Chapter 4
The Geopedologic Approach

J.A. Zinck

Abstract The relationships between geomorphology and pedology can be analyzed from different perspectives: 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 soil inventory, which can be represented by a hierarchic scheme of activities. The approach focuses on the reading of the landscape in the field and from remote-sensed imagery 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. There is explicit emphasis on the geomorphic context as an essential factor of soil formation and distribution.

Keywords Concept • Geopedologic landscape • Method • Geopedologic integration • Implementation • Contribution to soil survey

4.1 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

J.A. Zinck (✉)
Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Enschede, The Netherlands

Institute of Environmental Studies, University of New South Wales, Sydney, NSW, Australia
e-mail: alfredzinck@gmail.com

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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 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 as defined below). As such, geopedology is closely related to the concept of pattern and structure of the soil cover developed by Fridland (1974, 1976) and taken up later by Hole and 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 or type of the landscape in consideration (e.g. topographic, ecological, biogeographic, geomorphic). 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 and Schargel 1978; Wilding and Drees 1983; Hall and Olson 1991). Wilding and 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, 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 of the soil-landscape (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 their taxonomic components (i.e. the content). Therefore, the geopedologic map units are more comprehensive than the conventional soil map units, since they also contain information about 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 twentieth century at various scales and different orders of intensity. 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 extended and 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 over 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 many parts 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 levels. 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 described in Chap. 3 that 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 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 4.1, the general structure and main components of such a geoform classification sytem are presented. 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,

Table 4.1 Synopsis of the geoform classification system

Level	Category	Generic concept	Short definition
6	Order	Geostructure	Large continental portion characterized by a given 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

Zinck (1988)

pedology, landscape ecology, and land evaluation, among others. The expression *terrain form* would be 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 soil inventory, which can be represented by a hierarchic scheme of integrated activities.

4.2 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 underneath the interface. 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. Figure 4.1 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.

4.2.1 Common Forming Factors

Because geoform and soil develop along a common interface in the earth's epidermis, a thin and fragile envelope called earth's critical zone where soils, rocks, air, and water interact, they share forming factors that emanate from two sources of matter and energy, one internal and another external.

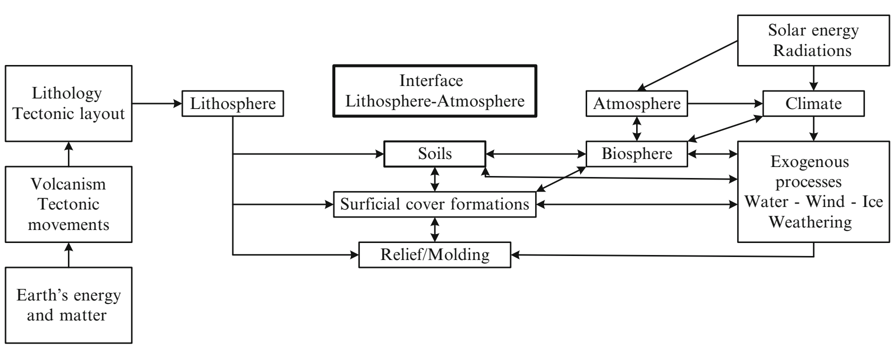


Fig. 4.1 The position of the geoform-soil duo at the interface between atmosphere and lithosphere (Adapted from Tricart 1972)

- 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). Many soils do 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 and Macaire 1989). The surficial cover formations constitute, in many cases, the parent materials of the soils. The nature and extent of these surface deposits often determine the conditions and limits of the interaction between processes of soil formation (Arnold and Schargel 1978).

The fact that geoform and soil share the same forming factors generates complex cause-effect relationships and feedbacks. One of the factors, namely 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 likely 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) lives within the soil and is considered part of it.

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. Figures 4.2 and 4.3 provide an example of this kind of integrated approach, showing each soil unit in its corresponding geomorphic landscape unit.

