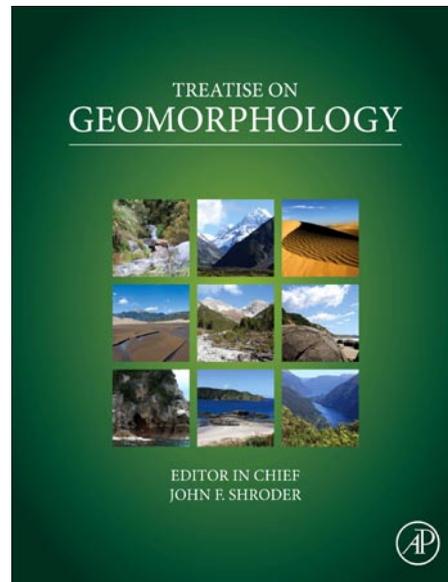


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## 4.11 Weathering in the Tropics, and Related Extratropical Processes

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### Glossary

**Allitization** Total loss of silica and alkaline elements, production of gibbsite (the aluminum oxide residual), ferric hydrates, and 1:1 clays (such as kaolin), as told by Pedro (1968), to be centered in the core tropics.

**Bisiallitization** Moderate loss of silica, formation of 2:1 clays such as smectite and vermiculite, some retention of alkaline cations, as told by Pedro (1968) to be typical of temperate climates.

**Bornhardt** A dome-shaped rock inselberg, named after West African explorer Wilhelm Bornhardt.

**Chelation** Biochemical weathering process, the preferential extraction in minerals of metal ions by organic compounds.

**Dissolution** Multiple-step chemical weathering process in the presence of acidic agents, sometimes referred to as incongruent solution or hydrolysis.

**Duricrust** An illuvial soil hardpan formed of secondary precipitates, such as iron or silica.

**Etchplain** A low-relief exhumed surface, in which deep weathered rock material has been removed.

**Ferrallitization** Extensive leaching, creating end-product soils (including ferrisols and ferricrete) in a transition zone beyond the wettest rainforest to the seasonally wet savannas.

**Ferricrete** An iron-rich duricrust or hardpan in the soil.

**Ferrisols** Iron-rich aluminum-silicate end product soil common in the tropics.

**Gibbsite** End product aluminum hydroxide mineral, a component of bauxite, common in but not limited to the tropics.

**Hydration** Chemical weathering process involving the absorption of a hydroxide molecule into the crystal matrix.

**Inselberg** Literally, 'island mountain', a resistant hill or peak derived from deep weathering; may be a single dome or bouldery.

**Kaolinite** A 1:1 clay mineral, hydrated aluminum silicate, lacking base cations. *Kaolinization* is the genesis of kaolinite, and end-stage weathering product.

**Laterite** An iron- and aluminum-rich, autochthonous (originating in-place) weathering product, variously defined in common and academic use. *Laterization* is the genesis of laterite, common but not limited to tropical regions.

**Monosiallitization** Partial loss of silica, total loss of alkaline elements, production of 1:1 clays (kaolinite) and ferric hydrates, as told by Pedro (1968) to be associated with subhumid tropics.

**Multiconvex topography** Also known as 'half-orange' or 'meias laranjas' hills; low, irregularly spaced dome-shaped hills known in tropically weathered locations.

**Neoformation** Refers to new minerals formed out of ions in solution, the product of weathering.

**Oxidation** Chemical weathering process by which oxygen molecules incorporate into the mineral lattice.

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**Oxisol** Deeply weathered soils, with prominent reddish tint brought about by iron oxidation, also known as ferralsol.

**Pedogenic** Referring to the process of soil formation.

**Pressure unloading** A type of mechanical weathering, in which rock sheets or segments separate along preferred weakness zones subparallel with the rock surface, due to the relaxation of pressure above the surface (such as overburden or glacial ice).

**Regolith** Accumulation of unconsolidated or poorly consolidated sediment and weathered rock, above bedrock, at the surface.

**Rubification** Reddening of soil color, by oxidation of iron.

**Saprolite** Weathered bedrock, *in situ*.

**Silcrete** A silica-rich duricrust or hardpan in the soil, formed of secondary deposition.

**Silica karst** A class of solution landforms, parallel to the more common carbonate karst, formed in silicate rocks such as sandstone or quartzite.

**Solution** Simple, single-stage dissociation of elements in the presence of water or acids; also referred to as congruent solution.

**Tor** Residual outcrop or pile of corestone boulders, the remains of exhumed deep weathering; a small boulder inselberg.

**Tower karst** Tall pinnacle of resistant rock remaining after karst solution, usually applied to limestone landscapes, though some instances of silicate rock tower karst exist.

**Ultisol** Well-developed soil with low base saturation, found in humid climates, but not leached to the extent of oxisols.

**Weathering** Rock and mineral decay by surface chemical and mechanical agents, the precursor to erosion and sediment generation and a source of dissolved elements in surface and near-surface waters.

**Weathering potential** A measure of the degree of weathering that can take place, expressed as a ratio of alkaline oxides in the rock to all oxides; high weathering potential would have a high alkaline oxide ratio, being less depleted of alkaline oxides.

**Weathering product** A measure of the degree of weathering that has occurred, expressed as a ratio of silica oxides over the combination of resistant oxides (silica, titanium, aluminum, and iron); rock more depleted in silica would have a lower weathering product.

## Abstract

Weathering processes are partially responsible for a characteristic geomorphology that occurs in the tropics and subtropics. Resistant landforms such as inselbergs, extreme solution processes such as silica karst, and deep weathering profiles with end stage weathering products such as laterite and kaolin are common features of tropical weathering. Many of these features also occur outside the tropics. In part, climate change and paleotectonics were responsible for tropical conditions in areas not now tropical. But, some processes assumed to require tropic conditions that are not so limited, sufficient moisture, and time sufficing for their development. This chapter reviews the weathering processes and distinctive landforms of the broadly defined tropics, and explores the debates over weathering factors as they pertain to tropic and extratropical environment.

### 4.11.1 Overview

Those who study weathering often look at optimal scenarios, in which conditions are most conducive to weathering. The literature gravitates toward the extremes: the hottest, coldest, driest, wettest, and most associated chemically active or physically excessive environments that bring about observed weathering. Indeed, much of the science of geomorphology is the same, and we commonly recognize today that the cataclysmic and extreme are as important if not more important than the average or moderate in shaping the landscape. The preoccupation with extremes quickly identified the tropics as an incubator of intense chemical weathering and associated landforms and soils, given the abundance of precipitation, higher temperatures, and omnipresence of organic acids. Yet, these assumed ingredients are not always necessary at once for the genesis of tropical-like weathering and geomorphology, and tropic-like geomorphology can be observed beyond the tropics. This chapter explores the processes of weathering relevant to the tropics, leading to characteristic landforms

and regolith. Convergenly, evolutionary landforms and regolith beyond the tropics are also discussed, revealing a debatable controversy that is ongoing but not always recognized beyond the introductory literature.

#### 4.11.1.1 Heritage

The processes of weathering provided seemingly sensible affirmation for the overarching theories of climatic geomorphology, initiated by Branner (1896) and Falconer (1911), and advanced in the mid- and later-twentieth century, the works of Büdel (1948, 1977), Derbyshire (1973), and Tricart and Cailleux (1972) being most prominent to the movement. Deep laterites and etchplains of the tropics seemed as obvious as sand dunes in the deserts and glaciers in the Arctic, and weathering (particularly in the tropics) received due attention. Three key figures emerged as seminal to the concepts of climate-controlled weathering in general: Louis Peltier, Nikolai Strakhov, and Georges Pedro. Their models influenced theory,

though with increasing criticism as weathering factors are rationalized.

Peltier's (1950) study, first among the three, focused on periglacial geomorphology and the numerous processes involved, including weathering. Despite the cold-climate focus, his Figures 1–3 (Peltier, 1950:219) of that paper presented a broad and appealing graphic model of weathering types across all climate zones (Figure 1(a)), precipitation and temperature being the primary controls of weathering in this view. This set of figures is perhaps the most widespread diagrammatic model of weathering factors seen, still common in introductory and more specialized textbooks (including this one) 60 years hence. In Peltier's model, as temperature and moisture increase, the efficacy (and dominance) of chemical weathering becomes stronger, whereas mechanical weathering diminishes to 'weak' to 'absent or insignificant' at the positive extremes of temperature and moisture. Strong chemical weathering thus dominates in the tropics. Peltier, however, was not aware of the ubiquity of chemical weathering in cold and arid climates. Though not necessarily as vigorous as in wetter regions, chemical weathering is in fact present and perhaps even dominant across most climatic regions (Pope et al., 1995), whereas mechanical weathering is also present and important in the humid tropics.

