Chapter Eighteen

Geology in the American Southwest: New Processes, New Theories

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Great innovations, whether in art or literature, in science or in nature, seldom take the world by storm. They must be understood before they can be estimated, and must be cultivated before they can be understood.

—*Clarence E. Dutton,* Tertiary History of the Grand Cañon District, with Atlas

In the late nineteenth century, the American Southwest emerged as one of the most important regions for geological study in the world. When geologists first encountered the canyon country of the Colorado Plateau, and the Grand Canyon in particular, they lacked vocabulary, methodology, and theory to describe and analyze the myriad stratigraphic and structural features and geomorphological processes that confronted them. Consequently, in numerous publications on the canyons and mountains of the Southwest, the region's initial explorers articulated theories that would come to inform a distinct "American school" of geology. John Wesley Powell, Clarence Edward Dutton, and Grove Karl Gilbert revolutionized the science of geology by revealing the primacy of streams in shaping the landscape (fluvialism) and by relating large-scale structures to motions in the earth's crust. At the heart of Powell's and Gilbert's geomorphological theory and Dutton's principle of isostasy is the concept of dynamic equilibrium. For these scientists, as for Darwin, natural processes inherent to our dynamic planet continuously work to correlate physical or biological structure with environmental conditions; for geologists, this process also works in reverse. Just as natural selection guides the evolution of life, processes of sedimentation and erosion, as well as crustal loading and rebound, perpetuate a tenuous, fleeting balance between the forces of creation and destruction. The crowning achievement of geology in the West was and remains the organization of time according to basic principles of geomorphology and structure revealed in the stunning geography of the American Southwest.

The first great geologist to describe the canyon was John Wesley Powell. Powell, a one-armed Civil War veteran and self-taught, home-schooled naturalist, developed the idea of exploring the canyons of the Colorado River when he was studying the headwaters of the Grand and Green rivers in Colorado and Wyoming during his Rocky Mountain Scientific Exploring Expedition of 1868. Through his research, he came to believe "the Grand Canyon of the Colorado will give the best geological section on the continent" (Hughes 1967, 44). Powell's first exploration of the Colorado commenced on May 24, 1869. He and his small party successfully negotiated the river from Green River, Utah, to the mouth of the Virgin River, today under Lake Mead. Because his first journey involved more survival than science, Powell led another expedition in 1871–72 with the explicit purpose of scientific exploration. The product of these expeditions is Powell's *Exploration of the Colorado River of the West and Its Tributaries* (1875). It is the first major description of the Grand Canyon and contains the first generalized stratigraphic column of the entire canyon section and the first physiographic diagram illustrating the cross-sectional nature of the region (Spamer 1989, 3).

Powell's most important contribution to geology is his system of stream classification; these divisions are basic principles in modern geomorphology. Streams and their drainages are categorized as *antecedent*, *consequent*, or *superimposed*. In the case of antecedence, the drainage is established prior to the elevation of the strata by folding or faulting, that is, streams predate structural deformation. Streams and their concomitant valleys that depend upon the structural features of a region are termed consequent, that is, structural deformation precedes the carving of the drainage. Superimposed waterways are not determined by the structural features of the rock through which they are carved but were in existence when the region last appeared above sea level. As a corollary, Powell also pioneered the concept of *base-level erosion*, defined as an imaginary surface inclining slightly in all parts toward the end of the principal stream draining the area through which the level is supposed to extend (Merrill 1964, 365). This is a vital insight, as all streams, regardless of their type of drainage system, work to achieve base level; the greater the deviation from base level, the greater the cutting power of the stream.

Powell characterized the Colorado as an antecedent stream. He noticed that the Colorado flowed across and incised Mesozoic strata upon entering the canyon. Then, as the region was uplifted, the Colorado stripped away the Mesozoic veneer, and cut down into the Paleozoic strata and metamorphic basement of the Colorado Plateau (Spamer 1989, 40). Powell likened the process to a buzz saw slicing through a log rising into the blade from below. As flexures on the Colorado Plateau rose, the river sought its level by cutting a canyon into the rising mountains (Merrill 1964, 479). Clarence Dutton would later agree with Powell's antecedence paradigm, while Grove Karl Gilbert would argue for cases of consequence and superimposition in addition to antecedence.

