AN ABSTRACT OF THE THESIS OF


Title: Spatial Analysis of Soil Depth Variability and Pedogenesis Along Toposequences in the Troodos Mountains, Cyprus.

Abstract

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Jay S. Noller

In unstable landscapes, modern pedological research explores the role of soils as products and indicators of geomorphologic change. Understanding the dynamics of hill slope pedogenesis is especially important in regions with limited, poor, or threatened soil resources. The island of Cyprus, situated in the eastern Mediterranean, is claimed by many authors to exhibit signs of severe soil degradation and is a prime site for comparative soil geomorphologic research. This study strove to 1) identify the controls of soil genesis and landscape stability within the Troodos Mountains of Cyprus using image and GIS analysis; 2) compare toposequence data to expected soil thickness trends from traditional models of xeric soil toposequences prevalent in current scientific literature; and 3) develop a predictive model for hillslope pedogenesis based on measured soil properties within the field area.
Study soils within the Troodos are thin, weakly developed Lithic and Typic Xerorthents formed in colluvium derived from fractured, igneous bedrock. Soil thickness was measured at 368 sites in seven transects across three watersheds in the Troodos, using interpretations of field profiles and image analysis of digital soil-bedrock profiles in photographed road-cuts along forestry paths. Soil thickness was compared through GIS and statistical analysis to landscape attributes derived from a 25-m DEM and other map data. Results indicate that lithology is the only factor of several studied to have a significant relationship with the variability of soil-profile thickness in the Troodos, and that soil thickness does not vary in a predictable manner across toposequences. These results, combined with differences between measured soil data and values predicted by the landscape stability model SHALSTAB, suggest that soil genesis in the Troodos is best described only within the context of a weathering-limited geomorphological system.

Short-term disruptive processes such as forest fires, land sliding, tree throw, and raindrop impact, combined with long-term processes such as tectonic uplift and stream incision, are the most likely driving forces behind the rapid erosion of hill slope sediments and the weak development of Troodos hill slope soils. These findings have important implications for DEM-based, predictive soil mapping in weathering-limited geomorphologic systems.
Spatial Analysis of Soil Depth Variability and Pedogenesis Along Toposequences in the Troodos Mountains, Cyprus.

by

Colin R. Robins

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Dean of the Graduate School

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Colin R. Robins, Author
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Spatial Analysis of Soil Depth Variability and Pedogenesis Along Toposequences in the Troodos Mountains, Cyprus.

INTRODUCTION

Literature Review

Hans Jenny's landmark publication *The Soil Forming Factors* identified and detailed five broad factors of pedogenesis: climate, organisms, topography, parent material, and time (Jenny, 1941). These factors have since been widely accepted and cited by soil scientists around the world. The scope of each factor is so broad and complex, however, that entire subdisciplines of study have arisen to better detail the processes and variables comprising each one. Moreover, the factors are so intricately related that it often proves meaningless to analyze them as separate factors. For example, the analysis of topography in studies of pedogenesis includes landscape pattern variables such as hill slope gradient, curvature, and aspect. The effect of each variable may be compared to one or more soil properties to test for correlation, but the necessary exclusion of time-dependent processes by such methods greatly oversimplifies depictions of pedogenetic processes, especially in geomorphologically active landscapes.

In unstable landscapes, modern pedological research explores the role of soils as products and indicators of geomorphologic change. The fundamental factors of soil formation on unstable hill slope landforms are identical to those acting upon flatter terrain. Research in landscape pedology assumes that much of a soil's characteristics are an indirect product of geomorphologic processes,
specifically the way water moves through and over the landscape (Moore et al., 1993). The hydrology of a landscape both affects and is affected by climate, organisms, parent material, and topography. The specific effects of hydrogeomorphology on soil genesis become clear when all pedogenetic factors apart from topography are held constant. A toposequence, therefore, is a series or pattern of distinct soils imparted on a landscape by changes in hydrogeomorphologic processes with topography. The distinction between soil or landscape pattern and geomorphologic process becomes crucial when modelling soil genesis along a toposequence. Many attempts by soil scientists and geomorphologists to characterize soil spatial variability across hill slopes have not sufficiently linked pattern to process (Moore et al., 1993).

Published toposequence studies range from simple regression analyses of soil properties along hill slope profiles (two dimensions) to more complex multivariate analyses that extend across landforms (three-dimensions). Soil properties investigated may include total profile thickness, specific horizon thickness, pH and the content of clay-sized particles, coarse fragments, organic matter, or specific nutrients.

Successful prediction of soil properties in a toposequence is considered an important goal of the field of pedometrics, given the new, detailed models of the Earth's surface: digital elevation models (DEMs) (McBratney et al., 2003). Some researchers suggest that certain soil properties, particularly those of the subsoil, do not correlate with satellite topographic data (e.g. Park and Burt, 2002), whereas other studies present an opposing view. In the latter case, researchers (Tsai et al.,
predict soil-depth characteristics across forest terrain based on multi-linear regression analysis.

In terms of general soil morphology, unstable landscapes are most frequently characterized by Entisols and Inceptisols because geomorphologic processes occur at rates or frequencies that preclude extensive soil-profile development. For this reason, soil thickness may serve as a proxy for soil development in the absence of diverse horizons or textural differentiation. In addition to representing long-term erosion, deposition, and soil building processes, soil thickness may also generally indicate water storage capacity, nutrient storage pool, and overall productivity, providing a basis for modelling the spatial distribution of landscape process zones.

The most informative toposequence studies relate pedogenesis to geomorphologic process by considering soil properties as a net by-product of the co-acting processes of soil or regolith development, soil and bedrock erosion, and tectonic uplift or subsidence (Heimsath et al., 1999; D'Olorico, 2000; Gessler et al., 2000; Braun et al., 2001). This net effect of slope process and pedogenesis determines the spatial distribution of select soil properties (Park & Burt, 2002).

Once the relationship between geomorphology and hill slope pedogenesis is understood for a given site, soil properties may be extrapolated across landforms of similar morphology, and over geomorphologically significant time scales (Dietrich et al., 2003). The question, then, is which pedogenetic factors and what level of geomorphologic detail are needed to accurately model soil development, or soil thickness, across a given hill slope system (Jenny, 1941). Because toposquences
have been described for many distinct environmental and ecological regimes, the geomorphologic aspects of the traditional soil forming factors are well-constrained. The following review addresses the dynamics of organisms, parent material, and climate, on toposequence pedogenesis.

**Factors in toposequence pedogenesis**

Organisms affect soil in many ways, however, their geomorphologic significance consists mainly of the downslope transport of soil material through bioturbation, for example: burrowing, root growth, or tree throw. In many instances, the mechanical disruption of parent material through bioturbation is the dominant soil production mechanism (Heimsath *et al.*, 2001). Although bioturbation by an individual organism may affect only a small volume of soil or regolith, studies suggest that bioturbation, especially in forested hill slopes, thoroughly mixes soil layers over geomorphologic time-scales and limits the maximum soil depth (Roering *et al.*, 2002; Gabet *et al.*, 2003). Researchers have also detailed the effects of soil mixing on organic and inorganic nutrient levels along toposequences (Weitkamp *et al.*, 1996; Norton *et al.*, 2003).

Parent-material characteristics also affect pedogenesis. Specifically, the porosity, permeability, physical integrity, and mineralogy of a substratum influences hydrology and stability. Moreover, fractured bedrock has long been considered more susceptible than intact material to physical weathering and erosion via root growth, freeze-thaw, and other processes. Research indicates that chemical weathering of parent material increases laterally towards the increased surface area
of rock fractures (Frazier & Graham, 2000; Ehlen, 2002). Therefore higher
degrees of regolith production may be found in parent material exhibiting high
bedrock fracture density. The relationship of soil thickness to bedrock fractures,
however, depends also on the temporal stability of the landscape. Under a
weathering-limited geomorphologic system, soil erosion is limited by the rate at
which sediment is made available by weathering of parent material (Birkeland,
1999).

Under transport-limited conditions, soil develops in accumulating
colluvium through time until erosional events disrupt pedogenesis and translocate
sediments. Expected soil thickness trends for weathering- and transport-limited hill
slopes are illustrated in Figure 1.1. The degree and depth of rock weathering
profiles may help determine geomorphologic processes of erosional landscapes and

![Figure 1.1. Expected relationship between fracture density and pedogenesis for distinct geomorphologic systems.](image)

Figure 1.1. Expected relationship between fracture density and pedogenesis for distinct geomorphologic systems.

sediment features (Migoń & Lidmar-Bergström, 2001). That is, the properties that
influence hill slope resistance to lowering through mass removal often depend less
upon the original parent material than they do upon the physical and hydrological
properties of soil and regolith (Taylor & Eggleton, 2001).
Climate exerts even greater pedogenetic controls on a landscape. The total amount of moisture received, the form of precipitation in which moisture arrives, the intensity of precipitation events, and the seasonal distribution of precipitation events all exert great influence on soil development and landscape stability (Birkeland, 1999). In turn, the flow of water is inherently dependent upon topography. Research by Moore et al. (1993) models pedogenesis as a function of the hydrologic characteristics, supported by slope and wetness index correlations, of a landscape. Other well-explored models include USLE (Wischmeier, 1976) and WEPP (Flanagan & Nearing, 1995), which employ similar topographic and hydrologic variables to characterize soil erosion rather than soil genesis. Where relief is high, orographic effects can greatly influence not only soil erosion, but also soil properties and regolith development at larger temporal and spatial scales. For the most part, however, toposequence study areas are developed at the kilometer scale, landform scale, or smaller and exhibit limited (tens to hundreds of meters) relief so climatic variability across modelled sites is often negligible.

Given the high number of studies describing different sub-processes of the soil forming factors, the geomorphologic aspects of traditional soil forming factors are well-constrained and may be applied to toposequence analysis. Because topography and hydrology are never uniform, geomorphologic processes vary even along individual hill slopes. Consequently, toposequences are usually subdivided into distinct hill slope position classes, based on natural breaks in hill slope gradient or curvature. Common classes include summit, shoulder, backslope, footslope, and toeslope positions (Ruhe and Walker, 1968). Recently, computer
programs have been developed to automate the classification of hill slope position for comparison to soil and other landscape attributes (e.g. Coops et al., 1998).

In two companion papers, Ruhe and Walker describe pedogenetic variability along toposequences as a function of hill slope gradient and landscape stability (Ruhe & Walker, 1968; Walker & Ruhe, 1968). Other researchers suggest that while pedogenesis may indeed depend partly on landscape position, slope length, and slope gradient, the spatial variation of pedogenesis is more significantly controlled by landform curvature (King et al., 1983). The relationship between topography and pedogenesis has been explored in diverse toposequences across the globe. For example, the research of Ruhe and Walker (1968) maintains that, for a given hillside, shoulder and backslope positions should exhibit weak soil development due to steep gradients and high rates and incidences of erosion, while summit soils should be well developed due to greater stability through time (Figure 1.2). In contrast, other authors remark that summits of many toposequences in the western U.S. are poorly developed because they retain the least soil moisture of all positions in their respective hill slopes (Birkeland et al., 2003). Results from another study, of rocky hill slopes in Mexico, suggest that summit, shoulder, and backslope segments are all predominantly unstable areas characterized by weak soil-profile development (Gama-Castro et al., 2004).

