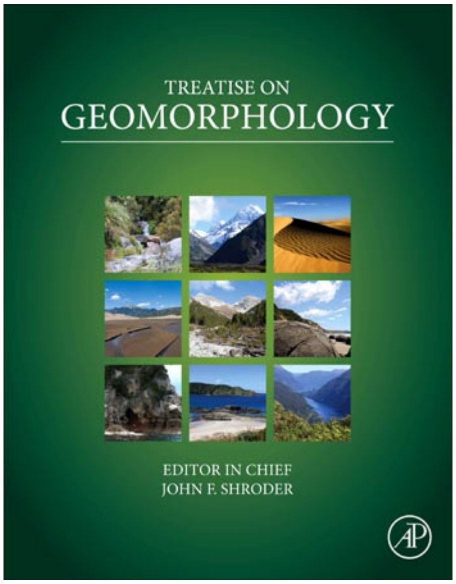




Pope G.A. (2013) Overview of Weathering and Soils Geomorphology. In: John F. Shroder (ed.) Treatise on Geomorphology, Volume 4, pp. 1-11. San Diego: Academic Press.

# 4.1 Overview of Weathering and Soils Geomorphology

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## Abstract

Weathering and soil geomorphology constitutes a specific subfield of earth surface processes, equally important in the process system in creating the surface landscape. While weathering and soils are of interest to a broad range of sciences, their role in geomorphology is specific and important. Weathering is the precursor to both chemical and mechanical erosion, thus important to the generation of sediments carried by other surface processes. Weathering is essential to the creation of soils. Weathering in all the cases is relevant to erosional and depositional landforms. However, specific in this volume are the landforms and landform processes dominated by weathering.

> …The fundamental control on landscape evolution in erosional landscapes is weathering.
>
> (Phillips, 2005)

Weathering is the precursor to erosion, and further, all sediments in depositional landscapes derive from weathering. It is not out of line to therefore conclude that all landforms are weathering related. Alluvial, aeolian, glacial, and marine sediments cannot exist without being liberated from their parent rocks by weathering. Erosion is eased along by the weakening of rock through weathering processes. Slopes are defined by the rate of exposure due to weathering and removal of material, and by the colluvial mantle derived from *in situ* weathering and downslope movement. Landforms that resist erosion also tend to resist weathering. However, there is a specific class of landforms that are particularly dependent on weathering processes, and these are the subject of weathering geomorphology (**Figure 1**).

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Soils are a direct byproduct of weathering, so are included with weathering geomorphology. Different authors present different definitions for what encompasses 'soil geomorphology.' Daniels and Hammer (1992: 1) used a methodological definition, ''…the application of geologic field techniques and ideas to soil investigations;'' essentially, an extension of sedimentology to soil science. Birkeland (1999) was more encompassing, and somewhat reverse of Daniels and Hammer, applying soils and pedogenesis toward the study of landform evolution and dynamics. Gerrard's (1992: 2) definition, also adopted by Schaetzl and Anderson (2005), stated simply that soil geomorphology strived to explain the ''genetic relationships between soils and landforms,'' a two-way view toward both pedogenesis and landform evolution.

## 4.1.1 Previous Major Works in Weathering and Soils Geomorphology

This edited text builds on a heritage of important publications in the fields of weathering and soils geomorphology. First, it is germane to define what this volume is, and is not. The aim here is to focus on the science of geomorphology, consistent with the intent for the *Treatise on Geomorphology* series. The study of weathering is not necessarily limited to geomorphology. Weathering is also pertinent to studies in mineralogy and petrology,

**Figure 1** A weathering landform. This granite tor, near Divide, Colorado (in the Pikes Peak Massif), is a resistant remnant of deep weathering. The landform owes its existence primarily to long-term weathering processes. Genesis involved the two-stage saprolite stripping model (*see* Chapter 4.8), first with long-term attack of chemical weathering agents progressively deeper into the bedrock, then later stripping of weathered material, revealing the resistant corestone boulders. Subsequent to exposure, mechanical weathering by way of ice, pressure release, and possible thermal extremes further shaped the rock as chemical weathering continued. Endogenic factors influenced the outcome: composition and joint density of the rock, regional tectonic uplift modifying base level (erosion) as well as climate. As with most weathering landforms, other geomorphic agents played a role as well, in this case slope colluvium movement and fluvial erosion removed weathered material, each responding differently in warm, mild, or cold climates known to exist in this region over the past several million years.

sedimentology, biogeochemistry, and mechanical engineering, to name several fields. Naturally, there is overlap to be found. Presently, there is considerable activity concerning weathering and biogeochemistry (cf. Drever, 2005 for a good reference, part of the *Treatise in Geochemistry* series). Some of this activity pertains directly to geomorphology, while the remaining research trends toward topics such as soil processes, hydrology, and chemical cycling. Likewise in soil science, not all studies pertain to geomorphology. In the very broad field of soil science, geomorphology sustains relative minority interest, with the much larger emphasis trending toward agronomy and ecology, hydrology, pollution, and engineering. The present volume strikes a course more specifically relevant to geomorphology. Though, in the interest of cross-fertilization, readers are encouraged to explore these allied fields. A quick survey of the references cited within this volume reveals diverse sources of information and ideas, proof of the interdisciplinarity expected within weathering and soil geomorphology.

