17 The Evolution of Geomorphology, Ecology, and Other Composite Sciences

W.R. Osterkamp
US Geological Survey, Tucson, Arizona

C.R. Hupp
US Geological Survey, Reston, Virginia

ABSTRACT

Geomorphology, ecology, and related disciplines are complex composites of the basic sciences - physics, chemistry, and biology. The basic sciences have developed through paradigm (exemplar) definition and replacement, but the composite sciences, too complex to generate applicable exemplars, developed from principles borrowed from basic science. Succeeding periods of speculation and observation, composite sciences adopted exemplars of evolution from biology and equilibrium from chemistry. Effort continues to unite these conflicting approaches.

Work of geomorphologists, ecologists, and other composite scientists suggests that periods of Darwinian evolution, equilibrium, and integration occurred in common sequence but with different timing in the composite sciences. Fundamental differences between the basic and composite sciences - simplicity versus complexity, suitability versus inappropriateness to direction by exemplars, and a generally theoretical versus applied quality - provide explanations for different patterns of development. Based on common characteristics and methods of investigation, future trends in composite science are anticipated.

The Scientific Nature of Geomorphology: Proceedings of the 27th Binghamton Symposium in Geomorphology held 27-29 September 1996. Edited by Bruce L. Rhoads and Colin E. Thorn

INTRODUCTION

Events defining a history of science and the branching and growth of disciplines within science are well-established, but the causes of the events and branching continue to inspire debate. This chapter, based on a thesis of Thomas Kuhn (1970), suggests how several branches of modern science have developed. Specifically, this overview considers geomorphology, including physical geography, and ecology within all science-related study. It is proposed that predecessors to contemporary geomorphologists and ecologists, largely observers through the mid-seventeenth century and beyond, were profoundly influenced by Darwin's *Origin of Species* in 1859. Furthermore, a predictable counterreaction to an evolutionary orientation followed. Finally, inevitable amalgamation of the poles is being adopted by recent natural scientists. The leaders of these tenures of thought are termed observationalists, Darwinists, equilibrists, and integrationists; a fifth group conceivably could be unifiers. If North American scientists are unduly emphasized, the bias is unintentional.

Numerous discussions treat the emergence of science from Greek philosophy, which typically viewed nature as an organism. The separation accelerated in the second millennium with the growth of Persian mathematics and the scientific technique. Roger Bacon, an early observationalist, was among the first, about AD 1720, to insist on observation, objectivity, and repeatable experimentation. As the speculations of Herodotus, Aristotle, Seneca, and others following them helped usher in the Renaissance, science increasingly became a separate component of philosophy (Bowler 1992).

With the Renaissance, a view of nature based on observation became predominant and rifting among philosophy, religion, and technology deepened. With turmoil of the sixteenth-century Reformation, emphasis was placed on quantitative techniques and experimentation of the scientific method. The advances did not depart from observation, but represented subtle change in technique. Hence, Renaissance and post-Renaissance observationalists were also epistomologists, bridging philosophy and science by attempting to understand the limits, validity, and methods to develop knowledge (Bowler 1992). Observationalists continue a presence, but few are engaged in quantitative experimentation without embracing an overriding doctrine.

Modern science, for this discussion, began with the separation of physics from the cosmology of Copernicus and Kepler in the early seventeenth century, and continued with Robert Boyle's studies on gases, a transition from alchemy to chemistry. Development of biology, the other basic science, was closely tied to late eighteenth- and early nineteenth-century work of William Smith, James Hutton, Rodney Murchison, and others in paleontology and stratigraphy. Systematic observations of blood circulation in animals were made by William Harvey (1628), but the timing of the first significant applications of experimental method to biology is unclear.

The Structure of Modern Science

Thomas S. Kuhn, a historian, suggested in *The Structure of Scientific Revolutions* (1970) that modern science, studies based on the experimental approach, has a history of data-gathering punctuated by shorter periods of 'paradigm' upheavals that force reevaluation and redirection. The history of modern science largely addresses events defining progress in the basic sciences, and Kuhn (1970) mostly discusses physics, chemistry, and biology. This chapter extends the paradigm concept to geomorphology, ecology, and other disciplines. that combine elements of the basic sciences and technology.

A *paradigm* (Kuhn 1970) is loosely synonymous with archetype, an all-inclusive model. Dominance of one style, however, gives way to another. With acceptance of a paradigm, *normal science* holds, a 'continuation of a particular research tradition' (Kuhn 1970, p. 11). Normal science extends '. . . the knowledge of those facts that the paradigm displays as particularly revealing, by increasing the extent of the match between those facts and the paradigm's prediction, and by further articulation of the paradigm itself' (Kuhn 1970, p. 24).

Normal science supports the prevalent paradigm, but with time, some data appear anomalous. When too many conflicting data reduce paradigm utility, the science becomes unstable and subject to discovery - the revolution of paradigm replacement. Acceptance of a paradigm implies acceptance of the rules and standards that define the system; thus, consensus is established for the conduct of normal science, including the goals of continuing research. Most importantly, adoption of a paradigm characterizes the science until replacement recurs: '... to desert the paradigm is to cease practicing the science it defines' (Kuhn 1970, p. 34). Because a new paradigm upsets custom, older scientists are threatened and tend to reject the model. Generally, full recognition of a paradigm requires one or two decades and results in a terraced advancement of the discipline - treads of normal science interrupted by paradigms.

Following criticism of his use of paradigm, Kuhn substituted *exemplar(s),* which 'are concrete problem solutions, accepted by the group as, in a quite usual sense, paradigmatic' (Kuhn 1977, p. 297). Through this chapter, therefore, exemplar replaces paradigm. The breadth of application that a concept classed as paradigmatic has remains in question (e.g. Haines-Young and Perch 1986); it is inferred here that Kuhn (1970, 1977) intended an exemplar to be broadly applicable to a science. Another difficulty that resulted in scant criticism was Kuhn's focus on the 'basic' sciences: physics, chemistry, and biology. Excepting geology, Kuhn gave no significant recognition to other disciplines - the 'composite' sciences. For responses to criticisms, see 'Postscript -1969' (Kuhn 1970, p. 174-210).

Diversity in Science

The term *composite science* refers to complex disciplines such as geomorphology and ecology, acknowledging that they are composed of distinct parts of other types of study. Thus, we define composite science as a discipline with specific and generally agreed-upon goals requiring various scientific and technological approaches of investigation to meet those objectives. A goal of geomorphology, for example, is a genetic interpretation of landforms, and techniques of physics, chemistry, biology, and engineering are employed to develop interpretations. Similar statements seem fitting for other disciplines regarded here as composite, or compound, sciences.

Because the composite sciences have diverse inputs, they typically are more applied than the basic sciences, making them less dominated by established order. Physics is cleanly defined as the study of the material universe, but ecology is concerned with interrelations of organisms and their environments and must account for variables including climate, soil physics and chemistry, and plant physiology of competing species. The basic sciences, products of early observationalists and gaining identity in the seventeenth century through exemplar sequencing, provided a basis for most composite science two to three centuries later but could not provide similar traits of exemplar structure. An exception composite science is geology, a principal source from which geomorphology arose. Geology established a modern identity late in the eighteenth century, is similar to basic science in some respects, and directly benefited from exemplars of basic science, especially evolution and advances in chemistry The genetic complexity of a composite science, including geology, largely precludes the rule of an encompassing exemplar that guides the research of its 'normal science'. In much the same manner as their parents, however, the composite sciences have exhibited a progression or evolution of development, two centuries later, but mostly without benefit of exemplar direction. The result has been the theft or appropriation of exemplars proposed for a basic science.

This chaper suggests a context for understanding the development and operation of the composite sciences. Numerous papers, including Kuhn's (1970, 1977), explore the basic sciences as a set; others treat a specific composite science (e.g. Chorley et al. 1973; Kitts 1977; McIntosh 1985; Sack 1992; Frodeman 1995). Few, however, consider the development of composite sciences as a group, which may be necessary to understand how any one member has matured. We propose that the composite sciences, lacking exemplar heredity of the basic sciences, exploited, with little modification, Darwinian evolution for use within each discipline. Charles Darwin (Figure 17.1), in *Origin of Species,* wrote two chapters on geology, largely paleontology, and the effect on geology and other disciplines was profound, self-evident, and has been discussed exhaustively. A thesis here is that a more subtle effect of evolution, largely ignored but persisting to the present, has been its dominant influence, both positive and negative, on other composite sciences.

