PROLOGUE

The Forgotten Ice Age

Twenty-thousand years ago, the earth was held in thrall by relentlessly probing fingers of ice—ice that drew its power from frigid strongholds in the north, and flowed southward to bury forests, fields, and mountains. Landscapes that were violated by the slowly moving glaciers would carry the scars of this advance far into the future. Temperatures plummeted, and land surfaces in many parts of the world were depressed by the unrelenting weight of the thrusting ice. At the same time, so much water was drawn from the ocean to form these gargantuan glaciers that sea levels around the world fell by 350 feet, and large areas of the continental shelf became dry land.

This period in the earth's history has come to be called the ice age. In North America, glacial ice spread out from centers near Hudson Bay to bury all of eastern Canada, New England, and much of the Midwest under a sheet of ice that averaged more than a mile in thickness. A second ice sheet spread out from centers in the Canadian Rockies and other highlands in western North America to engulf parts of Alaska, all of western Canada, and portions of Washington, Idaho, and Montana. In Europe, the ice reached outward from Scandinavia and Scotland to cover most of Great Britain, Denmark, and large parts of northern Germany, Poland, and the Soviet Union. A smaller ice cap, centered on the Alps, buried all of Switzerland and nearby portions of Austria, Italy, France, and Germany. In the southern hemisphere, small ice sheets developed over parts of Australia, New Zealand, and Argentina. In all, the ice covered about 11 million square miles of land that is today free of ice.

Immediately south of these great northern-hemisphere ice sheets, the landscape was treeless tundra. Here, during the short,

Figure 1 Earth today (left) and during the last ice age (right). Twenty-thousand years ago, great ice sheets covered parts of North America, Europe, and Asia; surface waters of the Arctic and parts of the North Atlantic Oceans were frozen; and sea level was 350 feet lower than it is today. Many parts of the continental shelf, including a corridor between Asia and North America, became dry land. (Drawing by Anastasia Sotiropoulos, based on information compiled by George Denton and other members of the CLIMAP project.)

cool summers, heather and other hardy, low-growing plants grew in the boggy soil. Migrating herds of reindeer and mammoths grazed upon this lush plant cover during the summer months, and in winter moved southward seeking more favorable pastures. In North America, the tundra was only a narrow belt of land that served to separate the ice sheets to the north from forested areas to the south. In the eastern part of the continent, spruce trees grew in a continuous forest; in the more arid Midwest, the stands of spruce followed the rivers, while in between there were dusty grasslands.

In Europe and Asia, the tundra belt was wider than it was in North America, giving way only gradually to a vast expanse of semiarid grassland that stretched from horizon to horizon—across two continents from the Atlantic coast of France, through central Europe, to eastern Siberia.

Stone Age hunters, following herds of mammoth and reindeer across the tundra, could glimpse the southern edge of the ice sheet. As the cold penetrated their deerhide clothing, and the wind from the north whipped their faces, it would have been difficult for these people to realize that their descendants would inhabit a very different world from their own.

Yet the ice age did come to an end. About 14,000 years ago, the ice sheets began to retreat. Within 7,000 years they had withdrawn to their present limits. Today, all that remains of the ice sheets in the northern hemisphere are the Greenland Ice Sheet and a few small ice caps in the Canadian Arctic. Where modern farmers reap Iowa corn and Dakota wheat, mile-high glaciers once ground their way over the land. And, where European forests stand today, treeless plains once stretched to the horizon.

As the glaciers melted back, the landscape they left behind was greatly altered—a landscape strewn with traces of its glacial origin. In northern regions, the ice sheets had ground away at the underlying surface, scratching deep grooves in the bedrock, and swallowing bits and pieces of eroded material. This material had been transported outward to the margins of the ice sheets where it was deposited in a chaotic jumble known as a moraine (Figure 2).

As the ice sheets withdrew, human recollections of them began to fade. Racial memory—if it exists at all—must be imperfect, for the world of the Stone Age hunters was soon forgotten. Even the

Figure 2. Glacial deposit on Cape Ann, Massachusetts: the landscape is typical of areas once covered by ice sheets. (From J.D. Dana, 1894.)

clues left behind by the great ice sheets were misinterpreted. By the eighteenth century, geologists surmised that the blanket of glacial sediments had been transported and deposited by the great flood described in the Bible. It was only in the early years of the nineteenth century that some scientists began to question this explanation. Were floodwaters—even divinely inspired ones—actually capable of transporting gigantic boulders hundreds of miles, or was some other agent responsible?

1

Louis Agassiz and the Glacial Theory

Few residents of the town of Neuchâtel in Switzerland were stirring at 4:15 A.M. on the morning of July 26, 1837. Had they been, they would have observed a long line of well-made carriages creaking slowly through the cobbled streets of their sleepy town. In fact, very few people were aware that three of the most respected scientists of the day shared the first and grandest carriage, which was drawn by four white horses.

Leopold von Buch—whose gray locks and bent frame belied his boundless energy—stared morosely at the floor of the swaying carriage. Jean Baptiste Elie de Beaumont—erect and outfitted with consummate good taste despite the ungodly hour at which his valet had awakened him—glared coldly at the ice-capped peaks of the Alps, 50 miles distant across the Swiss plain, and at the surrounding, and less daunting, Jura. The third passenger in the carriage—a dark-haired, broad-shouldered young man with a bright, curious gaze—looked out of the window and reflected grimly that only Elie de Beaumont's manner could rival the chilly remoteness of the Alpine peaks that seemed to hold themselves proudly aloof from the caravan of rattling carriages.