The geomorphic map of Fig. 4.2 represents the graben of Punata-Cliza in the eastern Andes of Bolivia, close to the city of Cochabamba. For some time this tectonic depression was occupied by a lake that dried up into a lagunary environment. Subsequently, detrital sediments coming from the mountain borders formed fans and glacis in the margins of the depression, leaving uncovered relict lagunary flats in the center of the depression. Photo-interpretation and fieldwork allowed segmenting the alluvial fans in proximal, central, and distal sectors. The geomorphic structure of the depression bottom resulting from this evolution during the Quaternary provides the basic framework for soil formation and spatial distribution. This is reflected in the coupled geomorphic-pedologic legend of Fig. 4.3. The sequential partitioning of the geomorphic environment into landscape, relief, facies, and landform units allowed identifying and mapping geomorphic units with their respective soil taxa, forming thus geopedologic units.

4.2.2 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 types of landscape. In flat areas, the

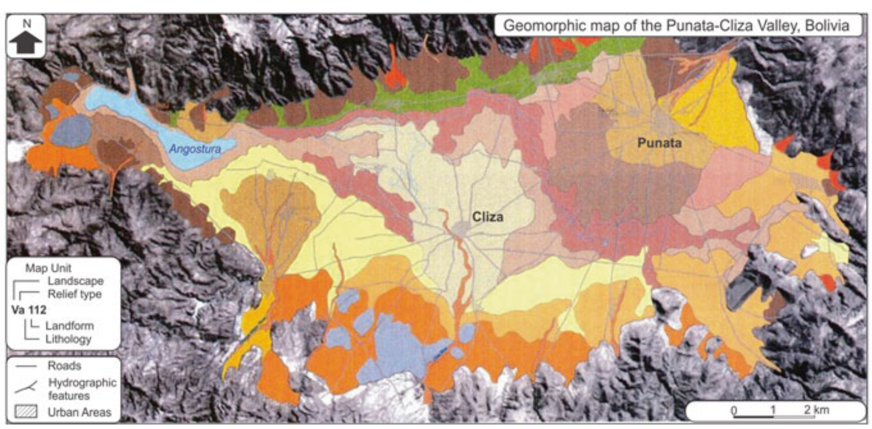


Fig. 4.2 Geomorphic map of the Punata-Cliza tectonic depression, eastern Andes of Bolivia (Metternicht and Zinck 1997)

GEOPEDOLOGIC 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 661	*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. 4.3 Geopedologic legend of the map shown in Fig. 4.2, referring to the Punata-Cliza tectonic depression, eastern Andes of Bolivia (Metternicht and Zinck 1997)

geopedologic landscapes are mainly constructional, while they are mainly erosional in sloping areas.

4.2.2.1 Flat Areas

In flat constructional areas, the sedimentation processes and the structure of the resulting depositional systems control often intimately the distribution of the soils, their properties, the type of pedogenesis, the degree of soil development and, even,

