) the uniaxial compression strength can reduce drastically.

In sound igneous rocks the grains and mineral aggregates promote high resistance and stability. Thus, the range of values for compressive strength varies in broad bands, being dependent on the degree of crystallization and mineralogy of the rocks. For sound materials the reduction of mechanical resistance can be influenced by grain size and by the presence of lamellar minerals (mica) and reduction of the amount of quartz. When these rocks undergo weathering, reduction of the strength

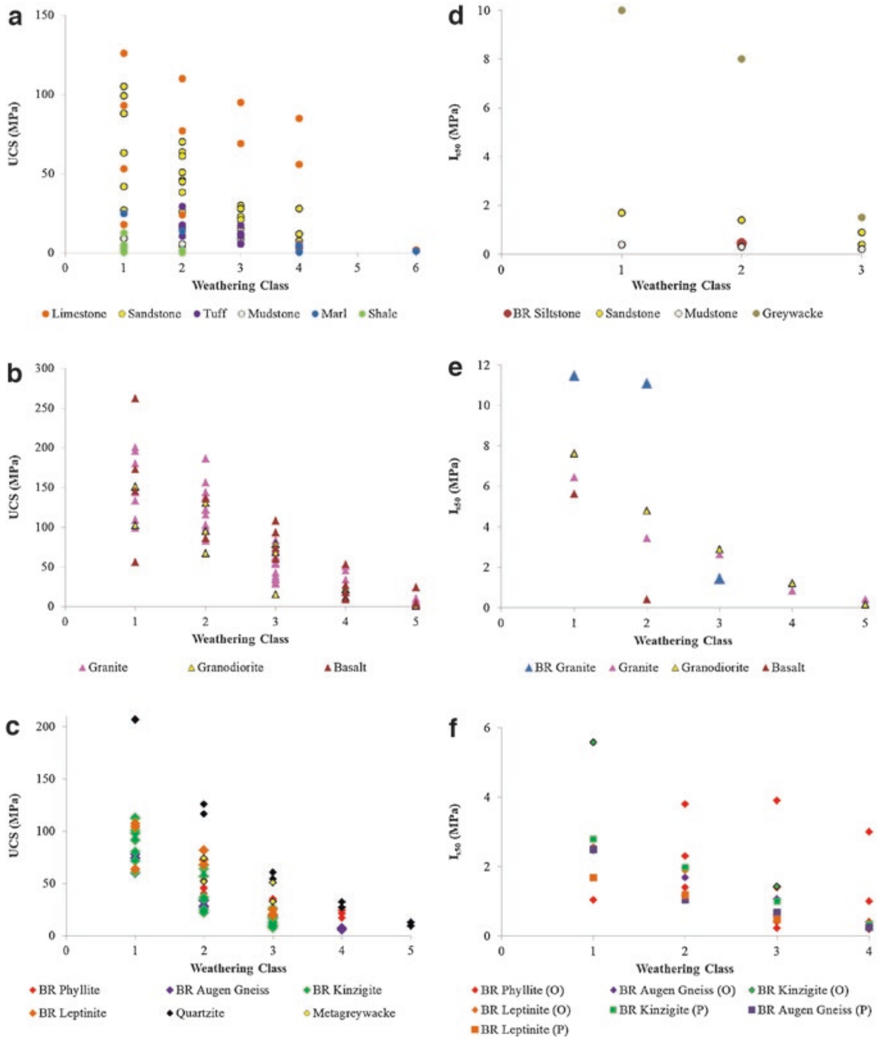

Fig. 10.17 Variation of resistance to simple compression and resistance to point load compression with weathering in sedimentary rocks (**a** and **d**), igneous rocks (**b** and **e**) and metamorphic rocks (**c** and **f**) in the orthogonal (O) direction and parallel (P) to foliation. Rocks from Brazil are identified by BR and highlighted in the charts

occurs according to the intrinsic properties of rocks. Thus, rocks such as granite and granodiorite present greater resistance when compared to basalts (Fig. 10.17b). In general, weathering promotes the development of microfractures, which may be responsible for stress relief in mineral grains (Dobereiner et al. 1993). Due to weathering rock microstructure becomes noticeably more fractured compared to sound materials.

For metamorphic rocks (Fig. 10.17c) strength is mainly dependent on the mineralogical composition of the rock. The presence of planar minerals (such as chlorite, biotite and mica) develops low resistance and alterability planes. Comparing the results presented in Fig. 10.17c, it can be observed that rocks with higher crystallinity (leptinites, augen gneisses and kinzigites) exhibit greater resistance to uniaxial compression when compared to rocks of low metamorphic degree, such as phyllites. Rocks that possess foliation are more susceptible to the presence of clay minerals in the planes and as in igneous rocks, the presence of these minerals reduces the resistance of the rock.