Strakhov's (1967) work was intended as an examination of sedimentary processes and the genesis of sedimentary rocks, but the chapter on weathering likewise offered a diagrammatic model that lived on well beyond the expected lifetime of a somewhat obscure text. The most cited diagram (Figure 1(b), from Strakhov, 1967: 6) expressed temperature and moisture controls similar to Peltier that added the influence of biotic agents in weathering (in the form of plant litter fall), translating to weathering efficacy evident in depth of weathering and regolith zonation across a latitudinal transect. An accompanying world map, seldom cited, generalized these weathering climate zones. Like Peltier's, the model was conceptual: Although actual values for latitude, temperature, moisture, and biomass were used, depths of weathering zones were approximate (but still attempted to suggest the vertical and spatial irregularity of weathering fronts, at least illustratively). The interesting feature of the diagram was the zonation (Al-oxide, Fe + Al oxides, kaolinite, illite-montmorillonite, and incipient weathering), the primary intensity peak of the tropics, a secondary intensity peak of the subpolar and middle latitudes (Strakhov used 'Taiga zone,' with the increase of acidic conifer needle mulch), and minimal weathering profiles in warm and cold drylands. The diagram illustrated a cumulative effect of abundant moisture (as both weathering agent and remover of solutes), plentiful decomposed vegetation, and high temperature to produce deep weathering profiles in the tropics. Strakhov's tropic zone included the regions dominated by ferrisols and ferrallitic soils, the product of rapid weathering and leaching. The diagram, however, was a broad generalization, not a data-based model, and with notable exceptions to the presumed weathering zonation (see Chorley et al., 1984; Ollier and Pain, 1996; Pope et al., 1994). For one thing, the assumed curves for the bioclimatic weathering factors do not closely approximate actual measurements now available (Figure 1(b)). As it turns out, leaf litter fall is actually greater in midlatitudes than in the tropics

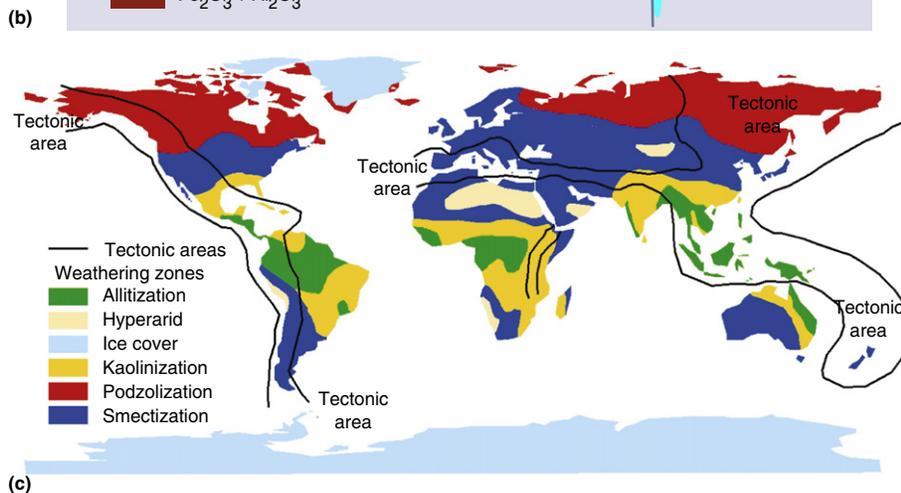
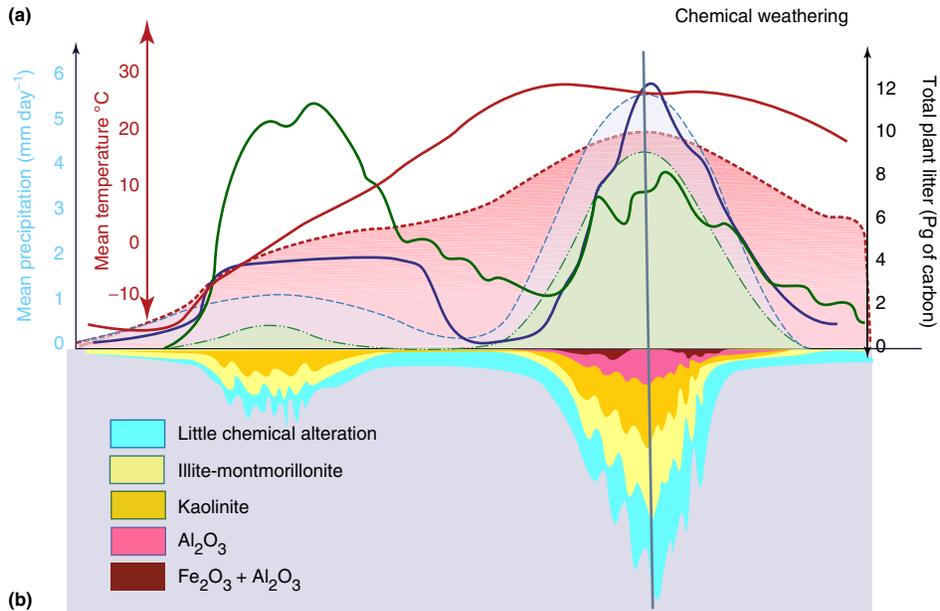
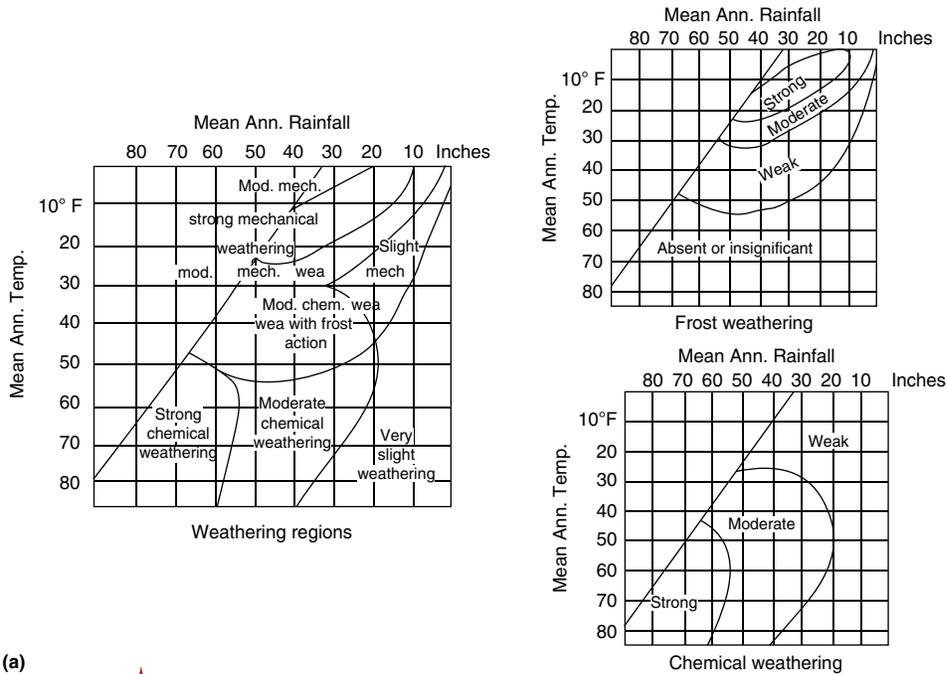
(Potter et al., 1993), and this corresponds to higher soil carbon in middle latitudes (Post et al., 1985), providing the midlatitudes with potentially greater biochemical weathering agents than in the tropics.

Pedro's (1968) study was parallel to Strakhov's, developed independently though using similar concepts. Pedro's work directly addressed weathering, particularly surface chemical weathering, translating globally across different climatic zones, resulting in different forms of weathering and associated soils. The geographic extents of certain phenomena (for instance, soil rubification in oxisols) was one example of weathering defining the region of tropical geomorphology. Broad pedogenic processes – allitisation (laterite, aluminum oxides), monosiallitisiation (kaolinite), bisiallitisiation (vermiculite-montmorillonite), and podsolization – were distinguished using ratios of silicon oxide to aluminosilicate and silicon oxide to bases (an important distinction from the Peltier and Strakhov models, which were not actually quantitative). These in turn corresponded directly with climatic zones (tropical, temperate, and cool) and rates of decomposition (rapid to slow). The resulting map (Figure 1(c), from Pedro, 1968: 463) of weathering pedogenesis somewhat matched the distribution of major soil orders (FAO, 1985; Thomas, 1974, 1994).

Recent authors built on the groundwork of these initial tropical weathering paradigms. Foremost among these are Ollier (1969, 1984), Ollier and Pain (1996), Twidale (1982, 2002), and Thomas (1974, 1996). Both Ollier and Twidale, while working with tropical geomorphology, importantly noted that many of their subjects were not by necessity tropical and were in fact controlled in many cases by nonclimatic factors. Thomas, in comparison, did emphasize the importance of tropic climates. Although recognizing with his studies the continuum of weathering and pedogenic processes beyond the tropics, he emphasized the unique qualities of the tropics in his definitive texts on tropical geomorphology, which relied heavily on the foundation of weathering.