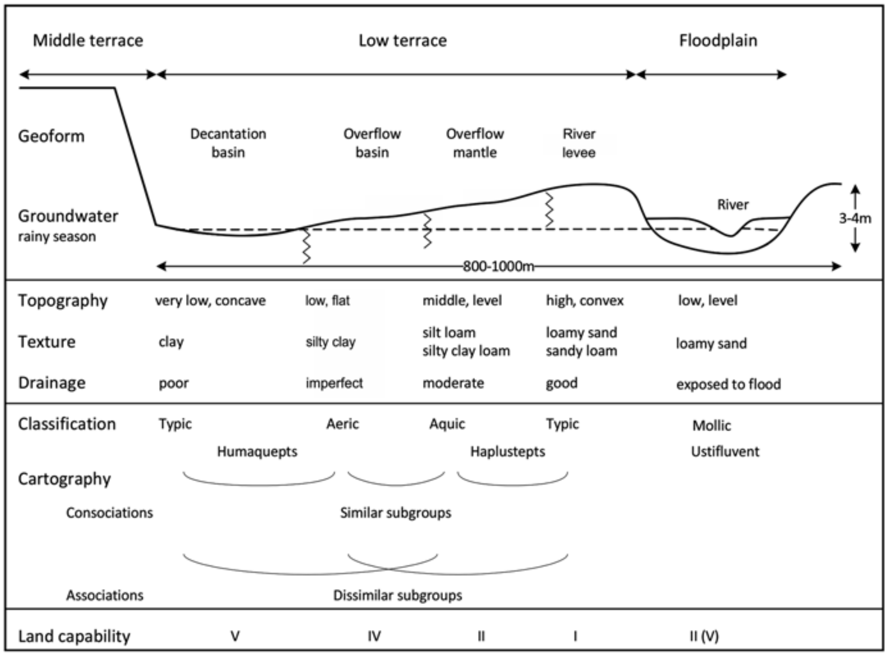


Fig. 4.4 Geopedologic landscape model of a young fluvial terrace. Example of the Guarapiche river valley, northeast of Venezuela; pedotaxa refer to the dominant soil type in each geoform

the use potential of the soils. The valley landscape offers good examples to illustrate these relationships. Figure 4.4 represents a transect crossing the lower terrace built by the Guarapiche river in the north-east of Venezuela 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 (pedotaxa refer to dominant soils):

- 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 Haplustepts (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 Haplustepts (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 Humaquepts; land capability class IV.

- Decantation basin: lowest position of the system, concave topography, closed oval configuration; usually very fine clay texture; poorly drained; Typic Humaquepts, sometimes associated with Aquerts; land capability class V.

The transitions between geomorphic positions are very subtle to imperceptible on the terrain surface. External markers such as slight undulations of field border fences and changes in color or compaction of dirt road trails help presume changes of positions. Unit boundaries and kinds were tentatively recognized by photo-interpretation on the basis of tone nuances, but definitively identified by field observations along transects. Parent material must be qualified to identify geoforms. The total relief amplitude between levee and decantation basin is approximately 2 m over a distance of about 600 m (0.3 % transversal slope).

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 Haplustepts and Aeric Humaquepts) or soil associations on the basis of dissimilar subgroups (e.g. Typic Haplustepts and Aeric Humaquepts), according to the soil distribution pattern and the mapping scale. The geomorphic framework, which controls the determination and delineation of the soil map units, makes that these units are relatively homogeneous, allowing for a reasonably reliable soil interpretation for land use purposes.

The Guarapiche valley example is an ideal textbook model, rather unfrequent in its full expression. The complete sequence in the right depositional order occurs mainly in the largest sections of the valley that have been sedimentologically stable over some time (see Fig. 4.9 in Sect. 4.3.3.1). In narrow sections, some of the geomorphic positions are usually missing, with for instance the levee running parallel to the basin. In other places, the river axis has been shifting over the depositional area, moving for instance during a heavy flood event from unstable channel between high levees to the low-lying marginal basin position. This results in less organized spatial geomorphic structures and more complex geopedologic units with contrasting sediment stratifications and superpositions.

The soil sequence in a given geopedologic landscape can also 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 example, may cause divergent pedogenesis and increase variations in the soil cover that are often not readily detectable. The resulting geopedologic landscapes are often 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.

4.2.2.2 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 within 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 usually results 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 on the upper slope facets, 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 and 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 °C average annual temperature. Slope gradient is 2–5° at slope summit, 40–45° at the shoulder, 30–40° along the backslope, and 10–25° 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. 4.5 and 4.6). 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 nearby 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 started covering 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 approximately 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

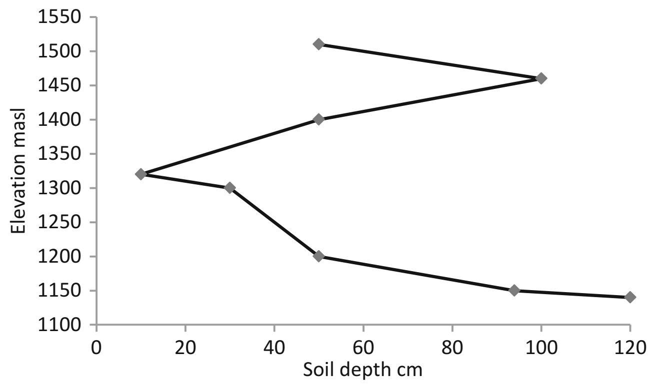


Fig. 4.5 Variation of soil depth with elevation along a mountain slope in the northern Coastal Cordillera of Venezuela (Zinck 1986)