Elie de Beaumont's frigid demeanor perturbed the young man. For Louis Agassiz, with his quick, inquisitive mind, found it incomprehensible that a scientist of Elie de Beaumont's mark could fail to see the import of this particular journey through the Jura mountains.

Two days earlier, the Swiss Society of Natural Sciences had held its annual meeting in Neuchâtel, and the young president of the society, Louis Agassiz, had startled his learned associates by presenting a paper dealing not, as the distinguished members of the society had expected, with the fossil fishes lately found in far-off

Brazil, but with the scratched and faceted boulders that dotted the Jura mountains around Neuchâtel itself (Figure 3). Agassiz argued that these erratic boulders (chunks of rock appearing helter-skelter in locations far removed from their areas of origin) could only be interpreted as evidences of past glaciation—and an ancient age of ice.

Figure 3. Scratched stone from a glacial deposit in Europe. Boulders of this kind are common features of glaciated landscapes. (From J. Geikie, 1877.)

Thus began a dispute—one of the most violent in the history of geology—that was to rage on for more than a quarter of a century and end with universal acceptance of the ice-age theory. Although the concept of an ice age did not begin with Agassiz, his controversial paper (later known as "the Discourse of Neuchâtel") served to bring the glacial theory out of scientific obscurity and into the public eye.

As president of a Swiss scientific society, Agassiz found himself in an ideal position to present his theory to the elite of the nineteenth-century scientific world. He was, however, only one link in a chain that eventually would lead to general acceptance of the startling theory that a moving sea of ice had at one time covered large areas of the globe.

This theory, initially rejected by the most renowned scientists of the age, had long been accepted as fact by many Swiss who lived and worked in the mountains and so came into daily contact with evidence of an extensive past glaciation. A few noted scientists and naturalists became early converts to the theory, but these few lacked opportunities to promote their ideas successfully.

As early as 1787, Bernard Friederich Kuhn, a Swiss minister, interpreted local erratic boulders as evidence of ancient glaciation. Seven years later, James Hutton—the Scottish geologist who is now regarded by many to be the father of the science of geology—visited the Jura and reached the same conclusions as Kuhn. In 1824, Jens Esmark saw evidence of former extensive glaciers in Norway. Esmark's views were known to Reinhard Bernhardi, a German professor of natural science who later made observations of his own. In 1832, Bernhardi published an article arguing that a polar ice cap had once spread across Europe to reach as far south as central Germany.

Many of these early pioneers developed their ideas completely independently, through personal observation and deduction. But so deeply entrenched was the accepted explanation of erratics as the deposit of a great flood, that none of these men was able to make their revolutionary ideas widely known. It would demand the combined efforts of some of the greatest scientific minds of the age, over a period of 25 years, to overthrow the established theory.

It is not surprising that in such a religious age scientists and laymen alike believed that these boulders had been transported by unimaginably huge currents of water and mud deriving from the biblical deluge of Noah's time. This theory did undergo some revision, however, and when Agassiz made his presentation to the Swiss Society of Natural Sciences in 1837, the accepted explanation for erratics was one that had been developed in 1833 by the great English geologist, Charles Lyell. Lyell argued that the agents responsible were boulder-laden icebergs and ice rafts that had drifted about in the great flood.

The chain of creative thinkers and fortunate circumstances which led up to Agassiz' presentation at Neuchâtel began with Jean-Pierre Perraudin, a mountaineer from the southern Swiss Alps. Perraudin made his living hunting chamois near Lourtier in the Val de Bagnes. As a result of his own observations, he came to the conclusion as early as 1815 that the glaciers, which then occupied only the higher, southern portion of the Val de Bagnes, had once filled the entire valley. He wrote:

> Having long ago observed marks or scars occurring on hard rocks which do not weather, I finally decided, after going near the glaciers, that they had been made by the pressure or weight of these masses, of which I find traces at least as far as Champsec. This makes me think that glaciers filled in the past the entire Val de Bagnes, and I am ready to demonstrate this fact to incredulous people by the obvious proof of comparing these marks with those uncovered by glaciers at present.

In 1815, Perraudin communicated his ideas to Jean de Charpentier, a naturalist who would later become an important advocate of the glacial theory. Impressed by the mountaineer's observations—but as yet unconvinced—de Charpentier wrote:

> Although Perraudin extended his glacier only [24 miles beyond its present limit to Martigny], because he himself probably had never been beyond that town, and although I agreed with him on the impossibility of transporting erratic boulders by water, I nevertheless found his hypothesis so extraordinary and even so extravagant that I considered it as not worth examining or even considering.

Sometime during the next three years, however, Perraudin was to find a sympathetic ear at last in the person of Ignace Venetz, who was by profession a highway and bridge engineer. From

Figure 4. Zermatt glacier in the Swiss Alps as depicted in an illustration published by Louis Agassiz in 1840. (From A.V. Carozzi, 1967, with permission of A.V. Carozzi and the University of Neuchâtel.)

1815 to 1818, Venetz spent a great deal of time in the Val de Bagnes area in connection with his work. During this period he had many discussions with Jean-Pierre Perraudin on the subject of glaciers. It was an historic and fortunate association.