These apparently conflicting results are explained in terms of the previously mentioned interaction of pedogenetic, geomorphologic, and geologic processes. The Iowa field site described by Ruhe and Walker (1968) falls within a tectonically
Figure 1.2 Measured soil depths and expected soil thickness trend between summit and backslope positions in Harrison County, Iowa (adapted from Ruhe & Walker, 1968).

stable region. In contrast, the authors of the study in Mexico suggest that landscape changes in their field site are rapid, and that episodes of change may be separated by long periods of stability (Gama-Castro et al., 2004). Not all differences between toposquences may be explained in this manner. Researchers at other sites note, as a caveat, that erosion rate estimates are often only poorly constrained, not only due to the spatial variability of soil properties but also due to the short time period in which data may be collected (Reneau & Dietrich, 1991). Researchers comparing diverse toposquence and erosion studies must also consider that the apparent order, complexity, or variability of earth surface systems depends upon the spatial and temporal scales of study (Phillips, 1999).

Toposequences span distinct geomorphologic and geologic systems. Sediment-limited and transport-limited regimes comprise two extremes between which pedogenesis and hill slope processes fluctuate due to random forcing
(D'Odorico, 2000). Thus, soils within traditionally defined toposequence position classes are shown to vary depending on site geology, climate, topography, vegetation, and even human land use. The expectation, however, is that soil characteristics within a given toposequence may be predicted when the pedogenetic and geomorphologic context of the site can be clearly identified. Similarly, soil toposequences may be compared between sites that have closely similar pedogenetic and geomorphologic environments.

Understanding the dynamics of hill slope pedogenesis is especially important in geomorphologically unstable regions with limited, poor, or threatened soil resources. The regions bordering the Mediterranean Sea face the increasing threat of large-scale, progressive soil desertification and subsequent soil erosion (Secretariat of the UN CCD, 2002). The island of Cyprus, situated in the eastern Mediterranean, is claimed by many authors to exhibit signs of severe soil degradation. Centuries of use, it is argued, have degraded soil quality on the island, leaving many soils as thin, alkaline, humus- and nutrient-poor mantles of regolith atop highly permeable, rocky substrata (Keefe et al., 1971). Analysis of historical land use records illustrates how millenia of extensive timber harvest and forest grazing by goats could have contributed to the diminution of the forests of Cyprus and the erosion of forest soils (Christodoulou, 1959).

Although hill slope processes have been detailed worldwide, much of the recent research (e.g.: Reneau & Dietrich, 1991; Heimsath et al., 1997; Frazier & Graham, 2000; Anderson et al., 2002) on hill slope processes and soil geomorphology has been conducted in the western mountains of North America.
Similar seasonal moisture patterns, geology, geomorphology, and land use make studies of landscape pedology in these regions ideal for comparison to the Troodos Mountains of Cyprus.

Although both provinces have Mediterranean climates, the mean annual precipitation (MAP) of the North American sites is much greater than that of Cyprus. Oregon data represent the wettest hill slopes, while studies conducted in California model landforms with intermediate MAP. Thus, research on hill slope soil processes in Cyprus may elucidate dynamics of drier (low MAP) regions under-represented in contemporary scientific literature. Models developed in wetter climate regimes can be applied to DEM and hydrologic data from the Mediterranean, and tested for applicability to drier climates. The island of Cyprus presents a virgin field for soil genesis and soil erosion research (Thirgood, 1987). Investigations of pedogenesis in forested toposequences of the Troodos Mountains extends the broader scientific knowledge of pedogeomorphologic processes to a region in great need of further geomorphologic and soil science research.

Objectives

The central hypothesis of this research holds that soil thickness within the Troodos Mountains varies in a predictable manner across geomorphic features due to topographic variations. Specifically, qualitative field observations made during the summer of 2003 suggest that soils are extremely thin (less than ten centimeters) or absent on summits and ridges, and thickest (greater than forty centimeters) along valley bottoms. This proposed toposequence departs from more traditional models
(e.g. Ruhe and Walker, 1968), which hold that summit soils are more stable and, thus, better developed than backslope soils. A further tenet of this research is that soil-profile thickness is a reasonable proxy for degree of soil development.

The objectives of this study are: 1) to identify the controls of soil genesis and landscape stability within the Troodos Mountains of Cyprus; 2) to compare field measurements to expected soil thickness trends from traditional models of soil toposquences prevalent in current scientific literature; and 3) to develop a predictive model for hill slope pedogenesis based on measured soil properties within the field area.

Site Description

Field Area

The boundaries of three adjacent watersheds - the Atsas, Elia, and Kargotis - along the northern flank of the Troodos Mountains delineate the study area of this thesis (Figure 1.3). The Atsas, Elia, and Kargotis watersheds drain north into Morphou Bay and, above the plains of the Mesaoria, are representative of general watershed characteristics throughout the Troodos. Their drainages also traverse Cyprus Department of Forestry lands that are an integral component of ongoing government forest restoration and fire-suppression efforts. The following descriptions of the geology, geomorphology, and land use characteristics of these watersheds are essential to the contextual analysis of pedogenetic processes in the Troodos Massif.
Figure 1.3.
Hillshade geological map of the Kargotis, Atsas, and Elia watersheds of the Troodos Mountains, Cyprus.
Geology and Geomorphology

The v-shaped valleys of the Troodos incise highly fractured intrusive and extrusive volcanic rocks of the Troodos Ophiolite. Intracontinental rifting initiated uplift of the ophiolite during the Late Triassic (Gass, 1975; Robertson & Woodcock, 1979). With time, channel incision and erosion produced a concentric outcrop pattern in which the oldest lithologic units of the ophiolite sequence are the most central (Gass, 1975). Within the study area, bedrock consists chiefly of the Upper Cretaceous Basal Group and Sheeted Dike (Diabase) units (Geological Survey Department, 1995). These units incorporate successions of basalt pillow lavas subsequently intruded by diabase dikes, but the prevalence and homogeneity of dikes increases down-section until the bedrock consists wholly of parallel dike bodies (Gass, 1975). In this way, laterally alternating dike swarms and pillow lavas characterize substrata in most of the field area.

Owing to the uplift and concurrent fluvial incision of the Troodos Ophiolite, the most characteristic landforms atop the igneous substrata consist of either long, linear bedrock spurs with narrow ridges and steep, contiguous side slopes, or conical bedrock landforms with triangular facets. Sheet, rill, and gully incision marks all landforms to varying degrees, and hill slopes may contain vegetated or bare, shallow colluvial hollows, or deep, rocky ephemeral gullies. Elevation across the complete Atsas, Elia, and Kargotis watersheds area ranges from mean sea level in the north to approximately 1900 meters above mean sea level in the south. The elevations of soil-profile sites analyzed in this research cover a significantly narrower range of 450 meters to 680 meters above mean sea level. Hill slope
gradients generally range from zero to ten degrees atop ridgelines and along valley bottoms, and from 20 to 45 degrees along backslopes.

Thin layers of gravelly colluvium mantle the landscape between ridge shoulders and narrow deposits of alluvium along gully bottoms. Soils developed within the colluvium either exhibit only weakly developed horizons or lack distinct horizons entirely. Mineralogical and textural differences between individual igneous bodies cause lateral variations in rock color, texture, and hydrology that are apparent within even small outcrops and roadcuts. These lithologic and regolith variations impart similar, though more muted, color and textural variations to hill slope soils. Five- to ten-centimeter thick surface organic layers are common, typically comprised of mosses, lichens, mycorrhizal fungi, and decomposing plant matter. The humus content of these soils is low, ranging from 4.6% in pine forests in the upper Troodos Mountains to 1.5 percent or less in cultivated lowlands (McDonald, 1949, as cited by Christodoulou, 1959).

The gravelly nature of these silt loam and silty clay loam soils also indicates that mass creep entrains coarse fragments from the upper layers of the fractured bedrock. Many trees exhibit markedly curved trunks, further suggesting gradual but persistent soil creep. Ridge summits are typically rocky, their fine sediments likely removed by raindrop impact, runoff, wind, and mass creep. However, the isolated boulders and exposed bedrock blocks common on ridge summits often bear weathering rinds and lichen assemblages (Rinocarpon sp.) indicative of long periods of in-situ weathering and, thus, inferred stability. Hilltops may constitute
stable surfaces for coarse boulders and bedrock blocks, while finer materials achieve stability only on footslope or toeslope terrain.

Besides igneous bedrock, some landforms developed on younger sedimentary substrata. Long, graded Pleistocene alluvial terraces composed of red channel gravels and silts demarcate ancient streams throughout the Troodos Massif and are readily discernable from surrounding igneous landforms. The alluvial landforms typically have a sub-uniform slope of five to fifteen degrees while the faceted bedrock spurs and rounded hill slopes have variable slopes that are generally steeper than 20 degrees. Where roadcuts have bisected multiple landforms, the red and grey silts and rounded cobbles of channel-form Quaternary sediments contrast strongly with the dominantly reddish yellow-brown, fractured bodies of the older, weathered volcanic bedrock. These alluvial landforms exhibit deeper soil profiles and are far more stable than surrounding colluvial slopes.

_Historical Perspectives on Land Use and Soil Genesis in Cyprus_

Because the soils of Cyprus have been tilled for the last 5,000 years, the long-term imprint of human land use on soils of the Troodos, especially the effects on soil erosion and soil cover, must be considered (Christodoulou, 1959). A commonly held theory suggests that Cyprus was once widely covered by forests, maquis, or scrub woodland but declined into progressively sparser assemblages of grasses and dwarf woody colonizers under persistent, heavy grazing and other poor land use practices (Thirgood, 1987). Compounding this history, it is thought, is the precipitation pattern. Precipitation occurs as intense, high energy events that
typically take place only during winter months, so the parched soil profiles of Cyprus are able to maintain vegetative cover only with difficulty (Christodoulou, 1959). Roughly fifteen percent of the total area of Cyprus exhibits steep slopes (Secretariat of the UN CCD, 2002), and the effects of sheet erosion have been described as widespread and severe, yielding very thin soils on even gently sloping land (Christodoulou, 1959). Much of the landscape is subject to high erosion potential, and large areas are thought to have been completely denuded of once-thicker topsoil (Keefe et al., 1971). This belief has led to the further, permanent modification of the Troodos landscape by humans, with the emplacement of extensive terraces and gully check dams.

