Chapter 8
The Geomorphic Landscape: The Attributes of Geoforms

J. A. Zinck

Abstract Attributes are characteristics used for the description, identification, and classification of the geoforms. They are descriptive and functional indicators that make the multicategorial system of the geoforms operational. Four kinds of attribute are used: (1) morphographic attributes to describe the geometry of geoforms; (2) morphometric attributes to measure the dimensions of geoforms; (3) morphogenic attributes to determine the origin and evolution of geoforms; and (4) morphochronologic attributes to frame the time span in which geoforms originated. The morphometric and morphographic attributes apply mainly to the external (epigeal) component of the geoforms, are essentially descriptive, and can be extracted from remote-sensed documents or derived from digital elevation models. The morphogenic and morphochronologic attributes apply mostly to the internal (hypogeal) component of the geoforms, are characterized by field observations and measurements, and need to be substantiated by laboratory determinations.

Keywords Morphography · Morphometry · Morphogenesis · Morphochronology · Attribute classes · Attribute weights

8.1 Introduction

Attributes are characteristics used for the description, identification, and classification of the geoforms. They are descriptive and functional indicators that make the multicategorial system of the geoforms operational. This implies two requirements: (1) select descriptive attributes that help identify the geoforms, and (2) select

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J. A. Zinck et al. (eds.), *Geopedology*,
https://doi.org/10.1007/978-3-031-20667-2_8

differentiating attributes that allow classifying geoforms at the various categorial levels of the taxonomic system.

To determine a geoform, it is necessary to sequentially perform the following operations:

- description and measurement, to characterize the properties and constituents
- identification, to compare the geoforms to be determined with established reference types
- classification, to place the geoforms to be determined in the taxonomic system

For this purpose, four kinds of attribute are used, following Tricart's proposal with respect to the four types of data that a detailed geomorphic map should comprise (Tricart 1965a, b):

- geomorphographic attributes, to describe the geometry of geoforms
- geomorphometric attributes, to measure the dimensions of geoforms
- geomorphogenic attributes, to determine the origin and evolution of geoforms
- geomorphochronologic attributes, to frame the time span in which geoforms originated

In order to simplify the expressions, it is customary to omit the prefix *geo* in the denomination of the attributes.

The morphometric and morphographic attributes apply mainly to the external (epigeal) component of the geoforms, are essentially descriptive, and can be extracted from remote-sensed images or derived from digital elevation models. The morphogenic and morphochronologic attributes apply mostly to the internal (hypogeal) component of the geoforms, are characterized from field observations and measurements, and need to be substantiated by laboratory determinations.

8.2 Morphographic Attributes: The Geometry of Geoforms

The morphographic attributes describe the geometry and shape of the geoforms in topographic and planimetric terms. They are commonly used for automated identification of selected geoform features from DEM (Hengl 2003).

8.2.1 Topography

Topography refers to the cross section of a portion of terrain (Fig. 8.1). It can be viewed in two dimensions from a vertical cut through the terrain generating the topographic profile (Table 8.1), and in three dimensions from a terrain elevation model generating the topographic shape (Table 8.2). The characterization of these features is particularly relevant in sloping areas. The shape and the profile of the topography are related to each other but described at different categorial levels. The

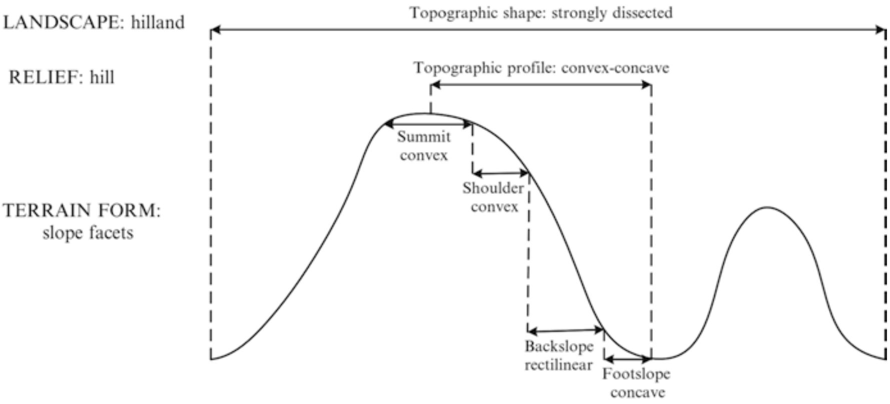

Fig. 8.1 Relationship between topographic attributes and categorial levels of the geoform classification system

Table 8.1 Topographic profile (2D)

Classes	Examples
Level	Mesa, terrace
Concave	Basin, footslope facet
Convex	Levee, summit/shoulder facet
Convex-concave	Slope facet complex
Convex-rectilinear-concave	Slope facet complex
Rectilinear (straight)	Backslope
With intermediate flat step(s)	Slope facet complex
With protruding rock outcrop(s)	Slope facet complex
With rocky scarp(s)	Slope facet complex, cuesta
Asymmetric	Hill, hogback
Irregular	Hillside

Table 8.2 Topographic shape (3D)

Classes	Slope %	Relief amplitude
Flat or almost flat	0–2	Very low
Undulating	2–8	Low
Rolling	8–16	Low
Hilly	16–30	Moderate
Steeply dissected	>30	Moderate
Mountainous	>30	High

topographic shape attributes are used at landscape level, while the topographic profile attributes are used at the levels of relief and terrain form. The third descriptor, the exposure or aspect which indicates the orientation of the relief in the four cardinal directions and their subdivisions, can be used at any level of the system.

8.2.2 Planimetry

Planimetry refers to the vertical projection of the geoform boundaries on a horizontal plane. It is a two-dimensional representation of characteristic geoform features that closely control the soil distribution patterns. Fridland (1965, 1974, 1976) and Hole and Campbell (1985) were among the first to recognize configuration models that delimit soil bodies and relate these with the pedogenic context. The configuration of the geoform, the design of its contours, the drainage pattern, and the conditions of the surrounding environment are the main attributes described for this purpose.

8.2.2.1 Configuration of the Geoforms

Many geoforms at the levels of relief/molding and terrain form show typical configurations that can be easily extracted from remote-sensed documents, especially air photos. This enables preliminary identification of geoforms based on the covariance between morphographic and morphogenic attributes. For instance, a river levee is generally narrow and elongated, while a basin is wide and massive. The configuration attributes give an idea of the massiveness or narrowness of a geoform (Table 8.3).

8.2.2.2 Contour Design of the Geoforms

The design of the contours describes the peripheral outline of the geoform at the levels of relief/molding and terrain form (Fig. 8.2 and Table 8.4). It can vary from straight (e.g., recent fault scarp) to wavy (e.g., depositional basin) to indented (e.g., scarp dissected by erosion). These variations from very simple linear outlines up to complex convoluted contours that approximate areal configurations, are reflected in

Table 8.3 Configuration of the geoforms

Classes	Examples
Narrow	Levee
Large	Overflow mantle
Elongate	Dike
Massive	Basin
Annular (ring-shaped)	Volcanic ring-dyke
Oval/elliptic	Doline, sinkhole
Rounded	Hill
Triangular	Fan, delta
Irregular	Dissected escarpment

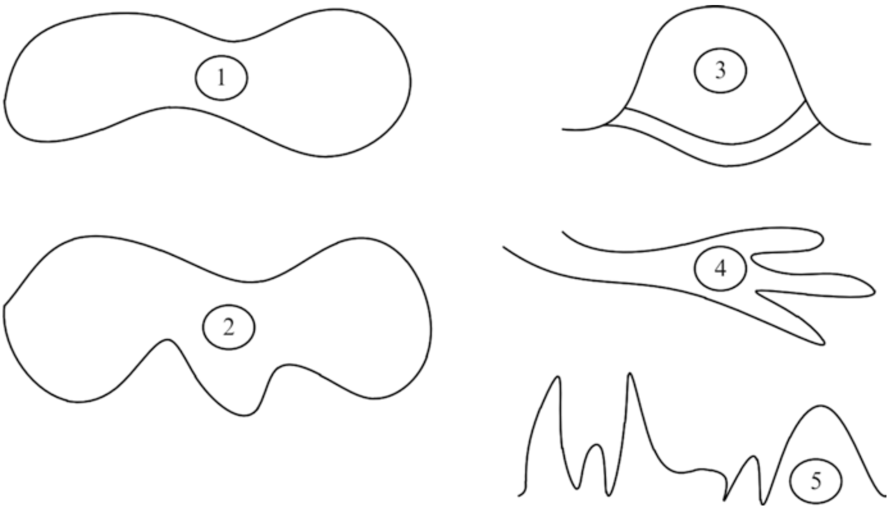

Fig. 8.2 Configuration and contour design of some geoforms (2D)

Table 8.4 Contour design of geoforms

Classes	Examples
Rectilinear	Escarpment
Arched (lunate)	coastal bar
Sinuate (wavy)	River levee
Lobulate	Basin
Denticulate	Dissected escarpment
Digitate	Deltaic channel levee (distal sector)
Irregular	Gully, badland

variations of the fractal dimension (Saldaña et al. 2011). The attribute of contour design can be used also as an indirect morphogenic indicator. For instance, an alluvial decantation basin has usually a massive configuration, but the shape of the boundaries can vary according to the dynamics of the neighboring forms. In general, a depositional basin has a sinuous outline, but when a crevasse splays that forms after opening a gap in a river levee in high water conditions penetrates into the basin, the different fingers of the splay create a lobulated distal contour. Thus, a lobulated basin contour can reflect the proximity of a digitate splay fan, with overlap of a light-colored sandy deposit fossilizing the argillaceous gley material of the basin (Fig. 8.3).