Venetz was somewhat slow to adopt Perraudin's theories. In 1816, at the annual meeting of the Swiss Society of Natural Sciences at Bern, he brought up the subject of glaciers, but only to present some ideas on glacial movement and to describe how elongate accumulations of rock debris (moraines) form along the surface of glaciers (Figure 4). Five years later, Venetz was still reluctant to commit himself fully to the glacial theory. In a memoir dated 1821 (unpublished until 1833), he noted that he had identified several ridges of rock debris located three miles beyond the terminus of the Flesch glacier and suggested that these deposits were moraines left by that glacier in earlier times.

Venetz did not fully develop the ideas he had gleaned from Perraudin until 1829 when at the annual meeting of the Society at the Hospice of the Great St. Bernard, he stated his conclusion that immense glaciers had once spread out from the Alps to cover not only the Swiss plain and the Jura, but other parts of Europe as well. In support of this theory he described the distribution of erratic boulders and moraines, and compared these deposits to those formed by contemporary Alpine glaciers.

Despite Venetz's forthright but long-delayed presentation, the theory was generally ignored or rejected outright by the scientists who were present at the meeting. One man, however, saw the truth of the theory, and subsequently came to Venetz's aid. That man was Jean de Charpentier, who had long been acquainted with Ignace Venetz. As director of the salt mines at Bex in Switzerland, de Charpentier took a lively interest in science and the natural world. Now—like the prodigal son—he was ready to back Venetz and to stand squarely behind the theory he had rejected almost 15 years earlier.

Over the course of the next five years (1829–1833), de Charpentier brought his remarkable powers of reasoning to bear on the problem of ancient glaciation. Although Venetz had been the first to accept the radically new ideas of Perraudin, it was de Charpentier who gave the glacial theory an unshakeable foothold in scientific fact by organizing and classifying the evidence that supported it. But de Charpentier was a pure scientist—lacking in those qualities of aggressiveness and perseverance that would be

required to win acceptance for the glacial theory. Resistance to the theory was strong; its defense must be equally so.

While the well-known scientists of the day clung steadfastly to the established ice-raft theory developed by Lyell and supported by the very words of the Bible, many Swiss people had long ago accepted the glacial theory. The irony of this situation struck de Charpentier forcefully when, on his way to present a paper on the glacial theory before the 1834 meeting of the society in Lucerne, he found some unexpected support.

> Traveling through the valley of Hasli and Lungern, I met on the Brunig road a woodcutter from Meiringen. We talked and walked together for a while. As I was examining a large boulder of Grimsel granite, lying next to the path, he said: "There are many stones of that kind around here, but they come from far away, from the Grimsel, because they consist of Geisberger [granite] and the mountains of this vicinity are not made of it."
>
> When I asked him how he thought that these stones had reached their location, he answered without hesitation: "The Grimsel glacier transported and deposited them on both sides of the valley, because that glacier extended in the past as far as the town of Bern, indeed water could not have deposited them at such an elevation above the valley bottom, without filling the lakes."
>
> This good old man would never have dreamed that I was carrying in my pocket a manuscript in favor of his hypothesis. He was greatly astonished when he saw how pleased I was by his geological explanation, and when I gave him some money to drink to the memory of the ancient Grimsel glacier and to the preservation of the Brunig boulders.

In spite of the woodcutter's toast, the theory was once again rejected by the society at Lucerne. But in the audience—and among those who rejected the theory—was Louis Agassiz.

Agassiz had first met de Charpentier while at school in Lausanne. Indeed, it may have been his great admiration for de Charpentier that influenced Agassiz in his decision to become a naturalist. Now, 10 years later, Agassiz himself was established as one of Europe's foremost men of science. Despite his admiration and liking for de Charpentier, however, Agassiz at first found it impossible to accept the glacial theory.

The older de Charpentier had often invited his young colleague to visit him at his home since the area around Bex boasted many fossils and geological features that he felt would be of interest to Agassiz. In 1836, two years after de Charpentier's presentation at Lucerne, Agassiz accepted de Charpentier's invitation and spent the summer at Bex. At this time, Agassiz was occupied chiefly with his research on fossil fishes. Although Agassiz, like the majority of scientists, subscribed to Lyell's ice-raft theory, he was not averse to seeing for himself whatever evidence his friend, de Charpentier, could show him in favor of the glacial theory. Agassiz went to Bex expecting to demonstrate to de Charpentier the fallacy of the glacial theory. Instead, he himself was speedily converted.

The gentle de Charpentier believed firmly in the idea that alpine glaciers had once extended far beyond their present limits, but he did not see it as the duty of a scientist to push for publication and widespread acceptance of this theory. De Charpentier was content to demonstrate the facts to friends and associates who visited him at Bex because he was confident that the theory would eventually prove itself. So it was that the glacial theory—born from the observations of simple peasants, developed by Ignace Venetz, and systematized by Jean de Charpentier—at last found a forceful spokesman in the person of Louis Agassiz (Figure 5).

Once converted, Agassiz was a quick and avid learner. In the company of de Charpentier and Venetz, he visited the glaciers of the Diablerets and the Chamonix valley, and the moraines of the Rhone valley. The evidence spoke for itself, and this time Agassiz listened. In a matter of weeks, he absorbed all that de Charpentier and Venetz could teach him. Agassiz soon outstripped his mentors. Using the facts that they had so painstakingly collected over the course of seven years, Agassiz quickly constructed a comprehensive glacial theory that he was confident would withstand the attacks of its enemies. Unfortunately, in his eagerness to present the theory, Agassiz took liberties with de Charpentier's work that the scrupulous gentleman found unforgivable. On several important points, Agassiz' expanded version of the theory went far beyond the available evidence.