Trudgill (1976: 89) rightly pointed out "... the unqualified tenet of climatic geomorphology ... states simply that different landforms occur in different climatic zones." Climatic geomorphology proved unsatisfying as an over-arching theory, as climate was not the only or even primary factor in many geomorphic systems (see Holzner and Weaver, 1965; Stoddart, 1969; Selby, 1985; Twidale and Lageat, 1994). Although conceptually and diagrammatically appealing, the climatic weathering models are problematic in their simplicity. Chorley et al. (1984) pointed out the absence of maritime temperate climates from the Strakhov concept. Huggett (2007) noted Peltier's omission of mechanical weathering not caused by ice (mentioning the importance of mechanisms involving heat and salt, but not going far enough by also mentioning the roles of roots, expansive clays, and rock stress relaxation). Thomas (1994) differed with the relative proportions of tropical rainforest and savanna climates. Pope et al. (1995) drew issue with both the Strakhov and Peltier models as too simplistic. The models, and a widespread repetition of them throughout the research and academic literature, ignored frequent evidence that contradicted the assumptions of the models:

1. Chemical weathering is not weak in cool or dry climates, nor is mechanical weathering absent in warm-wet climates;

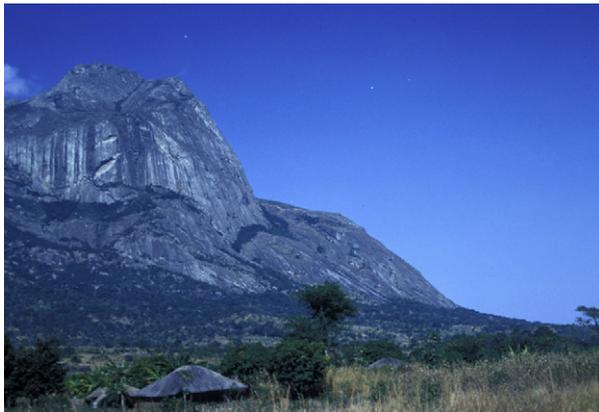


(c)

2. Deep weathering profiles occur commonly outside of the tropics (and taiga zones);
3. In terms of denudation rates (a function of both weathering and erosion), there is significant overlap in the range of values between climatic regions.

These revised beliefs are realized by a growing number of weathering geomorphologists reflected in this book.

Apart from the morphoclimatic debate, the summary message is that weathering processes in the tropics were identified by early climatic geomorphologists as important to the overall geomorphic landscape of the tropics, and key works, namely by Peltier (1950), Strakhov (1967), and Pedro (1968), provided conceptual models for weathering processes that persist to this day. The oft-repeated tenet is difficult to refute: The high temperatures and high moisture of the tropics provide an intense chemical weathering environment. Add to this the presence, in some areas, of abundant organic decomposition, providing organic weathering agents. Even when considered at the microscale boundary layer at which actual weathering takes place (Pope et al., 1995), large-scale bioclimatic factors should filter in to smaller scales to be relevant. Absent from the tropical weathering concept is the mention of mechanical weathering processes, though these too can be added. What requires further explanation is the observed landforms beyond the tropics that appear to be, and are claimed to be, derived from tropical processes. Are they? Can nontropical environments produce similar landforms? Or, do



**Figure 2** Chongra bornhardt face of part of Mount Mlange massif in eastern Malawi, Africa. The erosional residuals (inselbergs, bornhardts) of this part of the African erosion surface in East Africa are quartz- and orthoclase feldspar-rich and more resistant to chemical weathering than the mafic-rich country rock of the foreground which has weathered and been erosional stripped to a lower altitude (Shroder, 1973). Photograph courtesy of J. Shroder.

these outlying examples provide proof of previous tropical conditions?

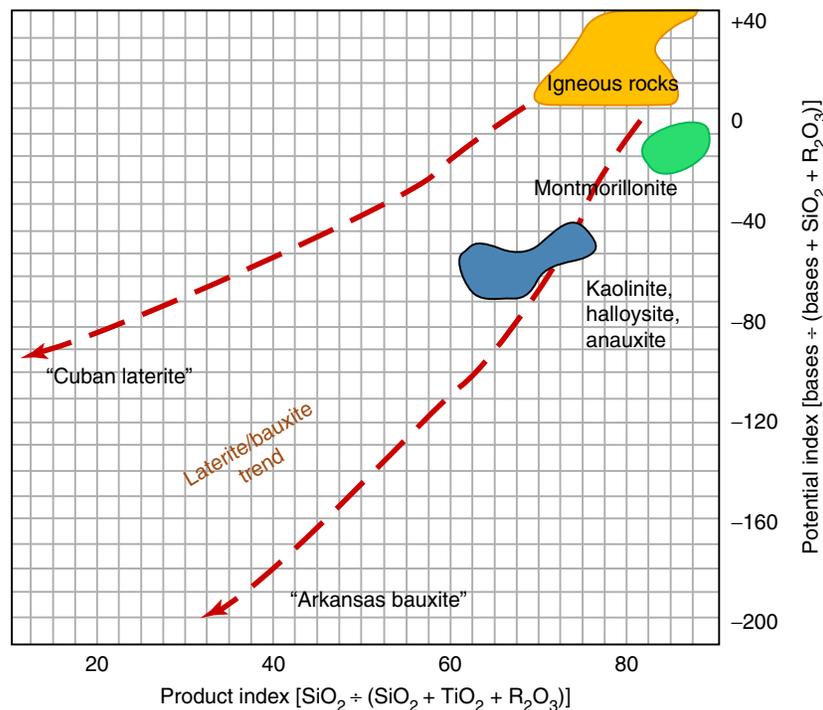
#### 4.11.1.2 The Tropical Geomorphic Region: Defining 'Tropical' in Geography and Time

The common notion of 'the tropics' – consistent heat, humidity, and abundant precipitation seasonally if not continuously – is complicated in the perspective of geomorphology. Naturally, it would incorporate regions of tropical rainforest and tropical savannah. With the help of ocean currents and regional prevailing wind variations, tropical climates can extend from the equator to beyond 25–30° N or S latitude (for instance, southeast Africa, northern India, and northwest Mexico). Given the long intervals of geomorphic evolution along with climate change, neighboring regions to the core tropical ones also experienced tropical conditions worth including. In contrast, highland areas (such as the South American Altiplano, East Africa, mountainous Southeast Asia, and Indonesia) within the tropics would not experience the same elevated temperatures. Areas under subtropical high pressure or in mountain rain shadows could be significantly drier, qualifying as deserts.

'Tropic' can be precisely defined, but depends on the context. The classic climate region classification of Köppen and Geiger specified 'tropical' or 'equatorial' ('A'-type climates) for areas of the world warmer than 18 °C (Kottek et al., 2006). One popular introductory textbook (Gabler et al., 2007) defines the tropical climatic region simply as 'warm all year', which probably suffices short of defining temperature thresholds for chemical or physical processes. Subsets to the tropical definition are based on the amount and seasonality of precipitation, which are of importance to geomorphic processes. At present, tropical climates cover ~22% of the continental surface (Kalvova et al., 2003). From an ecological perspective, 'tropical' also varies by temperature and precipitation, but defined in ways coinciding with vegetation types (also relevant to the types of weathering). Wolfe (1979) distinguished divisions in forest types between 'tropical' (>25 °C mean annual temperature, MAT), 'paratropical' (20–25 °C MAT), and 'subtropical' (13–20 °C MAT). The term 'paratropical' was defined in an earlier paper by Wolfe (1969), referring to a fossil Paleogene flora occurring in the present Gulf of Alaska (revealing a crucial point: in the time spans relevant to weathering landscapes, extents of climatic regimes vary greatly.)

Regions peripheral to the true tropics may also be relevant to the weathering geomorphology discussion, as will be discussed later in this chapter. These include the hot deserts (in the context of climate change and potentially more humid conditions in the past) as well as portions of mesothermal humid continental regions (Köppen-Geiger Cfa and Csa classification).

**Figure 1** Graphical models of weathering factors with implications for tropical weathering. (a) From Peltier (1950), weathering type by precipitation and temperature. Chemical weathering is now recognized to occur in all climate types. Reproduced from Peltier, L.C., 1950. The geographical cycle in periglacial regions as it is related to climatic geomorphology. *Annals of the Association of American Geographers* 40(3), 214–236, with permission from Taylor & Francis. (b) Weathering depth and factors, by latitudinal transect, derived from Strakhov (1967). Strakhov's estimation of temperature (red dotted line), precipitation (blue dashed line) and litter fall (green dash-dot line) do not correspond with realistic and up-to-date measurement of latitudinal mean temperature (solid red line) and mean precipitation (heavy blue line) (both from Kalnay et al. (1996)) and plant litter (Potter et al., 1993). (c) From Thomas (1974), based on Pedro (1968), soil types and weathering based on climatic region.