It should also be noted that for all rocks there is an influence of water on the mechanical properties. The water tends to reduce surface energy and crystalline arrangements, reducing the rock's resistance and increasing its deformability, which can be observed progressively in the classes of change. In this case, there may still be a chemical influence on the process, considering that quartz is a mineral with high resistance to chemical degradation (Gupta and Rao 2000). In particular, the clayey sedimentary rocks are very sensitive to variations of moisture content, directly affecting the mechanical properties. The structural arrangement of clayey rocks is far inferior in terms of resistance when compared to the structural arrangement observed in magmatic and metamorphic rocks.

Another issue that influences the resistance of metamorphic rocks is anisotropy (I_A), as shown in Fig. 10.18. This figure shows that for high-grade metamorphic rocks (gneisses) form Rio de Janeiro, there is a significant variability inside the same class of alteration. In general, the larger resistance under compressive stresses corresponds to the forces applied perpendicular to the foliation.

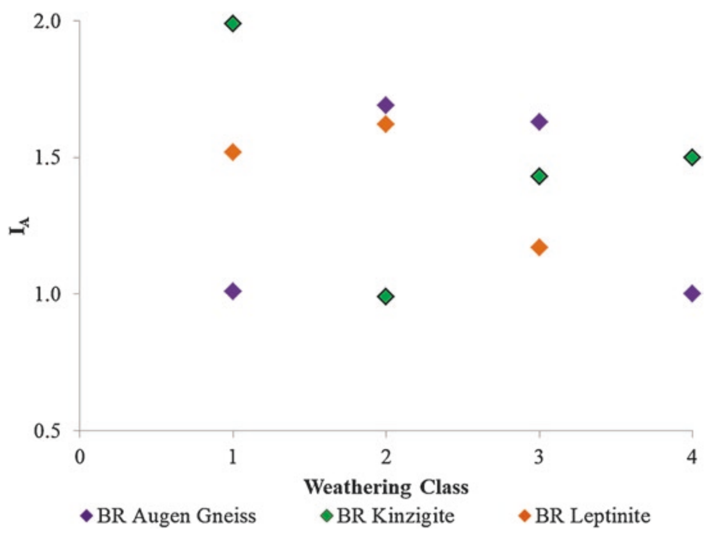

Fig. 10.18 I_A values for Brazilian metamorphic rocks

According to Fig. 10.18, the comparison between the I_A values for metamorphic rocks in Brazil shows a tendency of reduction of rock resistance and anisotropy, with the increase in weathering, whose values for rocks are very similar.

Another important and expeditious test used in the evaluation of rock weathering is the Schmidt hammer or sclerometer test. Due to its simplicity, it allows an in situ measurement without the need of any sample preparation. The presence of roughness on the tested surfaces and the proximity of discontinuities can generate dispersion in the values. Moreover, it is not very representative in very soft rocks (for R—"Rebound," lower than 10) (Pinho 2003). The Schmidt sclerometer, according to Brown (1981), as well as the point load test (PLT) has a reduced application for rocks of very low strength; however, for some soft rocks with some strength, such as cemented sandstones, good correlations can be achieved with the simple compressive strength. Leão and Marques (2016) have obtained good results for the evaluation of the weathering in phyllites by using sclerometry.

Disintegration of the rock in smaller portions due to the alternation of cycles of wetting and drying can occur during weathering. In this context, several methods are suggested as an index test for determining weatherability of rocks, such as slake durability test, cycling tests, and Soxhlet extractor. These tests accelerate rock decomposition more quickly than would occur in nature.

The slake durability test (ISRM 2015) is strongly recommended for soft rocks (Russel 1982; Ojima and Rodrigues 1983; Lee and Freitas 1988; Dick and Shakoor 1990, 1992; Lana 2014), due to its simplicity and speed. The durability index (I_d) is the percentage of dry rock that is retained in a metallic net drum after 1 or 2 complete cycles (I_{d1} or I_{d2}), based in which the rock can be classified according to the criteria proposed by Franklin and Chandra (1972). It is worth mentioning that Gökçeoglu and Aksoy, (2000) state that two cycles are not enough to evaluate the durability of soft rocks, when compared to other durability tests, and three or more cycles may be necessary.

