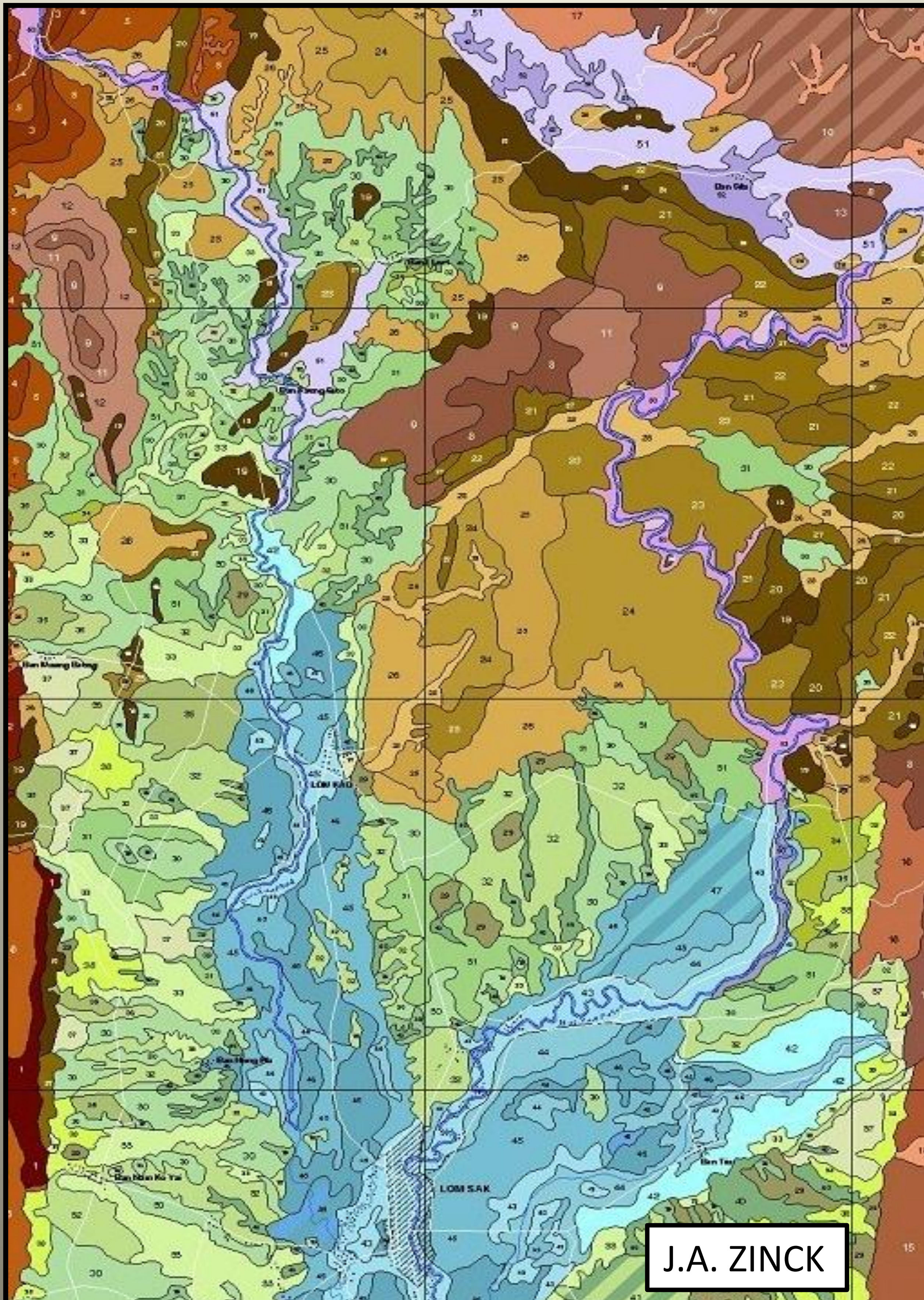
GEOPEDOLOGY



J.A. ZINCK

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Elements of geomorphology for soil and geohazard studies

J. Alfred Zinck

Cover page

Geopedologic map of the Pasak-Lomsak area in northern Thailand, showing the confluence of two alluvial valleys with their longitudinal deposits (blue) and lateral deposits (green) and their respective upper catchments (brown shades) (Hansakdi, 1998).

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FOREWORD

This text is drawn from lecture notes used in a course on geopedology given by the author on several occasions between 1970 and 2003 in various countries of Latin America, especially in Venezuela and Colombia. In Venezuela, the subject of geopedology was the essential component of a workshop organized periodically to train staff of the Ministry of Public Works (MOP) and, subsequently, the Ministry of Environment and Renewable Natural Resources (MARNR), both responsible for conducting soil surveys. The subject of geopedology was also taught as part of a postgraduate course on landscape ecology organized in repeated opportunities by the Faculty of Sciences of the Central University of Venezuela (UCV). In Colombia, similar workshops have taken place on several occasions within the framework of a cooperation program between ITC and the Geographical Institute Agustín Codazzi (IGAC). At ITC, the subject of geopedology, under the heading of *Physiography and Soils*, was taught as part of a annual postgraduate course on soil survey in the period 1986-2003.

After a long period of recession and neglect, soil as a resource for multiple uses, a life supporting base, and a provider of environmental services, has returned, though timidly, to appear on national and international political agendas. This is one of the reasons that motivated to formalize the present text. In a time where emphasis is on digital soil mapping, geopedology proposes a landscape approach that integrates geoform and soil. As such, it can be advantageously complementary to the digital approach and contribute to improving the conceptual frame of the latter.

The present text is the first part of a larger document that will include a series of case studies, in which the geopedologic approach was applied to soil survey and natural hazard analysis. Comments and criticisms are welcome to improve this first version (zincka@itc.nl; alfredzinck@gmail.com).

CONTENTS

Chapter 1

INTRODUCTION

Geopedology, as it is considered here, refers to the relations between geomorphology and pedology, with emphasis on the contribution of the former to the latter. More specifically, geopedology is in the first instance a methodological approach to soil inventory, while providing a the same time a framework for the analysis of the geographic soil distribution patterns. The prefix *geo* in geopedology refers to the earth surface - the *geoderma* - and as such covers, in addition to geomorphology, concepts of geology and geography. Geology intervenes through the influence of tectonics in the geoforms of structural origin and through the influence of lithology in the production of parent material for soils as a result of rock weathering. Geography relates to the analysis of the spatial distribution of soils according to the soil forming factors. However, in the concept of geopedology, emphasis is on geomorphology as a major structuring factor of the pedologic landscape and, in this sense, the term geopedology is a convenient contraction of geomorphopedology. Geomorphology covers a wide part of the physical soil forming framework through the relief, the surface morphodynamics, the morphoclimatic context, the unconsolidated or weathered materials that serve as parent materials for soils, and the factor time.

The relationship between geomorphology and pedology can be considered in the context of landscape ecology. With its integrative approach, landscape ecology tries to transcend the cleavages between related disciplines, both physical and human, that provide complementary perceptions and visions of the structure and dynamics of natural and/or anthropized landscapes. Landscape ecology as a discipline of integration has holistic vocation, but is often practiced de facto as parts of a whole. For instance, one stream puts emphasis on the ecosystem concept as the basis of the biotic/ecological landscape (Forman & Godron, 1986); another stream puts emphasis on the concept of land as the basis of the cultural landscape (Zonneveld, 1979; Naveh & Lieberman, 1984); and another one puts emphasis on the concept of geosystem as the basis of the geographic landscape (Bertrand, 1968; Haase & Richter, 1983; Rougerie & Beroutchachvili, 1991). Geomorphology and pedology participate in this concert, and their respective study objects, geoform and soil, constitute an essential, inseparable pair of the landscape.

Geoforms or terrain forms sensu lato are the study object of geomorphology. Soils are the study object of pedology, a branch of soil science. The relations between both objects and between both disciplines are intimate and reciprocal. Geoforms and soils are essential components of the earth’s epidermis (Tricart, 1972), which share the interface between lithosphere, hydrosphere, biosphere, and atmosphere, within the framework of the noosphere as soils are resources on which human beings make use decisions. It is not a mere static juxtaposition; there are dynamic relationships between the two objects, one influencing the behavior of the other, with feedbacks. Moreover, in nature, it is sometimes difficult to categorically separate the domain of one object from the domain of the other, because the boundaries between the two are fuzzy; geoforms and soils interpenetrate symbiotically. This integration of the geoform and soil objects, that coexist and coevolve on the same land surface, has fostered the study of the relations between the two. As it often happens, the interface between disciplines is a frontier area where new ideas, concepts, and approaches sprout and develop.

The analysis of the relationships and interactions between geoforms and soils and the practical application of these relationships in soil mapping and geohazard studies have received several names such as soil geomorphology, pedogeomorphology, morphopedology and geopedology, among others, denoting the transdisciplinarity of the approaches. By the position of the terms in the contraction word, some authors want to point out that they put more emphasis on one object than on the other. For instance, Pouquet (1966) who has been among the first ones to use the word geopedology, emphasizes the pedologic component and implements geopedology as an approach to soil survey and to erosion and soil conservation studies. In contrast, Tricart (1962, 1965a, 1994) who has possibly been one of the first authors to use the word pedogeomorphology, puts the accent on the geomorphic component.

To illustrate the variety of modalities implemented to address the relationships between geomorphology and pedology, a brief overview is presented in Chapter 2. The applied context in which geopedology was developed is different from other ways of visualizing the relationships between both disciplines; this specificity of geopedology is described in Chapter 3. The geopedologic approach focuses on the inventory of the soil resource. This means logically addressing themes such as soil characterization, formation, classification, mapping, and evaluation. Chapter 4 summarizes relevant aspects of these themes with emphasis on the hierarchic structure of the soil material, which allows to highlight that geomorphology is involved at various levels. The application of geomorphology in soil survey programs at various scales, from detailed to generalized, requires to establish a hierarchic taxonomy of the geoforms, so that the latter can serve as cartographic frames for soil mapping and, additionally, as genetic frames to help interpret soil formation. These aspects are addressed in Chapter 5 (criteria for classifying geoforms), Chapter 6 (geoform classification), and Chapter 7 (geoform attributes). Chapters 4 to 7 update a previous text used as lecture notes (Zinck, 1988).

Chapter 2

RELATIONS BETWEEN GEOMORPHOLOGY AND PEDOLOGY: BRIEF REVIEW

2.1 Introduction

The relationships between geomorphology and pedology, including the conceptual aspects that underlie these relationships and their practical implementation in studies and research, have been referred to under different names. Some of the most common expressions are *soil geomorphology* (Daniels et al., 1971; Conacher & Dalrymple, 1977; McFadden & Knuepfer, 1990; Daniels & Hammer, 1992; Gerrard, 1992, 1993; Schaetzl & Anderson, 2005; among others), *soils and geomorphology* (Birkeland, 1974; Richards et al., 1985; Jungerius, 1985a, 1985b; Birkeland, 1990, 1999), *pedology and geomorphology* (Tricart, 1962, 1965a, 1965b, 1972; Hall, 1983), *morphopedology* (Kilian, 1974; Tricart & Kilian, 1979; Tricart, 1994; Legros, 1996), *geopedology* (Principi, 1953; Pouquet, 1966), and *pedogeomorphology* (Conacher & Dalrymple, 1977; Elizalde & Jaimes, 1989), without mentioning the numerous publications that treat the subject but do not explicitly use one of these terms in their title. Due to this diversity of expressions, it is convenient to first define what the relations between geomorphology and pedology cover, and subsequently analyze the nature of the relationships.

2.2 Definitions and approaches

Soil geomorphology, sometimes called pedologic geomorphology or pedogeomorphology, is the term most frequently found in English-published literature, with the word geomorphology being a noun and the word soil being an adjective that qualifies the former. According to this definition, the center of interest is geomorphology, with the contribution of pedology. However, under the same title of soil geomorphology, there are research works in which the roles are reversed. Therefore, in practice, the relationship between geomorphology and pedology is going in both directions. The emphasis given to one of the two disciplines depends on a number of factors including, among others, the context of the study, the purpose of the research, and the primary discipline of the researcher.

The relations between geomorphology and pedology as scientific disciplines, and between geoform and soil as study objects of these disciplines, can be focused on from two points of view according to the center of interest and weight given to the leading discipline. In one case, emphasis is on the study of the geoforms, while soil information is used to help resolve issues of geomorphic nature, as for example, characterizing the geoforms or estimating the evolution of the landscape. Literally, this approach corresponds to the expression of soil geomorphology or pedogeomorphology. In the other case, the study interest centers on the formation, evolution, distribution and cartography of the soils, with the contribution of geomorphology. Literally, this approach corresponds to the expression of geomorphopedology or its contraction in geopedology. In practice, the various expressions have been used interchangeably, showing that the distinction between the two approaches is fuzzy. Based on this apparent dichotomy, two streams, initially separated, have contributed to the development of the relations between geomorphology and pedology: (1) an academic stream, oriented towards the investigation of the processes that take place at the geomorphology-pedology interface, and (2) a more practical stream, applied to soil survey and cartography. The first one flourished more in hillslope landscapes, which offer propitious conditions to conduct toposequence (catena) and chronosequence studies, whereas the second one developed more in depositional, relatively flat landscapes, which offer favorable conditions for the use of soils for agricultural or engineering purposes.

2.2.1 Academic stream

The academic stream consists of research conducted mainly at universities for scientific purposes. It is based on detailed site and transect studies to identify features of interdependence between geoforms and soils without preset paradigm. In general, what is sought is using geomorphology and pedology to analyze, in a concomitant way, the processes of formation and evolution of soils and landscapes. This current covers in reality a variety of approaches, as illustrate the definitions given by various authors with regard to their conceptions of the relationships between geomorphology and pedology and the study domains covering these relationships. Hereafter, some definitions of soil geomorphology are presented in chronological order.

- The analysis of the balance between geomorphogenesis and pedogenesis and the terms of control of the former on the latter in soil formation (Tricart, 1965a, 1965b, 1994).
- The use of pedologic research techniques in studies of physical and human geography (Pouquet, 1966).
- The study of the landscape and the influence of the processes acting in the landscape on the formation of the soils (Olson, 1989).
- The study of the genetic relationships between soils and landscapes (McFadden & Knuepfer, 1990).
- The assessment of the genetic relationships between soils and landforms (Gerrard, 1992).
- The application of geologic field techniques and ideas to soil investigations (Daniels & Hammer, 1992).
- The study of soils and their use in evaluating landform evolution and age, landform stability, surface processes, and past climates (Birkeland, 1999).
- The scientific study of the origin, distribution, and evolution of soils, landscapes, and surficial deposits, and of the processes that create and modify them (Wysocki et al., 2000).
- The scientific study of the processes of evolution of the landscape and the influence of these processes on the formation and distribution of the soils on the landscape (Goudie, 2004).
- A field-based science that studies the genetic relationships between soils and landforms (Schaetzl & Anderson, 2005).
- A subdiscipline of soil science that synthesizes the knowledge and techniques of the two allied disciplines, pedology and geomorphology, and that puts in parallel the genetic relationships between soil materials and landforms and the commensurate relationships between soil processes and land-forming processes (Thwaites, 2007).
- The study that informs on the depositional history in a given locality, and also takes into account the postdepositional development processes in the interpretation of the present and past hydrological, chemical and ecological processes in the same locality (Winter, 2007).

This short review, which is far from being exhaustive, shows the diversity of concepts and conceptions that contains the expression of soil geomorphology. From the above definitions, several main approaches may be derived:

- Geologic approach, with geomorphology as a subdiscipline of geology; this reflects the times when soil surveyors' basic training was in geology.
- Geomorphic approach, considering pedology as a discipline that gives support to geomorphology; etymologically, this approach could be called pedogeomorphology.
- Pedologic approach, considering geomorphology as a discipline that gives support to pedology; etymologically, this approach could be called geomorphopedology.
- Integrated approach, based on the reciprocal relations between both disciplines.
- Elevation of soil geomorphology at the level of a science, exhibiting therefore a status higher than that of a simple approach or type of study.

2.2.2 Applied stream

The applied stream is related to soil survey and consists in using geomorphology for soil cartography. Historically, the analysis of the relationships between geomorphology and pedology in their spatial dimensions and the implementation of the soil-geoform duo were born out of practice. Soil survey has been the field laboratory where the modalities of applying geomorphology to soil cartography were formulated and tested. The structure of the geomorphic landscape served as background to soil mapping, while the dynamics of the geomorphic environment helped explain soil formation, with feedback of the pedologic information to the geomorphic knowledge.

Originally, different modalities of combining geomorphology and pedology were used for cartographic purposes, including the preparation of separate maps, the use of geomorphology to provide thematic support to soil mapping, and various forms of integration. Some authors and schools of thought advocated the procedure of antecedence: first the geomorphic survey (i.e. the framework), then the pedologic survey (i.e. the content), carried out by two different teams (Tricart, 1965a; Ruhe, 1975). In other cases, there was more integration, with mixed teams making systematic use of the interpretation of aerial photographs (Goosen, 1968). Already in the 1930s, the soil survey service of the USA (National Cooperative Soil Survey) had an area of study in soil geomorphology (parallel mode), which later was formalized with the mission of establishing pedogeomorphic relation models at the regional level to support soil survey (Effland & Effland, 1992). The contribution of Ruhe (1956) meant a breakthrough in the use of geomorphology for soil survey in the USA. Ruhe was in favour of completely separating the description of the soils from the study of geomorphology and geology in a work area. Only after completing the disciplinary studies, could the interpretation of the relationships between soil characteristics and landforms be undertaken (Effland & Effland, 1992). In the second half of the 20th century, progress in systematic soil cartography, especially in developing countries, and progress in soil cartography to support agricultural development projects in a variety of countries have led to various forms of integration, with mixed teams of geomorphologists and pedologists. Work performed by French agencies such as ORSTOM (now IRD) and IRAT provide examples of this kind of soil cartography.

The need to boost agricultural production to support fast population growth has led many developing countries in the middle of the last century, especially in the tropics, to initiate comprehensive soil inventory programs. These were carried out mostly by public entities (ministries, soil institutes) and partly by consultancy agencies. In Venezuela, for instance, soil inventory began in the 1950-1960s as local and regional projects to support the planning of irrigation systems in the Llanos plains (MOP, MARNR) and, subsequently, as a nationwide systematic soil inventory (COPLANARH).These surveys implemented an integrated approach based on the paradigm of the geopedologic landscape, which is closely related to the concepts of pedon, polypedon and soilscape as entities for describing, sampling, classifying, and mapping soils. The integration between geomorphology and pedology took place all along the survey process, from the initial photo-interpretation up to the elaboration of the final map. The integration was reflected in the structure of the legend with two columns, a column for the geomorphic units that provide the cartographic frames, and a column for the soil units that indicate the soil types. This kind of approach is more appropriate for technical application than for scientific investigation. However, applied research underlies always the survey process, as new soil-geofom situations and relationships might occur and require analysis that goes beyond the strict survey procedure. This is a relatively formalized and systematic approach that can be applied with certain homogeneity by several soil survey teams working at various scales. One of the major requirements to make the implementation of geomorphology more effective in this kind of integrated survey is to apply a taxonomy of geoforms.

A novel way of integration can be found in the morphopedologic maps, based on the concept of the morphogenesis/pedogenesis balance (Tricart, 1965b, 1994). Integration takes place not only at the level of the concepts, but also at the level of the mapping procedure. The map distinguishes between stable elements and dynamic elements. The relatively stable geologic substratum, including lithology and structural settings, forms the map background, on which the geomorphic units are superimposed. Each map unit is characterized in the legend by the dominant pedogenic and dominant geomorphogenic processes. This information is used to derive a balance between pedogenesis and geomorphogenesis, which serves as a basis for identifying limitations to soil use.

The implementation of geomorphology in soil surveys contributed to strengthen the link between geomorphology and pedology. Probably, this practical cooperation enriched more the understanding of the reciprocal relations than academic studies in small areas or at site scale. These developments were closely related to the golden period of soil inventories during the second half of the 20th century, particularly in emerging countries that needed soil information at various scales for ambitious agricultural development and irrigation projects. By mid-century, the systematic use of photo-interpretation revolutionized the technique of soil survey and made the contribution and mediation of geomorphology indispensable for identifying and delineating the surficial expression of soil units on the landscape. The rise of the liberal economy and the globalization of the economic relations in the last decade of the past century resulted in letting the market laws decide on the occupation and use of the territory. This meant the suspension of many land-use planning projects and, by the same token, the cancellation of the supporting soil inventory and land evaluation programs (Zinck, 1990; Ibáñez et al., 1995). Lately, a growing societal awareness with regard to soil degradation and erosion is calling the attention on the threats affecting the soil resource, while creating new initiatives and opportunities for soil mapping (Hartemink & McBratney, 2008; Sánchez & al., 2009).

Simultaneously, the multiplication of databases to store and manage via GIS the variety of data and information provided by the inventories of natural resources revealed the need for a criterion able to structure the entries to the databases: geomorphology can provide this structuring frame. Hence the importance of having a classification system of the geoforms, preferably with hierarchic structure, to serve as comprehensive entry to the various information systems on natural resources, their evaluation, distribution, and degradation hazards (Zinck & Valenzuela, 1990).

In recent years, emphasis went on digital soil mapping based on remote-sensed data, together with the use of a variety of spatial statistics and geographical information systems (McBratney et al., 2003; Grunwald, 2006; Lagacherie et al., 2007; Boettinger et al., 2010; Finke, 2012; among others). The combination of remote sensing techniques and digital elevation models (DEM) allows to improve predictive models (Dobos et al., 2000; Hengl, 2003), but tends to see the soil as a surface rather than a three-dimensional body. Remote sensors provide data on individual parameters of the terrain surface and the surficial soil layer. There are also techniques and instruments able to detect soil property variations with depth via proximal sensing (e.g. ASD, FDEM, GPR sensors), but their use is still partly experimental. Digital elevation models allow to relate these parameters with variations of the relief, but the contribution of geomorphology is generally limited to geomorphometric attributes (Pike et al., 2009). Some authors put emphasis on improving the precision of the boundaries between cartographic units as compared with a conventional soil map (Hengl, 2003), or predicting spatial variations of soil properties and features such as for example the thickness of the solum (Dobos & Hengl, 2009), or comparing the cartographic accuracy of a conventional soil map with that of a map obtained by expert system (Skidmore et al., 1996). In all these cases, morphometric parameters are mobilized along with pre-existing soil information (soil maps and profiles). The essence of the soil-geomorphology paradigm, in particular the genetic relationships between soils and geoforms and their effect on landscape evolution, is not sufficiently reflected in the current digital approach. It is difficult to find any theoretical or conceptual statement on soil-geoform relationships, except the reference that is usually made to classic models such as the hillslope model of Ruhe (1975) and the soil equation of Jenny (1941, 1980). Technological advances in remote sensing and digital elevation modelling are mainly used to explore and infer soil properties and their distribution in the topographic space. From an operational point of view, digital soil mapping is still mostly limited to the academic environment and essentially consists in mapping attributes of the soil surface layer, not full soil bodies that are actually the units managed by users (e.g. farmers, engineers). In official entities in charge of soil surveys, digital cartography is frequently limited to digitizing existing conventional soil maps (Rossiter, 2004). There are few examples of national or regional agencies that have adopted automated methods for the production of operational maps (Hengl & MacMillan, 2009).

2.3 Nature of the relationships and fields of convergence

There is a collection of books on soil geomorphology that deal with the topic from different points of view according to the area of expertise of each author (Birkeland, 1974; Ruhe, 1975; Mahaney, 1978; Gerrard, 1981; Jungerius, 1985a; Catt, 1986; Retallack, 1990; Daniels & Hammer, 1992; Gerrard, 1992; Birkeland, 1999; Schaetzl & Anderson, 2005; among others). These works are frequently quite analytical, recording benchmark case studies and describing exemplary situations that illustrate some kind of relationship between geomorphology and pedology. An epistemological analysis of the existing literature is needed to highlight the variety of points of view and enhance broader trends. Synthesis essays can be found in some scientific journal articles. What follows here is based on a selection of journal papers and book chapters, which provide a synthesis of the matter at a given time and constitute milestones that allow to evaluate the evolution of ideas and approaches over time.

2.3.1 Evolution of the relationships

The purely geologic conception of Davis (1899) on the origin of landforms as a function of structure, process and time, excluded soil and biota in general as factors of formation (Jungerius, 1985b). For half a century, the denudation cycle of Davis has influenced the approach of geomorphologists, more inclined to develop theories than observe the cover materials on the landscape and to give preference to the analysis of erosion features rather than depositional systems. By contrast, the paradigm of soil formation, born from the pioneer works of Dokuchaiev and Sibirzew, and subsequently formalized by Jenny (1941, 1980), was based on a number of environmental factors including climate, biota, parent material, relief, and time. These original conceptual differences have led geomorphologists and pedologists to ignore each others for a long time (Tricart, 1965a), although Wooldridge (1949) had already written an early essay on the relationships between geomorphology and pedology. McFadden & Knuepfer (1990) note that soils have historically been neglected by many geomorphologists, who gave preference to the analysis of sedimentological and stratigraphic relations or morphometric studies. The situation changed by mid-20th century when recognizing that the two models could be combined based on interrelated common factors (geologic structure, parent material, relief, time, and stage of evolution) and complementary factors (processes, climate, biota). This has allowed researchers to use the concepts and methods of both disciplines in varying combinations and for various purposes.

Tricart (1965a) has been one of the first to draw attention on the mutual relations that unite geomorphology and pedology. According to this author, geomorphology provides a framework for soil formation as well as elements of balance for pedogenesis, while pedology provides information about the soil properties involved in morphogenesis. Jungerius (1985b) shows that, although geomorphology and pedology have different approaches, the study objects of these two disciplines, i.e. landforms and soils, share the same factors of formation; the same author also highlights the fact that the relationships are two-way, generating mutual contributions. Since the early works of synthesis, which focused on what one discipline could bring to the other, the field of soil geomorphology has evolved toward greater integration, variable according to the topics, with simultaneous use of geomorphology and pedology and less consideration for the conventional boundaries that separate both disciplinary domains. In some universities there are now departments that house the two disciplines under the same roof (e.g. Department of Geomorphology and Soil Science, Technical University of Munich, Freising, Germany).

2.3.2 Mutual contributions

Since the relationships between geomorphology and pedology are multiple, the spectrum of the areas and topics of interdisciplinary research is wide and varied, and the preferences depend on the orientation of each researcher. In the absence of a formal body of themes, here is how some authors have synthesized the content of soil geomorphology.

Already half a century ago, Tricart in his treatise on *Principes et Méthodes de la Géomorphologie* (Tricart, 1965a) showed that the relations between the two disciplines are reciprocal.

- Geomorphology contributes to pedology providing morphogenic balances that reflect the translocation of materials at the earth's surface. The concept of morphogenic balance is well illustrated in the case of the soil toposequences or catenas, where the removal of materials at the slope summit causes soil truncation, while the accumulation of the displaced materials at the footslope causes soil burying. Another example of balance between antagonistic processes that control soil development on slopes is the difference of intensity between the weathering of the substratum and the ablation of debris on the terrain surface. In active alluvial areas, the morphology of the soil results from the balance between the deposition rate of the sediments and their incorporation in the soil by the pedogenic processes.
- Geomorphology also provides a natural setting in which soil formation and evolution take place. The geomorphic environment, by way of integrating the factors of parent material, relief, time, and surface processes, constitutes an essential part of the spatial and temporal framework in which soils originate, develop, and evolve. Tricart argues that geomorphic mapping should precede soil mapping and is not in favor of integrating both activities.
- In return, pedology provides information on soil properties such as texture, structure, aggregate stability, iron content, among others, which play an important role in the resistance of the surface materials to the morphogenic processes. Privileging his own discipline, Tricart suggests that pedology ought to be a branch of geomorphology, for the reason that pedology studies specific features of the phenomena taking place at the contact between lithosphere and atmosphere, in particular in the stratum where living beings modify a surficial part of the lithosphere, while geomorphology covers the greater part of the earth's epidermis. This view is shared by other authors such as, for example, Gerrard (1992) or Daniels & Hammer (1992). Tricart, however, recognizes that the most important thing is actually to intensify the ties of cooperation between both disciplines.

The volume on *Pedogenesis and Soil Taxonomy* published in 1983 (Wilding et al.) has been a reference book in its time, the main purpose of which was to provide a balance between soil morphology and genesis to help understand and use the comprehensive classification system of Soil Taxonomy (Soil Survey Staff, 1975). The chapter written by Hall (1983) on geomorphology and pedology is an interesting inclusion in a work specifically oriented towards soil taxonomy. The above author shows that the soil is more than an object of classification and tries to reconcile soil and landscape, an aspect largely ignored in Soil Taxonomy. Hall emphasizes that it is necessary to map soils and geomorphic surfaces independently and establish correlations later, a point of view that coincides with positions previously defended by Tricart (1965a) and Ruhe (Effland & Effland, 1992). He says that it is not allowed, in a new study area, to predict soils from their location on the landscape or infer the geomorphic history of the area only on the basis of soil properties. Despite this somewhat old-fashioned position, Hall acknowledges that there are no clear boundaries between geomorphic and pedologic processes and that interdisciplinary studies are needed to explain the features that both sciences address.

In a supplement of the CATENA journal dedicated to *Soils and Geomorphology* (Jungerius, 1985a), Jungerius (1985b) presents the results of a broad literature review from the first works of the mid-20th century until the publication date of the supplement, with emphasis on papers published in CATENA. The author adopts a dichotomous approach, similar to Tricart's approach, to show the mutual contributions between both disciplines, but with emphasis on the contribution of pedology to geomorphology.

- To illustrate the significance of the landform studies for pedology, it is pointed out that pedologic processes such as additions, losses, translocations and transformations (Simonson, 1959) are under geomorphic control. Subsequently, reference is made to recurring themes in the literature that emphasize the relief as a factor of soil formation and geography. Highlighted topics address, for instance, the effect of the terrain physiography on the spatial distribution and the cartography of soils, the effect of the topography on the genesis and catenary distribution of soil profiles, and the effect of landscape evolution on soil differentiation.
- The significance of the soil studies for geomorphology is analyzed in more details. After showing how such studies contribute to prepare geomorphic and soil erosion maps, there is emphasis on two types of study that benefit substantially from the contribution of pedology: the studies of geomorphogenic processes and the paleogeomorphic studies. To investigate the nature of the processes that operate on a slope requires knowing the present soil system, with its spatial and temporal variations. Many of the authors cited by Jungerius (1985b) insist on the importance of the control that the horizon types exert on the geomorphic processes. A key differentiation is made between A horizons and surface crusts and their impact on the patterns of runoff and infiltration, on the one hand, and B horizons and subsurface pans and their impact on the formation of pipes and tunnels, gullies, and mass movements, on the other hand. With respect to the paleogeomorphic studies, these emphasize the importance of the paleosoils as indicators of a landscape stability phase, with the possibility of reconstructing factors and conditions that prevailed in the same period. The interpretation of the paleosoils helps the geomorphologist reconstruct past climate and vegetation conditions, infer the evolution time of a landscape, detect changes in a landscape configuration, and investigate past geomorphic processes.

2.3.3 Trend towards greater integration

A pioneer work focusing on soils as landscape units is that of Fridland (1974, 1976). Fridland shows that soils are distributed on the landscape according to patterns that shape the structure of the soil mantle. Although the term geomorphology does not appear in his texts, the relationships that he sets are relationships between genetic and geometric soil entities and landforms. Ten years later, Hole & Campbell (1985) took up Fridland's approach in their analysis of the soil landscape. Contemporaneously to the work of Fridland, Daniels et al. (1971) used the superposition of soil mantles to determine relative ages and sequences of events in the landscape, laying the foundations of pedostratigraphy.

In more recent synthesis articles, emphasis is on showing how the concepts and methods of the two disciplines have been integrated to investigate interface features, instead of identifying the specific contribution of each discipline individually. Modern studies of soil geomorphology transgress the boundaries between the two sciences of origin and integrate parts of the doctrinal body of both. This new research domain constitutes an interface discipline, or "border country" as it is called by Jungerius (1985b), which gains in autonomy and maturity, with its own methodological approach and topics of interest. This has led Schaetzl & Anderson (2005) to qualify soil geomorphology as a full-fledged science. Hereafter, reference is made to some key articles that attempt to formalize the domain of soil geomorphology.

Olson (1989) considers that a study in soil geomorphology should have three main components, including (1) the recognition of the surface stratigraphy and of the parent materials present in an area; (2) the determination of the geomorphic surfaces in space and time; and (3) the correlation between soil properties and landscape features. This approach is in accordance with the definition that Olson (1989) gives of soil geomorphology as the study of the landscape and the influence of landscape processes on soil formation. There is integration of the two disciplines, but geomorphology plays the decisive role. In a subsequent publication (Olson, 1997), the same author notes that the patterns or models of soil-geomorphology can be applied in a consistent and predictable manner in soil survey and considers that the pedologist should acquire the ability to use the pedogeomorphic patterns to interpolate within a study area or extrapolate to similar geographic areas.

In the journal *Geomorphology 3* (1990) are published the proceedings of a symposium dedicated to soil geomorphology (Proceedings of the 21st Annual Binghamton Symposium in Geomorphology, edited by Knuepfer & McFadden, 1990). In addition to numerous articles analyzing case studies in a variety of sites and conditions, the journal contains two introductory papers that present an overview of the trends in this area in the late 1980s. McFadden & Knuepfer (1990) analyze the link between pedology and surface processes. In a short historical account, they show how the pioneer work of some geologists, geomorphologists, and pedologists, concentrating on the study of the genetic relationships between soils and landscapes, resulted in forming the soil-geomorphology stream. The authors refer to three topics they consider central to the development of soil geomorphology. First, they point out the significance of the fundamental equation of Jenny (1941) to show the relevance of geomorphology in pedologic research through the factors of climate change, time, and relief. In particular, the study of chronosequences has contributed enormously to understanding geomorphic processes and landscape evolution, especially in river valleys with systems of nested terraces. The theme of fluvial terraces is an outstanding area of convergence, because understanding the genesis of the terraces is important to interpret the soil data. Secondly, the authors take up the issue of the models and simulation. They contrast the conceptual models, such as those of Jenny (1941) and Johnson et al. (1990), with the numerical models designed to simulate the behavior of complex systems, and consider that modelling is still limited by the poor definition of basic concepts such as polygenetic soils, soil-forming intervals, and rates of soil development, among others. Finally, the authors mention some of the problems that the investigation in soil geomorphology faces when dealing with complex landscapes. Hillslopes are a typical example of complex landscape, where the current morphogenic processes sometimes have no or little relationship with the formation of the slope itself, and often there is no clear relationship between the slope gradient and the degree of soil development. In synthesis, McFadden & Knuepfer (1990) consider that the soil-landform relationship is one of interaction and mutual feedback. The better we understand soils, including the speed at which the formation processes operate and the variations caused by the position of the soils on the landscape, the deeper will be our understanding of the processes that originate the landforms. Reciprocally, whenever we better understand the evolution of the landscape at variable spatial and temporal scales, we will be able to elucidate complex pedologic problems.

In the same special issue of *Geomorphology 3*, Birkeland (1990) points out that it is difficult to work in one of the fields of soil geomorphology without using information from the others. He illustrates this need to integrate information by analyzing various types of chronosequence and chronofuncion in arid, temperate, and humid regions. Generalizing, Birkeland considers that, in the majority of cases, the studies of soil geomorphology pursue one of the four following purposes: (1) establishing a soil chronosequence that can be used to estimate the age of the surface formations; (2) using the soils, on the basis of relevant properties of diagnostic horizons, as indicators of landscape stability in the short or long term; (3) determining relationships between soil properties that allow inferring climate changes; and (4) analyzing the interactions between soil development, infiltration and runoff, and erosion on slopes.

Following the same order of ideas, Gerrard (1993) considers that the challenge of soil geomorphology is to integrate elements from the four research areas recognized by Birkeland (1990) to develop a conceptual framework of landscape evolution. The author describes several convergent conceptual models, such as those addressing the relationship between thresholds and changes of the soil landscape, the formation of soils on aggradation surfaces, soil chronosequences, and the relationship between soil development and watershed evolution.

The book of Schaetzl & Anderson (2005) on *Soils, Genesis and Geomorphology*, contains an extensive section devoted to soil geomorphology (pp. 463-655). The authors raise soil geomorphology to the level of a discipline that deals specifically with the two-way relations between geomorphology and pedology. The relationships emerge from the fact that the soils are strongly related to the landforms on which they have developed. The authors emphasize that soil geomorphology is a science based primarily in field studies. They take up again, with new examples of more or less integrated studies, the three themes that soil geomorphology has been privileging: soil catena studies, soil chronosequences, and reconstruction of landscape evolution with the help of the paleosoils. As a relevant attempt to get closer to a definition of the basic principles of the discipline, Schaetzl & Anderson recognize six main topics that comprise the domain of soil geomorphology: (1) soils as indicators of environmental and climatic changes; (2) soils as indicators of geomorphic stability and landscape stability; (3)

studies of soil genesis and development (chronosequences); (4) soil-rainfall-runoff relationships, especially with regard to slope processes; (5) soils as indicators of current and past sedimentological and depositional processes; and (6) soils as indicators of the stratigraphy and parental materials of the Quaternary. This outline is similar, in more detail, to the list of objectives previously proposed by Birkeland (1990). This shows that certain constancy of approach has been achieved.