**Figure 3** Weathering product and weathering potential indexes, 'Arkansas Bauxite' and 'Cuban Laterite' are examples described in Reiche's text. Colman (1982) utilized the same graphic in for the Western United States, but extending only to the kaolinite field. Modified from Reiche, P., 1950. A Survey of Weathering Processes and Products. University of New Mexico Publications in Geology, No. 3. Albuquerque: The University of New Mexico Press, 91 pp.

In the familiar climatic geomorphology classification, the tropic morphoclimatic region can be defined in terms of weathering and soil development. Ferrisols and fersiallitic soils are roughly congruent to Pedro's (1968) world weathering zones: the zone of 'allitisation' (kaolinite + gibbsite) in the core lowland tropics; and the zone of 'kaolinization' (kaolinite) in surrounding areas, extending as far south as Uruguay, South Africa, and southeast Australia, and as far north as India, South China, and the southeast US, in other words, covering the classic tropics, and extending into subtropic to even middle latitude regions. These various classifications follow the foundation of morphogenetic regions, summed well in Chorley et al. (1984), but including the seminal works (overgeneralized though they may be) of Büdel (1948), Peltier (1950), Strakhov (1967), Pedro (1968), Tricart and Cailleaux (1972), and Derbyshire (1973).

Defining climate regions applies to current environments, though past environments are equally if not more important. Ollier and Pain (1996: 80) pointed out that assuming present-day climate is responsible for observed regolith features is 'naïve and misleading.' Weathering can be among the slowest of geomorphic processes. Significant weathering landforms may have evolved over millions or even tens of millions of years, a time span in which entire continents shift into different climatic latitudes or portions of landmass thrust upward into cooler elevations, not to mention large swings in climate cycles determined by solar input and ocean currents. Even smaller weathering forms may be relict of different climatic regimes due to the cycles of climate change. Thus, studies of tropical weathering in mid latitude and even subarctic regions are possible

(Cunningham, 1969; Dury, 1971; Derbyshire, 1972; Pavich, 1986; Yapp, 2008; and Solbakk et al., 2010), though there is sometimes legitimate debate as to whether the weathering observed is actually tropical in genesis.

#### 4.11.2 Weathering Processes and Their Relation to Tropical Conditions

The weathering processes of the tropics are similar to those elsewhere, with just a few exceptions. Apart from a few mechanical processes, all are relevant, but with special emphasis related to the climatic conditions and environment, enumerated here.

##### 4.11.2.1 Factors

Weathering is a synergistic system, the whole of which may be greater than the sum of its parts (see Chapter 4.2; Pope et al., 1995). Within this synergy, what factors contribute to rapid weathering, and are these factors prevalent in the tropics? Curtis (1976: 50) answered this question summarized as follows:

1. A warm climate translates to sustained high temperatures, influencing chemical reaction rates, following the Arrhenius equation:

$$k = A \exp(-E_A/RT)$$

where  $k$  is the reaction rate,  $A$  is the rate constant for the reaction (a function of molecular collision, related to

efficacy of the weathering agent in this case),  $E_A$  is the activation energy of the reaction,  $R$  is the gas constant, and  $T$  is the absolute temperature. From the perspective of the chemical reaction, temperature is a primary environmental variable.

2. High precipitation (or at least where precipitation is significantly greater than evapotranspiration, cf. Ollier and Pain, 1996) provides a long term presence of water as a medium for reactions, a supply of reacting agents (including  $H_2O$ ,  $CO_2$ , and  $O_2$ ), and removal of solutes without reaching saturation. Variability in precipitation influences the type of chemical reaction, discussed shortly. Large seasonal variations in precipitation and humidity, also present in some tropical areas, would be pertinent to several mechanical weathering processes.
3. Climate in turn fosters high organic productivity, which also supplies key reacting agents such as acids and chelates.

Bluth and Kump (1994) reinforced Curtis's observations in terms of chemical denudation, but also stressed the role of evacuating weathering products from the system:

... dissolved yield of a given drainage basin is determined by a balance between physical and chemical weathering; thus, a warm, wet climate, or the presence of abundant vegetation cannot guarantee high rates of chemical denudation unless accompanied by high rates of physical removal.

Nonclimatic factors are important as well. Fresh parent materials would have greater weathering potential (WPol), as would rocks of high surface exposure (by way of macro- or microporosity). The tropical region has examples of recent tectonism or volcanism that would easily expose fresh rock, but also examples of long term tectonic stability (such as Australia, South Africa, and Brazil). Tectonisms and erosion act to provide significant topographic relief, also relevant in providing good drainage, influencing the presence of water as reaction medium and solute remover. Time is a factor not mentioned above, completely divorced from climatic environment. Although process rates may be accelerated in the tropics, given enough time and stability, an equifinality of weathering extremes may be possible regardless of climate. In sum, although various weathering factors are aided by tropical environments, other factors occur regardless of climate.

#### 4.11.2.2 The Processes

Chemical processes are strong in the tropics, or at least obvious, but mechanical processes are present and important. Mechanical processes go together with chemical, it is seldom that one does not exist without the other, and rather positively reinforce each other. The processes will be reviewed here one by one, though in reality processes work together in a synergistic fashion (see also Chapter 4.2).

Of the mechanical processes, ice is unlikely to be an agent in the classically defined tropics, as well as stress from sub-freezing temperature excursions, apart from climate cycles that could be relevant at higher elevations or at higher latitudes. There is some debate as to whether thermal shock at high temperatures is relevant (see Bland and Rolls, 1998; Eppes et al., 2010). Even if the tropics do not attain the high

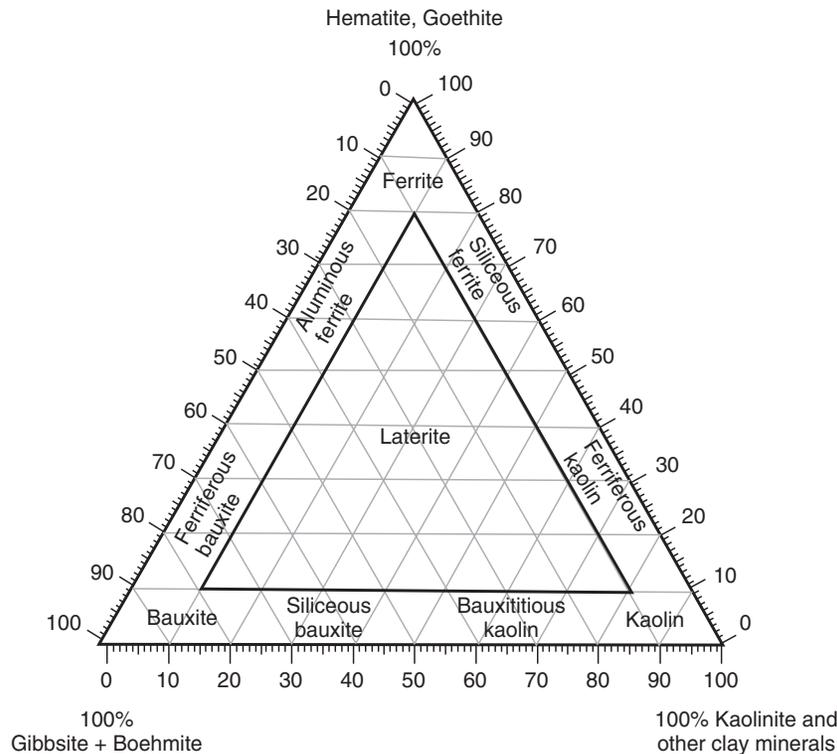
air temperatures of the deserts (though some may come close), rock surface temperatures may well exceed  $70^\circ C$ , particularly on dark colored rocks (Thomas, 1994). High temperature itself may not be sufficient to create brittle fracture without large temperature extremes, but the subject has not been well researched in the tropics. Fires, outside of the rainforest during the dry seasons and in droughts, are known to exert extreme temperatures capable of brittle rock fracture (Goudie et al., 1992; Dorn, 2003). Crystal growth within confined pores or fractures may be causes of mechanical weathering in the tropics. Normally, rapidly growing minerals such as salts, calcite, and gypsum are easily dissolved and flushed away by rain. However, in the aggressive chemical environment, rapid release of elements such as sodium, calcium, and potassium from rock forming minerals ensures a supply for new mineral growth, given a chance. That chance may take place during dry seasons – which can assume suddenly – and salts have the opportunity to accumulate within voids, fractures, and grain boundaries. Salt weathering plays a role in the granular disintegration and cavernous weathering of coarse crystalline rocks observed in wet-dry tropics as well as arid regions (Young, 1987; Turkington and Paradise, 2005). Seasonal wet-dry tropics are capable of sustaining pedogenic gypsum in soils over carbonate rocks (Luzzadder-Beach and Beach, 2008), another possible source of crystal expansion by means of hydrating calcite. Expansive clays and neoformed iron oxides may also exert pressure (Nahon and Merino, 1997). Silica reprecipitation after dissolution can be responsible for further opening grain boundaries and fractures at the micron scale and lattices and crystal faults at the nanometer scale (Chapter 4.4).

