Chapter 1

Introduction to the Critical Zone

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It ain't what they call you, it's what you answer to.

W.C. Fields

1.1 INTRODUCTION

Pick up a newspaper or magazine. Turn on the television or radio and watch or listen to the news or typical talk show. All of these will have articles or programs that focus on global change and human-caused actions that focus on drought, floods, earthquakes, oil spills, hurricanes, tsunamis, forest fires, coastal erosion, landslides, avalanches, and pollution of air and water resources. The list can go on and on. Partly as a result of the impact of these events on humans and the environment, the Nation Research Council's (NRC) Committee on Basic Research Opportunities in the Earth Sciences, and the National Science Foundation (NSF) created the Critical Zone Observatory (CZO) program (NRC, 2001). Whereas the NRC conceptualized the term, the funding of the program fell on the shoulders of NSF.

In the *Principles and Dynamics in the Critical Zone*, we have assembled a group of authors to provide a broad-ranging approach to Critical Zone research that extends beyond the current CZOs. Each chapter has been written with the perspective of integrating the viewpoints from specific fields into an interdisciplinary view of the Critical Zone. Each chapter provides a view of a specific discipline or from a specific environment and the contributions it brings to Critical Zone research. As a first step in reading this volume, we begin by providing a succinct overview of the Critical Zone.

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1.2 BRIEF HISTORY AND BACKGROUND OF THE CRITICAL ZONE OBSERVATION NETWORK AND CRITICAL ZONE OBSERVATORIES

In 2001, a panel of the US National Research Council (NRC, 2001) recommended an integrated study of the *Critical Zone* as one of the most compelling research areas in Earth sciences in the twenty-first century. They (NRC, 2001, p. 2) went on to define the Critical Zone as "… *the heterogeneous, near surface environment in which complex interactions involving rock, soil, water, air and living organisms regulate the natural habitat and determine availability of life sustaining resources*." From this original definition, many, now loosely worded definitions have been crafted to define the limits of this zone as ranging from the top of the canopy layer down to the bottom of the aquifer (Fig. 1.1).

Fortunately, today these various refinements and rewordings of the definition of the Critical Zone have brought additional clarity. For example, groundwater has been constrained from all groundwater to "*freely circulating fresh groundwater*," instead of groundwater *sensu lato*. Aquifers that contain deep connate brines and confined aquifers have also been excluded (White, 2012). In reading the original definition, it is unclear what environments were to be included, and in fact, if some had not been excluded. One was left to assume that any environment present on the surface of Earth was included, but that was not clear. White (2012) has provided clarity to the definition, so that it encompasses polar/arctic,

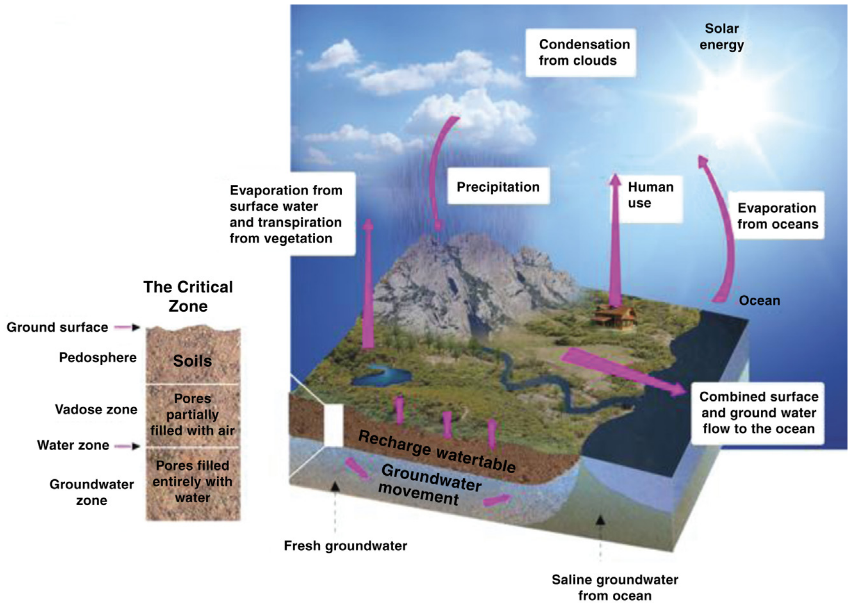

FIGURE 1.1 The diagram illustrates the extent of the Critical Zone from the top of the canopy to the bottom of the aquifer. The pathways, which act as linkages for flows of energy and mass between the various subsystems of Earth, are shown as gray arrows [purple arrows in the web version]. *(Modified from NRC (2001, p. 36).)*

alpine, and desert environments, but not coastal. Whereas still limited, we think this clarification of the broader definition of the term Critical Zone has a more meaningful application than originally penned.