Soil science has a long heritage (covered well in Schaetzl and Anderson, 2005), and the soil aspect of geomorphology has been recognized at least as far back as Dokuchaev and Glinka (late nineteenth and early twentieth centuries), who included a topographic factor in soil genesis (refer to Marbut's translation, Glinka and Marbut, 1927). Later authors such as Jenny (1941), Hole (1953), and Ruhe (1956) further advanced the ideas of soil geomorphic relationships.

Weathering geomorphology was recognized early on as one of the several key earth surface processes. Strabo and Herodotus observed the weathering processes in building stones (Camuffo, 1992). Said (1950) reported sophisticated concepts of weathering processes from a tenth century Arabic writing, *The Discourses of the Brothers of Purity.* By the time of the scientific revolution in geology in the late eighteenth and early nineteenth centuries, writers incorporated weathering, though briefly mentioned, as part of the rock cycle (as best understood at that time). Playfair (1802) was foremost among these pioneers to first elaborate on the system of geomorphology, including the role of weathering. Scattered examples of weathering research followed (e.g., Yates, 1830; Bischof, 1854–1859; Kinnahan, 1866; Gilbert, 1877). Van den Broek's (1881) and Merrill's (1897) works were the first major treatises published concerning the geomorphic and geologic aspects of weathering.

Still, weathering geomorphology has held a fraction of the interest compared to the other subfields of geomorphology. According to Yatsu (1988), in his comprehensive review of the foundation of weathering science, early twentieth century geomorphologists were preoccupied with erosion cycles to the exclusion of other aspects of landform modification (such as weathering). Evident in **Table 1** below is a skew toward more recent writings, demonstration of the growing interest in weathering geomorphology since the 1960s. Momentum launched by the successful British Geomorphological Research Group (BGRG) symposium in 1992 (Robinson and Williams, 1994) led to two successful symposia in recent years, attracting a broad international audience. Weathering 2000 (held in Belfast, Northern Ireland), and the 2005 Binghamton Symposium in Geomorphology (in Lexington, Kentucky) both featured weathering and landscape evolution. On an ongoing basis annually, the Goldschmidt Conference attracts several themed sessions concerning weathering geochemistry, and the weathering focus on stone conservation produces serial meetings, such as those of the Stone Weathering and Atmospheric Pollution Network (SWAPNet). The national and specialized organizations in Europe, Australia, Asia, and North America regularly see themed sessions on weathering geomorphology at their annual meetings as well. The field has attracted new participants, but credit is also due to collaborative efforts such as SWAPNet, the Critical Zone Exploration Network, and interdisciplinary symposia to connect already active researchers in allied and disparate fields, like minds working on similar ideas worth sharing.

**Table 1** presents an overview of the major previous works in weathering and soils geomorphology. While thorough, it is not necessarily exhaustive (no slight is intended for any omissions), but provides a reasonable cross-section over time.

In addition to these texts, research articles on soils and weathering geomorphology are regularly found in the main geomorphology journals; *Geomorphology*, *Catena*, and *Geoderma* (Elsevier), *Earth Surface Processes and Landforms* (Wiley), *Zeitschrift für Geomorphologie* (Schweizerbart) receiving the most coverage. Still, dozens of periodicals beyond these listed are apt to find weathering and soils geomorphology within their interest. These include many subfields in geology,

**Table 1** Major works in weathering and soils geomorphology over the last half century. A separate and large literature concerning soils and paleoenvironments is not included here apart from several examples under the category of 'other'