Although in situ and laboratory conditions are distinct, these durability tests show good results for identifying alteration processes. The lack of information for correlation between the results of durability tests and other tests (mechanical, chemical and physical), as well as the lack of clear understanding of the phenomenon of disaggregation (Akai 1997), limit the applicability of these tests.

Figure 10.19 presents weathering assessments using Schmidt sclerometry and slake durability test for sedimentary (a and d), igneous (b and e) and metamorphic (c and f) rocks.

The results of sclerometry (Fig. 10.19a–c) show that, in sedimentary rocks, the dispersion of results is much lower when compared to igneous and metamorphic rocks, but for all related lithotypes there is a reduction of this property with the increase of weathering. Some aspects of the rocks tested may influence R values such as the degree of rock polishing/machining, the presence of foliation planes, the existence of loose surfaces in the execution of the test, penetration of the tip in highly altered and friable materials, and rock heterogeneity. When performed in the laboratory, the stability of the sample should also be guaranteed (Katz et al. 2000).

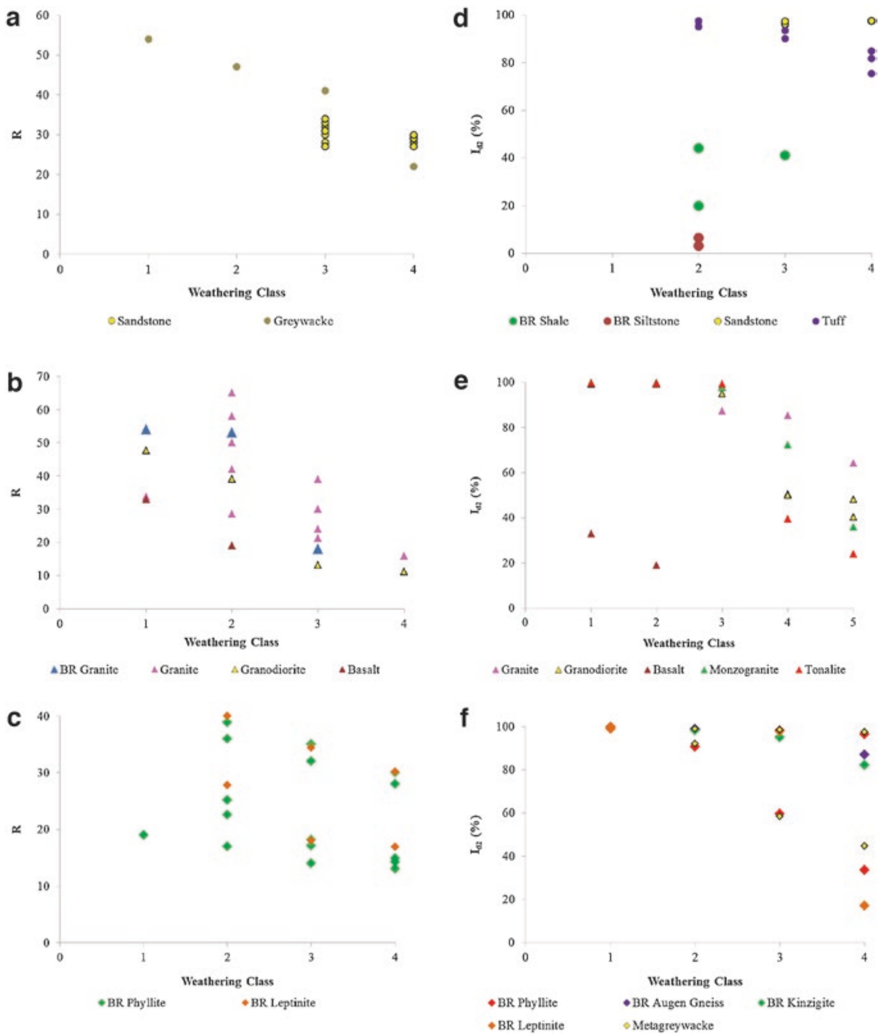

Fig. 10.19 Variability of sclerometric index and durability index with weathering in sedimentary rocks (**a** and **d**), igneous (**b** and **e**) and metamorphic (**c** and **f**). Brazilian rocks are identified by BR and highlighted in the charts

Mechanical anisotropy can be evaluated by performing the test in different directions in relation to the rock structures (foliation planes and bundles, for example), and it should be emphasized that in non-horizontal tests the influence of gravity occurs (Basu and Aydin 2004; Aydin and Basu 2005). Thus, tests performed in the orthogonal direction to the structures present higher values than tests carried out in the parallel direction.