As part of general restoration efforts, Department of Forestry practices over the last two centuries have focused on thorough terracing and reforestation of the Troodos, and the abolition of herds of goats and sheep from forest lands. Terraces emplaced within the study area vary in extent and morphology, perhaps dependent on contemporary land management policy. Terrace morphologies include large bulldozed earth and gravel; long, narrow, hand-dug, linear terrace cuts with path-like morphologies that contour hillsides; small scalloped excavations into bedrock; and pre-nineteenth century stacked stone terraces near abandoned or ruined settlements. Of these diverse morphologies, only the ancient check dams and terrace walls do not involve significant excavation and thus succeed in promoting rather than weakening local slope stability. Stone check dams of varying age are found in small, second- or third-order gullies near settlements, churches, or other sites. These structures consist of cobble- to boulder-sized stones stacked
perpendicular to flow direction, and typically have reservoirs of less than one or two cubic meters. Of these structures, the younger generation were built near forestry trails to control soil erosion, while the purpose of older structures may have been to support individual family olive trees, or small herb gardens.

The geomorphology of the northern flank of the Troodos Mountains exemplifies the close ties between human activity, natural resources, landscape, and slope stability. Thorough understanding of soil genesis in the context of geomorphic process and historic land use is needed to address modern issues in soil and forest resource management.
A network of seasonally-maintained, bulldozer-constructed gravel roads traverses the forested northern Troodos Mountains. Because these roads comprise part of ongoing government fire-suppression efforts, their track foregoes more conventional, contoured routes to allow access by firefighters to even the most remote areas of the Troodos. Consequently, these Forestry Department roads cut through landforms of all slope and elevation ranges, and roadcuts afford excellent cross-sections of diverse geomorphic and pedologic features. In this way, these roadcuts represent a quasi-random sampling of soil-bedrock profiles in transects across multiple watersheds. Soil-bedrock relationships are easily discernable in these outcrops, and regular maintenance of the roadways insures fresh, stable exposures indicative of natural soil profile characteristics. Accurate descriptions of soil and bedrock properties are readily obtainable from the outcrops themselves or, alternatively, from high-resolution digital photographs of the outcrop faces.

During the summer of 2002 and the spring of 2004, several hundred digital photographs were taken of soil-bedrock profiles in stable roadcuts within the Elia, Kargotis, and Atsas watersheds (Figure 2.1, below). The images were taken at a constant distance of approximately 4.5-meters from profile faces and share a 50-millimeter focal length. The resolution of the images affords accurate, quantitative measurement of soil thickness (apparent depth to bedrock) and bedrock fracture characteristics across each outcrop. Sample images are displayed in Figure 2.2.
Figure 2.1. Locations of soil photograph and soil pit transects. Numbered transects are described in greater detail below.
Figure 2.2. Examples of images used to measure area-normalized soil thickness and bedrock fracture density.

Concurrent global positioning system (GPS) data were collected at each outcrop using hand-held Garmin Geckos and Etrex GPS units.

Field Data

Field work conducted during the summer of 2003 and 2004 supplemented this research. Specifically, survey mapping performed in conjunction with the Troodos Archaeological and Environmental Survey Project (TAESP) provided a thorough, qualitative analysis of regional geology, geomorphology, land use, and vegetation. Survey work also facilitated the detailed description and classification of additional soil profiles from roadcut outcrops and hand-dug pits. Combined with
ground-truthing of select roadcut profiles, this information verified the temporal integrity of the soil-bedrock profiles and the accuracy of photo-derived measurements. Thus, the combined dataset employed by this research comprises 367 mapped records.

GIS Data

This project also relied on GIS data obtained through the assistance and kind permission of both the government of Cyprus and TAESP. These data include a 25-meter digital elevation model (DEM); 1:50,000 scale stream data, and 1:250,000 scale lithologic, soil, hydrologic, and mean annual precipitation maps. The DEM was produced by the Cyprus Geological Survey between 2000-2003. Arc polyline shapefiles of elevation were hand-digitized from 1:50,000 topographic maps, and a triangular integrated network (TIN) was then developed from the contour polylines via ArcMap 3D Analyst. The TIN, in turn, was then gridded to a cell size of 25 meters, using TauDEM extension in ArcMap 8.2. TauDEM processing included the filling of voids in the DEM. Information provided by the DEM and the described digital maps was vital to the spatial and pedogenetic context and analysis of the soil data.
METHODS

The general organization schematic and progression of methods used is displayed in Table 2.1, below. Specific procedures for image analysis, fracture characterization, soil-landscape correlations, toposequence analysis, and predictive soil-stability mapping are outlined here.

Data Processing and Database Construction

Soil thickness (depth to bedrock) was measured by importing the digital photographs of soil-bedrock outcrops as .tif files into the software program ESRI ArcGIS Desktop 8.2. Based on the known focal length and lens-to-outcrop distance for all images, associated world files (.tfw) were created in the software program Geotiff. These companion files assigned a non-earth coordinate system with metric units to each image so that individual measurements of soil profile thickness, in meters, might be determined using geographic information system (GIS) software. The resolution of the digital photographs employed to measure soil thickness and bedrock fracture density in roadcuts and outcrops is sufficient to interpret pedogenetic and lithologic contacts. Possible variations in image scale cannot be discounted entirely, because the distance between camera lens and outcrop face may have varied on the order of centimeters or decimeters. Similarly, the slope of roadcut faces may have strayed slightly from the vertical. However, such variability translates to very low magnitude differences in soil thickness. Global positioning system (GPS) coordinates of image sites are accurate within two to ten meters, well
Table 2.1. General organization of data, showing target attributes and analyses.

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Attributes Provided</th>
<th>Data Values and Categories (units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital Photographs</td>
<td>Soil, Fracture, and Spatial (GPS Coordinate) Information</td>
<td>Minimum, maximum, and mean soil thickness; soil and bedrock cross-sectional area; area-normalized fracture length; (meters)</td>
</tr>
<tr>
<td>Field Profiles</td>
<td>Soil Profile Descriptions; Landform Characteristics</td>
<td>Soil color, texture, structure, horizonation; root and bedrock fracture characteristics</td>
</tr>
<tr>
<td>Field Transects</td>
<td>Geomorphological and Archaeological Data; Land Resource Characterization</td>
<td>Hill slope stability, slope, aspect, substratum, morphology; Age of human land use; Historic land use industry, Toposequence Trends</td>
</tr>
<tr>
<td>Satellite Data</td>
<td>25-m DEM</td>
<td>Elevation (m), Slope (deg), Aspect, Hillshade Map, Relative Hill Slope Position, Ridgelines</td>
</tr>
<tr>
<td>Map Shapefiles</td>
<td>Geology, River, Watershed, Precipitation, and Hydrology</td>
<td>Parent lithology, stream order, stream proximity (m), watershed, MAP (mm)</td>
</tr>
</tbody>
</table>
below the scale of landforms within the study area, and permit detailed mapping and GIS analysis of the roadside soil-bedrock images. Universal transverse mercator (UTM) coordinates were used in this study.

Because soil thickness in the natural landscape can vary significantly across even small distances, and because the photographed profiles span up to five horizontal meters, the minimum and maximum soil profile thicknesses (depth to bedrock), the straight-line width of the weathering front from one side of the soil profile to the other, and the cross-sectional area of the soil profile were measured in each image. The mean soil depth at each site was defined as the ratio of the cross-sectional area of the soil profile divided by the straight-line distance between the lower left and lower right corners of the soil profile. This value mean soil depth per outcrop is more representative of field conditions than the average of the minimum and maximum soil depths per outcrop. Thus, the mean soil depth value was used in all analyses.

In most instances the soil-bedrock contact was abrupt, exhibiting strong textural contrast between fine-grained colluvial sediment and angular bedrock faces. In many images, coarse roots of *Pinus brutia* further demarcated and facilitated accurate delineation of the soil-bedrock contact. Roadcuts obscured by shadow, comprised of alluvial rather than bedrock substrata, graded at non-subvertical angles, unconstrained by spatial data, or otherwise deemed of poor quality were not analyzed.

General observations of soil texture, structure, depth, and color trends were noted on transects throughout the field area to characterize the general variation of
soil properties. Field descriptions of representative soil profiles and their geomorphic setting facilitated generalized morphologic interpretations of the photographed soil sites. Data from the detailed field description of additional profiles from GPS-located sites permitted classification of regional soils to the family level following the USDA soil classification system (Soil Survey Staff, 2003).

In total, this analysis includes measurements from 302 photographs and sixty-five excavated field pits. The mean soil depth for each profile was then entered into a tabular database containing also the site identification and GPS coordinates for each profile. The 367 records were then converted to a point shapefile for processing in subsequent GIS analyses.

Testing for Correlation between Soil Depth and Pedogenetic Factors

Correlation between soil depth and bedrock fracture characteristics

The sheeted diabase dike, pillow basalt, and plagiogranite units of the Troodos Massif are extensively fractured. One postulate of pedogenesis maintains that, other factors held constant, soils atop fractured bedrock may experience greater development because the fracture networks afford increased surface area for chemical and physical weathering. If the fracture characteristics of substrata in the Troodos do affect pedogenesis, there should exist an identifiable correlation between soil thickness and the spatial density of bedrock fractures. Assuming geomorphologic systems in the Troodos operate near a state of natural equilibrium, identified relationships between pedogenesis and bedrock fracture density should
match expected trends for either supply-limited or transport-limited conditions. A two-part analysis explored distinct means of quantifying fracture density and connectivity through image analysis and tested for possible correlations between soil depth and bedrock fracture density. One method was automated while the other was performed manually.

The first procedure employed Erdas Imagine 8.5 to cluster pixel signatures into two classes, essentially thresholding the images, and then exported pixel data to a spreadsheet program for additional analysis. Due to the nature of the soil mineralogy and bedrock lithology within the study area, the images afforded strong contrast between fracture pixels and pixels of soil and rock. Images exhibiting poor contrast or areas of shadow, roots, or vegetation were excluded because the similarity in spectral signature of such pixels to fracture pixels would otherwise inflate the measured fracture density. First, 13 vertical profiles extending from the soil surface down to bedrock were sub-sampled from the six images. Each profile was filtered using Erdas Imagine's 3x3 matrix cross edge detect spatial convolution. Next, an unsupervised classification was applied to both raw and filtered profile images. To ensure uniformity, the clustering options were held constant – each classification produced 10 classes through a maximum of 25 iterations, a convergence threshold of 0.99 and an automatic standard deviation function. Class interpretation was constant between profiles. Specific profile information for each classification is presented in Appendix A. Each signature group was interpreted as either "fracture" or "non-fracture" and assigned a class value of 1 or 0, respectively. Once the original ten class values had been recoded, and the new, processed image
saved, the pixel table was exported into a Microsoft Excel spreadsheet. The depth to bedrock was previously measured in each image as described above. Because each fracture pixel had a value of 1, the total number of fracture pixels divided by the total number of pixels below the bedrock-soil contact, per profile, yielded a percent area of fracture to rock. This value was then compared to the soil thickness to test for correlation.