1. Basin with ovate configuration and sinuous contour
2. Basin with ovate configuration and lobulate contour (lower part), reflecting the penetration of a digitate crevasse splay fan (see Fig. 8.3)
3. Bay closed by an arch-shaped offshore bar
4. Deltaic channel levee with digitate distal extremities
5. Dissected scarp with denticulate contour pattern

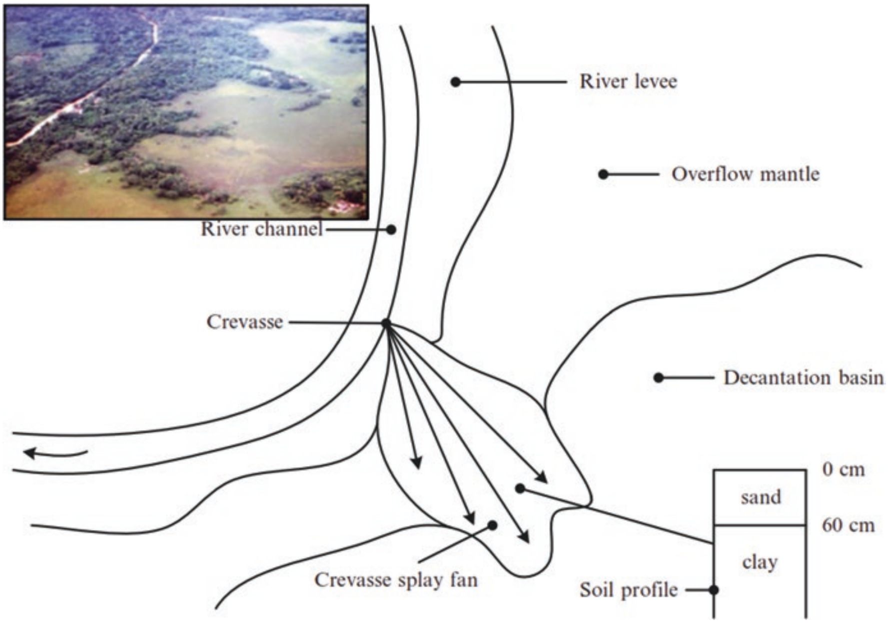

Fig. 8.3 Modification of a basin contour design by the penetration of a crevasse splay fan upon rupture of a levee during high channel water. The intrusion of the fan in the neighboring lateral depression results in the overlaying of sandy cover sediments on top of the clayey basin substratum, creating a lithologic discontinuity at 60 cm depth in this case, with the formation of a buried soil

8.2.2.3 Drainage Pattern

The drainage pattern refers to the network of waterways, which contributes to enhance the configuration and contour outline of the geoforms. It is mainly controlled by the geologic structure (tectonics, lithology, and volcanism) in erosional areas, and by the structure and dynamics of the depositional system in aggradation areas. Representative patterns taken from the Manual of Photographic Interpretation (ASP 1960) are shown in Figs. 8.4 and 8.5: radial pattern of a conic volcano, annular pattern in a set of concentric calderas, dendritic pattern in homogeneous soft sedimentary rocks without structural control, trellis pattern in sedimentary substratum with alternate hard and soft rock layers and with structural control (faults and fractures), parallel pattern in alluvial area, and rectangular pattern in a till plain. The network of waterways creates connectivity between the areas that it crosses and controls the various kinds of flow that traverse the landscape (water, materials, wildlife, vegetation, humans).

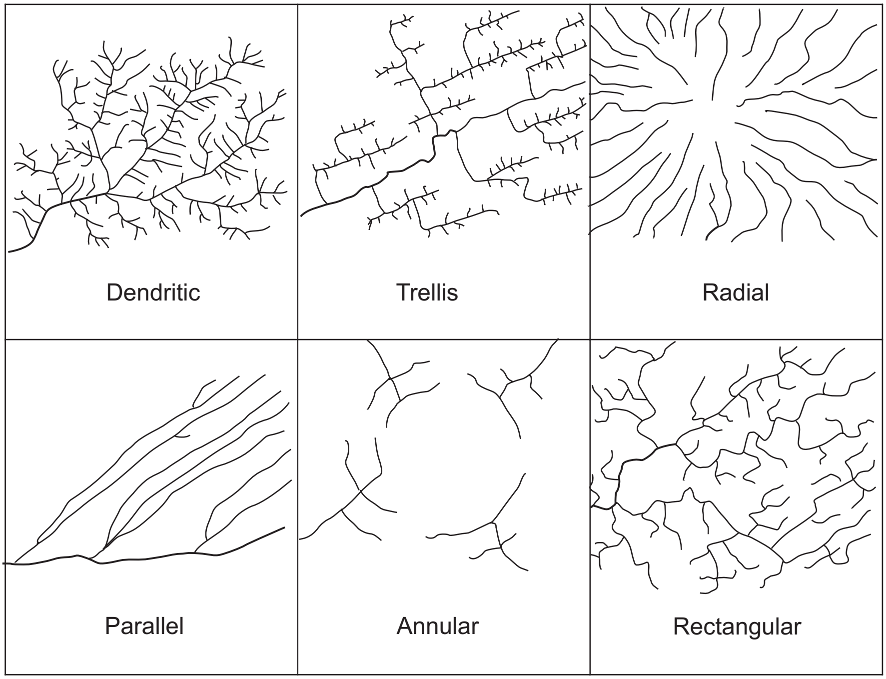

Fig. 8.4 Drainage patterns controlled by features of the geologic and geomorphic structure (see comments in the text). (Adapted from ASP 1960)

8.2.2.4 Neighboring Units and Surrounding Conditions

The geomorphic units lying in the vicinity of a geoform under description shall be mentioned along with the surrounding conditions. This attribute applies at the levels of landscape, relief/molding, and terrain form. According to its position in the landscape, a geoform can topographically dominate another one, be dominated by it, or lie at the same elevation (e.g., a plain dominated by a piedmont). These adjacency conditions suggest the possibility of dynamic relationships between neighboring geoforms and enable to model them. In a piedmont landscape, for instance, can start water flows that cause flooding in the basins of a neighboring alluvial plain, or material flows that cause avulsion in agricultural fields and siltation in water reservoirs. The segmentation of the landscape into functionally distinct geomorphic units provides a frame for analyzing and monitoring transfers of physical, chemical, mineralogical, and biological components within and between landscapes.

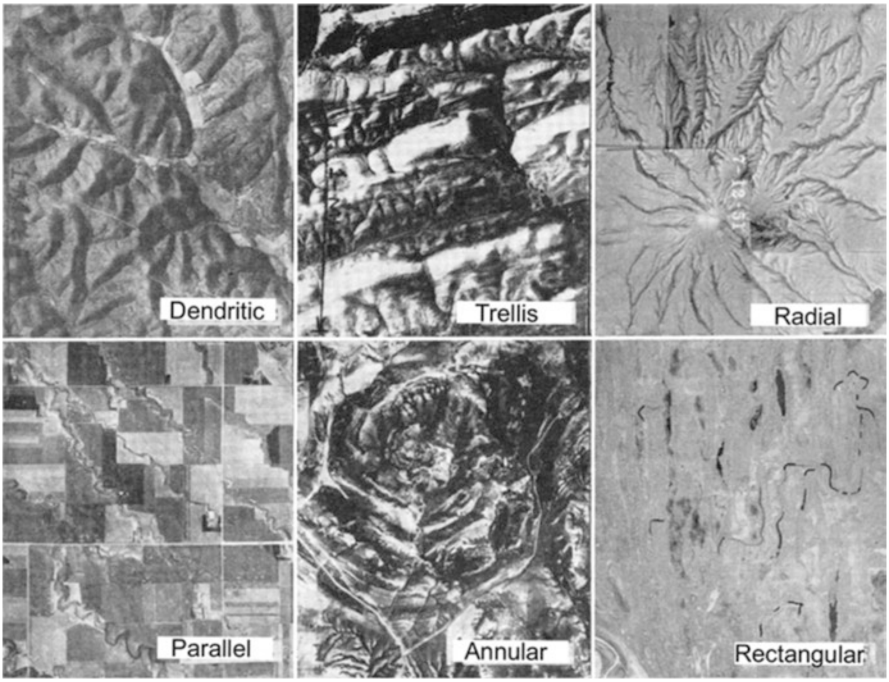

Fig. 8.5 Geologic and geomorphic structure features controlling the drainage patterns (see comments in the text). (Adapted from ASP 1960)

8.2.3 *Morphography and Landscape Ecology*

The morphographic attributes, in particular the configuration and contour design of the geoforms, have close semantic and cartographic relationships with concepts used in landscape ecology, such as mosaic, matrix, corridor, and patch (Forman and Godron 1986). A deltaic plain is a good example that illustrates the relationship between the planimetry of the geoforms and the metrics used in landscape ecology. A deltaic plain that occupies the distal area in a depositional system is a dynamic entity that receives materials and energy from the medial and proximal sectors of the same system. Delta channels are axes which introduce water and material in the system, conduct them through the system, and distribute them to other positions within the system such as overflow mantles and basins. Channels are elongated, sinuous, narrow corridors that feed the deltaic depositional system. In general, the mantles (overflow or splay) are extensive units that form the matrix of the system. The basins are closed depressions, forming scattered patches in the system (Fig. 8.6).