2.4 Conclusion

Several authors have produced books and synthesis articles on soil geomophology, with extensive lists of references that are suggested to consult for more information. This has contributed to make soil geomorphology a discipline in its own right. There is consensus on the basic relationship between geomorphology and pedology: geomorphic processes and resulting landforms contribute to soil formation and distribution while, in return, soil development has an influence on the evolution of the geomorphic landscape. The research themes that have received more attention (in the literature) are chronosequence and toposequence (catena) studies. These two kinds of study provide the majority of the examples used to illustrate the relationships between geomorphology and pedology. Some authors favor the chronosequences as integrated study subjects including pedostratigraphy and paleopedology. Many others emphasize the study of soil distribution and evolution within the framework of the catena concept popularized by the hillslope models of Wood (1942), Ruhe (1960, 1975), and Conacher & Dalrymple (1977). Some articles point out general principles, but there is still no unified body of doctrine. There are few references in international journals that provide some formal synthesis on how to carry out integrated pedogeomorphic mapping.

Chapter 3

THE GEOPEDOLOGIC APPROACH

3.1 Introduction: definition, origin, development

The first one to use the term *geopedology* was most probably Principi (1953) in his treatise on *Geopedologia (Geologia Pedologica); Studi dei Terreni Naturali ed Agrari*. In spite of the prefix *geo*, the relationships between pedology and geology and/or geomorphology are not specifically addressed, except for the inclusion of three introductory chapters on unconsolidated surface materials, hard rocks, and rock minerals, respectively, as sources of parent material for soil formation. Principi's *Geopedologia* is in fact a comprehensive textbook on pedology. Following the pioneer work of Principi, the term geopedology continues being used in Italy to designate the university programs dealing with soil science in general.

The geopedologic approach, as formulated hereafter, is based on the fundamental paradigm of soil geomorphology, i.e. the assessment of the genetic relationships between soils and landforms and their parallel development, but with a clearly defined applied orientation and practical aim. The approach puts emphasis on the reading of the landscape in the field and from remote-sensed documents to identify and classify geoforms, as a prelude to their mapping along with the soils they enclose and the interpretation of the genetic relationships between soils and geoforms (geoform defined below). As such, geopedology is closely related with the concept of pattern and structure of the soil cover developed by Fridland (1974, 1976) and taken up later by Hole & Campbell (1985), but with explicit emphasis on the geomorphic context as an essential factor of soil formation and distribution.

It is common acceptance that there are relationships between soils and landscapes, but often without specifying the nature of the landscape in consideration (topographic, ecological, biogeographic, geomorphic, etc.). The use of landscape models has shown that the elements of the landscape are predictable and that the geomorphic component especially controls a large part of the non-random spatial variability of the soil cover (Arnold & Schargel, 1978; Wilding & Drees, 1983; Hall & Olson, 1991). Wilding & Drees (1983), in particular, stress the importance of the geomorphic features (forms and elements) to recognize and explain the systematic variations in soil patterns. Geometrically, the geomorphic landscape and its components, which often have characteristic discrete boundaries, are discernible in the field and from remote-sensed documents. Genetically, the geoforms make up three of the soil forming factors recognized in Jenny's equation (1941), namely the topography (relief), the nature of the parent material, and the relative age (morphostratigraphy). Therefore, the geomorphic context is an adequate frame for mapping soils and understanding their formation.

Geopedology aims at supporting soil survey, combining pedologic and geomorphic criteria to establish soil map units and analyze soil distribution on the landscape. Geomorphology provides the contours of the map units (i.e. the container), while pedology provides the taxonomic components of the map units (i.e. the content). Therefore, the geopedologic map units are more than the conventional soil map units, since they also contain information on the geomorphic context in which soils are found and have developed. In this sense, the geopedologic unit is an approximate equivalent of the soilscape concept (Buol et al., 1997), with the particularity that the landscape is basically of geomorphic nature. This is reflected in the legend of the geopedologic map, which combines geoforms as entries to the legend and pedotaxa as components.

The geopedologic approach, as described below, was developed in Venezuela with the systematic application of geomorphology in the soil inventory programs, that this country carried out in the second half of the 20th century at various scales from detailed to generalized. In a given project, the practical implementation of geomorphology began with the establishment of a preliminary photo-interpretation map prior to fieldwork. This document oriented the distribution of the observation points, the selection of sites for the description of representative pedons, and the final mapping. As a remarkable feature, geoforms provided the headings of the soil map legend. The survey teams included geomorphologists and pedologists, who were trained in soil survey methodology including basic notions of geomorphology. This kind of training program had started in the Ministry of Public Works (MOP), responsible for conducting the basic soil studies for the location and management of irrigation and drainage systems in the alluvial areas of the country. It was subsequently developed in the Commission for the Planning of the Hydraulic Resources (COPLANARH) and the Ministry of the Environment and Renewable Natural Resources (MARNR). From this experience was generated a first synthesis addressing the implementation of geomorphology in alluvial environment, basically the Llanos plains of the Orinoco river where large soil survey projects for the planning of irrigation schemes were being carried out (Zinck, 1970). Later, with the extension of soil inventory to other types of environment, the approach was generalized to include landscapes of intermountain valleys, mountains, piedmonts, and plateaux (Zinck, 1974).

Subsequently, the geopedologic approach was formalized as a reference text under the title of *Physiography and Soils* within the framework of a postgraduate course for training specialists in soil survey at the International Institute for Aerospace Survey and Earth Sciences (ITC), now Faculty of Geo-Information Science and Earth Observation, University of Twente, Enschede, The Netherlands (Zinck, 1988). For a period of more than 20 years, were formed geopedologists originating from a variety of countries of Latin America, Africa, Middle East, and Southeast Asia, who contributed to disseminate and apply the geopedologic method in their respective countries. In these times, the ITC also participated in soil inventory projects within the framework of international cooperation programs for rural development. This in turn has contributed to spreading the geopedologic model in a wide part of the intertropical world. In certain countries, this model has received support from official agencies for its implementation in programs of natural resources inventory and ecological zoning of the territory (Bocco et al., 1996).

The geopedologic approach was developed in specific conditions, where the implementation of geomorphology was requested institutionally to support soil survey programs at national, regional and local levels. Originally, the first demand emanated from the Division of Edaphology, Direction of Hydraulic Works of the Ministry of Public Works in Venezuela.

This institutional framework has contributed to determining the application modalities of geomorphology to semi-detailed and detailed soil inventories in new areas for land use planning in irrigation systems and for rainfed agriculture at regional and local level. The same thing happened later with the small-scale land inventory carried out by COPLANARH as input for the water resources planning at national level. In order to simplify logistics and lower the operation costs, geomorphology was directly integrated into the soil inventory. Hence, *geopedology* turned out to be the term that best expressed the relationship between the two disciplines, with geomorphology at the service of pedology, specifically to support soil mapping. Geomorphology was considered as a tool to improve and accelerate soil survey, especially through geomorphic photo-interpretation.

Geopedology is one of several ways, as described in Chapter 2, which study the relationships between geomorphology and pedology or use these relationships to analyze and explain features of pedologic and geomorphic landscapes. Compared to other approaches, geopedology has a more practical goal and could be defined as the soil survey discipline, including characterization, classification, distribution and mapping of soils, with emphasis on the contribution of geomorphology to pedology. Geomorphology especially intervenes to understand soil formation and distribution by means of relational models (for instance, chronosequences and toposequences) and to support mapping. The central concept of geopedology is that of the soil in the geomorphic landscape. The geopedologic landscape is the paradigm.

The application of geomorphology to soil inventory requires a hierarchic geoform taxonomy, suitable to be used at various categorial levels according to the degree of detail of the soil inventory and cartography. In Table 3.1, the general structure and main components of such a taxonomic geoform classification sytem are represented. In this context, the word *geoform* refers to all geomorphic units regardless of the taxonomic levels they belong to in the classification system, while *landform/terrain form* is the generic concept that designates the lower level of the system. The *geoform* concept includes at the same time relief features and cover formations. The vocable *landform* may lead to confusion, because it is used with different meanings in geomorphology, pedology, landscape ecology, and land evaluation, among others. The expression *terrain form* is preferable.

The relationships between geomorphology and pedology can be analyzed from various points of view: conceptual, methodological, and operational. Geopedology (1) is based on the conceptual relationships between geoform and soil which center on the earth's epidermal interface, (2) is implemented using a variety of methodological modalities based on the three-dimensional concept of the geopedologic landscape, and (3) becomes operational primarily within the framework of the soil inventory, which can be represented by a hierarchic scheme of activities.

3.2 Conceptual relationships

Geoform and soil are natural objects that occur along the interface between the atmosphere and the surface layer of the terrestrial globe. They are the only objects that occupy integrally this privileged position. Rocks (lithosphere) lie mostly below. Living beings (biosphere) can be present inside or below, but essentially occur above. Air (atmosphere) can penetrate into the interface, but is mostly over it. Fig. 3.1 highlights the central position of the geoform-soil duo in the structure of the physico-geographical environment. The geoform integrates the concepts of relief/molding and cover formation.

Table 3.1 Synopsis of the geoform classification system (Zinck, 1988).

Level	Category	Generic concept	Short definition
6	Order	Geostructure	Large continental portion characterized by a type of geologic macro-structure (e.g. cordillera, geosyncline, shield).
5	Suborder	Morphogenic environment	Broad type of biophysical environment originated and controlled by a style of internal and/or external geodynamics (e.g. structural, depositional, erosional, etc.).
4	Group	Geomorphic landscape	Large portion of land/terrain characterized by given physiographic features: it corresponds to a repetition of similar relief/molding types or an association of dissimilar relief/molding types (e.g. valley, plateau, mountain, etc.).
3	Subgroup	Relief/molding	Relief type originated by a given combination of topography and geologic structure (e.g. cuesta, horst, etc.).
			Molding type determined by specific morphoclimatic conditions and/or morphogenic processes (e.g. glacis, terrace, delta, etc.).
2	Family	Lithology/facies	Petrographic nature of bedrocks (e.g. gneiss, limestone, etc.) or origin/nature of unconsolidated cover formations (e.g. periglacial, lacustrine, alluvial, etc.).
1	Subfamily	Landform/terrain form	Basic geoform type characterized by a unique combination of geometry, dynamics, and history.

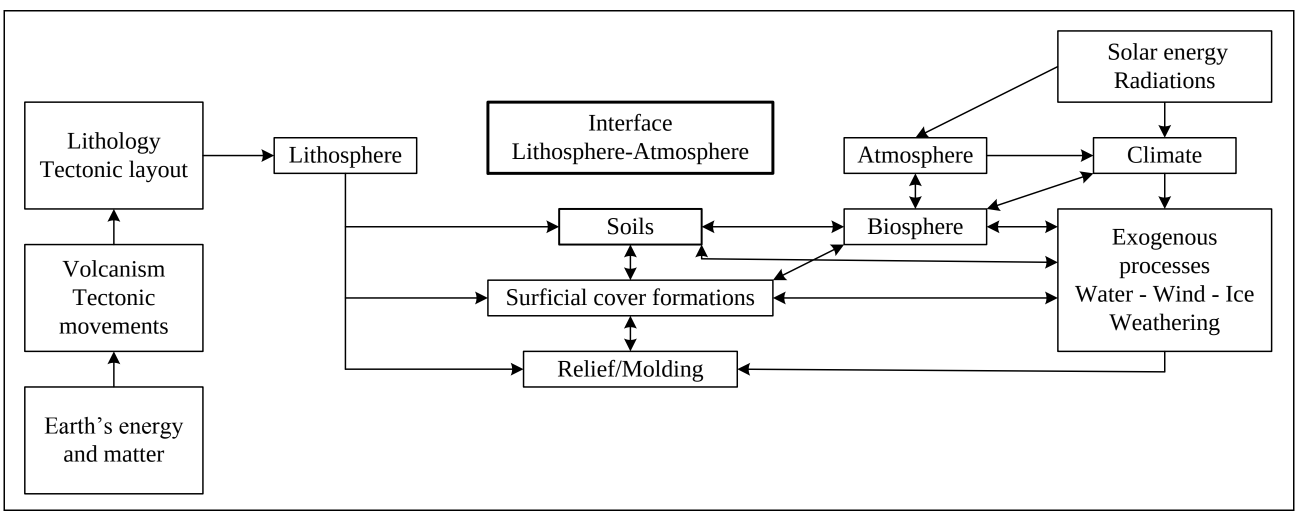


Fig. 3.1. The position of the geoform-soil duo at the interface between atmosphere and lithosphere (adapted from Tricart, 1972).

3.2.1 Common forming factors

Because they develop along a common interface in the earth's epidermis, geoform and soil share forming factors that emanate from two sources of matter and energy, one internal and another external.

- The endogenous source corresponds to the energy and matter of the terrestrial globe. The materials are the rocks that are characterized by three attributes: (1) the lithology or facies that includes texture, structure, and mineralogy; (2) the tectonic arrangement; and (3) the age or stratigraphy. The energy is supplied by the internal geodynamics, which manifests itself in the form of volcanism and tectonic deformations (i.e. folds, faults, fractures).
- The exogenous source is the solar energy that acts through the atmosphere and influences the climate, biosphere, and external geodynamics (i.e. erosion, transportation, and sedimentation of materials).

Geoform and soil are conditioned by forming factors derived from these two sources of matter and energy that act through the lithosphere, atmosphere, hydrosphere, and biosphere. The boundaries between geoform and soil are fuzzy. The geoform has two components: a terrain surface that corresponds to its external configuration (i.e. the epigeal component) and a volume that corresponds to its constituent material (i.e. the hypogeal component). The soil body is found inserted between these two components. It develops from the upper layer of the geomorphic material (i.e. weathering products - regolith, alterite, saprolite - or depositional materials) and is conditioned by the geodynamics that takes place along the surface of the geoform (e.g. aggradation, degradation, removal). A large part of the soils does not form directly from hard rock, but from transported detrital materials or from weathering products of the substratum. These more or less loose materials correspond to the surface formations that develop at the interface lithosphere-atmosphere, with or without genetic relationship with the substratum, but closely associated with the evolution of the relief of which they are the lithological expression (Campy & Macaire, 1989). The surficial cover formations constitute the parent materials of many soils. The nature and extent of these surface deposits often determine the conditions and limits of the interaction between processes of soil formation (Arnold & Schargel, 1978).

Tha fact that geoform and soil share the same forming factors generates complex cause-effect relationships and feedbacks. One of the factors, the relief that corresponds to the epigeal component of the geoforms, belongs inherently to the geomorphology domain. Another factor, the parent material, is partially geomorphic and partially geologic. Time is a two-way factor: the age of the parent material (e.g. the absolute or relative age of a sediment) or the age of the geoform as a whole (e.g. relative age of a terrace) informs on the presumable age of the soil; conversely, the dating of a humiferous horizon or an organic layer informs on the stratigraphic position of the geoform. Therefore, the relationships between these three forming factors are both intricate and reciprocal, the geoform being a factor of soil formation and the soil being a factor of morphogenesis (e.g. erosion-accumulation on a slope). Biota and climate influence both the geoform and the soil, but in a different way. In the case of the biota, the relationship is complex, since part of the biota (the hypogeal component) is within the soil and is considered part of this.

The geoform alone integrates three of the five soil forming factors of the classic model of Jenny (1941), while reflecting the influence of the other two factors. This gives geomorphology a role of guiding factor in the geoform-soil pair. Its importance as a structuring element of the landscape is reflected in the geomorphic entries to the geopedologic map legend. The latter shows each soil unit in its corresponding geomorphic landscape unit. Fig. 3.2 provides an example of this kind of integrated approach.

3.2.2. The geopedologic landscape

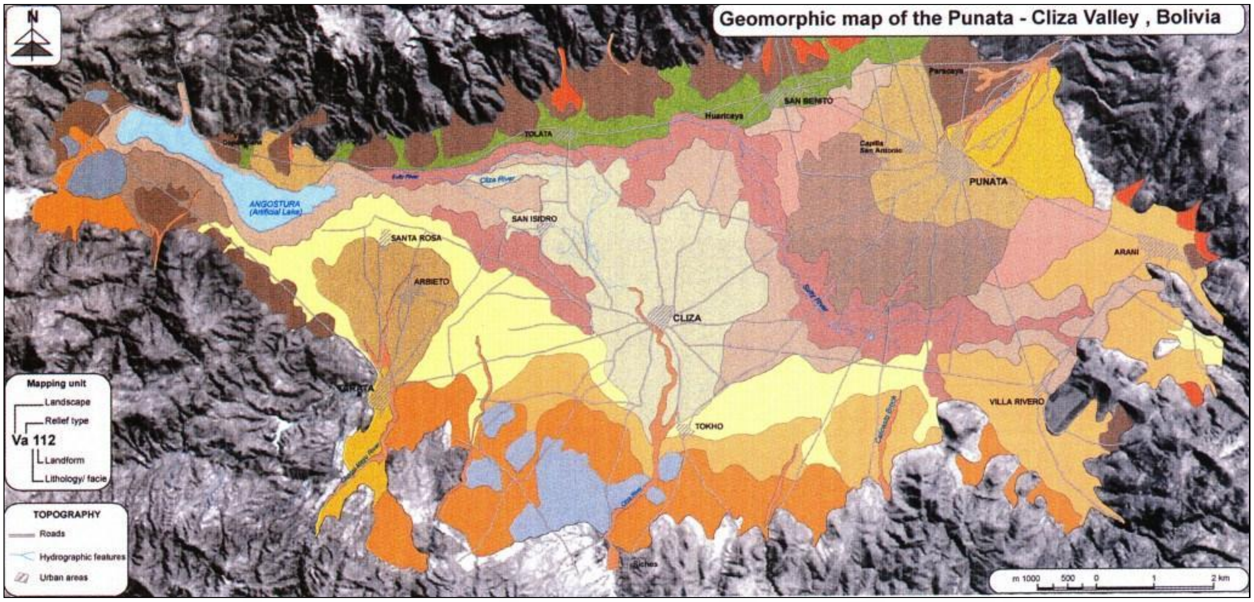
Geoform and soil fuse to form the geopedologic landscape, a concept similar to that of soilscape (Buol et al., 1997), to designate the soil on the landscape. Geoform and soil have reciprocal influences, being one or the other alternately dominant according to the circumstances, conditions, and type of landscape. In flat areas, the geopedologic landscapes are mainly constructional, while they are mainly erosional in sloping areas.

3.2.2.1 Flat areas

In flat constructional areas, the sedimentation processes and the structure of the resulting depositional systems control the distribution of the soils, their properties, the type of pedogenesis, the degree of soil development and, even, the use potential of the soils. The valley landscape offers a good example to illustrate these relationships. Fig. 3.3 represents a transect model crossing a low terrace built by a river during the late Pleistocene (Q1). In the wider sectors of the valley, the river activity produced a system that consists of a sequence of depositional units including river levee, overflow mantle, overflow basin and decantation basin, in this order across the valley from proximal positions close to the paleo-channel of the river, to the distal positions on the fringe of the valley.

The relevant characteristics of the four members of the depositional system are as follows:

- River levee (or river bank): highest position of the system, convex topography, narrow elongated configuration; textures with dominant sandy component (loamy sand, sandy loam, sometimes sandy clay loam); well drained; Typic Haplustept (or Fluventic); land capability class I.
- Overflow mantle: medium-high position, flat topography, wide configuration; textures with dominant silty component (silt loam, silty clay loam); moderately well drained; Aquic Haplustept (or Fluvaquentic); land capability class II.
- Overflow basin: low position, flat to slightly concave topography, wide oval configuration; mainly silty clay texture; imperfectly drained; Aeric Humaquept; land capability class IV.
- Decantation basin: lowest position of the system, concave topography, closed oval configuration; usually very fine clay texture; poorly drained; Typic Humaquept; land capability class V.



SOILS LEGEND

LANDSCAPE	RELIEF TYPE	FACIES	LANDFORM	CODE	SOILS
PIEDMONT	Dissected-depositional glacis	Alluvial	Proximal	Pi 111	*Association :* Typic Calciorthids Typic Camborthids
			Central	Pi 112	*Consociation :* Typic Camborthids (ca)* Ustochreptic Camborthids
			Distal	Pi 113	*Association :* Ustalfic Haplargids Ustochreptic Camborthids
	Depositional glacis	Colluvio-alluvial	Distal	Pi 213	*Consociation :* Ustochreptic Camborthids Typic Camborthids
	Active Fans	Alluvial	Active Channels	Pi 411	*Miscellaneous Land type :* Mixed Alluvial
			Inactive Channels	Pi 412	*Consociation :* Typic Torrifluvents Typic Torriorthents
	Recent Fans	Colluvio-alluvial		Pi 51	*Association :* Ustic Torriorthents Typic Torrifluvents
	Old Dissected Fans	Glacio-alluvial	Proximal	Pi 611	*Association :* Typic Camborthids Typic Haplargids
			Central	Pi 612	*Consociation :* Ustochreptic Camborthids (ca)*
			Distal	Pi 613	*Consociation :* Ustochreptic Camborthids
	Hills	Quartzitic sandstones		Pi 71	*Consociation :* Lithic Torriorthents
		Marls, sandstones, limestones		Pi 72	*Consociation :* Typic Calciorthids Lithic Calciorthids
VALLEY	Lagunary depressions	Alluvio-lagunary	Higher lagunary flats	Va 111	*Association :* Fluventic Camborthids Ustochreptic Camborthids
			Middle Lagunary flats	Va 112	*Association :* Ustalfic Haplargids Ustochreptic Camborthids
			Lower Lagunary flats	Va 113	*Association :* Ustalfic Haplargids (saso)* Ustochreptic Camborthids (sa)*
		Lagunary	Playas	Va 124	*Association :* Typic Salorthids Natric Camborthids

* Phases : (ca) calcareous, (saso) saline-alkaline, (sa) saline

Fig. 3.2 Geomorphic map and geopedologic legend of the Punata-Cliza valley, Bolivia (Metternicht & Zinck, 1997).

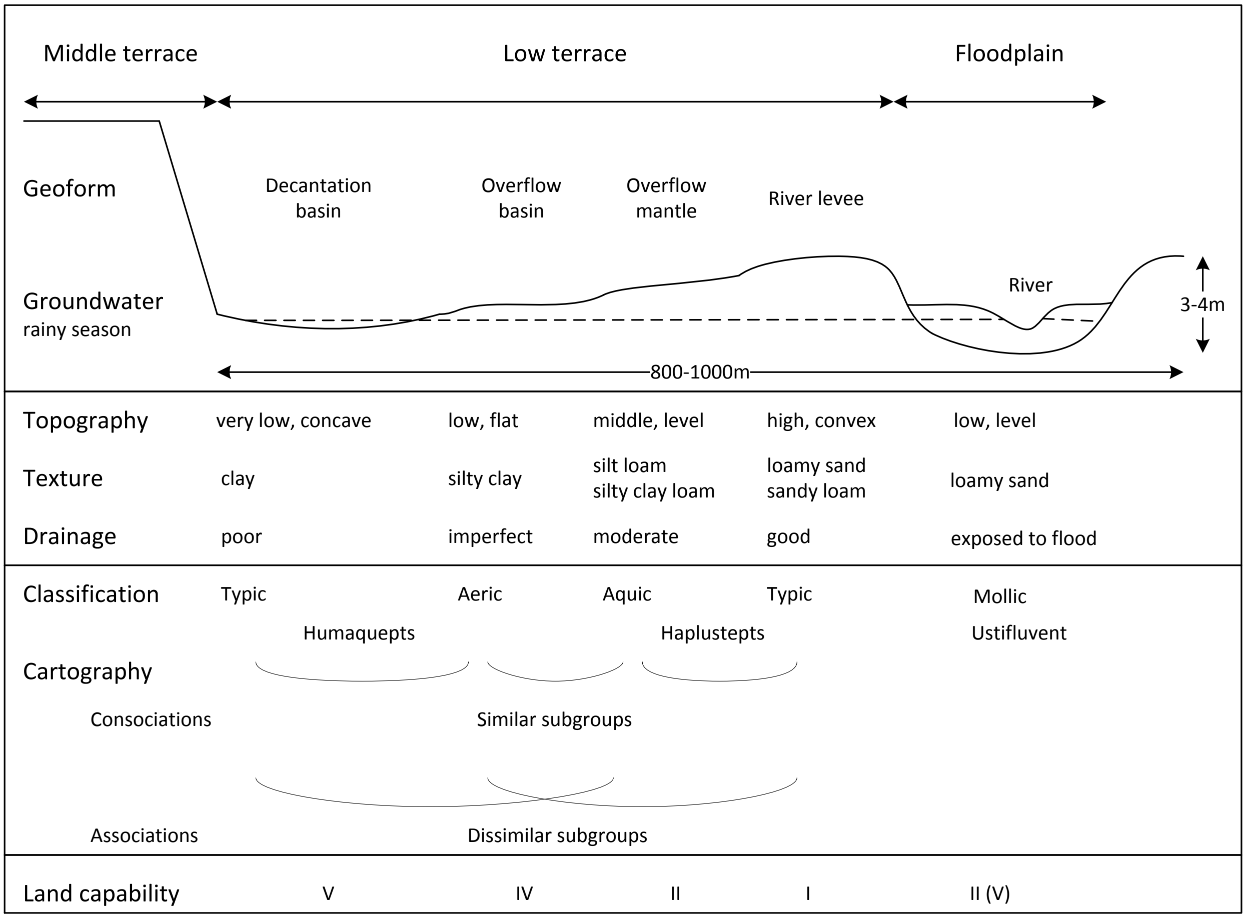


Fig. 3.3 Geopedologic landscape model of a fluvial terrace. Example of the Guarapiche river valley, northeast of Venezuela; pedotaxa refer to the dominant soil type in each geoform.

The soil classes referred to in this example correspond to the dominant soils in each geomorphic unit. Major soils are generally accompanied by subordinate soils that may have common taxonomic limits with the dominant soils in the classification system (i.e. similar soils) and some inclusions that are usually not contrasting. The geoform, with its morphographic, morphometric, morphogenic and morphochronologic features, controls a number of properties of the corresponding soil unit (e.g. topography, texture, drainage) and relates to its taxonomic classification and land use capability. The geoform also guides the composition of the cartographic unit, with the possibility of mapping soil consociations on the basis of similar subgroups (e.g. Aquic Haplustept and Aeric Humaquept) or soil associations on the basis of dissimilar subgroups (e.g. Typic Haplustept and Aeric Humaquept), according to how soils are distributed on the landscape. The geomorphic framework, which controls the determination and delineation of the soil map units, makes that these units are relatively homogeneous, allowing for a relatively reliable soil interpretation for land use purposes.

The soil sequence in a given geopedologic landscape can vary, for instance, according to the prevailing bioclimatic conditions (e.g. Mollisols sequence in a moister climate) or according to the age of the terrace (e.g. Alfisols sequence on a Q2 terrace and Ultisols sequence on a Q3 terrace). Post-depositional perturbations in flat areas, through fluvial dissection of older terraces or differential eolian sedimentation-deflation, for instance, may cause divergent pedogenesis and increase variations in the soil cover that are often not readily detectable. The resulting geopedologic landscapes are much more complex than the initial constructed ones (Ibáñez, 1994; Amiotti et al., 2001; Phillips, 2001; among others). McKenzie et al. (2000) mention the case of strongly weathered sesquioxidic soils in Australia that were formed under humid and warm climates during the Late Cretaceous and Tertiary and are now persisting under semiarid conditions, showing the imprints from successive environmental changes.

3.2.2.2 Sloping areas

In sloping areas and other ablational environments, the relationships between geoform and soil are more complex than in constructed landscapes. The classic soil toposequence is an example of geopedologic landscape in sloping areas. The lateral translocation of soluble substances, colloidal particles and coarse debris on the terrain surface and in the soil mantle results in the formation of a soil catena whose differentiation along the slope is mainly due to topography and drainage. Typically, the summit and shoulder of a hillslope lose material, which transits along the backslope and accumulates on the footslope. This relatively simple evolution results generally in the formation of a convex-concave slope profile with shallow soils at the top and deep soils at the base. When the translocation process accelerates, for instance after removal of the vegetation cover, soil truncation occurs in the upper sections of the slope, while soil fossilization takes place in the lower section because pedogenesis is no longer able to digest all the incoming material via continuous soil aggradation/cumulization. Such an evolution reflects relatively clear relationships between the geomorphic context and the soil cover, which can be approximated using the slope facet models. The segmentation of the landscape into units that are topographically related, such as the facet chain along a hillside, provides a sound basis for conducting research on spatial transfers of soil components (Pennock & Corre, 2001). However, this idealized soil toposequence model might not be that frequent in nature.

On many hillsides, soil development, properties and distribution are less predictable than in the case of the classic toposequence. Sheet erosion, controlled by the physical, chemical and biological properties of the topsoil horizons, along with other factors, causes soil truncation of variable depths and at variable locations. Likewise, the nature of the soil material and the sequence of horizons condition the morphogenic processes that operate at the terrain surface and underneath. For instance, the difference in porosity and mechanical resistance between surficial horizons, subsurficial layers and substratum controls the formation of rills, gullies and mass movements on sloping surfaces, as well as the hypodermic development of pipes and tunnels. The geopedologic landscapes resulting from this active geodynamics can be very complex. Their spatial segmentation requires using geoform phases based on terrain parameters (e.g. slope gradient, curvature, drainage, micro-relief, local erosion features, salinity spots, etc.).

Paleogeographic conditions may have played an important role in hillslope evolution and can explain a large part of the present slope cover formations. Slopes are complex registers of the Quaternary climate changes and their effect on vegetation, geomorphic processes, and soil formation. The resulting geopedologic landscapes are polygenic and have often an intricate, sometimes chaotic structure. The superimposition or overlapping of consecutive events causing additions, translocations and obliterations, with large spatial and temporal variations, makes it often difficult to decipher the paleogeographic terrain history and its effect on the geopedologic relationships.

The following example shows that an apparently normal convex-concave slope can conceal unpredictable variations in the covering soil mantle. The case study is a soil toposequence along a mountain slope between 1100 masl and 1500 masl in the northern Coastal Cordillera of Venezuela (Zinck, 1986). Soils have developed from schist under dense tropical cloud forest, with 1850 mm average annual rainfall and 19^{o}C average annual temperature. Slope gradient is 2-5^{o} at slope summit, 40-45^{o} at the shoulder, 30-40^{o} along the backslope, and 10-25^{o} at the footslope. By the time of the study, no significant erosion was observed. However, several features indicate that the current soil mantle is the result of a complex geopedologic evolution, with alternating morphogenic and pedogenic phases, during the Holocene period.

- Except at the slope summit, soils have formed from detrital materials displaced along the slope, and not directly from the weathering in situ of the geologic substratum.
- There is no explicit correlation between slope gradient and soil properties. For instance, shoulder soils are deeper than backslope soils, although at higher slope inclination.
- Many soil properties such as pedon thickness and contents of organic carbon, magnesium and clay show discontinuous longitudinal distribution along the slope (Figs. 3.4 and 3.5). The most relevant interruption occurs in the central stretch of the slope, around 1300 m elevation.
- Soils in the upper part of the slope have two Bt horizons (a sort of bisequum) that reflect the occurrence of two moist periods favoring clay illuviation, separated by a dry phase.

Pollen analysis of sediments from a lowland lake reveals that, by the end of the Pleistocene, the regional climate was semi-arid, vegetation semi-desertic, and soils probably shallow and discontinuous (Salgado-Labouriau, 1980). From the beginning of the Holocene when the cloud forest covered the upper ranges of the Cordillera, deep Ultisols developed. During the Holocene, dry episodes have occurred causing the boundary of the cloud forest to shift upwards and leaving the lower part of the slope, below approximatety 1350-1300 masl, exposed to erosion. The presence, in the nearby piedmont, of thick torrential deposits dated 3500 BP and 1500 BP indicates that mass movements have episodically occurred upslope during the upper Holocene. This would explain why soil features and properties show a clear discontinuity at mid-slope, around 1300 masl.

The alternance of morphogenic and pedogenic activity along mountain and hill slopes causes geopedologic relationships to be complex in sloping areas, in general more complex than in flat areas. The older the landscape, the more intricate are the relationships between soil and geoform because of the imprints left by successive environmental conditions.

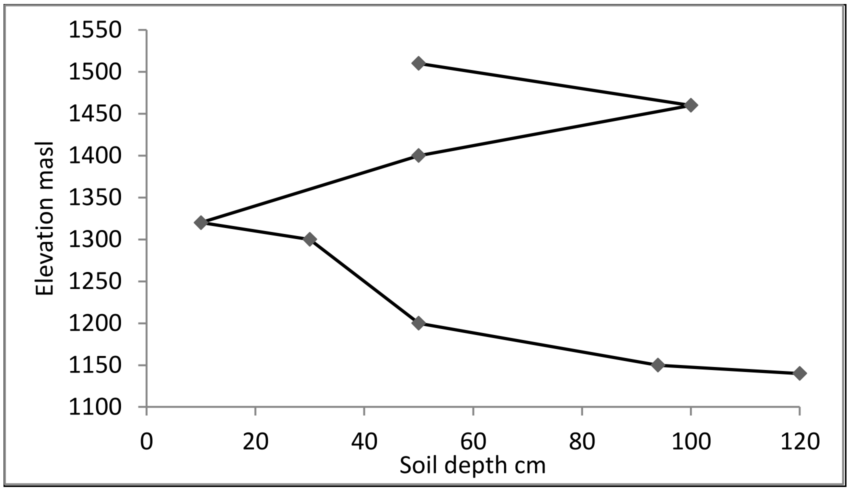


Fig. 3.4 Variation of soil depth with elevation along a mountain slope in the northern Coastal Cordillera of Venezuela (Zinck, 1986).

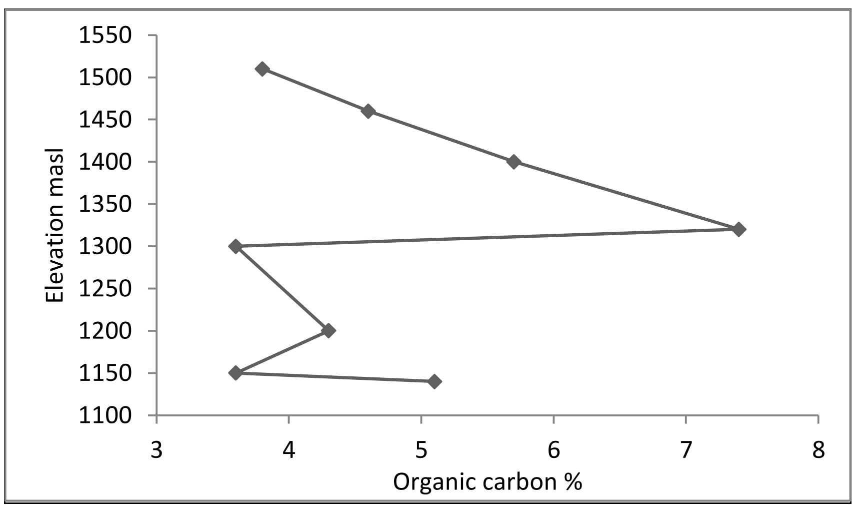


Fig. 3.5 Variation of organic carbon content (0-10 cm) with elevation along a mountain slope in the northern Coastal Cordillera of Venezuela (Zinck, 1986).

3.3 Methodological relationships

The methodological relationships refer to the modalities used to analyze the spatial distribution and formation of the geofom-soil complex. Geomorphology contributes to improving the knowledge of soil geography, genesis, and stratigraphy. In return, soil information feeds back to the domain of geomorphology by improving the knowledge on morphogenic processes (e.g. slope dynamics). The above needs the integration of geomorphic and pedologic data in a shared structural model to identify and map geopedologic units.

3.3.1 Geopedologic integration: a structural model

Fig. 3.6 shows the data structure of the geoform-soil complex in the view of the geopedologic approach (Zinck & Valenzuela, 1990). Soil survey data are typically derived from three sources: (1) visual interpretation and digital processing of remote-sensed documents, including aerial photographs, radar and spectral images, and terrain elevation models; (2) field observations and instrumental measurements, including biophysical, social and economic features; and (3) analytical determinations of mechanical, physical, chemical and mineralogical properties in the laboratory. The relative importance of these three data sources varies according to the scale and purpose of the soil survey. In general terms, the larger is the scale of the final soil map, the more field observations and laboratory determinations are required to ensure an appropriate level of information.