EXEMPLARS AND THE PARENT SCIENCES

Geomorphology and ecology grew from parents of basic science and geology and share histories entwined with them. Thus, exemplars controlling physics, chemistry, and biology provided form to composite science as well. Noteworthy examples of exemplars that have had but indirect effect on composite sciences include the laws of motion by Isaac Newton in the 1680s, discovery of oxygen by Joseph Priestley about 1770, development of atomic theory by John Dalton about 1805, and observations of Gregor Mendel that genes obey probabilistic laws (1865). Of greater pertinence, however, was publication of *The Origin of Species by Means of Natural Selection; or, the Preservation of Favored Races in the Struggle for Life,* by Charles Darwin (1859), and development of equilibrium theory, common to all of science but best expressed for chemical reactions by van't Hoff (1884):

$$A + B \leftrightarrow C + D \qquad (1)$$

Equation (1) quantifies Le Chatelier's principle, that a system at equilibrium adjusts to a stress (i.e. change in temperature, pressure, or concentration of matter) so as to reestablish equilibrium. Although the van't Hoff equation was new to physical science, equilibrium had long been observed in engineering and had been recognized by Latin speculators as signified by *vix medicatrix naturae* (loosely meaning the balance and effort of natural

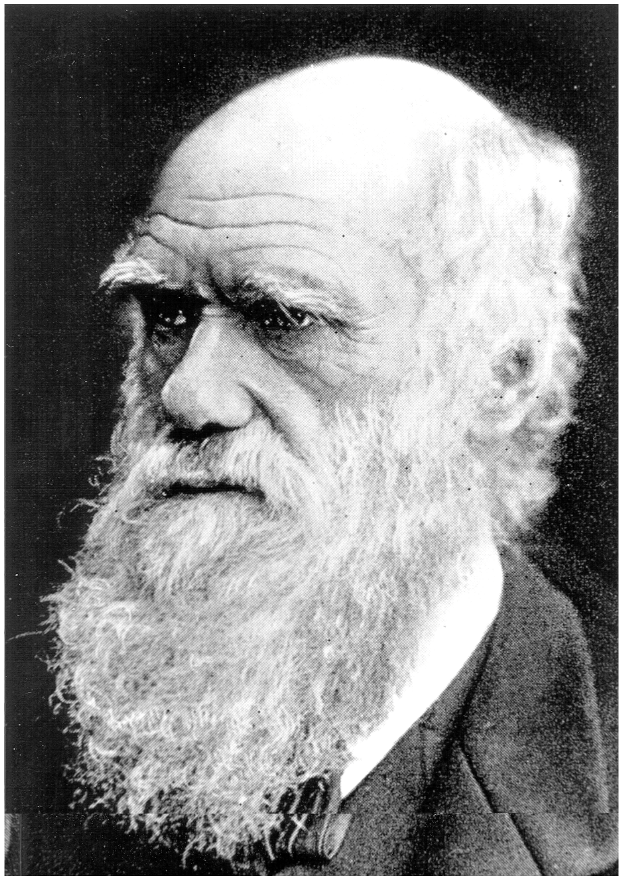

Figure 17.1 Portrait of Charles Darwin

healing). One of many applications of the van't Hoff equation to the composite sciences is the partition coefficient, K_d (Olsen et al. 1982), which is a mass ratio of a contaminant, C_s, sorbed to soil particles, to the equilibrium concentration of the contaminant, C_e, in water:

$$K_d = C_s/C_e \tag{2}$$

Much of twentieth-century chemistry, the study of changes of matter, has been governed by equilibrium theory of equation (1). Physical chemistry, the interface between physics and chemistry, was developed by Jacobus van't Hoff (Figure 17.2). Similarly, Darwinian evolution and its long time scales for over a century have been tenets of biology, simply defined as the study of life. Components of biology treating shorter temporal scales than evolution, biochemistry, biophysics, and ecology, among others, typically embrace equilibrium theory.

An exception to the generalization that the composite sciences evolved from and later than the basic sciences is geology. Dependent on history, tailored after physics (Kitts

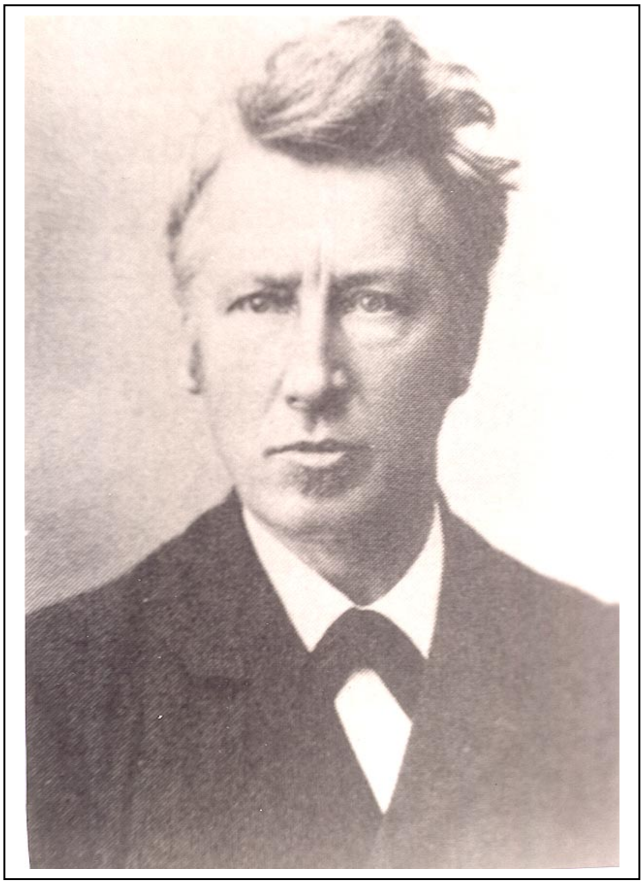

Figure 17.2 Portrait of Jacobus van't Hoff (courtesy of the Nobel Foundation)

1977; Frodeman 1995), but lacking susceptibility to experimentation, geology has been termed a derivative science (Schumm 1991; Frodeman 1995) and protoscience (Kitts 1977) that is parent to other composite sciences and is itself a composite. Geology, the study of the Earth, includes subdisciplines of petrology (treating the occurrence of rocks), stratigraphy (the description of divisions of rocks and their historical significance), sedimentology (the study of sedimentary rocks), tectonics (the study of the architecture of the Earth), historical geology (the study of temporal change on earth), geophysics (the study of the Earth, Moon, and other planets), and geochemistry (the study of the distributions of elements). An extreme example, the breadth of geology epitomizes the complexities of the composite sciences and demonstrates that an exemplar relevant to geochemists, for example, may have limited application to other segments of 'the group' (Kuhn 1977) of geologists.

As did physics and chemistry, geology separated from philosophy in the eighteenth century, largely due to naturalists such as Abraham Werner, James Hutton, Rodney Murchison, Alexander von Humboldt, and Charles Lyell (Bowler 1984; Tinkler 1989). Their studies included broadly scoped observations of mineralogy, rock types, geomagnetism, climatology, and the fossil record, which in 1798 led to recognition of evolution by William Smith's *Law of Faunal Succession,* about 60 years before Darwin's *Origin of Species.* Ironically, therefore, the exemplar of evolution initially may have been constructed for a composite science too complex to use it effectively, and perhaps was incorporated into biology only after it had matured sufficiently to accommodate the immensity of the concept.

An alternative view might suggest that geology has been guided by the Neptunist, Plutonist, and catastrophist schools of landscape formation, by uniformitarianism (Hutton 1795), which was an element of Plutonism based largely on faunal succession and later embraced by Darwin, or more recently by geochemical and convection models, including plate tectonics. We suggest, however, that the former were broad speculations to explain observed rocks and landforms, and the latter, however important they may be in explaining the occurrence of continents, are applicable only to part of geology. This viewpoint agrees with Giere's (1988), that generalizations applied to all science are too broad to be useful, but differs with his preference for models (as opposed to exemplars) of narrow scope and applicable perhaps only to a portion of a science. Regardless of perspective, no present exemplar seems sufficiently broad to serve geology fully, but geologic studies, being strongly tied to time, continue to embrace doctrines of faunal succession, uniformitarianism, and evolution.

THE COMPOSITE SCIENCES

A composite science is an area of study with well-defined objectives and scope, but which requires data from and overlapping with two or more of the basic sciences. With geology, geomorphology, ecology, soil science, and hydrology are examples discussed here. By this definition, psychology, economics, and other social sciences are either questionable or excluded, but developmental interpretations proposed for geomorphology and ecology may apply to those disciplines as well.

Although exemplars in geomorphology have been suggested (e.g. Ritter 1988; Sack 1992; Rhoads and Thorn 1994), heterogeneity may preclude the emergence of exemplars from within composite science. Thus, Kuhn (1970) scarcely mentions composite sciences and does not refer to aggregated lines of scientific study. Instead, the Kuhn model is defined uniquely for the basic sciences and cannot be extrapolated easily to composites. Both in theory and practice, an inability to generate an applicable exemplar and to provide regulation of a science with it results in a vacuum. The void forces the science to improvise, to borrow, to plagarize exemplars and accompanying techniques to establish its identity as a science, and these borrowed exemplars inevitably conflict with parts of the science.

The following examples show similar progressions that started with exemplar-deficient observation. In each case, possibly excepting hydrology, this stage was succeeded by a period dominated by Darwinian evolution - the initial borrowed exemplar. In each case but at different times, evolution was either partly or mostly replaced with a time-independent exemplar of equilibrium, which in turn was moderated by integrationists attempting to merge the extremes. Although this progression partially mirrors change in the basic sciences, it has greater resolution because the basic sciences evolved through exemplar replacement consistent with the science, whereas imposition of exemplars on the composite sciences eventually resulted in incompatibilities.