In hard rocks, such as granites, it is recommended to repeat multiple impacts on the same point (Aydin and Duzgoren-aydin 2002). For soft and very altered rocks this procedure modifies the characteristics of the application surface and is not suitable (Leão 2017). Greco and Sorriso-Valvo (2005) performed many measurements of sclerometry, considering the influence of the discontinuity characteristics of the rock mass. For the four groups of rocks studied: (1) plutonic rocks, (2) low to medium metamorphic rocks (phyllites and argillites), (3) augen gneisses and (4) medium to high metamorphic grade (shales, gneisses, amphibolites and migmatites), only the crystalline rocks showed low influence of the discontinuities, being more dependent of these characteristics than the foliated rocks. In this case, it is recommended to carry out the test on a grid drawn on a regular surface of the rock, with application points 5–10 cm apart, according to the conditions found.

The durability is mainly related to the mineralogical composition of rocks, texture and the nature of the fluids that are in contact with the rock during the test. This can be observed from the results for sedimentary rocks (Fig. 10.19d), igneous (Fig. 10.19e) and metamorphic rocks (Fig. 10.19f), where the former tend to show less dispersion than two other genetic lithotypes, but the reduction of I_{d2} with weathering is clear.

It is worth mentioning that, in clayey rocks such as siltstones, claystones and shales, as well as some types of phyllites and slates, characteristics such as contact surface, presence of discontinuities, moisture content, past erosive processes and genetic rock type can directly influence durability (Gautam and Shakoor 2013), as can be observed on I_{d2} values obtained for phyllites compared to coarse metamorphic rocks (Fig. 10.19f).

10.6.2 Deformability Characteristics

The elastic properties in the rocks vary in a wide and direction dependent manner, the value of the modulus of elasticity depends on the direction in which the measurement is made. In general, the modulus of elasticity of the rocks is smaller when the measurement is made perpendicular to the structures present in the rock (stratification, lineage, foliation, for example). In addition, weathering also influences this property, in that it reduces the stiffness of the samples.

The elastic modulus is an important parameter in the practice of geotechnical engineering, and can be obtained from the measurement of the velocity of P waves. Characteristics such as the decrease of calcite in calcareous rocks can exponentially decrease the modulus of elasticity, being a parameter that is important for the evaluation of weathering in these rocks, as shown in Fig. 10.20. The weathering action promotes the development of clay minerals, the decomposition of the texture and the crystalline arrangements, as well as the microfracture, causing a reduction in the modulus of elasticity of the rocks (Momeni et al. 2017).