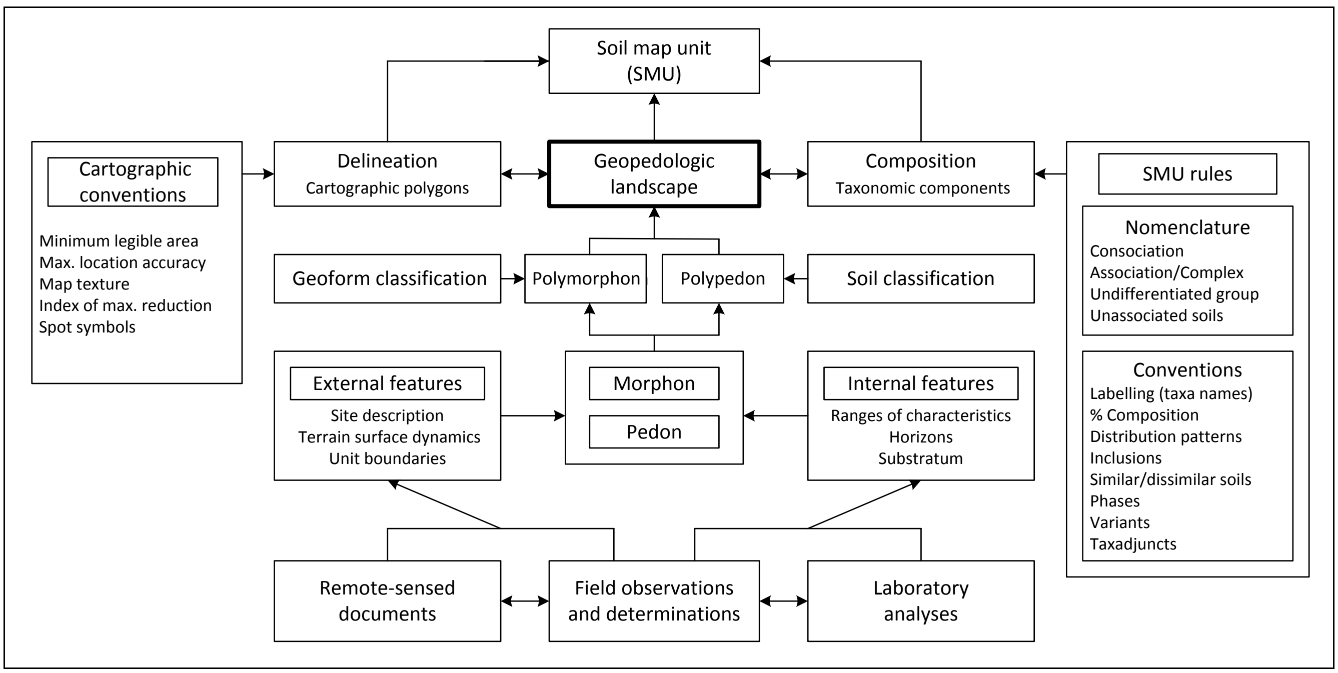


Fig. 3.6 Conceptual-structural model of the geopedologic approach (Zinck & Valenzuela, 1990).

As soils and geoforms are three-dimensional bodies, external and internal (relative to the terrain surface) features are to be described and measured to establish and delimit soil map units. The combination of data and information provided by sources (1) and (2) serves to describe the environmental conditions and areal dynamics (e.g. erosion, flooding, aggradation of sediments, changes in land uses, etc.) and to delineate the map units. At this level, the implementation of geomorphic criteria through interpretation of remote-sensed documents and field prospection plays a relevant role for the identification and characterization of the soil distribution patterns and the understanding of their spatial variability. The interpretation of remote-sensed documents (photo, image, DEM) can benefit from applying a stepwise procedure of features identification using the geoform hierarchy to highlight the nested structure of the landscape. The sequence of steps includes photo/image reading, identification of master lines, sketching the structure of the landscape to select representative cross sections, pattern recognition along the cross sections, delimitation of the geomorphic units via interpolation and extrapolation, and establishing a preliminary geomorphic interpretation legend for field verification.

The combination of data and information provided by sources (2) and (3) allows to characterize and quantify the properties of the pedologic materials, geomorphic cover formations, and geologic substrata. The horizon (or layer) is the basic unit of data collection. Horizon and substratum information is aggregated in observation profiles, modal pedons, and modal morphons. Pedon and polypedon are described and established according to the criteria of Soil Taxonomy (Soil Survey Staff, 1999). The morphon is the geomorphic equivalent of the pedon. It is described at the same site and according to the same size standards as the pedon. The description of the morphon includes internal and external features. The internal features correspond to the characteristics and properties of the geomaterial in the substratum, thus the parent material of the soil. The external features cover the conditions and dynamics of the terrain area at the site of description and its surroundings. The pedologic material (i.e. the solum) occupies the volume between the substratum and the terrain surface. As in the case of the pedon, the morphon is the description and sampling site. Therefore, pedon and morphon are two fundamentally related entities. This is nothing new, since the description of the pedon has always included that of the parent material and surface features. However, the contribution of the geomorphic analysis methods improves the characterization of the geomaterials in the substratum and that of the surface geodynamics. The methodological integration can be achieved by experts skilled in both geomorphology and pedology or by interdisciplinary teams.

The concepts of polypedon and polymorphon are significantly different from each other. The polymorphon corresponds to a geoform and is therefore a more comprehensive unit than the polypedon. A polymorphon can include more than one polypedon, and this is actually often the case, especially at the upper levels of the geoform classification system. The foregoing is reflected in the taxonomic composition of the map units: a relatively homogeneous geoform may correspond to a consociation of similar soils, while a less homogeneous geoform may correspond to an association of dissimilar soils. The identification and description of the polymorphon follow the criteria set out in Chapters 5, 6 and 7, which deal with the taxonomy and attributes of the geoforms. Variations among identification profiles by comparison with a modal profile (pedon or morphon) are expressed in terms of ranges of characteristics for each taxon present in a map unit.

At this stage, the available data consist of: (1) geopedologic point observations, with additional information on the spatial variations of the characteristics, and (2) a framework of spatial units based essentially on external geomorphic criteria (i.e. characteristics of the terrain surface). The combination of the two results in a map of geopedologic units.

For mapping purposes, both objects - soil and geoform – are given identification names (i.e. taxonomic names) that are supplied by their respective classification systems. Assemblies of contiguous similar soils, forming polypedons, are classified by comparison with taxonomic entities established in soil classification systems, such as Soil Taxonomy (Soil Survey Staff, 1999), the WRB classification (IUSS, 2007), or any national classification. A similar procedure is used for the classification of the geomorphic units, moving from the description and sampling unit (morphon) to the classification entity (polymorphon). A basic geomorphic unit (polymorphon) can contain one or more polypedons. For instance, Entisols (e.g. Mollic Ustifluvents) and Mollisols (e.g. Fluventic Haplustolls) can occur intermixed in a recent river levee position. The combination in the landscape of a polymorphon with the associated polypedons constitutes a geopedologic landscape unit.

Due to the inherent spatial anisotropy of the pedologic material, which is generally more pronounced than the anisotropy of the geomorphic material, soil delineations are usually heterogeneous. This requires that the taxonomic components of a map unit be named and their respective proportions quantified using conventional rules of soil cartography (Soil Survey Staff, 1993). The delimitation of polygons follows a number of cartographic conventions that assure a good readability of the soil map. In this way, the geopedologic landscape units, cartographically and taxonomically controlled, as unique combinations of geomorphic polygons and their pedologic contents, result being the soil map units.

This theoretical-methodological model of the geoform-soil complex can be implemented to design the structure of an integrated geopedologic database, such as shown in Zinck & Valenzuela (1990).

3.3.2 Geopedologic integration: soil geography, genesis, and stratigraphy

Within the framework of the previously described geopedologic model, themes such as soil geography, genesis and stratigraphy can benefit substantially from the integration of pedologic and geomorphic methods.

3.3.2.1 Soil geography

Soil survey generates information on the spatial distribution of soils. The implementation of geomorphic criteria in soil survey allows to improve the identification and delimitation of the soils. At the same time, the rationality of the geopedologic approach contributes to compensate or partially replace what Hudson (1992) called the acquisition of tacit knowledge for the application of the soil-landscape paradigm. The integrated geopedologic analysis facilitates the reading of the landscape, because the geomorphic context controls, in a large proportion, the soil types that are found associated in a given kind of landscape such as, for instance, the sequence levee-mantle-basin in an alluvial plain or the sequence summit-shoulder-backslope-footslope along a hillside. These models of geopedologic associations that are genetically related and produce defined spatial patterns, are the components (i.e soil combinations) of what Fridland (1974) calls *the structure of the soil cover* and Schlichting (1970) formulates as *Bodensoziologie*, or pedosociology.

- *Soil identification* is based on the description of the soils in the field, which leads to their characterization and classification. Geomorphology contributes to this activity through the selection of the description sites. The use of geomorphic criteria facilitates the choice of representative sites, regardless of the implemented sampling scheme. In oriented sampling, the observation sites are pre-selected based on geomorphic criteria within units delimited by interpretation of aerial photos or satellite images. Random sampling only makes sense if it is applied within the framework of units previously established with geomorphic criteria. A random sampling scheme is more objective and appropriate for statistical data analysis, but frequently generates a number of little representative profiles and, for this reason, is more expensive.

Grid-based systematic sampling is difficult to apply as an operational technique to an entire soil survey project because it would be too expensive. It is useful when applied locally to estimate the spatial variability of the soils within and between a selection of map units and to establish their degree of purity. Comparing two thematic soil maps, one derived from a conventional soil map and another one obtained by kriging of grid point data, Bregt et al. (1987) show that the average purity of the map units, determined on the basis of three criteria including thickness of the A horizon, depth to gravel, and depth to boulder clay, is 77% in both cases, with less dispersion in the first case (72-82%) than in the second (69-85%). The interpretation of geostatistical data is probably more meaningful when geomorphic criteria are used.

- *Soil delimitation* is based on the interpretation of aerial photos and satellite images, the use of digital elevation models, and fieldwork. The features detected by remote sensing are essentially ground surface features, which are often of geomorphic nature. Therefore, what is observed or interpreted in remote-sensed documents are characteristics of the epigeal part of the geoforms and soils. The hypogeal part is still largely inaccessible and some of its features can be detected at a distance only with special techniques (e.g. GPR). This is efficient when a three-dimensional representation of the geomorphic landscape is available, which can be obtained by stereoscopic interpretation of aerial photos or satellite images or based on a combination of images and elevation or terrain models.

  In this context, geomorphology contributes to the following tasks related to soil delimitation: (1) the selection of sample areas, transects, and traverses; (2) the drawing of the soil map unit boundaries based on the conceptual relations between geoforms and soils (common forming factors; geopedologic landscape); and (3) the identification, temporal monitoring, and explanation of the spatial variability of the soils.

- *Soil variability* is partly controlled by the geomorphic context, essentially referring to the systematic variations (Wilding & Drees, 1983). Geomorphology provides criteria for segmenting the soilscape continuum into discrete units that are relatively homogeneous. Such units are suitable frameworks for estimating the spatial variability of soil properties using geostatistical analysis (Saldaña et al., 1998; Kerry & Oliver, 2011). They have been used also as reference units to apply spatial analysis metrics, including indices of heterogeneity, diversity, proximity, size and configuration, for the purpose to quantitatively describe soil distribution patterns at various categorial levels of geoform (i.e. landscape, relief, terrain form) (Saldaña et al., 2011; Toomanian, 2013).

  The mapping scale and observation density influence the relationship between geoform and soil, as the spatial variability of the geomorphic and pedologic properties are not the same magnitude. In general, at large scales the latter vary more than the former, especially at short distances. Therefore, the geopedologic approach may perform better at smaller than at larger scales. Rossiter (2000) considers that the approach is adequate for semi-detailed studies (scales 1:35,000 to 1:100,000). Esfandiarpoor Borujeni et al. (2009) analyzed the effect of three observation point intervals (125m, 250m, and 500m) on the results of applying the geopedologic approach to soil mapping and concluded that this approach works satisfactorily in reconnaissance or exploratory surveys. To increase the accuracy of the geopedologic results at large scales, they suggest to add a category of landform phase. The geoform classification system already includes the concept of phase for any practical subdivision of a landform or of any geoform class at other categorial levels (Zinck, 1988). Using statistical and geostatistical methods, Esfandiarpoor Borujeni et al. (2010) show that the means of the soil variables in similar landforms within their study area were comparable but not their variances. They conclude that the geopedologic soil mapping approach is not completely satisfactory for detailed mapping scales (1:10,000 to 1: 25,000) and suggest, as above, the use of landform phases to increase the accuracy of the geopedologic results.

Similarly, the geoform-soil integration facilitates the extrapolation of information obtained in sample-areas to unvisited areas or areas of difficult access, using artificial neural networks and decision trees, among other techniques (Moonjun et al., 2010; Farshad et al., 2013). Using a set of terrain parameters extracted from a digital elevation model, Hengl & Rossiter (2003) show that supervised landform classification allowed to extrapolate geopedologic information obtained from photo-interpretation of selected sample-areas over a large hill and plain region with about 90% reproducibility.

The geomorphic context is far from embracing the full span of soil variability. However, its contribution to soil cartography decreases in general the amplitude of variation of the soil properties within map units enough to make practical interpretations and decisions for land use planning. Systematic soil surveys using the geopedologic approach in large areas have performed satisfactorily when used for general land evaluation. Specific applications such as precision farming or site engineering need to be supported by very detailed soil information.

3.3.2.2 Soil genesis and stratigraphy

The geomorphic processes and environments are used, respectively, as factors and spatial frameworks to explain soil formation and evolution. The geomorphic context, through parent material (weathering products or depositional materials), relief (slope, relative elevation, exposure), drainage conditions and morphogenesis, controls a large part of the soil forming factors and processes. In return, the soil properties influence the geomorphic processes. There is co-evolution between the pedologic and geomorphic domains. At the same time, the geomorphic history controls soil stratigraphy, while soil dating (i.e. chronosequences) helps reconstruct the evolution of the geomorphic landscape. The use of geomorphic research methods and techniques contributes to elucidate issues in soil genesis and stratigraphy.

Fig. 3.7 shows a model of geopedologic relationships in a chronosequence of nested alluvial terraces, in the Guarapiche river valley, Venezuela (Zinck, 1970). The geoform, here at the level of terrain form (see Table 3.1), controls soil formation in two directions. On the one hand, the relative age of the geomorphic material, i.e. the parent material of the soils, from Holocene (Q0) to lower Pleistocene (Q4), directly influences the *degree* of pedogenic development from the level of Entisol to that of Ultisol. On the other hand, the nature of the geomorphic position closely influences the *type* of pedogenic development, distinguishing between well drained soils with ustic regime in levee position and poorly drained soils with aquic regime in basin position.

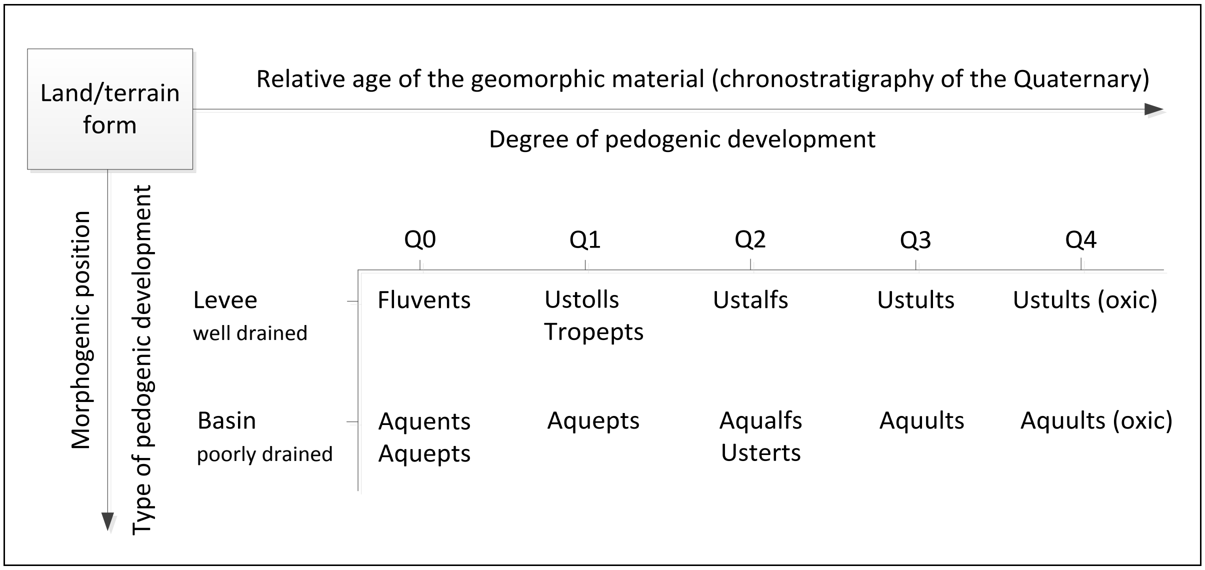


Fig. 3.7 Model of geopedologic relationships in alluvial soils, Guarapiche river valley, Venezuela (Zinck, 1970).

3.3.3 Geopedologic integration: a test of numerical validation

3.3.3.1 Materials and method

Within the soil survey framework, the contribution of geomorphology to soil knowledge and, in particular, to the spatial distribution of soils can be considered efficient if, among other things, it facilitates and improves the grouping of the soils into relatively homogeneous cartographic units. To substantiate the geopedologic integration and validate quantitatively the relationships between geoform and soil, the technique of numerical classification was implemented, as the latter allows to compare the performance of object classification systems in relation to a reference system (Sokal & Sneath, 1963).

A numerical classification test of the geopedologic units supplied by a semi-detailed soil survey (1:25,000) of the Guarapiche river valley, northeast of Venezuela (Zinck & Urriola, 1971), was run to estimate the efficiency of both the soil classification and the geoform classification in building consistent groups by comparison with the phenetic groups of the numerical classification (Zinck, 1972). The geopedologic units belong to a chronosequence of nested terraces, spanning the Quaternary from the lower Pleistocene (Q4) to the Holocene (Q0). Soils have formed mostly from longitudinal alluvial deposits, coming from the upper catchment area of the river, and secondarily from local colluvial deposits (Fig. 3.8).

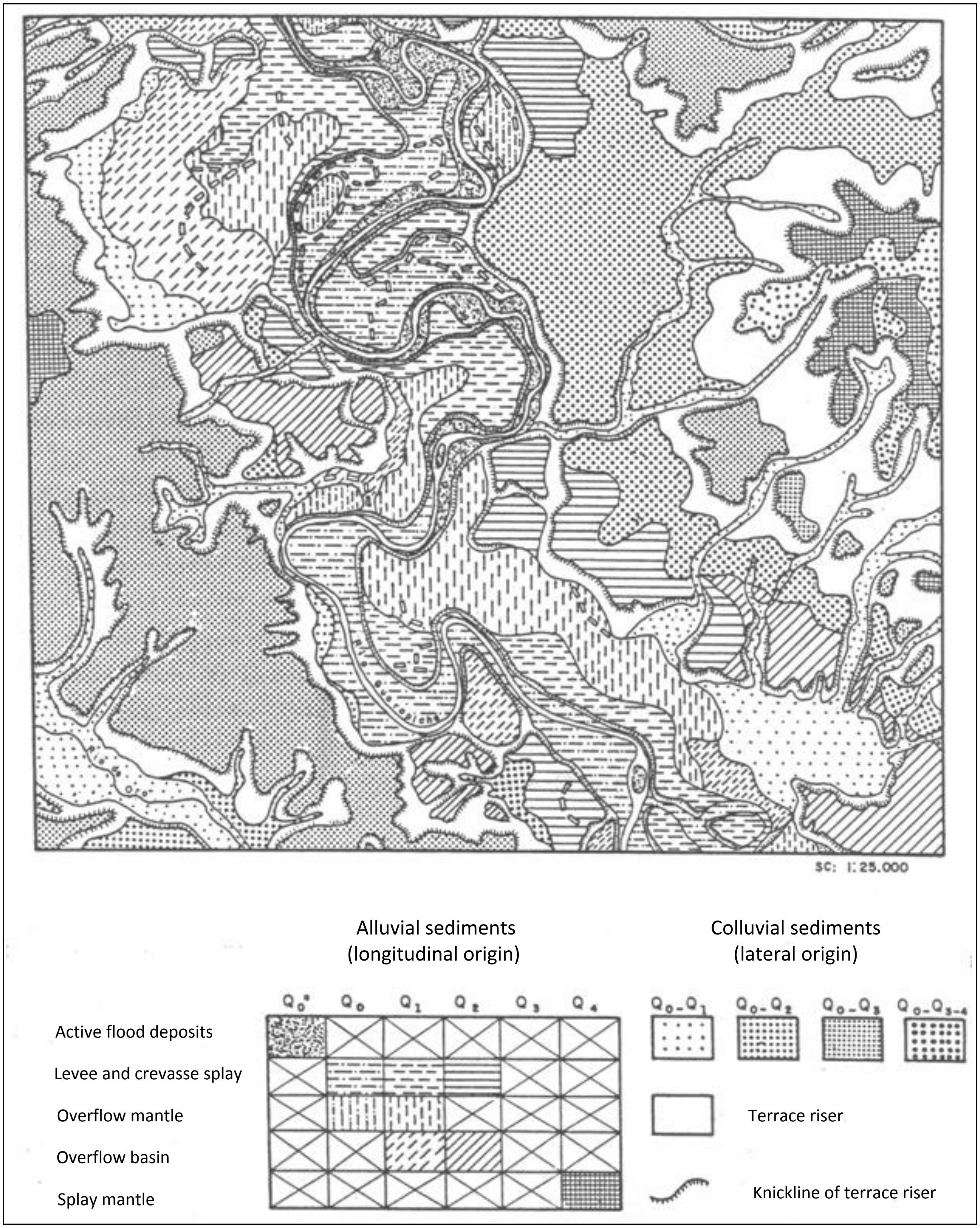


Fig. 3.8. Portion of the Guarapiche river valley, Venezuela, showing a chronosequence of nested terraces covering the whole Quaternary period (from Q0 to Q4). The boundaries of the cartographic units are essentially of geomorphic nature, while their contents are of pedologic nature (consociations and associations of soil series, not shown here). Extract of the original soil map at 1:25,000 scale (Zinck & Urriola, 1971).

Twenty-six pairs of modal pedons-morphons, representative of the soil series mapped in the survey area, were chosen, and 24 mechanical, physical and chemical properties were selected to characterize the pedologic material (solum) and the geomorphic material (parent material). Soil units classified at subgroup level (Soil Survey Staff, 1960, 1967) and geomorphic units classified by depositional facies and relative age were compared. Data handling implemented techniques and methods available in the 1960s when the essay was performed: (1) the method of Hole & Hironaka (1960) for estimating the index of similarity between pairs of units and elaborating the similarity matrix, and (2) the method using unweighted pair-groups with arithmetic mean as described in Sokal & Sneath (1963) to cluster the units, construct the dendrogram represented in Fig. 3.9, and calculate the average similarities.

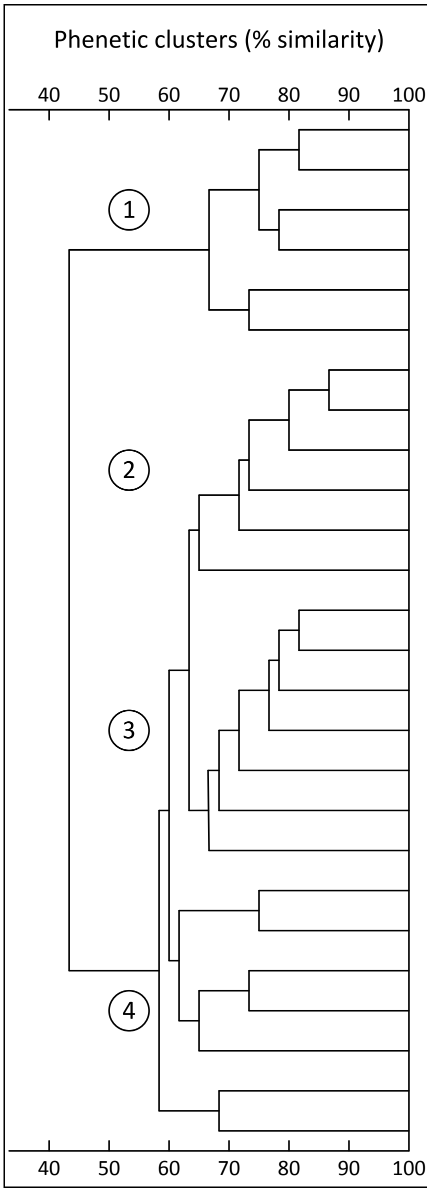
3.3.3.2 Results

The numerical classification generated four phenetic groups with a variable number of geopedologic units (i.e. soil-geoform combinations). The soils are reported as subgroup classes. Geoforms are identified by their sedimentary position at the terrain form level, their relative age, and the texture of the depositional material (i.e. the parent material of the soils).

- Group 1: six geopedologic units that share the following characteristics: low topographic positions of overflow basin (three) or decantation basin (three), poorly drained (five units with aquic regime), and fine-textured (silty clay or clay), regardless of the chronostratigraphy of the parental materials (relative age varying from Q1 to Q3) and the degree of soil development (one Vertisol, two Inceptisols, one Alfisol, two Ultisols).
- Group 2: six geopedologic units that share the following characteristics: medium to high topographic positions of levee (two), overflow mantle (two), and overflow basin (two), well drained, textures mostly loamy and silty, soils of incipient to moderate development (one Entisol, two Inceptisols, three Mollisols), all formed from recent to relatively recent materials (Q0 and Q1).
- Group 3: seven geopedologic units that share the following characteristics: medium to high topographic positions of splay axis, splay mantle and crevasse splay, moderately well to well drained, textures sandy loam and sandy clay loam, soils of advanced development (one Alfisol, six Ultisols), all formed from old materials (Q3 and Q4).
- Group 4: seven geopedologic units with predominantly sandy textures (loamy sand and sandy loam) that restrict soil development to an incipient stage (five Entisols including three Psamments, two Inceptisols); the soils occur in a variety of depositional sites (deltaic levee, splay mantle, colluvial glacis) and chronostratigraphic units (from Q0 to Q4; the colluvial deposits being of continuous, diachronic formation).

In all cases, the factor that most closely controls the grouping of the geopedologic units is of geomorphic nature:

- Group 1: basin depositional facies and low position in the landscape.
- Group 2: relatively recent age of the parental materials (late Pleistocene to Holocene).
- Group 3: advanced age of the parental materials (lower to early middle Pleistocene).
- Group 4: coarse textures of the parent materials.



Soil subgroups	Land/terrain forms	Relative age	Parent material
Typic Plinthaquult	Overflow basin	Q3	sic
Plinthic Umbric Paleaquult	Decantation basin	Q3	vfc
Aeric Tropaquept	Decantation basin	Q1	vfc
Aeric Tropaqualf	Overflow basin	Q2	sic
Vertic Tropaquept	Decantation basin	Q1	sic-c
Salic Entic Chromustert	Overflow basin	Q2	sic
Cumulic Haplustoll	Overflow mantle	Q1	sil-sicl
Cumulic Haplustoll	Overflow basin	Q1	sic
Cumulic Haplustoll	River levee	Q1	sl-scl
Typic Ustifluvent	River levee	Q0	sl
Fluventic Ustropept	Overflow mantle	Q0	sil-sicl
Fluvaquentic Ustropept	Overflow basin	Q1	sic
Epiaquic Plinthustult	Splay axis	Q3	sl-scl
Typic Plinthustult	Splay mantle	Q3	l-scl
Plinthic Paleustult	Splay axis	Q3	sl-scl
Oxic Plinthustult	Crevasse splay	Q4	sl-scl
Typic Plinthaquult	Splay mantle	Q3	sl-scl
Oxic Paleustult	Splay mantle	Q4	sl-scl
Udic Haplustalf	Splay mantle	Q2	sl-scl
Typic Ustorthent	Colluvial glacis	Q0-Q3	ls-sl
Typic Ustorthent	Colluvial glacis	Q0-Q3-4	ls
Ustifluventic Dystropept	Splay mantle	Q1	sl-l
Aquic Dystropept	Splay mantle	Q1	sl-l
Alfic Ustipsamment	Colluvial glacis	Q0-Q2	ls
Typic Ustipsamment	Deltaic levee	Q1	ls
Aquic Ustipsamment	Deltaic levee	Q1	s-ls

Fig. 3.9 Dendrogram showing four groups of geopedologic units; Guarapiche river valley, Venezuela (Zinck, 1972).
Soil classification according to Soil Survey Staff (1960, 1967).
Relative age of the geomorphic material (i.e. soil parent material) by increasing order from Q0 (Holocene) to Q4 (lower Pleistocene).
Texture of the parent material: s = sand; l = loam; si = silt; c = clay; vf = very fine.

3.3.3.3 Conclusion

Mean similarities at the level of great soil groups (73%) and that of terrain forms (75%) are comparable to the average similarity of the numerical groups (75%), indicating that the three classification modes are relatively efficient in generating consistent groupings. Groups 2 and 3 are more homogeneous than groups 1 and 4. The factors that most contribute to differentiate the four groups and generate differences within the heterogeneous groups are attributes of the geoforms, in particular their depositional origin (with their particle size distribution), their position in the landscape, and their relative age. These factors basically correspond to three of the five soil forming factors: i.e. parent material, topography-drainage, and time, which together highlight the contribution of geomorphology to pedology and constitute the foundation of geopedology.

3.4 Operational relationships

3.4.1 Introduction

The conceptual and methodological relationships between geoform and soil can be implemented basically in two ways: (1) through studies at representative sites, usually of limited extent, to analyse in detail the genetic relationships between geoforms and soils (scientific studies, mostly in the academic domain), and (2) through the inventory of the soils as a resource to establish the soil cartography of a territory (project area, region, entire country) and assess their use potential and limitations (practical studies, in the technical domain).

In what follows, the operational relationships are examined in the framework of the soil inventory, from the generation of the geopedologic information through field survey to its interpretation through land evaluation for multi-purpose uses. In this process, geomorphology can play a relevant role. The operational importance of geomorphology refers to the amount of information added to the information of the soil survey and the estimation of this quantity, when geomorphology is incorporated to the successive stages of the survey operation.

Soil survey is an information system, which can be represented by a model that describes its structure and functioning using systems analysis, and which allows to estimate the efficiency of the contribution of geomorphology to the soil survey. The opportunity to conduct a trial of this nature was given by a semi-detailed soil survey project to be carried out in the basin of Lake Valencia, Venezuela (Zinck, 1977). This is a region of approximately 1000 km^2 of flat land, traditionally used with intensive irrigated agriculture, but increasingly exposed to land-use conflicts as a result of fast, uncontrolled urban-industrial sprawling. The size of the study area, the level of detail of the survey, the diversity of objectives to meet, and the number of personnel involved, were decisive factors in the design of the study. A reference framework was needed to plan the survey activities, establish the timetable for implementation, and select the variety of soil interpretations required to supply the necessary information for land-use planning and contribute to mitigate the land-use conflicts.

3.4.2 The structure of the soil survey

Proceeding by iteration, a model structure with five categorial levels was obtained, as represented in Fig. 3.10. The three lower levels comprise the domain proper of the soil survey - its internal area - where the information is produced. The two upper levels represent the sphere of influence of the soil survey - its external area - where the information generated is implemented. Each level responds to a generic concept and, at each level, a series of tasks is performed (Tables 3.2 to 3.6).

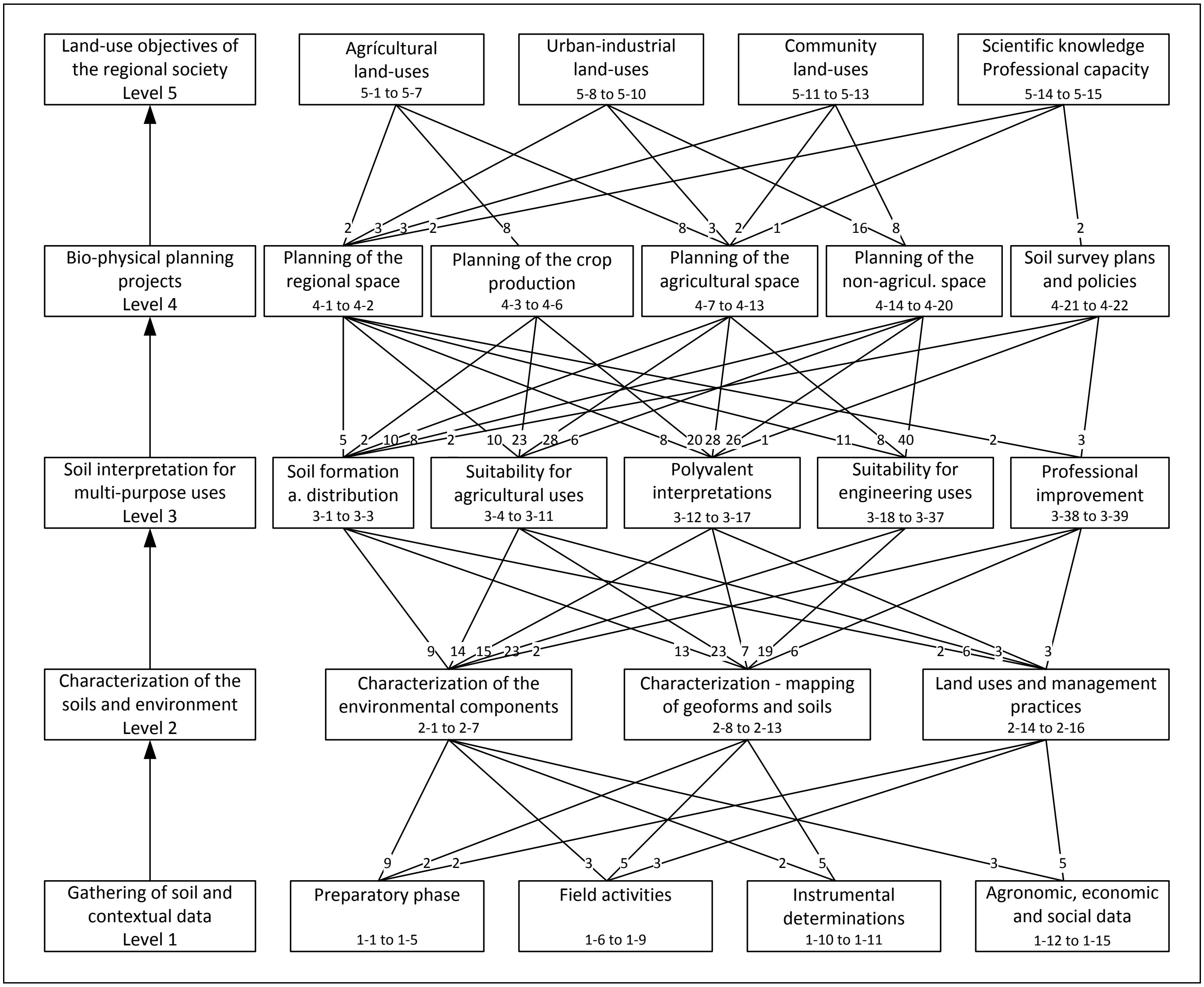


Fig. 3.10. Graph representing the soil survey as a system of production, interpretation, and dissemination of information. The numbers in the boxes refer to the themes labelled in Tables 3.2 to 3.6. The numbers inserted in the arrows indicate the amount of critical pathways through which information circulates from a given level to the following one (adapted from Zinck, 1977).

- Level 1: elementary tasks, which consist in the generation of the basic data, including the interpretation of aerial photos, satellite images and DEM, description and sampling of the soils, laboratory determinations, and gathering of agronomic, social, and economic data.
- Level 2: intermediate tasks, which consist in the synthesis of the information, including the characterization of the environmental components, characterization and mapping of the geoforms and soils, and description of the land-use types and management practices.

- Level 3: final tasks, which consist in the interpretation of the information for multiple purposes, including the genetic interpretation of the soils and their formation environments, land evaluation for agricultural, engineering, sanitary, recreational and aesthetic purposes, and professional improvement of the geopedologists.
- Level 4: primary external objectives, which correspond to biophysical planning in the local and regional contexts, including territorial ordering, planning of the agricultural and non-agricultural areas, planning of the agricultural production, and formulation of soil survey policies and plans.
- Level 5: final external objectives, which correspond to the concerns of the regional (or national) society in terms of agricultural land-use, urban-industrial land-use, use of community spaces, and creation of scientific knowledge and improvement of professional skills.

