Soils

Genesis and Geomorphology

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CAMBRIDGE

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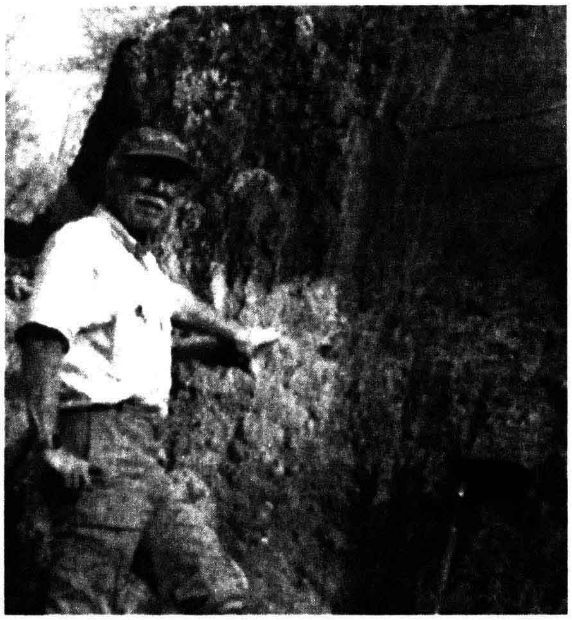
We dedicate this volume to those who have inspired us to write it...
through their lifelong scholarship, insatiable curiosity about the world around them, and their willingness to share it with all who have an interest...
innovative thinkers who have made many, including us, stop and think about the world through different intellectual "filters"...

Francis Doan Hole (1913–2002)
and
Donald Lee Johnson (1934–)

Francis D. Hole in 1978. Image courtesy of the University of Wisconsin, Photo Media Center.



Donald L. Johnson in 1999. Image by RJS.

Soil is the hidden, secret friend . . . the root domain of lively darkness and silence.

Francis D. Hole

Preface

This book is about soil geography, which we think is a difficult and challenging area of study. Our purpose in writing this book is to assert that only through a study of the spatial interactions of soils *on landscapes* can soil and landscape evolution be truly resolved.

This book can be used in courses on soil geography, soil genesis, pedology and soil geomorphology. Our assumption is that the readers have had some background in the natural sciences, and are eager to learn more about soils. We do not assume, nor does the reader need, a substantial background in soils to read and comprehend this book. Difficult as the task may seem, our goal was to write a soils text that could serve both as an initial soils text and as a cutting-edge resource book of research grade. Only time will tell if we met that goal.

Our emphasis, beyond that of soil geography, is deliberately intended to be broad. Other books of similar ilk (Daniels and Hammer 1992, Birkeland 1999) focus on geomorphology and the initial geologic setting as a guiding framework for the understanding of soil landscape evolution. We emphasize these issues in later chapters. Buol *et al.* (1997) and Fanning and Fanning (1989) focus on soil genesis while at the same time emphasizing classification.

Our book relies heavily on concepts and imagery to convey ideas. We have compiled a suite of figures, images and graphics that, in and of themselves, convey messages that cannot be put into words. Throughout the text we include brief "outtakes" on soil landscapes from around the world. We call these excursions "Landscapes," and believe that they convey, with pictures and graphics, what would otherwise take many hundreds of words to tell.

We believe in the necessity of soil taxonomy and soil classification; we use its terminology in the book but do not focus on it. Taxonomy exists to serve those who study and communicate about soils; it is not an end in and of itself. Because we feel that one of the best ways to "learn" and use taxonomy is to examine it in the context of landscapes, we include taxonomic descriptions within many "Landscapes."

We are proud of the extensive literature listing that our book makes use of. We hope that we have cited all the major works, both the classic ones and the recent cutting-edge papers. If we have missed something, we urge our readers to call it to our attention; we will be receptive. Where possible, we have tried to cite mainly papers and studies that are readily accessible in most academic libraries. That is, we have steered clear of papers that are difficult to find or in the gray literature, as well as theses and dissertations, unless we felt that they were essential reading. The end result is a book that relies heavily on work published in national and international scholarly journals and books. If you wish to have a digital copy of our References Section entries, just email us and ask.