Geomorphology

The establishment of geomorphology as a discipline distinct from geology, geography, or parts of engineering was relatively recent. A graph of geomorphology documents its emergence in the late nineteenth century (Vitek and Ritter 1989), and diagrams the labyrinth of topics comprising this complex science. Owing to this recency, domination by observationalists was short but observation has extended into succeeding periods. Most pre-Darwinian examples of geomorphic observationalists are best distinguished as geologists, geographers, or naturalists. Most notable, perhaps, was Alexander von Humboldt, a Prussian explorer of broad interests in geology, mineralogy, geophysics, climatology, and botany, who helped found physical geography and was a major stimulus for explorations of the American West (Pyne 1980). Among contemporaries of Darwin or those prominent shortly after was John Wesley Powell, who recognized structural control on stream courses, stating that folded structures tend to divert water around them. Powell, second director of the US Geological Survey (USGS), classified landforms and differentiated between valleys that trend perpendicular to the strike and those that trend parallel to rock layers. Based on Colorado River expeditions, Powell (1875) defined consequent, antecedent, and superimposed channels. Clarence Dutton, a companion of Powell, extended his ideas, such as the deduction that the leveling of the landscape is a product of river-bottom corrasion and slope weathering.

Another observationalist of the Darwinian period was Louis Agassiz, a dedicated follower of Humboldt (Pyne 1980). Agassiz was a Swiss zoologist and paleontologist -and later was an antievolutionist (McIntosh 1985), apparently threatened by the concept who, in 1837, proposed that 'a great ice period' had occurred prior to uplift of the Alps (Agassiz 1840). Agassiz came to the United States in 1846, was first in a series of renowned geomorphologists at Harvard University, gained international acceptance for glacial landscape development (Flint 1971), and (despite previous problems with chronologies) largely started in North America the subdisciplines of glacial and Quaternary geology and glacial geomorphology.

Kirk Bryan was among the last of the acclaimed geomorphic observationalists. Bryan replaced William Morris Davis at Harvard in 1926 and was mentor there to J.T. Hack. A field-oriented generalist who contributed important papers on channel changes, soil phenomena, erosion and sedimentation, alluvial chronology in the southwest United States, terraces, slope retreat, and gully gravure, Bryan never employed a specific doctrine or exemplar. He was supportive of an evolutionary approach to geomorphology, especially that of Walther Penck, but scorned emerging quantitative techniques (Higgins 1975).

Identity for geomorphology occurred with William Morris Davis. A disciple of Darwin, Davis (Figure 17.3) wrote papers, best expressed in 'The geographical cycle' (Davis 1899), that treated landforms as evolutionary, time-dependent landscape features. Essentials of Davis's geographical cycle of erosion are well-known, but are summarized as (1) initial uplift of an area or rock mass, (2) progressive wearing down of the rock mass by weathering and erosion through unequal stages of landscape youth, maturity, and old age,

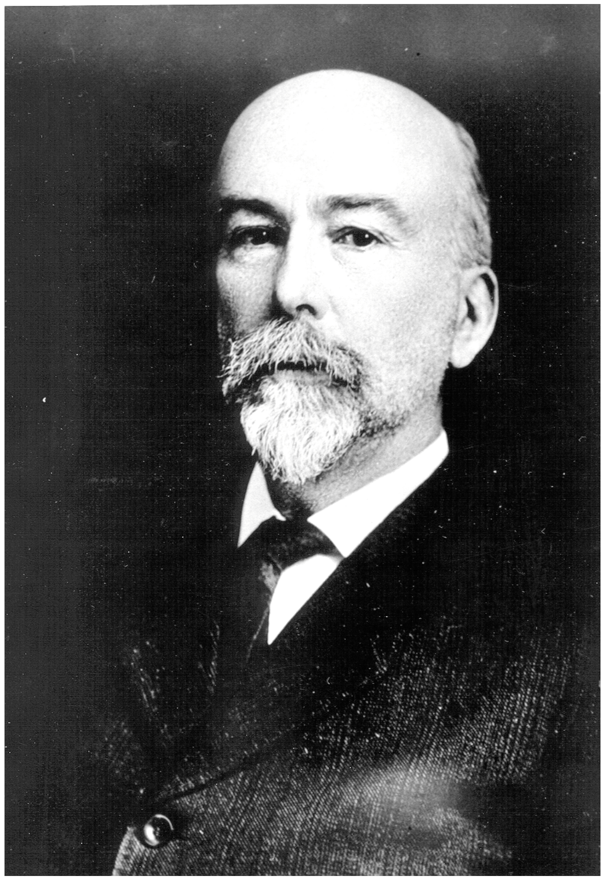

Figure 17.3 Portrait of William Morris Davis (from Photo Collection, US Geological Survey Library, Lakewood, Colorado)

and (3) an ultimate condition of landform reduction by erosion, yielding a peneplain of very gentle slope.

Davis patterned his model after Darwin's concept of evolution, and therefore subscribed to uniformitarianism. Writing of antecedent valleys (as previously defined by Powell) in the Appalachian Mountains, Davis (1883, p. 357) asserted that he 'tests the past by the present'. Time was mentioned repeatedly as the principal variable of landform genesis, and referrals to the 'origin of land-forms' and 'origin of cross valleys' intentionally followed Darwin's *Origins of Species*. With direct reference to organic evolution, Davis (1899, p. 485) wrote:

> The larva, the pupa, and the imago of an insect; or the acorn, the full-grown oak, and the fallen old trunk, are no more naturally associated as representing the different phases in the life-history of a single organic species, than are the young mountain block, the maturely carved mountain-peaks and valleys, and the old mountain peneplain, as representing the different

> stages in the life-history of a single geographic group. Like land-forms, the agencies that work upon them change their behaviour and their appearance with the passage of time.

Shortly following, Davis (1899, p. 485) wrote that the 'sequence in the developmental changes of land-forms is, in its own way, as systematic as the sequence of changes found in the more evident development of organic forms'. Earlier, Davis (1883, p. 325) had suggested that the 'many pre-existent streams in each (Appalachian) river-basin concentrated their water in a single channel of overflow, and that this one channel survives - a fine example of natural selection'.

Davis, an eloquent lecturer and writer, dominated geomorphology for a half century using Darwin's exemplar. He was responsible, for example, for establishment of the Association of American Geographers in 1904 (Chorley et al. 1973, p. 417). Through the mid-twentieth century, most geomorphologists practiced 'normal science' of Davis's cycle of erosion, but alternative viewpoints in a context of time-dependency were expressed by Walther Penck early in the century, and by Lester King in the 1950s and 1960s. Penck described *knickpunkte* and *piedmont treppen* within a system of noncyclic slope retreat and crustal movement. King modified Davis's concept of peneplain formation by suggesting that landscapes form through 'integration of pediments that are enlarged by headward recession of scarps' (Higgins 1975, p. 9).

Commenting on the appeal that Davis's system sustained during several generations of geomorphologists, Higgins (1975, pp. 12-14) listed features including simplicity, seeming applicability to prediction and interpretation, presentation, and rationality. Davis's application of organic evolution to the physical world was timely and enticing, and an evolutionary basis for geomorphic thought 'filled a void'. That void was the lack of a doctrine, an exemplar, explaining landform development conformably with uniformitarianism. Hence, the exemplar of organic evolution, following temporary rejection by some of the prior generation (e.g. Tarr 1898; Smith 1899), was readily applied to landscapes.

The enthusiastic adoption and prolonged popularity of the erosion cycle were gradually eroded by doubts of Davis's assumptions regarding structure, process, and especially time (Hack (1960, p. 87) sardonically added senility as a final stage of Davis's cycle). Analogously to basic science, data and observations ac 8(e)3(d popu)10.8(l)6(a)3(ri)6(ty)22.9(of)12.9(th)10.8(e eros)8.6(i)6(o)-

however, that the mood of the emerging discipline was insufficiently sophisticated to consider equilibrium concepts (e.g. Chorley et al. 1973, pp. 196-197; Higgins 1975, pp. 12-14; Ritter 1978, pp. 4-5; Pyne 1980, pp. 254-261).

Harbingers of exemplar shift were papers by Horton (1945), describing morphometric approaches to drainage basins, and Strahler (1950, 1952, 1954, 1957), who anticipated the application of equilibrium to landscapes through quantitative techniques. Robert Horton was, like Roger Bacon, insistent on the application of quantified data and mathematical techniques to investigate process; although a meticulous engineer steeped in equilibrium techniques, he was influenced by the popularity of the Davisian system. Arther Strahler stressed process and incorporation of mechanics, fluid dynamics, and quantitative techniques into geomorphic studies, although he too was inclined to blend the erosion cycle into an equilibrium format (e.g. Strahler 1954, p. 353). It was not until J.T. Hack (1960) revived Gilbert's concepts of geomorphic equilibria (himself initially unaware of this proposal nearly a century earlier) that doubts of the Davisian system presented a suitable climate for exemplar replacement. Although Hack's paper was the catalyst, change occurred more through a consensus of uneasiness than by a startling new idea. An imposed exemplar replaced an imposed exemplar, a result being, in the 1960s and 1970s, attention to equilibrium-related topics such as allometry, topology, and a variety of statistical techniques.

