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GROVE KARL GILBERT: EXPLORER AND SCIENTIST

By Harold L. Burstyn

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By Harold L. Burstyn
U.S. Geological Survey
Reston, Virginia 22092

ABSTRACT

Grove Karl Gilbert (1843-1918) was one of the most distinguished American geologists. He spent his career entirely in Government service. Gilbert joined the U.S. Geological Survey on its founding in 1879 and served as its first Chief Geologist (1889-1892). This report summarizes Gilbert's life and career, with special attention to his contributions to geomorphology, tectonics, hydrology, glaciology, earthquake studies, and geological methods.

INTRODUCTION

At eleven minutes past five on the morning of April 18, 1906, G. K. Gilbert of the U.S. Geological Survey woke up with a start. It took him only a few seconds to realize that the Earth was shaking beneath him. He quickly got out of bed in the redwood-framed building in Berkeley, California, and began to take notes. "A vigorous earthquake was in progress," he later wrote, and he did not want to miss a thing. Having narrowly missed the Southern California earthquake of 1872 and the Alaska earthquake of 1889, Gilbert was overjoyed that he was experiencing the great San Francisco earthquake of 1906. Though he felt compassion for those who lost their loved ones and their property, he thought that as a leading geologist he should be on the spot when the ground chose to move and shake. As soon as he could, Gilbert left Berkeley for San Francisco, which had just suffered one of the world's most devastating earthquakes and the fire that followed it.

Gilbert did not join in fighting the fire and tending the injured. His profession was geology, not firefighting or medicine. Instead he applied his lifelong training in observing the Earth and its surface to study what had happened and to explain why. And he carried his research beyond explanation to prediction. In the reports and articles he published for the Survey and elsewhere, he suggested what had to be done when San Francisco was rebuilt. "The new city should be earthquake proof," he wrote. "The ... danger ... is a thing to be dealt with ... by skillful engineering." Moreover, Gilbert hoped that in the future geologists might be able to forecast when such a fearsome earthquake might occur again. Gilbert was the first to suggest such forecasts, and only in the last few years, more than 75 years since his suggestion, have any credible forecasts been made. In 1975 the Chinese prevented a large loss of life by predicting the great Haicheng earthquake.

Who was this man who so eagerly sought disaster, the better to understand the planet that we live on? How do we account for the reputation of G. K. Gilbert among earth scientists, a reputation so strong that one of today's leading geologists, Robert Wallace of the Geological Survey, believes that "Gilbert would receive an overwhelming endorsement as the leading American geologist of all time"?

EARLY YEARS

Grove Karl Gilbert (1843-1918) was born in Rochester, New York. Shy, studious, and considered too delicate to go to school, Gilbert was educated at home until he went to the University of Rochester, where he had a classical education that included considerable science and mathematics. After a brief try at teaching school, which he hated, Gilbert joined Ward's Natural Science Establishment in Rochester. There he helped supply museums with specimens, including a mastodon's skeleton that he excavated at Cohoes Falls near Albany. What interested Gilbert most about the excavation was not this relic of ancient life. Rather, he was fascinated by the potholes, bowl-shaped hollows ground out of the stream's bed by stones whirling around at the base of the waterfall. The mastodon's bones were found in one of these potholes. By counting and measuring the potholes, and by counting the rings in tree trunks along the Falls, Gilbert concluded that at least 35,000 years had elapsed since the waterfall was opposite the place where the mastodon had stumbled into a hole and died. That is, Cohoes Falls had receded about a foot during each hundred years; presumably the Falls were still receding.

Gilbert reconstructed the environment of the mastodon, rather than its evolution. In so doing he found his career: applying ideas from physics and engineering science to the study of the Earth. As soon as he could, Gilbert found a job doing field geology. In 1869 he joined the Ohio Geological Survey as a volunteer assistant.

John Strong Newberry, professor of geology at Columbia University, was also director of the Ohio Survey. Newberry had been one of the first geologists to explore the Grand Canyon of the Colorado. For 2 years Gilbert was one of his assistants and Gilbert found his training incomparable. Gilbert drew with meticulous skill the fossils that his colleagues discovered. He mapped with exceptional accuracy the remains of the glaciers that had covered the valley of the Maumee River during the Ice Age. Not for another 50 years did others make glacial maps of the quality of Gilbert's.

WITH THE TERRITORIAL SURVEYS

Gilbert's 2 years work in Ohio led to nine articles and reports and a recommendation from Newberry to Lieutenant George Wheeler of the U.S. Army. Wheeler wanted a geologist to join his U.S. Geographical and Geological Surveys, west of the Hundredth Meridian, one of four government organizations that explored the American West between 1867 and 1878. These Territorial Surveys, as the four organizations are known, tried to map the western half of the United States and inventory its resources as the people rushed to settle the uninhabited land. The Surveys were the scientific reconnaissance that made possible one of history's great migrations, the peopling of the American West from the Civil War to the end of the century.

In May 1871 Gilbert joined Wheeler's party in Nevada for an assault on Death Valley, California, and the Grand Canyon of the Colorado River. In 1872 and 1873 the Wheeler Survey, including Gilbert, explored in Utah, New Mexico, and Arizona. The schedule was rigorous; Wheeler organized his parties like companies of soldiers, which most of his men were. Gilbert became a master of the panoramic sketch. Climbing a mountain top, he drew rapidly and clearly, resolving reams of geological description into a few quick lines in his field notebooks. But the pressure of the military-style campaign was too much for him; he longed for the chance to spend enough time to comprehend the breathtaking scenery around him. How had it been formed? What were the clues to the evolution of the strange and wonderful landscape that spread out before his eyes? Even when the summer in the field ended and Gilbert returned to Washington, there wasn't enough time to sit and ponder, to make sense of the bewildering geologic structures that he examined in the West. During the field season of 1874 Gilbert stayed in Washington to write up his results as best he could.