The glossary is rich in terms, many of which are only marginally touched upon in the text. Our philosophy with regard to the glossary was simple: if the reader needed to know a term to understand the book, include it in the glossary and define it clearly. The glossary adds length to the book but makes it more "readable."

We intend to continue to work at updating this book, without necessarily making it longer. We encourage you, the reader, to help us. For example, if you wish any topics added to the glossary or the body of the book, contact us with your request. More importantly, alert us to your papers, send reprints and citations, email or write to inform us of new findings or breakthroughs; we will include them as best we can. Contact us with your perceptions of the book, positive or otherwise. Help us make this book better and we promise to continue to work hard toward this goal.

Acknowledgements

We thank the many, many people who have made this book possible. We especially want to thank those who have inspired and taught us over the years. Too many to name, those of particular note are:

- My (RJS) family: my wife, Julie Brixie, has been a steadfast supporter of me, my work, my career, and this book, not to mention a solid proofreader and chapter/figure organizer. I could not have done it without her. My (RJS) children (Madeline, Annika and Heidi) have helped with many small tasks and have put up with their dad being at the office far too much; I will be home more now. My parents instilled within me, through example rather than spoken word, the importance and pay-offs of hard work.
- Don Johnson, a true academic free spirit and genuine thinker who is not afraid to look at the world through different glasses.
- Francis Hole, a one-of-a-kind scholar who will always hold a special place in my (RJS) heart and mind. I (RJS), like so many, would not have "found" the disciplines of soil science and soil geography were it not for Francis Hole.
- François Courchesne was a driving force behind the development of this book.
- Scott Isard, my (RJS) academic conscience and motivator, always willing to discuss academics and scholarship.
- Curt Sorenson, who taught me (RJS) to simply love soils and instilled within me a passion to excel.
- Leon Follmer, who taught me (RJS) to look closely at soils, and made me realize that soils and paleosols are truly remarkable things.
- Duke Winters, who put up with a young colleague (RJS) who was infatuated with soil science, while at the same time mentoring me to become a soil geographer first and foremost.

Those who assisted in the production, editing, or compilation of the book deserve special mention.

- Matt Mitroka, Ellen White, Beth Weisenborn, Peter Dimitriou and Beth Kaupa assisted Paul Delamater in the production of the figures, arguably the strength of the book. Paul was the consummate QA/QC person for graphics. His diligence and high standards permeate the book, and for that reason this is as much *his* book as it is ours. Thank you Paul!
- Ron Amundson, Dave Cremeens, Chris Evans, John Hunter, Don Johnson, Warren Lynn, Fritz Nelson, Jenny Olson, Paul Reich, John Tandarich, Charles Tarnocai, Pat Webber, Beth Weisenborn and Antoinette WinklerPrins provided images, graphs, charts and figures of soils and landscapes that have been reproduced within the book. Without these images, the book would have been much weaker.
- Bill Dollarhide, John Gagnon, Charles Gordon, Bill Johnson, Mike Risinger, Richard Schlepp, Bruce Thompson and Cleveland Watts (of the USDA–NRCS), and David Cremeens provided us with data and block diagrams from various NRCS soil surveys.
- Exceptional editing and reviews of individual chapters were provided by Bob Ahrens, Alan Arbogast, Linda Barrett, Janis Boettinger, Julie Brixie, Alan Busacca, François Courchesne, David Cremeens, Missy Eppes, Leon Follmer, Vance Holliday, Geoff Humphreys, Christina Hupy, Joe Hupy, Don Johnson, Christina Kulas, Johan Liebens, Jonathan Phillips, Greg Pope, Paul Rindfleisch, Mark Stolt, Julieann van Nest, Natasa Vidic, Beth Weisenborn, Gary Weissmann and Indrek Wichman.
- Patricia Brixie proofed the book in its entirety. It was then reviewed by Art Bettis, Donald Johnson, Vance Holliday and Dan Muhs.
- Judy Hibbler typed many of the tables, downloaded text from the web and was an invaluable "gal friday."
- Many others were quick to help or offer advice when a question or issue arose: Bob Ahrens, Alan Arbogast, Art Bettis, Steve Bozarth, George Brixie, David Cremeens, Bob Engel, Leon Follmer, Bill Frederick, Don Johnson, Bruce Knapp, Bruce Pigozzi, John Tandarich, Greg Thoen and Dan Yaalon.