The second, simpler but more time-intensive test involved manual digitization of bedrock fractures in 44 images using ArcGIS 8.2. All fractures visible at a scale of 1:15 or coarser and longer than approximately three centimeters were digitized as polyline segments. Polygon traces of outcrop faces were also constructed. All produced shapefiles were then converted to coverages, and the total fracture length, in meters, per outcrop was calculated. The area of each outcrop polygon, in square meters, was also measured and used to calculate the total area-normalized fracture length per profile. The quantitative relationships of fracture density to soil depth in all images were then compared for possible trends.

*Correlation between soil depth and the traditional soil-forming factors*

To better understand the active controls of soil genesis in the Troodos, GIS and statistical methods were developed to determine the relative importance of each of the traditional soil-forming factors of time, organisms, parent material, climate, and topography. This simple analysis focused on each pedogenetic factor individually and did not address all contributors. Distinct methods were developed
to address the more complex dynamics between multiple topographic and geomorphic factors, and will be presented in a separate section below.

In the simple GIS and statistical assessment of traditional pedogenetic factors described here, the role of time is not directly addressed because no age data currently exist for the studied soil profiles. Secondly, qualitative field observations indicate that vegetation is relatively uniform across the region and comprised most characteristically of *Cistus* sp. shrubs and the Calabrian Pine, *Pinus brutia*. Macrofauna assemblages are also relatively uniform across the region and include several reptile and small mammal species. Goats are no longer permitted within the Troodos forest (Thirgood, 1987). Because of the relative homogeneity of floral and faunal characteristics across the study area, the effect of biologic factors on soil-thickness variation is assumed negligible.

With the exception of plagiogranite substrata in upper elevations, the lithology of the igneous parent material does not vary greatly across the study area from sheeted diabase dike complexes and the basal group basalts they intrude. Moreover, soil development presumably varies only imperceptibly across geologic contacts because the boundaries between lithologic units are gradual (Morris, 1996). Nevertheless, the substratum lithology was identified for each data point using a 1:250,000 geologic map of Cyprus (Geological Survey Department, 1995) in polygon shapefile format. As in other portions of this research, soils derived from wholly alluvial sediments and landforms were excluded because such soils differ geomorphologically and genetically from the colluvial hill slope soils mantling the
igneous substrata. Soil thickness between lithologic classes was compared via a fixed-effect one-way analysis of variance.

Climate variability across the study area also appears relatively slight, however, topography does impart local changes in total mean annual precipitation (MAP) and precipitation intensity. Soils were analyzed for climatic influences through simple linear regression of soil depth and MAP. Precipitation values were estimated for each site using interpolated values from a precipitation map of Cyprus in grid format. The precipitation map itself was derived from 308 measurement stations scattered across the island.

The effect of topography on pedogenesis was also investigated. The different variables addressed included elevation, slope gradient, aspect and, on a broader scale, watershed. All topographic data were derived from the 25-meter DEM utilizing ArcMap's 3D Analyst and the complementary software package TauDEM (Tarboton, 2002). Simple linear regressions were used to test for soil thickness correlation with slope, aspect, and elevation. Differences in mean soil depth between watershed classes were analyzed using one-way ANOVA.

Attribute values for lithology, MAP, elevation, slope gradient, aspect, and watershed for each soil site were added to the database of point records. Attribute values were assigned in ArcGIS by overlaying the soil-bedrock point shapefile with the appropriate map layer, converting the point features to 3-D in 3D Analyst, and then running the Easy Calculate command 'get point z-value' in Raster Calculator. Through this process, attributes (e.g. substratum lithology, elevation value, etc.), for the coordinates of each site were recorded in the GIS directly from
corresponding locations on each map layer (e.g. geologic map shapefile, DEM raster, etc.). Complete point attribute (.dbf) tables were then exported to S-plus 6.0 and Microsoft Exel for statistical analysis. Statistical analyses included simple linear regression, ANOVA, and two-sample t-tests. In each case, the soil forming factors were the grouping variable and soil thickness the dependent, or response, variable.

**Topography Revisited: Hill Slope Position**

Simple statistical analyses of individual topographic elements may illustrate general trends, but more involved, multivariate approaches are required to explain in detail the topographic and geomorphologic controls of soil genesis. Soils vary depending upon slope gradient and morphology, erosion type, hydrology, and other factors (Birkeland, 1999). Thus, topography-dependent soil properties may be predicted across other hill slope soil traverses, or toposequences, under similar environmental conditions (Birkeland, 1999). Classical models (e.g., Ruhe & Walker, 1968; Walker & Ruhe, 1968) delineate hill slope position at changes in slope gradient or curvature along a two-dimensional profile. Methods of automated three-dimensional toposequence analysis are also possible (e.g., Coops *et al.*, 1998). Hill slope positions of all data points were identified to develop a working model for characteristic toposequences in the northern Troodos Mountains. Because implementation of a three-dimensional model is quite time and labor intensive, a more rapid, though less accurate, two-dimensional means of analyzing the variability of soil-profile thickness with topography was employed. The first,
automated, method computed the position of all soil profiles based simply on their distance from topographic extremes, *i.e.* streams and ridgelines. The second method identified 32 apparent toposequences within seven larger-scale transects, and classified each component profile based on visual interpretations of its slope and curvature characteristics. Specific procedures for these two methods are outlined here.

**Stream and ridgeline-derived classification of hill slope position**

In this procedure, a three-class system was established by buffering all areas within defined distances of ridgelines and streams in ArcGIS to establish crude interpretations of summit and footslope classes, respectively. This method was thought to suit well the long, narrow, linear nature of ridges and hill slopes in the Troodos Mountains. In this study, all soil sites situated within 15 meters of a stream or gully were classified as footslope soils, while sites falling within a 15-meter buffer of the ridgelines were classified as summit soils. Soil sites between the buffers were simply classified as backslope soils. Several wider and narrower buffer widths were explored, however, the 15-meter buffer appeared to best-fit landform morphology within the study area.

Ridgelines were mapped by first inverting the DEM in ArcMap, employing TauDEM to create flow paths, and then re-inverting the flow path grid to reflect ridge order. The Geoprocessing Wizard tool in ArcMap was used to identify, select, and export records for the profiles (points) from each class. The data were then imported into S-plus for statistical analysis. Statistical methods employed include
simple linear regression and fixed ANOVA, using hill slope position as the grouping variable and soil depth as the dependent variable.

One disadvantage of this method is that its simplified class definitions limit interpretation of toposequence trends to the two extremes of hill slope position: summit and footslope. To understand the processes and variability in effect within backslope and shoulder positions, and to explore uniformity of toposequence characteristics between hill slopes, a more detailed toposequence analysis is required. Automated GIS hill slope analyses classify DEM pixels into more detailed classes using a scale-dependent topographic position index algorithm. The algorithm developed by Weiss (2001) is a neighborhood, statistical method which classifies the elevation value and slope position of individual raster pixels. To better compare computer-automated and traditional methods, however, the five-position classification scheme of Ruhe and Walker (1968) was explored in this study.

**Slope-derived classification of hill slope position**

The second toposequence analysis was employed to better explore the role of slope processes on pedogenesis and soil thickness variability within the Troodos Mountains. This method was threefold, and involved: 1) a general identification of hill slope position for each site, similar to that discussed above; 2) identification of apparent catenas and their component profile characteristics; and 3) comparison of soil depth variability between individual catenas of similar geomorphology.
Because the majority of data points in this study lie along forestry roads or walked sampling lines, it proved feasible to construct seven distinct transects of profile data points. The transects ranged in length from 300 meters to 2 kilometers. Generalized topographic profiles were constructed in the GIS by digitizing each transect as a polyline with nodes established at each data point. The analytical tool ET Geowizards 8.7 calculated the distance along transect and the elevation of each node. In this way the generalized surface topographic profile for each transect could be drafted in a spreadsheet program. Classical hill slope positions were then assigned to all points along each cross-section through visual interpretation of the transect's surface topography. Hill slope class divisions were based on natural slope breaks and follow the definitions of Ruhe and Walker (1968) for summit, shoulder, backslope, footslope, and toeslope. As in the method described above, simple group-wise comparisons were used to explore statistical distinctions between hill slope classes.

In addition, the morphology of individual hillsides, as delineated in the generalized topographic profiles, was classified as rectilinear, curvilinear-convex, or curvilinear-concave, after Walker and Ruhe (1968). Soil thickness trends from summit to toeslope were compared for toposequences of similar morphology, to test the hypothesis that correlation between hill slope morphology and soil depth is more significant than that between slope gradient and soil depth (King et al., 1983). Soil thickness values from summit to toeslope position were plotted for 25 individual hillsides, each containing at least three profiles, and the overall results were compared.
Predictive Soil Models

*Predictive mapping through external slope stability models*

One of the key objectives of this research was to compare data from the Troodos to external models of soil properties and slope stability. The benefit of such a comparison lies in the assessment of how well accepted landscape models characterize diverse geomorphic environments. There currently exist many models which strive to accurately describe and quantify soil development, soil erosion, landscape stability, and related pedogenetic and geomorphic processes across landforms. These process-based models have been developed from and applied to studies in varied geologic and climatic regimes. The Troodos present an ideal opportunity to test the applicability of such models to a landscape where slope processes and pedogenesis have not yet been fully addressed in current scientific literature.

SHALSTAB, a software program developed by William Dietrich at the University of California at Berkeley, maps potential shallow slope instability through GIS analysis of a digital elevation grid (Dietrich & Montgomery, 1998). Such stability maps may facilitate soil thickness prediction and modelling. For this reason, SHALSTAB was used to produce a landscape stability map of the northern Troodos, in keeping with the assumption that higher instability implies greater erosion and, consequently, thinner soils.

The "q/T" file output during SHALSTAB analysis represents a hydrologic-slope stability model, in which more negative values indicate decreased stability (Dietrich and Montgomery, 1998). If the SHALSTAB prediction adequately
models active hill slope processes in the Troodos Mountains, there should exist a positive statistical correlation between mean soil thickness, slope, and the modelled stability values. To apply the model, the 25-meter resolution DEM was masked, or subsampled, to the three watersheds containing all described and photographed soil outcrops from this research. The smaller DEM was then processed in ArcView 3.3 following the methods put forth by Dietrich and Montgomery (1998).