Gilbert was dissatisfied with the subordination of science to the demands of military mapping, especially after the Corps of Engineers denied him the right to publish in the scientific literature. He resigned from Wheeler's Survey to join its rival, Major John Wesley Powell's Geological and Geographical Survey of the Rocky Mountain Region. His Survey, with the fewest resources and least political support of any of the four, was the most innovative in its geology. What Wheeler's scientists did and what was done by the other two Surveys, Clarence King's Survey of the Fortieth Parallel and F. V. Hayden's Geological and Geographical Survey of the Territories (largest of the four), was vitally important to the understanding of America's geology. But the techniques they used and the principles they developed were known already to the scientists of Europe. Only Powell's Survey developed entirely novel ideas about the way the surface of the land is shaped, chiefly by the power of water to erode layer after layer of rock.

Which of these pathbreaking ideas were Powell's and which were Gilbert's, or those of Powell's other principal assistant, Captain Clarence Dutton of Army Ordnance, we cannot tell. Powell and his assistants were so close, they spent so many nights around their summer campfire in the Rockies and in their parlors in Washington in the winter, that no one can say with certainty where the ideas of one leave off and another's begin. It is enough to recognize that the modern study of landforms, to which we give the name of geomorphology, began in the reports of the Powell Survey.

During the summer of 1875, his first with Powell, Gilbert led his party to the Henry Mountains, then, as now, a wilderness where there is barely enough grass for horses. He reconnoitered them for a week and returned for 2 months in 1876. In 1877 he wrote in Washington the first of his four great monographs, "Report on the Geology of the Henry Mountains," a volume to which geologists return again and again to learn their science from a master.

Gilbert divided his Report into three parts. In the first he gave a thorough description of the mountains, which Powell had named in 1869 after Joseph Henry, the first Secretary of the Smithsonian Institution.

In the second part, Gilbert described a new form of mountain building, which he called a "laccolite." (The name was later changed to "laccolith"). To form a laccolith, molten rock rises from deep in the Earth. When its pressure equals the weight of the layers above it, the molten rock spreads horizontally, creating a dome-shaped intrusion between two layers of sedimentary rock. The laccolith that results is shaped like a mushroom, and it deforms the rocks into which it intrudes until they form a circular mountain. Though this type of mountain building is known to be rare, the explanation given for it today is the same as Gilbert's. A five-summers' resurvey in the 1930's supported Gilbert's deductions.

The third part of Gilbert's Report is his masterpiece on the dynamics of erosion by running water. Beginning with the Henry Mountains as they were created by the intrusion laccoliths, Gilbert showed how they reached their present form: water running down the hillsides sculptured them. Some of these ideas had been expressed by river engineers in Europe, and some were in briefer form in Powell's and Gilbert's reports of 1876. But Gilbert's 1877 study of the Henry Mountains was the first account by an earth scientist of how water acts on land like a sculptor with a chisel. Running water continuously adjusts the shapes of the Earth's features. Gilbert showed how the water erodes the bed of its channel as it runs downhill, removes the debris of the erosion, and grinds it up into even finer particles. His most important concept was that of the graded stream, which adjusts the slope of its bed and the area of its cross-section to the load of sediment it has to carry.

WITH THE U.S. GEOLOGICAL SURVEY

As Gilbert mapped the Colorado Plateau (an area that he named) during the summer and fall of 1878, there were new developments in Washington, with Powell in the thick of them. President Rutherford B. Hayes, who had been Ohio's governor when Gilbert was on its Survey, took office in 1877 pledged to reform the Federal government. With the slump in business that began in 1873 still holding on, reform meant retrenchment. President Hayes and his Secretary of the Interior, Carl Schurz, got the Congress to consolidate the four Territorial Surveys into one civilian agency, the United States Geological Survey.

To direct the new Survey President Hayes had to choose among the three civilian leaders of Territorial Surveys--F. V. Hayden, Clarence King, and John Wesley Powell. Powell threw his support to King, whose choice the President announced in April 1879. Among the first to be hired by King was G. K. Gilbert. King put him in charge of the Division of the Great Basin.

In the fall of 1879 Gilbert began to work on the Ice Age lake he had named, after the French explorer B. L. E. de Bonneville, when he first traced the remains of its shorelines in 1872. Ten of thousands of years before, Lake Bonneville covered much of northeastern Utah. Its remnant is the Great Salt Lake. In their crossing of the Great Basin, King and his colleagues of the Fortieth Parallel Survey had traced the sequence of wet and dry periods in the sediments of glacial Lake Lahontan in Nevada. Now King encouraged Gilbert to do the same for Lake Bonneville.

For two field seasons Gilbert and his assistants traced the abandoned shorelines of the ancient lake. Though they had been known in a general way long before--from the days of the trapper Jim Bridger and the explorer John C. Frémont--Gilbert mapped them with a scientific precision. In the first of the Survey's Monographs, "Lake Bonneville," published in 1890, Gilbert showed that the Bonneville shoreline lay about 1,000 feet above the Great Salt Lake. Thus the ancient lake occupied about 54,000 square miles, a quarter of the entire Great Basin between the Rockies on the east and the Sierras on the west. Gilbert found two other shorelines below the Bonneville. The oldest, older even than the Bonneville, he called the intermediate shoreline. After an arid period, the lake filled up to the level of this first strand, which marked the line where the waves of the lake went back and forth for centuries. Sediments of yellow clay formed the lake's bottom.

After thousands of years, the lake dried out and filled up again, this time to the Bonneville shoreline. The bottom sediments changed from yellow clay to white marl. The lake overflowed, sending a stream of water north to the Snake River. This stream eroded the fine sediments of silt where it left the lake, until, in a flood, the level of the lake dropped more than 300 feet. Here the final, or Provo, shoreline formed, and since then a continued drying had divided the basin into a dozen independent parts, the largest of which held the Great Salt Lake. All the cities along the front of the Wasatch Mountains were built on deltas from the Provo stage of Lake Bonneville. There were virtually no deltas at the Bonneville level because of erosion when the lake fell to the Provo level.