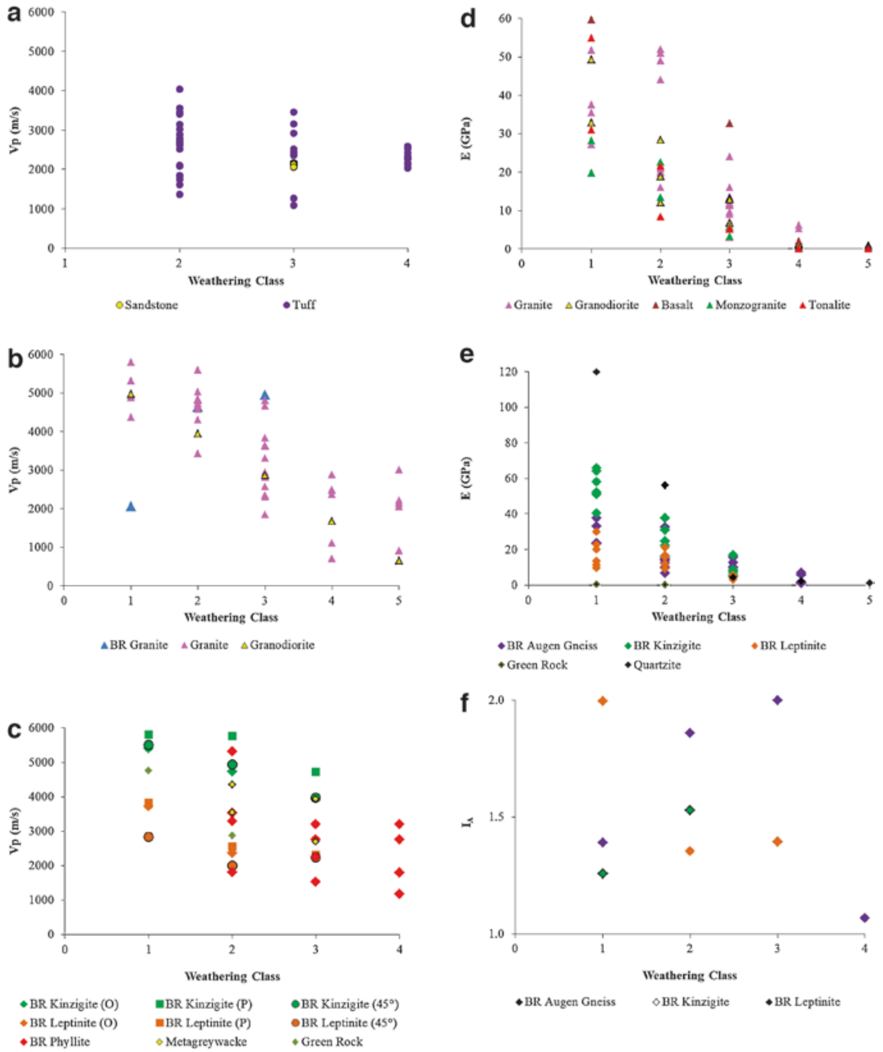

Fig. 10.20 Variation of the velocity of seismic waves and modulus of elasticity with weathering in sedimentary rocks (**a** and **d**), igneous (**b**) and metamorphic (**c** and **e**). Figure (**f**) presents the I_A for the deformability modulus for metamophic rocks. Rocks from Brazil rocks are identified by BR and highlighted in the charts

This effect can be observed in Fig. 10.20 for sedimentary rocks (a and d), igneous (b) and metamorphic (c and e) rocks. In the case of metamorphic rocks in Brazil, results of tests performed in samples are presented in the orthogonal direction (O), with 45° angle, and parallel (P) to the rock foliation. Figure 10.19f presents the I_A for the deformability modulus for metamorphic rocks.

By observing the results presented in Figs. 10.20a–c it can be seen that the values of Vp for all the rocks, reduce as the weathering progresses. The degree of entanglement of the mineral grains, when low, can influence in the composition of the rock primary minerals like quartz and feldspar, considered of low deformability. However, when this bonding is well developed, the values of strength and stiffness tend to be high. As weathering is responsible for the reorganization of the textured rock patterns, in addition to the alteration of primary minerals, the moduli of elasticity (Figs. 10.20d, e) tend to be smaller the larger the change in weathering class is. The development of microfractures and clay minerals also contributes to this effect, causing significant loss of rock elasticity. It should also be noted that the saturation of the sample also causes a reduction in the modulus of elasticity and Vp waves. Considering the direction of propagation of Vp waves due to banding, stratification, and foliations, it is possible to encounter anisotropy in the elastic properties. In this case, measurements performed in the direction perpendicular to stratifications, bundles, and foliations are larger when compared with measurements carried out parallel to these structures. The I_A values presented for metamorphic rocks (Fig. 10.20f) show that sound rocks tend to be more anisotropic when compared to more weathered stages of the same rock.

10.7 Recent Studies

Recently, the authors and their research group have been working on physical, chemical, and mechanical characterization of low-grade igneous, sedimentary, and metamorphic rocks in the southeast region of Brazil. In this context, some sandstone, limestone, and granite weathering profiles are currently under study.

For the study of influence of weathering on igneous rock, several outcrops of granitic rocks were selected, considering the scarcity of data in the scientific literature on complete weathering profiles developed in these rocks, under tropical climates. Several types of calcareous rocks were selected and comprise calcilutites, limestones and siltstones, whose outcrops exposed on road cuts in the State of Minas Gerais (Southeast Brazil). At the same time, the research group is continuing studying low-grade metamorphic rocks, mainly phyllites. The main purpose of all those studies currently under development is to understand the influence of weathering on physical, chemical, mineralogical, and mechanical properties of both the intact rock and the rock mass along the weathering profile and trying to correlate these properties.

It is expected that this study can determine the effect of weathering on the aforementioned properties, through evaluations and tests to be performed, both in intact rock and discontinuities, in situ and in the laboratory. In addition, it is expected to propose a simple and practical classification criterion suitable for different rock geneses (igneous, sedimentary and metamorphic) under tropical climate. Also, the study has the purpose of elucidating the following aspects: (1) morphological characterization of typical weathering profiles for different lithotypes; (2) field and/or laboratory characterization of the properties of the main discontinuities, and (3) identification of the main mechanisms (physical and chemical) responsible for the development of the weathering.

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