'Pressure unloading,' sometimes known as dilation or sheeting, is the relief of overburden stress that causes expansion and then brittle fracture of formerly buried rocks. Resistant rock bodies, by way of differing petrology or structure, survive weathering and erosion to become exposed as dome-shaped remnants (bornhardts, inselbergs, tors, or other related terms). The exposed outer surfaces are thus vulnerable to pressure release, fracturing parallel to the rock surface and normal to the surface to release slabs. Twidale (1973) offered an opposing opinion that dome-shaped jointing preexists exposure by way of compression (not extension), such that domed inselbergs are so because of their fractures, not that the fractures are so because the rock is domed. Regardless, although the phenomenon is commonly observed in doming rocks of various lithology in the tropics (Figure 2, see also Shroder, 1973), the process is not limited to the tropics.

It is important to note that the mechanical weathering processes, except for crystal growth of neoformed minerals, are restricted to and determined by surface conditions. Because the weathering profiles may be many meters in thickness, these surface conditions and processes are but a fraction of the total weathering system (Ahnert, 1976).

The combination of abundant weathering agents and higher temperatures ensures the potential for an active chemical weathering environment in the tropics. That said, weathering end-products – the kaolinite, gibbsite, and iron oxides common in tropical soils and regolith – also indicate an eventual chemical stability, explaining the dearth of nutrients available in some tropical soils. Details of chemical weathering are best explained in Yatsu (1988), Nahon (1991),





**Figure 4** Weathering end product ternary diagram. Modified from Bardossy, J., Aleva, G.J.J., 1990. Lateritic bauxites. *Developments in Economic Geology* 27, 624.

path (Figure 3). The weathering product index (WPrI) is the ratio of silica to combined silica + titanium + sesquioxides (e.g., iron and aluminum oxides), in molar oxide form, and decreases in value as silica leaches out with respect to less mobile titanium and sesquioxides

$$\text{WPrI} = \frac{\text{moles}(\text{SiO}_2)}{\text{moles}(\text{SiO}_2 + \text{TiO}_2 + \text{Al}_2\text{O}_3 + \text{R}_2\text{O}_3)}$$

The WPol is the ratio of the alkaline earths to the total of all common elements (also in molar oxide form). The potential index decreases as alkaline earths preferentially leach

A fresh igneous rock, for instance, has a high weathering potential and high product ratio (high proportion of silica to aluminum and iron oxides). End-stage bauxite and laterite have very low weathering potential and low product ratio (greater dominance of the sesquioxides). Intermediate mineral phases such as clays fall between the extremes.

The tropics are well known for end-stage weathering products such as iron, silica duricrusts, and residual alumina. Based on end-stage weathering products, Strakhov (1967) and Pedro (1968, 1983) assigned regions of dominant weathering processes (see also Figures 1(b), (c)) according to present climatic conditions:

- Allitization – total loss of silica and alkaline elements, production of gibbsite (the aluminum oxide residual), ferric hydrates, and 1:1 clays (such as kaolin); centered in the core tropics;
- Monosiallization – partial loss of silica, total loss of alkaline elements, production of 1:1 clays (kaolinite) and ferric hydrates; in the paratropics and subtropics (with a secondary frequency in the subpolar ‘taiga zone,’ according to Strakhov, 1967);
- Ferrallitization – the production of ferrisols and ferricrete in a transition zone beyond the wettest rainforest to the seasonally wet savannas.

(definitions from Thomas, 1994; Pedro, 1983; and Schaetzl and Anderson, 2005)

‘Laterite’ and ‘laterization’ fall in within these definitions, though the terms are complicated, as are correlating terms and regions described by Pedro and Strakhov. Bourman (1993) and Ollier and Pain (1996) contended that the use of the term ‘laterite’ was too diverse, Ollier and Pain preferring to fold it into the rubric of ferricrete or iron-based duricrusts. Thomas (1994), however, described the range of laterite, bauxite, and similar duricrusts by way of a Fe-kaolinite-gibbsite ternary diagram (Figure 4) after Bardossy and Aleva (1990). Widdowson (2007) generalized laterite to be an iron-rich,

$$\text{WPol} = \frac{\text{moles}(\text{CaO} + \text{Na}_2\text{O} + \text{MgO} + \text{K}_2\text{O} - \text{H}_2\text{O})}{\text{moles}(\text{SiO}_2 + \text{TiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 + \text{Cr}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O} + \text{MgO} + \text{K}_2\text{O})}$$

autochthonous weathering product of tropical or subtropical conditions, and distinct from allochthonous 'ferricretes,' though both are end members of the same spectrum of iron-based weathering residua.

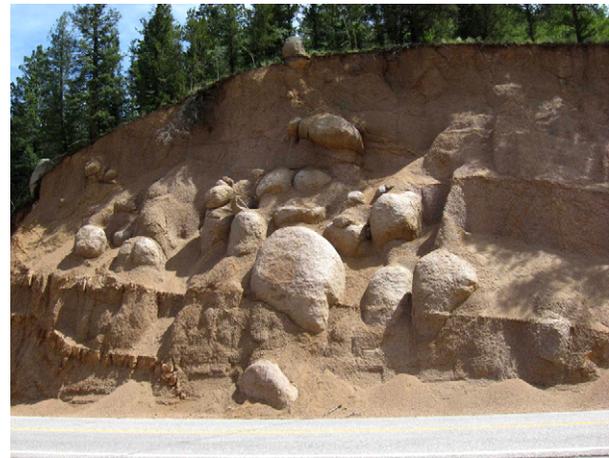
As per Pedro and Strakhov, it was assumed that lateritic processes required tropical conditions to form, given the obvious frequency of laterite in the tropics. Still, lateritic end products are not unique to the tropics, a point known for quite some time. In his chapter on tropical weathering, Reiche (1950) noted the presence of bauxite in Arkansas (USA) and laterite in the Mediterranean, and cited Jenny's (1941) mention of laterization in the Appalachian (USA) Piedmont as well as Goldschmidt's (1928) observation of aluminum hydrates in Norway. Dury (1971) assigned duricrust formation at several midlatitude locations to humid tropical conditions at the Eocene optimum; therefore the current exposures are relict. With the ability now to date or calibrate weathering profiles, several researchers pin ages to weathering formations and their paleoenvironments. Cecil et al. (2006) used (U-Th)/He thermochronology to date the exhumation history of the northern Sierra Nevada, California, and thereby equate a period of tectonic stability with a lateritic paleosol, the Ione formation, of Eocene age. Although this does not conclusively determine that laterite followed warm-wet conditions, Yapp (2008) established a paleotemperature 5 °C warmer than present, and wetter, at the same location and time period, using oxygen isotope ratios derived from the paleosol. Similarly, Retallack (2007) concluded that wet/warm conditions existed in northwest and west-central North America based on the weathering of Eocene, Miocene, and Pliocene paleosols.

The questions arise, then, were much larger regions subject to tropical processes, did the weathering take place when a landmass was at a different paleolatitude, or can the formation of tropic-like regolith proceed without tropical conditions? Are these nontropical examples exceptions to the rule, or within the spectrum? Conversely, why should end product Fe–Al–Si weathering residua appear so commonly in the tropics? There are several answers. It is easy to assume that the weathering derives from the distant tectonic past when currently nontropical land areas were at one time situated in or near the tropics, and have tectonically drifted over time out of the tropics. Some demonstrably old weathering profiles may fit this category, and it is possible to verify the age of these examples (Pillans, 2008) in order to correlate with their paleotectonic geography.

However, weathering-then-tectonic drift does not necessarily explain all 'tropical' profiles in the nontropics. A growing number of authors now recognize that genesis of these end products do not require tropical conditions (cf. Paton and Williams, 1972; Bird and Chivas, 1988; Ollier, 1988; Taylor et al., 1992; Bourman, 1993, 1995). Abundant moisture and time appear to be key factors, as well as exposure to groundwater in the weathering profile. Recognition of ferrous end-product saprolite in some present day drylands (see Figure 5(a)) may derive from wetter periods in the geologic past, or simply very long and stable exposures. Certainly the end-product regolith of coastal California (Burke et al., 2007), the California Sierra Nevada (Cecil et al., 2006; Yapp, 2008), the Rocky Mountains (Wanty et al., 1992; Figure 5(b)), the



(a)



(b)

**Figure 5** Examples of deep weathering. (a) Oxidized end-product saprolite exposed on the side of a granitic inselberg, near Phoenix, Arizona (USA). Photo courtesy of R. Dorn. (b) Deep weathered grus with corestones, near Pikes Peak, Colorado (USA). Presumed to be the result of warmer climates of the Eocene.