Gilbert saw that the Bonneville shoreline separated two different landscapes. Above the shoreline, running streams have sculpted the landforms by erosion. Most of the fan-shaped piles of debris at the foot of the mountain valleys were there long before the lake was formed. Below the shoreline, the beaches are almost horizontal, bowed upward towards the center of the basin as the land rebounded from the weight of the water that no longer covered it.

While Gilbert was writing his second major monograph, the first to be published by the new Geological Survey, he played a major part in running the organization. Clarence King resigned in 1881 after less than 2 years as Director. To replace him the new President, James A. Garfield, chose John Wesley Powell.

POWELL'S "RIGHT-HAND MAN"

Powell's ideas of how to run the Geological Survey differed from King's. King began with a small office in Washington and four Divisions in the field, their headquarters in Denver, two each in Salt Lake City, and San Francisco. Concerned lest his Division chiefs lobby against each other with the Congress or spend so much time in administrative tasks that their science suffered, Powell abolished the geographical Divisions, replacing them with Divisions by subject that were headquartered in Washington. Gilbert, brought back from the field ostensibly to finish his report on Lake Bonneville, stayed on in Washington to help Powell run the Survey, becoming the first person to hold the title of Chief Geologist.

To the young Bailey Willis, Gilbert was "Powell's better half," accepting from his Chief advancements in administrative responsibilities though he would have preferred to return to scientific research. "Perhaps no one else ever thought of them in that way," Willis reminisced 60 years later, "but in constant relations with the two I learned to know how much Gilbert, the true scientist, contributed to the geological thinking of Powell, the man of action. I do not think that they themselves were conscious of the degree to which the latter absorbed and gave out as his own the ideas that the former had silently thought through. But as Gilbert's assistant, I was sometimes jealous for that generous soul and devoted friend."

Under Powell the new, centralized Survey spent less effort on minerals and more on water, less on the physics of the past and more on the biology. Gilbert had to abandon his plans for a full-scale study of the Great Basin, of which his work on Lake Bonneville represented only the beginning. He had hoped to study all the glacial lakes and the structures that underlay them. Now he had barely time enough to write the monograph on Lake Bonneville. His assistant, I. C. Russell, wrote a monograph on Lake Lahontan; these two were the only glacial lakes that were studied in detail. Powell had succeeded where King had failed in getting the Congress's approval to extend the Geological Survey over the entire country. No longer confined to the public lands of the West, the Survey began to stretch over the rest of the country the limited resources provided by the Congress. In 1883 Powell transferred Gilbert from the Great Basin to the Appalachian region, even though the monograph on Lake Bonneville was not complete. No longer able to participate, Gilbert suggested the directions for future study of the Great Basin: its brines and their possible economic value, the extinct lakes in the south part of the Basin and their relation to climate, and the rebounding of the lake's floor after the water was removed. Only to the last problem, and to the even more significant one of the structure of the Great Basin, did Gilbert contribute before he died.

When Gilbert moved from Salt Lake City to Washington in 1881, he found the Survey's geologists fell naturally into two groups. The first, mostly companions of King, had been largely trained in Germany. They were wealthy enough to afford the luxuries of the metropolis, though Washington was hardly a rival to New York or Paris in offering them. The other group, Gilbert and those who had worked with him in the West, had more limited means. If they had acquired university educations, as most of them had, they did so in the smaller American institutions. Gilbert, Willard D. Johnson, I. C. Russell, and W J McGee began to eat a frugal lunch in the Survey offices. The diners were dubbed the "Great Basin Mess," an institution that lasted for 30 years. It began with each member taking a week's turn at bringing the food. It ended with an elegant meal brought in by a caterer. Throughout its existence Gilbert dominated the Great Basin Mess, whose invitation to lunch was eagerly sought by all the leading geologists of the world. In 1878 Powell founded in his living room the Cosmos Club for the intellectuals of Washington. Gilbert was one of the Club's illustrious members, who included Henry Adams. The Cosmos Club made Gilbert its president in 1904.

From his arrival in Washington in 1881 Gilbert reaped the rewards of his distinction as a scientist. The National Academy of Sciences elected him a member in 1883. From 1883 to 1892 he was an officer of the Philosophical Society of Washington, ending as president. He presided for 2 years running (1885-1887) over the American Society of Naturalists, and, when in 1888 the geologists formed an independent group, the Geological Society of America, Gilbert was a founder. Later the Society made him its only two-term president (1893, 1909). He was active in the American Association for the Advancement of Science, becoming its president in 1900, the year "Science" became the Association's official magazine. In the National Geographic Society, Gilbert served for 10 years on the Board of Managers, and as Vice President.

Thus during his 40's and 50's Gilbert was more of an office geologist than a field geologist. His leadership of the Appalachian Division of the Survey did bring him into the field for brief periods. He traced out he abandoned shorelines of the glacial lakes of New York, Ohio, and Michigan, discovering the relation between glacial Lake Iroquois in upstate New York and the valley of the St. Lawrence. He showed that the region tilted upward as the ice retreated. To the American Association for the Advancement of Science meeting in Toronto in 1889, Gilbert explained the geologic history of Niagara Falls and the Great Lakes.

THE IRRIGATION SURVEY

Early in his explorations, John Wesley Powell became concerned about the lack of water on the Great Plains and in the Great Basin west of the Rockies. From his boyhood on an ever-moving family farm, he knew how much water the farmer needed to grow his crops. Powell concluded that to attract settlers to the western Plains with the promise of free homesteads was a cruel hoax. Water, not land, should be the basis for the settlement of the West beyond the line where the annual rainfall was below 20 inches, a line that roughly coincided with the 100th meridian of longitude. The Federal government had to be persuaded to change the land laws.