3.4.3. The functioning of the soil survey

The operation of the system refers to the information flows that circulate through the soil survey. To identify the direction of the information flows and evaluate their intensity, several matrices relating the consecutive layers of the model were built. The matrices were subjected to the judgement of a team of ten experts in soil survey, who identified the relationships between themes of consecutive levels and assessed the intensity of these relationships through a rating procedure using two ranges: 0-9 for the internal area and 0-2 for the external area. The individual estimates were averaged to get the direction and intensity of the information flows. This resulted in a complex graph of flows that is shown simplified in Fig. 3.10. The graph indicates the orientation and the amount of flows (critical pathways) that connect each theme with others. The combination of the two criteria of orientation and number of flows allowed to establish a ranking of the soil survey tasks according to their importance in generating or transmitting information.

3.4.4 The contribution of geomorphology to soil survey

The direct contribution of geomorphology takes place at levels 1 and 2.

- Level 1: geomorphology contributes to the tasks of photointerpretation, selection of sample areas, identification of representative sites, and delineation of the geopedologic units.
- Level 2: geomorphic synthesis is one of the most prolific themes of the system by the number of flows issued and the number of themes reached at level 3 (30 themes). Based on this performance, the geomorphic synthesis ranked as the most efficient theme of level 2, along with the topography theme.

Thus, the incorporation of geomorphology allows to streamline, speed up and improve the soil survey. Unfortunately, nowadays the latter is not given priority on political agendas, despite the severe risks of degradation of the soil resource.

3.5 Conclusion

In addition to promoting integration between geomorphology and pedology, geopedology focuses on the contribution of the former to the latter for soil mapping and understanding of soil formation. This contribution is based on the following:

- The geoforms and other geomorphic features, including processes of formation, aggradation and degradation, can be recognized by direct observation in the field and by interpretation of remote-sensed documents (aerial photographs and satellite images) and products derived therefrom (DEM). Documents that allow stereoscopic vision have the advantage of providing the third dimension of the geoforms in terms of volume and topographic variations. In this regard, the aerial photographs are still the more faithful and explicit documents for the interpretation of the relief at large and medium scales.
- Many geoforms have relatively discrete boundaries, facilitating their delimitation. This is particularly the case of constructed geoforms in depositional systems (e.g. geoforms of alluvial, glacial, and eolian origin) and, to a lesser extent, those built in morphogenic systems controlled by endogenous processes (e.g. geoforms of volcanic and structural origin). By contrast, hillsides frequently show continuous variations, which can be approximated using the slope facet models.
- Geoforms are generally distributed in landscape systems controlled by a dominant forming agent (e.g. water, ice, wind). The foregoing results in families of geoforms associated in characteristic patterns that repeat in the landscape. This allows to interpolate/extrapolate information in mapping areas and predict the occurrence of geopedologic units at unvisited sites.
- Geoforms are relatively homogeneous at a given categorial level and with respect to the properties that are diagnostic at this level. The hypogeal component, corresponding to the morphogenic and morphostratigraphic features of the material, is usually more homogeneous than the epigeal component, corresponding to the morphographic and morphometric features of the terrain surface. The non-random, systematic variations of the geopedologic cover are frequently of geomorphic nature.
- The geomorphic context is an important framework of soil genesis and evolution, covering three of the five classic soil forming factors, namely the characteristics of the relief-drainage compound, the nature of the parent material, and the age of the geoform. Many soils have not formed directly from the hard bedrock, but rather from the geomorphic cover material (e.g. unconsolidated sediments, slope materials in translation, regolith, weathering layers).
- To sum up the foregoing, geomorphic analysis enables segmenting the continuum of the physiographic landscape into spatial units that are frameworks (1) to interpret soil formation along with the factors of biota, climate and human activity, (2) to compose the soil cartographic units, and (3) to analyze the spatial variations of the soil properties.

The geopedologic approach is essentially descriptive and qualitative. Geoforms and soils are considered as natural bodies, which can be described by direct observation in the field and by interpretation of aerial photos, satellite images, topographic maps, and digital elevation models. The approach relies on a combination of basic knowledge in geomorphology and pedology, incremented by working experience, in particular the experience gained from the practice of field observation. Expert knowledge, the acquisition and development of which constitute an inherent process in human societies in evolution, represents a source of cognitive richness that is nowadays attempted to be formalized before it disappears. Expert knowledge has been considered as a factor of subjectivity (Hudson, 1992) and personal bias (McBratney et al., 1992) in the conventional practice of soil survey, in contrast with the pedometric (digital) soil mapping which would be more objective (Hengl, 2003). Geopedology is a conventional approach with the particularity and advantage that bias and subjectivity can be minimized or compensated by the systematic and integrated use of geomorphic criteria. Geoforms provide a comprehensive cartographic framework for soil mapping, which goes beyond the mere morphometric terrain characterization. However, both modalities, the qualitative and the quantitative, can be usefully combined. Geopedologic units can provide a framework for more detailed geostatistical studies and for the spatial control of digital data that are used to measure soil and geoform attributes. "The full potential of (digital) terrain analysis in soil survey will be realized only when it is integrated with field programs with a strong emphasis on geomorphic and pedologic processes" (McKenzie et al., 2000).

Table 3.2 Level 1 themes: elementary soil study tasks; information collection.

1-1	Collection and analysis of existing no-pedologic information.
1-2	Photo-field exploration, analysis of existing soil information, identification soil legend.
1-3	Generalized 1: 50,000 photointerpretation, identification of the physical-natural macro-units.
1-4	Selection of the sample areas.
1-5	Detailed 1: 25,000 photointerpretation, identification of the geoforms, location of the sample areas.
1-6	Survey of the sample areas.
1-7	Control observations, photointerpretation adjustments.
1-8	Composition of the cartographic units, descriptive soil legend.
1-9	Description of representative pedons.
1-10	Physical field determinations and measurements.
1-11	Laboratory determinations.
1-12	Survey of crop yields, production costs and development costs.
1-13	Survey of irrigation practices.
1-14	Survey of cultivation and conservation practices.
1-15	Evaluation of deforestation, levelling, drainage, stone removal costs.

Table 3.3 Level 2 themes: intermediate soil study tasks; synthesis of the information on soil and environment characterization.

2-1	Characterization of the climate.
2-2	Characterization of the surface hydrology and hydrography.
2-3	Characterization of existing hydraulic works.
2-4	Characterization of the water quality.
2-5	Characterization of the topography.
2-6	Characterization of the geology and hydrogeology.
2-7	Characterization of the geomorphology and hidrogeomorphology.
2-8	Geopedologic mapping and soil map preparation.
2-9	Morphologic characterization of the soils.
2-10	Chemical characterization of the soils.
2-11	Mineralogical characterization of the soils.
2-12	Physical characterization of the soils.
2-13	Mechanical characterization of the soils.
2-14	Survey of current land-uses.
2-15	Survey of management practices and levels.
2-16	Evaluation of required improvements and their feasibility.

Table 3.4 Level 3 themes: final soil study tasks; multi-purpose interpretations.

3-1	Overall characterization of the natural environment (integrated study).
3-2	Spatial distribution of the soils (soil chorology).
3-3	Genesis and taxonomic classification of the soils.
3-4	Land suitability for rainfed agriculture.
3-5	Land suitability for irrigated agriculture.
3-6	Land suitability for ornamental plants and garden vegetables.
3-7	Agricultural productivity (productivity of the land).
3-8	Development costs for agricultural land-use.
3-9	Current soil fertility.
3-10	Soil salinity.
3-11	Limitations of the land for the use of mechanized farm implements.
3-12	Characterization of the natural drainage.
3-13	Drainability of the land.
3-14	Current morphodynamics (erosion, sedimentation).
3-15	Erodibility of the land.
3-16	Land irrigation requirements.
3-17	Water availability.
3-18	Sources of material for topsoil.
3-19	Sources of sand and gravel.
3-20	Sources of material for road filling.
3-21	Constraints for road network design.
3-22	Limitations for road cuts.
3-23	Limitations for placement of cables and pipes.
3-24	Limitations for foundations of low buildings and houses.
3-25	Limitations for embankment foundations.
3-26	Limitations for residential areas.
3-27	Limitations for streets and parking lots.
3-28	Limitations for excavation of channels.
3-29	Limitations for construction of farm ponds.
3-30	Limitations for construction of dikes.
3-31	limitations for septic filtration areas.
3-32	Limitations for oxidation ponds.
3-33	Limitations for waste disposal areas.
3-34	Limitations for recreation areas (picnic, play grounds).
3-35	Limitations for lawns, golf courses, landscaping.
3-36	Limitations for camping sites.
3-37	Limitations for sports fields.
3-38	Training of the technical personnel.
3-39	Scientific publications, conferences, education.

Table 3.5 Level 4 themes: regional planning and development projects, designed and executed by a variety of official and private entities.

4-1	Soil correlation.
4-2	Land-use zoning in the regional space (arbitration between competitive uses).
4-3	Ecological zoning of crops.
4-4	Selection of crop and rotation systems.
4-5	Substitution of crops in time and space.
4-6	Increase of land productivity (yields).
4-7	Determination of agricultural plot sizes.
4-8	Irrigation planning and management.
4-9	Improvement of poorly drained soils.
4-10	Improvement of saline soils.
4-11	Management of heavy soils (clay soils).
4-12	Soil conservation techniques.
4-13	Agricultural extension.
4-14	Urban and peri-urban planning (master zoning plan).
4-15	Supply of water and gas.
4-16	Control of soil and water pollution.
4-17	Disposal or recycling of industrial, urban and agricultural wastes.
4-18	Channelling and excavation of effluents.
4-19	Planning of communication routes.
4-20	Tourism development.
4-21	Professional training and improvement.
4-22	Expanding basic knowledge in geomorphology and pedology.

Table 3.6 Level 5 themes: relevant technical issues faced by the regional (or national) community.

5-1	Marginal agriculture.
5-2	Land reform.
5-3	Intensification processes of agriculture.
5-4	Incorporation of new areas to agricultural activities.
5-5	Supply of agricultural products for human consumption.
5-6	Supply of special agricultural products (flowers, out-of-season crops).
5-7	Supply of raw agricultural materials for the industry.
5-8	Creation of industrial zones.
5-9	Urbanization processes (cities, towns, secondary residences).
5-10	Transport of people, products, energy and information.
5-11	Areas for recreation and tourism (water bodies, areas for outdoor activities and sports).
5-12	Protected areas (parks, reserves, green areas).
5-13	Environmental conservation, protection and improvement.
5-14	Enlargement of the technical capacity of the regional community.
5-15	Increase in basic scientific knowledge.

Chapter 4

THE PEDOLOGIC LANDSCAPE: ORGANIZATION OF THE SOIL MATERIAL

4.1 Introduction

The soil material is organized from structural, geographic and genetic points of view. Structurally, the soil material is multiscalar with features and properties specific to each scale level. The successive structural levels are embedded in a hierarchic system of nested soil entities, or holons, that Haig (1987) has called the holarchy of the soil system (Fig. 4.1). Geographically, the soil material is not randomly distributed on the landscape; instead, it is organized according to spatial distribution patterns under the control of the soil forming factors (Fridland, 1974, 1976; Hole & Campbell, 1985). Genetically, the soil material is formed and develops as an open system of exchanges and transformations of matter and energy (Jenny, 1941; Simonson, 1959).

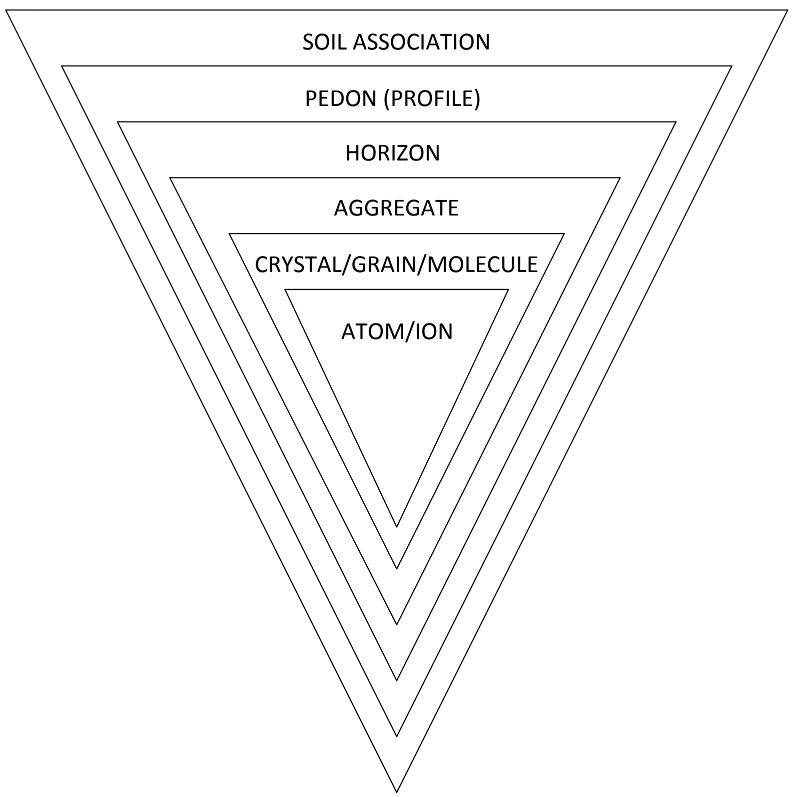


Fig. 4.1. The holarchy of the soil system (Haigh, 1987).

Hereafter, a model similar to Haigh's holarchy is used to introduce some basic soil notions and analyze their relationships with the geopedologic approach at various scalar levels (Table 4.1). This scheme of nested holons is a condensate of pedology ranging from molecular reactions to the (geo)pedologic landscape. At each hierarchic level of perception and analysis of the soil material, distinct features are observed that are particular to the level considered. The whole of the features describes the soil body in its entirety. At each level correspond an element of the soil holarchy, a unit (or range of units) measuring the soil element perceived at this level, and a means of observation or measurement for identifying the features that are diagnostic at the level concerned. The levels are labelled based on a connotation with the proper dimension of the soil element into consideration at every level: nano, micro, meso, macro and mega (Table 4.1).

Table 4.1 Hierarchic levels of the soil system (Zinck, 1988).

Level	Unit	Concept	Soil feature
Nano	nm-µm	Particle	Basic soil reactions
Micro	µm-mm	Aggregate	Micromorphologic structure
Meso	mm-cm-dm	Horizon	Differentiation of the soil material
Macro	m	Pedon	Soil volume for description and sampling
Mega	m-km	Polypedon	Soil classification and mapping – (geo)pedologic landscape

4.2 Nano-level

At the nano-level, the soil material is considered in its elementary form of molecules and combinations of molecules into particles, which can be either identified through chemical reactions, or observed using an electron microscope, or determined by X-ray diffraction. At this level take place the basic reactions of the soil material: chemical, mechanical, and physico-chemical. These reactions control processes and features such as rock weathering and soil formation, but also mass movements and other erosion phenomena that have the particularity of getting manifest and taking visual expression at coarser levels of perception.

4.2.1 Chemical reactions

The chemical reactions, which take place in the soil material as well as in the parent material (hard rock or unconsolidated sediment) to transform the latter into soil material, operate in two modalities: (1) by solubility changes of the chemical compounds in the salts, carbonates and silicates, and (2) by structural changes in the oxide minerals.

- Solution (salts): $NaCl + H_2O \Leftrightarrow Na^+ + Cl^- + H_2O$
- Carbonation (carbonates): $CO_2 + H_2O \Rightarrow HCO_3^- + H^+$
  $CaCO_3 + (HCO_3^- + H^+) \Rightarrow Ca(HCO_3)^2$
- Hydrolysis (silicates): $KAlSi_3O_8 + HOH \Rightarrow HAlSi_3O_8 + KOH$
- Hydration (oxides): $2Fe_2O_3 + 3H_2O \Rightarrow 2Fe_2O_3 * 3H_2O$
- Oxido-reduction (oxides): $4FeO + O_2 \Leftrightarrow 2Fe_2O_3$

The performance of these reactions depends on the bioclimatic conditions, the nature of the substratum, and the type of relief and associated drainage conditions, among other factors. These are basic processes of rock weathering, alteration of unconsolidated materials, and formation of pedogenic material. Some processes operate only in specific geopedologic environments. For instance, the dissolution, concentration and, eventually, (re)crystallization of salts and the resulting geoforms are typical of halomorphic conditions in coastal and dry inland areas. Likewise, the dissolution of carbonates into bicarbonates and the mobilization of the latter are typical of calcimorphic conditions and responsible, in particular, for the formation of karstic relief. The hydrolysis of potassium feldspar, favored by high humidity and high temperature in tropical environment, results in the formation of acid clay together with potassium hydroxide that is lost by lixiviation. Hydration makes iron oxide more fragile. Oxydo-reduction is a reversible process typical of the intertidal zone.

4.2.2 Mechanical reactions

The mechanical reactions depend on the way particles are arranged and associated. Coarse particles have the tendency to pile up into different kinds of packing, while the behavior of the fine particles depends on the intensity of their agglomeration into various kinds of fabric. In general terms, these mechanical reactions of nano-level determine the susceptibility of the materials to mass movements, the geomorphic expression of which is visible on the landscape at coarser levels of perception (from meso to mega).

4.2.2.1 Types of packing

Coarse particles, including sand and coarse silt grains (2-0.02 mm), cluster in piles the structure of which varies according to the degree of roundness of the grains. Rounded grains (e.g. sand grains of marine or eolian origin) usually present a cubic arrangement with limited contact surface and high porosity. This allows water to penetrate readily in the pore space, resulting in water pressure in the pores that tends to separate the grains. For this reason, the cubic packing is in general an unstable arrangement, which facilitates the process of moving sands (quicksands). Less rounded grains (e.g. sand grains of alluvial or colluvial origin) generally show a tetrahedral type of packing, with greater contact surface and lower porosity, which is a more stable arrangement. Irregular grains and rock fragments tend to be tightly interlocked, with large friction surface that ensures greater stability of the material.

4.2.2.2 Types of fabric

The fabric arrangement of the fine particles, including clay and fine silt (< 0.02 mm), depends on the mode and intensity of the contacts between particles in the soil solution. Various modes of particle association in clay suspensions are recognized, with four basic types of micro-mechanical fabric, ranging from the total absence of agglomeration (i.e. deflocculated state) to a strongly agglomerated condition (i.e. flocculated state), and a series of combinations of these basic types (Mitchell, 1976) (Fig. 4.2). The fabric types are related to the moisture content in the soil, which determines the mechanical state of the material, from liquid to solid, and the consistence limits (i.e. Atterberg limits) between mechanical states. Obviously, the fabric depends also on other factors such as the type of clay, organic matter content, and the presence of salts, among others.

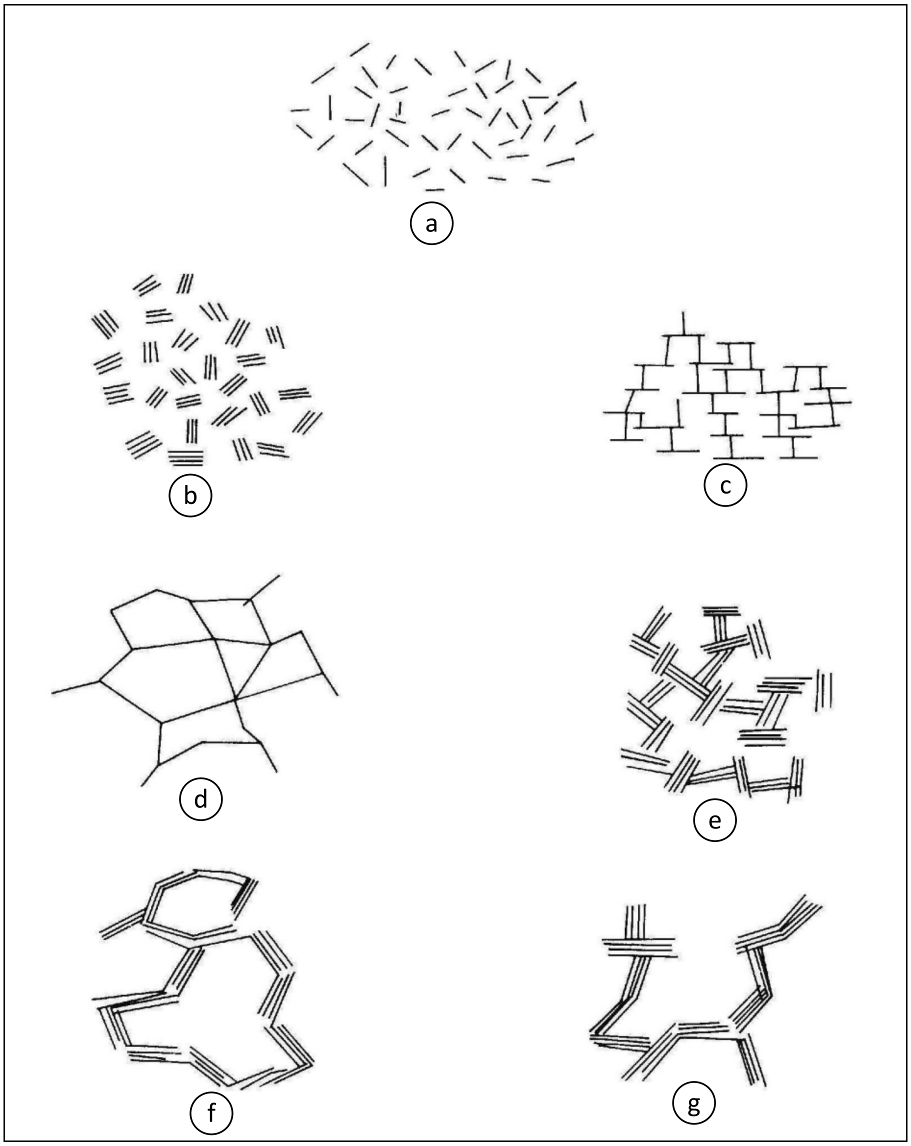


Fig. 4.2 Modes of particle association in clay suspensions (after van Olphen, 1963): (a) dispersed and deflocculated; (b) aggregated but deflocculated; (c) edge-to-face flocculated but dispersed; (d) edge-to-edge flocculated but dispersed; (e) edge-to-face flocculated and aggregated; (f) edge-to-edge flocculated and aggregated; (g) edge-to-face and edge-to-edge flocculated and aggregated (taken from Mitchell, 1976).

In geopedologic terms, the fabric of the soil material plays an important role in the generation of mass movements (Table 4.2).

- Deflocculated state: all particles are individually in suspension in the soil solution, without interaction between particles. This fabric condition favors the occurrence of mudflows.
- Dispersed state: there are elementary associations between individual particles, essentially contacts between particle edges and faces. This fabric condition creates a risk of solifluction.

- Aggregated state: there are associations between particle clusters, creating a situation that favors the potential occurrence of landslides.
- Flocculated state: all kinds of contact between faces and between edges and faces take place, generating the most stable arrangement of particles in the soil solution and resulting in high soil strength and stability.

Table 4.2 Influence of the fabric type and the consistence of the soil material in the generation of mass movements (most probable).

Fabric type	State of the material	Mass movement
Deflocculated	Liquid	Mudflow
Dispersed	Plastic	Solifluction
Aggregated	Semi-solid	Landslide
Flocculated	Solid	Metastability
Organization of the soil material	Soil property (consistence, Atterberg limits)	Morphogenic process (geomorphic response)

4.2.3 Physico-chemical reactions

The physico-chemical reactions are based on the colloidal properties of clay and humus. Both compounds have electronegative charges at the edges of the layers and in the space between layers. The electronegative charges attract cations with decreasing intensity according to the lyotropic sequence of preferential adsorption, which reflects the number of charges and the hydrated size of the cations: $Al^{+++} > Ca^{++} > Mg^{++} > K^{+} = NH_4^{+} > Na^{+}$. Divalent cations play an important role in establishing bridges between clay particles, which is a basic process for the formation of aggregates. The physico-chemical reactions that take place at the nano-level control soil fertility, aggregation, structural stability and its relationship with soil susceptibility to erosion.

4.2.4 Relationship with geopedology

The reactions taking place at the nano-level determine the fundamental processes of soil formation, evolution, differentiation, as well as degradation. The production of regolith through rock weathering, the alteration of the unconsolidated cover formations, and the transformation of these loose materials into soil material largely depend on the chemical and physico-chemical reactions that operate in the substratum - inherently the domain of geomorphology. The different mechanical reactions that take place in the soil material and regolith, according to variations in moisture content, control the morphogenesis by mass movements, the impact of which is directly visible in the landscape.

4.3 Micro-level

At the micro-level, the object of interest is the soil aggregate, which can be observed with the use of a petrographic microscope. This is the investigation domain of micromorphology. The observation of an aggregate in thin section under the petrographic microscope allows characterizing the micromorphologic structure of the soil matrix, both in its solid component and porous component, and identifying features derived from the addition of material and transformation of the matrix. Some of these micromorphologic characteristics are shown schematically in Fig. 4.3 and summarized in Table 4.3.

4.3.1 The micromorphologic components

At the micro-level, the soil material is divided into two main components: the soil matrix, which corresponds to the soil material in situ, and pedologic features. Each of these two components is subdivided into elements that play important roles in the functioning of the soil, including plasma, pore space, skeleton grains, and pedologic features (Table 4.3).

4.3.1.1 Skeleton grains

The skeleton grains consist of:

- Mineral grains, essentially sand and silt grains, which constitute the inert soil material, without colloidal properties, that dominates in coarse-grained soils.
- Organic fragments, which are pieces of undecomposed organic material, essentially fragments of leaves, twigs and branches (folic material), that dominates in the litter.

4.3.1.2 Plasma

The plasma is the active phase of the solid material, where the chemical and physico-chemical reactions take place and which controls the mechanical mobility of the fine particles. The plasma is endowed with relevant properties, among others:

- Colloidal property that provides the clay minerals and the humus with electronegative charges.
- Solubility property that allows salts and carbonates to be converted into ions.
- Chelation property, thanks to which insoluble compounds (e.g. Fe and Al sesquioxides) can migrate in association with organic molecules.

4.3.1.3 Pores

Pores vary in configuration and location within and between aggregates, and for these reasons fulfill different functions. Packing voids, vesicles, and chambers are examples of pore differentiation in the soil.

- Packing pores are located around the aggregates and control the permeability, with its influence on drainage, and the adhesion between aggregates.
- Vesicles are closed empty spaces, without active function.
- Chambers are pores open on one extremity, which retain moisture even when the soil appears to be dry; these are places where the microfauna (e.g. bacteria) responsible for the decomposition of the organic matter concentrates, and where the oxido-reduction mechanisms responsible for hydromorphism occur.

4.3.1.4 Pedologic features

Micromorphologic soil features derive essentially from the addition of new material to the soil and/or the transformation of the soil material in situ.

- The additions can be traced by the coatings (cutans) that form when fine particles move within the soil solution from eluvial horizons and deposit in the pores or on the surface of the aggregates in the underlying illuvial horizons. According to the nature of the constituents, different types of cutan are recognized, including clay cutans (argillans), iron cutans (ferrans), manganese cutans (manganans), etc.
- The transformations can be (1) physical: e.g. pressure faces (stress cutans) on the surface of the aggregates caused by contraction-expansion; (2) chemical: e.g. local concentration of chemical compounds (Fe_2O_3, $CaCO_3$, SiO_2) in the form of nodules and concretions; and (3) biological: e.g. fecal nodules, pedotubules.

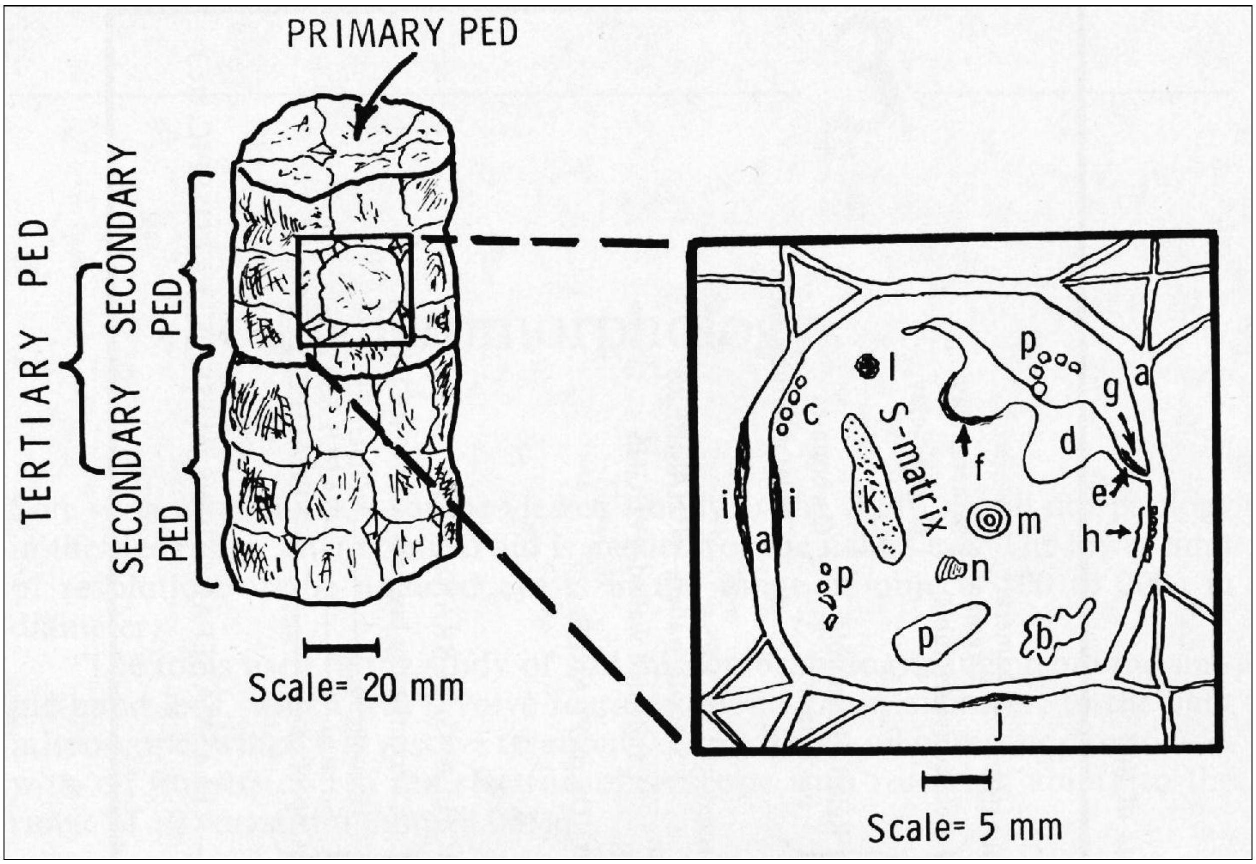


Fig. 4.3 Micropedologic features. Voids: (a) packing voids, (b) vugh, (c) vesicles, (d) chamber, (e) channel. Cutans: (f) chamber cutan, (g) channel cutan, (h) skeletans, (i) argillan or sesquan, (j) stress cutan. Other features: (k) pedotubule, (1) nodule, (m) concretions, (n) papule. Note that the S-matrix is the mass of plasma, skeleton grains (p), and voids (taken from Buol et al., 1997).

Table 4.3 Micromorphologic organization of the soil material.

<table>
<tr><td rowspan="4">Soil material</td><td rowspan="3">Soil matrix (S-matrix)
(soil material in situ)</td><td rowspan="2">Solids</td><td>Skeleton grains
(coarse material)</td></tr>
<tr><td>Plasma
(fine material)</td></tr>
<tr><td>Pore space
(voids, pores)</td><td>Vesicles
Chambers, vughs
Channels
Planes</td></tr>
<tr><td>Pedologic features
(addition to or transformation
of soil material)</td><td>Cutans
Glaebules
Tubules
Plasma separations</td><td></td></tr>
</table>

4.3.2 Relationship with geopedology

The micromorphologic characteristics represent an important source of information for the genetic interpretation of the soils and for inferring soil properties and qualities that control geomorphic processes.

- The pedologic features, which refer to the additions and transformations that take place in the soil material, are indicators of soil formation and evolution. The translocation of substances (e.g. clay illuviation) is a particularly good example that reveals a type of pedogenic dynamics. The micromorphologic analysis also allows identifying paleo-environmental influences in polygenic soils (Jungerius, 1985b) and correlatively in the evolution of the geomorphic landscape.
- The soil matrix has influence on geomorphogenesis. The nature of the plasma conditions the aggregate stability, which plays a relevant role in the processes of soil erosion by water and wind. Porosity controls the movement of water and air in the soil. The microporosity determines the capacity of water retention in the soil, while the macroporosity determines the surface runoff, the infiltration, and the percolation of water through the soil. An imbalance between these different terms of the water dynamics on the surface of and within the soil causes susceptibility to sheet erosion and mass movement.

4.4 Meso-level

At the meso-level, the organization entity of the soil material is the horizon, which usually consists of a mass of aggregates, except when the material is single-grain (sandy soil) or compact (clay soil). Horizons result from the differentiation of the parent material by pedogenic processes. The mode of analysis is direct observation and description in the field.

4.4.1 Horizon definition and designation

An horizon is a layer of soil material with a unique combination of properties, different from the properties of the soil in the horizons above and below this horizon (e.g. color, texture, structure). The concept of horizon refers to the pedogenic material and is therefore different from the concept of stratum that refers to the geogenic material (in the C layer). Soil horizons are identified at three successive levels using a designation nomenclature of letters and numbers.

4.4.1.1 Primary divisions: the master horizons

The primary divisions reflect the effect of the basic soil forming processes, resulting in the differentiation of the soil material in master horizons. These are identified by capital letters (O, A, E, B, C, R). At this level, the horizons are distinguished according to the nature of the material and according to their position in the soil profile.

(a) The distinction of the material according to its nature allows separating the organic material from the mineral material. A material is considered to be organic (O horizon) when it complies with the following contents of organic carbon (OC):

- In well drained soils: OC >20%.
- In poorly drained soils: OC ≥18%, if clay ≥60%; OC ≥12%, if clay = 0%; proportional percentages of OC for intermediate clay contents.

(b) The distinction of the material according to the position in the profile leads to separate four kinds of horizon/layer: surficial horizon (topsoil), subsurface horizon, subsoil, and substratum.

- Topsoil horizons: A and E horizons
  - *A horizon*: layer where the incorporation of organic matter occurs and where the biologic activity shows its maximum expression; there may also be some downwashing of constituents.
  - *E horizon*: layer that loses soil material through eluviation according to the degree of solubility of the constituents. A generalized sequence by order of decreasing susceptibility to leaching includes: salts, carbonates, bases, clay, OM, Fe and Al sesquioxides. In an extremely leached situation, only SiO_2 remains in situ, giving the horizon a whitish color (albic horizon).
- Subsurface horizons: B horizons

  The nature of the B horizon varies according to the process of formation, which can operate:
  - by weathering of the parent material (consolidated or loose).
  - by illuviation of chemical compounds (salts, carbonates, clay, OM, sesquioxides, etc.).
  - by neoformation of clay minerals.
- Subsoil: C layer = parent material.
- Substratum: R layer = bedrock.

4.4.1.2 Secondary divisions: specific genetic features

The secondary divisions inform on specific genetic features of the horizons, using lowercase letters:

- Degree of decomposition of the organic material:

  i = slightly decomposed organic material (F**i**brist).

  e = moderately decomposed organic material (H**e**mist).

a = strongly decomposed organic material (S**a**prist).

- Degree of weathering of the mineral material: w (Bw), r (Cr).
- Accumulation: z, y, k, n, t, h, s, q, in order of decreasing mobility of the chemical compounds, referring respectively to salts more soluble than calcium sulphate, gypsum, carbonates, sodic clay, clay, humus, sesquioxides, and silica.
- Concentration: c, o, v, referring respectively to concretions, no-concretionary nodules, and plinthite.
- Transformation: f, g, m, p, x, b, d, referring respectively to frozen soil, gleization, compaction, plouwpan, fragipan, buried horizon, and densified horizon.

4.4.1.3 Tertiary divisions

The tertiary divisions are concerned with a variety of unrelated features, using arabic numerals:

- Subdivision of genetic horizons based on differences in color and/or texture, among other criteria (e.g. Bt1-Bt2) (numerical suffixes).
- Lithologic discontinuity based on textural contrasts indicating several successive depositional phases that result in the superposition of profiles (e.g. Bt-2Bt-2C) (numerical prefixes).
- Bisequum that reflects the superimposition or imprint of a recent soil within a soil formed previously in different bioclimatic conditions, vegetation cover or land-use. For instance, a Spodosol developing under pine plantation that invades the upper part of an Alfisol previously formed under deciduous forest (e.g. O-A-E-Bs-E´-Bt´-C).