The model provides two means of calculating the hydrologic ratio. A constant cohesion parameter is introduced in the first, while the alternative omits cohesion entirely (Dietrich and Montgomery, 1998). The model used in this analysis omitted cohesion, and specified parameters included an internal friction angle of 45 degrees and a bulk density of 1700 kg m\(^{-3}\). SHALSTAB assumes uniform soil depth - for this analysis, soil depth was defined as 0.5 m. Once the q/T grid had been calculated, stability values were obtained for the soil sites using EZ Calculate "get_point_Z" command in ArcGIS 8.2. The mean soil depth values were then compared graphically and through simple linear regression to predicted stability to test for correlation.

**Predictive mapping through analysis of northern Troodos data**

Once the processes influencing pedogenesis and soil variability across the Troodos Mountains have been characterized, the logical progression is the development of a predictive model for hill slope soil development based on measured soil properties. Field observations suggest a general model wherein soils are thinnest on ridges and thickest along footslopes, however, a more specific
model is needed. Towards that aim, results from the preceding analyses were compiled to attempt a working model of soil-depth variability across the greater field area. Multiple linear regression analysis of soil depth, elevation, aspect and slope gradient have been shown to facilitate predictive mapping of soil properties across landscapes (Tsai et al., 2001). Similar methods are attempted here.
RESULTS AND ANALYSIS

General Soil-Profile Data

Soil-profile analyses performed in the field and laboratory yield a substantial matrix of results. General soil data are presented below, including soil thickness, regolith fracturing, and general profile descriptions. Statistical analyses of these data provide quantitative descriptions of correlation between soil thickness and pedogenetic factors.

Soil-thickness data

The core data of this research are the soil-thickness measurements obtained from digital photograph analysis and field soil-profile measurements. A data table containing all image analysis-derived and GIS analysis-derived values is presented in Appendix B. Summary statistics of the 367 site measurements are displayed in Table 3.1, and reveal an overall mean soil thickness of 17 centimeters. A histogram illustrating the general distribution of soil-thickness values is displayed in Figure 3.1. The data exhibit a high skewness value of 2.04 due to the weak soil development that characterizes the region: 269 of the 367 samples, or 73 percent, have thicknesses of 20 centimeters or less.
Morphology and classification of studied soils

Loamy, mixed, superactive, nonacid, mesic Lithic Xerorthents (less than 50 cm mean soil depth) comprise 348 of the measured soil sites, while the remaining 19 profiles classify as Loamy, mixed, superactive, nonacid, mesic Typic Xerorthents because their depth to a lithic contact is greater than 50 centimeters (Soil Survey Staff, 2003). Lateral variations in soil depth are common, with bedrock outcrops or extensive surfaces stripped of fine sediment. In general, the study soils are characterized by thin or absent O horizons and extremely weakly developed A horizons in thin (<< 1m) colluvium atop weathered bedrock. The A horizon may exhibit weak fine granular structure, but becomes structureless with depth (below 3-10 cm). No B horizons have been noted. Soil textures typically range from silt loam to silty clay loam, and may contain up to 30 percent fine or
medium angular coarse fragments. Soil color hue ranges from 2.5YR to 10YR, with moist values of four or higher. Soil color varies according to the predominant lithologic characteristics of the igneous substratum. C horizons lack pedogenetic structure and typically contain higher percentages of rock fragments than the A horizons. The contact between the C horizon and weathered bedrock may be gradual or abrupt. The R layer consists of fractured and oxidized bedrock, and tree roots often delineate fracture paths as deep as 2 meters below the surface of the bedrock. Sample profile descriptions from this study are provided in Appendix C.

Testing for Correlation between Soil Depth and Pedogenetic Factors

Correlation between soil depth and bedrock fracture characteristics

The importance of bedrock-weathering characteristics to pedogenesis was addressed in the analysis of bedrock-fracture density, as discussed in the methods section above. The results of the thresholding method for testing correlation of soil thickness to bedrock-fracture density are displayed in Figure 3.2(a) and 3.2(b), below. Wide data scatter precludes statistically significant linear regression analysis, however, it remains clear that no precise correlation exists between fracture density and soil depth. The two accuracy assessments yielded overall classification accuracy of 86.71% and 85.71%, while the overall kappa statistics were 0.8340 and 0.7496, respectively. The user's accuracy for the three fracture classes was 100% in both assessments.
Manual digitization of fractures yields trends that support the findings of the automated technique. A low correlation coefficient ($R^2 << 1.00$) confirms the absence of statistically significant linear trends in the data (Figure 3.3). These findings reveal that the pedogenetic and geomorphologic processes operating in the
Figure 3.3. Results from manual fracture digitization.

Troodos Mountains are certainly not transport-limited. If the generally negative trends of the regression lines are considered, the data instead suggest that present-day conditions in the Troodos Mountains approach a supply-limited state. In such a scenario it would be impossible to expect historically thicker soils. Given the low magnitude of the correlation coefficients, however, any trends in the data that are consistent with supply-limited conditions are statistically inconclusive.

Correlation between soil depth and the traditional soil-forming factors

Soil-depth measurements also were compared to landscape-attribute values. Table 3.2 displays results from simple linear regression analyses of the elevation, slope, aspect, lithology, and precipitation effects on soil development. Low p-values ($p$-value < 0.05) suggest a high significance of correlation coefficients for all regressions except slope aspect, however, the individual linear regression models
for specific pedogenetic variables failed to account for enough of the variability to indicate any trend. That is, for all pedogenetic variables, $R^2 << 1.00$. These findings are further illustrated by the wide scatter of data points in the plots of soil thickness versus precipitation, elevation, slope gradient, and aspect displayed in Figures 3.4(a), 3.4(b), 3.4(c), and 3.4(d).

**Table 3.2.** Summary of individual linear regression analyses for pedogenetic variables and soil thickness.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$R^2$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithology</td>
<td>0.083</td>
<td>&lt;&lt;0.001</td>
</tr>
<tr>
<td>Precipitation (MAP)</td>
<td>0.107</td>
<td>&lt;&lt;0.001</td>
</tr>
<tr>
<td>Elevation</td>
<td>0.081</td>
<td>&lt;&lt;0.001</td>
</tr>
<tr>
<td>Slope gradient</td>
<td>0.011</td>
<td>0.043</td>
</tr>
<tr>
<td>Aspect</td>
<td>0.004</td>
<td>0.219</td>
</tr>
</tbody>
</table>

**Figure 3.4(a).** Regression test of correlation between M.A.P. and soil thickness.
Figure 3.4(b) Regression test of correlation between elevation and soil thickness.

Figure 3.4(c) Regression test of correlation between slope gradient and soil thickness.
Figure 3.4(d) Regression test of correlation between aspect and soil thickness, showing high degree of soil variability.

Initial comparison of mean soil thickness between aspect classes reveals apparently thinner soils on south-facing slopes (Table 3.3), however, analysis of variance reveals that these apparent differences are not significant \((p\text{-value} = 0.260)\). Soil thickness was also compared between different lithologies using fixed effects analysis of variance (Table 3.4). Differences in mean soil thickness for the three represented rock types in the study area were found to be highly significant, with a \(p\text{-value} \text{ well below} 0.0001\). Soil depths were thickest for plagiogranites and thinnest for rocks of the sheeted dike and diabase complex (Table 3.5). A similar

<table>
<thead>
<tr>
<th>Mean soil depth</th>
<th>E</th>
<th>NE</th>
<th>N</th>
<th>NW</th>
<th>W</th>
<th>SW</th>
<th>S</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.20</td>
<td>0.17</td>
<td>0.16</td>
<td>0.18</td>
<td>0.16</td>
<td>0.13</td>
<td>0.15</td>
<td>0.20</td>
</tr>
<tr>
<td>(n)</td>
<td>50</td>
<td>76</td>
<td>25</td>
<td>16</td>
<td>25</td>
<td>39</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>Std. dev. ((s))</td>
<td>0.186</td>
<td>0.130</td>
<td>0.147</td>
<td>0.184</td>
<td>0.158</td>
<td>0.107</td>
<td>0.145</td>
<td>0.180</td>
</tr>
<tr>
<td>Variance ((s^2))</td>
<td>0.035</td>
<td>0.017</td>
<td>0.021</td>
<td>0.034</td>
<td>0.025</td>
<td>0.011</td>
<td>0.021</td>
<td>0.032</td>
</tr>
</tbody>
</table>
Table 3.4. One-way ANOVA of soil thickness between substratum lithologies.

<table>
<thead>
<tr>
<th></th>
<th>d.f.</th>
<th>Sum of Sqrs</th>
<th>Mean Sqr</th>
<th>F-statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithology</td>
<td>2</td>
<td>0.728</td>
<td>0.364</td>
<td>16.369</td>
<td>&lt;&lt;0.0001</td>
</tr>
<tr>
<td>Residuals</td>
<td>364</td>
<td>8.100</td>
<td>0.022</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual Std Err</td>
<td></td>
<td>0.149</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.5. Variation of soil thickness with bedrock lithology.

<table>
<thead>
<tr>
<th></th>
<th>Basal Group</th>
<th>Plagiogranite</th>
<th>Sheeted Dike Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean soil depth (m)</td>
<td>0.18</td>
<td>0.31</td>
<td>0.15</td>
</tr>
<tr>
<td>n</td>
<td>58</td>
<td>30</td>
<td>279</td>
</tr>
<tr>
<td>Std Deviation (s)</td>
<td>0.088</td>
<td>0.216</td>
<td>0.151</td>
</tr>
<tr>
<td>Variance (s²)</td>
<td>0.008</td>
<td>0.047</td>
<td>0.023</td>
</tr>
<tr>
<td>SE Mean</td>
<td>0.012</td>
<td>0.039</td>
<td>0.009</td>
</tr>
</tbody>
</table>

Comparison was made of soil depths between watersheds. A box plot of soil thickness data grouped by watershed (Figure 3.5) reveals similar mean soil thickness values, but different variances, between classes. The large number of

Figure 3.5. Box plot of soil thickness variability between watersheds. The Elia is the largest watershed, whereas the Atsas is the smallest.
outliers in the Elia watershed most likely reflects the greater number of samples 
\( n=270 \) in the Elia as compared to the Atsas \( n=61 \) and Kargotis \( n=36 \).

Alternatively, the range of outliers may reflect watershed size - there exists greater 
probability of high outliers when the measurement area is large. One-way analysis 
of variance among soil sites grouped by watershed suggests that variation of soil 
thickness between watersheds is not statistically significant given the \( p \)-value of 
0.247 (Table 3.6). The findings suggest that of the traditional pedogenetic variables

| Table 3.6. One-way ANOVA of soil thickness between watersheds. |
|-------------------------|-----------------|-----------------|-----------------|-----------------|
|                        | d.f. | Sum of Sqr | Mean Sqr | F-statistic | p-value |
| Watershed               | 2    | 0.068       | 0.034     | 1.405        | 0.247   |
| Residuals               | 364  | 8.761       | 0.024     |              |         |
| Resid. Std. Err.        | 0.155|              |           |              |         |

addressed in this study, only lithology can be said to exhibit a statistically 
detectable effect on soil development. None of the pedogenetic variables exhibit a 
clear relationship, causal or otherwise, with soil thickness in the Troodos 
Mountains.