In his excitement, Agassiz underestimated the opposition to the theory. The address that he presented to the Swiss Society of

Figure 5. A portrait of Louis Agassiz at the Unteraar Glacier by Alfred Berthoud, now in the Library of the University of Neuchâtel. (From A.V. Carozzi, 1967, with permission of A.V. Carozzi and the University of Neuchâtel.)

Natural Sciences at Neuchâtel on July 24, 1837 had been hurriedly written the night before, and Agassiz was ill prepared for the reaction he received. The members of the society had expected to hear news of their young president's research on fossil fishes. They were somewhat startled when he launched into a very different subject.

> Just recently, two of our colleagues [de Charpentier and Venetz] have generated through their investigations a controversy of far-reaching consequences for the present and the future. The characteristics of the place in which we meet today suggest my talking to you again of a subject which, in my opinion, may be solved by the investigation of the slopes of our Jura. I have in mind glaciers, moraines and erratic boulders.

Agassiz went on to describe in detail his own observations and those of Venetz and de Charpentier. He interpreted these observations as evidence that masses of glacial ice once blanketed the Jura. This ice, he said, was part of an immense polar ice sheet that had covered Europe as far south as the Mediterranean, as well as large parts of North America. Borrowing a term from his friend Karl Schimper, a botanist, he described this period of the earth's history as an ice age (*Eiszeit*). The ice sheet was supposed to have originated before the Alps were formed, then to have slid downward toward the Jura during a later uplift of the region. The erratic boulders and polished rocks still visible in the area indicated the path taken by these moving masses of ice (Figure 6).

Agassiz' concept of an ice age shocked many in the audience. In fact, Agassiz' "Discourse" caused such a furor that the scheduled proceedings for the day were thrown into confusion. One timid soul, Amanz Gressly, was so upset by the commotion that he never got around to reading the manuscript he had brought with him on the theory of sedimentation, later an important addition to geology.

Agassiz' address succeeded in rousing strong emotions on both sides of the glacier issue. In the lively discussion that took place in the geology section afterwards, tempers ran high and sharp words flew. Almost every scientist present found Agassiz' statements impossible to accept.

The meeting continued into the next day when Agassiz brought up observations he had made in the Jura mountains

Figure 6. An illustration of polished bedrock near Neuchâtel, Switzerland published by Louis Agassiz in 1840. Agassiz argued that polished and grooved rock surfaces, occurring many miles from existing glaciers, were clear evidence of a former ice age. (From A.V. Carozzi, 1967, with permission of A.V. Carozzi and the University of Neuchâtel.)

around Neuchâtel itself. He also read an endorsement of the theory by Karl Schimper. But resistance to the theory was still strong. With the arrival of Elie de Beaumont, the opposition closed ranks.

Agassiz was sure that even the toughest of skeptics could not fail to be convinced, as he himself had been, by the evidence contained in the rocks themselves. A field trip to the Jura mountains was planned for the following day, and arrangements were hastily made for the members of the society to travel by carriage from Neuchâtel to La Chaux-de-Fonds in the heart of the Jura. An amused participant later wrote:

> In general, I was convinced by my short acquaintance with the leading scientists of the party that a great amount of jealousy and egoism existed between them. Elie de Beaumont was, during the entire trip, as cold as ice. Leopold von Buch was walking straight ahead, eyes on the ground, mumbling against an Englishman who was talking to Elie de Beaumont on the Pyrenees while we were in the Jura, and complaining rather offensively about the stupid remarks made by some amateurs who had joined the group. Agassiz, who was probably still bitter about the sharp criticisms made by von Buch of his glacial hypotheses, left the group immediately after departure and was walking a quarter of a league ahead all by himself . . . .

Angry that his colleagues seemed to be unimpressed by the evidence of glaciation all around them, Agassiz may well have reflected unhappily that the long journey into the mountains, over the rough road with the tired horses, had been to no purpose after all.

If that is what he thought, he was wrong. For his "Discourse," the field trip, and his monumental *Studies on Glaciers* (published in 1840), would at long last focus the attention of the scientific world on the issue of ancient glaciation. Despite some exaggerations, the courageous address Agassiz had delivered at Neuchâtel in 1837 served an important purpose. From that time on, however forcefully its opponents might argue against it, the glacial theory could no longer be ignored.

In the years that followed the Neuchâtel meeting, Agassiz continued his research on ancient glaciation, despite strong criticism from leading European scientists. In December 1837, Alexander von Humboldt urged Agassiz to return to his research on fossil fishes: "In so doing," he wrote, "you will render a greater service to positive geology, than by these general considerations (a little icy besides) on the revolutions of the primitive world, considerations which, as you well know, convince only those who give them birth."

It would be many years before von Humboldt came to realize that Agassiz—far from pursuing a chimera—had actually been among the first to recognize the truth. Now it would be Agassiz' task to convince other scientists that the earth had indeed experienced an ice age.