The NRC was not the creator of the "Critical Zone" term. It has been around for a long time. Tsakalotos (1909) first introduced the term into the chemical literature to describe the binary mixture of two fluids and geologists have long used the term to refer to the complex geology of the Bushveld Complex in South Africa (Cameron, 1963). The precursor application of the term Critical Zone to this relatively thin zone of Earth was first suggested by Gail Ashley (1998). She noted that the term applied where the soil connects the vegetation canopy to the soil; the soil connects to the weathered materials, and the weathered materials connect to bedrock, and bedrock provides the connection to the aquifer.

Critical Zone is a term that brings attention to both the scientific community and the layperson, of the important, critical role of what this relatively thin zone plays in the existence of life on Earth. Latour (2014) provided an interesting view of the Critical Zone from a geopolitical point-of-view. He argued that the important contributions of CZOs and the data they produce are providing various types of consistent observations from selected locations on Earth. More importantly, the Critical Zone concept deconstructs the planet into much smaller components of the "*living planet.*" Using the Critical Zone concept that focuses on an individual location brings understanding to the public of the linkages between a single, garden parcel to a total watershed to the complete planet. He pointed out how important the concept of scale is for humans to understand and accept responsibility for stewardship of Earth. This idea has been pushed by environmental groups who have coined the phrase "*Think globally – Act locally.*"

The creation of the CZOs is not the first time NSF has been involved with major contributions that benefit society. In fact, several authors have suggested that it was the contribution of scientists and engineers that helped win World War II that ultimately lead to the establishment of NSF (Mazuzan, 1988; Bronk, 1975; Kleinman, 1995). Today NSF is the only federal agency solely dedicated to the support of fundamental research and education. Over the past few years, NSF has shifted their focus from funding strictly fundamental research to requiring researchers to expand fundamental research to include contributions to society and outreach. The CZOs is one outcome of this new, important focus at NSF.

It was not until 2003 that funding for Critical Zone research appeared. The initial step in creating CZOs began with the funding of *The Weathering System Science Workshop*. The main focus was on the development of weathering-system science. The initial idea was that this new field should embrace the fields of chemistry, biology, physics, and geology (Brantley et al., 2006). During the following year, The Weathering System Science Consortium (WSSC) was formed, and it was morphed in 2006 to what has been referred to as the Critical Zone Exploration Network (CZEN).

NSF issued a request for proposal in 2005 to commence the establishment of Critical Zone research. Soon after this, NSF sponsored the *Frontiers in Exploration of the Critical Zone Workshop* to help establish goals and agenda for future directions and research. Attendees at the workshop suggested the need for creating an initiative to study the Critical Zone based on an international focus. This eventually led to the establishment of CZOs in various parts of the planet. In addition to the NSF-funded CZOs, the Soil Transformations in European Catchment (SoilTrEC), which is a consortium of European Union members, also established Critical Zone centers.

In 2006, NSF solicited proposals to establish CZOs; the solicitation was through the Division of Earth Sciences. From the first solicitation, three locations (Southern Sierra (California), Boulder Creek (Colorado), and Susquehanna Shale Hills (Pennsylvania)) were selected and established in 2007. Three more CZOs were launched in 2009; the three CZOs are Jemez River Basin – Santa Catalina Mountains (Arizona/New Mexico), Christina River Basin (Delaware/Pennsylvania), and Luquillo Mountains (Puerto Rico). In 2013, four additional CZOs were established. These four CZOs are the Calhoun Forest (S. Carolina), Intensively Managed Landscape (Minnesota, Illinois, Iowa), Reynolds Creek (Idaho), and Eel River (northern California) (Table 1.1). Thus, the number of

TABLE 1.1 Locations of Critical Zone Sites Located Around the World

	CZO	Location
1	Southern Sierra CZO	Southern Sierra Nevada, California
2	Boulder Creek CZO	Colorado Front Range, Rocky Mountains
3	Susquehanna Shale Hills CZO	Central Pennsylvania
4	Jemez River Basin CZO	New Mexico
5	Christina River Basin CZO	South-eastern Pennsylvania and Northern Delaware
6	Luquillo	Luquillo, Puerto Rico
7	Calhoun LTSE	South Carolina
8	Intensively Managed Landscape	Minnesota, Illinois, Iowa
9	Reynolds Creek Watershed	Southwest Idaho
10	Eel River	California
11	Clear Creek	Iowa
12	Adirondack Mountains	Southwestern Adirondacks
13	AGRHYS	Brittany
14	AMMA-CATCH	S-N ecoclimatic gradient in West Africa