With Gilbert's help, Powell wrote "Report on the Lands of the Arid Region of the United States" and presented it to Secretary Schurz in 1878. He argued that the government could no longer continue to parcel out the land to settlers in strict rectangles. Such a system, Powell suggested, worked well so long as there was enough water. In the West, where water was in short supply, the later arrivals would be at the mercy of those who had come before and gained control of the water.

No one took much notice of Powell's warnings until the droughts of the 1880's. Then the Congress, which had earlier refused to act, appealed to Powell to search out the sources of water for irrigation, so that they could be reserved for public use and not pass into the hands of monopolists. In 1889 Powell began the Irrigation Survey as a Division of the Geological Survey, and at the same time he elevated Gilbert to the newly-created post of Chief Geologist.

Powell, in his eagerness to help America realize his vision of a nation of family farms spread across the dry western countryside, had overreached himself. When the drought ended, the same Senators and Representatives who had eagerly embraced Powell's plans turned to attack his leadership of the Geological Survey. As the political storm broke, Gilbert was forced out as Chief Geologist by the Congress's cuts in the Survey budget.

GILBERT RETURNS TO RESEARCH

No lover of administration, Gilbert retreated with relief into his beloved research. As the budgetary storm clouds gathered about the Survey during the summer of 1892, Gilbert spent the nights at the Naval Observatory studying the face of the Moon. During the day he experimented by throwing clay balls against a slab of clay. What he was searching for was an explanation of the Moon's craters, an explanation that he hoped to extend to similar craters on the Earth. He had visited one such crater the previous summer, Coon Butte in Arizona, where a circular rim surrounds a basin known as Meteor Crater. The question Gilbert tried to answer was: Was it really a meteor, a body from outer space, that hit the Earth so hard that it made the crater? He concluded in the face of obvious evidence, that the impact of a meteor was less likely the cause of Coon Butte than was some kind of volcanic explosion.

History has disagreed with Gilbert's explanation of Coon Butte, but the reasoning that he used to arrive at it, together with his reasoning on other geological matters, had a profound impact on the methods of the earth sciences. Every scientist tries to discover what the world really is, not what we would like it to be. Science turns the power of human imagination, not to creating an ideal universe, but to understanding in detail the one that we inhabit. So Gilbert, as he explored the sparsely inhabited plains and mountains of the American West, tried to imagine the geological processes that had made what he saw.

As he struggled to complete his monograph "Lake Bonneville," Gilbert distilled the essence of his style of scientific research into his Presidential address to the Society of American Naturalists in Boston in December 1885, which he titled, "The Inculcation of Scientific Method by Example." For his example, Gilbert took the explanation he had worked out for the warping upward of Lake Bonneville's shoreline. As the lake evaporated, and the weight of its water was lifted from the basin, the land rose. With the steps that led him to this explanation Gilbert illustrated the fundamental principle of scientific research. The scientist devises as many reasonable hypotheses as possible to explain the observations. Each hypothesis is carefully tested against those observations. Only that "hypothesis that remains unscathed after all the tests [the scientist's] imagination can suggest" can be a truly scientific explanation. Thus, Gilbert concluded, "the great investigator is primarily ... the [one] who is rich in hypotheses." The "guessing faculty" ought to be encouraged among students of science, and any teaching of science that stresses facts rather than methods is misguided.

Gilbert returned to scientific method in his study of Coon Butte. In great demand as a lecturer on scientific subjects, he spoke about it to the National Geographic Society, the National Academy of Sciences, the American Association for the Advancement of Science, and at Chicago, Cornell, and Kansas Universities. Finally, he published his ideas in 1896 in "The Origin of Hypotheses," his presidential address to the Geological Society of Washington. Once again, as with Lake Bonnneville, Gilbert drew his examples of how to do earth science directly from a study of his own.

This time Gilbert went into greater detail about how the earth scientist worked. Once again the beginnings of scientific explanation lie in framing hypotheses to explain observation. Hypotheses "flash into consciousness without premonition," Gilbert wrote. They are suggested to the inquiring mind by analogy between the new phenomenon that has to be explained and some accepted explanation. Then the scientist tries out the hypothesis by inventing tests for it. Only if it passes all the tests that the scientist's ingenuity can devise does the hypothesis become a scientific theory.

Gilbert had two hypotheses to explain the depression in the Arizona desert known as Coon Butte. The first was the impact of a meteor or "buried star"; the second, a volcanic explosion below the surface. Trying all the tests his fertile mind could imagine, Gilbert ruled out the meteor because he found no deflection of the magnetic needle in the crater. For an iron meteorite not to make the needle deviate, it would have to be buried more than 10 miles below the crater. This seemed impossible to Gilbert, so he rejected his meteorite hypothesis. Modern science has revived it, estimating that the meteor was far smaller than Gilbert imagined, about 80 rather than 500 feet in diameter. And rather than burying itself in the ground beneath the crater, the meteor disintegrated on impact, leaving only fragments behind.

Gilbert's second hypothesis to explain Coon Butte was that molten rock came up from the inside of the Earth as in a volcano and exploded just beneath the surface. Though Gilbert found this the more plausible explanation, he concluded that all the evidence was not in. So he left uncertain the origins of Coon Butte, and he concluded that all scientific results, and science's methods as well, are tentative. They can, and probably will, improve as time passes.