| *Author and date* | *Title* | *Broad themes or topics* |
|---|---|---|
| *Texts specifically concerning weathering* | | |
| Bland and Rolls (1998) | Weathering: An Introduction to the Scientific Principles | 1 2 3 4 |
| Boyer (1971) | Field Guide to Rock Weathering | 1 3 7 |
| Carroll (1970) | Rock Weathering | 1 2 3 |
| Colman and Dethier (1986) | Rates of Chemical Weathering of Rocks and Minerals | 1 2 3 4 5 6 |
| Delvigne (1998) | Atlas of Micromorphology of Mineral Alteration and Weathering | 2 |
| Drever (1984) | The Chemistry of Weathering | 2 3 |
| Drever (2005) | Surface and Ground Water, Weathering, and Soils | 1 2 4 5 |
| Goudie and Viles (1997) | Salt Weathering Hazards | 1 2 3 |
| Kittrick (1986) | Soil Mineral Weathering | 1 2 |
| Lerman and Meybeck (1988) | Physical and Chemical Weathering in Geochemical Cycles | 3 4 |
| Loughnan (1969) | Chemical Weathering of the Silicate Minerals | 1 |
| Marshall (1964, 1977) | The Physical Chemistry and Mineralogy of Soils, vols. 1 and 2 | 2 4 5 |
| Martini and Chesworth (1992) | Weathering, Soils, and Paleosols | 2 3 4 5 6 |
| Nahon (1991) | Introduction to the Petrology of Soils and Chemical Weathering | 1 2 3 4 5 6 |
| Ollier (1984) | Weathering[a] | 1 2 3 5 |
| Ollier and Pain (1996) | Regolith, Soils, and Landforms | 1 2 3 6 |
| Reiche (1950) | A Survey of Weathering Processes and Products | 1 2 3 4 5 |
| Taylor and Eggleton (2001) | Regolith Geology and Geomorphology | 1 2 3 4 6 |
| Yatsu (1988) | The Nature of Weathering | 2 3 4 5 |
| *Conference proceedings or special journal issues devoted to weathering and/or soils geomorphology* | | |
| Kneupfer and McFadden (1990) | Soils and Landscape Evolution (Binghamton Symposium) | 1 3 5 6 |
| Robinson and Williams (1994) | Rock Weathering and Landform Evolution (from BGRG 1992) | 1 2 3 4 5 7 |
| Deriving from the Weathering 2000 conference: | | |
| Smith and Turkington, 2004 | Stone decay: its causes and controls (from Weathering 2000) | 1 2 3 6 7 |
| Warke, 2001 | Weathering 2000 (Special issue, ESP and L) | 1 2 3 7 |
| Whalley and Turkington, 2001 | Weathering and Geomorphology (Special Issue, Geomorphology) | 1 2 3 5 6 |
| Turkington et al. (2005) | Weathering and Landscape Evolution (Binghamton Symposium) | 1 2 3 5 6 7 |
| *Texts specifically concerning soil geomorphology* | | |
| Birkeland (1999) | Soils and Geomorphology, 3rd ed.[a] | 1 2 3 4 5 6 7 |
| Catt (1986) | Soils and Quaternary Geology | 1 4 5 6 7 |
| Daniels and Hammer (1992) | Soil Geomorphology | 1 4 5 7 |
| Gerrard (1992) | Soil Geomorphology[a] | 1 3 |
| Jungenius (1985) | Soil and Geomorphology (Catena supplement) | 1 3 4 5 6 |
| Schaetzl and Anderson (2005) | Soils: Genesis and Geomorphology | 1 3 4 5 6 |
| *Other texts with substantial coverage of weathering or soils geomorphology* | | |
| Bourke and Viles (2007) | A Photographic Atlas of Rock Breakdown Features… | 1 2 3 |
| Brunsden (1979) | Process in Geomorphology (Chapter 4) | 1 3 5 |
| Buol et al. (2003) | Soil Genesis and Classification[a] | 1 3 4 5 |
| Dorn (1998) | Rock Coatings | 1 2 3 4 6 |
| Gerrard (1988) | Rocks and Landforms | 1 2 3 |
| Migon (2006) | Granite Landscapes of the World | 1 2 3 |
| Nash and McLaren (2007) | Geochemical Sediments and Landscapes | 1 2 3 4 5 6 |
| Scott and Pain (2008) | Regolith Science | 1 2 4 5 6 |
| Small (1982) | Slopes and Weathering | 1 3 |
| Thomas (1994) | Geomorphology in the Tropics[a] | 1 3 5 6 |
| Twidale (1982) | Granite Landforms | 1 2 |
| Yatsu (1966) | Rock Control in Geomorphology | 1 2 3 |
| Young et al. (2009) | Sandstone Landforms | 1 2 3 |

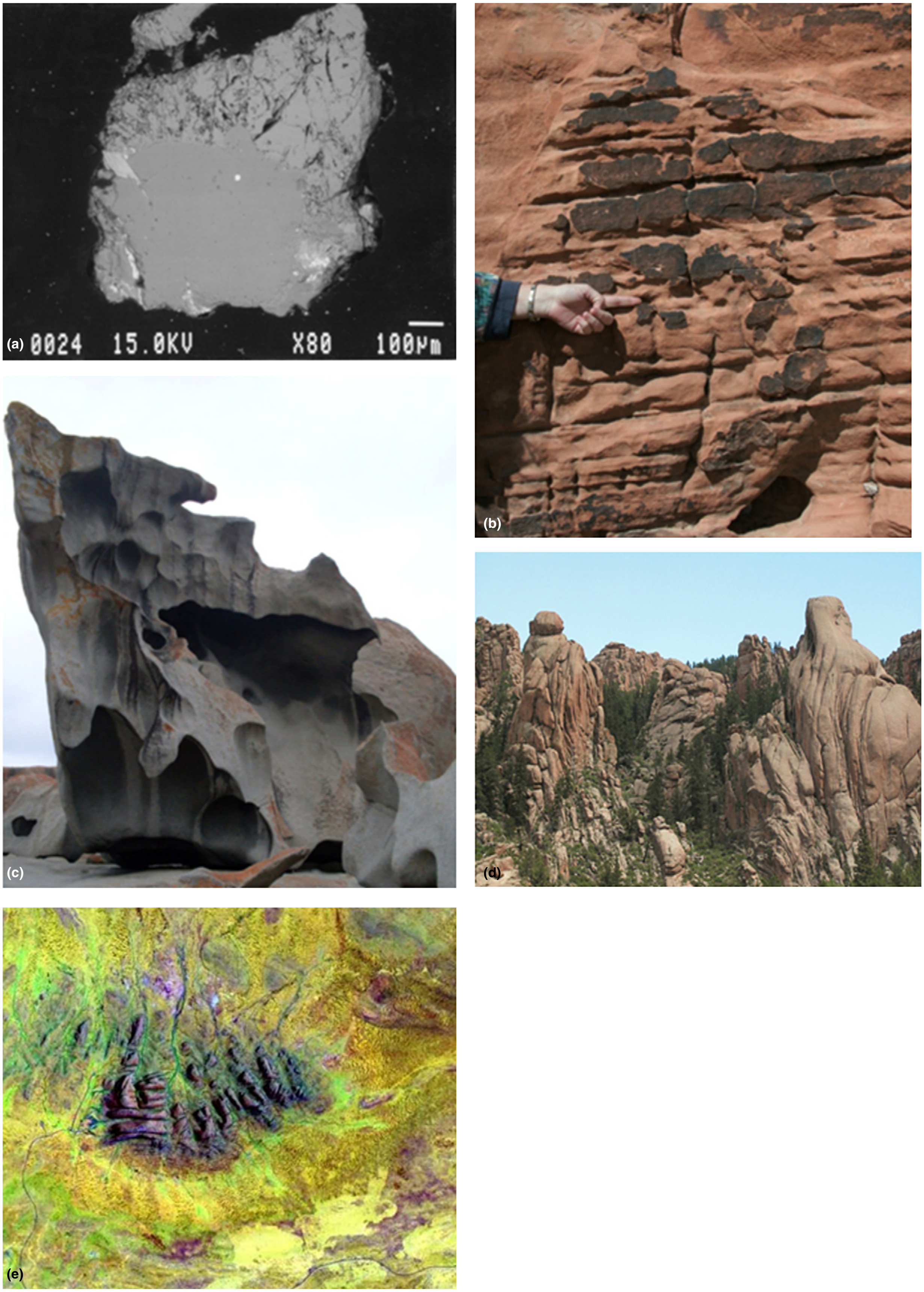
[a]Indicates that earlier editions were published, but not included here.