In the center and to the right, a deltaic alluvial system with relative age Q1 (i.e., upper Pleistocene) fossilizes a previous depositional system of relative age Q2 (i.e., late middle Pleistocene) of which the elongated patches of overflow basin are

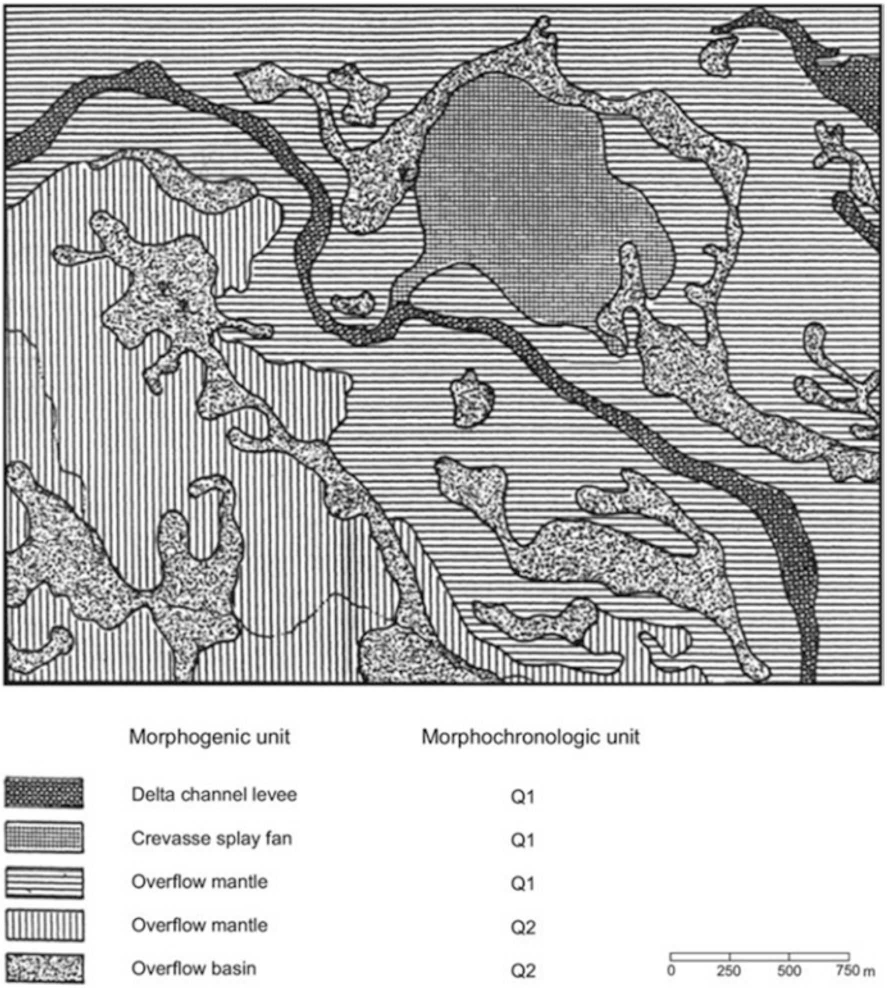

Fig. 8.6 Contact area between two depositional systems differentiated by relative age
Extract from a soil series map of the Santo Domingo river plain, Venezuela; survey scale 1: 25,000. (Adapted from Pérez-Materán 1967)

remnants. The delta channel is the axial unit of the depositional system and functions as a corridor through which water and sediments transit before being distributed within the system. A unit of triangular configuration is grafted on the delta channel, corresponding to a crevasse splay fan that originated upon the opening of a gap in the levee of the channel. The overflow mantles are the matrices of both depositional systems (Q1 and Q2). The basins and the splay fan correspond to patches.

8.3 Morphometric Attributes: The Dimension of Geoforms

Morphometry covers the dimensional features of the geoforms as derived from a numerical representation of the topography (Pike 1995; Pike and Dikau 1995). Computerized procedures allow the extraction and measurement of a variety of morphometric parameters from a DEM, some being relevant at local scale and others at regional scale, including slope, hypsometry, orientation (aspect), visual exposure, insolation, tangential curvature, profile curvature, catchment characteristics (extent, elevation, slope), and roughness (Gallant and Hutchinson 2008; Olaya 2009). While many of these land-surface parameters are used in topography, hydrography, climatology, architecture, urban planning, and other applied fields, only a few actually contribute to the characterization of terrain forms, in particular the relative elevation, drainage density, and slope gradient. These are subordinate, not diagnostic attributes which can be used at any categorial level with variable weight. Morphometric attributes are interrelated: at a specific range of relative elevation, there is a direct relationship between drainage density and slope gradient; the higher the drainage density, the greater is the slope gradient, and conversely (A and B, respectively, in Fig. 8.7).

8.3.1 *Relative Elevation (Relief Amplitude, Internal Relief)*

The relative elevation between two geoforms is evaluated as high, medium, or low. Ranges of numerical values (e.g., in meters) can be attributed to these qualitative classes within the context of a given region or project area. Numerical ranges are established on the basis of local or regional conditions and are valid only for these conditions. Relative elevation is a descriptive attribute, and the classes of relative elevation can be differentiating but are not diagnostic. Likewise, the absolute altitude is not a diagnostic criterion, because similar geoforms can be found at various elevations. For instance, the Bolivian Altiplano at 3500–4000 masl, the Gran Sabana area in the Venezuelan Guayana at 800–1100 masl, and the mesetas of eastern Venezuela at 200–400 masl show all three the diagnostic characteristics of the plateau landscape, although at different elevations.

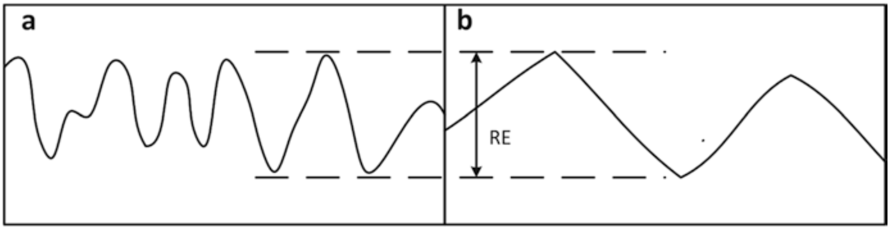

Fig. 8.7 Relationship between drainage density and slope gradient in similar conditions of relative elevation (RE). (Adapted from Meijerink 1988)

8.3.2 Drainage Density

Drainage density measures the degree of dissection or incision of a terrain surface. Density classes are set empirically for a given region or project area. For instance, Meijerink (1988) determines drainage density classes (called valley density VD) based on the relationship $VD = \Sigma L/A$, where ΣL is the cumulative length of drainage lines in km and A is the area in km^2. Not only the conditions of the region studied but also the study scale affects the numerical values of VD (Fig. 8.8). The FAO Guidelines for soil description (2006) define potential drainage density values based on the number of "receiving" pixels within a window of 10×10 pixels.

8.3.3 Relief Slope

The slope gradient is expressed in percentages or degrees. There are geoforms that have characteristic slopes or specific slope ranges. For instance, a coastal cliff or a young fault escarpment is often vertical and has therefore a slope close to 90°. A debris talus has an equilibrium slope of 30–35°, which corresponds to the angle of repose of the loose debris covering the slope. However, the mere knowledge of these numerical values does not contribute directly to identify the corresponding geoform. The slope gradient is essentially a descriptive attribute, at the most covariant with other attributes of higher diagnostic value. Obviously, a hill has a slope greater than a valley floor.

8.3.4 Terrain and Soil Surface Features

Morphometry is not limited to the extraction of topographic parameters from a DEM. Remote sensing also contributes to the characterization of the epigeal component of the geoforms. A variety of terrain and soil surface features can be identified, measured, and delineated from remote-sensed data. An inventory of parameters that can be characterized from optical and microwave sensors includes mineralogy, texture, moisture, organic carbon, iron oxides, salinity, carbonates, terrain roughness, and erosion features (Wulf et al. 2015). Spectral signatures covariate with laboratory determined or field observed property values. Some of these attributes may perform better al local scale to identify patches of specific surface features such as spatial variations in texture, organic matter content, or soil erosion in a given geomorphic unit. Others can contribute to delineate entire geoforms or associations thereof, for instance, in poorly drained, salt-affected or land degraded areas. Landscapes with no or sparse vegetation cover in dry environments offer the best possibilities for remote-sensed morphometry characterization (Metternicht and Zinck 1997, 2003; del Valle et al. 2010; Metternicht et al. 2010). Del Valle et al.

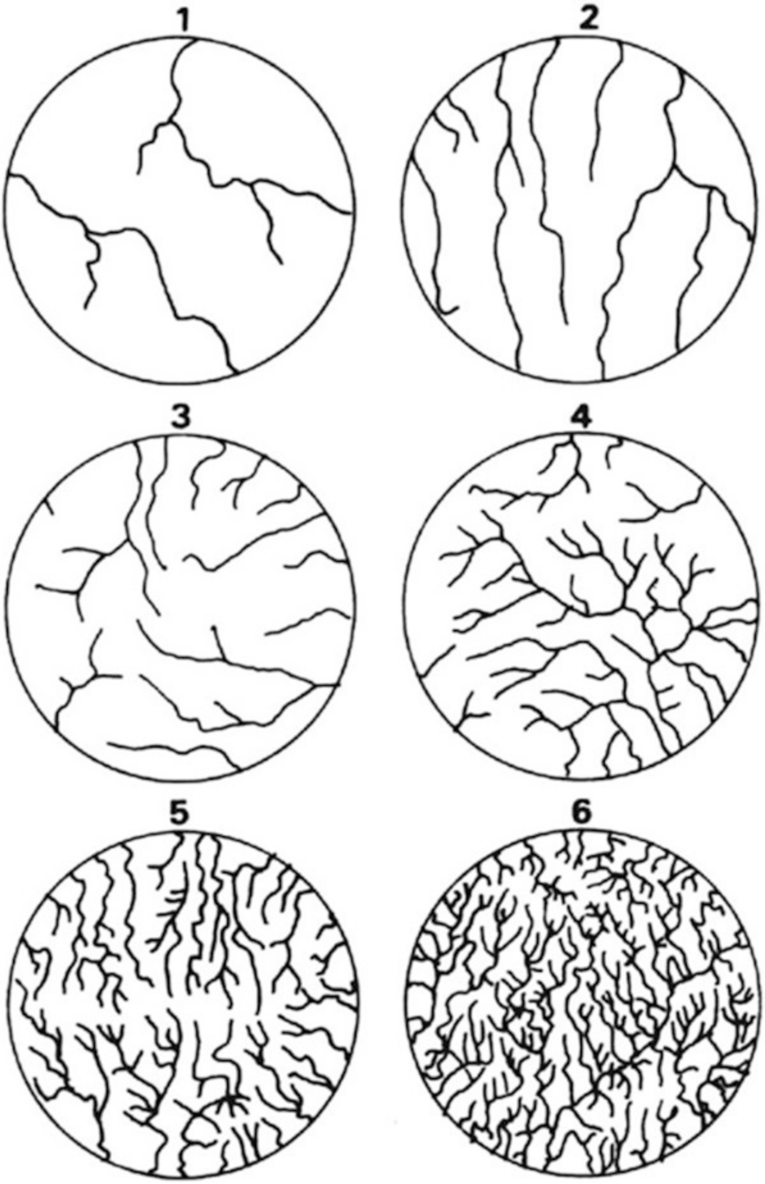

Fig. 8.8 Drainage density classes. (Adapted from Meijerink 1988)

(Chap.19 in this book) show the capability of the PALSAR L-band to penetrate coarse-textured materials several decimeters below the terrain surface to detect buried geological and geomorphic features. So far less widely used than remote sensors, proximal sensors present promising opportunities to further explore the hypogeal component of the geoforms.