John Hack completed his doctorate at Harvard under Kirk Bryan in 1940. After two years of teaching, he joined the USGS and served with its Military Geology Unit. Following World War 11, Hack began pursuing research interests along the Maryland coastal plain and in the Appalachian Ridge and Valley Province where Davis had developed many of his ideas. Hack joined a group of scientists working in the Shenandoah Valley; others were C.C. Nikiforoff, C.B. Hunt, and Harvard graduate-student friends M.G. Wolman, C.S. Denny, J.C. Goodlett (Figure 17.4), and L.B. Leopold. Hunt, Wolman, Denny, and Leopold were geomorphologists/hydrologists, whereas Nikiforoff was a Russian refugee soil scientist (Figure 17.5) and Goodlett a plant ecologist. Members of this unique band of equilibrists interacted, reinforcing equilibrium concepts expressed in numerous papers on geomorphology, ecology, pedology, and hydrology (Osterkamp 1989).

Among Hack's products were reports on longitudinal stream profiles (Hack 1957), entrenched meanders (Hack and Young 1959), and the geomorphology and plant ecology of an Appalachian watershed (Hack and Goodlett 1960). These studies revealed conflicts with erosion-cycle concepts and led to 'Interpretation of erosional topography in humid temperate regions' (Hack 1960), which explicitly offered time-independent equilibrium as an alternative to the Davisian system. Although detractors such as J. Hoover Mackin were antagonistic, acceptance occurred rapidly, and it became fashionable to be critical of Davis.

Dominance of equilibrium was short because many geomorphologists realized the futility of discarding time. Thus, integrationists - those trying to reconcile systems of evolution and equilibrium - soon offered explanations of compatibility, that a system is applicable depending on scales of space and time. Richard Chorley (1962), although preferring open-system dynamic equilibrium, concisely analyzed differences between the systems and benefits of each. Schumm and Lichty (1965) presented objective-dependent guidelines for applying the conceptual models to landscapes. Efforts to reconcile the polar

Figure 17.4 Photograph of mid-twentieth-century equilibrists J.T. Hack (geomorphology) on the left and J.C. Goodlett (plant ecology), in the Little River Basin, Virginia, 1955 (courtesy of Clare Hack)

extremes of geomorphic systems have yielded recently to models of integration including geomorphic thresholds (e.g. Schumm 1973, 1979), complex response (Schumm 1973), nonlinear dynamics (Middleton 1990), and renewed recognition of a systems approach (Ritter 1978).

Ecology

The term ecology, and its goal of relating organisms and environment, generally are attributed to German zoologist Ernst Haeckel (1866), who later tied the concept firmly to evolution by stating that 'ecology is the study of all complex interrelations referred to by Darwin as the conditions of the struggle for existence' (Allee et al. 1949). The first significant practice of ecology, however, may be attributable to Humboldt's pre-Darwinist studies in South America (Gendron 1961).

Created as normal science to validate the exemplar of evolution, ecology experienced a short period of unbiased yet poorly directed observation. Plant communities were assumed static, and vegetation of large areas was described simply by compiling species lists (Joyce 1993) or by assuming simple relations between vegetation and climate (Merriam 1894). In a discussion of the origins of ecology, McIntosh (1985) suggests polymorphic to describe ecology, and notes that prior to about 1910, ecologists were criticized for being too

Figure 17.5 Photograph of mid-twentieth-century equilibrists C.C. Nikiforoff (soil science), on the left and J.T. Hack, Christmas 1954 (courtesy of Clare Hack). Figures 17.4 and 17.5 signify the interdisciplinary interactions that have contributed to the imposition of exemplars by the composite sciences

concerned with observation and description. One culprit was W.M. Spalding (1903, p. 207), who maintained that ecologists should '... ascertain and record fully, definitely, perfectly and for all time facts'. Process or interpretation were not objectives.

The temporal aspect of evolution was introduced into ecology by Darwinists Henry Cowles, Frederick Clements, and Victor Shelford. They rejected the compilation of species lists but instead emphasized species change through time (Allen and Hoekstra 1992). Cowles studied geology and botany at the University of Chicago, where he took his doctorate in 1898 and taught. Earlier Cowles had been a student of Davis at Harvard (H.M. Raup, oral presentation, Rutgers University, 1972). In 1895 Cowles worked with the USGS and may have interacted with Davis, who conducted USGS field studies then in the New England area. As student and professor in Chicago, Cowles, who was influenced strongly by Davis's teaching and writing, worked with distributions of xeric vegetation on the sand-dune and beach deposits bordering the south shore of Lake Michigan (Cowles 1899), and applied the erosion model to vegetation patterns of the sandy shorelines. As a direct impetus 'from the contemporary studies of the cycle of erosion by the physiographer, William Morris Davis' (Raup 1952, p. 306), Cowles identified *successions* of plants relative to distance from the lake edge and the time required, following *disturbance,* for shoreline retreat to have progressed that distance. The oldest, most distant stand was dominated by beech and maple trees, termed the climax community (Colinvaux 1973). The ecology of Cowles, therefore, was fully parallel to the cycle-of-erosion model and direct analogies are evident between initial uplift and disturbance, stage of erosion and succession (the assumed sequence by which plant communities change in an orderly progression through time), and peneplain and climax community. As did the Darwinian and Davisian systems, succession relied on deduction and minimized process (Mayr 1982). Presumably, 'succession', as used in ecology, was derived directly from William Smith's 'faunal succession', as applied to the fossil record over 100 years earlier.

Frederick Clements (Figure 17.6) grew up on the prairie and attended the University of Nebraska. Clements's observations of prairie plants, and changes he saw in their distributions following disturbance by frontier wagon traffic and land development, made him responsive to Cowles's shoreline observations. Clements (1928, p. 3) viewed plants as members of a highly organized community, or *complex organism* that 'arises, grows, matures, and dies . . .'; environment was given little attention. With the persuasiveness of Davis, Clements promoted Cowles's concepts of succession, and thereby imposed the exemplar of evolution on plant ecology. Clements (1916) expanded the concept of the climax community, applying it globally to *formations,* plant communities controlled by climate but exhibiting a range of seral stages of various primary successions, all subject to eventual areal climax or formation. In this manner, Clements developed classes of global formations. Whether 'formation', which was applied to plant communities of Midwestern landscapes in the 1890s (Allen and Hoekstra 1992), was extracted from similar usage in earth science is unclear.

Victor Shelford was an animal ecologist and a student/colleague of Cowles who also worked on the Lake Michigan sand dunes; predictability, and conforming to a normalscience effort to ratify an ecological use of evolution, he claimed animal succession in parallel to Cowles's observations for plants (Colinvaux 1973). Shelford worked closely with Clements, adopted his system, including convergence toward a regional climax, and collaborated on 'bio-ecology' (Clements and Shelford 1939), a combining of animal and plant ecology (McIntosh 1985).

Succession remains dominant in plant ecology owing to obvious changes in species composition that occur after disturbance and because of the same simplicity and applicability (H.M. Raup, oral presentation, Rutgers University, 1972) noted by Higgins (1975) for the Davisian system. The lack of recognized process, however, soon exposed the Clementsian system to criticism and the potential for an exemplar shift. Partial replacement during the 1920s was effected by L.G. Ramensky, in Russia, and by H.A. Gleason in Illinois. As Strahler had favored quantitative approaches to geomorphology, Ramensky and Gleason advocated techniques, largely environment-dependent rather than time-dependent, that required detailed measurements. Instead of using Clements's community concept, Ramensky and Gleason emphasized survival of individual plants, maintaining

Figure 17.6 Portrait of Frederick Clements (from Desert Laboratory, Tucson, Arizona)

that the collection of individuals in an area is a consequence of similar conditions of dispersal and environmental requirements. Moreover, Gleason stressed vegetative change as a function of environmental change along a continuous gradient (McIntosh 1975, 1983; Allen and Hoekstra 1992). Ramensky (1924), quoted by McIntosh (1983, p. 8), anticipated conversion by ecologists toward a structure founded on process and equilibrium when he wrote that ecology's future lies 'in deeper analysis of relations, acting factors and equilibrium mechanisms'.

As did Ramensky and Gleason, equilibrists William Cooper, Hugh Raup, and Robert Sigafoos recognized that climax forests are theoretical and cannot be documented. They dismissed succession, maintaining that plant associations depend strictly on migration and environmental selection. Although a student and advocate of Cowles, Cooper envisioned a mosaic of vegetation patches (McIntosh 1985), in which a 'forest as a whole remains the same, the changes in various parts balancing each other' (Cooper 1913, p. 43). Cooper too used landform as a parallel to ecologic change by cogently comparing long-term vegetation development to stream braiding (Allen and Hoekstra 1992). Raup, professor and director of the Harvard Forest, 1946 to 1967, and Sigafoos, USGS, were advisors to Hack and Goodlett, and Sigafoos and Goodlett were students of Raup and Bryan at Harvard. During a career in which he strongly questioned the steady-state ideal of succession to a climax forest, Raup (1941) preferred vegetative adjustment toward dynamic equilibrium.

Reflecting Raup's disdain of Clementsian ecology and his attention to process, Robert Sigafoos was first to detail interactions among vegetative development, flood damage, and floodplain dynamics. Sigafoos (1964) demonstrated widespread disturbance to bottomland vegetation by floods and thereby -emphasized dynamic equilibrium and change on temporal scales too short to result in climax. The British animal ecologist, Charles Elton, also disregarded Darwinian concepts of adaptation and evolution, preferring process, group dynamics, and equilibria of the food chain and the food cycle -'the sociology and economics of animals' (Elton 1927, p. vii).