Because single-variable statistical analyses may not be able to detect partial 
contributions by individual variables in complex geomorphologic systems, however, 
a multivariate linear regression analysis was employed to attempt to model 
pedogenetic relationships in the study area. The best-fit model found was:

\[ Y = \beta_1*(\text{slope factor}) + \beta_2*(\text{precipitation factor}). \]

The significance of the pedogenetic variables and the multiple coefficient of 
correlation value for the regression model are displayed in Table 3.7. \( P \)-values
Table 3.7. Results of multivariate linear regression model.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Std. Error</th>
<th>t-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>0.026</td>
<td>0.031</td>
<td>0.829</td>
<td>0.4079</td>
</tr>
<tr>
<td>slope gradient</td>
<td>-0.004</td>
<td>0.001</td>
<td>-3.769</td>
<td>0.0002</td>
</tr>
<tr>
<td>M.A.P.</td>
<td>0.000</td>
<td>0.000</td>
<td>7.395</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Multiple R-Squared: 0.1404
$F$-statistic = 29.71 (on 2 and 364 degrees of freedom, $p$-value $<0.0001$)

Calculated within this model suggest a high significance of detected correlation ($p$-value $< 0.0001$). However, the low multivariate correlation coefficient, $R^2 = 0.1404$, suggests that this model does not accurately describe soil-thickness variance within the study area. The model presented here represents the most successful of several richer multivariate regression models tested, suggesting that pedogenesis cannot be described solely on the basis of traditional geomorphologic and pedogenetic landscape attributes.

Topography Revisited: Hill Slope Position

Buffer-derived classification of hill slope position

A preliminary review of the data suggests a trend of downslope-thickening soil profiles consistent with qualitative field observations and hill slope pedogenesis models. To better describe how soil thickness varies across landforms, the hill slope position of soil measurement sites were classified in the GIS based on their proximity to ridgelines and summits. Three buffer widths of 10 meters, 15 meters, and 25 meters were explored. Table 3.8 illustrates the effect of varying
buffer width on soil toposequence analysis. It is thought that the 15-meter buffer
best models the narrow morphology of ridges and landforms in the study area,

<table>
<thead>
<tr>
<th>Table 3.8. Comparison of results for varied buffer width.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>mean soil thickness (m)</td>
</tr>
<tr>
<td>n</td>
</tr>
<tr>
<td>Std Deviation (s)</td>
</tr>
<tr>
<td>Variance (s²)</td>
</tr>
</tbody>
</table>

moreover, the sample variance was least for samples identified using this buffer
width. Table 3.9 illustrates general trends for classes established via the automated,
15-meter buffer classification method. The mean depth to the soil-bedrock contact

<table>
<thead>
<tr>
<th>Table 3.9. Summary of buffer-derived hill slope classes.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>mean soil thickness (m)</td>
</tr>
<tr>
<td>n</td>
</tr>
<tr>
<td>Std Deviation (s)</td>
</tr>
<tr>
<td>Variance (s²)</td>
</tr>
<tr>
<td>SE Mean</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3.10. ANOVA of mean soil thickness between buffer-derived hill slope classes.</th>
</tr>
</thead>
<tbody>
<tr>
<td>d.f.</td>
</tr>
<tr>
<td>Hill Slope Class</td>
</tr>
<tr>
<td>Residuals</td>
</tr>
<tr>
<td>Residual Std Error</td>
</tr>
</tbody>
</table>

was 13 centimeters along ridges, 17 centimeters along backslopes, and 19
centimeters along footslopes. This trend corroborates field observations of a
downslope-thickening soil profile; however, a fixed-effects one-way analysis of
variance of mean soil depth between hill slope classes under a null hypothesis of no difference (Table 3.10), suggests that the differences in mean thickness of soil between hill slope positions are not statistically significant ($p$-value $>>0.05$).

Analysis of data from the 10-meter and 25-meter buffers yields similar results. In this way, the data are weakly suggestive but statistically inconclusive. Therefore, more detailed means of classifying soil hill slope position using the full five classes proposed by Ruhe and Walker (1968) must be employed to accurately model pedogenesis within the Troodos Mountains.

**Slope-derived classification of hill slope position**

Topographic cross-sections of the seven transects - individual landforms of which were investigated in detail - are presented in Figure 3.6, below. The toposequences investigated in all but Transect 7 are apparent toposequences only, because they are constructed from profiles from a "random walk" along forestry roads. This method is most appropriate where hill slopes less than approximately one hundred meters in length are being investigated. Longer subdivisions of transects are more likely to include discontinuous landforms. The apparent toposequences described here are thought representative of hill slopes throughout the study area. Transect 7 consists entirely of field soil-bedrock profiles, dug at approximately 20-meter intervals along the axis of a single rectilinear landform. In total, 32 toposequences comprising 149 data points were identified. Each toposequence was classified as rectilinear, curvilinear-convex, or curvi-linear concave according to slope-profile characteristics. Slope profiles of individual
Figure 3.6. Generalized topographic and solum profiles.
Figure 3.6 (continued). Generalized topographic and solum profiles.
toposequences for each morphological class may be compared in Figures 3.7(a), 3.7(b) and 3.7(c).

**Figure 3.7 (a).** Slope characteristics of rectilinear hill slope morphology classes.

**Figure 3.7 (b).** Slope characteristics of curvilinear-convex hill slope morphology classes.
If pedogenesis in the Troodos mountains is chiefly a function of hill slope morphology then soil thickness should vary with hill slope position in a closely similar manner for all landforms of similar geomorphological classification. Analysis of soil thickness in the 32 toposequences in this study, however, produces wide scatter within each of the three distinct landform morphology classes (Figure 3.8(a), (b) and (c)). This scatter suggests that pedogenesis does not vary consistently with slope morphology across the study area.

Soil thickness for rectilinear hill slopes was expected to remain relatively constant along backslopes but to increase in footslope and toeslope positions, however, the data suggest that alternate models must be developed. Several toposequences show decreases in soil thickness with distance downslope (e.g., hill slope 2.6), or stochastic oscillation (e.g. hill slopes 2.3, 6.1). Soils for curvilinear-
Figure 3.8(a). Soil depth trends for rectilinear hill slope toposequences.

Figure 3.8(b). Soil depth trends for curvilinear-convex hill slope toposequences.
convex toposequences were predicted to be thinnest on backslopes, with sharply deeper soils in footslope and toeslope positions. However, only three sites conform to this model (hill slopes 1.3, 2.5, and 2.7) while others exhibit apparently stochastic soil depth variability (e.g. hill slopes 1.7, 3.2, and 5.7). Soil thickness for curvilinear-concave hill slopes was hypothesized to increase with distance downslope, with generally shallower soils in the backslope positions. As with the other landform morphologies, however, the data exhibit apparently stochastic soil depth variability and cannot be described by a single trend.

From Figure 3.8(a), (b), and (c) it may be noted that longer hill slopes often exhibit greater variability in soil thickness than shorter hill slopes. In some instances this results from the discontinuity of the "apparent" toposequences, however, other sites indicate that such variability represents natural hill slope soil
patterns. For example, soil depth to bedrock was measured in the field at 20-meter intervals along the axis of the 650 meter-long, continuous toposequence of Transect 7, and was found to be quite variable (Figure 3.9). Concurrent with the

![Figure 3.9](image)

**Figure 3.9.** Stochastic variability in slope and solum profiles for transect 7.1, and varying solum-slope relationships along toposequence. Inverse soil normalized slope gradient was used to better compare amplitudes of variability.

variability in soil thickness are changes, in the relationship, from inverse to positive, of soil thickness to hill slope gradient. Slope values for measurement sites along the transect were derived from the 25-m DEM in the GIS.

Scaling effects also bear consideration when reviewing these soil data. Given the narrow morphology of mountain spurs and ridgelines in the Troodos, slope morphology may be considered at a broader geomorphologic scale. Thus, rectilinear slopes are the backslopes of larger mountain spurs, curvilinear-convex slopes represent mountain shoulders, and curvilinear-concave landforms comprise the footslopes. Initial comparison of group means reveals that footslopes exhibit the
greatest mean soil depth while backslopes have intermediate soil depths, and shoulder positions exhibit the smallest mean soil depth (Table 3.11). One-way

<table>
<thead>
<tr>
<th>Table 3.11. Summary of distinct hill slope morphology classes.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concave (footslope)</td>
</tr>
<tr>
<td>mean soil thickness (m)</td>
</tr>
<tr>
<td>n</td>
</tr>
<tr>
<td>Std Deviation (s)</td>
</tr>
<tr>
<td>Variance (s^2)</td>
</tr>
<tr>
<td>SE Mean</td>
</tr>
<tr>
<td>Rectilinear (backslope)</td>
</tr>
<tr>
<td>mean soil thickness (m)</td>
</tr>
<tr>
<td>n</td>
</tr>
<tr>
<td>Std Deviation (s)</td>
</tr>
<tr>
<td>Variance (s^2)</td>
</tr>
<tr>
<td>SE Mean</td>
</tr>
<tr>
<td>Convex (shoulder)</td>
</tr>
<tr>
<td>mean soil thickness (m)</td>
</tr>
<tr>
<td>n</td>
</tr>
<tr>
<td>Std Deviation (s)</td>
</tr>
<tr>
<td>Variance (s^2)</td>
</tr>
<tr>
<td>SE Mean</td>
</tr>
</tbody>
</table>

ANOVA between the three hill slope morphology classes reveals, however, that these apparent differences are not statistically different given the high p-value of 0.4013.

Similar suggestive, but statistically insignificant, trends result when all slope-derived hill slope position data are compared independent of specific toposesquences. Comparison of mean soil depths for the five traditional hill slope classes corroborates field observations of a general soil pattern in the northern Troodos (Table 3.12). Soils are generally thinnest on summits and deepest along toeslopes, and there exists a greater range of variability among footslope, backslope, and shoulder soils. As with previous analyses, however, the results of one-way

<table>
<thead>
<tr>
<th>Table 3.12. Summary statistics for toposequence analysis hill slope classes.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toleslope</td>
</tr>
<tr>
<td>mean soil depth (m)</td>
</tr>
<tr>
<td>n</td>
</tr>
<tr>
<td>Std Deviation (s)</td>
</tr>
<tr>
<td>Variance (s^2)</td>
</tr>
<tr>
<td>SE Mean</td>
</tr>
</tbody>
</table>
ANOVA of mean soil depth for each of the five hill slope classes ($p$-value > 0.05) strongly suggests that apparent differences in mean soil thickness between classes are not statistically significant (Table 3.13). No one model explored here accurately describes relationships between slope processes and pedogenetic factors within the Troodos in sufficient detail to predict toposequence patterns across the sites or scale of study.