Funding for the many costs associated with the development of a book of this type were provided by various agencies of Michigan State University: the Agricultural Experiment Station, the Office of the Vice President for Research and Graduate Studies, and the Department of Geography. Some of the data on Michigan soils and landforms was developed in conjunction with NSF grants made to RJS (NSF awards BCS-9819148 and SBR-9319967); any opinions, findings, and conclusions or recommendations expressed in this material are, however, those of the authors and do not necessarily reflect the views of the National Science Foundation or Michigan State University.

We thank the professional staff at Cambridge University Press (CUP) and their affiliates for their help on, and support of, this book project. Matt Lloyd, our editor, has been a strong supporter of the book from its inception. The staff at CUP, especially Jayne Aldhouse, Sally Thomas and Anna Hodson, made the typescript and figures into a book. We also thank the many "behind the scenes" people whose tireless work often goes unseen and unappreciated; we did it!

Last and most important, we acknowledge that we have approached this book from the perspective of St. John Vianney, the Curé of Ars, when he said, "I have been privileged to give great gifts from my empty hands."

Contents

Part I

The building blocks of the soil

Chapter 1

Introduction

Soils form and continually change, at different rates and along different pathways. They continually evolve and are never static for more than short periods of time. Along these lines, we embrace Daniels and Hammer's (1992) statement that soils are four-dimensional systems. They are not simply the two-dimensional profile, nor is the study of the spatial variation in soils (a three-dimensional effort) enough. Soils must be studied in space *and* time (the fourth dimension). We incorporate these ideas by synthesizing complex, overlapping topics and tying them into a cohesive message: soil landscapes – how they form and change through time. To do this, we necessarily take a process-based approach.

Soil genesis and geomorphology, the essence of this book, cannot be studied without a firm grasp on the processes that shape the *distributions* of soils. We will, however, never fully understand the complex patterns of the Earth's soils. Even if we do claim to understand it, we must be mindful that the pattern is ever-changing. Again we quote Daniels and Hammer (1992: xvi), "One cannot hope to interpret soil systems accurately without an understanding of how *the landscape and soils have coevolved* over time" (emphasis ours). Every percolation event translocates material within soils, while every runoff event moves material across their surfaces, changing them ever so slightly. The worms, termites and badgers that continually burrow, mix and churn soils make them more different tomorrow than they were yesterday. Biochemical reactions within soils weather minerals and enable microbes to decompose organic matter, perpetuating the cycle from living matter to humus to chemical elements and back again. Because this can all be quite complex, we provide information, tools, resources and background data to bring the reader closer to deciphering this most complicated of natural systems.

Whitehead (1925) wrote, "It takes a genius to undertake the analysis of the obvious." Soil is seemingly everywhere, yet, we would argue, comparatively few study it. Additionally, soils are usually hidden from view and require excavation to be revealed. Soils are not discrete like trees, insects, lakes or clouds, which have seemingly identifiable outer boundaries. Instead, they seem to grade continuously, one into another, until they end at the ocean, a sheer rock face or a lake. When broken into discrete entities, like a geologist might break apart a rock, soils appear to lose their identity. This soil science . . . it's not easy. But therein lies the challenge!

We argue that a geographic approach to the study of soils is absolutely necessary (Boulaine 1975). Soils are spatial things, varying systematically across space at all scales. To study them fully you must understand not only *what* they are, but also how they relate to their adjoining counterparts. Soil geography focusses upon the geographic distributions of soils with emphasis on their character and genesis, their interrelationships with the environment and humans, and their history and likely future changes. It is operationalized at many scales, from global to local. Soil geography *encompasses* soil genesis; it is not simply a part of it. One cannot explain soil patterns without knowing the genesis of the soils

Table 1.1 Some of the academic domains of soil geography

Distribution of soils and soil taxa across the landscape
Soil survey and mapping
Soil genesis, both within and among pedons
Interactions among soils and the natural and human environment
Paleopedology
Soil geomorphology
Soil-slope and soil catena studies
Soil landscape analysis and the study/explanation of soil pattern
Pedometrics
Cartographic representation of soils
Evolution of soils and landscapes