2

The Triumph of the Glacial Theory

With his daring imagination, bold assertions, and vigorous prose style, Agassiz had little difficulty capturing the attention of a wide audience. Certainly statements like the following would attract attention in any age:

> The development of these huge ice sheets must have led to the destruction of all organic life at the Earth's surface. The ground of Europe, previously covered with tropical vegetation and inhabited by herds of great elephants, enormous hippopotami, and gigantic carnivora became suddenly buried under a vast expanse of ice covering plains, lakes, seas, and plateaus alike. The silence of death followed . . . springs dried up, streams ceased to flow, and sunrays rising over that frozen shore . . . were met only by the whistling of northern winds and the rumbling of the crevasses as they opened across the surface of that huge ocean of ice.

The idea that a catastrophe of awful intensity might once have extinguished the life of the entire planet was not a new one. In fact, it was commonly believed that the history of the earth was divided into several epochs, each one of which had terminated in a catastrophe powerful enough to deform existing layers of sediment and rock, set off floods of incredible magnitude, uplift mountains, and destroy all plant and animal life on the planet. At the beginning of each succeeding epoch, it was believed, new life was breathed into the ravaged world—life which would survive only until the next great cataclysm occurred.

Catastrophism was the dominant geological philosophy in the eighteenth and nineteenth centuries because it neatly accounted for the fossilized animal remains that were being unearthed by geologists. The fact that the concept explained the fossil record without undermining the word of God, as set forth in the Old Testament, made it all but unshakeable.

It seemed obvious to scientists and laymen alike that the great flood that depopulated the earth, sparing only Noah and his ark full of animals, was in fact the catastrophe that had brought the last epoch to a watery close and launched the present one. For example, when the huge fossilized tooth of a mastodon was unearthed in a peat bog near Albany, New York in 1706, it was confidently judged to belong to one of the unfortunate and sinful people who had inhabited the earth before the Deluge of Noah. Governor Dudley of Massachusetts examined the specimen and then sent it off to the Boston preacher, Cotton Mather:

> I suppose all the surgeons in town have seen it, and I am perfectly of the opinion that it was a human tooth. I measured it, and as it stood upright it was six inches high lacking one eight, and round 13 inches, lacking one eight, and its weight in the scale was 2 pounds and four ounces, Troy weight . . . . I am perfectly of the opinion that the tooth will agree only to a human body, for whom the flood only could prepare a funeral; and without doubt he waded as long as he could keep his head above the water, but must at length be confounded with all other creatures and the new sediment after the flood gave him the depth we now find.

And 20 years later, in Switzerland, Johan Scheuchzer uncovered a collection of fossil bones in the deposits of an ancient lake. He concluded that they were the remains of an antediluvian man, destroyed by the Flood. Scheuchzer published a book under the title *Homo diluvii testis* ("The Man Who Witnessed the Flood"). Almost a century passed before the great French anatomist, Baron Georges Cuvier, examined the bones and correctly identified them as those of a giant, now extinct, salamander.

Agassiz himself had furthered the doctrine of catastrophism with his marvelously detailed illustrations of fossil fish and other extinct animals that were supposed to have lived during earlier epochs. Thus, in substituting an ice age for a flood, Agassiz challenged the established view of the nature of the last great catastrophe, but not the belief that a catastrophe had occurred.

A strong supporter of the flood theory—and an important ally

for Agassiz if he could be won over—was the Reverend William Buckland of England. Since assuming the professorship of mineralogy and geology at Oxford in 1820, Buckland had become the most widely respected geologist in England. Like Agassiz, he had a flair for lecturing and created a stir wherever he spoke. Even at Oxford, a university noted for harboring eccentrics in many fields, Buckland was notable for the force of his personality and the oddity of his behavior. His classrooms were crammed to the rafters with a jumble of rocks, skulls, and skeletons that was famous throughout the university. Buckland believed in getting out of the classroom whenever possible and viewing geological deposits in their natural environments. On these excursions, he wore his academic robe and a dapper top hat—a habit that undoubtedly contributed to his popularity on campus. But, despite his eccentricities, Buckland was a dedicated and greatly respected scientist. Most of the leading geologists in England, including Charles Lyell, regarded themselves as his pupils.

Buckland was an ardent catastrophist. In his inaugural lecture at Oxford, "The Connexion of Geology with Religion Explained," he expressed his conviction that the objective of geology should be "to confirm the evidences of natural religion; and to show that the facts developed by it are consistent with the accounts of the creation and deluge recorded in the Mosaic writings." He was also the first scientist to devote most of his time to investigating the irregular accumulations of gravel, sand, clay, and large boulders that cover large areas of bedrock in Britain. Buckland's aim was to determine exactly how this seemingly chaotic deposit had been formed. Although there was no doubt in his mind that a flood had been the agent that had left the deposits, many questions remained to be answered.

Exactly how had the flood transported such vast quantities of debris? Buckland subscribed to the traditional view that floodwaters alone were sufficient to account for the diluvium (as it was termed by those who believed in this theory). In part, Buckland leaned towards this view because it accorded well with the biblical record. He was also convinced that this record was supported by evidence contained in the sediments themselves.

In 1821 a large number of strange bones had been discovered in a cavern in the Vale of Pickering. On hearing of this discovery, Buckland immediately traveled to Yorkshire to investigate. He found that most of the bones were those of hyenas, but scattered among them were bones of twenty-three other species including birds, lions, tigers, elephants, rhinoceroses, and hippopotamuses.

Buckland concluded that the cavern was an antediluvian hyena den that had been submerged in Noah's flood. He argued that the manner in which the bones had been covered with silt indicated that the animals had been drowned. From the quantity of post-diluvian stalagmites that had covered the floor of the cavern, he judged that the flood had occurred 5,000 or 6,000 years ago—a date, he noted, which was entirely consistent with genealogical records in the Bible.