### Table 3.13. ANOVA of mean soil thickness between toposequence classes.

<table>
<thead>
<tr>
<th></th>
<th>d.f.</th>
<th>Sum of Sq</th>
<th>Mean Sq</th>
<th>F-Statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hill slope Class</td>
<td>5</td>
<td>0.213</td>
<td>0.043</td>
<td>1.788</td>
<td>0.1145</td>
</tr>
<tr>
<td>Residuals</td>
<td>361</td>
<td>8.615</td>
<td>0.024</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual Std Error</td>
<td></td>
<td>0.154</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Predictive Soil Models

**Predictive mapping through external slope stability models**

The hydrologic-slope stability predictions from the SHALSTAB model were compared to soil thickness measurements using a simple linear regression. No detectable linear relationship exists between the two, given the correlation coefficient $R^2 << 1.0$ (Figure 3.10). A map of SHALSTAB-predicted landscape stability is presented in Figure 3.11 below. The predominance of landforms classified as "stable" suggested by the model contradicts field observations of severely eroded, rocky slopes even within areas of low relief, especially near the measured soil sites.

Alternative tests of the model explored variations of soil cohesion and soil thickness values but failed to produce results realistic for the Troodos. In some cases, values of high stability ($q/T \approx 10.0$) defined up to 95% of the output grid area.
Based on these data, neither the default nor the user-defined parameters of the SHALSTAB model adequately characterize hill slope stability within the field area.

![Figure 3.10. Comparison of SHALSTAB stability to soil development.](image)

$R^2 = 0.0182$
Figure 3.11. SHALSTAB stability map of the Kargotis, Atsas, and Elia watersheds.
Predictive mapping through analysis of northern Troodos data

Given the low-magnitude coefficients of correlation produced by the rich and simple linear regression models, accurate predictive mapping based on soil and landscape attribute data from this study did not prove feasible. Soils within the Troodos are thin and exhibit high degrees of variability that cannot be accounted for based on hill slope position, slope, precipitation, or other measured landscape attributes. High variability within individual toposequences also precludes spatial interpolation of soil thickness across landform or catchment boundaries for these reasons. Furthermore, correlation between soil thickness and bedrock fracture characteristics prevent any soil depth prediction based on lithologic characteristics across the study area. The results presented here suggest that accurate modelling of soil landscape patterns in the Troodos, may require a finer scale and better-tailored methods of soil-landscape attribute analysis.
DISCUSSION

Soil-Profile Thickness

Troodos soils have been described by many authors as thin, parched, and rocky, a by-product of centuries of timber harvesting by humans and grazing by domesticated goats. To put the thin Troodos soils into proper geomorphologic and pedologic context, a comparison to soils from similar geomorphologic settings around the world is presented here. Similar seasonal soil moisture patterns, substratum lithology, geomorphology, and land use make studies of landscape pedology in regions such as the western coast of North America ideal for comparison to the Troodos. Soil thickness, mean annual precipitation (MAP), and elevation are compared in Table 4.1 (below) between hill slope, colluvial soils from Oregon, California, and Cyprus.

It is noteworthy that the two thickest soils occur under extremely high MAP values, and that a highly suggestive, inverse trend exists between soil thickness and elevation (if the Felcher series is excluded). Although no statistically significant patterns were detected in the Troodos data presented above, one general observation may be made. The upper envelope of the data exhibit a general trend consistent with traditional pedogenetic models: greater soil thickness values appear more likely to occur at higher elevation and MAP levels, and at lower slope gradient values. Such an observation does not permit precise, predictive mapping of soil thickness, however, the general, upper-envelope trend and greater variability at high elevation and MAP values are consistent with expectations of a weathering-
Table 4.1. Comparing soil depths among xeric soil series formed in colluvium derived from weathered, fractured, basic igneous rocks (e.g., basalt, serpentinite) in distinct total mean annual precipitation (MAP) regimes.

<table>
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<tr>
<th>Series</th>
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<th>MAP (mm)</th>
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<th>Avg. Elevation (m)</th>
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<tr>
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<td>N. Troodos, Cyprus</td>
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<td>490</td>
<td>20</td>
<td>720</td>
<td>Lithic Xerorthent</td>
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</tbody>
</table>

* Soil Survey Staff, 1975
** Soil Survey Staff, 2002
*** Soil Survey Staff, 1977
° Soil Survey Staff, 1983
" Average values for all Troodos data obtained in this research
limited geomorphological system. Isolated hill slopes that remain undisturbed by erosional events for longer-than-average time periods will exhibit greater soil development and will appear less stochastic. The resulting soil prediction model holds, therefore, that there should exist greater numbers of moderately-well-developed soils in stable areas of high precipitation and low slope gradient.

**Implications of Correlation with Traditional Soil-forming Factors**

It has already been noted that the five broad factors of pedogenesis are often so intricately related that fully independent analysis of each can prove meaningless (Hugget, 1998). Certainly, the results of the linear regression and ANOVA analyses presented above suggest that such may be the case for soil genesis in the Troodos. Nevertheless, implications of the individual correlation tests for climate, slope, elevation, aspect, and lithology do require further discussion.

Climate analysis in this research involved a simple comparison of MAP to soil thickness, because increased soil moisture levels are known to facilitate biological activity, chemical weathering of parent minerals, and the translocation of clays and soil nutrients. On the other hand, increased precipitation may promote soil erosion, especially in steep terrain. Climate factors such as temperature and MAP in mountainous regions such as the Troodos are largely orographic, so pedogenetic measures may be dominated by topographic rather than climatic signatures. For these reasons, lack of conclusive linear correlations in the comparison of soil thickness to MAP is not surprising. Increased soil thickness variability and greater numbers of thicker profiles in regions of high MAP may
reflect strong storm effects on weathering-limited hill slope soils. Combined analysis of high-resolution storm intensity and rainfall erosivity data, and other landscape attribute data might more precisely constrain dominant pedogenetic and geomorphologic processes.

Statistically inconclusive slope correlation tests were more surprising, especially given qualitative impressions of downslope-thickening soil profiles imparted through field observations in the Troodos. However, slope does not always correlate closely with pedogenesis. Other researchers (e.g. King et al., 1983) have found that neither slope length nor slope gradient showed a persuasive or consistent relationship to soil development in their study. Alternatively, lack of correlation between soil development and slope angle may suggest that the thin soils of the Troodos fall below some depth threshold at which slope angle is no longer influential. Such a scenario might also account for discrepancies between soil thickness data and SHALSTAB hydrologic-slope stability estimates. These possibilities will be discussed in more detail below.

Elevation signatures in soil thickness data may reflect concurrent changes in related pedogenetic factors such as climate (temperature, moisture, rainfall erosivity) and topography (slope gradient, slope length) and for that reason elevation data should serve as a simpler, alternate pattern indicator in multivariate regression analyses. The lack of correlation between elevation and soil thickness further suggests that rock-to-regolith conversion is independent of climate and relief.
Lack of significant trends among aspect classes is also not surprising, given that slope aspect is an amalgamation of climatic and topographic variables. In the northern hemisphere, southwest-facing slopes generally experience higher temperature ranges and drier conditions than slopes facing northeast, and also exhibit vegetative differences as a result (Birkeland, 1999). However, in weathering-limited regimes where soils are thin and weakly developed, aspect should not be expected to promote major differences in soil thickness given relatively greater importance of more specific variables such as temperature or slope gradient.

Lithology was the only factor found to have a significant relationship with changing soil-profile thickness. As mentioned above, multivariate linear regression models detected no trends in association with MAP and elevation; however, the possibility of concurrent orographic contributions cannot be entirely discounted given that the volcanic-intrusive-plutonic lithologic succession of the northern Troodos occurs in tandem with topographic and climatological gradations. That is, the three identified lithologic classes occupy different topoclimatic positions. If the small but significant soil thickness variation between lithologic classes does indicate an influence on pedogenesis by parent material, then the results from the bedrock fracture analysis are indeed intriguing. Lack of linearity in plots of bedrock fracture density against soil thickness suggests that slope processes in the Troodos are weathering-limited. Therefore, the anticipated positive correlation between soil thickness and rock fracture density does not occur because weathering products are eroded soon after their genesis.
Lithologic controls of Troodos soils are corroborated by other authors. For example, the rocks of the diabase unit crumble easily and yield sandy, gray soils, whereas the pillow lavas present at lower elevations erode rapidly and typically generate immature soil-profiles of thin, gravelly sandy loam texture along topographic lows (Christodoulou, 1959). Where soils are thin and weakly developed, bedrock comprises an integral part of the forest substrate. This is the case for xeric soil moisture regimes in the mountains of other Mediterranean areas (Noller, Personal Communication) and in California, where weathered bedrock stores plant-available water along fracture zones (Hubbert et al., 2001). In dry Mediterranean climates, moisture may drain rapidly into fractured soil-bedrock profiles, leaving the upper profile dry and rendering weathering processes ineffective (Taylor and Eggleton, 2001).

Relict Topography and Soil Inheritance

Narrow temporal scope is one of the chief limitations of pattern-based approaches to landscape analysis. Present-day soil properties are typically compared to present-day landscape properties, but such an approach is not necessarily valid. Landscapes can retain topographic characteristics from past periods of rapid geomorphologic change that have yet to reach equilibrium with present-day conditions (Hunt & Wu, 2004). Similarly, Phillips (1999) cites several studies in which landform soil profile variations unrelated to observed variations in contemporary topography, parent material, drainage, and vegetation, in fact resulted from the lasting effects of tree throw in ancient, vanished forests. The
pedologic effects of tree throw comprise just one example of soil memory or inheritance (Phillips, 1999). Such patterns that take decades or hundreds of years to evolve are stabilizing functions of ecosystems that may also help them recover from disturbance or to resist stressors (Thomas, 2001). Moreover, it is often difficult to prove that present-day soil properties are in steady state with the current form of the hill slope (Park & Burt, 2002). Hence, the concepts of relict topography and inherited soil properties must be addressed by process-based studies.

Temporal components of the Troodos landscape were integrated into this study through observation of Quaternary geomorphologic units, archaeological units, and hill slope stability throughout the study area. Incised Pleistocene channel gravels indicate episodes of relatively rapid geomorphologic change in the distant past, while archaeological finds, including medieval pottery sherds and intact, centuries-old, stone check dams, indicate relative stability of toeslopes and coarse surface material, respectively, during the Late Holocene (Given et al., 2003).