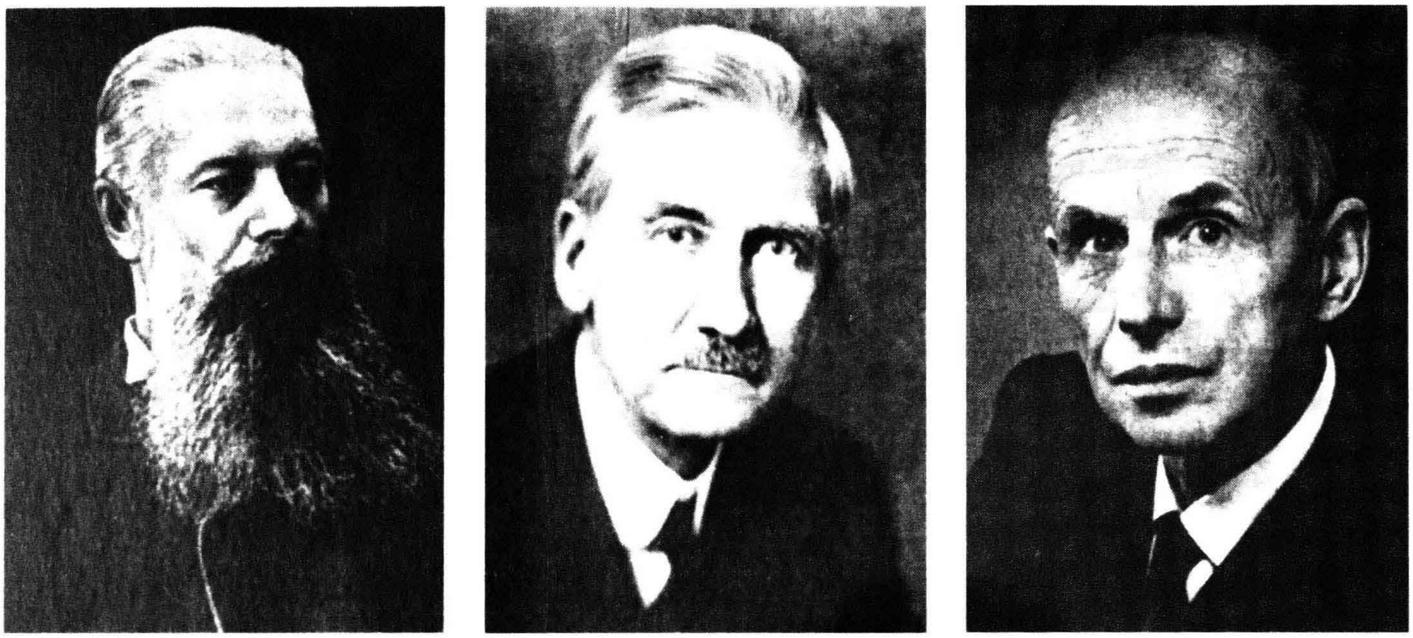
Not an exhaustive list. In no particular order. *Source:* Hole and Campbell (1985).

that comprise that pattern. Soil geography also incorporates geomorphology; one cannot fully explain soil patterns without knowledge of the evolution of the landforms and rocks of which they form the skin. Soil geography involves soil evolution; changing patterns of soils over time are a reflection of a multitude of interactions, processes and factors, replete with feedbacks, inertia and flows of energy and mass. Soil geography is manifested in soil survey (mapping) operations, which are extremely useful databases but are only as good as our understanding of the evolution of the soil pattern. This book, then, is about soil geography and all that it encompasses. Tandarich *et al.* (1988) used the term geopedology to refer to the interesction of the disciplines of geology, geography and soil science. We embrace that term and view it as a central component of this book.