8.3.5 Contribution of Digital Morphometry

With the development of digital cartography, (geo)morphometry is increasingly used to characterize terrain units based on individual numerical parameters that are extracted from a DEM, such as altitude, relative elevation, slope, exposure, and curvature, among others. Attributes such as slope, and curvature can present continuous variations in space and are therefore suitable for fuzzy mapping. This is in particular the case of banal hillside reliefs with convex-concave slope profiles according to the model of Ruhe (1975). However, many geoforms have relatively discrete boundaries that reflect their configuration and contour design. This is especially the case of constructed geoforms. In brief, the contribution of digital morphometry resides essentially in the automated estimation of dimensional attributes of the geoforms. However, limiting the description of the geoforms to their morphometric characteristics, just because the latter can be extracted automatically from a DEM, carries the risk of replacing field observation and image reading by numerical parameters which do not reflect satisfactorily the structure and formation of the geomorphic landscape. The scope of the morphometric characteristics to interpret the origin and evolution of the relief is limited, because morphometry covers only part of the external features of the geoforms, their epigeal component.

8.4 Morphogenic Attributes: The Dynamics of Geoforms

Selected geoform attributes reflect forming processes and can therefore be used to reconstruct the morphogenic evolution of an area or infer past environmental conditions. In general, the attribute-process relationship is more efficient for identifying geoforms in depositional environment than in erosional environment. Constructed geoforms are usually more conspicuous than erosional geoforms, except for features such as gullies or karstic erosion forms, for instance. Hereafter, some morphogenic attributes are analyzed by way of examples. Particle size distribution, structure, consistence, mineralogical characteristics, and morphoscopic features are good indicators of the origin and evolution of the geoforms.

8.4.1 Particle Size Distribution

8.4.1.1 Relevance

Particle size distribution, or its qualitative expression of texture, is the most important property of the geomorphic material, as well as of the soil material, because it controls directly or indirectly a number of other properties. The particle size distribution provides basic information for the following purposes:

- Characterization of the material and assessment of its suitabilities for practical uses (e.g., agricultural, engineering, etc.).
- Inference of other properties of the material that closely depend on the particle size distribution (often in combination with the structure of the material), such as bulk density, specific surface area, cohesion, adhesion, permeability, hydraulic conductivity, infiltration rate, consistence, erodibility, CEC, etc.
- Inference and characterization of geodynamic and pedodynamic features such:
  - transport agents (water, wind, ice, mass movement)
  - depositional processes and environments
  - weathering processes (physical and chemical)
  - soil-forming processes

8.4.1.2 The Information

The particle size distribution of the material is determined in the laboratory using methods such as densitometry or the pipette method to separate the fractions of sand, silt, and clay, and sieves to separate the various sand fractions. The analytical data are used to classify the material according to particle size scales. The most common of these grain size classifications are the USDA classification for agricultural purposes, and the Unified and AASHTO classifications for engineering purposes (USDA 1971). Significant differences between these classification systems concern the following aspects:

- The upper limit of the sand fraction: 2 mm in USDA and AASHTO; 5 mm in Unified.
- The lower limit of the sand fraction: 0.05 mm (50 μm) in USDA; 0.074 mm (74 μm) in Unified and AASHTO (solifluidal threshold).
- The boundary between silt and clay: 0.002 mm (2 μm) in USDA; 0.005 mm (5 μm) in Unified and AASHTO (colloidal threshold).

8.4.1.3 Examples of Inference and Interpretation

Hereafter, some examples are analyzed to show the type of information that can be derived from particle size data to characterize aspects of sedimentology, weathering, and soil formation. The granulometric composition of the material allows inferring and interpreting important features relative to the formation and evolution of the geoforms: for instance, the nature of the agents and processes that mobilize the material, the modalities of deposition of the material and their variations in time and space, the mechanisms of disintegration and alteration of the rocks to form regolith and parent material of the soils, and the differentiation processes of the soil material.

(a) Transport agents

Wind and ice illustrate two extreme cases of relationship between transport agent and granulometry of the transported material.

- Wind is a highly selective transport agent. The competence of the wind covers a narrow range of particle sizes, which usually includes the fractions of fine sand, very fine sand, and coarse silt (250–20 μm). Coarser particles are too heavy, except for saltation over short distances; smaller particles are often immobilized in aggregates or crusts, a condition that causes mechanical retention in situ. As a result, the material transported by wind is usually homometric.
- Ice is a poorly selective agent. Glacial deposits (e.g., moraines) include a wide range of particles from clay and silt (glacial flour) to large blocks (erratic blocks). This results in heterometric material.

(b) Transport processes

Cumulative grain size curves at semi-logarithmic scale, established from the analytical laboratory data, allow inferring and characterizing processes of transport and deposition, especially in the case of the processes controlled by water or wind. The granulometric facies of a deposit reflects its origin and mode of sedimentation (Rivière 1952). According to Tricart (1965a), granulometric curves are basically of three types, sometimes called canonical curves (Rivière 1952): namely, the sigmoid type, the logarithmic type, and the parabolic type (Fig. 8.9).

Granulometric curves that correspond to three types of sediments deposited by a flood event of the Guil river, in southern France, are displayed in Fig. 8.9 (Tricart 1965a).

- The sigmoid or S-shaped curve shows that a large proportion of the sample (ca 85%) lies in a fairly narrow particle size range (150–40 μm), which corresponds mostly to the fractions of coarse silt and very fine sand. This material results from a very selective depositional process, which is common in areas of calm, no-turbulent, fluvial overflow sedimentation. In such places, the vegetation cover of the soil, especially when it comes to grass, operates an effect of sieving and biotic retention mainly of silt and fine sand particles (overflow process). Eolian deposits of particles that have been transported over long distances, as in the case of loess, generate similar S-shaped curves.
- The logarithmic curve, with a more or less straight slope, reveals that the deposit is distributed in approximately equal proportions over all particle size classes. This reflects a poorly selective depositional mechanism that is characteristic of the splay process. Glacial moraine sediments can also produce logarithmic type curves.
- The parabolic curve shows an abrupt slope inflection in the range of 30–20 μm. All particles are suddenly laid down upon a blockage effect caused by a natural or artificial barrier. For example, a landslide or a lava flow across a valley can obstruct the flow of a river and lead to the formation of a lake where the solid load is retained.

(c) Depositional terrain forms

A transect across an alluvial valley usually shows a typical sequence of positions built by river overflow. A full sequence may include a sandy to coarse

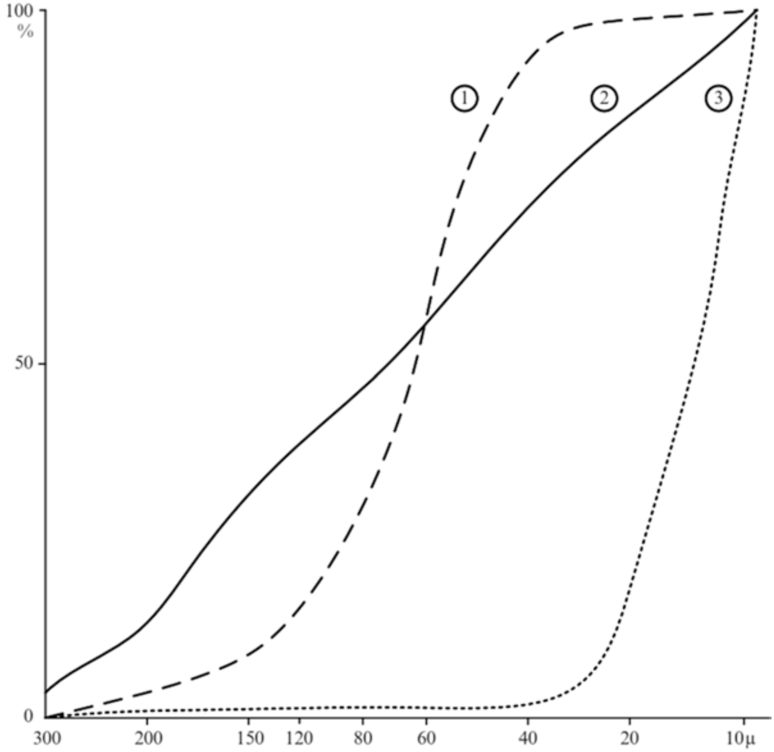

Fig. 8.9 Types of granulometric curves in depositional materials. Sediments of a flood event (June 1957) in the watershed of the Guil river, southern France. (Taken from Tricart 1965a)
1 Sigmoid curve, characteristic of free sediment accumulation
2 Logarithmic curve, characteristic of a torrential lava flow (in this case) or splay deposits
3 Parabolic curve, characteristic of an accumulation forced by an obstacle obstructing the flow

loamy levee, a silty to fine loamy overflow mantle, and a clayey basin, in this order from the highest position, closest to the river channel, to the lowest and farthest position in the depositional system (see Fig. 4.4 in Chap. 4).

(d) Lithologic discontinuity

The soil profile included in Fig. 8.3 shows a contrasting change of texture from sand to clay, which constitutes a lithologic discontinuity at 60 cm depth. This particle size change reveals an event of splay deposition following a basin depositional phase.

(e) Weathering processes

- Physical weathering of rocks produces predominantly coarse fragments. This is particularly common in extreme environmental conditions such as the following:

  - Cold environments, where frequent recurrence of freezing and thawing in the cracks and pores causes rock fragmentation. Cryoclastism or gelifraction is common at high latitudes and high altitudes.
  - Hot and dry environments, where large thermic amplitudes between day and night favor the repetition of daily cycles of differential expansion-contraction between leucocratic (felsic) minerals and melanocratic (mafic) minerals. Termoclastism is common in desert regions with large daily temperature variations.