TABLE 1.1 Locations of Critical Zone Sites Located Around the World *(cont.)*

	CZO	Location
15	Damma Glacier	Canton URI, Switzerland
16	Bonanza Creek	Alaska
17	Central Great Plains	Colorado
18	DRAIX_BLEONE	6.3′ E-44.1′ N, French South Alps
19	Riviere des Pluies Erorun	Reunion Island, Indian Ocean
20	French Karst Observatory	Langiedoc, Jura, Provence, Pyrenees, Paris Basin, Aquitanien Basin
21	Fuchsenbigl	East Austria
22	Galapagos CZO	Santa Cruz Island, Galapagos
23	Guadeloupe	Guadeloupe, French West Indies
24	Hawaii	Hawaii
25	Hoffman Creek site	Oregon
26	Hubbard Brook Experimental Forest	New Hampshire
27	HYBAM: Hydrological and Geochemical observatory of the Amazon Basin	Amazon Drainage Basin
28	Illinois River Basin	Illinois
29	Kindla	Kindla, Bergslagen
30	Kouliaris River Basin	
31	Lowlands CZO	Netherlands
32	Lysina	Slavkov Forest
33	Marcellus Shale	Pennsylvania
34	Merced River Chronosequence	California
35	Montousse	Gascogne
36	MSEC: Management of Soil Erosion Consortium	SE Asia (three sites)
37	MSEC Dong Cao long-term monitoring catchments	20′57′40″ N-105′29′10″ E
38	MSEC Houay Panoi long-term monitoring catchments	19′51′10″ N-102′10′45″ E
39	Mule Hole (Bandipur National Park)	Southern India (Mule Hole:11′72′N 76′42E
40	Muskingum Watershed	Ohio
41	Na Zelenem	Western Bohemia
42	NC2	New Caledonia

(Continued)

TABLE 1.1 Locations of Critical Zone Sites Located Around the World *(cont.)*

	CZO	Location
43	NevCAN Sheep Range and Snake Range Transects (NevCAN)	Southern and East Central Nevada
44	North Ogilvie Mountains	Yukon Territory
45	North Eastern Soil Monitoring Cooperative	North eastern Soil Monitoring Cooperative
46	Nsimi	Cameroon
47	OBSERA	Guadeloupe (Lesser Antilles)
48	OHM-CV	Cervennes-Vivarais (four sites)
49	OMERE	Brie, Paris Basin
50	ORACLE	Languedoc and Cap Bon (two sites)
51	Panola Mountain	Atlanta
52	Pluhuv Bor	Slavkov Forest
53	Plynlimon	Mid Wales
54	Red Soil Site	Yingtan Jiangxi Province
55	Santa Catalina Mountains CZO	Saguaro National Park
56	SEQ periurban supersite	South East Queensland
57	Stengbach	Vosges Mountains
58	Tenderfoot Creek Experimental Forest	Montana Southwest Alberta and Wyoming
59	The Prairie Pothole Region CZO	South Central North Dakota
60	The Rogers Glen (Shale Hills CZO) Satellite Site	Chadwicks, New York
61	Trindle Road Appalachian Trail Diabase	Pennsylvania
62	TUM CZO	Bavaria
63	Beacon Farm 1	Rakaia River Catchment, Canterbury Plains
64	Omere Site	Tunisia

The numbers in the table correspond to the Critical Zone sites shown on the map in Fig. 1.2.

CZOs funded by NSF today is 10. In 2014, NSF established a National Critical Zone Office with Lou Derry serving as the first director and Tim White serving as the first coordinator. To date to carry out the directive of the Critical Zone mission, NSF has created 10 CZOs and a national office (Fig. 1.2).

The 10 NSF CZOs, each operate as environmental laboratories and focus on specific problems. A detailed discussion of the 10 NSF-funded CZOs is provided by White in Chapter 2 of this volume.