4.4.2 Relationship with geopedology

The designation symbols are information vectors that summarize the relevant characteristics of a horizon, including properties, mode of formation, and position in the profile. The nomenclature is used to identify genetic horizons based on the qualitative inference of the process(es) responsible for their formation. For instance, a Bw horizon reflects weathering of primary minerals, whereas a Bt horizon reflects clay illuviation. To be diagnostic for taxonomic classification of the soils, genetic horizons must comply with quantitative requirements (e.g. color, depth, thickness, % content, etc.) specified by the taxonomic system that is implemented. For this reason, it can be said that all argillic horizons are Bt horizons, but not all Bt horizons are argillic horizons.

The soil information describing the nature of the horizons and, especially, their sequence in the profiles is very useful in geomorphic research on the susceptibility of the soils and cover formations to erosion processes. As highlighted by Jungerius (1985b), A and B horizons exert different control on the geomorphic processes. The difference in strength between surficial horizons (A) and subsurface horizons (Bt) often determines the depth of soil truncation by sheet erosion. Similarly, differences in physico-mechanical properties between consecutive horizons can cause shear planes that control surface mass movements. Suffusion, piping, and tunnelling processes also depend on the sequence of and contrasts between horizons.

4.5 Macro-level

4.5.1 Definition

At the macro-level, the basic concept is the pedon, which is defined as the minimum soil volume for describing and sampling a soil body. Conventionally, the pedon is represented with a hexagonal configuration (Fig. 4.4). It covers a large part of the lateral and vertical variations of a soil body. The normal size of the area is 1 m^2 in the case of a soil with approximately parallel horizons and isotropic spatial variations. The maximum size of the area is 10 m^2 when horizons show cyclic variations. The theoretical depth is down to the parent material of the soil, but for practical reasons it is usually limited to the upper 2 m.

4.5.2 Related concepts

Several other concepts that characterize the soil body are related with the pedon concept, such as soil profile, solum, and control section.

- Soil profile: is a face of the pedon including the entire sequence of horizons, commonly used to describe and sample. Statistical trials have shown that, when collecting material of a horizon laterally in all faces of the pedon to obtain a composite sample, probable mean errors can be divided approximately by two for most of the physical and chemical parameters (Wilding & Drees, 1983).
- Solum: includes soil horizons O + A + E + B, the C and R layers being excluded.
- Control section: is the specific depth of the pedon within which selected soil characteristics need to occur to be considered diagnostic for taxonomic classification. For instance, for most of the soils, the family of particle-size distribution is determined within the depth of 25-100 cm. Likewise, to be diagnostic, plinthite should be present at <125 cm depth at great group level (e.g. Plinthustult) and at <150 cm depth at subgroup level (e.g. Plinthic Paleustult).

4.5.3 Relationship with geopedology

Geomorphic literature does not provide any criteria or norms that specify the size of the minimum area for description and sampling. In practice, there is no space limitation for the description of the epigeal component of the geoform, since processes and features of the terrain surface are directly observable. However, defining a minimum observation area can be useful for comparison between sites and for generalization of field information. With respect to the hypogeal component of the geoform, thus the proper geomorphic material (i.e. regolith, depositional material) that constitutes the C layer of the soils, it is not directly accessible to observation, description and sampling, except when there are natural or artificial exposures. Therefore, geomorphic research faces an issue of minimum volume for description and sampling similar to the one that has been solved in pedology with the concept of pedon. As the geopedologic survey integrates the description of the geoform and the soil in one place, the size criteria of the pedon may also apply to the morphon. The morphon covers the features of both the terrain surface and the subsoil/substratum, while the pedon covers the volume of the intermediate material that corresponds to the solum. In the geopedologic practice, the two are inseparable and their distinction may be regarded as superfluous.

These comments apply primarily to the lower level of the hierarchic classification of the geoforms, thus that of landform/terrain form (see Chapter 6). They are less pertinent at the higher categories of the system, since the external features of the geoform often allow inferring the nature of the substratum.

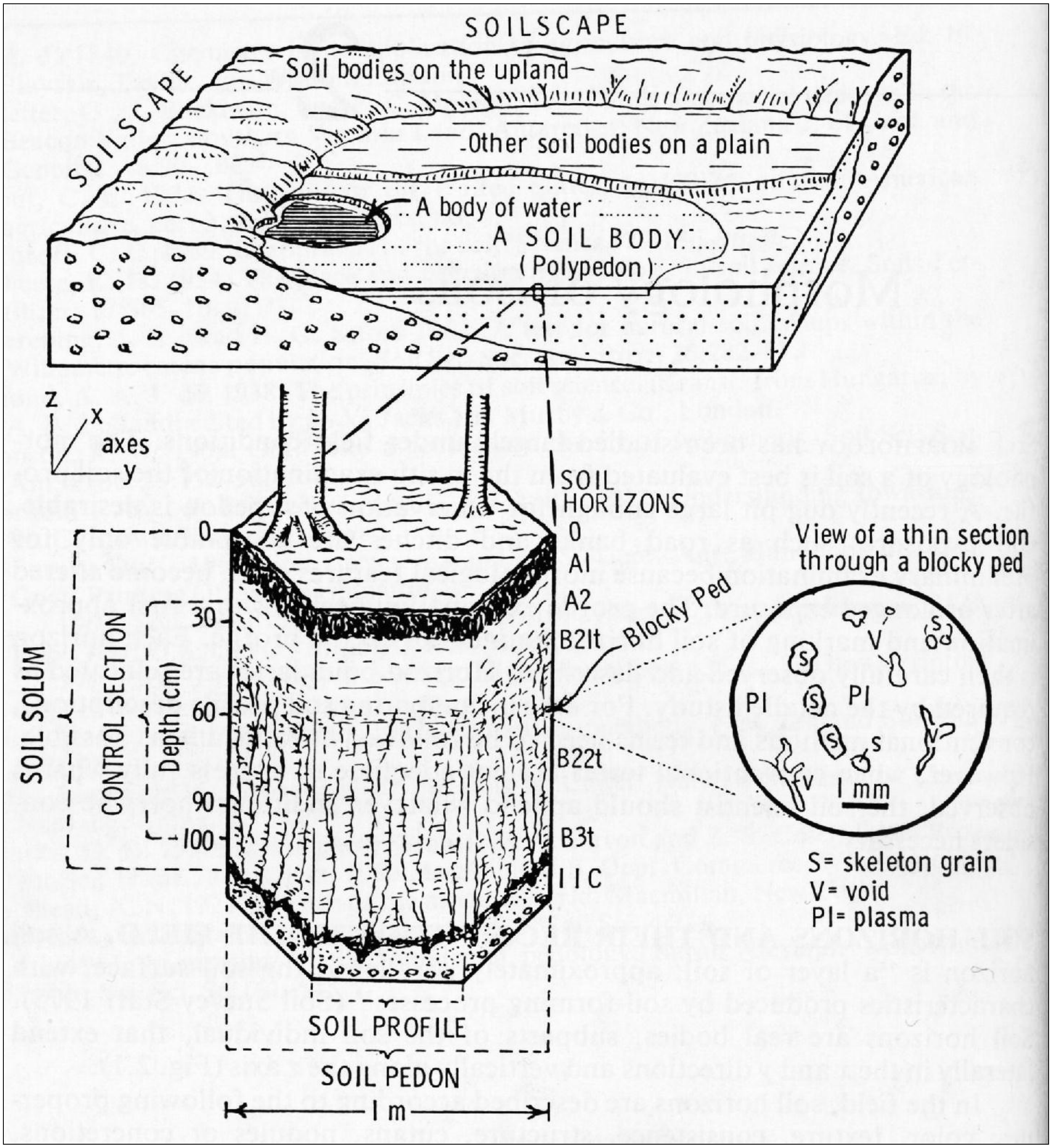


Fig. 4.4 Soil profile, pedon, polypedon and soilscape (taken from Buol et al., 1997).

4.6 Mega-level

4.6.1 Definition

At the mega-level, the polypedon is the basic concept. The polypedon is a set of adjacent similar pedons that fit within the range of variation of a single taxonomic unit (e.g. soil series). It is a real physical soil body, limited by "no-soils" (e.g. rock outcrops, water bodies, built areas, etc.) or by pedons that exhibit dissimilar characteristics. The minimum area is 2 m^2 (i.e two pedons), but there is no specification of maximum area. The concepts of soil body and soil individual are synonyms of that of polypedon. In similar terms, Boulaine (1975) has proposed the concept of *genon* to designate the soil volume of all pedons that have the same structure and characteristics and that result from the same pedogenesis.

4.6.2 Relationship with geopedology

- The polypedon constitutes the fundamental link between the actual soil volume (i.e. pedon) and the taxonomic unit in the classification system. It is the concept used to taxonomically classify the soil bodies. A polypedon comprises all contiguous pedons of equal classification.
- The polypedon provides the pedologic content of the cartographic unit. A polypedon is a concrete soil individual (i.e. soil body) on the landscape. Polypedon and landscape together form the soilscape. Polypedons can constitute (1) relatively pure map units with one dominant polypedon per unit (consociacion), or (2) composite map units comprising more than one dominant polypedon (association, complex).
- The polypedon correlates with the geomorphic unit (polymorphon), especially at the lower taxonomic level (landform/terrain form). In its simplest expression, a polypedon in the corresponding geomorphic framework forms a geopedologic landscape unit. However, the geopedologic landscape is usually more complex, because a single geoform often comprises more than one polypedon.

4.7 Conclusion

The holarchy of the soil system allows highlighting relevant relationships between soil properties and geomorphic response at different hierarchic levels. These relationships form the conceptual essence of geopedology. A phenomenon particularly notable refers to the cause-effect relationships between reactions that occur in the soil material at micro-scale, thus not directly perceptible, and their geomorphic expression in the landscape at macro-scale. This is especially the case of landscape shaping by mass movements, which are controlled by micro-mechanical reactions in the soil fabric. With respect to soil cartography, the most conspicuous relationship takes place at the mega-level, where polypedon and polymorphon integrate to form a geopedologic landscape unit.

Chapter 5

THE GEOMORPHIC LANDSCAPE: CRITERIA FOR CLASSIFYING GEOFORMS

5.1 Introduction

Unlike other scientific disciplines, geomorphology still lacks a formally structured taxonomic system to classify the forms of the terrestrial relief, hereafter designated as *geoforms*. There is some consensus for grouping the geoforms by families of processes that operate on given rock substrata or in given bioclimatic zones. Examples of the former are the karstic forms generated by the dissolution of calcareous rocks, desert forms shaped by the wind in dry environments, glacial forms resulting from the activity of ice, or alluvial forms controlled by the activity of the rivers. However, these geoforms are not integrated in a structured hierarchic scheme. It is necessary to create a system that allows accommodating and organizing the geoforms according to their characteristics and origin and according to their hierarchic relationships. This requires a multicategorial framework.

Geoform is the generic concept that designates all types of relief form regardless of their origin, dimension and level of abstraction, similarly to how the concept of soil is used in pedology or the concept of plant in botany (Zinck, 1988; Zinck & Valenzuela, 1990). The term of geoform, with generic meaning, has been introduced recently in the Spanish version of the FAO Guidelines for soil description (FAO, 2009). Geoforms have an internal (hypogeal) component and an external (epigeal) component in relation to the terrain surface. The internal component is the material of the geoform (the content), the characteristics of which convey genetic and stratigraphic (i.e. chronological) information. The external component of the geoform is its shape, its "form" (the container), which expresses a combination of morphographic and morphometric characteristics. The external component is directly accessible to visual perception, proximal or distal, either human or instrumental. Ideally, the classification of the geoforms should reflect features of both components, i.e. the constituent material and the physiographic expression. The external appearance of the geoforms is very relevant for their direct recognition and cartography. For this reason, a system of geoform classification must necessarily combine perception criteria of the geomorphic reality and taxonomic criteria based on diagnostic attributes.

Seemingly, geoform taxonomy has not fomented the same interest as plant taxonomy or soil taxonomy did. This might be due to the fact that more importance has been given to the analysis of the morphogenic processes than to geomorphic mapping which requires some kind of classification of the geomorphic units. There are few countries that have had, at some time, a systematic program of geomorphic mapping similar to those carried out in several Eastern European countries after the Second World War or in France in the second part of the last century (Tricart, 1965a; CNRS, 1972).

Soil map legends often ignore the geomorphic context that, however, largely controls soil formation and distribution. Usually, the legend of the soil maps shows only the pedotaxa, without mentioning the landscapes where the soils are found, although the concept of "soilscape" is considered to provide the spatial framework for mapping polypedons (Buol et al., 1997). A mixed legend, showing the soil in its geomorphic landscape, facilitates the reading, interpretation and use of the soil map by nonspecialists working in academic and practitioner environments (see the example in Fig. 3.2, Chap. 3). With the use of GIS, the geomorphic context is emerging as the structuring element of a variety of legends, including legends of taxonomic maps, interpretive maps, and land-use planning maps, among others.

5.2 Examples of geomorphic classification

Geomorphologists have always shown some interest in classifying geoforms, but the criteria used for this purpose have changed over the course of time and are still very diverse. After mentioning some geomorphic classification approaches, we describe the structure of a taxonomic system for geoform classification that has been developed from geopedologic surveys in Venezuela and later used in the ITC (Enschede, The Netherlands) to train staff from a variety of countries in Latin America, Africa, Middle East, and Southeast Asia (Zinck, 1988; Farshad, 2010).

5.2.1 Classification by order of magnitude

The dimensional criterion has been used by several authors to classify the geomorphic units (Tricart, 1965a; Goosen, 1968; Verstappen & Van Zuidam, 1975; among others). These classifications are hierarchic, with emphasis on structural geomorphology in the upper levels of the systems. The classification proposed by Cailleux-Tricart (Tricart, 1965a) in eight temporo-spatial orders of magnitude is a representative example of this approach (Table 5.1). The spatial dimension and the temporal dimension of the geomorphic units vary concomitantly from global to local and from early to recent. Tricart (1965a) considers that the dimension of the geomorphic objects (facts and phenomena) intervenes not only in their classification, but also in the selection of the study methods and in the nature of the relationships between geomorphology and neighboring disciplines.

Table 5.1 Taxonomic classification of the geomorphic units by Cailleux-Tricart (summarized from Tricart, 1965a).

Order	Unit types	Unit examples	Extent (km^2)	Time (years)
I	Configuration of the earth's surface	Continent, ocean basin	10^7	10^9
II	Large structural assemblages	Shield, geosyncline	10^6	10^8
III	Large structural units	Mountain chain, sedimentary basin	10^4	10^7
IV	Elementary tectonic units	Serranía, horst	10^2	10^7
V	Tectonic accidents	Anticline, syncline	10	10^6-10^7
VI	Relief forms	Terrace, glacial cirque	10^{-2}	10^4
VII	Microforms	Lapies, solifluction	10^{-6}	10^2
VIII	Microscopic features	Corrosion, disaggregation	10^{-8}	-

With a similar but less elaborate approach, Lueder (1959) distributes the geoforms in three orders of magnitude. The first order includes continents and ocean basins. Mountain ridges are an example of second order. The third order includes a variety of forms such as valley, depression, crest, and cliff.

5.2.2 Genetic and genetic-chorologic classifications

There are variants of genetic classification of the geoforms based on the conventional division of geomorphology as a scientific discipline in specialist areas concerned with different types of geoforms (Table 5.2).

Table 5.2 Families of geoforms as per origin

Study fields of geomorphology	Types of geoforms
Structural geomorphology: types of relief	Cuesta, fold, shield reliefs, etc.
Climatic geomorphology: types of molding	Glacial, periglacial, eolian moldings, etc.
Azonal geomorphology: types of form	Alluvial, lacustrine, coastal forms, etc.

The genetic-chorologic classification of geoforms is based on the concept of morphogenic zone. The latitudinal and altitudinal distribution of the morphogenic zones parallels the division of the earth's surface in large bioclimatic zones, generating a series of morphoclimatic domains, each with a specific association of geoforms: glacial, periglacial, temperate (wet, dry), mediterranean, subtropical, and tropical (wet, dry). The classification combines origin and geographic distribution of the geoforms. It is often used to present and describe the geoforms by chapters in textbooks on geomorphology. This type of classification is based on some kind of hierarchic structure and leads to a typology of the geoforms, but does not provide a clear definition of the criteria used in the ranking and typology. There is tendency to emphasize one type of attributes of the geoforms to the detriment of others: for instance, the dimension, or the genesis, or the geographic distribution.

The project of the Geomorphic Map of France (CNRS, 1972) establishes a hierarchy of geomorphic information in five levels, called *terms*, as reference frames to gather the data, represent them cartographically, and enter them in the map legend. These five terms are in descending order: the location, the structural context (type of structural region, lithology, tectonics), the morphogenic context (age, morphogenic system), surface formations (origin of the material, particle-size distribution, consolidation, thickness, morphometry) and, finally, the forms. The last term contains the entire collection of recognized forms, with grouping into classes and subclasses according to the origin of the forms. Each form has a definition and a symbol for its cartographic representation. Two main groups of forms are distinguished: (1) the endogenous forms (volcanic, tectonic, structural), and (2) the forms originated by external agents (eolian, fluvial, coastal, marine, lacustrine, karstic, glacial, periglacial and nival forms, and slope and interfluve forms).

For the purpose of soil mapping, Wielemaker et al. (2001) proposed a hierarchic terrain objects classification, qualified as morphogenic by the authors, which includes five nested levels, namely region, major landform, landform element, facet, and site. This system was derived from the analysis of a concrete case study located in Southern Spain, using a methodological framework to formalize expert knowledge on soil-landscape relationships and an interactive GIS procedure for sequential disaggregation of the landscape (de Bruin et al., 1999).

A variant of genetic-chorologic classification is the ordering of landscapes and geoforms in the context of a given country (Zinck, 1974; Elizalde, 2009). This type of classification combines physico-geographic units at the higher levels of the system with taxonomic units at the lower levels. The physico-geographic units belong to a specific regional context and, therefore, cannot be generalized or extrapolated to other regional situations. The division of a country into physiographic provinces and regions is an example of this type of nomenclature. Instead, the taxa of the lower categories (e.g. landscape types or relief types) convey sufficient abstraction to be recognizable on the basis of differentiating features in a variety of regional contexts.

5.2.3 Morphometric classification

First attempts of morphometric relief characterization go back to mid-19th century in the Germanic countries. However, it was only after the Second World War that systematic use of morphometric techniques was made to describe features of the topography, parameters of the hydrographic network, drainage density and other measurable attributes of the relief (Tricart, 1965a). In recent decades, the technology of the digital elevation models (DEM) has given a new impulse to morphometry and automated extraction of morphometric information (Pike & Dikau, 1995; Hengl & Reuter, 2009). Geomorphometry focuses on the quantitative analysis of the terrain surface with two orientations: a specific morphometry that analyzes the discrete features of the terrain surface (e.g. landforms/terrain forms), and a general morphometry that deals with the continuous features. In its present state, geomorphometry pursues essentially the characterization and digital analysis of continuous topographic surfaces (Pike et al., 2009).

The use of DEM has allowed measuring and extracting the attributes that describe the topographic features of the landscape (Gallant & Wilson, 2000; Hutchinson & Gallant, 2000; Olaya, 2009). The most frequently measured parameters include altitude, slope, exposure, curvature and roughness of the relief, among others. The spatial distribution of these parameters allows inferring the variability of hydrologic, geomorphic and biological processes in the landscape. The combination of data derived from DEM and satellite images contributes to improve predictive models (Dobos et al., 2000).

There are attempts to classify landforms and model landscapes using morphometric parameters (Evans et al., 2009; Hengl & MacMillan, 2009; Nelson & Reuter, 2012). Idealized geometric primitives (Sharif & Zinck, 1996) and ideal elementary forms (Minár & Evans, 2008) have been used to segment the landscape and approximate the representation of a variety of terrain forms. The implementation of automated algorithms to classify landforms has led to determine and map landform elements and relief classes (Pennock et al., 1987; MacMillan & Pettapiece, 1997; Ventura & Irvin, 2000; Meybeck et al., 2001; Iwahashi & Pike, 2007; MacMillan & Shary, 2009). Ventura & Irvin (2000) analyze different methods of automated landform classification for soil landscape studies, but the experiments are basically restricted to slope situations according to the classic models of Ruhe (1975) and Conacher & Dalrymple (1977). The use of quantitative parameters allows describing continuous variations of the topographic features with the fuzzy sets technique (Irwin et al., 1997; Burrough et al., 2000; MacMillan et al., 2000). However, this approach may result being a drawback, when ignoring or disregarding the differentiating characteristics of the geoforms as discrete units, which are frequent in erosional areas (e.g. gullies, solifluction features) as well as in depositional areas (e.g. alluvial or eolian systems). The DEM-based analysis leads to a classification of the topographic features of the relief and contributes to the morphometric characterization of the terrain forms, but does not generate a terrain form classification in the geomorphic sense of the concept. The classification of slope facets by shape and gradient is essentially a descriptive classification which does not convey information on the origin of the relief. However, this kind of classification results in an organization of the relief features that allows formulating hypotheses about their origin (Small, 1970). Compared with the multiplication of tests carried out in rugged areas, the possibilities of digital mapping in flat areas, especially areas of depositional origin, have been so far less explored.

In the FAO Guidelines for soil description (2006), landforms are described by their morphology and not by their origin or forming processes. The proposed landform classification in a two-level hierarchy is based mainly on morphometric criteria. At the first level, three classes called, respectively, level land, sloping land, and steep land, are considered. These classes are subdivided according to three morphometric attributes including slope gradient, relief intensity, and potential drainage density. Applying this procedure to the level-land class, for instance, four subclasses are recognized, namely plain, plateau, depression, and valley floor. Sloping-land and steep-land include plain, valley, hill, escarpment zone, and mountain subclasses, differentiated by the above morphometric features.

5.2.4 Ethnogeomorphic classification

Indigenous people in traditional communities use topographic criteria, before taking the soils into consideration, to identify ecological niches suitable for selected crops and management practices. Their approach to segment a hillside into relief units is similar to the slope facet models of Ruhe (1975) and Conacher & Dalrymple (1977). Likewise in depositional environments, where the topographic variations are often subtle and less perceptible, farmers clearly recognize a variety of landscape positions, as for instance the characteristic *banco-bajio-estero* trio (bank-depression-backswamp) for pasture management in the Orinoco river plains. Trials of participatory mapping, with the collaboration of local land users and technical staff, show that the mental maps of the peasants visualize the relief using a detailed nomenclature, which allows converting them into real maps that are very similar to the geomorphic maps prepared by specialists (Fig. 5.1) (Barrera-Bassols et al., 2006, 2009).

Indigenous soil classifications usually include the relief at the top level of the classification system, forming the basis of ethnogeopedology. In their perception of the environment, indigenous farmers use the relief, along with other features of the landscape, as a main factor for identifying, locating and classifying soils. Because of the importance that both disciplines give to the relief factor, ethnopedology and geopedology are strongly related.

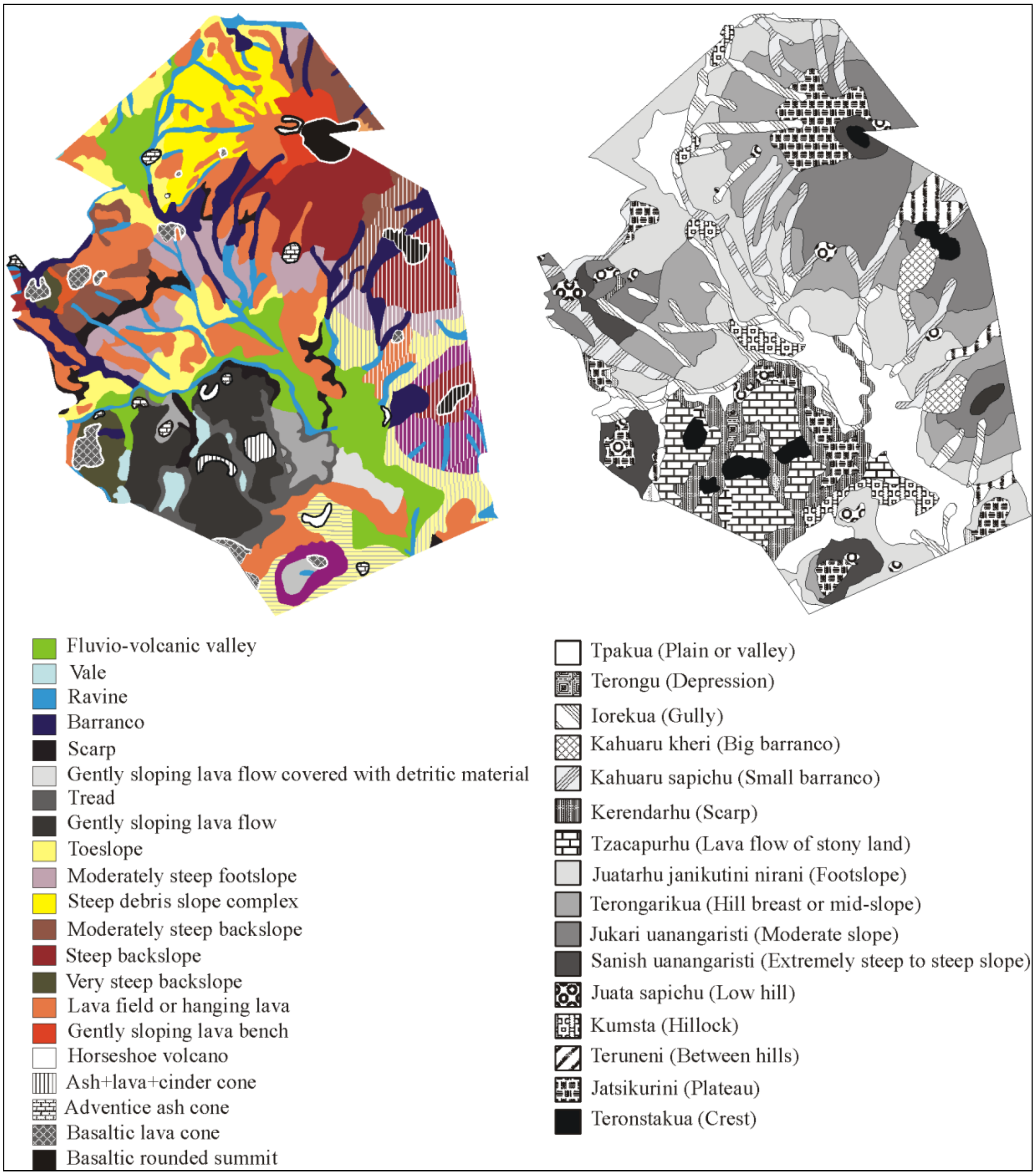


Fig. 5.1 Comparison of a geomorphic map made using technical criteria (left) and a relief map drawn up according to the indigenous Purhépecha nomenclature (right) of the territory of San Francisco Pichátaro, Michoacán, in the volcanic belt of Central Mexico (Barrera-Bassols et al., 2006).

5.3 Bases for a taxonomic classification system of the geoforms

5.3.1 Premises and basic statements

To contribute improving the traditional approaches to geomorphic classification, hereafter a set of assumptions is formulated as a basis for structuring a taxonomic system of the geoforms.

- The object to be classified is a unit of the geolandscape (or subdivision thereof) that can be recognized by its configuration and composition. The most commonly used term to designate this entity in English-written geomorphic literature is *landform.* The same term is indistinctly used by geomorphologists, geologists, pedologists, agronomists, ecologists, architects, planners, contemplative and active users of the landscape, among others, but there is no standard definition accepted by all. In the FAO Guidelines for soil description (2006), the concept of *major landform* is considered to refer to the morphology of the whole landscape. Way (1973) provides a kind of satisfactory definition in the following terms: "*Landforms* are terrain features formed by natural processes, which have a defined composition and a range of physical and visual characteristics that occur wherever that the form is found and whatever is the geographic region". In Spanish language, landform literally means *forma de tierra(s*), a term that has an agricultural or agronomic connotation. *Land* in landscape ecology includes not only the physical features of the landscape but also the biota and the human activities (Zonneveld, 1979, 1989). The term *terrain form* is more appropriate to designate the elementary relief forms, while the term *geoform* is the generic concept that encompasses the geomorphic units at all categorial levels. *Terrain form* is etymologically equal to terms with similar geomorphic meaning used in other languages, such as *forma de terreno* in Spanish and *forme de terrain* in French.
- The objects that are classified are the geoforms, or geomorphic units, which are identified on the basis of their own characteristics, rather than by reference to the factors of formation. Local or regional combinations of criteria such as climate, vegetation, soil and lithology, which are associated with the geoforms and contribute to their formation, can be referred to in the legend of the geomorphic map, but are not intrinsically part of the classification of the geoforms. The climate factor is implicitly present in the geoforms originated by exogenous morphogenic agents (snow, ice, water, wind).
- Classes of geoforms are arranged hierarchically to reflect their level of membership to the geomorphic landscape. For instance, a river levee is a member of a terrace, which in turn is a member of a valley landscape. Therefore, levee, terrace, and valley shall be placed in different categories in a hierarchic system, because they correspond to different levels of abstraction. Similarly, the slope facets (i.e. summit, shoulder, backslope, and footslope) are members of a hill, which is a member of a hilland type of landscape.
- The genesis of the geoforms is taken into consideration preferably at the lower levels of the taxonomic system, since the origin of the geomorphic units can be a matter of debate and the genetic attributes may be not clear or controversial, or their determination may require a number of additional data. At higher levels, the use of more objective, rather descriptive attributes is privileged, in parallel with the criteria of pattern recognition implemented in photo and image interpretation.

- The dimensional characteristics (e.g. length, width, elevation, slope, etc.) are subordinate attributes and are not diagnostic for the identification of the geoforms. A geoform belongs to a particular class regardless of its size, provided it complies with the required attributes of this class. For instance, the extent of a dune or a landslide can vary from a few m^2 to several km^2.
- The names of the geoforms are often derived from the common language and some of them may be exposed to controversial interpretation. Priority is given here to those terms that have greater acceptation by their etymology or usage.
- The concepts of physiographic province and natural region, as well as other kinds of chorologic units related to specific geographic contexts, are not taken into account in this taxonomic system, because they depend on the particular conditions of a given country or continental portion, a fact that limits their level of abstraction and geographic repeatability.
- The geographic distribution of the geoforms is not a taxonomic criterion. The chorology of the geoforms is reflected in their cartography and in the structure of the geomorphic map legend.
- Toponymic designations can be used as phases of the taxonomic units (e.g. Cordillera de Mérida, Pantanal Basin).

5.3.2 Prior information sources

The development of the geoform classification system uses prior knowledge in terms of concepts, methods, information, and experience.

- Existing geoform typologies, with definitions and descriptive attributes, have been partially taken from the literature. The purpose of the proposed classification is to organize the available knowledge in a hierarchic taxonomic system. Some of the key documents that were consulted for this purpose are as follows:
  - Various classic texbooks of geomorphology: Tricart & Cailleux (1962, 1965, 1967, 1969), Tricart (1965a, 1968, 1977), Derruau (1965, 1966), Thornbury (1966), Viers (1967), CNRS (1972), Garner (1974), Ruhe (1975), Huggett (2011), among others.
  - Dictionaries and encyclopedias: Visser (1980), Lugo-Hubp (1989), Fairbridge (1997), Goudie (2004), among others.
  - Manuals of geomorphic photo-interpretation: Goosen (1968), Way (1973), Verstappen & Van Zuidam (1975), Verstappen (1983), Van Zuidam (1985), among others.
- For the structure of the system, inspiration was taken from the conceptual framework of the USDA Soil Taxonomy (Soil Survey Staff, 1975, 1999) with regard to the concepts of category, class, and attribute.
- Development and validation of the system have taken place essentially in Venezuela and Colombia, within the framework of soil survey projects at different scales from detailed to generalized, with the implementation of geomorphology as a tool for soil mapping (applied geomorphology). The system was modified and improved progressively as ongoing field surveys provided new knowledge. Subsequently, the already established system became teaching and training matter in postgraduate courses in soil survey at the ITC (Zinck, 1988) for students from different parts of the world, especially Latin America, Africa, Middle East, and Southeast Asia.

5.3.3 Searching for structure: an inductive example

Let's consider the collection of objects included in Fig. 5.2 (Arnold, 1968). Squares, triangles, and circles can be recognized. The objects are large or small, green (G) or red (R). Thus the objects are different by shape, size and color. Based on these three criteria, the objects may be classified in various ways. One option is to sort the objects first by size, then by color, and finally by shape (Fig. 5.3). They can also be sorted successively by shape, color and size. Six hierarchization alternatives are possible. This simple experiment shows that artificial or natural objects may be classified in various ways. Any alternative is valid, if it meets the objective pursued.

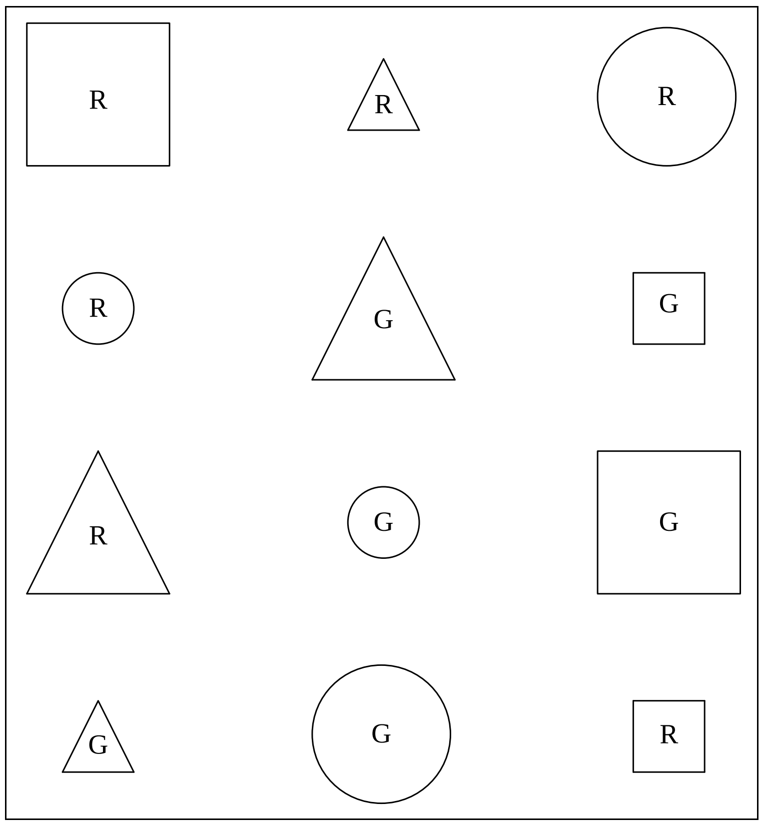


Fig. 5.2 Collection of objects different by shape, size and color (Arnold, 1968).

From example in Fig. 5.2, three basic elements of a hierarchic classification system can be induced by effect of generalization: category, class, and attribute.

- The categories are hierarchic levels that give structure to the classification system. Three categories are present, identified by generic criteria (size, color, shape). Several (6) hierarchic arrangements are possible.
- Classes are groups of objects that have one or more differentiating characteristics in common. There are seven differentiating characteristics: large, small, red, green, square, triangular, and circular. The aggregation of characteristics generates an increase of classes from the top to the bottom of the system.

- Attributes are characteristics or properties of the objects, such as red, green, large, small, square, triangular, and circular.

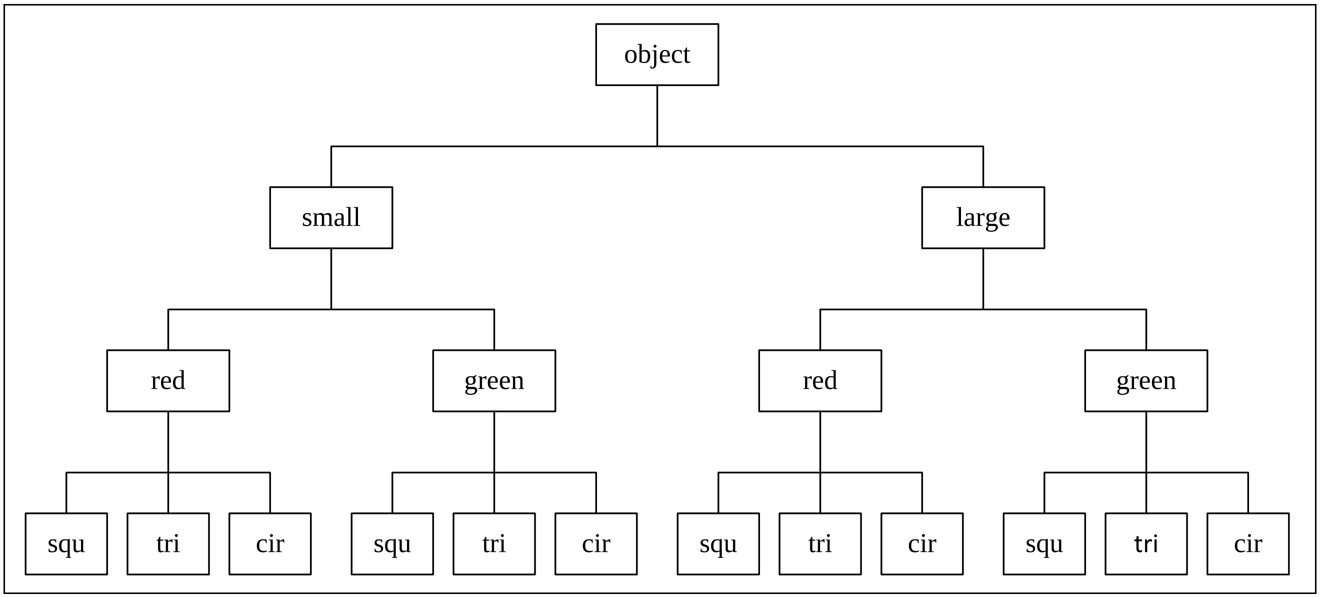


Fig. 5.3 Hierarchic arrangement of the objects displayed in Fig. 5.2 by size (2 classes), color (4 classes), and shape (12 classes) (squ = square, tri = triangular, cir = circular).