Gilbert brought just such an improvement to the explanation of the craters of the Moon. As he looked through the telescope he sketched what he saw. His pictures of lunar craters look like photographs from spacecraft. The system he developed to classify craters is still in use. He made a convincing case that the craters are produced by impact, reproducing similar features by throwing clay balls at a clay slab. But where could the bodies come from that crashed into the Moon? Since the craters are circular rather than oval, Gilbert thought they must be formed by impact from directly above rather than at an angle. To Gilbert, this vertical impact meant that stray meteorites were unlikely to have made the craters. Rather, Gilbert thought, the Moon formed from bits of debris that circled the Earth in a ring, rather like the rings of the planet Saturn. The pieces of debris collided with one another, and over time they formed a single body, the Moon. The Moon's craters marked the last stages of the collisions among the bits of debris. Until the exploration of space began in the 1960's, the subject of the moon's geology remained where Gilbert left it in his 1893 article on "The Moon's Face."

Besides the Moon, Gilbert studied a number of things after he returned full-time to research in 1893. In eastern Colorado he mapped the underground water of the Arkansas River valley and the area around Pueblo and he helped the Coast and Geodetic Survey interpret their measurements of the variation in the force of gravity across the United States. He also continued to study Niagara Falls and the Great Lakes.

GILBERT AND THE ALASKAN GLACIERS

In 1889 the railroad magnate Edward H. Harriman sponsored a scientific expedition to Alaska. Twenty-five scientists, with Gilbert as their chief, joined Harriman and his family on a special train from New York to Seattle, where they boarded a chartered steamship. For the months of June and July the ship sailed along the coast from Puget Sound to Bering Strait and back again, travelling wherever the scientists wanted to go. The results of the expedition, published in 12 handsome volumes, gave the first scientific account of America's largest and most northerly possession.

What interested Gilbert most in Alaska was its huge, coastal glaciers, among the most spectacular features of the American landscape. Some of them flow right down to the ocean, where pieces break off to form icebergs in a process called "calving." Gilbert described nearly 40 of Alaska's glaciers. He paid particular attention to those his predecessors had already seen, because he wanted to determine how the glaciers fluctuated with time.

There was no pattern in the movements of Alaska's glaciers, Gilbert discovered. The same conditions that cause one glacier to expand will make another contract. Whether any particular glacier is growing or shrinking can be determined only by local examination. Gilbert and his colleagues paid special attention to the glacier they named Columbia, in Prince William Sound, with its 4 miles of sea wall. Columbia is the only Alaskan glacier that has not shrunk drastically in the past several hundred years. Because of the data brought back by Gilbert, detailed comparisons of the Columbia Glacier's status can be made for almost 100 years. Such comparisons are very important, for icebergs calved from this glacier could endanger the tankers that now carry Alaskan oil from the pipeline terminal at Valdez.

Never content with description, Gilbert wanted to know how glaciers worked. Why is a glacier's surface more level than its bed? How does a glacier erode the terrain it passes over? How does it dig a deep fjord? What controls the calving of icebergs? To all these questions Gilbert gave at least partial answers, answers that have been confirmed by the most recent studies. In the study of glaciers, as in most other subjects he touched, Gilbert was a pioneer. What stands out are the names he gave both to particular features like the Columbia Glacier and to types of features. For example, he coined the term "hanging valley" to describe the result of erosion where the weaker tributary rivers of ice join the main glacier.

GILBERT AND THE GOLD MINERS

The Geological Survey arose from the need of the people of the United States to make the best use of their land, water, and minerals. Different groups often have different ideas about how the land ought to be used. The founders of the Survey hoped that scientific research could supply the answers to questions of land use.

It turns out that there is rarely an obvious best use of any piece of land. If you need lumber, you have to cut down trees. If you want to mine a piece of land, you can't use it at the same time for a park. Cutting the trees along the river bank can lead to floods downstream. In every case there is a group that wants one use of the land pitted against another group that wants another. The decision on which use of the land to favor has to be made, not by the impersonal standards of earth science, but by the institutions of our democratic society: the legislature, the executive agencies, and the courts.

After Powell got into trouble with the Congress over his Irrigation Survey, the Geological Survey tried to stay away from political controversies over the use of land. However, as the Federal government's principal source of scientific expertise on the land and its products, the Survey was often called upon for advice. Anxious to keep out of politics, the Survey offered its advice as objectively as it could, pointing out the consequences of alternative actions rather than recommending a single one.

Beginning in 1905, G. K. Gilbert got involved in one of the most delicate questions of land use to face the Survey. From it came some of his most distinguished contributions to science. The locale was the Sacramento Valley of California. This northern half of California's Great Valley occupies a basin between the Sierra Nevada and Coast Range of mountains. It is one of the most fertile farming regions on Earth. The Sacramento River built, from the silt that it carried down from the mountains, natural levees that were higher than the surrounding valley floor. In time of flood the river overflowed these levees and deposited a rich alluvium that renewed the valley's fertility. Some of the earliest settlers of California discovered gold in the alluvium laid down by the Sacramento, and they followed the traces of the yellow metal back to its source in the mountains. The banks of the streams that fed the Sacramento soon gave up their riches. The miners then took to washing away entire hillsides with high-pressure hoses as they searched for the buried beds of ancient rivers in whose gravel more gold might be found.

This hydraulic mining worsened the effects of the Sacramento's periodic floods. Once the miners sent their huge amounts of tailings down the streams that fed the Sacramento, the channel became clogged, shipping was interrupted, and the river when in flood dumped a coarse, infertile load of mining debris that covered the rich soil. In a single generation hydraulic mining caused as much erosion as a million years of natural forces.

A titanic political struggle erupted as the farmers of the valley and their allies in the towns along the rivers fought to restrain the miners of the mountains. The first phase of the struggle ended in 1884 when a Federal court banned hydraulic mining because of the debris it created. Limited mining returned in 1893 with an Act of Congress. The miners kept pressing for the hills to be opened to unlimited hydraulic mining. In 1904 they persuaded President Theodore Roosevelt to ask the Geological Survey to investigate.

The Survey sent their most distinguished geologist, Gilbert, to California. There he set up headquarters at the University of California in Berkeley. From Berkeley Gilbert set out to explore the mining areas of the Sierras and the valleys through which the mining wastes had passed. After he satisfied himself with what the problem was, he spent 2 years on a series of experiments.