In addition to his work on streams and drainages, Powell was the first geologist to describe the rocks that unconformably underlie the Paleozoic strata of the canyon. Powell's "non-conformable rocks" included the metamorphic basement and the Grand Canyon Supergroup: a tilted, down-faulted series of Proterozoic sedimentary and metamorphic rock (Spamer 1989, 15). The beveled nature of the basement and Grand Canyon Supergroup, coupled with his own concept of base-level erosion, prompted Powell to realize the transitory nature of earth's mightiest features and the vastness of geologic time: "Mountains cannot long remain mountains [as] they are ephemeral topographic forms. Geologically all existing mountains are recent; the ancient mountains [implied by the canyon's beveled Precambrian rocks] are gone" (Moore 1956, 237).

Powell's other major geological publication is his *Report on the Geology of the Eastern Portion of the Uinta Mountains* (1876). In the *Report*, Powell divided the region west of the Great Plains, east of the Sierra Nevada, and south of the North Platte, Shoshone, and Sweetwater rivers into three physiographic provinces. The *Park Province* is characterized by massive ranges and great parks that serve as the watersheds and drainages of the Colorado and Rio Grande rivers. The *Plateau Province* is denoted by tablelands bordered by canyons and cliffs, is marked with occasional lone mountains and short ranges, and drains into the Colorado. The *Basin Province* consists of short north-south trending mountains and valleys, and it is remarkable for its internal drainage into salt lakes and sinks (Merrill 1964, 543–544).

As for Utah's Uinta Mountains, Powell correctly describes them as a fault-block mountain range with its longer axis oriented in a west-east direction. Faulting began in the late Mesozoic and ended in the late Cenozoic era, producing 30,000 feet of uplift. The erosion that accompanied the uplift removed more than 7,000 cubic miles of material from a 2,000-square-mile area (Merrill 1964, 543–544). Gilbert and Dutton would later use Powell's physiographic classifications, and Gilbert would be the first to articulate fully the structure of the Basin and Range (Basin) Province. Taken together, Powell's *Colorado River* and *Uinta Mountains* reports of 1875 and 1876 initiated the modern science of physical geology (Stegner 1954, 155).

While Powell provides the definitive view of the Grand Canyon from the river's edge, Captain Clarence E. Dutton, U.S. Army Ordnance, articulated the view from the rim. Dutton's first report on the region concerns the geology of Utah's plateaus (Dutton 1880). In the realm of structural geology, Dutton concurred with Powell's idea that the great flexures that are the dominant features of the high plateau country are due to faults and subsequent monoclinal flexure. Because unbroken anticlinals are underlain by faults, one form of displacement passes continuously into the other (Merrill 1964, 545). Most importantly, Dutton's *Report on the Geology of the High Plateaus of Utah* (1890) contains his first ruminations on isostasy. Dutton realized that the erosion of 6,000 to 10,000 vertical feet of rock from a 10,000-square-mile area precipitates regional uplift (Merrill 1964, 545).

Dutton's greatest work, however, remains *The Tertiary History of the Grand Cañon District, with Atlas* (1882). The volume itself is a monumental production and quickly and deservedly became the definitive geological description of the canyon region. The atlas, a folio-sized volume of twenty-three sheets, contains the first geological (time-stratigraphic units in color, structure) and topographic maps of the Grand Canyon (Spamer 1989, 5, 50). In addition, the sublime, atmospheric works of Thomas Moran and the photographically precise panoramas of William Henry Holmes provide visuals to accompany Dutton's poetic, richly descriptive narrative. Indeed, Dutton's stirring analysis of the Grand Canyon region, coupled with his ability to fuse aesthetic appreciation and scientific insight, launched southwestern North America as a premier field for geological study and marks the founding of the American school of geology (Spamer 1989, 5, 50).

In *Tertiary History*, Dutton studies the canyon's geomorphology by relating the structure of the region to the development of the chasm's drainage systems and consequent landforms. His main conclusion is that a geologically short time is all that is necessary for a river to cut through a great thickness of rock rising isostatically as a result of large-scale denudation (Faul and Faul 1983, 204). According to Dutton, "Erosion depends for its efficiency principally upon the progressive elevation of a region, and upon its climatical conditions. . . . The present Grand Canyon is the work of late Tertiary and Quaternary time" (Dutton 1882, 1, 7–8).

Dutton thus fuses the insights of Powell about geomorphology and the primacy of fluvial action with his own work on geomorphology and isostasy. Dutton's analysis of the dynamics of cliff recession is an example of a basic geomorphological tenet established in his canyon studies. Differential rates of erosion, controlled by strata of varying lithologic competence, "explain how [the canyon's] abnormal architectural forms so abundantly displayed in the chasm and the region round-about have been formed" (Dutton 1882, 8).