Broad themes and topics: 1. Geomorphology. 2. Minerals or petrology. 3. Weathering factors. 4. Geochemistry and hydrochemistry. 5. Pedogenesis. 6. Palaeoenvironments. 7. Education/Field Methods. All the above include weathering or soil processes as a topic.

physical geography, soil science, hydrology, environmental change, ecology, material science, and heritage conservation, as well as the general science venues such as *Nature* and *American Journal of Science*.

#### 4.1.1.1 Relevant Topics not Covered in this Text

Several topics relevant to weathering geomorphology are not covered in this text. Fortunately, there are excellent current


(a) 0024 15.0KV X80 100μm
(b)
(c)
(d)
(e)

works on the topics of karst geomorphology, biogeochemical landscapes, and weathering dating methods, which readers may avail beyond this text.

Karst geomorphology is a direct result of weathering processes: the solution weathering of susceptible rocks (such as limestone, marble, dolomite, sometimes sandstone, or quartzite) to produce holes, caverns, and depressions of various scale. Authors in this volume do discuss solution as a process. But, the breadth and importance of karst geomorphology is sufficient to warrant full coverage in a dedicated text. Hence, the *Treatise on Geomorphology* series does include a separate volume.

Weathering plays an important role in biogeochemical cycles, and in defining the geochemical landscape. This geochemical landscape has geomorphic expression (such as in pedogenesis, weathering mantles, and chemical denudation). The geochemical landscape can also be regarded without geomorphology, as some research in hydrochemistry, mineralogy, pedology, and ecology does. Several chapters herein make mention of geochemical cycles related to soils and weathering, but there is no specific chapter on geochemical landscapes. These concepts are well covered in Drever (2005).

A number of dating methods are dependent on weathering, if not entirely based on weathering: weathering rind thickness, rock coating properties, degree of mineral etching, mineral depletion and sediment maturity, rock face recession rates, rock integrity, morphology of mesoscale weathering features (such as tafoni), and soil profile development. All are at least capable of relative dating of geomorphic features or surfaces, some are useful as calibrated quantitative dating methods. The use of weathering dating methods dates back to Blackwelder (1931) and Kay (1931), a larger proliferation of quantitative and semiquantitative methods began in the late 1960s and early 1970s (cf. Brookes, 1981 for review). Continuing studies advance the utility of weathering dating methods wedded to modern technology. The basis for some of these dating methods are covered in chapters in this volume by Dorn (Chapter 4.5), Oguchi (Chapter 4.6), Paradise (Chapter 4.7), Dixon (Chapter 4.3), and Schmid (Chapter 4.16). Readers are encouraged to reference works by Birkeland (1999), Martini and Chesworth (1992), Dorn and Phillips (1991), Catt (1986), Mahaney (1984), Drever (1984), and Brookes (1982) for a more complete foundation on dating methods.

Paleosols, like soils, are originally pedogenic and thus weathering related. Paleosols are, however, more stratigraphic than geomorphic, though useful in establishing time and past environments useful for geomorphology. They can be altered by diagenetic processes similar to weathering when buried in deeper geologic context. Works by Wright (1986), Martini and Chesworth (1992), and Retallack (2008) provide background in this active field.

## 4.1.2 What Constitutes Weathering Geomorphology?

It is convenient to parse out the individual processes or individual environments for purposes of discussion. Weathering landforms can be defined in various ways, depending on the frame of reference and how much erosion is paired with the weathering process. The discussion of weathering-related landforms and soil-based geomorphology may be classified by means of generalized morphology: weathering voids, weathering resistance, weathering residua (including soils), and weathered landscapes. This classification has an inherent scalar and temporal organization (**Figure 2**). At increasing spatial and temporal scales, specific individual weathering processes diminish in importance replaced by the works of the entire weathering system.