Appalachian Piedmont (Pavich, 1986), and Bohemian Massif (Vitek, 1983) benefit from abundant precipitation.

Second, long exposure and stable tectonics tend to favor preservation of deep and highly evolved weathering residua. Thus, deep 'tropical' weathering mantles survive. It so happens that the Brazilian Shield, Australia, and the tropical African Plateau satisfy these conditions. Though Thomas (1994: 19) downplayed this chance relationship to deep weathering, several subcontinental areas have been placed in an equatorial position and relatively unscathed by major orogenic events for more than 20 million years (more than 100 million years in some cases). Table 1 compares a rough estimate of the proportion of gross geomorphic surfaces between 'tropical' and 'mid-latitude' belts, showing that exposed Precambrian shields are more than three times more prevalent in tropical zones than they are in midlatitudes. In other locations of the world with suitable weathering conditions and tectonic stability, there are also deep weathering mantles. Surprisingly, these can survive major glaciations; remnant saprolites, tors, and inselbergs remain in Scotland (Hall and Mellor, 1988), on the Fennoscandian Shield (Lidmar-Bergstrom, 1995;

**Table 1** Comparison of landform categories between Tropical and Mid-Latitude zones. Landform classification is based on that of Murphy (1968)

Landform/region	Tropics and subtropics (30° N to 30° S) <sup>a</sup>		Mid-latitudes (31° N to 60° N + 31° S to 60° <sup>e</sup>	
	% of latitude zone	% of earth's land area	% of latitude zone	% of earth's land area
'Recent mountains' of the Alpine Orogeny, + newly rifted areas <sup>a</sup>	29	17	30	12
Caledonian/Hercynian/Appalachian mountain remnants <sup>b</sup>	1	1	15	6
Exposed Gondwana or Laurasian Shield <sup>c</sup>	43	25	13	5
Sediment-covered lowlands <sup>d</sup>	27	15	42	17

<sup>a</sup>The post-Jurassic Alpine orogenic belt includes the Cordillera of the Western Hemisphere and Circum-Pacific subduction chain, and the Eurasian-Himalayan System, mountains or widely-spaced mountains. Newly rifted areas include the African-Red Sea rift system, the Flinders region of Australia, and the Baikal Rift System.

<sup>b</sup>The Caledonian, Hercynian, and Appalachian range mountain remnants are from Paleozoic to early Mesozoic orogenies and have had no significant rejuvenation.

<sup>c</sup>Exposed surfaces of the Gondwana and Laurasian shields are primarily Tertiary erosion surfaces on mainly Precambrian parent material, and include tablelands, plains, and some mountains.

<sup>d</sup>Sediment-covered lowlands include plains and low hills, mostly covering shield areas with Paleozoic to Recent sediments.

<sup>e</sup>Latitudinal belts include areas of tropical desert or mid-latitude desert.

Percentages are calculated based on combined area of 5° × 5° grid cells, in which each cell is assigned a single dominant landform class.

Ebert and Hättestrand, 2010) and on the Canadian Shield (Bouchard and Jolicoeur, 2000). Where erosion has become more efficient, weathering residua have been removed, exposing etch surfaces.

#### 4.11.2.4 Rates of Weathering

Of the myriad factors that influence weathering processes (Pope et al., 2005), time is probably the dominant factor in the evolution of major weathering landforms. Simply, the more time evolved, regardless of other factors including climate, the greater the degree of weathering. Landscapes of great antiquity usually exhibit the most extensive weathering landforms. Likewise, antiquity allows for inheritance of landforms from previous environments (Thomas, 1994).

Weathering rates in tropical regions are generally accelerated, following the expectations of the Arrhenius equation temperature kinetics (increasing rate with increasing temperature), demonstrated by numerous studies (cf. Haantjens and Bleeker, 1970; Dorn and Brady, 1995; Navarre-Sitchler and Brantley, 2007). White et al. (1998) described a 'regolith propagation rate' of 58 m Ma<sup>-1</sup> (or 58 B, where B = Bubnoff units = 1 mm per 1000 years) in Puerto Rico. They considered this rate of chemical dissolution of silicate rock (granodiorite in this case) to be the 'fastest' on Earth, and happens to be equivalent to Thomas's (1994) presumed maximum rate of tropical weathering, and an order of magnitude greater than the global mean of ~6 B. Saunders and Young (1983), in their review of denudation studies, reported a range of 2 to 15 B for chemical denudation or weathering of silicate rocks in regions spanned by the tropics (subtropic wet-dry to tropical rain-forest); and 11 to 500 B for carbonate rocks. This compared to a range of 0–126 B for silicate rocks and 13–210 B for carbonate rocks of the temperate midlatitudes. Rates of denudation overlap for several reasons. Apart from temperature, other factors account for variation in weathering rates. Moisture or precipitation (and subsequently stream runoff discharge) is a

prominent factor in weathering rates (cf. Langbein and Dawdy, 1964; Haantjens and Bleeker, 1970; Dunn, 1978; Bluth and Kump, 1994; Li et al., 2011). Organic chemistry (Viers et al., 1997) and presence of organic weathering agents (Dorn and Brady, 1995; Kelly et al., 1998), lithology (Bluth and Kump, 1994), strength of weathering agents, including variations in pH (Casey and Sposito, 1992; Cama et al., 2002), soil and weathering profile depth (White et al., 1998), seasonal hydroclimatic changes (Li et al., 2011), and topographic or geomorphic position (Stallard, 1992) are all influential in determining weathering rates.

There are some cases where tropical weathering rates are not as great as expected. In Sri Lanka, von Blanckenburg et al. (2004) reported a low weathering and denudation rate, despite high temperatures and precipitation. In this case, an already-weathered plateau (low on Reiche's (1950) Weathering Potential and Weathering Product indexes) was the source of chemical denudation. Chemical denudation rates in Taiwan were also lower, but for the opposite reason, according to Selvaraj and Chen (2006). In steep terrain, immature sediments had only a brief residence time within the weathering system; the topographic factor dominated the mountain environment. In this system, Selvaraj and Chen claimed that 'physical weathering dominates,' a direct contradiction of Peltier's (1950) prediction that chemical weathering should dominate in warm, wet regions.

#### 4.11.2.5 Weathering Maxima Outside the Tropics

Several studies, from disparate sources, suggest weathering process maxima unrelated to tropical characteristics, but possibly responsible for tropical-like landforms. Strakhov (1967) is frequently referenced. Apart from the major overwhelming tropical factors, he suggested a midlatitude/subpolar submaximum of weathering depth (Figure 1(b)). Like comparable works of the period, there was ample simplification, and most modern weathering process studies focus not on the

top-down factors (regional climatic) but rather the bottom up (microscale dominance, see Pope et al., 1995). A novel reversal of this was undertaken by Scull (2010), a study of soil forming factors in the continental US, but still relevant in that outcomes such as profile development and clay genesis are also weathering events. Scull's spatial model, utilizing fine-scale environmental data based on temperatures and precipitation, was more black-box, with future work required to elucidate the reasons for relationships. What is interesting at this stage is the variegated spatial correlation between environmental factors and soil (weathering) factors. The study showed strong positive correlation between total clay and precipitation (increasing precipitation → increasing clay) in New England and portions of the Midwest (regions with moderate to abundant precipitation), but not in the South or Pacific Northwest, equally if not more humid but quite different in temperatures. The assumption of the Arrhenius temperature function associated with weathering rate was not apparent. When temperature, in turn, was related to total clay, areas of strong positive correlation (increasing temperature → increasing clay) appeared along the Pacific Coast and in a variegated pattern in the Central US from the Gulf Coast to the Canada, but poor or negative correlation in warm locations such as the Deep South and Desert Southwest. Again, tropical temperature and moisture factors appeared to show no logical spatial gradient.

Another detailed attempt at top-down weathering factors was made by Fowler and Petersen (2004), applying Peltier's (1950) parameters (Figure 1(a)) to predict theoretical weathering regions in the continental US using fine-scale climatic data. Independently, Pope and Pobanz (2011) used coarser climate data but a combined chemical + mechanical weathering potential in one index. Both studies predicted 'strong chemical weathering' in the Gulf Coast states – expected as the outer fringe of the subtropics – and also mountainous locations in the Southern Appalachians and Northeast States, and a wide continuum of strong chemical weathering in the Sierra Nevada, Cascade Range, and Coast Ranges of the Pacific Coast states. It is interesting that abundant moisture and related biomass were seen as sufficient for aggressive chemical weathering despite cooler temperatures, particularly in the Sierra Nevada case where oxisols were shown to be formed in warmer, wetter climatic conditions (Yapp, 2008). Not only does this partially match Scull's (2010) predictions for deeper soil profiles or higher clay genesis, it also closely corresponds with the occurrence of ultisols (of any suborder) in the US. Further work on these geospatial models would use proxy weathering data for validation, for instance, small stream solute loads or depth of weathering profile. A more appropriate estimate of temperature would be an integration of temperatures over the presumed lifetime of the weathering profile, similar to Wehmler's (1982) 'Equivalent Quaternary Temperature' curve used for amino acid racemization geochronology.