The Army Engineers had made two reports on mining debris in the Sacramento Valley before Gilbert came on the scene. Though Gilbert found them useful, he realized that they were limited to the Sacramento and its tributaries. Gilbert decided that he could not answer with finality the question put to him until he understood how the mining debris behaved as it moved down the mountainside and into the valleys. He had to find out exactly how rivers transport sediments.

On the Berkeley campus Gilbert built a series of flumes through which he and his assistant sent water and sediment. They painstakingly varied the size of the sediment and the amount of water, carefully tabulating the results over many months. They carried out the most widely cited series of experiments on the transport of sediment that have ever been done. Professional Paper 86, "The Transport of Debris by Running Water" (Gilbert, 1914) was the first of Gilbert's debris investigations.

The second appeared in 1917, a year before Gilbert's death at age 75. Also published in the Geological Survey's most respected series, as Professional Paper 105, Gilbert's final report was titled "Hydraulic Mining Debris in the Sierra Nevada." He traced the travels of the tailings from the mines in the mountains to their final resting place in the seabed outside the Golden Gate. There they added to the bar outside the entrance to San Francisco Bay, moving it closer to the shore. He discussed in great detail the entire operation of the bay, one of the world's greatest estuaries. His report of 1917 was so thorough that its data are the first complete set we have for this important area. Gilbert's "Hydraulic Mining Debris" is the baseline from which all subsequent studies of San Franciso Bay begin.

Of course Gilbert had been given a task in 1904 with urgent political implications: to investigate the debris from hydraulic mining. Why should it take him 13 years to complete it? How could political decisions depend on such slow scientific research? There are a number of answers to these questions. In the first place, it was not entirely Gilbert's choice that so much time elapsed between his first trip to the Sierras and his final report. The San Francisco earthquake of 1906 interrupted his work for many months. He had a second interruption of over a year when he suffered a stroke in 1909.

Secondly, Gilbert's recommendation, when it came in 1917, was beside the point. He did indeed conclude that, were hydraulic mining to resume without restrictions, it would destroy navigation on the Sacramento River and ultimately in San Francisco Bay. But what ended the clamor of the California Miners Association was not the actions or even the recommendations of the Federal government. Rather, hydraulic mining disappeared for economic reasons. In the first place, the price of gold fluctuated. In the years before World War I it wasn't high enough to create any great demand for mining in California, where the most accessible desposits had already been worked out. Secondly, in water-short California, the huge quantities that the miners needed to wash away the hillsides commanded a higher price for alternative uses, irrigation and hydroelectric power. While the mines were idle, their owners sold their water rights to farmers and power companies. There was no way to get them back.

Did Gilbert, then, waste his time and the Government's money by writing a full report to answer an obsolete question? To the contrary, his report was more valuable precisely because he spent so much time on it that it became definitive. Gilbert went back to the scientific principles he needed to explain what was happening. Where these principles did not exist, as in the way rivers transport sediments, he developed them in his experiments in the flumes at Berkeley. Thus Gilbert did not stop his researches when he had answered the question at hand. Rather he made his work stand for all time.

Gilbert acknowledged in his Preface to "Hydraulic Mining Debris" that his response to an economic question like whether hydraulic mining should resume, should have been "a prompt report." Yet what survives from his research is not his answer to President Roosevelt's question. Gilbert answered the question, but it's not his answer that earth scientists still study. Rather they return again and again to his two reports on the Sierra mining debris because they teach the principles and practice of earth science. Both Gilbert's results and the ways he arrived at them set standards for the earth science profession and for the U.S. Geological Survey.

GILBERT AND THE SAN FRANCISCO EARTHQUAKE

The great San Francisco earthquake of April 1906 interrupted Gilbert's work in the Sierras. Awakened by the tremors, he lay in bed timing the intervals between them and deducing the motion of the ground from the shifting of the furniture around him. As a geologist, he was happy to be right there when one of the great shakings of the Earth's surface took place. Glaciers, volcanos, and earthquakes--these are the most spectacular of planetary phenomena. Gilbert had never been in a major earthquake before, and he was overjoyed.

As soon as the ferry resumed service, Gilbert left Berkeley, where he was staying, and crossed the Bay to San Francisco. There he found most of the masonry buildings in ruins, especially those that had been built on land made by filling in the old dockyards and swamps. Most of the buildings that still stood were made of wood, and many of them hung at crazy angles because their brick or stone foundations had collapsed. Fire started when chimneys and gas mains ruptured. It swept through the buildings until most of downtown San Francisco was consumed.

Both State and Federal governments organized commissions to investigate the catastrophe. Gilbert served on both. In the field he worked mostly north of the Golden Gate. There he searched for scars on the land that marked the San Andreas Fault. Along this break in the Earth's crust two parts of the surface had slipped past each other in opposite directions. This movement along the fracture was the cause of the devastating tremors. The earthquake was a rupture of the Earth's surface; the Earth's crust responded with a sudden snap to the accumulation of strain within elastic rock.

Tracing the San Andreas Fault reminded Gilbert of the fresh fault scars he had noted two decades earlier at the base of the Wasatch Mountains in Utah. These scars led Gilbert to predict an earthquake for Salt Lake City, one that has yet to occur. Near San Francisco he noted the wave-like shapes that appeared on mud flats and filled land, contributing to the destruction on the latter.

Back in Berkeley he wrote major sections of the reports of both commissions. He pointed out that each part of California had been mapped with precision only once. Hence the mapmakers had missed the changes over time caused by slow, steady movement of the Earth along the fault. Perhaps the measurers of the Earth's surface, the geodesists, should go back to the same place again and again. Then they would discern how fast the two parts of California on either side of the San Andreas fault were moving. Perhaps such continuous precision mapping might make it possible to predict when and where an earthquake would occur.