### 4.1.2.1 Weathering Voids

Weathering, with erosion, creates voids, in other words, places where rock used to be. To borrow from visual arts, this is the 'negative space' of geomorphology, and sculptor Henry Moore's assertion that "a hole can itself have as much shape-meaning as a solid mass" (Friedenthal, 1963: 251) is as relevant to

**Figure 2** Weathering morphology at increasing scale. (a) A sand grain, seen in cross section with backscatter scanning electron microscope, approximately 1000 μm (1 mm) in diameter. The grain was sampled from an *in situ* soil profile with granitic parent material, on a marine terrace near Carmel, CA, USA. The grain exhibits differential weathering along grain and crystal weaknesses. The lower half of the grain is relatively unweathered quartz, the upper half is plagioclase, riddled with secondary porosity from dissolution (Pope, 1995). (b) Rock coatings, case hardening, and differential weathering of aeolian-bedded, Triassic Aztec Sandstone, Valley of Fire State Park, NV, USA. Iron and manganese rock coatings, derived from weathering and dust, impart a dark color to the outer surface. Cementation of an outer crust or rind, also a product of weathering, protects parts of the rock face, though more rapid weathering occurs when this crust is breached, particularly vigorous along joints and bedding planes. (c) Tafoni and cavernous weathering in Cambrian Remarkable Granite (Fairclough, 2008), Remarkable Rocks, Kangaroo Island, South Australia. The rock pictured is approximately 10 m high. Proximity to the ocean shoreline adds moisture and salt, both aggressive weathering agents. The cavernous weathering forms are partially governed by internal rock weaknesses and surface induration (case hardening), but also a regulated pattern of intersecting surface declivities that positively enhance the weathering environment by retaining moisture and surface organisms. (Photo courtesy of Dr. P. Beyer, Bloomsburg University.) (d) Granite pinnacles and tors in Cathedral Park (Pikes Peak batholiths), near Victor, CO, USA (cf. Blair, 1976). Vertical relief of the rock pinnacles is ~60 m, based on the proportion of the trees on the slopes. Weathering is joint controlled, and a covering of saprolite developed along the tertiary erosion surface has been exhumed during more recent uplift. Fluting from subaerial weathering and erosion is visible, as well as pressure-release jointing parallel to rock surfaces. (e) A weathered landscape, centering on Kata Tjuta ('The Olgas'), NT, Australia. The Kata Tjuta inselbergs, composed of Cambrian Mt. Currie Conglomerate, are remnant and resistant landforms in an exhumed etch plain, in which the surrounding weathered regolith has been stripped (Twidale, 2010). Fracture control is evident. The inselberg group rises 500 m above the plain, and spans about 8 km; the left-to-right dimension of this image is approximately 15.5 km. (Image source: NASA Earth Observatory (http:earthobservatory.nasa.gov), acquired by Landsat 7 Enhanced Thematic Mapper plus (ETM+), October 16, 1999, false-color composite (bands 7, 4, and 1) image with panchromatic.)

weathering as it is to art. Lack of weathering product (residua, particles, solutes) implies that erosion necessarily follows weathering to create these landforms. What remains are holes or declivities by many names: rillenkarren, tafoni, cavernous weathering, alveolar weathering (*see* Chapter 4.7). Most of these are small- and medium-scale features. Even so, weathering voids are apparent from submillimeter (*see* Chapter 4.5) to landscape scale. At the scale of landscapes, weathering paired with erosion derives the concept of denudation. Lowering of land surface can be observed in small scale, as in small drainage basins, but this is the one form of weathering that can assume regional or even continental relevance. It is quantified more often as dissolved load carried by rivers over years.

### 4.1.2.2 Weathering-Resistant Landforms

A second class of weathering landform is actually lack of weathering effectiveness, or resistance to weathering. There is variability in weathering and erosion, and areas that are resistant stand out prominently. Landforms that are resistant to erosion are first resistant to weathering; hence, it is possible to classify resistant bodies as weathering-related landforms. Von Engeln (1948: 276) considered this tenet to be "the Law of Weathering: *differential weathering causes resistant beds and structures to stand out in relief*" (his use of italics), as valid as any of the laws of geomorphology (cf. Rhodes and Thorn, 1996). A wide variety of resistant forms permeate the literature and language of geomorphology: bornhardts, inselbergs, monadnocks, tors, castle kopjes, hoodoos, towers, fins, and others. (Ollier's, 1969 original text provided a comprehensive description of the myriad weathering landform names.) These tend to be medium to large scale, the largest being entire plateaus of resistant rock, such as the *tepuis* of the highland region at the Brazil–Guiana–Venezuela frontier. Even so, small-scale rock knobs and pedestals are equivalent examples of this process, and weathering-resistant forms are evident even at microscopic scales (*see* Chapter 4.5).

### 4.1.2.3 Weathering Residua: Soils and Sediments

Byproducts of weathering become part of the geomorphic environment. Weathering byproducts occur as secondary minerals such as clays and iron and aluminum oxides (in which original mineralogy has been altered), as smaller particles (essentially, pieces of larger mineral crystals or rocks), and as dissolved elements in solution with ground and surface waters. All three byproducts may exist *in situ* within a weathering and soil profile, or may be transported. Transported particles become part of the detrital sediment system. Transported secondary minerals and solutes can become cementing agents in rock and soil.