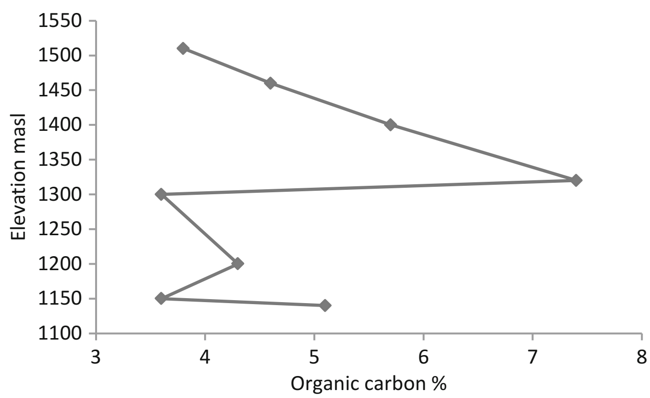


Fig. 4.6 Variation of organic carbon content (0–10 cm) with elevation along a mountain slope in the northern Coastal Cordillera of Venezuela (Zinck 1986)

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.

4.3 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.

4.3.1 Geopedologic Integration: A Structural Model

Figure 4.7 shows the data structure of the geoform-soil complex in the view of the geopedologic approach (Zinck and 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 multi-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.

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

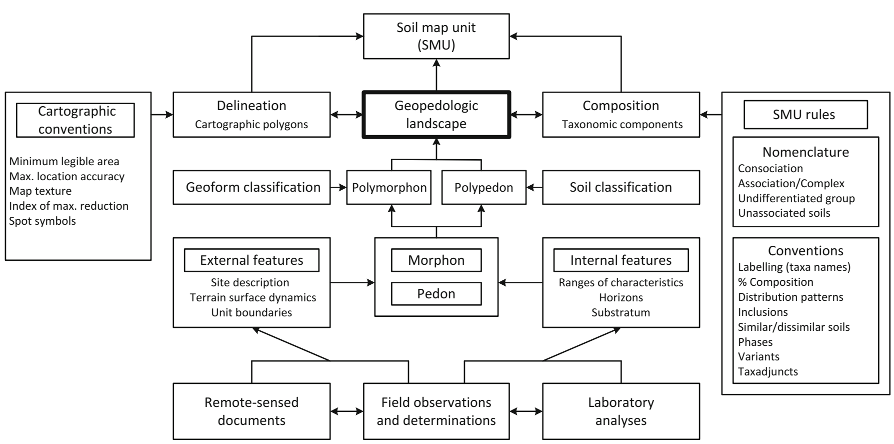


Fig. 4.7 Conceptual-structural model of the geopedologic approach (Zinck and Valenzuela 1990)

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 (see Table 4.1). 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 characterizing and quantifying 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 as the pedon but without fixed size standards. Conventionally, the areal size of a pedon varies from 1 m^2 for horizontally layered soils to 10 m^2 for soils having cyclic horizons. The extent of a morphon is obviously larger to capture the variations of the terrain surface. 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 whole 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 Chaps. 6, 7 and 8, 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 with contrasting inclusions 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 and Valenzuela (1990).

4.3.2 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.

4.3.2.1 Soil Geography

Soil survey generates information on the spatial distribution of soils. The implementation of geomorphic criteria in soil survey improves 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 of levee-mantle-basin in an alluvial plain or the sequence of summit-shoulder-backslope-footslope along a hillside. These models of geopedologic associations that are genetically related and produce characteristic 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* (i.e. pedosociology). Geopedologic spatial patterns depict the landscape and its elements the same way they can be seen in nature, in contrast to the artificial delineations shown on some geostatistically-based soil maps. This is why geopedologic maps are easy to read, even for non-specialists. For instance, on Fig. 4.2 it is easy to recognize the triangular shape of the alluvial fans.