Buckland presented his findings in a book dedicated to the Bishop of Durham: *Reliquiae Diluvianae; or, Observations on the Organic Remains Contained in Caves, Fissures, and Diluvial Gravel, and on Other Geological Phenomena, Attesting the Action of an Universal Deluge* (1823). Also included in this monumental work were the results of Buckland's studies of no fewer than twenty caves scattered over England and Europe. The book won for Buckland the Royal Society's Copley Medal and made him famous in geological circles.

Since none of these antediluvian caves contained human remains, Buckland concluded that the human species had been created only very recently. He was, therefore, somewhat shaken when the skeleton of a woman—dyed a rusty red and adorned with bits of ivory—was found in the deposits of a cave in Paviland on the southern coast of Wales. To many, this skeleton seemed to stand in direct contradiction to one of the primary tenets of the flood theory.

Buckland was able to explain the skeleton's existence, however, by pointing out that it had been encased in the uppermost layers of the sediment succession and that some clue to the reason for the lady's presence there might be found in the remains nearby of a Roman-age encampment. Putting two and two together, and suppressing a Victorian shudder of disapproval, Buckland wrote: "The circumstance of a British camp existing on the hill immediately above the cave, seems to throw much light on the character and date of the woman under consideration; and whatever may have been her occupation, the vicinity of a camp would afford a motive for residence, as well as the means of subsistence, in what is now so exposed and uninviting a solitude."

But other features of the diluvium were not as easily explained

as the skeleton of a scarlet woman. Chief among these were the erratic boulders, many the size of small houses, which had been transported from their original locations hundreds of miles away (Figure 7). In addition, scratches and grooves displayed by the bedrock surface underlying these deposits, and the unsorted nature of the deposits themselves, were puzzling indeed.

Some catastrophists argued that such phenomena were the result of huge waves of a very special type that had never been observed. The dynamics of these "waves of translation" were elaborately analyzed by mathematicians at Cambridge who carefully calculated depths and velocities and published their conclusions in scholarly journals.

Other geologists did not believe that violent currents could have been the agents responsible for moving these huge erratics. They espoused a version of the flood theory proposed by Charles Lyell in the 1833 edition of his influential textbook *Principles of Geology*. Lyell suggested that the boulders might simply have become frozen in icebergs and slowly drifted to their present erratic locations. Devotees of this iceberg theory, which nicely preserved the idea of a universal flood, named the deposit "drift" to indicate the method by which it had been transported.

Additional support for the iceberg theory was found in reports by explorers in the north and south polar regions. No less a figure than Charles Darwin, in the *Journal* (1839) of his voyage on the *Beagle*, observed that some icebergs he had seen in the southern ocean contained boulders.

But Buckland was the first to admit that neither Lyell's iceberg-drift theory nor the classical diluvial theory could provide explanations for all of the evidence. For instance, a rise in sea level of more than 5000 feet would be necessary to account for some of the drift deposited in mountainous regions. Where would this water have come from? Where would it have gone? In their frantic efforts to answer such questions, some diluvialists let their imaginations run riot—untrammeled by awkward facts. Waters gushed from underground reservoirs and disappeared as suddenly into uncharted caverns. The earth—wobbling on its axis—created tidal waves that swept up and over the highest mountains. Or a great comet had once grazed the earth's surface, causing watery convulsions of a magnitude never witnessed by humans.

Although Lyell's theory did not eliminate the "sea level problem," it could be modified to explain some drift observed at high

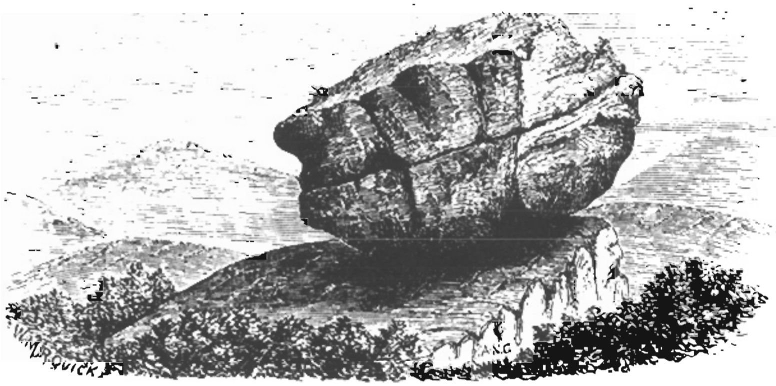

Figure 7. Erratic boulder in Scotland. Louis Agassiz attributed the occurrence of large boulders, many miles from a possible bedrock source, to the action of ice-age glaciers. (From J. Geikie, 1894.)

elevations. To account for the erratic blocks in the Jura mountains, for example, Lyell invoked not icebergs floating on the ocean, but ice rafts drifting in large lakes—lakes that had been formed when rivers had become dammed by earthquakes or avalanches.

From Buckland's journals, it is clear that he was not completely satisfied with the answers provided by either the flood theory or the iceberg theory, and he continued his search for a means of explaining every aspect of the drift. Then, in September 1838, he attended a meeting of the Association of German Naturalists in Freiberg, Germany. There he listened as his friend, Louis Agassiz, presented forceful arguments in support of the ice-age theory first presented the year before at Neuchâtel. Buckland had heard rumors of Agassiz' radical theory and had come to Freiberg with the intention of examining the evidence at first hand.