- Chemical weathering produces predominantly fine-grained products, especially clay particles that are neoformed upon weathering of the primary minerals of the rocks.

(f) Soil forming processes

A classic example is the comparison of clay content between eluvial and illuvial horizons to infer the process of clay translocation. Soil Taxonomy (Soil Survey Staff 1975, 1999), as well as other soil classification systems, uses ratios of clay content between A and B horizons to recognize argillic Bt horizons. For instance, a B/A clay ratio > 1.2 is required for a Bt horizon to be considered argillic, when the clay content in the A horizon is 15–40%. The B/A clay ratio is also used as an indicator of relative age in chronosequence studies of fluvial terraces.

8.4.2 Structure

8.4.2.1 Geogenic Structure

The geogenic structure refers to the structure of the geologic and geomorphic materials (bedrocks and unconsolidated surface materials, respectively).

(a) Rock structure

The examination of the rock structure allows evaluating the degree of weathering by comparison between the substratum R and the Cr horizon, especially in the case of crystalline rocks (igneous and metamorphic) where the original rock structure can still be recognized in the Cr horizon (saprolite). For instance, gneiss exposed to weathering preserves the banded appearance caused by the alternation of clear stripes (leucocratic felsic minerals) and dark stripes (melanocratic mafic minerals). The weathering of the primary minerals, especially the ferromagnesians, releases constituents, mainly bases, that are lost by washing to the water table. In the Cr horizon, the rock volume remains the same as that of the unweathered rock in the R substratum, but the weight has decreased. For example, the density could decrease from 2.7 Mg m^{-3} in the non-altered rock to 2.2–2.0 Mg m^{-3} in the Cr horizon. This process has received the name of isovolumetric alteration (Millot 1964).

(b) Depositional structures

The sediments show often structural features that reveal the nature of the depositional processes. Rhythmic and lenticular structures are examples of syndepositional structures, while the structures created by cryoturbation and bioturbation are generally postdepositional.

- The rhythmic structure reflects successive depositional phases or cycles. It can be recognized by the occurrence of repeated sequences of strata that are granulometrically related, denoting a process of cyclic aggradation. For example, a common sequence in overflow mantles includes layers with texture varying between fine sand and silt. Consecutive sequences can be separated by lithologic discontinuities.
- The lenticular structure is characterized by the presence of lenses of coarse material within a matrix of finer material. Lenses of coarse sand and/or gravel, several decimeters to meters wide and a few centimeters to decimeters thick, are frequent in overflow as well as splay mantles. They correspond to small channels of concentrated runoff, flowing at a given time on the surface of a depositional area, before being fossilized by a new phase of sediment accumulation.
- Cryoturbation marks result from the disruption of an original depositional structure by ice wedges or lenses.
- Bioturbation marks result from the disruption of an original depositional structure by biological activity (burrows, tunnels, pedotubules).

8.4.2.2 Pedogenic Structure

The soil structure type is often a good indicator of how the geomorphic environment influences soil formation. For instance, in a well-drained river levee position, the structure is usually blocky. The structure is massive or prismatic in a basin position free of salts, while it is columnar in a basin position that is saline or saline-alkaline. On the other hand, the grade of structural development may reflect the time span of soil formation.

8.4.3 Consistence

Consistence limits, also called Atterberg limits, are good indicators to describe the mechanical behavior, actual or potential, of the geomorphic and pedologic materials according to different moisture contents. In Fig. 8.10, consistence states, limits, and indices, which are relevant criteria in mass movement geomorphology, are related to each other. These relationships are controlled by the particle size distribution and mineralogy of the materials. In general, clay materials are mostly susceptible to landsliding, while silt and fine sand materials are more prone to solifluction. A low plasticity index makes the material more susceptible to liquefaction, with the risk of

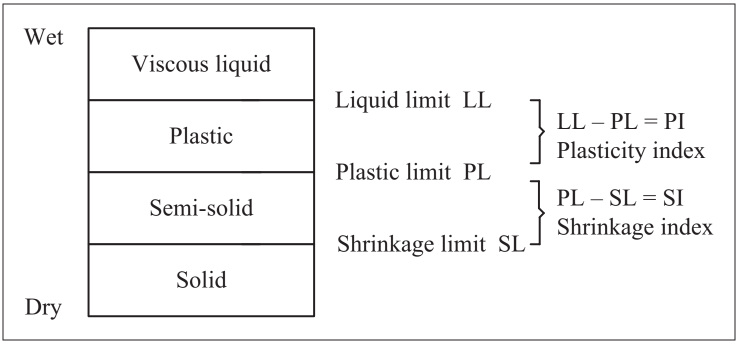

Fig. 8.10 Consistence/consistency parameters

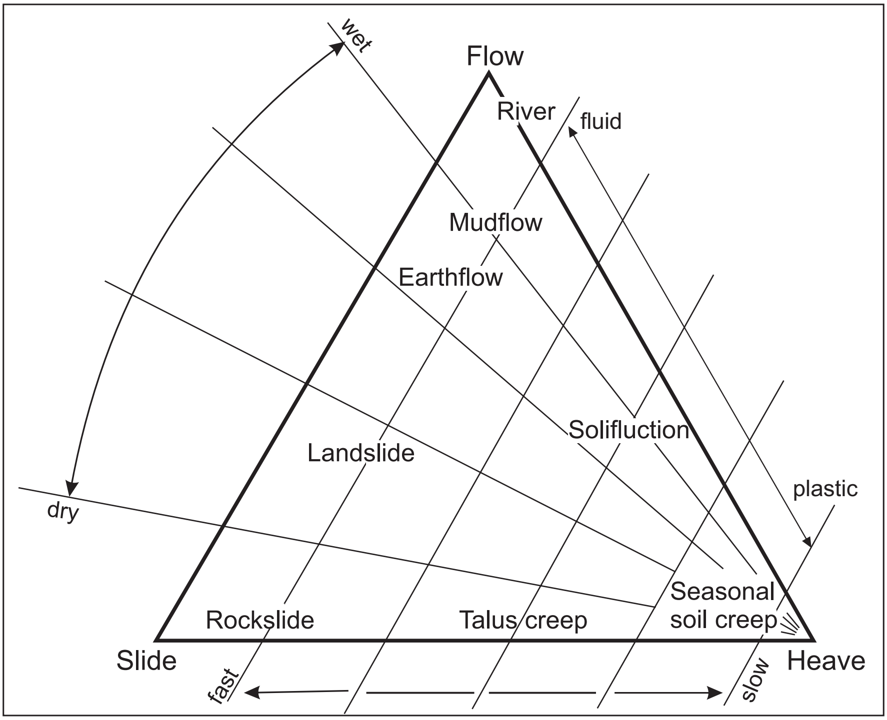

Fig. 8.11 Relational model for classifying mass movements. (Adapted from Carson and Kirkby 1972)

creating mudflows. The graphic model of Carson and Kirkby (1972) shows how continuity solutions in terms of speed, water content, and plasticity that relate the basic mechanisms of swell, slide, and flow, can be segmented for differentiating types of mass movement (Fig. 8.11).

8.4.4 Mineralogy

The mineralogical composition of the sand, silt, and clay fractions in the unconsolidated materials of surface formations is an indicator of the geochemical dynamics of the environment, as related to or controlled by morphogenic processes, and helps follow the pathways of tracer minerals. The associations of minerals present in cover formations allow making inferences about the following features:

- They reflect the dominant lithologies in the sediment production basins.
- They help distinguish between fresh and reworked materials; the latter result from the mixing of particles through the surficial translation of materials over various terrain units.
- They reflect the morphoclimatic conditions of the formation area: for instance, halites in hot and dry environment; kandites in hot and moist environment.
- They reflect the influence of topography on the formation and spatial redistribution of clay minerals along a slope forming a catena of minerals. In humid tropical environment, a catena or toposequence of minerals commonly includes kandites (e.g., kaolinite) at hill summit, micas (e.g., illite) on the backslope, and smectites (e.g., montmorillonite) at the footslope.

Table 8.5 shows an example of determination of minerals in sand and silt fractions to reconstitute the morphogenic processes acting in the contact area between a piedmont and an alluvial valley. The sampling sites are located on the lower terrace of the Santo Domingo river (Barinas, Venezuela) at its exit from the Andean foothills towards the Llanos plain. Sites are distributed along a transect perpendicular to the valley from the base of the piedmont to the floodplain of the river. Site A is close to the piedmont, site C is close to the floodplain, and site B is located in an intermediate position.

- *Site A: colluvial deposit (reworked material).* Rubified colluvium, coming from the truncation of a strongly developed red soil lying on a higher terrace (Q3). The reworking effect can be inferred from the high contents of clean quartz grains, washed during transport by diffuse runoff, and soil aggregates, respectively. The absence of rock fragments and micas indicates that colluviation removed fully pedogenized material from the piedmont.

Table 8.5 Mineralogy of silt and sand fractions (%); eastern piedmont of the Andes, to the west of the city of Barinas, Venezuela

Site	Clean quartz + feldspars	Ferruginous quartz	Soil aggregates	Rock fragments	Micas	Total
A	40	5	55	0	0	100
B	21	14	22	42	1	100
C	22	0	0	0	78	100

Data provided by the Institute of Geography, University of Strasbourg, France. Courtesy J. Tricart

- *Site B: mixed deposit, colluvial and alluvial.* Mixture of red colluvium (presence of aggregates) removed from an older soil mantle on a middle terrace (Q2), and recent alluvium (presence of rock fragments) brought by the Santo Domingo river.
- *Site C: alluvial deposit*. Holocene alluvial sediments exclusively composed of clean quartz and fresh micas. The high proportion of micas results from the retention of silt particles trapped by dense grass cover.

8.4.5 Morphoscopy

Morphoscopy (or exoscopy) consists of examining coarse grains (sand and coarse silt) under a binocular microscope to determine their degree of roundness and detect the presence of surface features.

- The shape of the grains can vary from very irregular to well rounded:
  - Well rounded grains reflect continuous action by (sea)water or wind.
  - Irregular grains indicate torrential or short-distance transport.
- The brightness of the grains and the presence of surface marks, such as striae, polishing, frosting, chattermarks, gouges, among others, indicate special transport modes or special environmental conditions:
  - Shiny grains: seawater action.
  - Frosted grain surface: wind action.
  - Grains with percussion marks: chemical corrosion or collision of grains transported by wind.