- *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 preselected 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 costly. It is useful when applied locally to estimate the spatial variability of the soils within and between selected map units and to establish their degree of purity. Bregt et al. (1987) compare two thematic soil maps, one derived from a conventional soil map and another one obtained by kriging of grid point data. 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 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, especially systematic variability (Wilding and Drees 1983). Landform and soil patterns match often on a one-to-one correspondence (Wilding and Lin 2006). 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 and 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 quantitatively describing 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 (125, 250, and 500 m) 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 adding 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 and Rossiter (2003) show that supervised landform classification allowed extrapolating 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.

4.3.2.2 Soil Genesis and Stratigraphy

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, aspect), 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.

Figure 4.8 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 categorial level of terrain form (see Table 4.1), controls soil

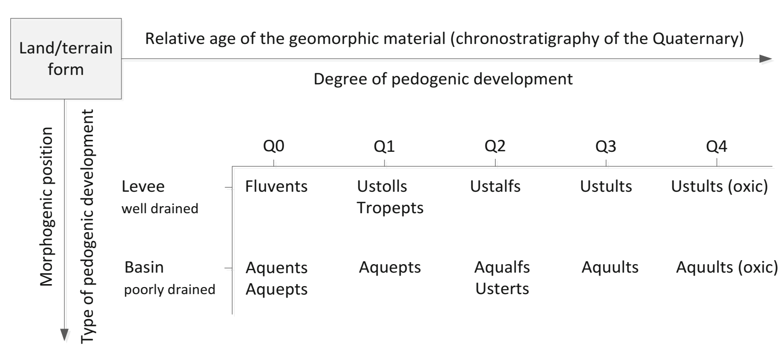


Fig. 4.8 Model of geopedologic relationships in alluvial soils, Guarapiche river valley, Venezuela (Zinck 1970)

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.

4.3.3 Geopedologic Integration: A Test of Numerical Validation

4.3.3.1 Materials and Method

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 comparing the performance of an object classification system in relation to a reference system (Sokal and 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 and 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. 4.9).

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 and 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 and Sneath (1963) to cluster the units, construct the dendrogram represented in Fig. 4.10, and calculate the average similarities.