After the meeting, Buckland and his wife traveled to Neuchâtel—to the mountains that had not long before convinced Agassiz himself of the truth of the ice-age theory. There were two other people in the group of travelers. Agassiz, excited at the prospect of converting the influential Buckland, was one. The other was Charles Lucien Bonaparte, Prince of Canino and brother of the former French emperor, Napoleon. Charles was a

wealthy man with a passionate interest in natural history and little else with which to occupy his time since the French defeat at Waterloo in 1815.

Buckland had arranged the visit with Agassiz for personal as well as scientific reasons. He and his wife had met the Swiss naturalist several years earlier when they had offered Agassiz the hospitality of their home while he toured England studying collections of fossil fish. The three had become fast friends, and now the Bucklands looked forward happily to meeting Agassiz' young wife, Cecile, in Neuchâtel.

As he traveled through the mountains to Neuchâtel, Buckland's mind must have been busy. What evidence could his friend show him that would convince him of the validity of the ice-age theory? The small party wasted no time in setting out into the mountains around Neuchâtel, and Agassiz led the way, pointing out the evidences of glaciation that he was sure would tell their own story. But Buckland remained stubbornly unconvinced. Finally, Agassiz led the group into the Alps where he hoped that the actual sight of the glaciers in action would convince the professor. Buckland was convinced but only temporarily. When Mrs. Buckland wrote to thank Agassiz for his hospitality, she added: "But Dr. Buckland is as far as ever from agreeing with you." Apparently, Buckland had had second thoughts once he was out of Agassiz' commanding presence and far from the evidence in the Alpine rocks.

Agassiz was disappointed at this turn of events, for Professor Buckland was a widely respected scientist. Once converted, the Oxford geologist would be as important to the glacial theory as the Emperor Constantine had been to Christianity. In fact, although Agassiz could not know it at the time, he did not have long to wait. In the fall of 1840, the tide began to turn in his favor.

The critical event was a trip to England that Agassiz took in the summer of 1840, primarily to study fossil fish. In September, he attended the annual meeting of the British Association for the Advancement of Science in Glasgow. There he read a paper summarizing his glacial theory, emphasizing once more that: "At a certain epoch all of the north of Europe and also the north of Asia and America were covered by a mass of ice."

Predictably, the reaction of most of the audience was negative. The leader of the attack was one of the outstanding geologists in Britain, Charles Lyell. Buckland himself remained silent, for reasons that are not known. But his journals indicate that he had recently reexamined the evidence in favor of the glacial theory. Perhaps the seeds sown by Agassiz two years earlier had simply needed time to germinate, or perhaps conversion came to Buckland as it did to Saint Paul—in a blinding flash of light. In any case, soon after the meeting, Buckland invited Agassiz and another well-known geologist, Roderick Impey Murchison, to join him on a field trip to study drift in Scotland and northern England. It was this trip that finally convinced Buckland that the theory so staunchly defended by his friend Agassiz was correct. Overnight, Buckland became the first major British convert to the theory. (Murchison, however, remained unconvinced and, for the rest of his life, argued strongly in favor of iceberg drift.)

One of Buckland's first acts as a new convert was to read the scientific gospel to Charles Lyell. This he managed to accomplish in surprisingly good time, for on October 15 he wrote to Agassiz triumphantly: "Lyell has adopted your theory *in toto*!!! On my showing him a beautiful cluster of moraines within two miles of his father's house, he instantly accepted it, as solving a host of difficulties which have all his life embarrassed him."

The ice-age theory was an idea whose time had come at last. Lyell, the newest convert, lost no time in preparing a lecture entitled: "On the Geological Evidence of the Former Existence of Glaciers in Forfarshire," which he presented at the November meeting of the Geological Society of London. Agassiz himself presented a paper: "Glaciers and the Evidence of their having Once Existed in Scotland, Ireland, and England." And this time, Buckland came forward to defend the theory with his paper on the "Evidence of Glaciers in Scotland and the North of England."

With this trio of internationally famous geologists proselytizing in favor of the ice-age theory, it might be supposed that all opposition would crumble. Far from it—the general reaction of the assembled scientists was quite negative, and a heated debate took place after the lectures by Agassiz and Buckland. According to notes taken by one observer, Buckland concluded the debate:

> . . . amidst the cheers of the delighted assembly, who were by this time elevated by the hopes of soon getting some tea (it was a quarter to twelve P.M.), and excited by the critical acumen and antiquarian allusions . . . poured forth by the learned doctor, who . . . with a look and tone of triumph, pronounced upon his opponents who dared to question the orthodoxy of the scratches and grooves and polished surfaces of the glacial mountains . . . the pains of eternal itch without the privilege of scratching.

In science as in religion, belief is often the strongest in a recent convert. Less than a month earlier, Buckland had sat on his hands at the Glasgow meeting while the Agassiz theory was vigorously attacked. Understandably, his abrupt about-face at the London meeting did not go unnoticed. A popular cartoon showed the Oxford professor, complete with robe and geological kit, standing upon a scratched and deeply grooved bedrock pavement (Figure 8). Two specimens lie at the professor's feet bearing these labels: "Scratched by a glacier thirty three thousand three hundred and thirty years before the creation," and, "Scratched by a cart wheel on Waterloo Bridge the day before yesterday."