Pioneers of soil science, soil survey and soil geography

Pedology is the science of soil genesis, classification and distribution; to many it is synonymous simply with *soil science*. Because soils have sustained human life since its inception, one may think that pedology has a long history. In fact, it was a late arrival among the natural sciences (Hole and Campbell 1985). Many attribute its founding to V. V. Dokuchaev (1846–1903), a Russian scholar and teacher. Others place emphasis on the work of Charles Darwin (1809–1882), perhaps the world's most underappreciated soil scientist. Regardless of who gets the credit for jump-starting this discipline, pedology is unquestionably little more than a century old! Our brief overview of the founders of soil science (below) should underscore that they were multifaceted thinkers who understood that the soil landscape was a complex system, requiring that it be studied using a geographic approach. More detailed accounts of the personalities involved in the development of the field are presented elsewhere (Kellogg 1974, Cline 1977, Tandarich and Sprecher 1994).

Vasili Vasilevich Dokuchaev is often called the father of soil science, although he acknowledged the influence of several others (particularly in the field of agricultural chemistry) in the development of his ideas (Tandarich and Sprecher 1994) (Fig. 1.1). Trained in Russia, he wrote his most reputed works on the soils of the Russian steppes, primarily Chernozems. He developed and used concepts on the nature and genesis of soil profiles, as well as soil landscapes, in his research. His geographic study of soils spanned local to regional scales. Dokuchaev and his students produced the first scientific classification of soils and developed soil mapping methods, laying the foundation for modern soil genesis and soil geography (Buol *et al.* 1997). He is known for developing the basic A–B–C horizon nomenclature, and



(a) (b) (c)

Fig. 1.1 Three influential scholars in the field of soil science. (a) Vasili V. Dokuchaev (1846–1903), Russian agriculturalist, geographer and pedologist. Image courtesy of John Tandarich. (b) Curtis F. Marbut (1863–1935), American agriculturalist, soil scientist and early developer of the US soil classification system. Image courtesy of John Tandarich. (c) Hans Jenny (1899–1992), Swiss pedologist and agricultural chemist; professor at the University of California. Image by R. Amundson.

a factorial model of soil development in which soils and soil patterns were seen as a function of independently varying state factors of the environment. Although not universal, this model remains, in various revised forms, the primary explanatory model for soils worldwide (see Chapter 11). Using this model, Dokuchaev's work allowed others to develop the concept of the *zonal soil* – one which characterized vast tracts of land and represented the epitome of soil development for that region. Zonal soil concepts, although conceptually flawed, essentially jump-started soil survey and mapping worldwide, and made the complex world of soils more understandable to the masses. Dokuchaev's teachings, carried across the Atlantic by E. W. Hilgard (1833–1903), were highly influential on many prominent soil scientists.

Unfortunately, by omitting the ideas of Charles Darwin from his writings, Dokuchaev would essentially bury them. Darwin's ideas focussed on local-scale biological origins of many soil properties, and on biomechanical processes in soils, such as mixing by worms (Darwin 1881). The lack of soil terminology in his works, coupled with the growing acceptance of Dokuchaev's factorial model for soil development, doomed *biomechanical soil processes* to the theoretical back seat, until resurrected years later.

In 1899, the United States started its soil survey program, under the direction of Professor Milton Whitney (1860–1927), primarily using geological concepts of soils, e.g., granite soils and alluvial soils (Shaler 1890). This practice continued for some time, e.g., Marbut *et al.* (1913). Shortly after this, Curtis Marbut (1863–1935), who earned his Ph.D. in geology at Harvard under the eminent geographer William Morris Davis (1850–1932), was appointed soil scientist in charge of the US Bureau of Soils (Tandarich *et al.* 1988) (Fig. 1.1). While at Harvard, Marbut had been influenced by the writings of Konstantin Glinka (1897–1927), a student of Dokuchaev, and the soils-related work of Nathaniel Shaler (1841–1906). He had translated Glinka's book *Die Typen der Bodenbildung* from German into English and applied many of the ideas within to the budding soil survey program (Cline 1977, Tandarich and Sprecher 1994). Marbut's impact on soil science in the USA proved to be strong and longlasting. Indirectly but strongly influenced by the ideas of Dokuchaev, he changed the way soils were viewed, emphasizing that they should be