5.4 Structure and elements for building a taxonomic system of the geoforms

A taxonomic system is characterized by its structure (or configuration) and its elements (or components).

5.4.1 Structure

Various configuration models are possible: hierarchic, relational, network, and linear, among others (Burrough, 1986). In general, the hierarchic multicategorial model is considered appropriate for taxonomic purposes. Haigh (1987) states that the hierarchic structure is a fundamental property of all natural systems, while Urban et al. (1987) consider that breaking a landscape into elements within a hierarchic framework allows to partially solve the problem of its apparent complexity. Although a hierarchic structure is less efficient than, for instance, a relational system or a network system in terms of automated data handling by computer, it is however particularly suitable for archiving, processing and retrieving information by the human mind (Miller, 1956, 2003).

A system can be compared to a box containing all the individuals belonging to the object that is sought to be classified: for example, all soils, all geoforms. The collection of individuals constitutes the universe that is going to be divided into classes and arranged into categories. The classification results in (1) a segmentation of the universe under consideration (e.g. the soil cover continuum) into populations, groups, and individuals by descending disaggregation, and (2) a clustering of individuals into groups, populations, and universe by ascending aggregation.

5.4.2 Elements

5.4.2.1 Category

A category is a level of abstraction. The higher the level of the category, the higher the level of abstraction. Each category comprises a set of classes showing a similar level of abstraction. A category is identified by a generic concept that characterizes all classes present in this level (color, size, shape, in Fig. 5.3). For instance, a valley landscape, a fluvial terrace, and a river levee are objects belonging to different levels of abstraction. The levee is a member of the terrace, which in turn is a member of the valley. In a hierarchic system of geoforms, these geomorphic entities shall be placed in three successive categories.

5.4.2.2 Class

A class is a formal subdivision of a population at a given categorial level. A class can be determined using different modalities among which the two following are commonly implemented: (1) the range of variation of a diagnostic attribute or a combination thereof, and (2) a central class concept in relation to which other classes deviate by one or more characteristics.

An example of the first modality is provided by the way the percentage of base saturation is used in soil taxonomy as a threshold parameter to separate Alfisols (≥35%) and Ultisols (<35%). Using a similar procedure, the strata dip in sedimentary rocks allows separating several classes of monoclinal relief, including mesa, cuesta, creston, hogback, and bar (Fig. 5.4). A similar approach can be applied to the classification of the geoforms caused by mass movements through segmentation of the continuum between solid and liquid states using the consistence limits (Fig. 5.5). There are very few references in the geomorphic literature where the segmentation of a continuum is used to differentiate related geoforms.

The central typifying concept is used to position a typical class in relation to intergrades and extragrades, which depart from the central class by deviation of some attributes. This is the case, for instance, of the "Typic" as used at subgroup level in the USDA Soil Taxonomy (Soil Survey Staff, 1975, 1999). No examples were found in the geomorphic literature that formally implement this concept to distinguish modal situations from transitional situations.

5.4.2.3 Taxon

A taxon (or taxum) is a concrete taxonomic unit as a member of a class established at a given categorial level. Usually, a particular taxon covers only part of the range of variation allowed in the selected attributes that define the class. For instance, the texture of a river bank, above the basal gravel strata, can vary from gravelly to sandy clay loam. A particular bank can be sandy to sandy loam without covering the entire diagnostic textural range.

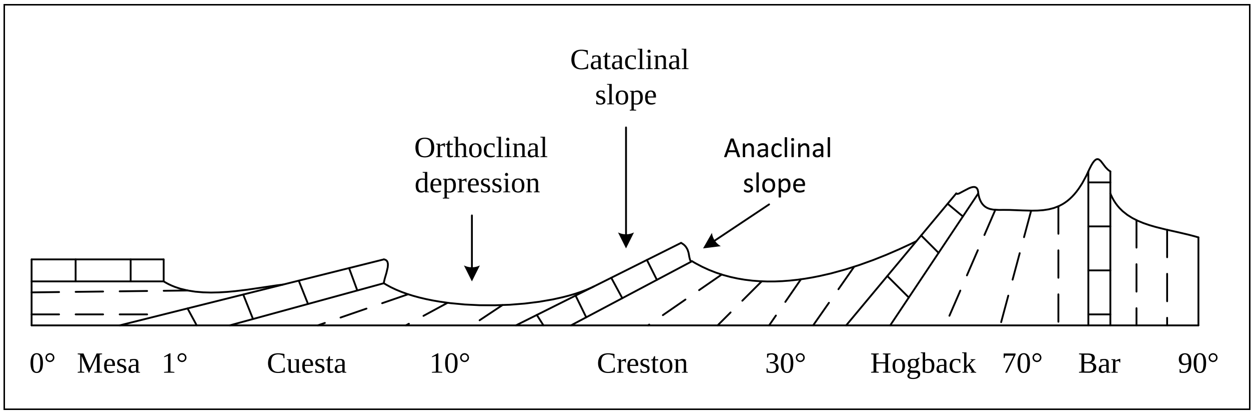


Fig. 5.4 Monoclinal relief classes determined based on strata dip ranges in sedimentary bedrocks (e.g. limestone, sandstone) (adapted from Viers, 1967).

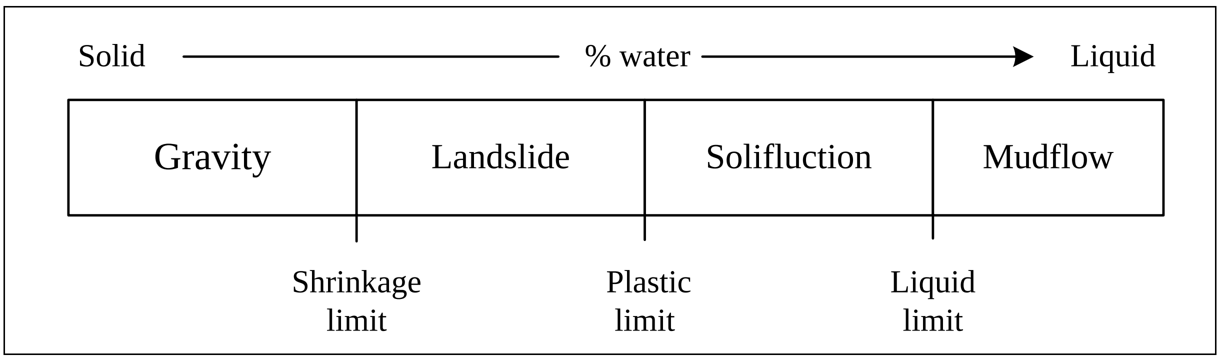


Fig. 5.5 Classes de geoforms originated by different kinds of mass movement.

5.4.2.4 Attribute

An attribute is a characteristic (or variable) used to establish the limits of the classes that make up the system and to implement these limits in the description and classification of individuals. There are several kinds of attribute, as for instance:

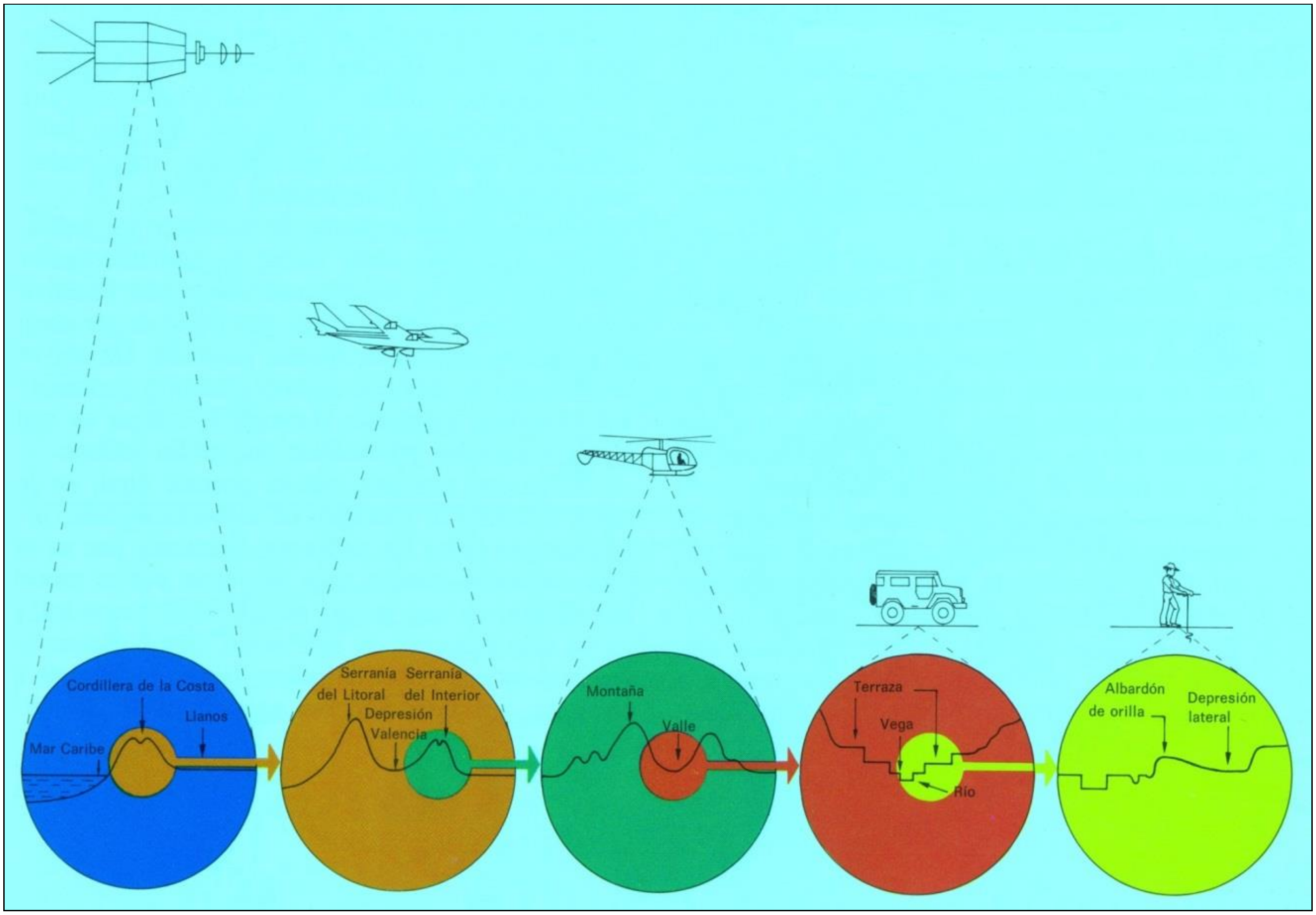
- Dichotomous: e.g. presence or absence of iron reduction mottles, concentration of carbonates or other salts.
- Multi-state without ranges: e.g. types of soil structure, types of depositional structure.
- Multi-state with ranges: e.g. size of structural aggregates, plasticity and adhesion classes.
- Continuous variation: e.g. base saturation, bedrock dip.

To implement these basic taxonomic criteria in geomorphology requires the following: (1) the inventory of the known geoforms and their arrangement in a hierarchic system, and (2) the selection, categorization (diagnostic or not), hierarchization, and measurement of the attributes used to identify and describe the geoforms.

5.5 Levels of perception: exploring the structure of a geomorphic space

Geomorphology is primarily a science of observation, aiming at the identification and separation of landscapes from topographic maps, digital elevation or terrain models, and remote-sensed documents allowing stereoscopic vision, but mainly by reading the physiographic features in the field. Geoforms can be perceived by human vision or artificial sensors, because they have a physiognomic appearance on the earth's surface (i.e. geolandscape). Physiography describes this external appearance corresponding to the epigeal component of the geoforms. Thanks to their scenic expression, the geoforms are the most directly structuring elements of the terrain, more than any other object or natural feature. Even a non-scientific observer can notice that any portion of the earth's crust shows a structure determined by the relief, which allows subdividing it into components. The times that a terrain area can be subdivided into elements depend on the level of perception used for the segmentation. Although the concept of perception level is subjective when the human eye is used, it helps hierarchize the structural components of a terrain surface.

Hereafter, an example is developed that illustrates the effect of the perception scale on the sequential identification of different terrain portions. The example refers to the contact area between the Caribbean Sea and the northern edge of the South American continent in Venezuela (Zinck, 1980). The use of successive perception levels, increasingly detailed, materialized by observation platforms of decreasing elevation in relation to the earth's surface, allows dividing the selected portion of continent into classes of geoforms that are distributed over various hierarchic categories (Fig. 5.6 and Table 5.3). An observer mounted on a spaceship at about 800-1000 km elevation would distinguish two physiographic provinces, namely the east-west oriented coastal mountain chain of the Cordillera de la Costa to the north and the basin of the Llanos Plains to the south. These two macro-units of contrasting relief correspond to two types of geostructure: a folded cordillera-type mountain chain and a geosincline-type sedimentary basin, respectively. From a airplane flying at about 10 km elevation, one can distinguish the two parallel branches of the Cordillera de la Costa, namely the Serranía del Litoral range to the north and the Serranía del Interior range to the south, separated by an alignment of tectonic depressions such as that of the Valencia Lake. These units are natural regions that correspond to types of morphogenic environment: the mountain ranges are structural environments undergoing erosion, whereas depressions are depositional environments. When increasing the level of perception as from an helicopter flying at two km elevation, a mountain range can be divided into mountain and valley landscapes. A field transect through a valley will allow to cross a series of topographic steps with risers and treads that correspond to fluvial terraces. Detailed field observation of the topography and sediments in a given terrace will reveal a sequence of depositional units from the highest, the river levee (bank), to the lowest, the decantation basin (swamp). The results of this exploratory inductive procedure, leading to a sequential segmentation of a portion of continent, are summarized in Table 5.3. This empirical approach generates a hierarchic scheme of geoforms in five nested categorial levels, each identified by a generic concept from general to detailed (Fig. 5.7).



Physiographic province | Natural region | Geomorphic landscape | Relief/Molding | Terrain form

Fig. 5.6 Successive levels of perception of geoforms from different observation elevations (Zinck, 1980). The features referred to are explained in Table 5.3.

Table 5.3 Sequential identification of geoforms according to increasing levels of perception (based on the features observed in Fig. 5.6) (Zinck, 1988).

Observation platform	Observation area	Observed features	Criteria used Inferred factors	Resulting geoforms	Derived generic categorial concepts
Satellite	Large continental portion	*Cordillera de la Costa* narrow, longitudinal, high relief mass; abrupt limits	Topography Internal geodynamics (orogenic area)	Cordillera (folded mountain chain)	Geostructure
		Llanos del Orinoco Extensive, flat, low relief mass	Topography Internal geodynamics (sinking area)	Geosyncline (sedimentary basin)	
Airplane	Cordillera	*Serranía del Litoral* *Serranía del Interior* parallel, dissected mountain ranges	Topography Internal/external geodynamics (erosion)	Structural/ erosional environment	Morphogenic environment
		Depresión de Valencia Low-lying, flat terrain areas; concave margins	Topography Internal/external geodynamics (sedimentation)	Depositional environment	
Helicopter	Structural/ erosional environment	Parallel mountain ridges	Topography Tectonics Hydrography	Mountain	Geomorphic landscape
		Narrow longitudinal depressions, parallel or perpendicular to the ridges	Topography Tectonics Hydrography	Valley	
Earth surface	Valley	Topographic step treads separated by risers	Topography	Terrace	Relief/molding
		Valley bottom, river system, riparian forest	Topography Drainage Vegetation	Floodplain	
Terrain surface and subsurface	Terrace	Longitudinal, narrow, convex bank; well drained, coarse-textured	Topography Drainage Morphogenesis	Levee	Terrain form
		Large, concave depression, poorly drained, fine-textured	Topography Drainage Morphogenesis	Basin	

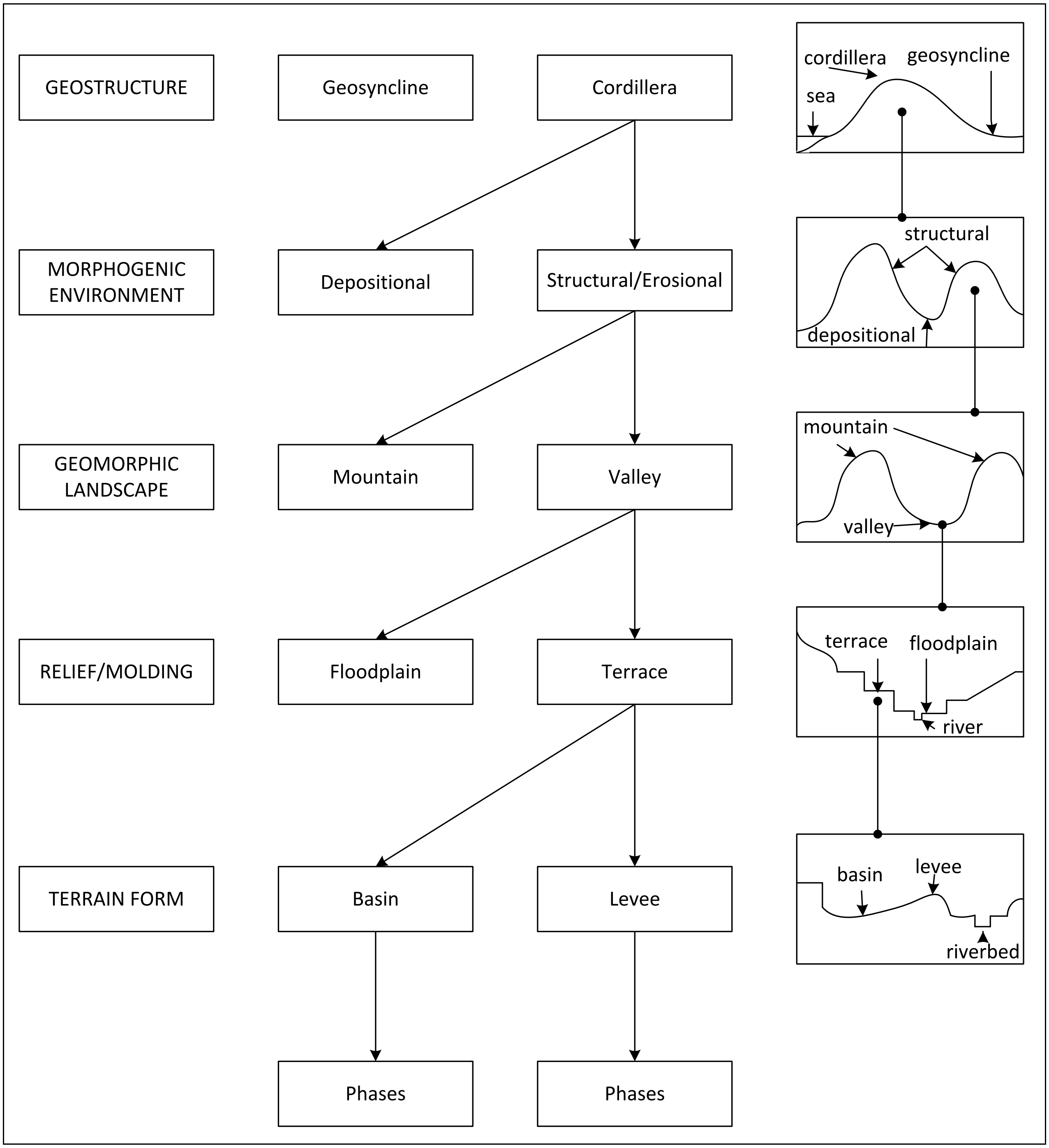


Fig. 5.7 Generalization of the information displayed in Table 5.3 (Zinck, 1988).

5.6 Structure of a taxonomic system of the geoforms

Combining the basic criteria to build a taxonomic system (sections 5.3 and 5.4) with the results of the exploration aimed at detecting guidelines of hierarchic arrangement in the geomorphic environment (section 5.5), a structure of nested categorial levels is obtained. Five of these levels are essentially deduced from the epigeal physiographic expression of the geoforms. The units recognized at the two upper levels are identified by local names, because they belong to a particular national or regional context. These are chorologic units which are formalized as taxonomic units under the generic concept of geostructure and morphogenic environment, respectively. To substantiate the relationship between geoform and soil, it is necessary to introduce in the system information on the internal hypogeal component of the geoforms, namely the constituent material, which is in turn the parent material of the soils. As a result of the foregoing, an additional level is needed to document the lithology in the case of bedrock substratum or the facies in the case of unconsolidated cover materials. After several iterations, it was chosen to insert this category between the level of relief/molding (level 3) and the level of terrain form (level 1). Its inclusion in the lower part of the system is justified by the fact that field data are often needed to supplement or clarify the general information provided by the geologic maps (see Fig. 6.3 and Table 6.2 in Chap. 6). This leads finally to a system with six categorial levels (Table 5.4), identified by their respective generic concepts that are explained in Chapter 6. It can be noted that obtaining a system with six categories complies with the rule called *Miller's Law*, which postulates that the capacity of the human mind to process information covers a range of seven plus or minus two elements (Miller, 1956, 2003).

Table 5.4 Synopsis of the geoform classification system (Zinck, 1988).

Level	Category	Generic concept	Short definition
6	Order	Geostructure	Large continental portion characterized by a type of geologic macro-structure (e.g. cordillera, geosyncline, shield).
5	Suborder	Morphogenic environment	Broad type of biophysical environment originated and controlled by a style of internal and/or external geodynamics (e.g. structural, depositional, erosional, etc.).
4	Group	Geomorphic landscape	Large portion of land/terrain characterized by given physiographic features: it corresponds to a repetition of similar relief/molding types or an association of dissimilar relief/molding types (e.g. valley, plateau, mountain, etc.).
3	Subgroup	Relief/molding	Relief type originated by a given combination of topography and geologic structure (e.g. cuesta, horst, etc.). Molding type determined by specific morphoclimatic conditions and/or morphogenic processes (e.g. glacis, terrace, delta, etc.).
2	Family	Lithology/facies	Petrographic nature of the bedrocks (e.g. gneiss, limestone, etc.) or origin/nature of the unconsolidated cover formations (e.g. periglacial, lacustrine, alluvial, etc.).
1	Subfamily	Landform/terrain form	Basic geoform type characterized by a unique combination of geometry, dynamics, and history.

Chapter 6

THE GEOMORPHIC LANDSCAPE: CLASSIFICATION OF THE GEOFORMS

6.1 Introduction

The terms used here to name the geoforms have been taken from a selection of textbooks, compendia and other general books of geomorphology, including among others: Tricart & Cailleux (1962, 1965, 1967, 1969), Tricart (1965a, 1968, 1977), Derruau (1965, 1966), Thornbury (1966), Viers (1967), CNRS (1972), Garner (1974), Ruhe (1975), Verstappen & Van Zuidam (1975), Visser (1980), Verstappen (1983), Van Zuidam (1985), Lugo-Hubp (1989), Fairbridge (1997), and Goudie (2004). Presumably, the readers may not unanimously agree with the proposed terminology, as some terms can be subject to controversial interpretation or variability of use among geomorphologists, geomorphology schools, and countries.

A part of the geomorphic vocabulary is of vernacular origin, derived from terms used locally to describe landscape features and transmitted orally from generation to generation (Barrera-Bassols et al., 2006). Many of these terms, originally extracted from indigenous knowledge by explorers and field geomorphologists, subsequently received more precise definitions and were gradually incorporated into the scientific language of geomorphology. A typical example is the term karst, which refers to a mound of limestone fragments in Serbian language, and now applies to the dissolution process of calcareous rocks and the resulting geoforms. Many terms are used with different meanings depending on the country. For instance, the term *estero* (i.e. swamp), as it is used in Spain, means salt marsh, or tidal flat, or an elongated saltwater lagoon lying between sandbanks in a coastal landscape. In Venezuela, the same term refers to a closed depression, flooded by rainwater most of the time, in an alluvial plain. This kind of semantic alteration of concepts is common in countries colonized by Europeans, who intended to describe unfamiliar landscapes by similarity with their home experience. This resulted in vocabulary confusions and ambiguities that endure today. There is still no uniformly recognized terminology lo label the geoforms, with additional semantic problems when the terms are translated from one language to another. Hereafter, an amalgam of vocables coming from various sources is used to name and describe the classes of geoforms in the six categories of the classification system (see Table 5.4).

6.2 The taxonomy: categories and main classes of geotaxa

The categories in descending order are as follows:

- Geostructure
- Morphogenic environment
- Geomorphic landscape
- Relief/molding
- Lithology/facies
- Terrain form/landform

6.2.1 Geostructure

The concept of geostructure refers to an extensive continental portion characterized by its geologic structure, including the nature of the rocks (lithology), their age (stratigraphy) and their deformations (tectonics). These macro-units are related to plate tectonics. They include three taxa: cordillera, shield, and geosyncline.

- *Cordillera*: a system of young mountain chains, including also plains and valleys, that have been strongly folded and faulted by relatively recent orogenesis. The component ranges may have various orientations, but the mountain chain as a whole usually has one single general direction.
- *Shield*: a continental block that has been relatively stable for a long period of time and has undergone only slight deformations, in contrast to cordillera belts; it is composed mainly of Precambrian rocks.
- *Geosyncline (or sedimentary basin):* wide basin-like depression, usually elongate, that has been sinking deeply over long periods of time and in which thick sequences of stratified clastic sediments, layers of organic material, and sometimes volcanic deposits have accumulated. Through orogeny and folding, geosynclines are transformed into mountain ranges.

6.2.2 Morphogenic environment

The morphogenic environment refers to a general type of biophysical setting, originated and controlled by a style of internal and/or external geodynamics. It comprises six taxa.

- *Structural environment*: controlled by internal geodynamics through tectonic movements (tilting, folding, faulting, overthrusting of bedrocks) or volcanism.
- *Depositional environment*: controlled by the deposition of detrital, soluble and/or biogenic materials, under the influence of water, wind, ice, mass movement, or gravity.
- *Erosional* e*nvironment* (or denudational): controlled by processes of dissection and removal of materials transported by water, wind, ice, mass movement, or gravity.
- *Dissolutional environment:* controlled by processes of rock dissolution generating chemical erosion (karst in calcareous rocks, pseudokarst in non-calcareous rocks).
- *Residual environment:* characterized by the presence of surviving relief features (e.g. inselberg).
- *Mixed environment*: e.g. a structural environment dissected by erosion.

6.2.3 Geomorphic landscape

6.2.3.1 Definition

Landscape is a complex concept which covers a variety of meanings:

- In common language: scenery of a portion of land or its pictorial representation.
- In media language: political, financial, intellectual, artistic landscape, etc.
- In scientific language: term used differently in landscape ecology, pedology, biogeography, geomorphology, architecture, etc.

- In the geomorphic literature: the expression *geomorphic landscape* is used without taxonomic connotation or mention of the level of generalization; it can thus correspond to any of the six categories of the system described here.
- Adopted definition: large land surface characterized by its physiographic expression; it is formed by a repetition of similar types of relief/molding or an association of dissimilar types of relief/molding. For instance, an active alluvial plain may consist of a systematic repetition of the same molding type, namely a set of floodplains. In contrast, a valley usually shows an association of various molding types, such as floodplain, terrace, fan, and glacis.
- Ambiguity of the concept of landscape: a valley, for instance, can cover three different kinds of spatial frame (Fig. 6.1):
  - An area of longitudinal transport and deposition of sediments, including the floodplain and terraces of the valley bottom. This space corresponds to the concept of valley sensu stricto.
  - An area similar to the previous one plus the sectors of lateral deposition forming fans and glacis. This space modeled by side deposits actually corresponds to the concept of piedmont landscape.
  - An area controlled by human settlements, including the lower parts of the surrounding mountain slopes. This portion of space in fact belongs to the mountain landscape.

  There is no consensus on whether restricting the concept of valley to the area covered by longitudinal deposits or also including one or both of the two other components.

6.2.3.2 Taxa

The present system of geoform classification recognizes seven taxa at the categorial level of geomorphic landscape: valley, plain, peneplain, plateau, piedmont, hilland, and mountain (Fig. 6.2).

- *Valley*: elongated portion of land, flat, lying between two bordering areas of higher relief (e.g. piedmont, plateau, hilland, or mountain). A valley is usually drained by a single river. Stream confluences are frequent. For recognition, a valley must have a system of terraces which, in its simplest expression, comprises at least a floodplain and a lower terrace. In the absence of terraces, it is merely a fluvial incision, which is expressed on a map by the hydrographic network.
- *Plain*: extensive portion of land, flat, unconfined, low-lying, with low relief energy (1-10 m of relative elevation difference) and gentle slopes, usually less than 3%. Several rivers contribute to form a complex fluvial system. Stream diffluences are frequent.
- *Peneplain*: slightly undulating portion of land, characterized by a systematic repetition of low hills, rounded or elongated, with summits of similar elevation, separated by a dense hydrographic network of reticulated pattern. The hills and hillocks are formed either by dissection of a plain or plateau or by downwasting and flattening of an initially rugged terrain surface. Often, a peneplain consists of an association of three types of relief/molding: namely hills surrounded by a belt of glacis and, further, by peripheral colluvio-alluvial vales.
- *Plateau*: large portion of land, relatively high, flat, commonly limited at least on one side by an escarpment relating to the surrounding lowlands. It is frequently caused by tectonic

uplift of a plain, subsequently subdivided by incision of deep gorges and valleys. The summit topography is table-shaped or slightly undulating, because erosion is mostly linear. The plateau landscape is independent of specific altitude, provided it complies with the diagnostic characteristics of this kind of geoform, such as high position, tabular topography, and escarpments along the edges and along water courses that deeply incise the relief. According to this definition, the table-shaped relief of the Mesa Formation in eastern Venezuela, cut by valleys of variable depth (40-100 m), makes up a plateau landscape at no more than 200-300 masl, while the Bolivian Altiplano is a plateau landscape lying at 3500-4000 masl.

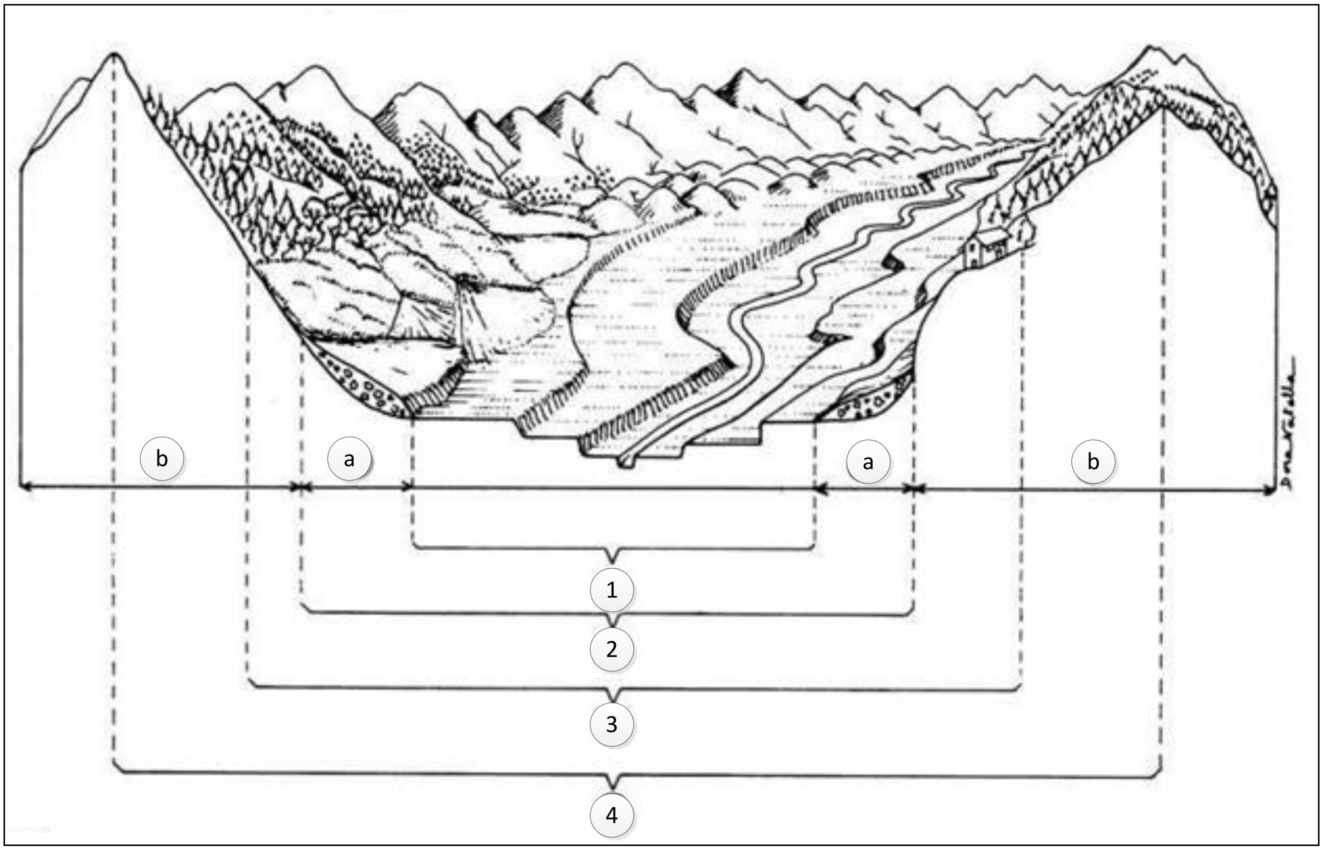


Fig. 6.1. Various definitions of the "valley" concept and their spatial expressions (Zinck, 1980).

1. Valley as an area where sediments of longitudinal origin, coming from the catchment area of the upper watershed, are deposited in the floodplain and terraces of the valley bottom.
2. Valley as an area where longitudinal as well as lateral sediments are deposited, including therefore piedmont glacis and fans.
3. Valley as an area directly influenced by human occupation and activities, including the lower reaches of the surrounding mountain slopes.
4. Hydrographic basin delineated by the water divides between adjacent watersheds.

a. Piedmont
b. Mountain

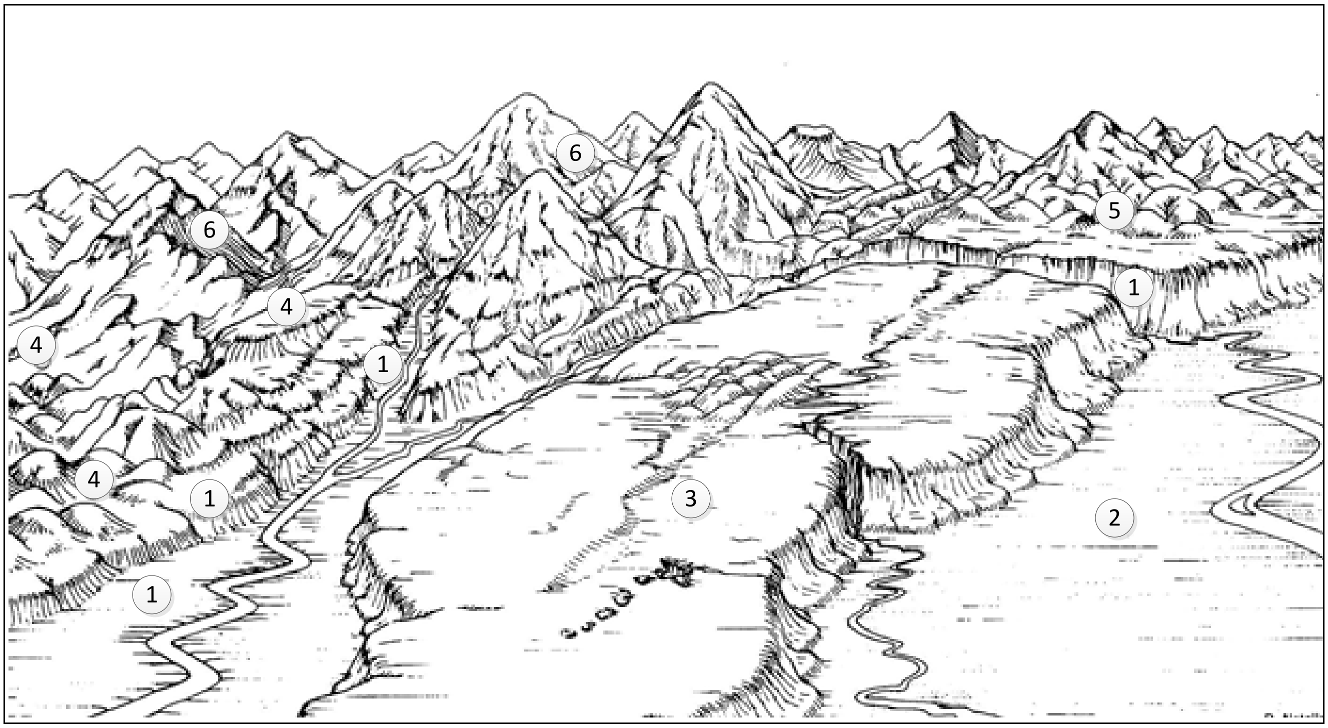


Fig. 6.2 Types of geomorphic landscape (Zinck, 1980).
1: valley; 2: plain; 3: plateau; 4: piedmont; 5: hilland; 6: mountain

- *Piedmont:* sloping portion of land lying at the foot of higher landscape units (e.g. plateau, mountain). Its internal composition is generally heterogeneous and includes:
  - hills and hillocks formed from pre-Quaternary substratum, exposed by exhumation after the Quaternary alluvial cover has been partially removed by erosion;
  - fans and glacis, often in terrace position (fan-terrace, glacis-terrace), composed of Quaternary detrital material carried by torrents from surrounding higher terrains.