Once again Gilbert was ahead of his time. In his presidential address to the Association of American Geographers in 1909 he spoke on "earthquake forecasts." His was the only serious discussion of the subject until the 1960's. Gilbert pointed out that identifying areas likely to suffer severe earthquake damage was comparatively simple. Geology could supply the criteria to pick out places subject to earthquakes, and engineering could estimate the amount of possible damage. So a prediction of the place of an earthquake could be made, but not a prediction of the time. There were no obvious criteria that Gilbert could see to estimate the time that an earthquake might strike. If one could make an approximate prediction, tension would build among the populace in that area. It might be worse for the public to predict an earthquake than to live in happy ignorance, especially since no prediction can be perfect. It would be sufficient, Gilbert thought, to build earthquake-proof buildings in places where the risk of earthquakes was high. It took about half a century before this point of view became public policy in earthquake-prone parts of the United States. Though we have vastly greater knowledge, we are not much nearer predicting the time of great earthquakes than we were in Gilbert's day.

GILBERT'S FINAL MASTERPIECE

When he finished his work on the Sierra mining debris, Gilbert was past 70. There remained one final project to complete. With the Wheeler Survey in the 1870's Gilbert discovered that the Colorado Plateau and the Great Basin were both the result of large vertical motions. The Basin and Range Province was formed when huge blocks of terrain were alternately dropped into troughs, or raised, along parallel zones of faults. These blocks that moved up or down were not uniform; rather they contained layer after layer of rock that had been folded in complex ways. Gilbert's theory of the Basin and Range was the first theory of how mountains were built that did not require that compression make the Earth's crust crumple.

Gilbert described the Basin and Range system in his reports for the Wheeler Survey, and he had longed to give it the monographic treatment it deserved. When he first put forward his novel idea that large vertical movements built mountains, it was rejected by most geologists. They could be convinced only by a full-length study.

Gilbert published little on the subject after he left the Wheeler Survey. In 1891 he wrote the section on the Salt Lake Region in the guidebook for the excursion to the West from the International Geological Congress of 1891. He described in the guidebook and pointed out in the field the fault scars at the base of the Wasatch Mountains. They were the evidence from which he predicted an eventual earthquake near Salt Lake City.

Then in 1900 another member of the Geological Survey, J. E. Spurr, put forward a theory of the Basin and Range Province that was totally different from Gilbert's. To Spurr the Rocky Mountains, to the east of the Great Basin, were just like the folded mountains of the Appalachians. These eastern mountains, all geologists agreed, were formed when horizontal layers of the Earth were compressed together. The folded layers or strata were then eroded. The strata that resisted erosion the most became mountains. Those that resisted erosion the least became valleys.

Eager to prove Spurr wrong, Gilbert got himself assigned to the Great Basin region for the summer of 1901. There he worked out the structure of the House and Fish Spring Ranges of mountains in Utah. But he abandoned the writing of his results when all the maps and topographic records were destroyed by his topographer, Willard D. Johnson (1859-1917), in a psychotic episode.

Sickened over the loss of his maps, Gilbert interrupted his work on the basin ranges for more than a decade. Then in 1914, on his way to San Francisco, he stopped at Odgen, Utah, for half a month in the field. After he completed his mining-debris studies, Gilbert threw all his energies into investigating the basin ranges. He travelled to Klamath Falls, Oregon, where he found the same features on the east side of the Cascades--the other side of the Great Basin from the mountains of Utah. In the summers of 1916 and 1917 Gilbert drove along the Wasatch front. During the winters he began writing his monograph on the basin ranges, the greatest problem of his geologic career.

Gilbert's health failed before he could complete the work. Weakened by his earlier stroke, he had recovered enough to resume a normal life, but by 1916 he was an old man who tired easily. He could write only a few hours a day. Yet he soldiered on.

Early in 1918 Gilbert set out for California to celebrate his birthday and to marry Alice Eastwood, a botanist. As usual on his cross-country journeys, he stopped to visit his sister in Jackson, Michigan. Gilbert never made it any further. Just before his 75th birthday he collapsed and died, never to see the congratulatory letters that poured in from all over the world to honor the man whom one distinguished foreigner called "the most highly esteemed geologist of America."

Thus Gilbert did not live to complete his study of the Basin and Range Province. What he did finish appeared in 1928, ten years after his death. "Studies of Basin-Range Structure" (Gilbert, 1928), though not so comprehensive as it might have been, is Gilbert's final masterpiece.

Beginning in the 1880's, geologists had developed, through committees of the Geological Survey, the Geological Society of America, and the successive International Geological Congresses (held every 3 or 4 years), a precise technical language. Through careful use of this language and through close observation in the field, Gilbert in his posthumously published monograph gave final form to his insights of 50 years before.

During that half century a context had developed within which his arguments could be made in precise detail. He demonstrated conclusively that the mountains of the Wasatch Range were formed by faulting. Huge blocks of the Earth's crust were lifted up, leaving sharp scars as they separated from the blocks to the west. These scars became covered in places by the debris eroded from the rising blocks of mountains.

Gilbert's demonstration joined the evidence from the sculpture of the land on the evidence from the structure of the mountains and valleys. There were two kinds of observations that both showed the Wasatch Range to be formed by faulting. Having shown the association between the two kinds of evidence, Gilbert could search for only one in the other areas of basins surrounded by ranges. If he found it, he could conclude that the same process was at work.

Here Gilbert turned from the Wasatch to other areas. In them he found sculptural but not structural evidence for faulting. His proof that these ranges, too, had originated in the vertical movements of huge blocks of the Earth's crust was only sketched. He did not complete the extension of his demonstration of the origin of the Wasatch Range. Thus he missed, as his biographer William Morris Davis lamented, the chance to put forward a comprehensive theory of mountain building, one that would add great horizontal movements of crustal extension to the great vertical movements he had demonstrated.