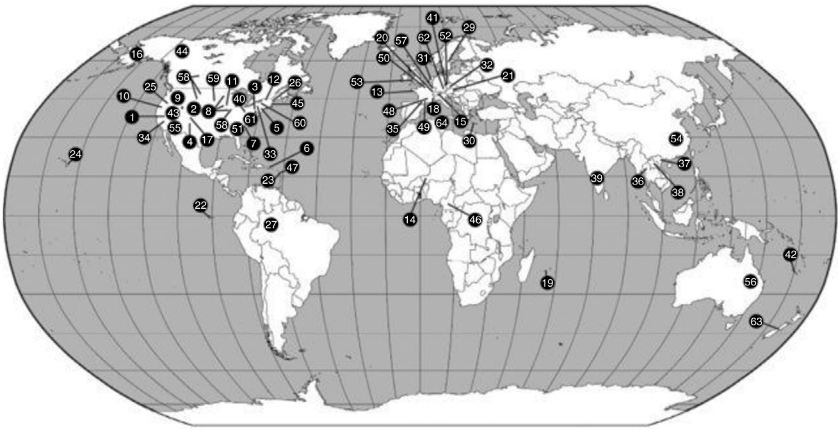

FIGURE 1.2 Locations of Critical Zone sites located around the world. The number in the marker corresponds to the Critical Zone site listed in the table. *(Map compiled from Banwart et al. (2013) and NRC (2001).)*

1.3 DEVELOPMENT OF THE GLOBAL CRITICAL ZONE NETWORK

The number of CZOs and the spatial distribution were increased in 2009 when the European Commission funded the development of an international network of observatories, which are located in Europe, China, and the United States. A major requirement of the new program was to work with the US- established CZOs (Banwart et al., 2013). Soon after, France, Germany, and China founded additional CZOs. Today the number of CZOs around the world stands around 64 (Fig. 1.2 and Table 1.1). Participants at 2013 Critical Zone Meeting in Delaware, USA, originally compiled the table (Banwart, 2015). Additional sites in France (Critex programme), Germany (TERENO), and China will be coming on board in the coming years. In addition, several locations in Australia are being developed as future CZOs (Banwart, 2015). We have added additional sites to the table produce by Banwart et al. (2013).

The raison d'être of the Critical Zone network is driven by basic principles of science. All the research at each location is focused on asking fundamental questions and collecting and building data banks. The modus operandi of the CZOs can be summed up as seven tasks: (1) hypothesis testing; (2) process understanding across temporal and spatial scales; (3) development of mathematical models; (4) utilization of multiple sensor and sampling methods; (5) installation and use of high-density instrument arrays; (6) undertaking time series/ real-time measurements of coupled process dynamics; and (7) combination of large data sets with numerical simulations (Banwart et al., 2011, 2013).

Banwart et al. (2013) provided an excellent summary of progress being made by the CZO Network, as well as the short- and long-term goals. The scientific foundation of the Observatories was strengthened with the articulation of six big science questions being formulated. Banwart et al. (2012, p. 20) list the six big science questions as:

Short-Term Processes and Impacts

- What controls the resilience, response, and recovery of the CZ and its integrated geophysical–geochemical–ecological functions to perturbations such as climate and land use changes, and how can this be quantified by observations and predicted by mathematical modeling of the interconnected physical, chemical, and biological processes and their interactions?
- How can sensing technology, e-infrastructure, and modeling be integrated for simulation and forecasting of essential terrestrial variables for water supplies, food production, biodiversity, and other major benefits?
- How can theory, data, and mathematical models from the natural- and social-sciences, engineering, and technology be integrated to simulate, value, and manage Critical Zone goods and services and their benefits to people?

Long-Term Processes and Impacts

- How has geological evolution and paleobiology of the CZ established ecosystem functions and the foundations of CZ sustainability?
- How do molecular-scale interactions between CZ processes dictate the linkages in flows and transformations of energy, material, and genetic information across the vertical extent of aboveground vegetation, soils, aquatic systems, and regolith – and influence the development of watersheds and aquifers as integrated ecological–geophysical units?
- How can theory and data be combined from molecular to global scales in order to interpret past transformations of Earth's surface and forecast CZ evolution and its planetary impact?

To solve these six big questions, it requires integrative research that spans traditionally siloed disciplines and the long-term studies that are hierarchically structured in both space and time. Each CZO works on shared CZO goals, but also focuses on aspects of Critical Zone science that fits the strengths of its investigators and its environmental setting. Each CZO consists of field sites within a watershed. The sites are instrumented for a variety of ecological, geomorphological, pedological, hydrological, and geochemical measurements, as well as sampled for soil, canopy, and bedrock materials, but unfortunately research at the CZOs is not always integrative in space or in time.