Soils are influenced by geomorphology (among other factors, Jenny, 1941), a fact well covered by several existing texts (cf. Schaetzl and Anderson, 2005; Birkeland, 1999; Ollier and Pain, 1996; Gerrard, 1992). More relevant in to this volume, soils are also part of the geomorphology, and a pathway to understanding geomorphic processes. The soil is a segment of the weathering residuum (cf. Phillips et al., 2005), the outer skin of the earth–atmosphere–biosphere interface (**Figure 3**). Most soil, essentially any soil containing mineral matter, is a weathering product at least partially. Mineral soils are either *in situ* residua of bedrock weathering, or formed in the transported sediment deriving from previously weathered material (which still continues to weather as part of pedogenic processes).

### 4.1.2.4 Weathered Landscapes

Any terrestrial surface is exposed to weathering, though some landscapes retain a more obvious weathering signature because of aggressive weathering, lithology particularly vulnerable to weathering, long-term exposure, and relative lack of disturbance from other geomorphic processes. Multiple weathering agents, defining factors, and weathering morphologies are apparent at the landscape scale.

Regions with thick weathering mantles as well as areas stripped of weathering mantle to expose the basal weathering front (etchplains) are examples of weathered landscapes. The classic definition of weathering-limited and transport-limited landscapes is often used to define the presence (or absence) of regolith or exposed bedrock. The most simplistic illustration is that in areas where weathering is less rapid or extensive, erosive processes are more efficient, cleaning off the weathering material to reveal more bedrock. Transport limitation is the opposite, in which erosion processes are less efficient in removing weathered material, allowing more of a residual mantle to accumulate with the soil. The presumption is that aggressive weathering, e.g., in the tropics by whatever accelerated means, should allow for increased regolith mantle, while less intense or extensive weathering (i.e., in areas defined by early researcher as 'weakly weathered') allows regolith stripping to dominate. Of course, weathering intensity is but one of several factors that allow regolith accumulation or stripping, the others being slope, uplift with respect to the base level, vegetation cover, and time. In any event, weathering is an important factor, so that it is possible to discuss regolith mantle accumulation as a weathering-related landform. Weathering mantles can be seen as medium to large scale.

## 4.1.3 Major Themes, Current Trends, and Overview of the Text

Of the myriad themes incorporating weathering and soils geomorphology, several trends can be traced, and these form the basis of organization for this book: Synergistic systems, environmental regions, processes and morphology at different scales, and soils and other weathering residua.

This volume is divided into the four general themes, allowing a bit of connective overlap between themes and chapters. The aim of this organization is to provide a system of content while capturing the current state of knowledge within the field. The first three chapters, the present one included, provide an introduction to weathering and soils geomorphology, emphasizing the synergistic nature of weathering and pedogenic processes. Following this introduction, five chapters