Equilibrist J.C. Goodlett (Figure 17.4) studied relations of vegetation to landforms and the processes that develop landforms. Goodlett (1969, p. 35) stated that 'plant cover is a part of the open system that constitutes the landscape, and the vegetation is in a state of continuous adjustment with its environment'. Commenting on landform change and its effect on vegetation, Goodlett (1969, p. 38) extended concepts of Gleason by suggesting that 'the plant cover must adjust to these modifications, or pass on. Geomorphic processes, that act to mould the landscape, take place on, in, or through the plant cover. The plants adjust to the environmental variations produced by the geomorphic processes, and in turn they affect the processes and their products.' Thus, Goodlett (1969) subscribed strongly to equilibrium, stressing that geomorphology and biology cannot be separated, and that the individualistic concept of plant ecology is similar to dynamic equilibrium of geomorphology. The Ramensky/Gleason/Goodlett model was a process-oriented, time-independent, open-system approach based on interplay between vegetation and environmental factors responsible for its composition. The equilibrium, or individualistic, concept of ecology addresses present processes to explain features, without need for final, ideal condition (Hupp 1984).

Integrationists in ecology overlapped with equilibrists. For this discussion, integrationists are those who proposed complete, interacting systems in biology, and those who provided guidance by identifying trends within ecology. Representatives of the former group are Forrest Shreve and E.P. Odum. The latter group includes Ramon Margalef, who published *Perspectives in Ecological Theory* (1968), and Robert McIntosh, whose historical works on ecology culminated with *The Background of Ecology* (1985). For rangeland ecology, E.J. Dyksterhuis (1949) modified Clementsian succession by noting that grazing influences rangeland succession in a predictable and quantitative manner.

Forrest Shreve, at the Carnegie Institution's Desert Laboratory on Turnamoc Hill, Tucson, from 1907 into 1940 (Bowers 1988), was a colleague of Clements. Clements spent winters of 1917 through 1924 at the laboratory, when incompatibility may have led to Shreve's rejection of portions of Clementsian doctrine, especially as applied to deserts (Bowers 1988). Shreve (1936, p. 213) wanted 'to weave together the separate threads of knowledge about the plants and their natural setting into a close fabric of understanding in which it will be possible to see the whole pattern and design of desert life'. Reflecting Ramnesky and Elton, Shreve (1936, p. 213) remarked that the 'distribution of a plant species reflects its tolerance for a range of environmental conditions, thus few if any species have identical distributions; trends in establishment and mortality in plant populations tell much about the conditions necessary for growth; changes in climate and vegetation along an environmental gradient reveal the conditions that limit a plant's distribution'. In earlier work, Shreve (1919) suggested dispersal processes to account for species populations in isolated mountains, a paper that inspired integrationist models of nonequilibrium insular biogeography (e.g. Brown 1978).

Like Shreve, E.P. Odum had a holistic perspective conflicting with the more publicized ideas of Clements. Ironically, *holism* was coined by philosopher/statesman, J.C. Smuts, who credited Clements for the idea (Colinvaux 1973). Odum (1953, 1969) developed the concept of *ecosystem,* an open-system ecological approach (similar to Hack's for landscapes) for fluxes of matter and energy (McIntosh 1985). As Chorley (1962) later did for geomorphology, Bertalanffy (1951) united thought in biology and ecology by applying systems theory.

Soil Science

The history of soil studies has differed from that of geomorphology owing to agricultural and economic considerations. The study of a natural resource, the science of soil processes treats the formation, properties, classification, and mapping of soils. An observationalist period that began by the late nineteenth century was largely one of noting characteristics to classify and map soils. The first widely recognized attempts, by V.V. Dolcuchaev (1879) and other Russian soil scientists, were based on climate and vegetation (Nikiforoff 1949), criteria still used worldwide in soil classification. Refinements were added by K.D. Glinka in Russia, Emil Ramann in Germany, and C.F. Marbut, M. Baldwin, and James Thorp and G.D. Smith, United States. Marbut's (1928) scheme was nearly restricted to mature soil and did not consider process. Baldwin et al. (1938) added detail and nomenclature to the Marbut system, but made little attempt to account for soil differences. Thorp and Smith (1949) added complexity to prior classifications by subdividing into Great Soil Groups. These classifications were largely based on genetic factors of climate and vegetation; not until 1960 was a nongenetic system devised in the United States, by the Soil Conservation Service, founded on quantitative physical and chemical criteria (Ritter 1978).

Soil studies, applied and stressing resource management, belatedly evolved to soil science or pedology. Although weathering and soil chemistry were investigated in Europe in the 1930s, imposition of an exemplar occurred later than for other composite sciences, and when it did, evolution and equilibrium appeared nearly simultaneously. Hans Jenny (Figure 17.7), the first noteworthy Darwinian of pedology, applied evolution to soil development in a seminal treatise on soil formation. With his 'fundamental equation of soil-forming factors', Jenny (1941, p. 16) proposed that soils (S) and soil properties (s) are results of climate (cl), biota (o), topography (r), parent material (p), and time (t):

$$S, s = f(cl, o, r, p, t \ldots.) \qquad (3)$$

For constant climate, organisms, parent material, and topography, Jenny (1941, pp. 31, 49) asserted that the soil profile is 'solely a function of time':

$$S = f(\text{time})_{cl,o,r,p...} \qquad (4)$$

Figure 17.7 Photograph of Hans Jenny (courtesy of P.W. Birkeland)

Equation (4) implies orderly soil changes through time, dependent on other independent variables (Jenny 1941, 1980); hence, the system is directly analogous to Davis's erosion cycle, Clementsian succession, and Darwinian evolution (Figure 17.8). Jenny's work led to concepts of chronosequences and chronofimctions of soils (Birkeland 1990), and referred specifically to soil evolution due to influxes of heat, rainfall, and light. End members of chronosequences suggested by Jenny were soils of iron and aluminiurn oxides and hydroxides, equivalent to a peneplain of Davis or climax forest of Clements.

Pedologist C.C. Nikiforoff (Figure 17.5) emigrated to the United States from Russia following World War I and joined the Soil Survey. From ideas developed earlier, and recognizing but disagreeing with Jenny's (1941) equation, Nikiforoff (1942) published 'Fundamental formula of soil formation', which, analogous to earlier work of Odum, viewed soil processes as fluxes of matter and energy. As Gilbert's equilibrium was overlooked for the Davisian system, Nikiforoffs (1942) paper attracted scant attention owing to the immediate popularity of Jenny's Darwinian model. Nikiforoffs work may never have gained recognition had not John Hack used the approach to develop his own

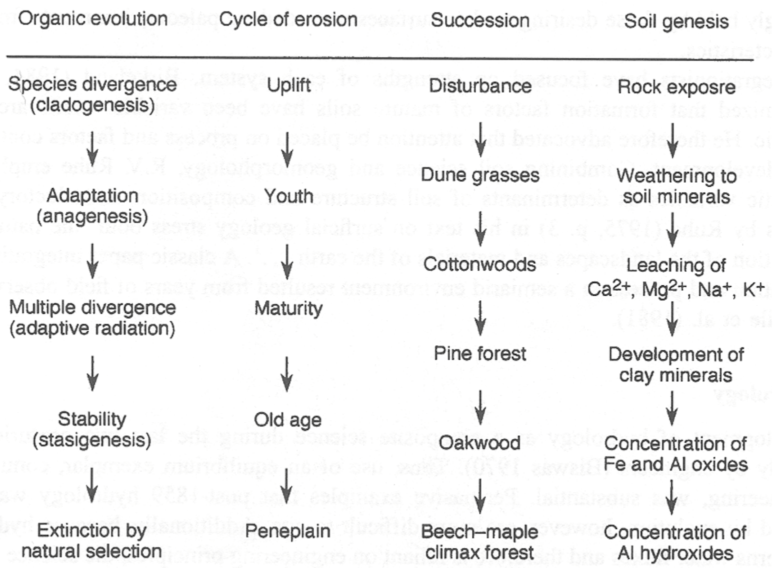

Figure 17.8 Diagram comparing generalized organic evolution with evolutionary systems imposed on geomorphology (cycle of erosion), plant ecology (succession), and pedology (soil genesis)

model of landscape dynamics. Because equilibrium, applied to pedology and other composite sciences, considers fluxes, progressive change is not emphasized and a flow diagram analogous to that for evolution (Figure 17.8) is impracticable.

Nikiforoff (1942, p. 847) maintained that if 'nothing is synthesized in the soil which does not decompose and nothing decomposes which is not synthesized', neither accumulation nor depletion of soil components can continue 'without coming to a certain equilibrium between the losses and gains'. A limiting expression for balance was derived as

$$S_n = A/r \qquad (5)$$

in which S_n is the amount of soil substance after n years, when equilibrium has been attained, A is the mass, assumed constant, that is synthesized each year, and r is the annual rate of mass lost by decomposition. Thus, dynamic equilibrium is achieved after n years, when soil processes may still be intense but do not alter features of the profile.