**Dynamics of Geomorphological Systems**

Flights of uplifted marine terraces, deeply incised stream channels, and thin, weakly developed soils of the Troodos Mountains indicate that the landscape of Cyprus continues to experience tectonic uplift and corresponding geomorphologic change. High uplift or erosion rates, or both, typically yield soils that are thin or absent (Anderson et al., 2002). Fracture flow limits both the contact time and surface contact area of rock minerals with water, leading to low chemical denudation rates associated with bedrock weathering (Anderson et al., 2002).
Estimates of erosion rates have been calculated for catchments near this study area and are compared to rates from the more humid North American West Coast in Table 4.2. The Kalavasos Reservoir catchment, which exhibits similar lithologies, is located approximately 20-25 kilometers southeast of this study area.

Erosion rates put forth by Burdon apply to lightly forested foothills of the Troodos Mountains above elevations of 150 meters (Christodoulou, 1959). Dörflinger (2003) notes that the average value reported for the greater catchment of the Kalavasos reservoir is based on a sediment delivery ratio and therefore includes an inherent degree of uncertainty. It is also noted that sediment yields in neighboring watersheds may be an order of magnitude higher, due to potential differences in soil type, lithology, vegetative cover, and land use (Dörflinger, 2003).

By comparison, the implication of these studies (Table 4.1) is that high erosion rates in the steeper mid-ranges of the Troodos may be too high, and rock weathering rates too low, to permit soil development—the geomorphological balance is limited by sediment supply. Although not statistically significant on an

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<th>Source</th>
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<td>Reneau &amp; Dietrich, 1991</td>
<td>0.057 mm/yr</td>
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individual case basis, the factors of pedogenesis in aggregate support a weathering-limited geomorphologic system. For example, the hint at such a system is seen in the data for fracture density (compare Figure 1.1(a) with Figures. 3.2 and 3.3), though unsupported.

**Hill Slope Models and Soil Prediction**

Lack of statistically significant correlation between the hydrologic-slope stability model and measured soil thickness is best addressed within the geomorphologic context of a weathering-limited system, because soil memory is transient or of short duration. The inability of SHALSTAB to accurately characterize Troodos hill slopes is due to differences between modelled and real properties of the soil-bedrock profile. SHALSTAB is not designed for regions dominated by rocky outcrops or cliffs. The Troodos do exhibit stripped and rocky slopes, but slopes mantled by thin, gravelly colluvium are more typical. In any case, testing the utility of the SHALSTAB model in the Troodos was deemed worthwhile given the similarity between hypothesized soil spatial patterns of this research and soil spatial characteristics assumed by the model. Specifically, SHALSTAB is designed to predict correctly the observed tendency for soils to be thick in valleys and thin on ridges, and it models the soil mantle as a mobile layer of colluvium atop fractured bedrock (Dietrich & Montgomery, 1998). Such a model considers ridges relatively stable except during unusually heavy storms, while steep valley axes require only minor rainfall events to fail. Therefore, soil thickness is expected
to vary across the landscape in a systematic manner (Dietrich & Montgomery, 1998).

Comparing SHALSTAB stability values to soil-thickness data reveals that the model does not suit hill slope surface mechanics in the Troodos. Authors of the SHALSTAB model strongly recommend that any predictions be compared to actual landslide data, which can help determine if failed correlations result from poorly defined parameters or, instead, inapplicability of the model to field site geomorphology (Dietrich & Montgomery, 1998). One shortfall of this research, however, is its lack of mapped landslide data for the Troodos. Without this data, the true reasons for the utility or inapplicability of the SHALSTAB model cannot be identified precisely.

Scale

Given the lack of trends not only among the SHALSTAB data, but also among landscape attribute data, the scale of surface process variability merits discussion. The soil processes that promote important morphological distinctions within and between distinct soil series occur at microscopic scales as well as macroscopic. Research has demonstrated that the rate of mass loss is approximately three times greater in soil than in parent bedrock; this mass loss, viz-a-viz the degree of weathering which occurs at the top of the weathered rock profile, varies significantly throughout catchments (Anderson et al., 2002). Study of soil morphological variability must address downward and lateral variability at extremely fine scales before the interactions and results of soil surface processes
may be predicted across landforms. Soil variability in the Troodos might better be understood, therefore, through detailed chemical analysis of complete soil, regolith, and rock profiles.

Conversely, a landscape scale may be most appropriate for studies of landscape sensitivity. Whereas no landscape property has yet been found to be an effective guide in all cases, research has not yet fully linked watersheds, slope changes, or ecotones to the scales of spatial variability in regolith, soil, or water movement (Thomas, 2001). Still it is suggested that a grasp of wide-scale factors such as stream sediment capacity, uplift rates, stream incision rates, climate limits, and landsliding are necessary before fine-scale soil variability can be fully understood in complex, semi-arid landscapes.

Because of the connectivity within environmental systems, soil spatial variation must be regarded as dynamic (Phillips, 1999). Thus, the methods employed in this research were inadequate to achieve stated objectives. To realistically model natural soil landscape patterns in the Troodos, a mixed temporal- and spatial- scale approach is recommended. Soils, however thin, of a complex landscape such as the Troodos must be understood as products of gradual, geological scale processes (tectonics) further imprinted with millenia- and annual-scale signatures (climate, regolith production).
CONCLUSION

This research comprised a pattern-based approach at an intermediate scale that strove to: 1) identify the controls of soil genesis and landscape stability within the Troodos Mountains of Cyprus; 2) compare field measurements to expected soil thickness trends from traditional models of soil toposequences prevalent in current scientific literature; and 3) develop a predictive model for hillslope pedogenesis based on measured soil properties within the field area.

Definitive pedogenetic controls could not be constrained based on the results of this study. Expected correlations between soil thickness and MAP, slope, elevation, aspect, and watershed were not found. Soil thickness values were found to vary with rock type, however, additional chemical and mineralogical data might better define lithologic effects on pedogenesis. Soil spatial patterns were not found to vary consistently along hill slopes, nor, unexpectedly, were significant differences in soil thickness detected between hill slope segments of different morphology. Differences between measured soil data and values predicted by an external landscape stability model suggest that the Troodos are best described only within the context of a weathering-limited geomorphological system. For that reason, predictive maps of soil thickness are likely feasible with greater and more comprehensive soil and landscape information, or development of appropriate models.

Given the results and analysis of this study, the view presented here considers that 5,000 years of potentially adverse human land use practices did not promote insidious and severe soil erosion in the Troodos because development of
mature soil-profiles may never have been possible. Exceptions to this low pedogenetic potential include isolated hill slopes in which erosional events did not transpire with the normal frequency, and the margins of large-order streams with stable alluvial terraces. Typical, weathering-limited hill slopes of the Troodos are characterized by a geomorphologically rapid loss of any fine sediments produced through weathering of the igneous bedrock. Short-term disruptive processes such as forest fire, land sliding, tree throw, and raindrop impact, combined with long-term processes such as tectonic uplift and stream incision, are the most likely driving forces behind the net erosion of hill slope sediments. Barring large-magnitude climate fluctuations akin to the Little Ice Age, pedogenetic rates seem unlikely to increase within the next 500 or even 5,000 years.

The complex soil, geological, hydrological, and cultural systems of the Troodos Mountains of Cyprus present an ideal opportunity for further, integrated soil geomorphologic research. Future research into geomorphologic and pedologic processes in the Troodos would benefit enormously from chemical and mass-balance analysis of rock or mineral weathering rates similar to those employed by Anderson et al. (2002) for small catchments in western Oregon. Alternatively, sediment delivery models might be developed for Holocene and Pleistocene river systems within the Troodos, with the aim of constraining better soil erosion estimates. Better hill slope models for the Troodos might be established through the application of more refined algorithms of topographic position to the DEM through GIS analysis. In addition, the rich cultural resources of forests in the Troodos Mountains should not be overlooked. Millenia of human land use practices
have introduced archaeological features of determinable age that are indicative of past environmental conditions. Therefore, there exists great potential for illuminating soil-geoarchaeological research into the dynamic human and environmental past of the Troodos Mountains of Cyprus.
REFERENCES


APPENDICES
### Table A1. Data from soil-fracture correlation test in classified filtered images

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Appendix C - Soil Profile Descriptions

The following are simple soil profile descriptions of two Entisols representative of regional soil profile characteristics. Soil colors are moist except where noted. No chemical data are available.

Site P1

Slope = 26 degrees
Aspect = N
Landform = Colluvial hillslope (Backslope position)
Vegetation = Pinus brutia, Cistus sp.
Soil Cover = 100% pine litter, moss, cistus litter, cistus plants, and pine trees.
Location = E0497719, N3877449: Forest roadcut; elevation 576m;
O -- 10 to 0 cm; (min thickness = 3cm; max thickness = 20cm). Moss and lichen, decomposing pine needles and twigs.
A -- 0 to 7 cm; dark yellow brown (10YR 4/4) silty clay loam, 10YR6/4 dry; moderate, fine granular structure; hard; friable; slightly-sticky, slightly plastic; many (5) very fine to medium roots throughout; many very fine pores throughout; no redoximorphic features; 2% fine, weathered, basalt gravel; white fungal mycorrhizae throughout; clear wavy boundary.
A2 -- 7 to 15 cm; dark yellow brown (10YR 3/4) silty clay loam, 2.5Y 6/4 dry; weak fine to medium granular structure; slightly hard, friable; nonsticky, non-plastic; no redox features; common fine to very fine roots (3/cm²); few (1) fine to medium (4mm) pores; <2% fine basalt fragments; gradual wavy boundary.
C -- 15 to 20 cm; dark yellow brown (10YR 3/4) gravelly silty clay loam; massive; hard; friable; nonsticky, non-plastic; gradual irregular boundary.
2R -- 20cm to 200cm+ hydrothermically weathered Basal Group rocks (sheeted diabase dikes and pillow lavas); highly fractured.

Site P6

Slope = 25 degrees
Aspect = N
Landform = Active gully – colluvial alluvial slope (footslope position).
Vegetation = Cistus sp., domesticated olive, Pinus brutia, and others.
Soil Cover = 100% moss, pine litter, and lichen.
**Location** = E0497795, N3877460: Bulldozed cross-section of gully channel; elevation 586

Oi -- 1 to 0 cm. lichen, moss, and decomposing pine litter.

A -- 0 to 11 cm; very dark brown (10YR2/2) silt loam; moderate fine granular structure; very soft, friable; non-sticky; and non-plastic; many (10/cm²) very fine roots; many very fine pores (5/cm²); no redoximorphic features; mycorrhizae present; 2% fine (0.5 to 1.5 cm) angular basalt pebbles. Smooth gradual contact.

C -- 11 to 21 cm: very dark brown (10YR2/2) silt loam; massive; common (4) medium to fine pores; few (2) medium roots; gradual irregular contact.

R -- 21 cm plus: fractured basaltic bedrock; fractures filled with SiL and few medium roots to 150cm depth; black manganese stains and reddish, oxidized-iron stains on rock faces.