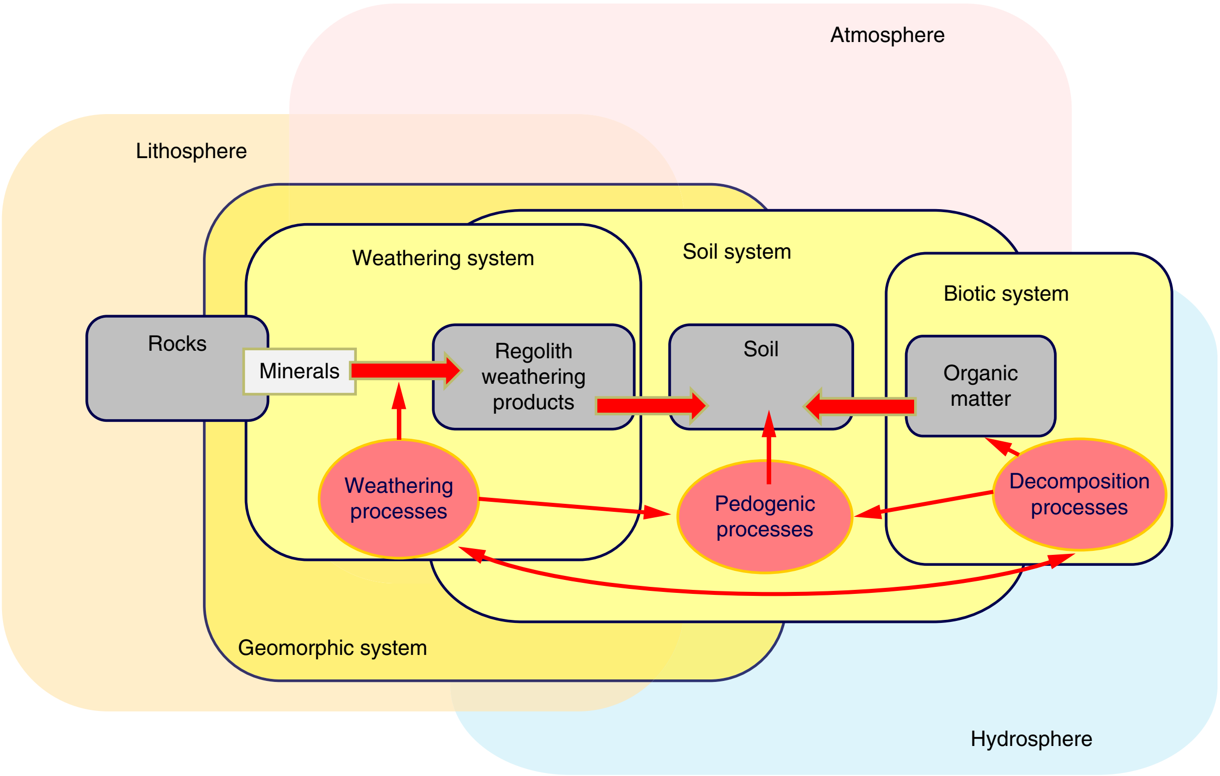



**Figure 3** The weathering and soil systems reside within the interface between the hydrosphere, lithosphere, and atmosphere at Earth's surface. The biosphere also exists at this interface, and contributes to both weathering and pedogenic processes. Soil and weathering systems are part of the geomorphic system, the focus of interest for this text. Precise interactions within the geosystem interface are considerably more complex than indicated in this figure, but encompassed within the chapters herein. Modified from White, I.D., Mottershead, D.N., Harrison, S.J., 1992. Environmental Systems: An Introductory Text, Second ed. Chapman and Hall, London, 616 pp.

elaborate on weathering processes and factors in different environmental zones on the planet: tropical regions, cold regions, arid regions, and coastal environments. Next, a series of chapters detail the processes responsible for different weathering morphologies. These chapters are arranged in increasing spatial scale, beginning at the submicron scale, continuing to the scale of rock coatings and weathering rinds, then to the scale of rock depressions. Slopes and weathering mantles finalize the upper range of scale morphologies. The text completes with three chapters focusing on soils and sediments: the geomorphic processes of soil catenas, the utility of soil chronosequences in geomorphology, and the role of weathering in producing sediments.

### 4.1.3.1 Synergistic Systems

A dominant premise throughout research in the last two decades is the realization of interactive, synergistic systems in the environment, and the soil and weathering realm is one of the best examples of synergism on the planet. Every author presenting in this text embraces the concept that weathering and soils are complex interacting systems residing within the lithosphere–hydrosphere–atmosphere interface (**Figure 3**; see also Chesworth, 1993). Weathering and soils are not always part and parcel with geomorphology, though the impetus for this text concerns geomorphology, hence the focus. The weathering/soil interface has also been termed the 'Critical Zone' (Anderson et al., 2004; Brantley et al., 2006), an apt term given its importance to life and biogeochemical cycles. As defined by its authors, the 'Critical Zone' extends from the vegetation canopy to groundwater, so includes nonlithosphere materials. Alternately, 'regolith' also encompasses the interface from a strictly lithosphere skin perspective, and this term maintains preference in some circles. Regardless, the omnifarious scope afforded by either term has become both impetus and focus for new research. The introductory chapters in this text by Heather Viles (Chapter 4.2) and John Dixon (Chapter 4.3) on weathering and soil geomorphic processes, respectively, provide the needed sense of interacting systems relevant to the chapters that follow.

### 4.1.3.2 Environmental Regions

From the early pioneering studies to present, the science of weathering and soils geomorphology has been rooted in an environmental context: the environment is one of the dominant if not most dominant determinants in process and outcome. The environmental context is obvious: weathering processes and pedogenesis require exogenic factors. Climate is often and readily recognized as the overriding factor, in turn influencing hydrology and biota. As with the greater field of geomorphology, there is a risk of assigning too much influence of any single factor. Other influences (such as lithology and tectonic history) are equally if not sometimes more important. That said, this volume maintains a discussion of environmental factors classified by environment, in Chapters 4.11 (the tropics, by Pope), 4.12 (arid regions, by Warke), 4.15 and 4.14 (cold regions, by Hall and Dixon, respectively), and 4.13 (coastal areas, by Mottershead). Why perpetuate this organization The first reason harkens to the first premise of the book: interactive systems. The holistic environmental system is easily approached in the context of specific and unique environments. The second reason is to embrace an extant literature that is already organized by means of global environmental regions. To reclassify the deep heritage of, say, arid lands geomorphology, or tropical geomorphology, or cold regions geomorphology, would involve an effort beyond the scope of this volume, but may prove to be an interesting exercise for future researchers.

Readers will note a lack of 'temperate' regions set aside with a unique chapter. These midlatitude regions are susceptible to frequent and noticeable climate change, such that significant weathering environments are subsumed under discussions of tropical, arid, or cold conditions over geologic time spans, presuming that these extremes dominate the weathering environment (see also discussions in Chapter 4.11). There are two unique additions of this text not addressed extensively in previous works. The first involves separate chapters for chemical and mechanical weathering in cold regions. While difficult to discuss one without the other, advances in both subfields are significant and groundbreaking enough to warrant separate treatments. The second original distinction in this text is the inclusion of coastal environments as a separate environment, limited in areal extent but distinct in the weathering agents and factors, and significant to coastal geomorphology.

### 4.1.3.3 Processes at Different Scales

Geomorphology readily recognizes scale-dependent (and sometimes scale-independent) processes, weathering and pedogenesis included. The detailed processes responsible for weathering and pedogenesis have seen increased investigation, particularly at the extremes of microscale and regional scale. The third section of this book engages the analysis of weathering and soil geomorphic processes to explain morphologies from the smallest to largest scales.