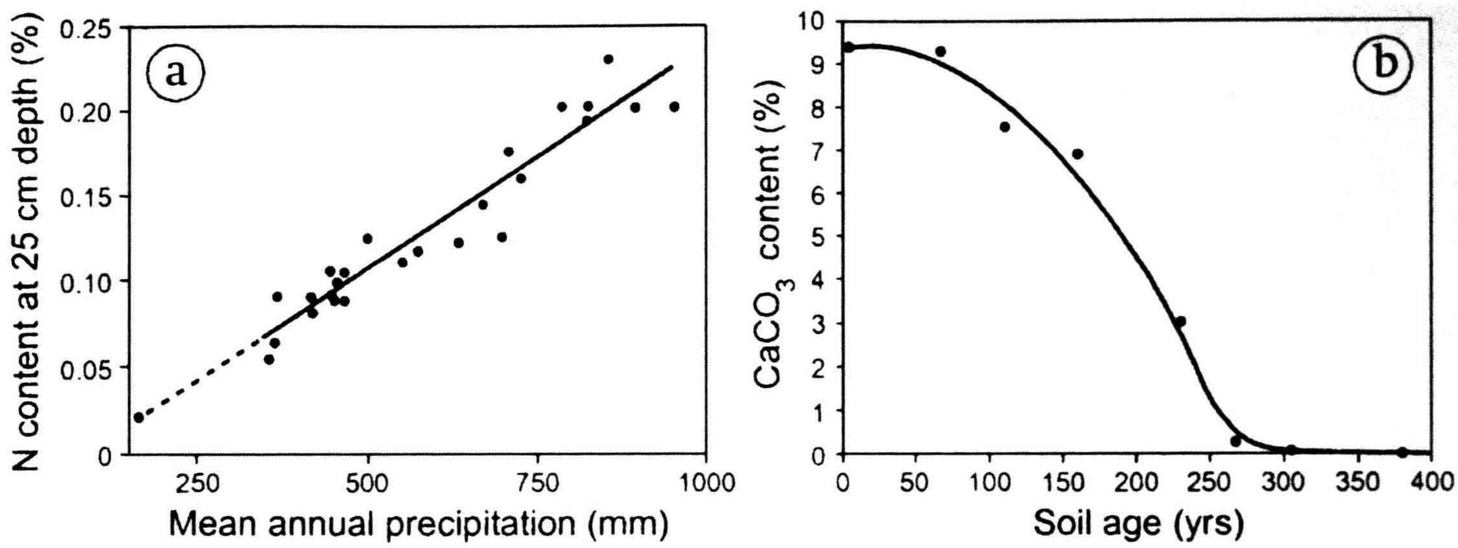


Fig. 1.2 Examples of two functional relationships that Hans Jenny produced for his 1941 book, *Factors of Soil Formation*.

classified and mapped based on horizon and profile characteristics, thereby reducing the influence of geology. Marbut eventually developed a multicategoric soil classification system (Marbut 1928, 1935; see Chapter 7). He thought about soils geographically, and his ideas translated into his classification system.

In 1941, Hans Jenny (1899–1992), at the University of California, published a landmark treatise entitled *Factors of Soil Formation*. Much of this book is devoted to his functional–factorial model of soil formation, in which soils are seen as the product of five interacting factors: climate, organisms, relief, parent material and time (see Chapter 11). Jenny developed many numerical soil functions in this book, each being an equation showing how soils change as four of the factors are held constant and one is allowed to vary (Figs. 1.1, 1.2). In this regard, Jenny (1941a: 262) noted that, "the goal of the soil geographer is the assemblage of soil knowledge in the form of a map. In contrast, the goal of the functionalist is the assemblage of soil knowledge in the form of a curve or an equation." He commented that soil maps display areal arrangement but give no insight into causal relationships, and that mathematical curves reveal dependency of soil properties on state factors but the conversion of such knowledge to the field is impossible without a soil map (Arnold 1994). Thus, Jenny proposed that the union of geographic and functional methods provided the most effective pedological research. Arnold (1994:105) restated this idea as follows – spatial soil patterns need to be understood through functional relationships of the soil-forming factors in *space and time*. Since Jenny's (1941a) model provided the theoretical framework for soil functional relationships, it stands today as perhaps one of the most geographic of the several soil models, because it is used subliminally or overtly by almost every soil mapper and geographer. More recent models, which refine and elaborate on Jenny's, as well as those that propose very different ways of looking at the soil landscape (Johnson and Hole 1994) are discussed in Chapter 11.