Finally, Dutton also introduces the concept of the Great Denudation, an elaboration on Powell's sense of deep time and the transformative power of fluvial systems. Powell realized that the Great Unconformity—the boundary between the crystalline basement and lowermost Paleozoic strata—marks two orogenies and their associated mountains' obliteration to a nearly level plain by erosion. The Great Denudation, the wearing-away of the Mesozoic and Cenozoic strata in the region, illustrates the principle of "dynamic equilibrium," as it is the consequence of isostatic rebound and the river's relentless quest to reestablish base level (Pyne 1982, 35). Dutton's genius lay in his ability to render the Grand Canyon as a comprehensible whole, as the product of evolutionary physical laws that are best revealed through scientific and aesthetic insight.

In 1883 Dutton wrote a positive review of Osmond Fisher's *Physics of the Earth's Crust* (1881). In his volume, Fisher reviews the secular-contraction hypothesis, the dominant paradigm of his day on crustal deformation and on the earth's inner structure (Greene 1982, 244). At the time, the earth's crust was thought to move vertically, not laterally. In short, continents were elevated when contractions (the result of heat loss) under ocean basins relieved the crust of its stress. Ocean basins were uplifted when the base of uplifted continents solidified, cooled, and sank. Fisher believed that such a "contraction" mechanism could not account for the amount of compression seen in sedimentary sequences or the inequalities in relief that existed on the earth's surface (Greene 1982, 244). Accordingly, Fisher suggested that the earth consists of a series of concentric shells of increasing density and is composed of a solid outermost crust, a semi-solid layer made "mobile" by heat and pressure, and a highly pressurized, solid nucleus (Greene 1982, 245).

Dutton's positive evaluation stemmed from his own geophysical model of the earth, as he also envisioned an inhomogeneous planet with regional differences in density that could cause bulges and depressions on the earth's surface. The heterogeneity of the earth's composition is necessary, Dutton reasoned, because a spinning earth of homogenous density would be utterly featureless. In 1889 Dutton finally defined isostasy as the tendency of the rotating earth to seek "dynamic equilibrium" with regard to the distribution of materials of different densities (Greene 1982, 248–249). However, a dynamic equilibrium is never reached because of the ceaseless processes of erosion and deposition. In practical terms, erosion along continental margins causes a gradual crustal subsidence in the area of greatest accumulation while the bordering upland that is shedding sediment rises as it is divested of its sediment load by way of erosion. For Dutton, then, the earth's crust and the earth itself are dynamic structures that continuously seek a Darwinian-like state of balance between internal structure and external process.

Also in 1889, Dutton addressed the Philosophical Society of Washington. In his speech on "some of the greater problems of physical geology," Dutton fully articulated the paradoxical nature of isostasy. Erosion creates uplift, as the "flanks of platforms with the upturned edges of strata reposing against them, or with giant faults measuring their immense uplifts, plainly declare to us that they have been pushed upward as fast as they were degraded . . . by erosion" (Moore 1956, 251). Furthermore, Dutton correctly reasons that such "rebound" necessitates the existence of a "viscous" or "plastic" under crust. While geology would have to await the theory of plate tectonics to explain large-scale regional uplift, Dutton's modern law of isostasy remains valid on a smaller scale. In short, mountains are raised in unstable areas by the earth's maintenance of its crustal balance (Moore 1956, 255); this corresponds to his own as well as Powell's and Gilbert's concept of dynamic equilibrium.

The final member of early American Southwest geology's triumvirate is Grove Karl Gilbert, perhaps the most talented of the three. Upon Gilbert's death in 1918, T. C. Chamberlain, an important American geologist, stated that it "is doubtful whether the products of any geologist of our day will escape revision at the hands of future research to a degree equal to the writings of Grove Karl Gilbert" (Wallace 1980, 42). Indeed, Gilbert's analyses of the Basin and Range Province, the Henry Mountains of Utah, and Lake Bonneville remain valid for the most part, and they are the sources for several principles basic to structural geology and geomorphology today.

Gilbert first realized that faulting—not folding, as in the Appalachians—is the force behind mountain-building in the intermountain West during his explorations as chief geologist with G. M. Wheeler's survey of the lands west of the one-hundredth meridian in 1871 and 1872. In 1875 Gilbert, in "Report on the Geology of Portions of Nevada, Utah, California, and Arizona," first applies the terms "Basin Range System" and "Basin Ranges" to "all that system of short ridges separated by trough-like valleys which lies west of the Plateau System" (Gilbert 1875, 22). Gilbert correctly surmised that blocks of mountains were raised along nearly vertical, deep-seated faults (Wallace 1980, 36). Furthermore, the valleys between the upthrusted blocks are not erosional features but are intervals existing between planes of maximum uplift (Merrill 1964, 541). This analysis is the contemporary understanding of the Basin and Range physiographic province.