  Piedmonts located at the foot of recent mountain systems (cordilleras) usually show neotectonic features, as for example faulted and tilted terraces.
- *Hilland:* rugged portion of land, characterized by a repetition of high hills, generally elongated, with variable summit elevations, separated by a moderately dense hydrographic network and many colluvio-alluvial vales.
- *Mountain:* high portion of land, rugged, deeply dissected, characterized by:
  - important relative elevations in relation to external surrounding lowlands (e.g. plains, piedmonts);
  - important internal dissection, generating a net relief energy between ridge crests and intramountain valleys.

6.2.4 Relief/molding

6.2.4.1 Definition

The concepts of relief and molding are based on the definition that is commonly given to both terms in the geomorphic French literature (Viers, 1967).

- Relief: geoform that results from a particular combination of topography and geologic structure (e.g. cuesta relief); largely controlled by the internal geodynamics.
- Molding: geoform determined by specific morphoclimatic conditions or morphogenic processes (e.g. glacis, fan, terrace, delta); largely controlled by the external geodynamics.

6.2.4.2 Taxa

Relief and molding include an ample variety of taxa that can be grouped into families according to the dominant forming process: structural, erosional, depositional, dissolutional, and residual (Table 6.1). In general, the geomorphic literature does not establish a clear differentiation between geoforms of level 4 (relief/molding) and geoforms of level 6 (terrain form/landform). The list of geoforms in Table 6.1 was obtained by iteration, taking into account the possibility to subdivide types of relief and molding into terrain forms/landforms at level 6 of the system. It is an open-ended collection, which can be improved by the incorporation of additional geoforms.

Table 6.1 Relief and molding types (Zinck, 1988).

Structural	Erosional	Depositional	Dissolutional	Residual
depression	depression	depression	depression	planation surface
mesa (meseta)	vale	swale	dome	dome
cuesta	canyon (gorge)	floodplain	tower	inselberg
creston	glacis	flat (e.g. tidal flat)	hill (hum)	monadnock
hogback	mesa (meseta)	terrace	polje	tors (boulders field)
bar	hill (hillock)	mesa (meseta)	blind vale	…
flatiron	crest	fan	dry vale	
escarpment	rafter (chevron)	glacis	canyon	
graben	ridge	bay	…	
horst	dike	delta		
anticline	trough (glacial)	estuary		
syncline	cirque (glacial)	marsh		
excavated anticline	…	coral reef		
hanging syncline		atoll		
combe		…		
ridge				
cone (dome)				
dike				
…				

6.2.5 Lithology/facies

6.2.5.1 Definition

Level 5 provides information on (1) the petrographic nature of the bedrocks that serve as hard substratum to the geoforms, and (2) the facies of the unconsolidated cover formations that often constitute the internal hypogeal component of the geoforms. In both cases, the information concerns the parental material of the soils.

If the taxonomic system were restricted to depositional geoforms, the present categorial level could result redundant and therefore superfluous, as the lithology would be conveniently covered by the facies of the geomorphic material (i.e. the parent material of the soil) at level 6 of the system (i.e. the terrain form level). However, in areas where the soils are formed directly or indirectly from consolidated geologic material, the system should allow entering information about the lithology of the bedrocks.

In some geomorphic classification systems, the lithology is referred to at high categorial levels. For instance, in the case of the geomorphic map of France, lithology is the second information layer in the structure of the legend, following a first level that deals with the location of the description sites (CNRS, 1972).

Analyzing the portion of terrain represented in Fig. 6.3, an observer would recognize successively (hierarchically) the patterns identified in Table 6.2, by reasoning in the field or by photo-interpretation. The example shows that lithology is best positioned below the categorial levels where the concepts of landscape and relief/molding are located, respectively, taking into account factors such as the hierarchic subdivision mechanism, the level of perception and the degree of resolution through interpretation of aerial photos (API), and the need for field and laboratory data.

6.2.5.2 Taxa

- Bedrocks (according to conventional rock classification):
  - igneous rocks, including intrusive rocks (e.g. granite, granodiorite, diorite, gabbro) and extrusive rocks (e.g. rhyolite, dacite, andesite, basalt)
  - metamorphic rocks (e.g. slate, schist, gneiss, quartzite, marble)
  - sedimentary rocks (e.g. conglomerate, sandstone, limolite, shale, limestone)
- Facies of unconsolidated materials:
  - nival (snow)
  - glacial (ice, glacier)
  - periglacial (ice, cryoclastism, thermoclastism)
  - alluvial (concentrated water flow = fluvial = river)
  - colluvial (diffuse water flow)
  - diluvial (torrential water flow)
  - lacustrine (freshwater lake)
  - lagoonal (brackish water lake)
  - coastal (fringe between continent and ocean; tidal)
  - mass movement (plastic or liquid debris flow; landslide)
  - gravity (rock fall)
  - volcanic (surface flow or aerial shower of extrusive igneous materials)
  - biogenic (coral reef)
  - mixed (fluvio-glacial, colluvio-alluvial, fluvio-volcanic)
  - anthropic (kitchen midden, sambaqui, tumulus, rubble, urban soil, etc.)

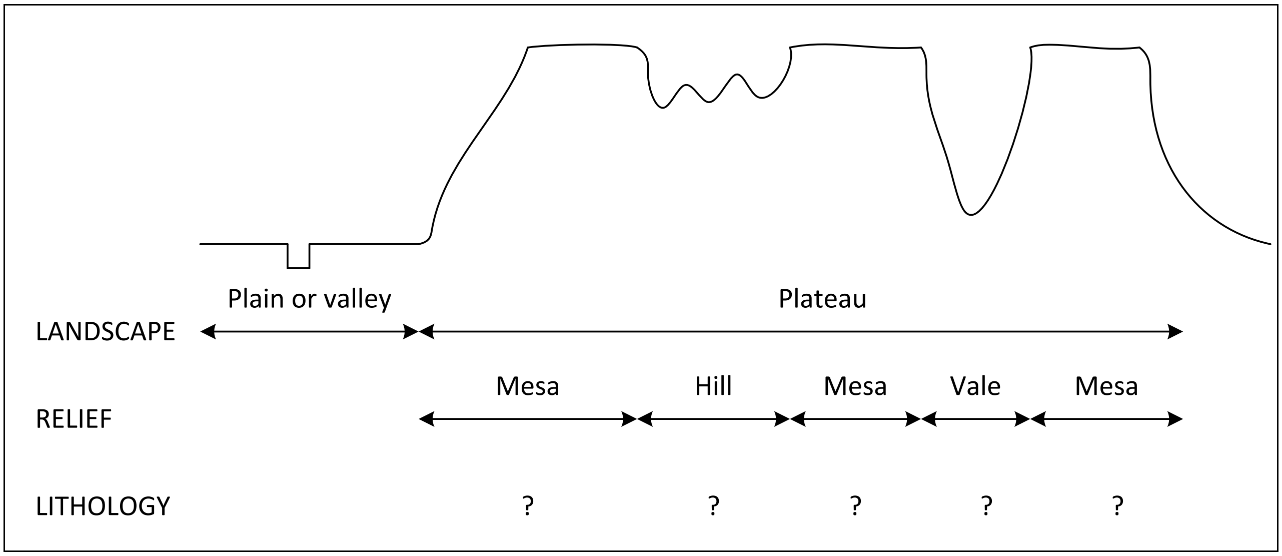


Fig. 6.3 Sequential partition of a plateau landscape into relief patterns to infer the lithology of the substratum (see Table 6.2 for lithology alternatives) (Zinck, 1988).

Table 6.2 Inference of the substratum lithology related to the plateau landscape depicted in Fig. 6.3 (Zinck, 1988).

Categorial level	Identification features	Geoform or material inferred	Generic concept	Resolution	
				API	Field
High	Flat summit topography High position in relation to the surrounding lowlands Abrupt edges (escarpments) Deep river incision	Plateau	Landscape	+	-
Intermediate	Summit topography divided into: (1) level areas (2) undulating areas	(1) Mesas (2) Hills	Relief/ molding	+ -	+ -
Low	(1) If concordance between the slope of the terrain surface and the dip of the underlying rock layers, then structural surface supported by horizontally-lying rock strata. (2) If no concordance between terrain surface and rock dip, then erosional surface truncating no-horizontally-lying rock strata.	(1a) Hard sedimentary rocks (e.g. limestone, sandstone) or (1b) Hard extrusive igneous rocks (e.g. basalt) (2a) Tectonized stratified rocks (sedimentary or volcanic) or (2b) Intrusive igneous rocks	Lithology	-	+

API: aerial photo-interpretation

6.2.6 Terrain form/landform

6.2.6.1 Definition

In general, geomorphology textbooks do not establish a formal hierarchic differentiation of geoforms below the level of landscape. The terms *terrain form* and *landform* are often used as a general concept that covers any type of geomorphic unit from landscape level down to the lower levels of the system, without distinction of the degree of abstraction or hierarchy. In this sense, both terms are synonyms of the generic term *geoform*.

In the present hierarchic system of geoform classification, terrain form/landform is considered as the generic concept of the lower level of the system. It corresponds to the elementary geomorphic unit, which can be divided only by phases. It is characterized by its geometry, dynamics, and history.

The hierarchic arrangement of the collection of geoforms in Tables 6.3 to 6.11 is based on expert judgement and field experience (Zinck, 1988). Geoforms can be conveniently distributed in two groups: the geoforms predominantly controlled by the geologic structure (internal geodynamics) and the geoforms predominantly controlled by the morphogenic agents (external geodynamics). Section 6.3 provides more details.

6.2.6.2 Taxa

- Geoforms predominantly controlled by the geologic structure
  - structural (monoclinal, folded, faulted)
  - volcanic
  - karstic
- Geoforms predominantly controlled by the morphogenic agents
  - nival, glacial, periglacial
  - eolian
  - alluvial and colluvial
  - lacustrine
  - gravity and mass movements
  - coastal
- Banal geoforms

6.3 Classification of the geoforms at the lower levels

6.3.1 Introduction

The geotaxa belonging to the upper and middle levels of the system are defined in the previous section. The present section describes the classification of the geoforms at the lower categorial levels of the system: relief/molding and terrain form. The taxa lists are neither exhaustive nor free of ambiguity. It is mainly an attempt to categorize the existing geotaxa according to their respective level of abstraction and place them either at level 4 or level 6 of the classification system. A variety of synonymous terms can be found in the specialized literature, and the same type of geoform may be referred to with different names. With further progress in geomorphic mapping, probably new types of geoform will be identified and new names will appear. The concepts and terms used here are extracted from general texbooks and treatises in geomorphology. In case of multiple terms for a particular geoform, preference is given to the most commonly used term. Terms borrowed from different languages are kept in their original form and spelling, especially when already internationally accepted.

A criterion often used for grouping the geoforms in families is their origin or formation mode. Hereafter, the concept of origin is used in a broad sense, referring indistinctly to a type of environment (e.g. structural), an agent (e.g. wind), a morphogenic system (e.g. periglacial), or a single process (e.g. decantation).

The concept of origin, as a synonym for formation, is implicitly or explicitly present at all levels of the taxonomic system, but its diagnostic weight increases at the lower levels. The origin controlled by the internal geodynamics is more relevant in the upper categories, while the origin controlled by the external geodynamics is more important in the lower categories. It results from the former that there is a differential hierarchization of the diagnostic attributes according to the origin of the geoforms. For instance, in the case of the structural geoforms, genetic features have maximum weight at the level of the relief type, while in the case of the geoforms caused by exogenous agents (e.g. water, wind, ice), the genetic features have maximum weight at the lower levels of the system (i.e. facies and terrain form).

A morphogenic agent can cause erosional as well as depositional features according to the context in which the process takes place. For this reason, a distinction is made between erosional and depositional terrain forms. Likewise, structural geoforms may have been strongly modified by erosion, a fact which leads to distinguish between original (primary) and derived forms.

A geoform is considered erosional when the erosion process, operating either by areal removal of material or by linear dissection, is responsible for creating the dominant configuration of the geoform. Local modifications caused, for instance, by the incision of rills and gullies or surficial deflation by wind are identified as phases of the affected taxonomic unit. Similarly, point features and phenomena of limited extent are not considered as taxonomic units and are represented by cartographic spot symbols on the maps (e.g. geysers, erratic blocks, pingos, etc.).

For the definition of the geoforms, the names of which are reported in the attached tables, it is recommended to consult the textbooks and dictionaries of geomorphology, namely Derruau (1965), CNRS (1972), Visser (1980), Lugo-Hubp (1989), among others. The multilingual *Geological Nomenclature* (Visser, 1980) is particularly useful, in the current context of unstandardized vocabulary, for short definitions of geoforms and multilingual equivalents. Some geoforms may appear named at both levels of relief/molding and terrain form, because their taxonomic position in the classification system is not yet clearly established.

6.3.2 Geoforms mainly controlled by the geologic structure

Geostructural control acts through tectonics, volcanism and/or lithology. Therefore, the internal geodynamics is determinant in the formation of this kind of geoforms, in combination with external processes of erosion or deposition in varying degrees. The dissection of primary structural reliefs by mechanical erosion, for instance, results in the formation of derived relief forms. Chemical erosion through limestone dissolution or sandstone disintegration causes the formation of karstic and pseudokarstic reliefs. Deposition of volcanic ash or scoriae can alter the original configuration of a structural relief.

6.3.2.1 Structural geoforms proper

Geoforms directly caused by structural geodynamics (folds and faults) cover a large array of relief types (Table 6.3):

- Monoclinal reliefs: rock layers uniformly dipping up to 90^{o} (see Fig. 5.4). Strata of hard rocks (e.g. sandstone, quartzite, limestone) overlie softer rocks (e.g. marl, shale, slate). The duo hard rock/soft rock can be recurrent in the landscape, causing the same relief type to repeat several times (e.g. double cuesta).
- Jurassian fold reliefs: symmetrical folds in regular sequences of structural highs (anticlines) and structural lows (synclines) in their original or almost original form; related to important volumes of stratified sedimentary rock layers.
- Appalachian fold reliefs: fold reliefs in advanced stage of flattening and dissection.
- Complex fold reliefs: primary or derived fold reliefs controlled by overthrust tectonics and complex folding.
- Fault reliefs: primary or derived reliefs caused by faults or fractures; the faulting style (i.e. normal, reverse, rotational, overthrust, etc.) controls the type of resulting relief.

6.3.2.2 Volcanic geoforms

Volcanic materials can constitute the whole substratum or an essential part thereof or be limited to cover formations in a variety of landscapes including mountain, plateau, piedmont, plain and valley. Volcanic geoforms are of variable complexity, and this makes it difficult to strictly separate relief types and terrain forms. An ash cone, for instance, can be a very simple geoform and constitute therefore an elementary terrain form, while a stratovolcano cone is usually a much more complex geoform with various terrain forms (Table 6.4).

6.3.2.3 Karstic geoforms

Karst formation operates by chemical erosion of soluble rocks and originates sculpted surface terrains and underground gallery systems of complex configuration, characterized by residual geoforms of positive or negative relief. The resulting taxa enter the system essentially at the relief/molding level. The karstic geoforms are both endogenous by the influence of the lithology in their constitution and exogenous by the dissolution process which originates them (Table 6.5).

Table 6.3 Structural geoforms.

Relief		Terrain form
Primary	Derived	
Monoclinal		
Cuesta (1-10^{o} dip)	Double cuesta	Relief front (front slope)
Creston (10-30^{o})	Outlier hill	Scarp (overhang)
Hogback (30-70^{o})	Flatiron	Debris talus
Bar (70-90^{o})	Orthoclinal (subsequent) depression	Relief backslope
Flatiron	Cataclinal (consequent) depression	Structural surface
	Anaclinal (obsequent) depression	Substructural surface
		Cataclinal gap
Folded (Jurassian)		
Mont (original anticline)	Excavated anticline	Anticlinal hinge zone
Val (original syncline)	Hanging syncline	Synclinal hinge zone
	Rafter (chevron)	Fold flank
	Creston	Scarp
	Combe	Debris talus
	Cluse	
	Ruz	
Folded (Appalachian)		
	Truncated anticline	Scarp
	Bar	Debris talus
	Hanging syncline	
	Cataclinal gap	
Folded (complex)		
Overthrust nappe	Klippe	Scarp
Overthrust fold	Creston of overturned fold	Debris talus
Box fold	Escarpment of faulted fold	
Diapiric fold	Combe	
Faulted/fractured		
Fault scarp	Faultline scarp	Scarp
Horst	Fault escarpment facet	Debris talus
Graben	Cuesta	
Faults en échelon		
Block-faulted area		

Table 6.4 Volcanic geoforms.

Relief	Variety of geoforms
Depression	Crater
	Caldera
	Maar
	Lake
Cone	Ash cone
	Cinder cone
	Lava cone
	Spatter cone
	Stratovolcano
Dome	Cumulo-volcano
	Shield-volcano
	Intrusion dome
	Extrusion dome
	Extrusion cilinder
Flat	Lava flow
	Block lava (aa lava)
	Ropy lava (pahoehoe lava)
	Pillow lava
	Volcanic mudflow (lahar)
	Fluvio-volcanic flow
	Cinder field
	Ash mantle
	Pyroclastic deposit
Mesa	Planèze
Cuesta	Hanging lava flow
	Sill
Bar	Longitudinal dyke
Dyke	Annular dyke (ring-dyke)
Tower	Volcano scarp
Escarpment	Volcanic plug (neck)
	Volcanic chimney (vent)
	Volcanic spine

Table 6.5 Karstic geoforms.

Relief	Terrain form
Cockpit karst (dolines)	Karren
Hum karst (hills)	Sima (aven)
Tower karst	Ponor
Cone karst	Doline
Polje (karstic plain)	Uvala
Karrenfeld	
Collapse valley	
Blind valley	
Dry valley	

6.3.3 Geoforms mainly controlled by the morphogenic agents

Water, wind and ice are morphogenic agents that cause erosion or deposition according to the prevailing environmental conditions. The resulting geoforms are usually more homogeneous than the geoforms controlled by the internal structure. For this reason, many of the geoforms originated by exogenous agents can be classified at the level of terrain form. Hereafter, six main families of geoforms are distinguished according to their origin.

6.3.3.1 Nival, glacial and periglacial geoforms

The nival, glacial and periglacial geoforms have in common the fact that they develop in cold environments (high latitudes and high altitudes) by the accumulation of snow (nival geoforms), alternate freezing-thawing causing gelifraction (periglacial geoforms) or accumulation of ice mass (glacial geoforms). Some geoforms result from deposition (e.g. moraines), others from erosion (e.g. glacial cirque) (Fig. 6.4). Some can be recognized and mapped as elementary terrain forms (e.g. a moraine). Others are molding types that consist of more than one kind of terrain form. A glacial trough, for instance, can contain different types of moraine (e.g. ground, lateral, frontal), surfaces with “roches moutonnées”, hanging valleys, and lagoons, among others (Tables 6.6 and 6.7). Strictly speaking, the nival forms are not terrain forms, since they are covered with snow (e.g. nivation cirque, permanent snowpack, and snow avalanche corridor and fan).

Table 6.6 Glacial geoforms.

Molding	Terrain form
Cirque	Trough threshold
Trough	Cirque threshold
	Trough basin
	Trough shoulder
	Hanging valley (gorge)
	Roches moutonnées
	Ground moraine
	Lateral moraine
	Medial moraine
	Frontal moraine
	Knob-and-kettle till
	Blocks stream
	Dead-ice depression
Flat	Roches moutonnées field
	Drumlin field
	Ground moraine
	Push moraine
	Kame
	Esker
	Fluvio-glacial outwash fan (sandur)

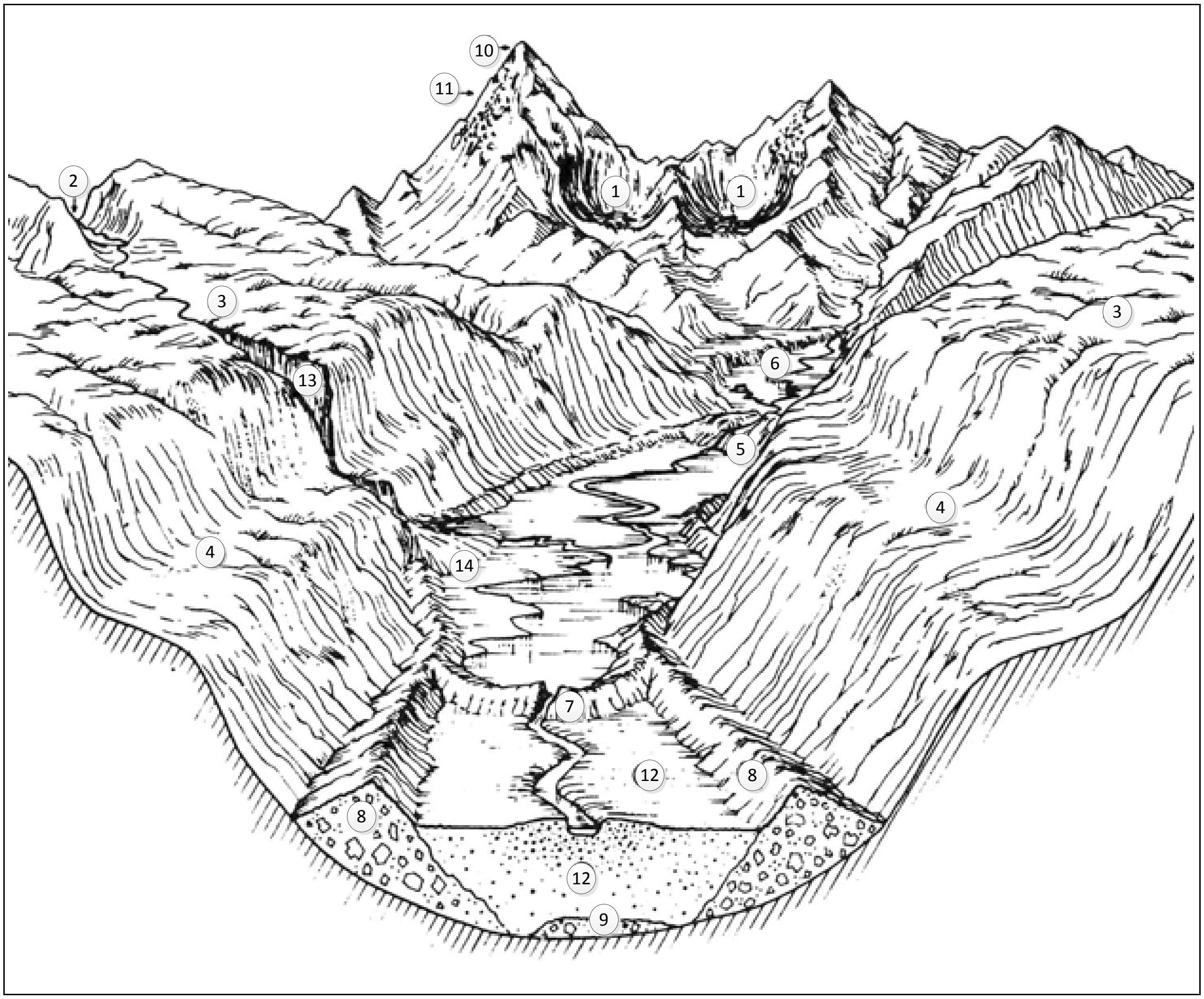


Fig. 6.4 Configuration and components of a glacial valley or glacial trough (Zinck, 1980).

Glacial erosion molding
1 Glacial cirque with lagoon
2 Glacial diffluence pass
3 Roches moutonnées (striated surface)
4 Trough shoulder (staircase tread)
5 Threshold with trough narrowing
6 Basin with trough widening and deepening (lake)

Glacial deposition molding
7 Frontal moraine barring the water flow (lake)
8 Lateral moraine
9 Ground moraine

Periglacial molding
10 Gelifraction horn
11 Scree talus

Postglacial fluvial molding
12 Trough filling by fluvial aggradation
13 Hanging lateral valley with steps
14 Alluvial fan

Table 6.7 Periglacial geoforms.

Molding	Terrain form
Crest (gelifraction)	Nunatak (horn)
	Debris talus (scree talus)
	Debris fan (scree fan)
Flat	Polygonal ground
	Mud field
	Stone field (pavement)
	Permafrost
	Tundra hummock
	Peatland (moor, bog)
	Dune field
	Loess mantle
Slope	Gravity scree
	Patterned ground
	Striped ground
	Stone stream
	Mud flow (solifluction)

6.3.3.2 Eolian geoforms

Dry environments, from desert to subdesert, are most favorable to forms arising from the action of the wind. Eolian geoforms occur mainly in coastal or continental plains where the effect of the wind is more pronounced (Table 6.8).

Table 6.8 Eolian geoforms.

Molding	Terrain form
Flat (dune field, erg)	Barchan
	Nebka
	Parabolic dune
	Longitudinal dune
	Transverse dune
	Pyramidical dune (ghourd)
	Reticulate dune
	Blowout dune (eolian levee)
	Loess cover
	Blowout depression
	Reg (deflation pavement)
	Yardang
Meseta	Hamada (rocky deflation surface)

6.3.3.3 Alluvial and colluvial geoforms

Alluvial geoforms can occur in almost all types of landscape, but mostly in plains and valleys where they form terraces, floodplains, glacis, and fans. The colluvial geoforms are typical features of the piedmont landscape where they form fans and glacis (Table 6.9).

Table 6.9 Alluvial and colluvial geoforms.

Depositional facies/erosion	Terrain form
Overload facies	Scroll bar
	Point bar complex
	River levee
	Distributary levee
	Delta channel levee
	Splay axis
	Splay mantle
	Crevasse splay
	Splay fan
	Splay glacis
	Alluvial fan
Overflow facies	Overflow mantle
	Overflow basin
Decantation facies	Decantation basin
	Backswamp (lateral depression)
	Cut-off meander with oxbow lake
	Infilled channel
Colluvial facies	Colluvial fan
	Colluvial glacis
Water erosion features	Sheet erosion
	Rill
	Gully
	Badland

6.3.3.4 Lacustrine geoforms

The receding of lake shorelines, which is a common process in drying lakes originated after the last glaciation, leaves exposed lacustrine material in the form of terraces. In arid and semi-arid environments, stratified fluvio-lacustrine deposits occur in playa-type depressions. In areas emerging from proglacial lakes there are stratified varve deposits.

6.3.3.5 Gravity and mass movement geoforms

The mechanical condition of the material, with continuity from solid state to liquid state, controls the mass movement processes, including creep, flow, slide and fall, that give rise to the geoforms (Table 6.10).

6.3.3.6 Coastal geoforms

The most typical coastal geoforms are developed in the coastal lowlands, including molding types such as salt marsh, mangrove marsh, estuary, delta, bay, reef, and atoll. Cliff is the most common form in rocky coasts (Table 6.11).

Table 6.10 Gravity and mass movement geoforms.

Process (consistence states)	Terrain form
Creep (variable)	Creep mantle
	Pied-de-vache
	Terracette
Flow (plastic/líquid)	Rock flow
	Earth flow
	Debris flow
	Mud flow
	Solifluction sheet
	Solifluction tongue (stripe)
	Solifluction lobe
	Torrential lava
Slide (semi-solid)	Rotational slide (slump)
	Translational slide (slip)
	Rock slide
	Block slide
	Debris slide
	Landslide
	Landslide scar
Fall (solid)	Rock fall
	Scree talus

Table 6.11 Coastal geoforms.

Formation mode	Terrain form
Mechanical deposition	Beach
	Beachridge (coastal bar)
	Offshore bar (barrier beach)
	Offshore trough
	Baymouth bar (restinga)
	Cuspate bar
	Spit
	Tombolo
	Slikke-schorre (tidal mudflat)
	Lagoon
	Dune
	Sand cay
	Beachrock platform
Biogenic formation	Fringing reef
	Barrier reef
	Reef flat
	Reef front
	Lagoon
Erosion	Cliff
	Wave-cut platform/terrace
	Tidal channel
	Grao

6.3.4 "Banal" geoforms

Geoforms without remarkable physiographic features are called *banal* (CNRS, 1972). Such geoforms are frequent in soft sedimentary rocks, devoid of structural control (e.g. marls and other argillaceous rocks), and in igneous-metamorphic rocks without marked schistosity (e.g. granite, gneiss). Their most common physiographic feature is expressed by convex-concave hillslopes.

6.3.4.1 Main characteristics

- General topography of hills, ridges and crests, originated by dissection.
- Little or none structural influence, in particular lack of specific control by fault tectonics in the topography.
- Presence of fractures that favor and control the incision and organization of the hydrographic network.
- The drainage pattern has a relevant influence on the configuration of the resulting dissection topography, especially in peneplain and hilland landscapes.
- Homogeneous rock substratum over wide expanses.
- Material of moderate to weak resistance to physical and/or chemical erosion. Banal geoforms are frequent in shale and marl. In warm and moist tropical environments, chemical erosion of granite or gneiss produces also banal geoforms in peneplain landscape.

6.3.4.2 Classes of banal geoforms

Banal geoforms occur at the levels of relief/molding and terrain form in mountain, hilland, peneplain, and piedmont landscapes.

(a) At the level of relief/molding

Two classes are frequent:
- The *backbone* configuration which consists of an association between a main longitudinal dorsal and a set of perpendicular hills (chevron, rafter, nose) separated by vales (Fig. 6.5). This type of relief is common in fractured sedimentary rocks. Its further evolution generates elongated horseback-shaped hills.
- The *half-orange* configuration which consists of a systematic repetition of rounded hills of similar elevation. This type of relief is typical of the peneplain landscape developed in homogeneous but intensively fractured igneous or metamorphic substratum, with reticulate drainage pattern. It is common in the Precambrian shields of the intertropical zone.

(b) At the level of terrain form

Slope facet seems to be the most convenient criterion to subdivide any hilly relief. To this effect, the slope models such as the nine-unit-land-surface model of Conacher & Dalrymple (1977) or the five-hillslope-element model of Ruhe (1975) can be implemented. Table 6.12 shows the relationships between slope facet, topographic profile, and dominant morphogenic dynamics according to Ruhe's model (Fig. 6.6). It is worth noting that the toeslope is actually not a slope facet; it is a unit that belongs to the adjoining valley or vale, with slope perpendicular to the hillside and with longitudinal deposits.

Models are suitable generalizations of real situations. The general hillside model with convex-concave profile can be disturbed by irregularities. For instance, the cross section of a hill shows often complications that must be considered in the mapping of the geoforms and soils. These complications can be caused by the heterogeneity of the local geologic substratum or the local morphodynamics. A convex-concave slope can be interrupted by treads and scarps that reflect tectonic influence or lithologic changes. Likewise, the general topographic profile can be locally disturbed or modified by water erosion (e.g. rills and gullies) or mass movements (e.g. terracettes, landslides, solifluction scars and tongues).

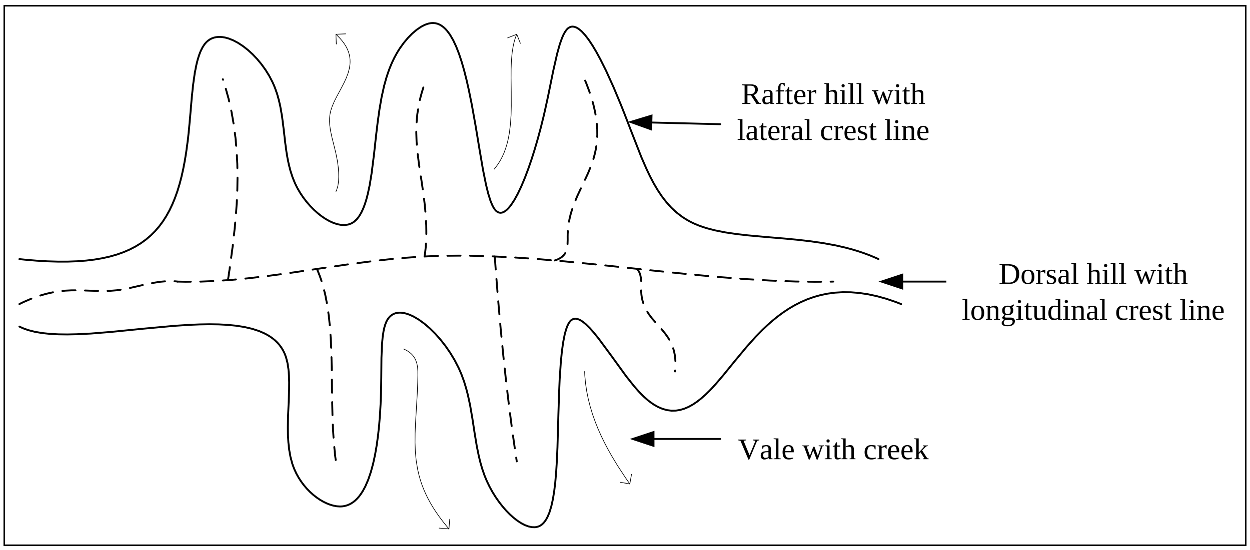


Fig. 6.5 Hilland with backbone configuration comprising a longitudinal dorsal and perpendicular hills.

Table 6.12 Slope facet model (adapted from Ruhe, 1975).

Slope facet	Topographic profile	Dominant morphodinamics
Summit	Level/convex	Ablation/erosion
Shoulder	Convex	Erosion
Backslope	Rectilinear-inclined	Material in transit
Footslope	Concave	Lateral accumulation
Toeslope	Concave/level	Longitudinal accumulation

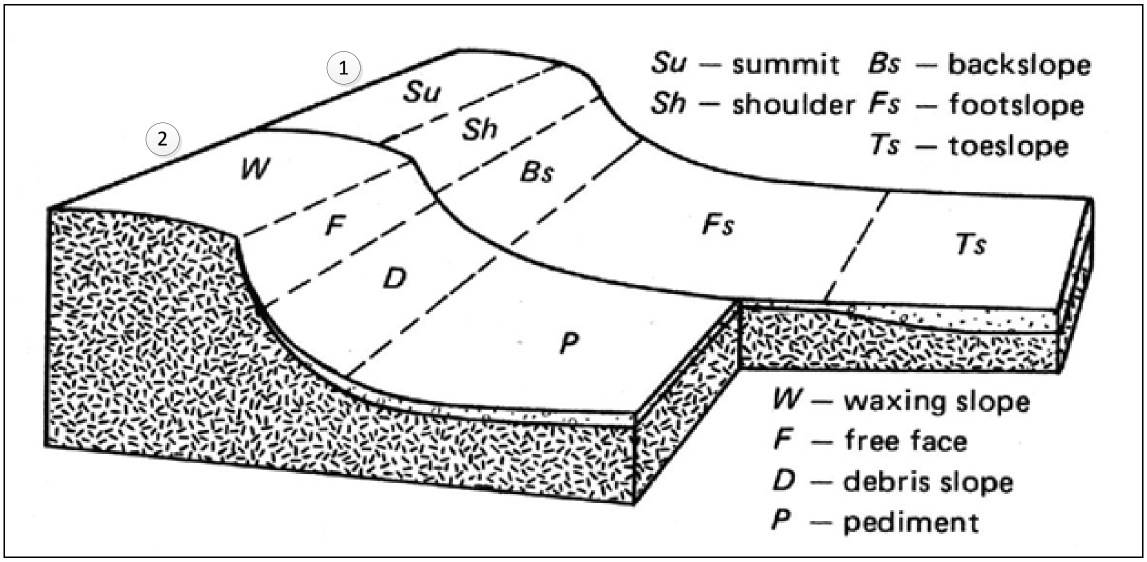


Fig. 6.6 Models of convex-concave "fully developed hillslopes" with lateral deposits (taken from Ruhe, 1975).
1. Ruhe's model (note that the toeslope deposits are of longitudinal origin);
2. Model combining elements taken from Wood (1942) and King (1957).