Nikiforoff's thesis, tentatively accepted, exposed an elemental difficulty in applying evolution to Earth science. That difficulty was the assumption that a soil or landscape can be stable long enough to yield an excessively thick soil of oxides and hydroxides underlying a peneplain and climax forest. If stability could persist, the earth '. . . would be wrapped in a *lifeless mantle thoroughly deprived of the unstable minerals, composed entirely of those most resistant to any further changes, and, hence, essentially static'* (Nikiforoff 1949, p. 222). Recent pedologists have acknowledged this difficulty, but a consensus continues that even where geology and climate are constant, the effects of denudation necessitate consideration of time (e.g. Birkeland 1990). This view is especially strongly held by those desiring to date surfaces or to deduce paleoenvironments from soil characteristics.

Integrationists have focused on strengths of each system. Birkeland (1984, 1990) recognized that formation factors of mature soils have been variable - soils are polygenetic. He therefore advocated that attention be placed on process and factors controlling soil development. Combining soil science and geomorphology, R.V. Ruhe emphasized climatic variables as determinants of soil structure and composition. Introductory comments by Ruhe (1975, p. 3) in his text on surficial geology stress both 'the nature and evolution of the landscapes and materials of the earth . . .'. A classic paper integrating soil evolution and process in a semiarid environment resulted from years of field observations by Gile et al. (1981).

Hydrology

Development of hydrology as a composite science during the last two centuries was largely by engineers (Biswas 1970). Thus, use of an equilibrium exemplar, common to engineering, was substantial. Persuasive examples that post-1859 hydrology was controlled by evolution, however, are more difficult to cite. Additionally, because hydrology concerns water fluxes and therefore is reliant on engineering principles, the science is only weakly susceptible to a controlling creed. Trends have been apparent in the development of hydrology, however, especially because of interactions and overlap with geomorphology, ecology, pedology, and basic science.

Observationalism in hydrology began with the start of modern science in the seventeenth century; an example was French lawyer Pierre Perrault who, about 1670, suggested that rainfall in the upper Seine River basin could account for runoff in the river (Biswas 1970). French physicist Edme Mariotte confirmed Perrault's observation by measuring flows in the Seine River, and accordingly was a founder of hydrology (Todd 1967). O.E. Meinzer (1923) was late among observationalists in hydrology, recognizing geology as an important control of groundwater recharge and discharge: Meinzer was responsible for defining groundwater study as a major component of the USGS program.

As previously noted, John Wesley Powell initially was a geomorphic observationalist. He clearly showed evolutionary thinking in surface-water hydrology and erosion, however, when writing of his explorations of the Colorado River (1875) and the Unita Mountains (1876). His concept of denudation to base level anticipated the Davisian system, and his recognition that all mountains are reduced by streamflow became fundamental to the cycle of erosion (Chorley et al. 1973). Robert Horton, the scientist and engineer who insisted on quantification, published 'Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology' (1945), a benchmark Davisian treatment of drainage evolution using quantitative approaches.

Equilibrium approaches are basic to hydrology, especially water-balance studies. A particular advance in hydrologic equilibrium, however, was 'The hydraulic geometry of stream channels and some physiographic implications', by L.B. Leopold and Thomas Maddock, Jr (1953) who extended hydraulic-geometry relations from engineering regime theory (Kennedy 1895; Lacey 1930) and the graded-stream concept (Mackin 1948). Discussing hydraulic adjustments, Leopold and Maddock (1953, p. 51) stated that a '.. . particular rate of increase of both velocity and depth downstream is necessary for maintenance of approximate equilibrium in a channel . . .'. Within groundwater hydrology, C.V. Theis, from the University of Cincinnati, was recruited to the USGS by Meinzer. Theis (1935) proposed the 'nonequilibrium' equation, a watershed advance in groundwater theory based on equilibrium and assumptions of infinite areal extent and homogeneity of aquifers.

Hydrologic integrationists are regarded here as those combining attention on processes with rates at which processes change owing to external inputs of climate, biotic alteration, or land disturbance. Among recent integrationists, Walter Langbein and M.G. Wolman recognized effects that short-term climate change and land-use change have on streamflow, channel morphology, and sediment discharge.

Social Science

Social sciences, including economics, are not composites as defined. Their histories, however, also show forcing of concepts, exemplars of 'cultural equilibrium', from basic science (Schumpeter 1934, p. xi). For example, response to evolution, following speculations of Adam Smith, David Ricardo, and John Stuart Mill, was shown within economics by Karl Marx. If not an evolutionist, Marx reflected late-1800s Darwinism by writing of temporal factors in profits, social impoverishment, and business-cycle trends. Herbert Spencer, a British philosopher and biologist who was repeatedly cited by Clements and was the probable source of his 'complex organism' (Worster 1977), espoused 'social Darwinism', the suggestion that elite classes of wealth and power possess biological superiority and thus attain superior socioeconomic position. Combining evolution with Greek tradition regarding nature as an organism, French geologist/cleric Pierre Teilhard de Chardin (1959) compared the ontogeny of human society to species whose evolutionary histories necessarily direct their destinies.

Anticipating economic 'marginalists', Alfred Marshall applied 'partial equilibrium analysis' to the balance between supply and demand. F.H. Knight, an unabashed equilibrist, was among those proposing economic analogs to mass, inertia, momentum, force, and space, thereby applying Newtonian laws of motion to economic dynamics; he asserted that the 'root idea in economic statics is clearly the notion of *equilibrium,* and hence of forces in equilibrium' (Knight 1935, p. 162). P.A. Samuelson noted that economists, Marx and Marshall as examples, have applied biological and physical concepts to economic study in which evolution and organic growth is used as the antithesis to statical equilibrium analysis' (Samuelson 1961, pp. 311-312). Although Samuelson failed to appreciate the extent to which evolution and equilibrium affected the social sciences, he seemed to recognize that exemplars of another discipline could not be imposed successfully when he mused that results had been hazy and disappointing.

Early this century, unilinear sequences of social stage - evolutionary sociology - yielded to universal patterns of equilibrium and associated periods of disequilibrium. Integrationist John Maynard Keynes analyzed determinants of effective demand and levels of national income and employment rather than corporate equilibrium or allocation of resources. Thus, Keynes de-emphasized business equilibria and time. Although the enjoining of evolution, equilibrium, and integration on the social sciences cannot be documented as forcefully as for composite science, writings of leaders from Marx through the present clearly show similar and vigorous impacts by borrowed and probably inappropriate exemplars.

CONCLUSIONS

In this discussion, extending ideas of Thomas, Kuhn, we propose that composite sciences have matured much differently than basic sciences. A principal reason for differences in development is that basic sciences are defined by exemplars (Kuhn 1970), whereas composite sciences are too complex to be defined by an exemplar and, lacking exemplar superstructures, normal science is undirected. The necessary and partly beneficial result is the imposition of exemplars that may rule effectively but are ill-suited and hence fail to define. Because imposed exemplars cannot guide the conduct of composite science appropriately, their acceptance may lead to doctrine if not dogma.

This thesis, with supporting examples, are interpretations (for a similar premise, see Stoddart 1986, Chapters 8 and 11), but regardless of how the composite sciences have grown, their periods of growth may be better identified by style or fad than as functions of scientific discovery. Styles of normal composite science proposed here are Darwinian evolution followed by equilibrium theory. The former was preceded by observation and the latter was followed by attempts to combine the extremes. This pattern of exemplar imposition on the composite sciences seems less similar to the use of definitive exemplars by the basic sciences than it does to styles in the arts (i.e. the baroque, classical, romantic, and impressionist periods). As the romantic period differed in time and duration for each art form, the period and duration of dominance by evolution differed within each composite science. Furthermore, the time scales of models depicted in Figure 17.8 differ, ranging from centuries for succession to millions of years for peneplanation.

If borrowed exemplars guided composite science, a secondary factor was personal interactions. As Mozart was influenced by Haydn, and Monet by contemporaries of French impressionism, style lineage has been apparent in composite science. Examples are close relationships that Nikiforoff, Hack, Leopold, and others enjoyed in the Shenandoah Valley, and contacts among Cowles, Clements, Shelford, Davis, and, in an opposite manner, Shreve. Linear influences in the USGS seem apparent for Humboldt, Powell, Dutton, Gilbert, Meinzer, Bryan, Theis, Hack, Sigafoos, and possibly even Davis and Cowles, and similarly with students and faculty at Harvard as represented by Agassiz, Davis, Cowles, Bryan, Hack, Leopold, Raup, Sigafoos, and Goodlett. During formative years of the natural sciences in the British Isles, Darwin was influenced by Hutton, who enriched ideas of Smith. Although effects of personal interactions within basic science are also obvious, they may be less pronounced when exemplar replacement helps direct the science instead of the science embracing an attractive exemplar.