8.5 Morphochronologic Attributes: The History of Geoforms

8.5.1 Reference Scheme for the Geochronology of the Quaternary

The Quaternary period (2.6 Ma) is a fundamental time frame in geopedology, because most of the geoforms and soils have been formed or substantially modified during this period. Pre-Quaternary relict soils exist but are of fairly limited extent. The Quaternary has been a period of strong morphogenic activity due to climatic changes, tectonic paroxysms, and volcanic eruptions, which have caused destruction, burial, or modification of the pre-Quaternary and syn-Quaternary geoforms and soils, while at the same time new geoforms and soils have developed.

In temperate and boreal zones, as well as in mountain areas, glacial and interglacial periods have alternated several times. In their classic scheme based on observations made in the Alps, Penck and Brückner (1909) considered a relatively limited number of glacial periods (i.e. Würm, Riss, Mindel, Günz). A similar scheme was established for the chronology of the Quaternary period in North America. Recent research shows that the alternations of glacial-interglacial periods were actually more numerous. In Antarctica, up to eight glacial cycles over the past 740,000 years (740 ka) have been recognized. The average duration of climatic cycles is estimated at 100 ka for the last 500 ka and at 41 ka for the early Quaternary (before 1 Ma), with intermediate values for the period from 1 Ma to 500 ka (EPICA 2004). In addition, shorter climate variations have occurred during each glacial period, similar to the Dansgaard-Oeschger events of the last glaciation. Many regions are now provided with very detailed geochronologic reference systems for the Pleistocene and especially for the Holocene. In the intertropical zone, climate change is expressed more in terms of rainfall variations than in terms of temperature variations. Dry periods have alternated with moist periods, in approximate correlation with the alternation between glacial and interglacial periods at mid- and high latitudes.

Quaternary geochronology is conventionally based on the recurrence of climatic periods, which are assumed of promoting alternately high or low morphogenic activity and high or low pedogenic development. Erhart (1956), in his bio-rhexistasis theory, summarizes this dichotomy by distinguishing between (1) rhexistasic periods with unstable environmental conditions, rather cold and dry, conducive to intense morphogenic activity, and (2) biostasic periods with more stable environmental conditions, rather warm and humid, favorable to soil development. The biostasic periods are assumed of having been longer than the rhexistasic periods (Hubschman 1975). Butler's model of K cycles (1959) is based on the same principle of the alternation of stable phases with soil development and unstable phases with predominance of erosion (soil destruction) or sedimentation (soil fossilization). In the context of soil survey, various rather simple geochronologic schemes have been implemented to record the relative age of geoforms and associated soils, using letters such as K (from kyklos), t (from terrace), and Q (from Quaternary), with increasing numerical subscripts according to increasing age of the geopedologic units, assimilated to chronostratigraphic units (Table 8.6). Although these relative chronology schemes have a spatial resolution limited, for instance, to a region or a country, they also allow coarse stratigraphic correlations over larger territories.

Comments on Table 8.6:

- Q identifiers refer to the inferred relative age of the geomorphic material that serves as parent material, thus not directly to the age of the soil derived from this material. In erosional, structural, and residual relief areas, there is often a large gap between the age of the geologic substratum and the age of the overlying soil mantle. In many cases, the bedrock may even not be the parent material of the soil. This occurs in hill and mountain landscapes, where soils often develop from allochthonous slope formations lying atop the rocks in situ. By contrast, in depositional environments, the initiation of soil formation usually coincides fairly well with the end of the period of material accumulation. However, in sedimentation areas of considerable extent, deposition does not stop abruptly or does not

Table 8.6 Relative geochronology scheme of the Quaternary (Zinck 1988)

		Rhexistasic periods	Biostasic periods
HOLOCENE			Q0
	Upper	Q1	
			Q1-2
	Late middle	Q2	
PLEISTOCENE			Q2-3
	Early middle	Q3	
			Q3-4
	Lower	Q4	
			Q4-5
PLIO-PLEISTOCENE		Q5	

stop in all sectors at the same time. For this reason, Q1 deposition in floodplains, for example, can extend locally into Q0 without notable interruption.

- The numerical indices (Q1, Q2, etc) indicate increasing relative age of the parental materials. Where necessary, the relative scale can be extended (e.g., Q5, etc) to refer to deposits that overlap the end of the Pliocene (Plio-Quaternary formations).
- Each period can be subdivided using alphabetical subscripts to reflect minor age differences (e.g., Q1a more recent than Q1b).
- Some geoforms, such as for example colluvial glacis, may have evolved over the course of several successive periods. A composite symbol can be used to reflect this kind of diachronic formation (e.g., Q1-Q2; Q1-Q1–2).

8.5.2 Dating Techniques

Ideally, age determination of a geoform or a soil requires finding and sampling a kind of geomorphic or pedologic material that allows using any of the absolute or relative dating techniques available, or a combination thereof, including:

- Carbon-14 (organic soils, charcoal, wood; frequently together with analysis of pollen)
- K/Ar (volcanic materials)
- Thermoluminescence (sediments, e.g., beach sands, loess)
- Dendrochronology (tree growth rings)

- Tephrochronology (volcanic ash layers)
- Varves (proglacial lacustrine layers)
- Analysis of historic and prehistoric events (earthquakes, etc.).

These techniques are relatively expensive and their implementation within the framework of a soil survey project is generally limited for budgetary reasons. On average, a determination of carbon-14 costs 300–350 euros. Some techniques are applicable only to specific kinds of material (e.g., ^{14}C only on material containing organic carbon; K/Ar only on volcanic material). Certain techniques cover restricted ranges of time (e.g., ^{14}C for periods shorter than 50–70 ka; thermoluminescence up to 300 ka). Interpretation errors can result from the contamination of the samples or the residence time of the organic matter (in the case of ^{14}C).

The former suggests that the most common materials in the geomorphic and pedologic context likely to be dated in absolute terms are soil horizons and sedimentary strata containing organic matter. In many situations, this limits practically absolute dating to about 60,000 years BP, a time span that covers the Holocene and a small part of the upper Pleistocene corresponding to half of the last glacial period. This underlines the need for indirect dating means such as those provided by pedostratigraphy.

8.5.3 Relative Geochronology: The Contribution of Pedostratigraphy

8.5.3.1 Definition

Relative geochronology is based on establishing relationships of temporal antecedence between the various geoforms or deposits in a study area and building correlations at several spatial scales. This procedure practically consists in extending the stratigraphic system used in pre-Quaternary geology to the Quaternary period. Geologic maps often provide scarce information about the Quaternary (e.g., Qal for alluvial cover formations, Qr for recent deposits), in comparison with the detailed lithologic information concerning the pre-Quaternary. This information is usually to coarse to determine the temporal frame of soil formation. In contrast, the geopedologic information provided by the proper soil survey can contribute to improving the stratigraphy of the Quaternary.

Pedostratigraphy or soil-derived stratigraphy consists in using selected soil and regolith properties to estimate the relative age of the cover formations and the geoforms on which soils have developed. This makes it possible to determine the chronostratigraphic position of a material or a geoform in a geochronologic reference scheme (Zinck and Urriola 1970; Harden 1982; Busacca 1987; NACSN 2005), with the possibility of recognizing successive soil generations.

Etymologically, pedostratigraphy means the use of soils or soil properties as stratigraphic tracers to contribute establishing the relative chronology of geologic, geomorphic, and pedologic events in a territory. However, according to the definitions provided by the North American Stratigraphic Code (NACSN 2005), the concepts of pedostratigraphy and soil stratigraphy are not strictly synonymous. According to this code, the basic pedostratigraphic unit is the geosol, which differs in various ways from the basic unit of soil stratigraphy, the pedoderm. One of the key differences is that the geosol is a buried weathering profile, while the pedoderm may correspond to a buried soil, a surficial relict soil, or an exhumed soil. Disregarding these definition differences, what is in fact relevant is that soils are recognized as stratigraphic units and, in this sense, the term pedostratigraphy has been used in geomorphology and pedology without complying with the strict definition of geosol. Pedostratigraphy is a privileged area of the geopedologic relationships with mutual contribution of geomorphology and pedology. The chronosequences of fluvial terraces provide illustrative examples of this close interrelation. The relative age of the terraces as determined on the basis of their position in the landscape, the lowest being usually the most recent, generally correlates fairly well with the degree of soil development and conversely. Morphostratigraphy and pedostratigraphy complement each other.

8.5.3.2 Indicators

A variety of pedologic and geomorphic indicators has been used to establish relative chronology schemes of the Quaternary in regions with different environmental characteristics (Mediterranean, tropical, etc). These criteria include, among others, the following.

- The degree of activity of the geoforms, distinguishing between active geoforms (e.g., dune in formation), inherited geoforms in survival (e.g., hillside locally affected by solifluction), and stabilized geoforms (e.g., coastal bar colonized by vegetation).
- The degree of weathering of the parent material based on the color of the cover formations and the degree of disintegration of stones and gravels (Fig. 8.12). In humid tropical environment, the fragments of igneous and metamorphic rocks found in detrital formations are usually much more altered than most of the sedimentary rock fragments. Quartzite is most resistant in all kinds of climatic condition and often provides the dominant residual fragments in detrital formations of early Quaternary.
- The degree of soil morphological development, inferred from criteria such as color, pedogenic structure, solum thickness, and leaching indices, among others.
  - Color is a good indicator of the relative age of soils, particularly in humid tropical climate, with gradual increase of the red color (rubification) as the weathering of the ferromagnesian minerals in the parent material proceeds. The possibility of differentiating soil ages by color dims over time in well-developed soils. Red soils can also be recent, when they arise from materials eroded from older rubified soils and redeposited in lower portions of the landscape. Likewise, red soils on limestone can be relatively young.