1.4 WATER, THE TRUE THREAD OF THE CRITICAL ZONE

As the Critical Zone was being defined, three recommendations associated with the Critical Zone were tenured by the NRC Committee: make soil science stronger, continue to build hydrological sciences, and strengthen study of coastal zone processes (NRC, 2001, p. 6). From our perspective, it is interesting to note that from these recommendations somehow soil, and not water, became the thread that ties the various systems of the Critical Zone together. We understand and appreciate that focus on world hunger and increasing rates of soil erosion along with The Millennium Ecosystem Assessment (MEA, 2005) and the EU Thematic Strategy for Soil Protection (European Commission, 2006) provided a strong foundation for soil being viewed as the link between soil erosion, food production, and worldwide human welfare. We also agree that soil plays an important role, but we do not think it is the link between all the systems. It is easy to understand that the soil profile does connect the vegetation canopy to the soil; the soil connects to the weathered materials and the weathered materials connect to bedrock, and bedrock provides the connection to the aquifer. These pathways facilitate flows (i.e., energy, mass, biogeochemical) from the top to the bottom and vice versa. But, none of these energy and material flows would be possible without water.

Thus, we strongly argue that the link between all these components or systems is water, rather than soil. Water is the true thread that stitches these systems together. It is water that travels from the atmosphere, to and through the biosphere, and into the lithosphere where it is stored as surface water, soil water, and groundwater. Water is a key component in chemical weathering processes, a sustainer of life, and is responsible for floods or absent to cause drought. Although the NSF never mentioned the above concern, we believe that they (NRC, 2005) also saw the "*thread problem*" when they recommended that focus needed to be brought to water as the unifying theme in the study of complex environmental systems.

As Lin (2010) has pointed out, the Critical Zone term has been met with both enthusiasm as well as skepticism. These two visions have led to numerous perceptions, both right and wrong of the concept. Lin (2010) presented an excellent summary and discussion on the mixed messages of the Critical Zone concept. He listed four issues: (1) researchers consider the Critical Zone (nearly) synonymous with the term soils; (2) some researchers equate the Critical Zone with the term regolith; (3) some researchers question the effectiveness of the Critical Zone concept because (they think soil is the Critical Zone) the lower boundary is so highly inconsistent and ill-defined; and (4) some believe the Critical Zone concept is useful because it is intrinsically process-oriented and serves as a uniting concept accommodating the various components and systems of Earth. If no clear definition exists of the Critical Zone concept, it is hard to imagine that Critical Zone research is sufficiently integrated and directed to solve the six big questions outlined by Banwart et al. (2012).

We do not want the reader to develop the opinion that we have unenthusiastic feelings about the Critical Zone concept. This is not so. We are very strong supporters of the Critical Zone concept, and we applaud the foresight of creating a 4D approach to studying the processes that form and shape the surface and near-surface features and resources of Earth. This is critical since the Critical Zone concept calls for a focus on the zone where humans live and work. For life, as we know it, it is the most important and critical area for the human species. Human activities are significantly influencing the environment of Earth in many ways, in addition to greenhouse gas emissions and climate change.

Anthropogenic changes to the land–surface, oceans, coasts, and atmosphere; biological diversity; the water cycle and biogeochemical cycles of Earth are clearly discernable beyond natural variability. This impact is on a par with some of the greatest forces of nature in spatial extent and magnitude. Unfortunately, many are accelerating. In spite of wholesale neglect and outright denial, global change is real and appears to be happening now.

Earth-System dynamics are characterized by critical thresholds and abrupt changes. Human activities could inadvertently trigger such changes with severe consequences for the environment and inhabitants of the planet. The Earth System has operated in different states over the last half million years, with abrupt transitions (a decade or less) sometimes occurring between them. Human activities have the potential to switch the Earth System to alternative modes of operation that may prove irreversible and less hospitable to humans and other life. The probability of a human-driven abrupt change in the environment of Earth has yet to be quantified but is not negligible. In terms of some key environmental parameters, the Earth System has moved well outside the range of the natural variability exhibited over the last half million years, at least. The nature of changes now occurring simultaneously in the Earth System, their magnitudes and rates of change are unprecedented. Earth is dynamic.