6.4 Conclusion

This chapter attempts to organize existing geomorphic knowledge and arrange the geoforms in a hierarchically structured system with six nested levels. It is thought that this multicategorial geoform classification scheme reflects the structure of the geomorphic landscape s.l. It helps segment and stratify the landscape continuum into geomorphic units belonging to different levels of abstraction. This geoform classification system has shown to be useful in geopedologic mapping and could be useful also in digital soil mapping.

Chapter 7

THE GEOMORPHIC LANDSCAPE: THE ATTRIBUTES OF THE GEOFORMS

7.1 Introduction

The 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 differentiating attributes that allow classifying the 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, 1965b):

- geomorphographic attributes, to describe the geometry of the geoforms;
- geomorphometric attributes, to measure the dimensions of the geoforms;
- geomorphogenic attributes, to determine the origin and evolution of the geoforms;
- geomorphochronologic attributes, to circumscribe the temporal context 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 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.

7.2 Morphographic attributes: the geometry of the geoforms

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

7.2.1 Topography

Topography refers to the cross section of a portion of terrain (Fig. 7.1). It can be viewed in two dimensions from a vertical cut through the terrain generating the topographic profile

(Table 7.1), and in three dimensions from a terrain elevation model generating the topographic shape (Table 7.2). 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 topographic shape attributes are used at the 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.

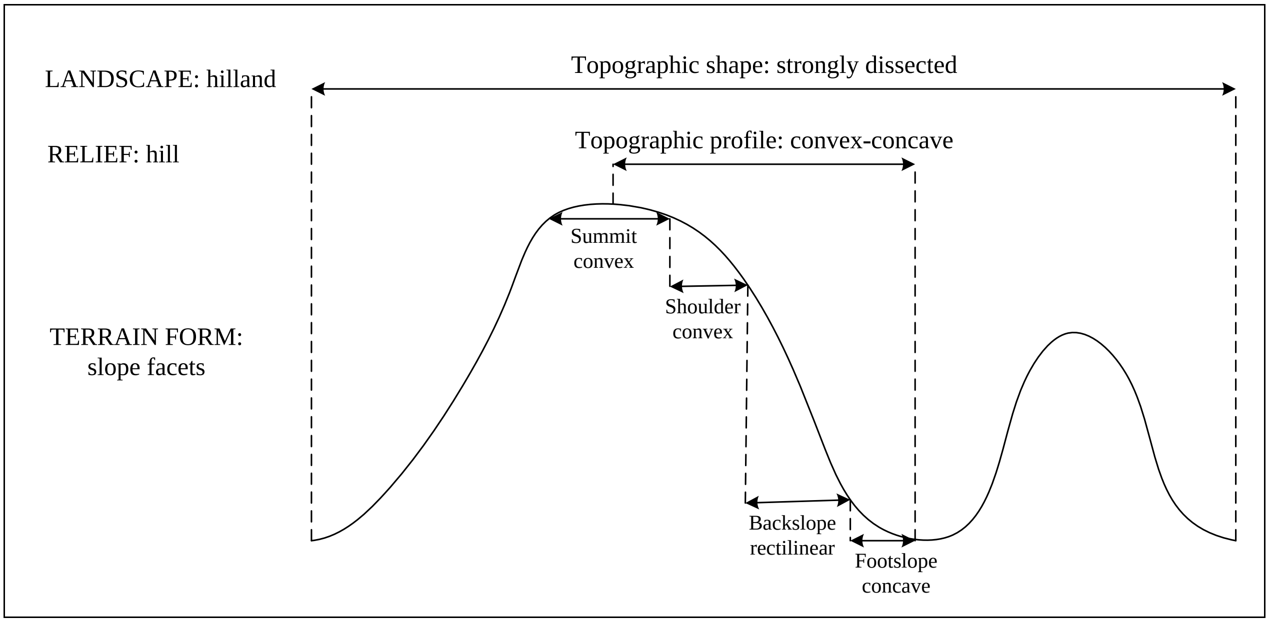


Fig. 7.1 Relationship between topographic attributes and categorial levels of the geoform classification system.

Table 7.1 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 7.2 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

7.2.2 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 & 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.

7.2.2.1 Configuration of the geoforms

Many geoforms at the levels of relief/molding and terrain form show typical configurations, enabling to make a preliminary identification 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 7.3).

Table 7.3 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

7.2.2.2 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. 7.2 and Table 7.4). 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 variations of the fractal dimension (Saldaña et al., 2011). The attribute of contour design can also be used as an indirect morphogenic indicator. For instance, an alluvial decantation basin usually has a massive configuration, but the shape of the boundaries can vary according to the dynamics of the neighboring forms. Usually, a depositional basin has a sinuous outline, but when an crevasse splay 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 clear-colored sandy deposit fossilizing the argillaceous gley material of the basin (Fig. 7.3).

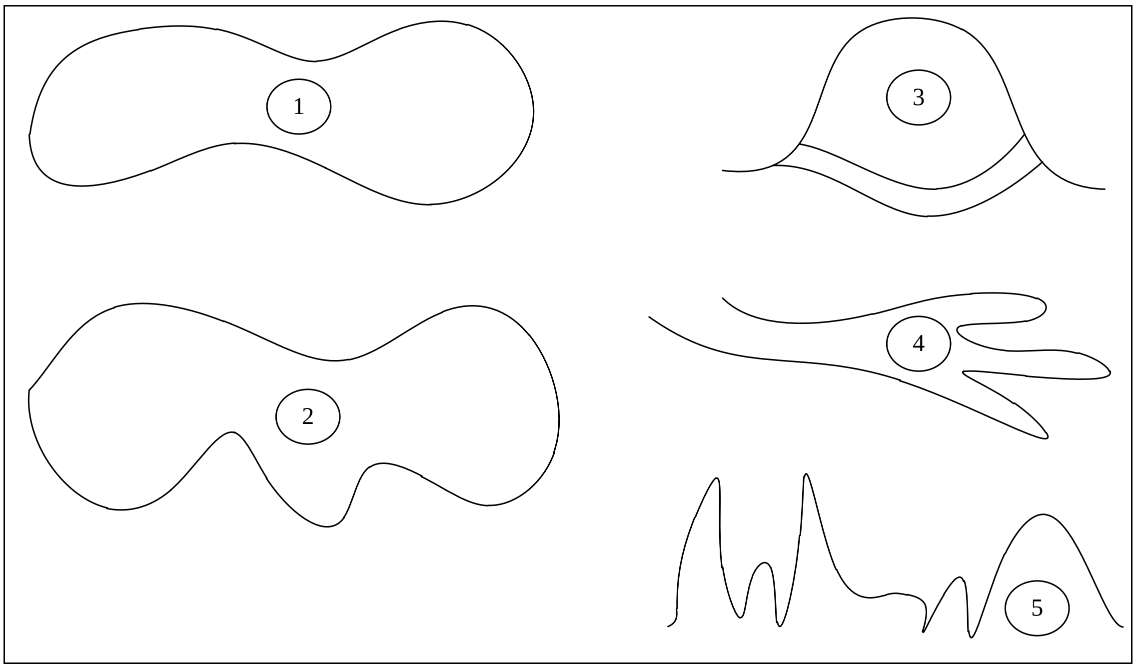


Fig. 7.2 Configuration and contour design of some geoforms (2D).
1 Basin with ovate configuration and sinuous contour
2 Basin with ovate configuration and lobulate contour (lower part), reflecting the penetration of a digitate crevasse splay fan (see Fig. 7.3)
3 Bay closed by an arch-shaped offshore bar
4 Deltaic channel levee with digitate distal extremities
5 Dissected scarp with denticulate contour pattern

Table 7.4 Contour design of the 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

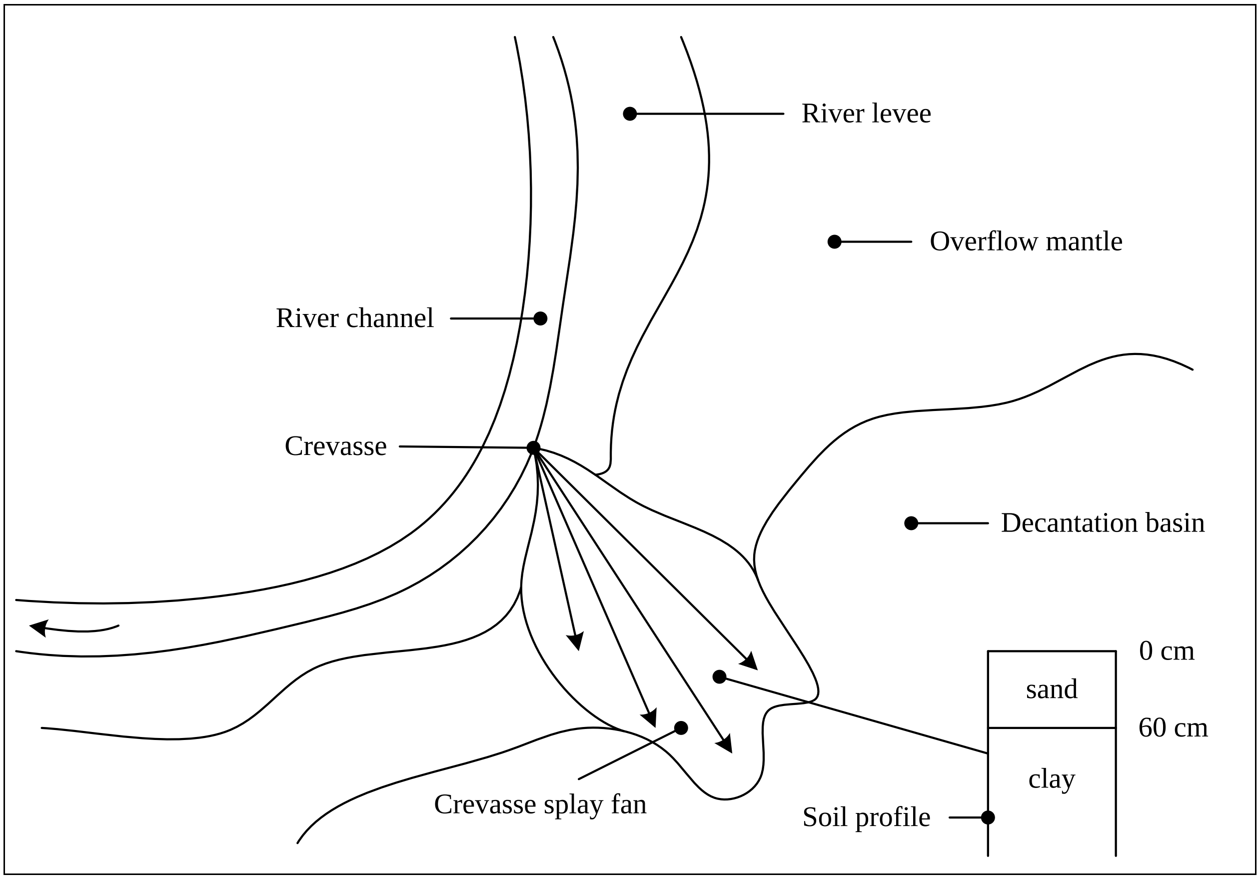


Fig. 7.3 Modification of a basin contour design by the penetration of a crevasse splay fan upon rupture of a levee during high channel water. The intrusion of the fan in the neighboring lateral depression results in the overlaying of sandy sediments on top of the clayey basin substratum, creating a lithologic discontinuity at 60 cm depth, with the formation of a buried soil.

7.2.2.3 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, 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 found in Fig. 7.4: 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).

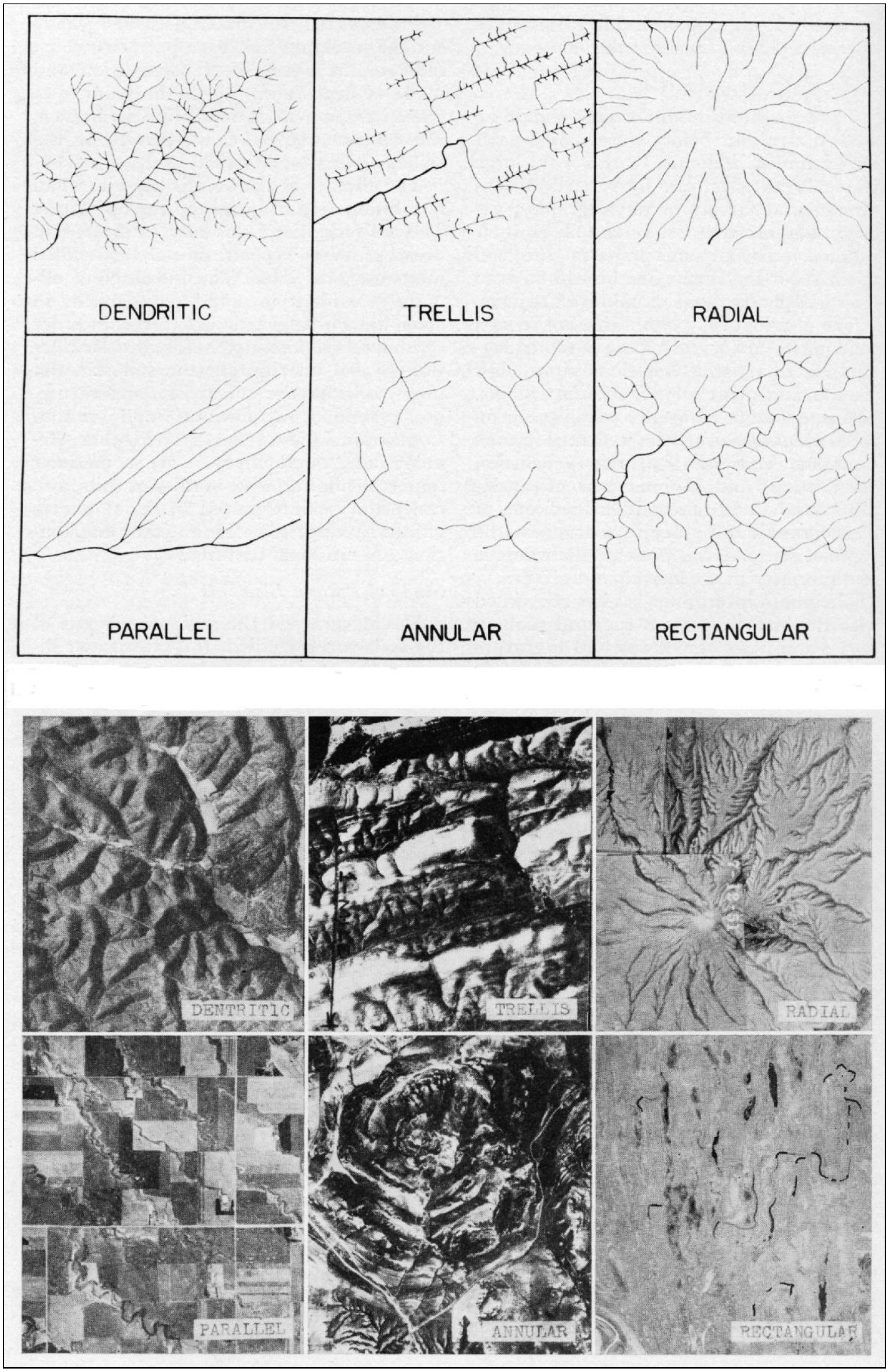


Fig. 7.4 Drainage patterns controlled by features of the geologic and geomorphic structure (see comments in the text) (taken from ASP, 1960).

7.2.2.4 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.

7.2.3 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 & 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. 7.5).

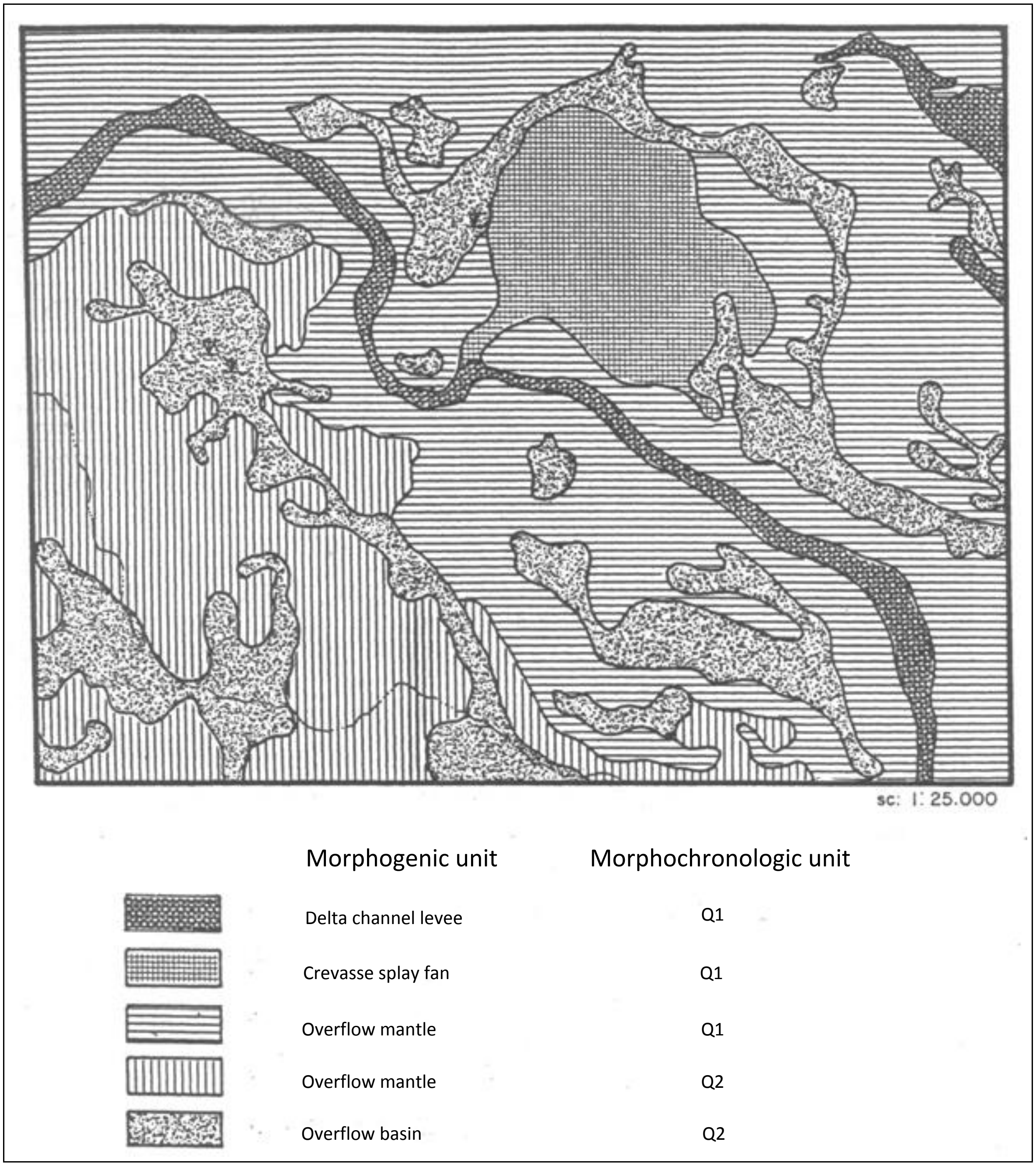


Fig. 7.5 Contact area between two depositional systems differentiated by their relative age. Extract of a soil series map of the Santo Domingo river plain, Venezuela; survey scale 1: 25,000 (Pérez-Materán, 1967).

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 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.

7.3 Morphometric attributes: the dimension of the geoforms

Morphometry covers the dimensional features of the geoforms as derived from a numerical representation of the topography (Pike, 1995; Pike & Dikau, 1995). Computerized procedures allow the extraction and measurement of a variety of morphometric parameters from 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 & 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 the terrain forms, in particular the relative elevation, the drainage density, and the 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 the slope gradient, and conversely (A and B, respectively, in Fig. 7.6).

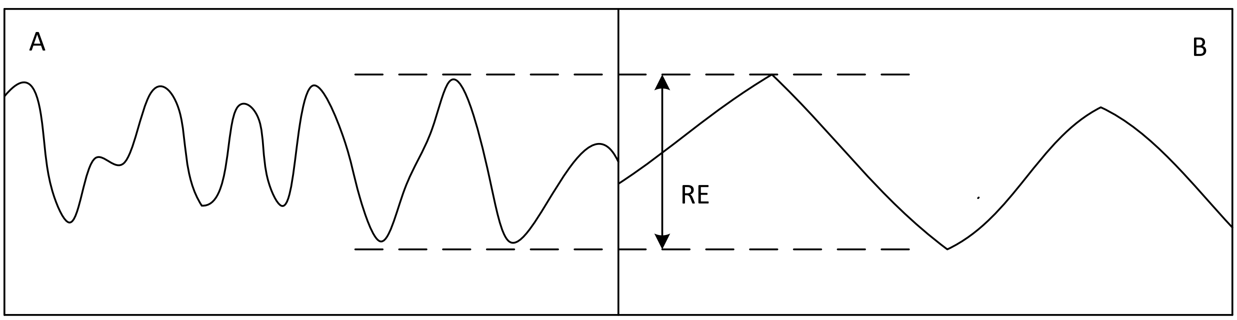


Fig. 7.6 Relationship between drainage density and slope gradient in similar conditions of relative elevation (RE) (adapted from Meijerink, 1988).

7.3.1 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.

7.3.2 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 affect the numerical values of VD (Fig. 7.7). The FAO Guidelines for soil description (2006) define potential drainage density values based on the number of "receiving" pixels within a window of 10x10 pixels.

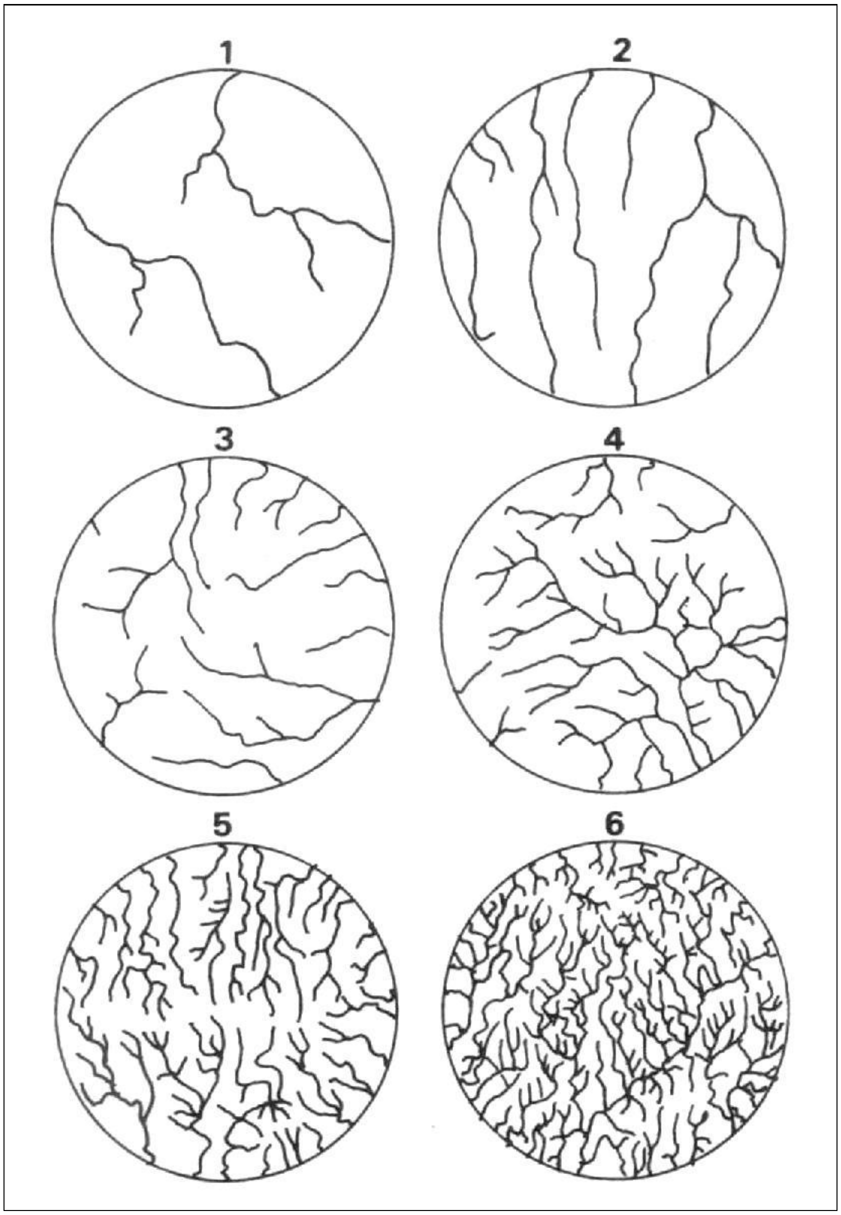


Fig. 7.7 Drainage density classes (adapted from Meijerink, 1988).

7.3.3 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 it. 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.

7.3.4 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 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 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 characterization 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 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.

7.4 Morphogenic attributes: the dynamics of the geoforms

Given 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 the forms that result from karstic erosion, 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.

7.4.1 Particle size distribution

7.4.1.1 Relevance

The 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 the 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.

7.4.1.2 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).

7.4.1.3 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.7.8).

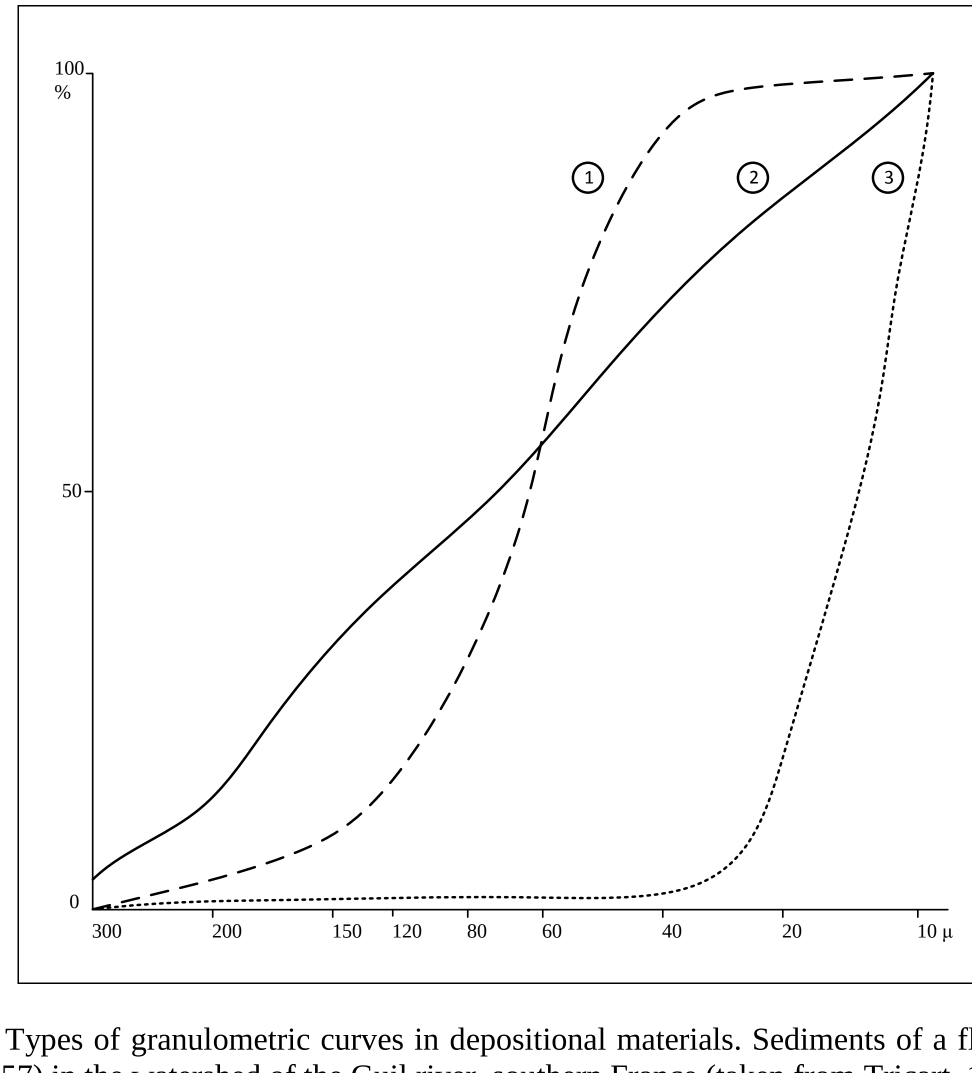


Fig. 7.8 Types of granulometric curves in depositional materials. Sediments of a flood event (June 1957) in the watershed of the Guil river, southern France (taken from Tricart, 1965a).
1: Sigmoid curve, characteristic of free sediment accumulation;
2: Logarithmic curve, characteristic of a torrential lava flow (in this case) or splay deposits;
3: Parabolic curve, characteristic of an accumulation forced by an obstacle obstructing the flow.

Granulometric curves that correspond to three types of sediments deposited by a flood of the Guil river, in southern France, are displayed in Fig. 7.8, (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 all 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 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 (Fig. 3.3 in Chap.3).

(d) Lithologic discontinuity

The soil profile included in Fig. 7.3 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 for the purpose of recognizing 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.

7.4.2 Structure

7.4.2.1 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 rocks) where the original rock structure can still be recognized in the Cr horizon (saprolite). For instance, a 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 ferromagnesian minerals, 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).

(c) 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 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).

7.4.2.2 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.

7.4.3 Consistence

The 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. 7.9, 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 creating mudflows. The graphic model of Carson & Kirkby (1972) shows how continuity solutions that relate the basic mechanisms of swell, slide and flow, can be segmented for differentiating types of mass movement (Fig. 7.10).

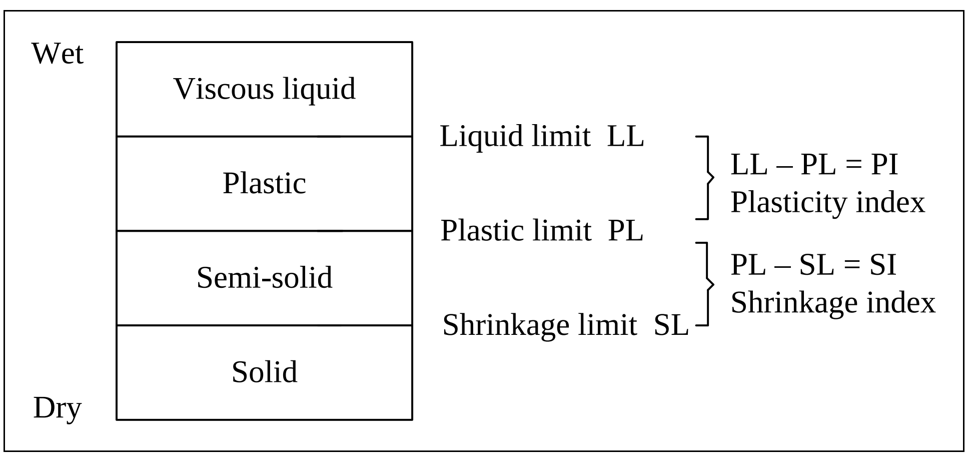


Fig. 7.9 Consistence/consistency parameters

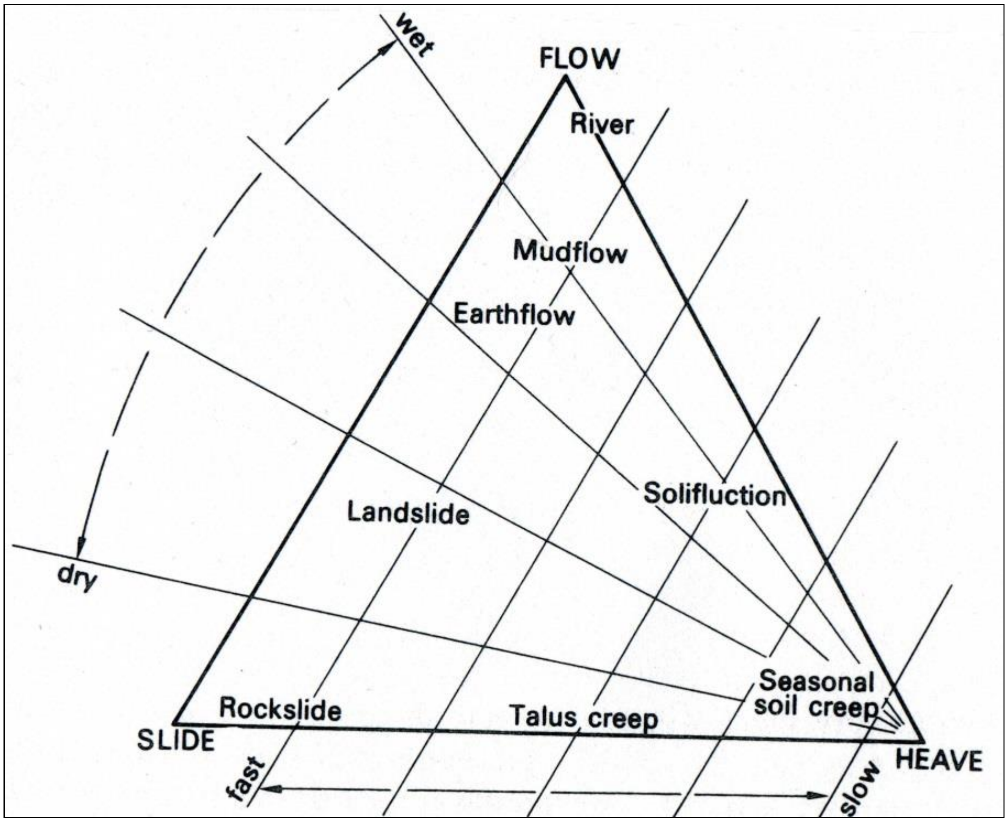


Fig. 7.10 Relational model for classifying mass movements (taken from Carson & Kirkby, 1972).

7.4.4 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 7.5 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 study 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.

Table 7.5 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 from the Institute of Geography, University of Strasbourg, France (courtesy J. Tricart)

- *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.
- *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 result form the retention of silt particles trapped by dense grass cover.

7.4.5 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.

7.5 Morphochronologic attributes: the history of the geoforms

7.5.1 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 relictual 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 new soils have developed.

In temperate and boreal areas, 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 & 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 7.6). 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.

Table 7.6 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	

Comments on Table 7.6:

- 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 are often formed 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 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).

7.5.2 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. A determination of carbon-14 costs on average 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.

7.5.3 Relative geochronology: the contribution of pedostratigraphy

7.5.3.1 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), by comparison with the detailed lithologic information concerning the pre-Quaternary. This information is usually insufficient to efficiently support soil survey. In contrast, the geopedologic information provided by soil survey has shown that it 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 & 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.

7.5.3.2 Criteria

A variety of pedologic and geomorphic criteria 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. 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 red soils and redeposited in lower portions of the landscape.

- 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 are 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 are depleted in mobilizable substances, resulting in a 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, the 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).

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 time frame that spans the chronosequence of the Merced River. The index has been applied to other sites with successive adjustments (Busacca, 1987; Harden et al., 1991).

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).

7.6 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.

7.6.1 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.

7.6.1.1 Differentiating attributes

An attribute is differentiating if it 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. 5.4).
- 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 has more than 60% clay fraction. In this case, the particle size distribution is the differentiating attribute and the attribute state is expressed by 60-100% clay.

7.6.1.2 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 lenticular structure is not enough to recognize a type of geoform.

7.6.1.3 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).

7.6.2 Attribute weight

7.6.2.1 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 every slope facet is in itself differentiating.

7.6.2.2 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.

7.6.2.3 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.

7.6.2.4 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.

7.6.3 Attribute hierarchization

Not all attributes are used at each categorial level of the geoform classification system. Table 7.7 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 7.8).

7.6.3.1 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.

7.6.3.2 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.

Table 7.7 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 7.8 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

CONCLUSION

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 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. 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 can be complementary and advantageously combined. The segmentation of the landscape s.l. 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 documents that help characterize the geomorphic units, mainly the morphographic and morphometric terrain surface features.

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