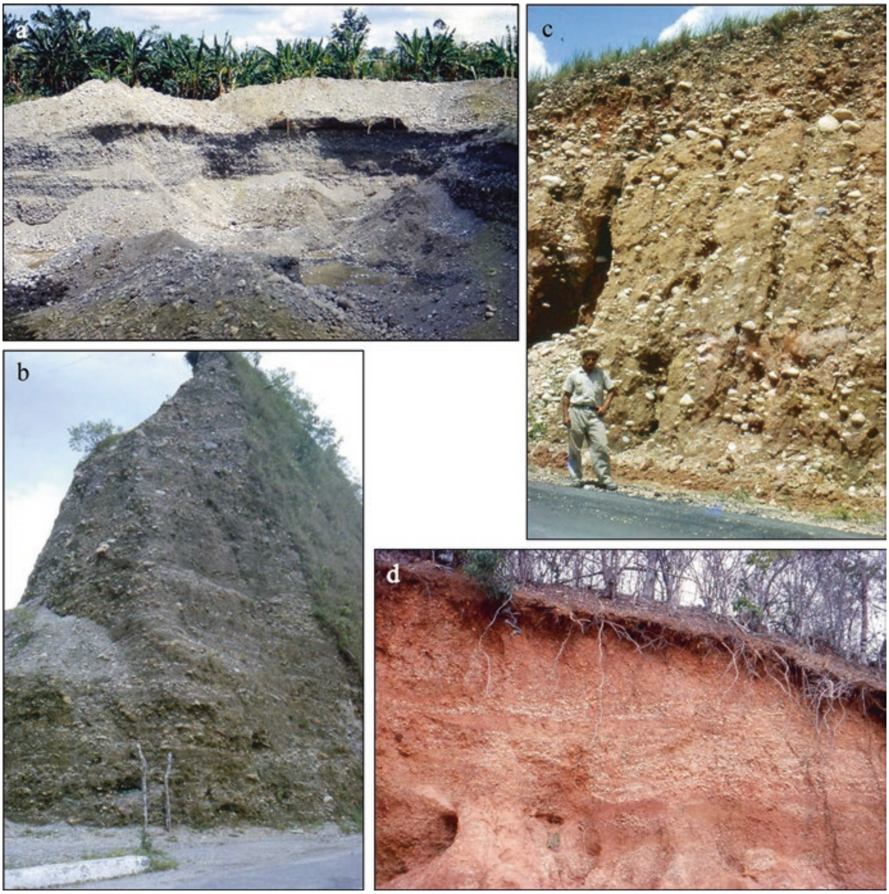

Fig. 8.12 Quaternary alluvial cover formations differentiated by color resulting from increasing rubefaction through time; materials belonging to (**a**) Holocene to upper Pleistocene (Q0-Q1), western piedmont of Venezuelan Andes; (**b**) late middle Pleistocene (Q2), eastern piedmont of Venezuelan Andes; (**c**) early middle Pleistocene (Q3), eastern piedmont of Venezuelan Andes; (**d**) lower Pleistocene (Q4), mesetas of the eastern Venezuelan Plateau

- The pedogenic structure reflects (1) the conditions of the site and the nature of the parent material which together control the type of structure (e.g., blocky, prismatic, columnar), and (2) the elapsed time that influences the grade of structural development (from weak to strong). The relationship between development grade and time reaches a threshold in well-developed soils, beyond which structure tends to weaken because of the impoverishment in substances that contribute to the cohesion of the soil material (e.g., organic matter, type and amount of clay, divalent cations).
- The thickness of the solum generally increases with the duration of pedogenic development in conditions of geomorphic stability. As in the case of structural

  development and rubification, solum thickness reaches a threshold over time beyond which increases become gradually insignificant.
  - Leaching indices allow evaluating the intensity of the translocation of soluble or colloidal substances from eluvial horizons to the underlying illuvial horizons. The most commonly implemented are the clay and calcium carbonate ratios. The leaching intensity decreases with time as the eluvial horizons become depleted in mobilizable substances, resulting in stabilization of the translocation rates.

- The status of the adsorption complex. In general terms, the adsorption complex of the soil changes quantitatively and qualitatively with increasing time. Soil reaction (pH), cation exchange capacity, and base saturation are among the most sensitive indicators. With the passage of time, soils lose alkaline and alkaline-earth cations, resulting in a decrease or a change of composition (more H^+ and/or Al^{+++}) of the adsorption complex and an increase in acidity of the soil solution.
- Clay mineralogy changes with soil development as a function of time, among other factors. The associations of clay minerals originally present in the Cr or C horizons will be replaced by other associations with increasing time. In general, the 2:1 type clays (e.g., smectites, micas) are going to be replaced by or transformed into 1:1 type clays (e.g., kandites).

8.5.3.3 Combining Indicators

The simultaneous use of several of the above-mentioned soil properties allows determining pedostratigraphic units. To this effect, Harden (1982) established a quantitative index to estimate degrees of soil development and correlate these with dated soil units. The index was originally developed based on a soil chronosequence in the Merced River valley, central California, combining properties described in the field with soil thickness. Eight properties were integrated to form the index, including the presence of clay skins, texture combined with wet consistence, rubification based on change in hue and chroma, structure, dry consistence, moist consistence, color value, and pH. Other properties described in the field can be added if more soils are studied. The occasional absence of some properties did not significantly affect the index. Quantified individual properties and the integrated index were examined and compared as functions of soil depth and age. The analysis showed that the majority of the properties changed systematically within the 3 Ma that span the chronosequence of the Merced River. The index has been applied to other sites with successive adjustments (Busacca 1987; Harden et al. 1991).

Stepped alluvial terrace systems usually offer the possibility to establish illustrative soil chronosequences. Table 8.7 reports data on selected properties of soils that have developed on five consecutive Quaternary terraces in the Guarapiche river valley, northeast of Venezuela. Melanization with mollic horizon and soil structure formation on terrace Q1 corresponds to the first stage of soil development from raw depositional material of Q0. From period Q2 onwards clay illuviation starts upon

Table 8.7 Pedostratigraphic thresholds; Guarapiche river valley, Venezuela (Zinck and Urriola 1970)

Relative age of parent material	Dominant color	Average solum thickness cm	$CaCO_3$ eq. %	Clay illuviation B/A index	pH 1:1 H_2O	Base saturation %	CEC cmol+ kg^{-1} clay	Clay mineral associations	Main taxa
Q0	Grayish-brown	30	>3	–	+/−8	100	80–120	S > K = M	Entisols Inceptisols
Q1	Dark- brown	80	1–3	–	6–7.5	80–100	60–95	S > K > M	Mollisols Inceptisols
Q2	**Reddish-yellow**	**200**	**<1**	**1.2–1.6**	4.5–6	40–60	40–60	S > K > M	Alfisols Vertisols
Q3	Yellowish-red	250	<0.5	2.1–2.7	**4–5**	**20–40**	40–50	V > K > M	Ultisols
Q4	Red	300	0	2.4–2.5	4–5	<20	**20–30**	**K>> > V > M > HIV**	Ultisols oxic subgr.

Based on the soil subgroups included in the phenetic clusters 1-2-3 of the dendrogram in Fig. 4.10 (Chap. 4)
Properties refer mainly to the solum (mean values or ranges of values)
Properties in bold represent pedostratigraphic thresholds reflecting discontinuities in soil evolution during the Quaternary
Q0 Holocene, Q1 Upper Pleistocene, Q2 Late Middle Pleistocene, Q3 Early Middle Pleistocene, Q4 Lower Pleistocene
S smectite, *K* kaolinite, *M* mica, *V* vermiculite, *HIV* hydroxy-interlayered vermiculite

descarbonation, together with substantial solum deepening. This is followed on level Q3 by important desaturation of the soil complex and soil solution. On the older Q4 terrace kaolinite formation takes place, causing degradation of the adsorption complex. Each terrace is characterized by a different stage of soil development, adding up to further soil evolution. The properties quantifying these consecutive pedogenic stages show value leaps that correspond to pedostratigraphic thresholds. The latter reflect discontinuities in soil formation during the Quaternary. The pedotaxa sequence comprising increasingly developed soils parallels the Quaternary pedogenic evolution, from Entisols to Mollisols to Alfisols to Ultisols to oxic (kanhaplic) Ultisols (Fig. 8.13).

There is no single model describing the relationship between time and soil development. Pedogenic development rates vary according to the considered time segment and the geographic conditions of the studied area. In general, soil development rates decrease when time increases above a given threshold and with increasing aridity (Zinck 1988; Harden 1990).

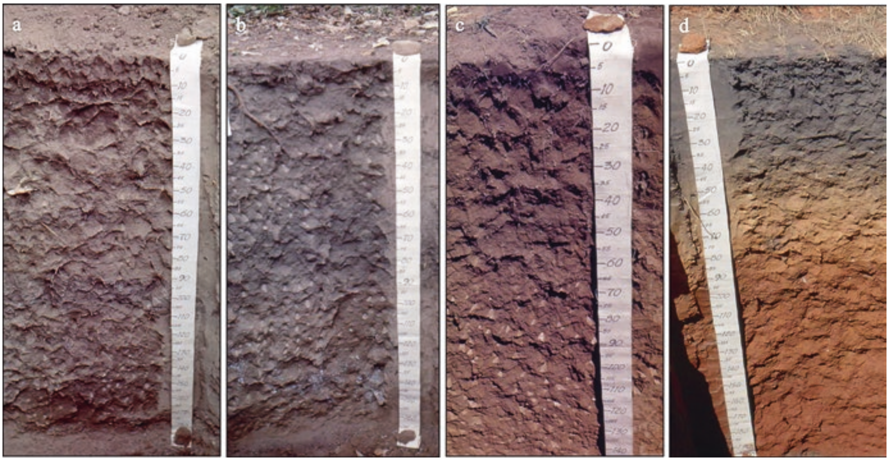

Fig. 8.13 Well-drained soil profiles belonging to the chronosequence of the Guarapiche river terrace system, eastern Venezuela (see Table 8.7). All soils have similar parent materials (sandy loam C horizons with mixtures of smectite, kaolinite, and mica minerals) originating throughout the Quaternary from the sedimentary rocks (sandstone, lutite, limestone) of the southern slope of the Coastal Cordillera. The sequence shows the factor time effect on soil formation and differentiation: (**a**) Entisol (Mollic Ustifluvent), Fluvisol, in the floodplain (Q0); (**b**) Mollisol (Cumulic Haplustoll), Phaeozem, on the lower terrace (Q1); (**c**) Alfisol (Typic Haplustalf), Luvisol, on the lower middle terrace (Q2); Ultisol (‘Kanhaplic’ Paleustult), Acrisol, on the upper terrace (Q4) under savanna cover. The Ultisol (Typic Paleustult), Lixisol, of the higher middle terrace (Q3) is not depicted here

8.6 Relative Importance of the Geomorphic Attributes

Not all attributes are equally important to identify and classify geoforms. For instance, the particle size distribution of the material is most important, because it has more differentiating power and therefore more taxonomic weight than the relative elevation of a geoform.