GILBERT'S PERSONAL LIFE

Grove Karl Gilbert grew up in Rochester, New York, the youngest of three children of the artist Grove Sheldon Gilbert and his wife Emma. Throughout his life G. K. remained close to his brother Roy, who stayed in Rochester, and his sister Emma Loomis, who settled in Jackson, Michigan.

Shy and solitary, G. K. Gilbert spent most of his youth with books and nature. But the warmth of his parents' family and his years in the field made him a good companion. In Washington for the winter to write his reports, Gilbert lived with his fellow naturalists Henry Henshaw and E. E. Howell and developed a strong friendship with Archibald Marvine, also a geologist with Wheeler.

Gilbert soon took to courting Marvine's wife's younger sister, Fannie Porter. She and Gilbert married in November, 1874, but tragedy marred their marriage. Fanny's brother-in-law, Gilbert's close friend Archibald Marvine died in March 1876, followed by the Gilberts' eldest child, Betsy, in 1883. After 1881 Mrs. Gilbert became chronically ill. She died in 1899, leaving her husband to care for their two young sons, Arch and Roy. With his wife an invalid for almost 20 years and his sons at boarding school, summer camp, or visiting their uncle in Rochester, Gilbert never developed for his children the home life of his youth. His substitute for it for himself, once his wife died, was to share in the family life of colleagues. In Washington he lived with C. Hart Merriam, director of the Biological Survey. During the summer Gilbert generally spent a month in the household of Professor J. H. Comstock of Cornell University. With both the Comstocks and the Merriams Gilbert enjoyed both the warmth of family and the solitude he needed for his science.

GILBERT THE MAN

Frank, direct, and courteous, Gilbert lived a long life without apparently making a single enemy. His generosity was as legendary as his frugality. Mindful of his own penniless college days, he arranged through the Comstocks to lend money without interest to needy students at Cornell. At his death he left $1,000 for a revolving loan fund there.

Like any person who leaves a mark on history, Gilbert had immense powers of self-discipline. He never let himself get angry because anger was useless and unscientific. But his unremitting preoccupation with the ways our planet works did not make him dull or cold. Far from it; he always had a good story for his friends or was ready to laugh at theirs. Behind a gracious dignity he hid a nature so emotional that he had trouble suppressing tears when he read a moving passage from a book. Everyone he met seems to have loved him.

His religious views were a paradox. He was raised in a free-thinking household, and the death of his beloved daughter at the age of 7 extinguished the last traces of his belief in a supernatural Deity. Yet no one lived a more unselfish life. One of his devout colleagues said of him that "Gilbert was one of the most Christlike men I ever knew." He never forced his opinions, geological, religious, or political, on others. Rather he had an abiding faith that the evidence he did so much to unearth would in time convince all the doubters as it had convinced him.

GILBERT THE EARTH SCIENTIST

It's hard to convey what the life of an earth scientist means. When we study the Earth and the processes that formed it, we study particular places. To each of these places we bring a set of general principles and a complicated technical vocabulary. Most of what we have to say gets expressed in a map, drawn in innumerable colors, and marked with strange symbols. Geology is not easily explained to the uninitiated.

Gilbert's life work thus has a remote and abstract quality to it that makes his importance difficult to demonstrate. Yet, of all the geologists who have tried to understand the evolution of the North American continent, Gilbert stands out. He wrote about every subject he took up in clear, simple (though technical) language that has stood the test of time. His four great monographs: on the Henry Mountains, on Lake Bonneville, on Sierra mining debris, and on basin-range structure, are among the greatest geological literature ever written. They and his other voluminous writings are studied and restudied by earth scientists today. Each is filled with important insights into the way our planet and its satellite, the Moon, work. Not all of Gilbert's profound insights have yet been fully digested. The astonishing range of his investigations continues to inspire earth scientists, especially those of the Geological Survey.

In spite of many tempting offers to teach at universities, Gilbert remained with the Survey for his entire career. Part of his reluctance to leave was probably his devotion to his chief, John Wesley Powell. But part was also his sense that his commitment to the highest standards of scientific research could be fulfilled as well, if not better, in this agency of the Federal government. The Geological Survey has striven constantly to make its science reach the highest standards. Gilbert's career in its service demonstrates the Survey's past commitment to these standards and offers a challenge for the future to continue to meet them.

The final words on Gilbert's career ought to be left to those who knew him personally. The first is T. C. Chamberlin, geologist with the Survey, President of the University of Wisconsin, and founder of the University of Chicago's distinguished Department of Geology. In his memorial to Gilbert in 1918, Chamberlin said: "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."

The second witness to Gilbert's importance is W. C. Mendenhall, a younger colleague at the Survey who served as its Director from 1930 to 1943. To Mendenhall, "In sheer balanced mental power, Gilbert was probably unsurpassed by any geologist of his time. Fundamental among the qualities of his mind were self-knowledge and self-control. These qualities he possessed in a degree equaled by few. That mind which he knew and controlled so well as a quiet, efficient, powerful instrument, which functioned perfectly. Thus he was the very antithesis of the brilliant, temperamental, erratic genius."

Finally, we hear from George Otis Smith, Director of the Survey when Gilbert died. Smith tried hard in his 23 years as Director, the longest term by far, to bring the Survey's high scientific standards to bear on the great public problems of land use and resource allocation. So to Smith the highest praise he could offer was to say that "Pure science as given to the world by Grove Karl Gilbert was useful science." Indeed Gilbert's science was useful, and it continues to be. He transcended the immediate practical questions to try to answer only the most fundamental ones. He answered them at the deepest level he could reach. Gilbert made his science useful not only to his contemporaries. He made it useful far beyond his own lifetime and our own. Gilbert's science will last for as long as people live on the planet Earth.

SUGGESTIONS FOR FURTHER READING

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