New and widespread availability of research technology (such as electron microprobes, scanning electron microscopes, atomic force microscopes, confocal laser microscopes, tomography, cf. Lee, 2010; Ip et al., 2010; Ersoy et al., 2010; Krinsley et al., 1998; Dorn, 1995) afford the opportunity to visually and chemically observe weathering phenomena at small scales. Processes of dissolution, microfracturing, rind formation, and case hardening, are apparent at the mineral grain scale and as deep as the molecular and atomic scale. Dorn, Gordon, Krinsley, and Langworthy (Chapter 4.4) extend the frontier to unprecedented fine extremes at the nanoscale, at the scale of crystal lattices and molecules; the phenomena observed here directly explain and encompass the wider appreciation of microscale weathering. One byproduct of nano- and microscale weathering is the production of rock coatings, discussed by Dorn (Chapter 4.5). Rock coatings have their own morphology and dynamics, with many of the same considerations as larger scale stratigraphy, but also the unique chemical and environmental interactions at the microscale. Higher in scale dimensions, weathering rinds (Oguchi, Chapter 4.6) are the product of weathering processes at the smaller scales, but are visible in a range from millimeters to centimeters ($\sim 10^{-3}$–$10^{-1}$ m).

Mesoscale features measure on the order of meters ($\sim 10^{-1}$–$10^{1}$ m), which can include residual boulders (left from *in situ* weathering) or talus (derived from weathering, discussed in Section 4.1.3.4, and to a lesser degree by Hall, Chapter 4.15), unloading sheets from domes, as well as weathering void features such as rillenkarren and tafoni (**Figure 2(c)**). Examples of the mesoscale are covered by Paradise (Chapter 4.7), process and factors in tafoni and other rock basins, while Mottershead (Chapter 4.13) also discusses tafoni in the coastal context.

Finally, at the macroscale, weathering features assume the dimensions of slope surfaces and landscapes ($\sim 10^{1}$–$10^{4}$ m), including vertical relief and subsurface depths of many meters. Large weathering-related structures such as tors (**Figure 1**), domes (**Figure 2(d)**), and inselbergs (**Figure 2(e)**); weathering-controlled slopes; weathering mantles; and etchplains and exhumed weathering profiles are found at this scale. Migon covers macroscale features of weathering mantles and landscapes (Chapter 4.8) and hill slope formation (Chapter 4.10) while Pope (Chapter 4.11) and Dixon (Chapter 4.3) include examples of macroscale forms in their respective chapters on tropical weathering and pedogenesis.

### 4.1.3.4 Soils Geomorphology, Regolith, and Weathering Byproducts

One of the key approaches to understanding geomorphology is through soils. The soil is the living shell of the deeper geology and the interactive conduit between the external atmosphere/hydrosphere/biosphere (**Figure 2**) to the deeper geology. As such, soil is sensitive to geology as well as surface processes, including the living environment. Soil development, being time dependent, is directly indicative of the rate and dynamism of surface processes, certainly at a relative comparison if not in more concrete and quantitative way. Thus, soils tell a geomorphic story. And, as mineral soils are nearly inseparable from weathering processes, continuous with the greater scale of regolith, soil geomorphology also overlaps with weathering geomorphology.

Soils have a diffuse and ill-defined transition into nonsoil regolith. (The term, regolith, most often includes soils, but for lack of a distinguishing term, use of regolith in this instance extends from the soil.) Regolith provides investigators a larger scope on landscape dynamics, as well as interaction with geohydrologic systems and greater contact with geology. Regolith science has been highly active in recent years in a variety of themes. The aforementioned impetus for research in the biogeochemical systems of the 'critical zone' includes dedicated long-term studies from a range of environments (Brantley et al., 2006). As a long-term feature, regolith is a focus of studies on landscape evolution, aided by the capabilities of dating control (cf. Taylor and Eggleton, 2001; Phillips, 2005; Pillans, 2008). Applications in mineral resource exploration extend from these landscape evolution studies (Jones, 1998; Butt et al., 2000). As earth-based geomorphology is applied to other worlds, so too are studies of regolith landscapes on Mars, the Moon, and other celestial bodies (Lindsay, 1992; Vanimen and Chipera, 2006; Clark, 2008).

Addressing soil geomorphology and weathering byproducts in this volume, Dixon (Chapter 4.3) provides an overview of soil dynamics and pedogenesis from the geomorphic perspective. The specific controls of soil profiles modified by and influencing slope processes, the catena, are covered by Schaetzl (Chapter 4.9), while Migon (Chapter 4.10) incorporates soils and deeper regolith in his discussion of slope geomorphology. Dixon (Chapter 4.14), Warke (Chapter 4.12) and Pope (Chapter 4.11) discuss soils in their respective environmental region chapters. Schmid (Chapter 4.16) explains the important relationships and geomorphic tools provided by soil chronosequences. Last, as addendum to the weathering geomorphology system, Pope (Chapter 2.6) relates the role of weathering in the production of detrital sediments, relevant in the erosion, transport, and deposition systems of geomorphic processes, and a connection to the field of sedimentology.

## 4.1.4 Conclusion

Given the connection to erosional and depositional processes, weathering and soils interface with every aspect of geomorphology, and with any branch of earth science pertaining to surface processes. This volume on weathering and soil geomorphology thus provides some essential new material of potential interest to those interested in a foundation in the field of geomorphology. Some examples of areas where less is known than perhaps could be researched are also provided, which will enable development of future new research. Overall, the subdisciplines of weathering geomorphology and soil geomorphology continue to provide fertile ground for those interested in pursuing a difficult but fruitful area of knowledge.

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