8.6.1 Attribute Classes

Following an approach that Kellogg (1959) applied to distinguish between soil characteristics, the attributes of the geoforms can be grouped into three classes according to their weight for taxonomic purposes: differentiating, accessory, and accidental attributes, respectively.

8.6.1.1 Differentiating Attributes

A differentiating attribute is one that enables to distinguish one type of geoform from another at a particular categorial level. Therefore, a change in an attribute's state, expressed by a range of values, leads to a change in geoform classification. An attribute that has this property is considered diagnostic. Such an attribute, along with other differentiating attributes, contributes to the identification and classification of the geoforms.

A few examples:

- The dip of the geologic layers is a diagnostic criterion for recognizing monoclinal reliefs and the degree of dipping is a differentiating feature for distinguishing classes of monoclinal reliefs (see Fig. 6.4 in Chap. 6).
- A slope facet should be concave to classify as footslope. In this case, the topographic profile is the differentiating attribute and "concave" is the state of the attribute.
- The material of a decantation basin normally comprises more than 60% clay fraction. In this case, the particle size distribution is the differentiating attribute, and the attribute state is expressed by the high clay content.

8.6.1.2 Accessory Attributes

An attribute is accessory if it reinforces the differentiating capability of a diagnostic attribute with which it has some kind of correlation (covariant attribute). For instance, the lenticular type of depositional structure can occur in several alluvial facies but is more common in deposits caused by overload flow accompanied by mechanical friction (river levee, different kinds of splay). By itself, the presence of a lenticular structure is not enough to recognize a type of geoform.

8.6.1.3 Accidental Attributes

An accidental attribute does not contribute to the identification of a particular type of geoform but provides additional information for its description and characterization. This kind of attribute can be used to create phases of taxonomic units for the purpose of mapping and separation of cartographic units (e.g., slope classes or classes of relative elevation).

8.6.2 Attribute Weight

8.6.2.1 Morphographic Attributes

Morphographic attributes are essentially accessory, sometimes differentiating.

- Accessory weight. For instance, a newly formed river levee has a characteristic morphology (elongated, narrow, sinuous, convex shape), which facilitates its identification in aerial images. An older levee, the contours of which have been obliterated with the passing of time, is more difficult to recognize from its external features. In the case of a levee buried underneath a recent sediment cover, it is possible to reconstruct the configuration and design of the contours by means of perforations. In these last two cases, the identification of the geoform rests primarily on the granulometric composition of material, with accessory support of the morphographic features.
- Differentiating power. In hill and mountain landscapes, the morphographic attributes can be differentiating. For instance, in the case of a convex-concave hillside, the characteristic topographic profile of each single slope facet is in itself differentiating.

8.6.2.2 Morphometric Attributes

Morphometric attributes are predominantly accidental. They contribute to the description of the geoforms, but seldom to their identification. For instance, the difference of elevation (i.e., relative elevation) between the summit surface of a plateau and the surrounding lowlands (e.g., valley or plain landscapes) can be as little as 100–150 m (e.g., the mesetas in eastern Venezuela) or as much as 1000–1500 m (e.g., the Bolivian Altiplano). In both cases, however, the geoform meets the diagnostic plateau attributes at the categorial level of landscape. In general, the dimensional features have low taxonomic weight, but are relevant for the practical use of the geomorphic information, for instance, in evaluation of environmental impacts or land-use planning. To this end, phases of relative elevation, drainage density, and slope gradient can be implemented.

8.6.2.3 Morphogenic Attributes

The morphogenic attributes are essentially differentiating, either individually or in group, especially when they are reinforced by accessory attributes. For instance, the consistence is a diagnostic attribute for assessing the susceptibility of a material to mass movement and for interpreting the origin of the resulting geoforms. The depositional geoforms show always specific ranges of granulometric composition, which is a highly diagnostic attribute in this case.

8.6.2.4 Morphochronologic Attributes

Morphochronologic attributes are mostly differentiating, because the relative age of a geoform is an integral part of its identity. The fact that a river levee has formed during the Holocene (Q0) or during the middle Pleistocene (Q2) probably does not have great effect on its configuration, although the contour design may have been obliterated with the passage of time. However, the chronostratigraphic position of the geoform is differentiating because it determines a time frame in which the morphogenic processes take place, and which controls the evolution of the soils and their properties.

8.6.3 Attribute Hierarchization

Not all attributes are used at each categorial level of the geoform classification system. Table 8.8 shows an attempt of differential hierarchization of the geomorphic attributes according to their diagnostic weight. This aspect is of growing importance for the automated treatment of the geomorphic information. Hereafter are mentioned the criteria that have guided the hierarchization in terms of attribute amount, nature, function, and implementation at the upper and lower levels of the system, respectively (Table 8.9).

8.6.3.1 Upper Levels

- Limited number of attributes.
- Preferably descriptive attributes, reflecting external features of the geoforms (i.e., morphographic and morphometric attributes).
- Function of generalizing and aggregating information.
- Information about attributes is mostly obtained by interpretation of aerial photos, satellite images, and digital elevation models.

Table 8.8 Hierarchization of the geomorphic attributes (Zinck 1988)

Attributes	Landscape	Relief	Lithology	Terrain form
Morphometric				
Relative elevation	+	+	–	o
Drainage density	+	+	–	–
Slope	+	+	–	+
Morphographic				
Topographic shape	+	o	–	–
Topographic profile	–	+	–	+
Exposure	–	+	–	+
Configuration	–	+	–	+
Contour design	–	+	–	+
Drainage pattern	+	+	–	–
Surrounding conditions	+	+	+	+
Morphogenic				
Particle size distribution	–	o	+	+
Structure	–	–	+	+
Consistence	–	–	+	+
Mineralogy	–	–	+	+
Morphoscopy	–	–	+	+
Morphochronologic				
Degree of weathering	–	–	+	+
Degree of soil development	–	–	o	+
Leaching indices	–	–	o	+
Adsorption complex status	–	–	o	+
Clay mineralogy	–	–	+	+

+ Very important attribute
o Moderately important attribute
– Less important attribute

Table 8.9 Relations between geomorphic attributes according to the categories of the system

Attributes	Amount	Nature	Function	Implementation
Upper levels	Few	Descriptive external characterization	Generalizing aggregation	Interpretation of photos, images, and DEM
↕	↕	↕	↕	↕
Lower levels	Many	Genetic internal characterization	Detailing disaggregation	Field and laboratory

8.6.3.2 Lower Levels

- Greater number of attributes, resulting from the addition of information.
- Preferably genetic attributes, reflecting internal characteristics of the geoforms (i.e., morphogenic and morphochronologic attributes).
- Function of differentiating and detailing information.
- More field information and laboratory data are required.

8.7 General Conclusion on Geopsedology

Geopedology is an approach to soil survey that combines pedologic and geomorphic criteria to establish soil map units. Geomorphology provides the contours of the map units ("the container"), while pedology provides the soil components of the map units ("the content"). Therefore, the units of the geopedologic map are more than soil units in the conventional sense of the term, since they also contain information about the geomorphic context in which soils have formed and are distributed. In this sense, the geopedologic unit is an approximate equivalent of the soilscape unit, but with the explicit indication that geomorphology is used to define the landscape. This is usually reflected in the map legend, which shows the geoforms as entries to the legend and their respective pedotaxa as descriptors.

In the geopedologic approach, geomorphology and pedology benefit from each other in various ways:

- Geomorphology provides a genetic framework that contributes to the understanding of soil formation, covering three of the five factors of Jenny's equation: nature of the parent material (transported material, weathering material, regolith), age and topography (Jenny 1941, 1980). Biota is indirectly influenced by the geomorphic context.
- Geomorphology provides a cartographic framework for soil mapping, which helps understand soil distribution patterns and geography. The geopedologic map shows the soils in the landscape.
- The use of geomorphic criteria contributes to the rationality of the soil survey, decreasing the personal bias of the surveyor. The need of prior experience to ensure the quality of the soil survey is offset by a solid formation in geomorphology.
- Geomorphology contributes to the construction of the soil map legend as a guiding factor. The hierarchic structure of the legend reflects the structure of the geomorphic landscape together with the pedotaxa that it contains.
- The soil cover or soil mantle provides the pedostratigraphic frame based on the degree of soil development, which enables to corroborate the morphostratigraphy (e.g., terrace system).
- The soil cover through its properties (mechanical, physical, chemical, mineralogical, biological) provides data that contribute to assess the vulnerability of the geopedologic landscape to geohazards and estimate the current morphogenic balance (erosion-sedimentation).
- The geopedologic approach to soil survey and digital soil mapping are complementary and can be advantageously combined. The segmentation of the landscape sensu lato into geomorphic units provides spatial frames in which geostatistical and spectral analyses can be applied to assess detailed spatial variability of soils and geoforms, instead of blanket digital mapping over large territories. Geopedology provides information on the structure of the landscape in hierarchically organized geomorphic units, while digital techniques provide

information extracted from remote-sensed imagery that help characterize the geomorphic units, mainly the morphographic and morphometric terrain surface features.

This first part of the book addresses the basic concepts and ideas underlying geopedology, with emphasis on the identification, characterization, and classification of geoforms to support soil survey and field soil studies at large. The following parts comprise a variety of studies that implement the geopedologic approach here introduced or other modalities based on soil-landscape relationships, using different methods and techniques, for soil pattern recognition, analysis and mapping, soil degradation assessment, and land use planning.

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