Things we hold self-evident...

Following the lead of Buol *et al.* (1997) and Hole and Campbell (1985), we provide below a listing of concepts or truisms in soil science and soil geography, slightly modified from their original sources.

- Complexity in soil genesis is more common than simplicity.
- Soils lie at the interface of the atmosphere, biosphere, hydrosphere and lithosphere. Therefore, a thorough understanding of soils requires some knowledge of meteorology, climatology, ecology, biology, hydrology, geomorphology, geology and many other earth sciences.
- Contemporary soils carry imprints of pedogenic processes that were active in the past, although in many cases these imprints are difficult to observe or quantify. Thus, knowledge

of paleoecology, paleogeography, glacial geology and paleoclimatology is important for the recognition and understanding of soil genesis and constitute a basis for predicting the future soil changes.
- Five major, external factors of soil formation (climate, organisms, relief, parent material and time), and several smaller, less identifiable ones, drive pedogenic processes and create soil patterns.
- Characteristics of soils and soil landscapes, e.g., the number, sizes, shapes and arrangements of soil bodies, each of which is characterized on the basis of horizons, degree of internal homogeneity, slope, landscape position, age and other properties and relationships, can be observed and measured.
- Distinctive bioclimatic regimes or combinations of pedogenic processes produce distinctive soils. Thus, distinctive, observable morphological features, e.g., illuvial clay accumulation in B horizons, are produced by certain combinations of pedogenic processes operative over varying periods of time.
- Pedogenic (soil-forming) processes act to both create and destroy order (anisotropy) within soils; these processes can proceed simultaneously. The resulting profile reflects the balance of these processes, present and past.
- The geological *Principle of Uniformitarianism* applies to soils, i.e., pedogenic processes active in soils today have been operating for long periods of time, back to the time of appearance of organisms on the land surface. These processes do, however, have varying degrees of expression and intensity over space and time.
- A succession of different soils may have developed, eroded and/or regressed at any particular site, as soil genetic factors and site factors, e.g., vegetation, sedimentation, geomorphology, change.
- There are very few old soils (in a geological sense) because they can be destroyed or buried by geological events, or modified by shifts in climate by virtue of their vulnerable position at the skin of the earth. Little of the soil continuum dates back beyond the Tertiary period and most soils and land surfaces are no older than the Pleistocene Epoch.
- Knowledge and understanding of the genesis of a soil is important in its classification and mapping.
- Soil classification systems cannot be based entirely on perceptions of genesis, however, because genetic processes are seldom observed and because pedogenic processes change over time.
- Knowledge of soil genesis is imperative and basic to soil use and management. Human influence on, or adjustment to, the factors and processes of soil formation can be best controlled and planned using knowledge about soil genesis.
- Soils are natural clay factories (clay includes both clay mineral structures and particles less than 2 μm in diameter). Shales worldwide are, to a considerable extent, simply soil clays that have been formed in the pedosphere and eroded and deposited in the ocean basins, to become lithified at a later date.

The framework for this book

In this book, we introduce the building blocks of soil in Part I, because we do not require that the reader be extremely well grounded in the fundamentals of soil; those with a strong background may choose to skim this section. We continue adding to the basic knowledge base in Part II (Chapters 8–12), but add a great deal more material on theory and soil genesis/processes. In Chapter 11, for example, we introduce a large dose of pedogenic and geomorphic *theory*, which in combination with the previous chapters allows us to discuss soil genesis and pedogenic *processes* at length in Chapter 12. Knowledge of soil genesis provides important information to scientists who classify them. Finally, we pay considerable attention in Part III (Chapters 13–15) to examining soil landscapes over time and how soils can be used as dating tools and as keys to past environments. This is how and when we really bring in the concept of change over time – the fourth dimension. Part III is the synthesis section, for within it we pull together concepts introduced previously and apply them to problems of dating landscapes and understanding their evolution. Lateral flows of materials and energy link soil bodies to adjoining