Gilbert's work in the Southwest next found expression in his *Report on the Geology of the Henry Mountains* (1877). He suggested that the Henrys were created by the intrusion from below of igneous material through Paleozoic and lower Mesozoic strata, causing the overlying Cretaceous and Tertiary beds to bulge outward (Merrill 1964, 546). Gilbert was the first to show that intrusive igneous masses can deform rocks into which they are extruded (Hunt 1980, 25). These intrusions were termed *laccolites* (later laccoliths). His analysis is even more remarkable when placed in its historical context. As late as the 1830s, geologists were still skeptical about the igneous origin of rocks and were even more reluctant to accept Gilbert's idea that igneous masses may intrude and be younger than their host rocks (Hunt 1980, 29). Indeed, he showed that rock that is brittle and rigid on the scale of a hand specimen will bend and deform plastically on a regional scale (Faul and Faul 1983, 204).

Gilbert employs Powell's drainage schematic in his discussion of the drainage patterns of the Henry Mountains. The streams are, he asserted, generally consequent. It is here that Gilbert relates dynamic equilibrium to geomorphology and fully articulates the concept that landforms are the manifestation of process, the central theme of contemporary geomorphology (Yochelson 1980, 140). In brief, drainage systems are the manifestation of a self-regulating process, driven by the force of gravity, whereby topographic form is adjusted to correspond to changes in mass and energy flow (Yochelson 1980, 130). In addition, Gilbert formulated the *law of uniform slopes* ("The tendency [of streams] is to abolish all difference of slope and produce uniformity"), the *law of structure* ("Erosion is most rapid where resistance is least"), and the *law of divides* ("The nearer the water-shed or divide the steeper the slope; the farther away the less the slope") (Gilbert 1877, 115–116). Just as Dutton's crust seeks dynamic equilibrium, so do Gilbert's streams.

In his *Lake Bonneville* report of 1890, Gilbert expands on Powell's isostatic studies of Utah by establishing geomorphology as a quantitative science. His meticulous mapping and correlation of petrified beaches proved that the level of Lake Bonneville, a great inland lake of Pleistocene age, varied by approximately one thousand feet over time, resulting in differential loading of the crust (Faul and Faul 1983, 207). The phenomenon of "non-horizontal" beaches led Gilbert to propose a model of the earth similar to that of Dutton's. He concluded that major deformations of the crust reflect "horizontal movements of the upper rocks (the lithosphere) without corresponding movements in the nucleus, thereby [implying] mobility in an intervening layer." Furthermore, the driving forces of such movements result from "a primal heterogeneity of the earth which gives diversity to the flow of heat energy" (Yochelson 1980, 61). These two ideas clearly predict the modern geophysical picture of the earth and the motive force (convection) behind contemporary tectonic theory.

In 1875 Gilbert succinctly articulated the value of the canyon lands and mountains of the American Southwest for geological study: "It is impossible to overestimate the advantages of this field for the study . . . of mountain building (and other processes). [Here] can be found differentiated the simplest initiatory phenomenon, not obscured, but rather exposed, by denudation, and the process can be followed from step to step, until the complicated results of successive dislocations and erosions baffle analysis" (Wallace 1980, 36). Thus, the Grand Canyon in particular and the American Southwest in general stimulated new geological theories because the region reveals stratigraphic relations, three-dimensional structural features, and geomorphological processes with textbook clarity.

The work of Powell, Dutton, and Gilbert produced a series of fundamental principles in the areas of geomorphology and structural geology that have come to define a distinct branch of American geology. This is geology on an appropriately monumental scale, as Powell, Dutton, and

Gilbert sought to relate the origin of the Grand Canyon to the genesis of the modern Colorado River, and to the regional uplift of the Colorado Plateau and its associated structures. In addition, these pioneering geologists strove to associate structure with historical geology, thereby revealing the causation of major depositional and erosional events and their spatial and temporal extent. At the core of their analyses and theories lay an unabashed faith in the timelessness of geological process, of nature's relentless quest to establish a "dynamic equilibrium" between structure and the environment. Most notably, the early geologists of the Southwest believed in the power of scientific insight and aesthetic awareness to reveal the fundamental processes of physical geology. Their legacy lives in introductory geology textbooks and profoundly shapes the minds of all who peer into the mysterious, beautiful depths of the Grand Canyon.

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