### 4.11.3 Weathering-Related Landforms of the Tropics

Legitimate questions exist as to whether landforms said to be tropical are truly dependent on tropical conditions of

weathering and erosion. The discussion of weathering-related landforms here is classified by means of generalized morphology introduced in Chapter 4.1 of this *Treatise*: weathering voids, weathering resistant landforms, and weathering residua. This classification has an inherent scalar and temporal organization. At increasing spatial and temporal scales, specific weathering processes diminish in importance replaced by the works of the entire weathering system.

#### 4.11.3.1 Weathering Voids: Solutional Landforms

Karst geomorphology is, of course, a product of solutional weathering. The acidic properties of groundwater act on sedimentary rock (generally, but not limited to, carbonate rocks) to produce caves, karst landscapes, and microscale solution features. Karst geomorphology is included along with weathering, lumped into the same chapter, in most introductory textbooks, but the uniqueness and variety of karst geomorphology justifies complete and separate treatment (Frumkin, 2013). This chapter makes brief mention of solutional landforms relevant to weathering in tropical regions.

Carbonate karst refers to solutional features primarily not only in limestone but also in marble, dolomite, and some carbonate-cemented sandstones. As much as these rock types are quite common across the planet, karst landscapes are also widely distributed. Dramatic karst landscapes of southeast Asia and Indonesia, Central America, and the Caribbean attest to the active elements of solutional weathering in the tropics: abundant rainfall and high CO<sub>2</sub> content via high biomass, combined with fast chemical reaction due to warmer temperatures (Monroe, 1976). One aspect of the greater relief (and more common representation) of karst development in the tropics is the lack of interfering geomorphic processes (such as glaciation and periglaciation). Still, extensive karst is also seen in temperate regions, in areas such as southeast Europe (the type locality of 'karst'), England, the Ozark and Appalachian highlands of the US, and southern Australia. Extensive cave systems perhaps evolved over several million years (Granger et al., 2001), though many sizeable systems are Quaternary in age, and surface karst formations seen in England, Ireland, and Germany are certainly postglacial. The combination of precipitation and CO<sub>2</sub> saturation in groundwater is sufficient for karst development in these areas. Major karst systems are thought to be influenced by warmer and wetter climates; Ford (2010), Twidale (2002), and Maslyn (1977) suggested that the significant tower karst evident in mid- and high-latitudes are exhumed weathering relicts from the warm-humid past (either by paleogeography or climate change).

Not as common as carbonate solution (though more common than previously thought), 'silica karst' solution landforms in sandstone, quartzite, and siliceous igneous rocks are recognized in numerous locations. Wray (1997) see also Chapter 6.36 and Young et al. (2009) provide the most complete review of silica solutional landforms. Wray (2003) argued that any rock-solutional feature, including those in silicate rocks, is true karst (as opposed to 'pseudokarst'). Because of the higher activation energies of dissolving quartz, warmer temperatures would be most conducive to silica karst,

and indeed silica karst was first recognized in the tropics (Martini, 1979; Twidale, 1984; Young, 1986). In tropical environments, the constant supply of water establishes a continuous chemical disequilibrium, pertinent to the congruent solution process. That said, there are silica karst regions outside of the tropics. Netoff et al. (1995) and Netoff and Chan (2009) reported large doline-like pits in the Entrada and Navajo sandstones of arid southern Utah (USA). They attributed the formation of these pits to mainly mechanical weathering processes (such as clay and salt growth) and some solution of calcium cements in the sandstone matrix, with debris winnowed out of the pit bottoms by wind. But, although the region is presently arid, wetter conditions were possible at times over Quaternary period when chemical weathering may have been more efficient. May and Warne (1999) theorized that the so-called Carolina Bays (elliptical, oriented basins, and ponds found in coastal sediments along the US Atlantic and Gulf coasts) are silica-karst features, and include alteration of kaolinite to gibbsite and concomitant loss of volume, hence sinkholes. This is but one of many different theories used to explain Carolina Bays. Vitek (1983) and Demek and Kopecký (1994) recognized pseudokarst forms, including tower karst, in the sandstones of the Bohemian Massif. Vitek (1983) suggested that their development occurred in recent mild humid conditions. Other 'rock forest' or 'rock city' formations may qualify as silicate karst. Cammeraat and Seijmonsbergen (2010) reclassified the 'Bosques de Rocca' area in the Peruvian Andes, an ignimbrite formation widely thought to be wind-eroded, as silica karst. The vitreous nature of ignimbrite would have a lower solution threshold than quartz, compensating for the cooler temperatures and slower rates at high altitudes. This author noted similar 'pinnacle' formations in ignimbrite and tuff in the San Juan Mountains of Colorado (USA) and the famous Cappadocia region of Turkey. City of Rocks, in southwestern New Mexico (USA), may be another example. Described by Mueller and Twidale (1988) as a joint-controlled, exhumed etch surface formed in a warmer-wetter subsurface environment, which may well be correct, the difference between solutional karst and dissolutional subsurface etching is probably fuzzy.

#### 4.11.3.2 Weathering-Resistant Landforms

Weathering-resistant landforms include positive-relief features that are first more durable to weathering attack, and then secondly more resistant to erosion. These include the inselbergs (boulder or domes) and plateaus, and are resistant mostly for structural or lithologic reasons (Twidale, 1982, 2002; Migon, 2009) or heterogeneous groundwater distribution, less a factor of subaerial weathering agents or regional or microclimates. Still, many introductory textbooks include a picture of a bornhardt or boulder inselberg as an example of resistant landforms in the tropics. Indeed, weathering-resistant landforms have been a focus of research in tropical geomorphology, even if weathering resistance is not a function of climate. Thomas (1994:343) noted the widespread occurrence of boulder inselbergs (including tors) and domed inselbergs regardless of latitude in the tropics and subtropics, suggesting that 'their distribution appears not to be controlled by climate.' However, tropical weathering provides ideal

conditions for their development: periods of aggressive deep weathering.

Classic domed inselbergs (bornhardts) abound in the tropics, including Brazil, Australia, South, West, and East Africa, (Figure 2) and at the tropical fringes as far as Texas and Georgia (cf. Shroder, 1973; Twidale, 1982; Thomas, 1978, 1994). They are massive, not necessarily of a single lithology (Petersen, 1988), but distinctly less jointed and fractured compared to surrounding terrain (except for the near-surface parallel joints that develop out of expansion to create unloading slabs). Thomas (1994) believed that deep weathering and saprolite development takes place preferentially along the well-jointed rock. Later, this easily eroded weathered rock is stripped, leaving the resistant bornhardt. The domed morphology is a result of pressure release due to exposure, or as Twidale (1973) argued, preexisting compression stress due to pluton emplacement.

The formation of boulder inselbergs is discussed thoroughly by several authors (Linton, 1955; Thomas, 1978; Twidale, 1982; Ollier, 1984). Included here are the conical, boulder-mantled inselberg hills, as well as classic tors. Boulder inselbergs are formed in a similar manner to bornhardts, except that the preexisting rock is more jointed, allowing for stacks of segmented, *in situ*, spheroidally weathered boulders. The size of these boulders depends on the degree of weathering and the spacing of preexisting joints. Tors occur on all continents including the present extremes of temperature and moisture. Where they are seen outside of the present tropics, it is sometimes assumed that previous tropical conditions were responsible for the first part of their formation, the deep weathering that isolates resistant blocks and corestones (cf. Linton, 1955; Cunningham, 1969). A completely different explanation uses frost weathering and periglacial slope action to expose the resistant corestones of tors (Palmer and Neilson, 1962). Yet, chemical weathering is valid even in cold regions, and Derbyshire (1972) attributed chemical weathering processes responsible for the formation of tors in favorable microclimates within the prevailing polar desert conditions of Southern Victoria Land, Antarctica. Mechanical weathering by ice and temperature extremes is likely in this case, though the granular disintegration and rounding of edges is typical of chemical weathering.

The evidence of tors in tropical and nontropical locations as diverse as West Africa, Dartmoor, the central Rocky Mountains, the Bohemian Massif, Portugal, the Mojave Desert, and even Antarctica is one to suggest convergent evolution (cf. Campbell and Twidale, 1995; Twidale, 1984: 333–334). Weathering landforms are often seen as good examples of convergent evolution, or the alternate term, equifinality. Harrison (2009:359), for instance, exemplified tors as developing in either 'periglacial action or by deep chemical weathering.' Convergence or equifinality presume that different processes in different climates are responsible for similar forms, an idea parallel to the biologists' 'convergent evolution' (Dendy, 1916). This may not be the case, in the strictest sense: It is possible that geomorphic processes themselves (in this case, chemical weathering) are identical or at least very similar. The only difference might be the rates of change over time (through concomitant climatic change) and the sequence of events. Antarctic and Tropical Savanna tors would be convergent if formed

differently, if chemical weathering was responsible for the granular disintegration and block rounding in the warmer regions, whereas ice weathering was responsible for the same in cold regions. It is more likely that chemical weathering is active in both areas, and that tors were primarily the result of chemical weathering, thus not convergent but in fact identical.