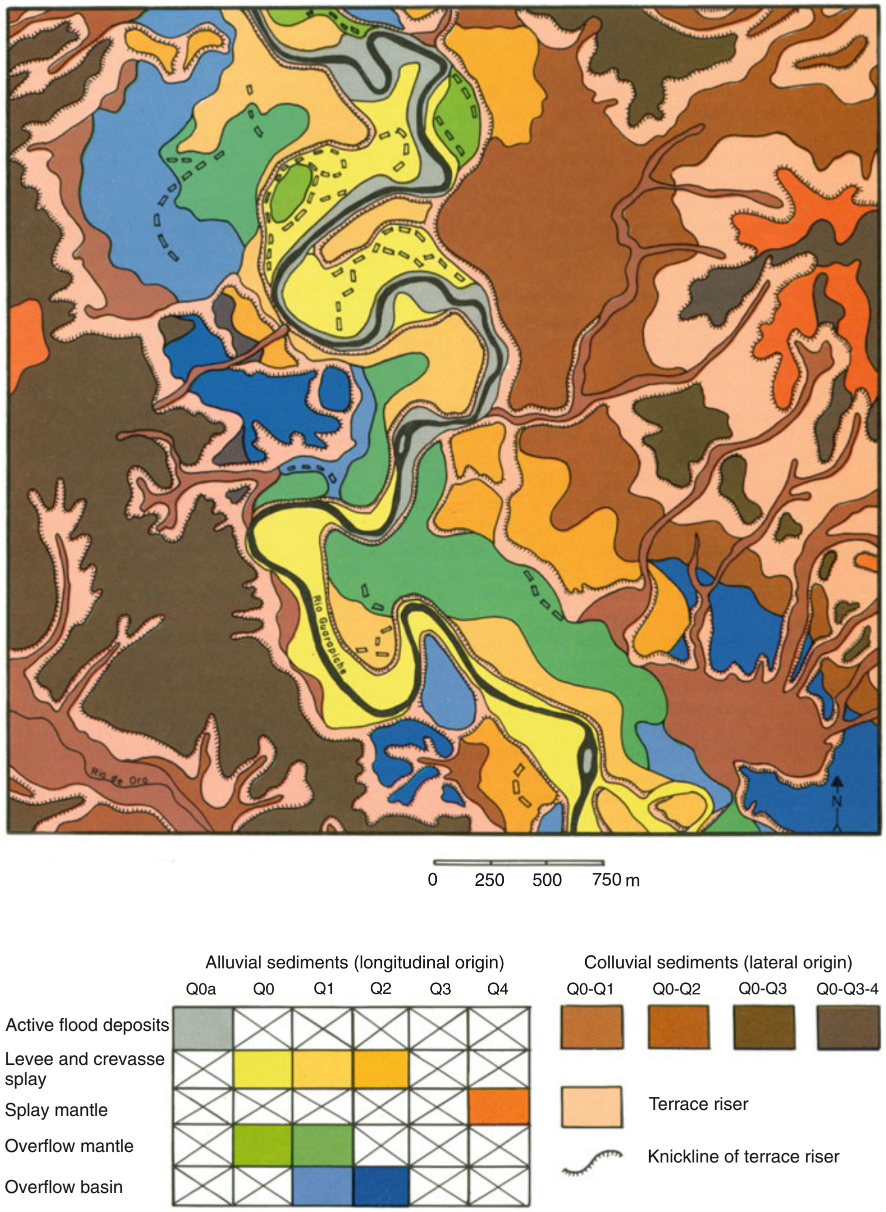
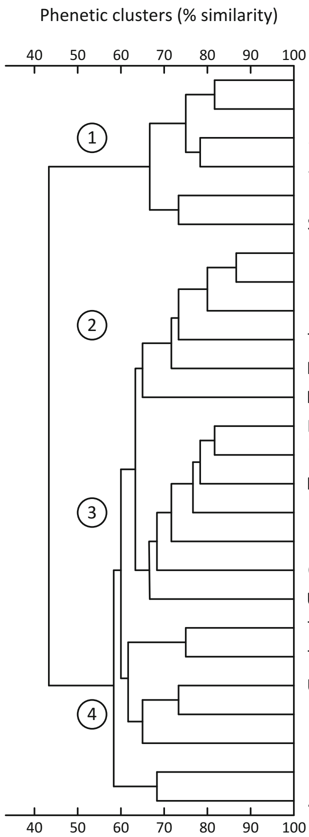


Fig. 4.9 Portion of the Guarapiche river valley, northeast of Venezuela, showing a chronosequence of nested terraces covering the Quaternary period (from Q0 to Q4). The boundaries of the cartographic units are essentially of geomorphic nature, while their contents are of pedologic nature (consociations and associations of soil series, not shown here). Extract of the original soil map at 1:25,000 scale (Zinck and Urriola 1971)



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. 4.10 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

4.3.3.2 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, with specific leading factors clustering the soils in each group:

- 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.

4.3.3.3 Conclusion

Mean similarities of great soil groups (73 %) and 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.

4.4 Operational Relationships

4.4.1 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).

The operational relationships are examined here 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 value added to the soil survey information when geomorphology is incorporated into 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 bordered by mountains, traditionally used for 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.

4.4.2 The Structure of the Soil Survey

Proceeding by iteration, a model structure with five categorial levels was obtained, as represented in Fig. 4.11. 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 4.2, 4.3, 4.4, 4.5, and 4.6).