The choice of evolution as an exemplar by composite scientists may have been hasty. Figure 17.8 represents models as parallel flow diagrams, but actual parallels between evolution and its use in geomorphology, ecology, and soil science are questionable. Of the models diagrammed, evolution starts with variability, but variability develops through time in the others. Extinction is not the culmination of evolution as is peneplanation or climax communities for erosion and succession. Extinction occurs at any stage of evolution, and some species persist indefinitely. Whereas evolution is linear, erosion, succession, and soil genesis are cyclic. As these discrepancies between evolution and its use in the composite sciences became apparent, the need for exemplar replacement became imperative. More as integrationist than equilibrist, these thoughts were expressed succinctly but differently by Raup (1964, p. 26):

> The geologists had their peneplain; the ecologists visualized a self-perpetuating climax; the soil scientists proposed a thoroughly mature soil profile, which eventually would lose all trace of its geological origin and become a sort of balanced organism in itself It seems to me that social Darwinism, and the entirely competitive models that were constructed for society by the economists of the nineteenth century, were all based upon a slow development towards some kind of social equilibrium. I believe there is evidence in all of these fields that the systems are open, not closed, and that probably there is no consistent trend towards balance. Rather, in the present state of our knowledge and ability to rationalize, we should think in terms of massive uncertainty, flexibility, and adjustment.

The composite sciences continue to integrate disparate points of view. Recently the maturing process has narrowed with normal-science studies of limited scope and scale, examples being the use of fluvial dynamics to analyze river-channel islands, use of cosmogenic radioisotopes to estimate denudation rates, or documentation of numerically small occurrences of adult plants suggestive of specific ecological conditions. Conversely, an ultimate goal of any science is a sweeping exemplar, or symbolic *generalization* (Kuhn 1977, p. 297), of unified theory. If the cosmology of Copernicus and Kepler or relativity of Einstein in particle (nonquantum) physics represent unifying theory, another cycle of exemplar replacement may not be feasible, and normal-science decline may be assured. Essential problems of planetary motion have long been solved, and already many look back at the *Golden Age of Physics.*

Owing to complexity and inability of composite sciences to be defined by exemplars, unifying principles may not be possible. Holism as an ideal provides a goal, but does not present explanation. The Gaia hypothesis (Lovelock 1965) is a holistic suggestion that the dynamics of physical and biological processes on Earth are integrated and function as one evolving system (Margulis 1993). A full-circle journey from early Greek speculation, holism, as represented by the Gaia hypothesis, does seem to have application to composite science. A unifying theory may be unattainable, but future goals of composite science, being broadly scoped, may emphasize complete integration of physical and biotic processes at various scales of time and space.

Attention to integrated process studies at decadal and watershed scales increases with environmental concern. New exemplars, original or imposed, seem unlikely to direct further conduct of the composite sciences. It seems, however, that small-scale studies of integrated process, driven by borrowed exemplars of limited application, must yield to global perspectives. A unified theory may be an unrealistic objective, but a unified perspective seems desirable.

REFERENCES

Agassiz, L. 1840. *Études sur les glaciers:* Neuchâtel, privately published, 346 pp.

Allee, W.C., Emerson, A.E., Park, 0., Park, T. and Schmidt, K.P. 1949. *Principles of Animal Ecology,* Saunders, Philadelphia, 837 pp.

Allen, T.F.H. and Hoekstra, T.W 1992. *Toward a Unified Ecology,* Columbia University Press, New York, 384 pp.

Baldwin, M., Kellogg, C.E. and Thorp, J. 1938. Soil classification, in *Soils and Men,* US Department of Agriculture Yearbook, pp. 979-1001.

Betalanfly, L. von 1951. General systems theory: a new approach to unity of science, in *Problems of General Systems Theory,* Symposium of the American Philosophical Society, Toronto, 1950, pp. 302-311.

Birkeland, PW 1984. *Soils and Geomorphology,* Oxford University Press, New York, 372 pp.

Birkeland, P.W. 1990. Soil-geomorphic research - a selective overview, *Geomorphology*, **3**, 207-224

Biswas, A.K. 1970. *History of Hydrology,* North-Holland, Amsterdam, 336 pp.

Bowers, J.E. 1988. *A Sense of Place - the Life and Work of Forrest Shreve,* The University of Arizona Press, Tucson, 195 pp.

Bowler, P.J. 1984. *Evolution - the History of an Idea,* University of California Press, Berkeley, 412 pp

Bowler, P.J. 1992. *The Fontana History of the Environmental Sciences,* Fontana Press, London, 634 PP.

Brown, J.H. 1978. The theory of island biogeography and the distribution of boreal birds and mammals, *Great Basin Naturalist Memoirs*, **2,** 209-227.

Chorley, R.J. 1962. Geomorphology and general systems theory, *US Geological Survey Professional Paper 500-B,* 10 pp.

Chorley, R.J., Beckinsale, R.P. and Dunn, A.J. 1973. *The History of the Study of Landforms or the Development of Geomorphology - Vol.* 2: *The Life and Work of William Morris Davis,* Methuen, London, 874 pp.

Clements, R.E. 1916. *Plant Succession - an Analysis of the Development of Vegetation,* Carnegie Institution of Washington Publication No. 242, Washington, DC.

Clements, F.E. 1928. *Plant Succession and Indicators,* H.W. Wilson, Washington, D.C.

Clements, R.E. and Shelford, V.E. 1939. *Bio-ecology,* Wiley, New York, 425 pp.

Colinvaux, P.A. 1973. *Introduction to Ecology,* Wiley, New York, 621 pp.

Cooper, W.S. 1913. The climax forest of Isle Royale, Lake Superior, and its development, *Botanical Gazette,* **55**, 1-44, 115-140, 189-235.

Cowles, H.C. 1899. The ecological relations of the vegetation of the sand dunes of Lake Michigan, *Botanical Gazette,* **27**, 95-117, 167-202, 281-308, 361-391.

Darwin, C.R. 1859. *The Origin of Species by Means of Natural Selection; or, the Preservation of Favored Races in the Struggle for Life,* John Murray, London, 502 pp.

Davis, W.M. 1883. Origin of cross valleys, *Science,* **1**, 325-327, 356-357.

Davis, W.M. 1899. The geographical cycle, *Geographical Journal,* **14,** 481-504.

Dokuchaev, V.V. 1879. Abridged historical account and critical examination of the principal soil classifications existing, *Transactions, Saint Peterburg Society of Nature,* **10**, 64-67 (in Russian).

Dyksterhuis, E.J. 1949. Conditions and management of range land based on quantitative ecology, *Journal of Range Management,* **2**, 104-115.

Elton, Charles 1927. *Animal Ecology,* Macmillan, New York, 207 pp.

Flint, R.F. 1971. *Glacial and Quaternary Geology,* Wiley, New York, 892 pp.

Frodeman, R. 1995. Geological reasoning: geology as an interpretive and historical science, *Geological Society of America Bulletin,* **107**, 960-968.

Gendron, V. 1961. *The Dragon Tree - a Life of Alexander, Baron von Humboldt,* Longmans, Green, New York, 214 pp.

Giere, R.N. 1988. *Explaining Science, a Cognitive Approach,* University of Chicago Press, Chicago, 321 pp.

Gilbert, G.K. 1877. Geology of the Henry Mountains (Utah), *US Geographical and Geological Survey of the Rocky Mountains Region,* US Government Printing Office, Washington, DC, 160 pp.

Gile, L.H., Hawley, J.W and Grossman, R.B. 1981. *Soils and Geomorphology in the Basin and Range Area of Southern New Mexico - Guidebook to the Desert Project,* New Mexico Bureau of Mines and Mineral Resources, Memoir 39, 222 pp.