Both boulder and domed inselbergs have an implication of climate change in their genesis (Thomas, 1994). Deep weathering would progress under one regime (tropical conditions, for instance), whereas exhumation and stripping would require either seasonal or drier conditions (swinging, for instance, toward the weathering-limited direction of the spectrum).

Although Migon (2006), Twidale (1982), and others questioned the requirement of tropical conditions for many bedrock landforms, Migon (2009) revived the notion of granitic 'multiconvex topography' as occurring in the tropics and not reported in any other climatic region. Multiconvex topography falls within a spectrum of morphologies of weathered granitic terrain extending from plains to all-slopes topography of considerable relief and steep slopes (Migon, 2006). Multiconvex topography, also mentioned by Thomas (1994), with alternate names 'demi orange' or 'meias laranjas' hills was described as having developed out of deep weathering, consisting of closely-spaced, irregularly distributed low hills resembling 'half-cut oranges.' These hills retain weathered mantles, and some may be weathered throughout, establishing a sort of equilibrium in form between continued weathering mantle development and erosion. Unlike other bedrock weathering landforms, it is thought that multiconvex topography and the weathering-stripping equilibrium cannot survive major climate changes, and thus exists entirely within the tropical regime (in areas that have retained consistent tropical characteristics). Rates of formation and times of persistence of these and other resistant landforms is worthy of further investigation.

A class of weathering-resistant landform involves duricrusts, which protect surfaces. Duricrusts are the product of weathering, cemented by secondary mineralization of weathering products. Laterite is a duricrust (Widdowson, 2007), as is silcrete (Nash and Ullyott, 2007). Silcrete, like the iron duricrusts, occurs in many type of environments, not just the tropics, and may be the result of pedogenic, weathering, or groundwater processes. Laterite, ferricrete, and silcrete are capable of indurating surface regolith, and like resistant caprock, can form plateaus by protecting softer underlying regolith. Where silcrete has been deposited in association with stream courses, sinuous paleochannels can be protected and remain in positive relief as the remaining landscape erodes down.

#### 4.11.3.3 Deep Weathering Mantles

Deep weathering mantles are fairly common and familiar in the tropics but certainly not limited to the tropics (Figure 5(b), see also Chapter 4.8) Deep weathering is naturally associated with the humid tropics, with plentiful moisture and biomass. Thomas (1994: 80) outlined ten 'optimal conditions for deep weathering,' occurring in any combination of conditions:

1. wet equatorial or monsoon climates, rainfall  $> 1500 \text{ mm yr}^{-1}$ , together with rainforest vegetation;
2. predominantly warm and humid conditions during substantial periods ( $\sim 10^6$  years) over  $\sim 10^8$  years of paleoclimatic history;
3. cratonic terranes in continental interiors or passive margins;
4. domed and plateau uplifts with strong tensional stress fracture patterns;
5. shear zones and intersections of dense fracture patterns;
6. hydrothermal altered rock (diagenesis, not weathering);
7. fissile metamorphic rocks or igneous rocks with dense microcrack systems;
8. old (pre-Neogene) land surfaces at moderate to high altitude, even in suboptimal climates, where long-term denudation rates have been low;
9. proximity to structural depressions promoting a strong groundwater gradient;
10. free-draining sites beneath interfluves and hillslopes  $< 20^\circ$ , particularly if protected by a duricrust cap.

Note that only the first two factors concern climate, and therefore relevance to tropical conditions. All others are rooted in climatically-azonal lithologic, tectonic, topographic, or historical conditions. Chapter 4.3, discusses processes in which chemical weathering in cool environments would be responsible for extensive soil development and deep weathering.

The classic transport-limited (versus weathering limited) landscape relationship is relevant here, keeping in mind other factors also responsible for erosion or lack of erosion of regolith (including vegetation cover, slope, and precipitation intensity). Where terrain is stable, and not liable to rapid erosion, regolith greater than 100 m thickness is possible (Thomas, 1994; Ollier and Pain, 1996). Deep weathering profiles are conducive to further weathering because they are commonly in contact with groundwater, and tend to be moist all the time above groundwater (Ollier, 1988). Ahnert (1976) expressed a zone of 'optimal chemical weathering' somewhat below the surface, decreasing as overburden cover increased. Recent evidence from Burke et al. (2007) refined this model (but in granite terrain of coastal California) to verify that soil production rates, chemical weathering indexes, and acidity decreased with increasing soil thickness, but immediately from the soil surface and not, as Ahnert suggested, from an optimum subsurface point.

The age of these weathering profiles is a matter of contention, and therefore the process of their creation would vary. Climatic extremes may be important. A frequent response in geomorphic studies is to assume that deep weathering is a product of tropical conditions (cf. Pavich and Obermeier, 1985; Pavich, 1986; Kabata-Pendias and Ryka, 1989; Cecil et al., 2006; Solback et al., 2009). These cases may well be the result of tropical paleogeography or climate change, but development of deep weathering is possible in temperate to cool climates (therefore in the midlatitudes during colder phases, or seasonally). Molina Ballesteros and Canto Martin (2002) questioned the need to invoke tropical conditions for deep saprolites in Iberia, when time under climate conditions analogous to today's may be sufficient. Deep weathering

profiles recognized in the Canadian Shield, Scotland, and the Baltic Shield are attributed to preglacial or periglacial conditions, and are also perhaps quite ancient (Goodfellow, 2007; Bouchard and Jolicoeur, 2000; Lidmar-Bergstrom, 1995; Hall and Mellor, 1988).

Saprolites on Appalachian ridgetops and summits provide an example of the debate between temperate or periglacial weathering and tropical weathering. Cryoplanation, the periglacial process of weathering and freeze-thaw heave, is suggested for the creation of deeply weathered profiles in highland areas of the eastern and central US (Clark and Ciolkosz, 1988). Similar formations are reported in the Rocky Mountains (Munroe, 2006). In these once-colder areas, summit lowering and weathered regolith to depths of several meters are possible within a Pliocene to Pleistocene time frame. Marsh (1999: 61–63), however, argued for deep weathering that easily predates any periglacial climate. On the flat ridge tops of the very resistant Tuscarora quartzite, there exists an *in situ* weathered sandy soil approximately two meters deep, underlain by eight to ten meters of weathered quartzite saprolite. Further, subsurface profiles indicated an irregular regolith boundary, similar to that produced by weathering and not by periglacial process. Small, low quartzite tors crop out at the summit. Marsh believed that Pennsylvania mountaintop weathering profiles were much older, tens of millions of years (and has been argued, perhaps even dating to late Paleozoic), and not cryoplanated in Pleistocene times. This would associate the deep weathering to much warmer climates, both globally and latitudinally for North America.

#### 4.11.4 Conclusion

Weathering processes form an integral part of tropical geomorphology, perhaps more so than any other environment on earth. Areas dominated by the existence of deep and long-term weathering are known for characteristic landforms and soils: duricrusts, saprolite, resistant bedrock landforms, and solutional formations on both carbonate and silicate rocks. These in turn influence the other geomorphic processes of this environment, including groundwater and surface water flow, sediment transport and deposition by rivers, and slope movements.

Weathering processes of the tropics are not unlike those elsewhere on the planet, but owing to the availability of water and enhanced temperature, rates of chemical weathering are accelerated and more aggressive. Pervasive conceptual models of weathering and weathering factors distinguish weathering efficacy based on climate, though these generalizations tend to obscure or marginalize observations that do not fit the models. Despite the obviousness of weathering landforms in the tropics, similar landforms occur elsewhere, outside of the present tropics. These outer examples initiate a debate, whether other processes are responsible for similar landforms – convergent evolution – or whether climatic conditions change over weathering-process time scales such that tropical conditions existed in greater areas at different intervals of the geologic past. In fact, both sides of the debate can be true. Climates have changed, and land masses that existed within tropical regions have drifted out. As well, so-called tropical

landforms can exist without the temperatures of the tropics, simply given abundant moisture (and weathering agents) and increased time.

Recent research recognizes the spectrum of weathering landforms, and accepts factors for weathering types and rates relevant to specific situations, which may include climate but may also find over-riding factors. The frontiers of weathering geomorphology continue to work on integrating observations across different environment. New techniques in surface and regolith dating methods, geographic information systems, and remote sensing, biogeochemical process modeling, as well as continued refinement of the understanding of environmental change at global as well as regional scales, will afford rapid expansion of new ideas and integration with old ideas in order to answer persistent questions.

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## Biographical Sketch



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