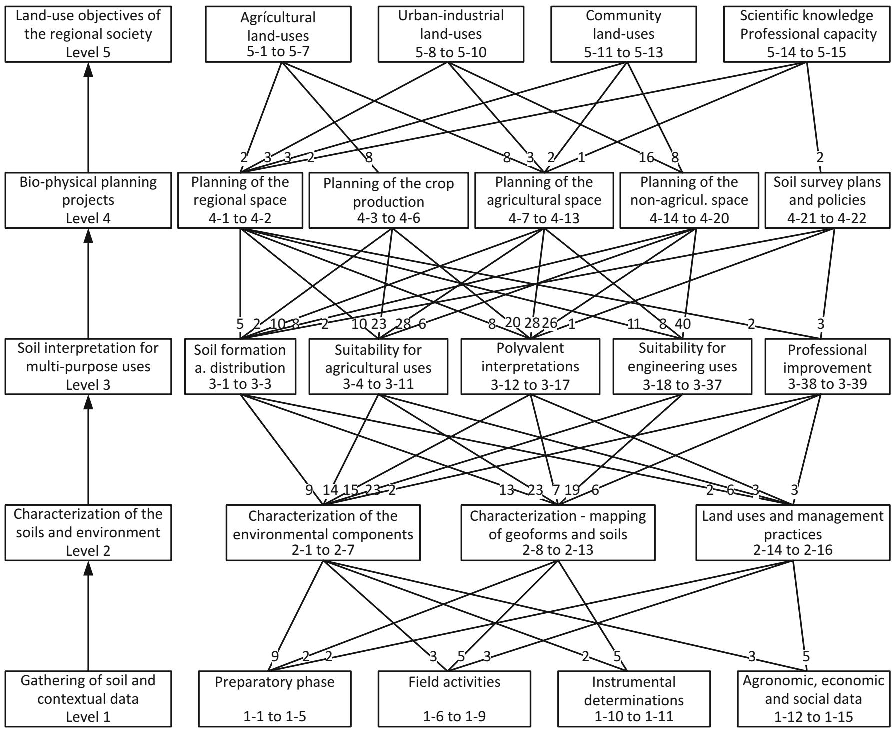


Fig. 4.11 Graph representing the soil survey as an information system, with production, interpretation, and dissemination of data and information, Lake Valencia project (Zinck 1977). The numbers in the boxes refer to the themes labelled in Tables 4.2, 4.3, 4.4, 4.5, and 4.6. The numbers inserted in the arrows indicate the amount of critical pathways through which information circulates from a given level to the following one

The numbers in the boxes refer to the themes labelled in Tables 4.2, 4.3, 4.4, 4.5, and 4.6. The numbers inserted in the arrows indicate the amount of critical pathways through which information circulates from a given level to the following one.

- Level 1: elementary tasks, which consist in the generation of the basic data, including the interpretation of aerial photos, satellite images and DEM, soil description and sampling, 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.

Table 4.2 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 photo-interpretation, identification of the physical-natural macro-units
1-4 Selection of the sample areas
1-5 Detailed 1: 25,000 photo-interpretation, identification of the geoforms, location of the sample areas
1-6 Survey of the sample areas
1-7 Control observations, photo-interpretation 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

Lake Valencia project (Zinck 1977)

Table 4.3 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

Lake Valencia project (Zinck 1977)

Table 4.4 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 Publications, conferences, education

Lake Valencia project (Zinck 1977)

Table 4.5 Level 4 themes: regional planning and development projects, designed and executed by 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

Lake Valencia project (Zinck 1977)

- Level 4: primary external objectives, which correspond to biophysical planning in the local and regional contexts, including territorial zoning, 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, perceptions, and priorities 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.

4.4.3 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 themes of the consecutive layers of the model

Table 4.6 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

Lake Valencia project (Zinck 1977)

were built. The matrices were subjected to the judgement of a team of ten experts in soil survey, who identified the relationships between the themes of pairs of levels and assessed the intensity of these relationships through a rating procedure using two score 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. 4.11. 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 establishing a ranking of the soil survey tasks according to their importance in generating or transmitting information.

4.4.4 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 photo-interpretation, 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 helps streamline, speed up and improve the soil survey. Unfortunately, nowadays soil inventory is not given priority on political agendas, despite the severe risks of degradation of the soil resource.

4.5 Conclusions

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 (e.g. 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, 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 interpolating/extrapolating information in mapping areas and predicting 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 soil mantle 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 features 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 for (1) interpreting soil formation along with the influence of biota, climate and human activity, (2) composing the soil cartographic units, and (3) analyzing 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 and landscape reading. 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 to 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 are reference units for more detailed geostatistical studies and for the spatial control of the 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).

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