Goodlett, J.C. 1969. Vegetation and the equilibrium concept of the landscape, in *Essays in Plant Geography and Ecology,* edited by K.N. Greenidge, Nova Scotia Museum, Halifax, pp. 33-44.
Hack, J.T. 1957. Studies of longitudinal stream profiles in Virginia and Maryland, *US Geological Survey Professional Paper 294-B,* pp. 45-97.
Hack, J.T. 1960. Interpretation of erosional topography in humid temperature regions, *American Journal of Science, Bradley Volume,* **258-A,** 80-97.
Hack, J.T. and Goodlett, J.C. 1960. Geomorphology and forest ecology of a mountain region in the central Appalachians*, US Geological Survey Professional Paper 347,* 66 pp.
Hack, J.T. and Young, R.S. 1959. Intrenched meanders of the North Fork of the Shenandoah River, Virginia, *US Geological Survey Professional Paper 354-A, 10 pp.*
Harvey, W. 1628. *De motu cordis et sanguinis in animalibus,* R. Willis (translator), 1848, London.
Haeckel, E. 1866. *Generelle Morphologie der Organismen: Allgemeine Grundzüge der organischen Formen-wissenschaft mechanisch begründet durch die von Charles Darwin reformirte Descendenz-Theorie,* 2 vols, Reimer, Berlin.
Haines-Young, R.H. and Petch, JR. 1986. *Physical Geography: Its Nature and Methods,* Harper & Row, London, 230 pp.
Higgins, C.G. 1975. Theories of landscape development - a perspective, in *Theories of Landscape Development,* edited by WN. Melhorn and R.C. Flemal, Publications in Geomorphology, State University of New York, Binghamton, NY, pp. 1-28.
Horton, R.E. 1945. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology, *Geological Society of America Bulletin,* **56,** 275-370.
Hupp, C.R. 1984. Forest ecology and fluvial geomorphic relations in the vicinity of the Strasburg Quadrangle, Virginia, Ph.D. dissertation, George Washington University, Washington, DC, 168 pp.
Hutton, J. 1795. *Theory of the Earth, with Proofs and Illustrations*, Vols 1 and 2, Edinburgh; Vol. 3, London, 1899.
Jenny, H. 1941. *Factors of Soil Formation,* McGraw-Hill, New York, 281 pp.
Jenny, H. 1980. *The Soil Resource - Origin and Behavior,* Springer-Verlag, New York, 377 pp.
Joyce, L.A. 1993. The life cycle of the range condition concept, *Journal of Range Management,* **46,** 132-138.
Kennedy, R.C. 1895. Prevention of silting in irrigation canals, *Institute of Civil Engineers Proceedings,* **119,** 281-290.
Kitts, D.B. 1977. *The Structure of Geology,* Southern Methodist University Press, Dallas, 180 pp.
Knight, F.H. 1935. *The Ethics of Competition,* Harper and Brothers, New York, 363 pp.
Kuhn, T. S. 1970. *The Structure of Scientific Revolutions,* 2nd edn, The University of Chicago Press, Chicago, 210 pp.
Kuhn, T.S. 1977. *The Essential Tension,* The University of Chicago Press, Chicago, 366 pp.
Lacy, G. 1930. Stable channels in alluvium, *Institute of Civil Engineers Proceedings,* **229***,* 259-384.
Leopold, L.B. and Maddock, T. Jr. 1953. The hydraulic geometry of stream channels and some physiographic implications, *US Geological Survey Professional Paper 252,* 57 pp.
Lovelock, J.E. 1965. A physical basis for life detection experiments, *Nature***, 207***,* 568-569.
McIntosh, R.P. 1975. H.A. Gleason, 'individualistic ecologist,' 1882-1975: his contributions to ecological theory, *Bulletin of the Torrey Botanical Club,* **102***,* 253-273.
McIntosh, R.P. 1983. Excerpts from the work of L.G. Ramensky, *Bulletin of the Ecological Society of America*, **64***,* 7-12.
McIntosh, R.P. 1985. *The Background of Ecology - Concept and Theory,* Cambridge University Press, Cambridge, 383 pp.
Mackin, J.H. 1948. Concept of the graded river, *Geological Society of America Bulletin*, **59***,* 463-512.
Marbut, C.F. 1928. A scheme for soil classification, *Proceedings and Papers of the First* International Congress *of Soil Science, Vol.* 4, pp. 1-3 1.
Margalef, R. 1968. *Perspectives in Ecological Theory,* University of Chicago Press, Chicago, 111 pp.
Margulis, L. 1993. Gaia and the colonization of Mars, *GSA Today*, **3,** 277-280, 291.
Mayr, E. 1982. *The Growth of Biological Thought,* The Belknap Press of Harvard University Press, Cambridge, Mass., 974 pp.

Meinzer, O.E. 1923. Outline of ground-water hydrology with definitions, *US Geological Survey Water-Supply Paper 494,* 71 pp.
Merriam, C.H. 1894. Laws of temperature control of the geographic distributions of terrestrial animals and plants, *National Geographic Magazine,* **6**, 229-238.
Middleton, G.V. 1990. Non-linear dynamics and chaos: potential applications in the earth sciences, *Geoscience Canada,* **17**, 3-11.
Nikiforoff, C.C. 1942. Fundamental formula of soil formation, *American Journal of Science,* **240**, 847-866.
Nikiforoff, C.C. 1949. Weathering and soil evolution, *Soil Science*, **67**, 219-230.
Odum, E.P. 1953. *Fundamentals of Ecology,* Saunders, Philadelphia, 546 pp.
Odum, E.P. 1969. The strategy of ecosystem development, *Science,* **164**, 262-270.
Olsen, C.R., Cutshall, N.H. and Larsen, I.L. 1982. Pollutant-particle associations and dynamics in coastal marine environments: a review, *Marine Chemistry,* **11**, 501-535.
Osterkamp, W.R. (compiler) 1989. A tribute to John T. Hack by his friends and colleagues, in *History of Geomorphology from James Hutton to John Hack,* edited by K. Tinkler, Allen & Unwin, Boston, pp. 283-291.
Powell, J.W. 1875. *Exploration of the Colorado River of the West (1869-72),* US Government Printing Office, Washington, DC, 400 pp.
Powell, J.W. 1876. *Report on the Ecology of the Eastern Portion of the Unita Mountains,* US Government Printing Office, Washington, DC, 218 pp.
Pyne, S.J. 1980. *Grove Karl Gilbert, a Great Engine of Research,* University of Texas Press, Austin, Texas, 306 pp.
Ramensky, L.G. 1924. Basic regularities of vegetation covers and their study, *Vẽstnik Opytnogo dêla Stredne-Chernoz. Ob., Voronezh,* 37-73 (in Russian).
Raup, H.M. 1941. Botanical problems in boreal America, *Botanical Review,* **7**, 147-248.
Raup, H.M. 1952. Review of Braun, E.L., Deciduous forests of eastern North America, *Ecology*, **33**, 304-307.
Raup, H.M. 1964. Some problems in ecological theory and their relation to conservation, *Journal of Ecology,* **52**, supplement, 19-28.
Rhoads, B.L. and Thorn, C.E. 1994. Contemporary philosophical perspectives on physical geography with emphasis on geomorphology, *Geographical Review,* **84**, 90-101.
Ritter, D.F. 1978. *Process Geomorphology,* William C. Brown, Dubuque, Iowa, 603 pp.
Ritter, D.F. 1988. Landscape analysis and the search for geomorphic unity, *Geological Society of America Bulletin,* **100**, 160-171.
Ruhe, R.V. 1975. *Geomorphology - Geomorphic Processes and Surficial Processes,* Houghton Mifflin, Boston, 246 pp.
Sack, D. 1992. New wine in old bottles: the historiography of a paradigm change, *Geomorphology,* **5**, 251-263.
Samuelson, P.A. 1961. *Foundations of Economic Analysis* (sixth printing), Harvard University Press, Cambridge, Mass., 447 pp.
Schumm, S.A. 1973. Geomorphic thresholds and complex response of drainage systems, in *Fluvial Geomorphology,* edited by M.E. Morisawa, Allen & Unwin, London, pp. 299-3 10.
Schumm, S.A. 1979. Geomorphic thresholds: the concept and its applications, *Transactions, Institute of British Geographers,* **4**, 485-515.
Schumm, S.A. 1991. *To Interpret the Earth: Ten Ways to be Wrong,* Cambridge University Press, Cambridge, 133 pp.
Schumm, S.A. and Lichty, R.W. 1965. Time, space, and causality in geomorphology, *American Journal of Science,* **263**, 110-119.
Schumpeter, J.A. 1934. *The Theory of Economic Development,* Harvard University Press, Cambridge, Mass., 255 pp.
Shreve, F.S. 1919. A comparison of the vegetational features of two desert mountain ranges, *Plant World,* **22**, 291-307.
Shreve, F.S. 1936. Plant life of the Sonoran Desert, *Scientific Monthly,* **42**, 213.
Sigafoos, R.S. 1964. Botanical evidence of floods and flood-plain deposition, *US Geological Survey Professional Paper 485-A,* 35 pp.

Smith, W.S.T 1899. Some aspects of erosion in relation to the theory of peneplains, University of California Publications, Bulletin *of* the Department *of* Geology, **2**, 155-178.
Spalding, V.M. 1903. The rise and progress of ecology, *Science*, **17**, 201-2 10.
Stoddart, D.R. 1986. *On Geography and its History*, Basil Blackwell, Oxford, 335 pp.
Strahler, A.N. 1950. Equilibrium theory of erosional slopes approached by frequency distribution analysis, *American Journal of Science*, **248**, 673-696.
Strahler, A.N. 1952. Dynamic basis of geomorphology, *Geological Society of America Bulletin*, **63**, 923-938.
Strahler, A.N. 1957. Quantitative geomorphology of erosional landscapes, *Proceedings of the l9th International Geological Congress*, Algiers, 1952, section 13, part 3, pp. 341-354.
Tarr, R.S. 1898. The peneplain, *American Geologist*, **21**, 351-370.
Teilhard de Chardin, P. 1959. *The Phenomenon of Man*, Harper & Brothers, New York, 318 pp.
Theis, C.V. 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage, *Transactions, American Geophysical Union*, **16**, 519-524.
Thorp, J. and Smith, G.D. 1949. Higher categories of soil classifications - order, suborder, and great soil groups, *Soil Science*, **67**, 117-126.
Tinkler, K.J. 1989. Worlds apart: eighteenth century writings on rivers, lakes, and the terraqueous globe, in *History of Geomorphology*, edited by K. Tinkler, Unwin Hyman, London, pp. 37-71.
Todd, D.K. 1967. *Ground Water Hydrology*, Wiley, New York, 336 pp.
Van't Hoff, J.H. 1884. *Études de dynamique chimique*, Frederik Muller, Amsterdam, 296 pp (in German).
Vitek, J.D. and Ritter, D.F. 1989. Geomorphology in the USA: an historical perspective, *Transactions, Japanese Geomorphological Union*, **10-B**, 225-234.
Worster, D. 1977. *Nature 's Economy - a History of Ecological Ideas*, Cambridge University Press, Cambridge, 404 pp.