Global change cannot be understood in terms of a simple cause-and-effect paradigm. Human-driven changes cause multiple effects that cascade through the Earth System in complex ways. These effects interact with each other and with local- and regional-scale changes in multidimensional patterns that are difficult to understand and even more difficult to predict. It is in this arena that the CZOs will play a significant role. The CZOs are intended to identify flow pathways, and energy transformations at various scales. Through this research they will be creating a continuum of change that will provide keys to understanding the linkages between the components in Earth Systems. Many of the CZOs are employing a hind-casting approach to accomplish a forecasting approach to their research. This type of research will provide the data to predict and understand future change and global impacts.

1.5 THE FASHION OF CRITICAL ZONE RESEARCH

Critical Zone is a fashionable term. Much of what is being undertaken at the various CZOs is proven science. What the term Critical Zone is driving is a new awareness of interdisciplinary study of single locations. The CZO fosters conventional studies, governance, and coordination of data on a global scale. Banwart et al. (2013) pointed out that the real contributions from the CZO network will be the understanding of the relationship between the strength of a response, the time of recovery, and the overall resilience, to environmental perturbations of our planet. A 4D architecture approach will be required to achieve this goal. Pursuit of that goal will result in the development of new sensing technologies, as well as new spatial statistics and modeling.

After studying all the research being produced by the various CZOs, we were both elated and depressed. Elated to see that researchers from various disciplines are focusing on specific locations, creating a warehouse of data, and beginning to engage in what we would describe as true interdisciplinary work. We were depressed to see that it appears that a lot of the research being produced at the various CZOs is still discipline-focused and published in discipline-specific journals. After we delved into all the Critical Zone literature, we came to the conclusion that much of what is being referred to as a new approach, the Critical Zone is, in fact, a new name for old science. We find ourselves in a sort of a dichotomy in accepting the new approach and concept of the Critical Zone. On the one hand, the concept of the Critical Zone is a fresh way of showing the connection and flow of mass and energy from the top of the canopy to the bottom of the aquifer. The fundamental precepts of the Critical Zone appear to be based on much of the conceptualization of General Systems Theory as developed by von Bertalanffy in the 1950s (von Bertalanffy, 1950, 1951, 1968). And, although the Critical Zone is a very useful concept, it is by no means a new or novel idea. This attitude also underlines the importance of the system perspective.

However, much positive exists about the Critical Zone concept. It is resulting in enormous amounts of data being collected at specific locations by a wide range of disciplines; it is developing new ways to collect and model these data; it is providing methods and data to combine data from various CZOs to model change of Earth in both longitudinal as well as latitudinal directions that is engaging researchers from various fields to once again visit the idea of interdisciplinary research and to view activity on Earth from a system's point of view. Probably one of the most important applied aspects of the global CZO network will be the development of reliable data that will lead to enlightened policy and management of the geoscience base of Earth. As geoscientists continue on their quest for a unifying principle, the Critical Zone approach might just be that step in the right direction.

The current popularity of the Critical Zone concept is very welcome, as it refocuses attention on the need to study the complex nature of the upper zone of Earth from an integrative, holistic approach. This fresh approach reminds us of the argument of Sperber's (1990) and Sherman's (1996, p. 87) comments on "*fashion change from the design and arts disciplines to explain one means of controlling the developments and directions of science ... changes in the goals, subjects, methods, philosophies, or practice of science can often be attributed to the emergence of an opinion (or fashion) leader, pointing toward a different path – setting out the new fashion. The fashion process relies upon fashion dudes to advance their disciplines*." We think we are seeing a large group of fashion dudes, stepping forward to configure a transformative science of the surface Earth; the Critical Zone concept is a perfect unifying principle for the geosciences and the means by which we are going to move towards integrative studies of the biophysical environment and the role of humans within that environment.

As we mentioned at the beginning of the introduction, *Principles and Dynamics of the Critical Zone* contains chapters written by various professionals in their respective fields. Our purpose in writing this book is to provide an all-encompassing, broad view of the Critical Zone. The chapters run the gamut from very general discussions on the paradigm of the Critical Zone to chapters that focus on more detailed aspects of the Critical Zone and include environments that have never been traditionally described from a Critical Zone perspective. We have tried to be somewhat systematic in the order of the Table of Contents. The reader will note that our coverage is not complete. Whereas we set out with the goal of providing a complete coverage of all aspects of the Critical Zone, unfortunately, a couple of authors who agreed to provide chapters never followed through and we had to supply a manuscript to the publisher. Although not able to accomplish what we set out to do, we offer this as an overview of the first approximation of the principles and dynamics of the Critical Zone.

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