Despite the ready wit of the popular press and the adverse reaction of the members of the Geological Society, it seemed for a time that all of British geology would soon be converted to the Agassiz theory. In the following year, 1841, colleague Edward Forbes wrote to Agassiz: "You have made all the geologists glacier-mad here, and they are turning Great Britain into an ice house. Some amusing and very absurd attempts at opposition to your views have been made by one or two pseudogeologists." Events proved this report by Forbes a bit optimistic. It was another 20 years before the majority of British geologists had accepted the ice-age theory.

Why did this theory, whose validity now seems self-evident, encounter so much resistance 100 years ago? In part, the slow acceptance of the theory may be attributed to a natural resistance to new ideas—particularly if those ideas run counter to long-held scientific principles or to religious convictions. The Agassiz theory challenged both, although religious conviction was probably less of a factor than scientific orthodoxy.

For one thing, geologists had indisputable evidence that the ocean had overwhelmed land areas, not once but many times in the past. Fossil fish and fossil shells preserved in sedimentary rocks on every continent were ample proof of this. Page after page of Lyell's textbook is devoted to explaining these marine inundations and to establishing their geographic extent. The idea that the drift itself was evidence of a particularly turbulent flood

Figure 8. The Reverend Professor Buckland, equipped as a "glacialist." A contemporary cartoon by Thomas Sopwith, showing the Oxford professor well equipped to study glaciers, and standing on a scratched bedrock surface. In the original cartoon, the specimens at his feet are labeled: "Scratched by a glacier thirty three thousand three hundred and thirty years before the creation," and "Scratched by a cart wheel on Waterloo Bridge the day before yesterday." The version reproduced here was published by Archibald Geikie, who removed the labels in deference to his friend. (From A. Geikie, 1875.)

was the natural extension of a general and familiar principle.

In fact, it was the almost complete absence of marine fossils in the drift that led many researchers to doubt its marine origin. If this absence had been complete, the glacial theory would probably have been accepted much earlier. Unfortunately, however, some drift deposits did contain marine fossils, and these "shelly drifts" were a thorn in the side of glacial theorists like Agassiz. Shelly drifts are not widespread; they occur near modern coastlines in New England, in Germany, and in several places in Scotland and northern England. But they do exist, and in the mid-1800s diluvialists studied these marine fossils carefully and pointed to them as further proof that the drift that encased them has been transported not by glaciers but by icebergs floating in floodwaters.

The deposits of shelly drift succeeded in confounding even the staunchest defenders of the glacial theory until, in 1865, a Scot named James Croll was able to explain them as the work of ice sheets moving over areas that are now covered by shallow seas. The moving ice had scraped shells and mud from the sea floor and subsequently deposited them in their present locations. According to Croll, the fossilized sea shells are simply erratic boulders in miniature, transported from their submarine homes by glacial ice.

Another factor that worked against acceptance of the Agassiz theory was the general ignorance of glaciers among geologists. If these geologists found it difficult to understand glaciers, they found it next to impossible to imagine ice sheets of the magnitude that Agassiz postulated. Not until 1852 did a scientific expedition clearly establish that the Greenland glaciers form a huge ice sheet. It was only later in the century that the true dimensions of the Antarctic Ice Sheet were established (Figure 9). Inevitably, as these polar explorations proceeded, and as geologists working in mountainous areas observed the action of valley glaciers, it became easier for the scientific community to accept the idea that Europe had once been submerged under an ice sheet similar to those now found in Greenland and Antarctica. Predictably, those geologists who lived in mountainous regions of Scotland, Scandinavia, and Switzerland found this idea easier to accept than did those who lived in lowland areas near the sea. To this latter group of geologists, the concept of a marine flood seemed the most reasonable explanation for the drift deposits.

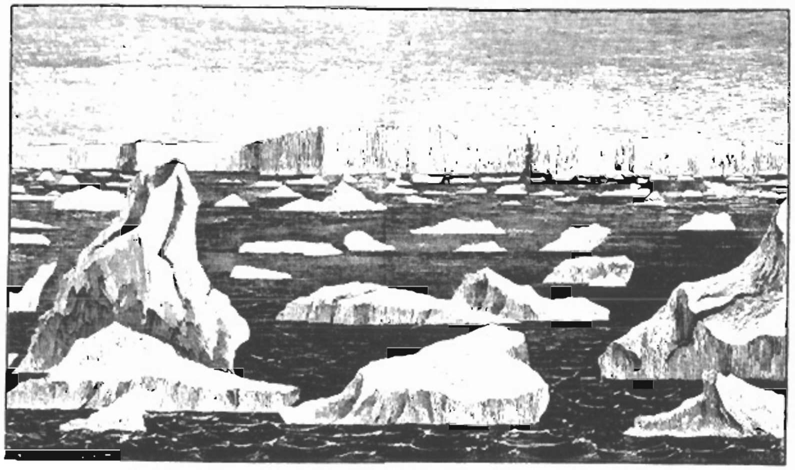

Figure 9. Antarctic Ice Sheet. As knowledge of the polar regions advanced during the nineteenth century, geologists were able to draw comparisons between modern ice sheets and conditions during the ice ages. (From J. Geikie, 1894.)

Yet another factor that worked against the glacial theory was the extravagance of Agassiz' assertions. In his excitement, the Swiss naturalist persisted in claiming a much greater geographic extent for the ice sheets than the evidence supported. In 1837 he stated that the ice had extended as far south as the Mediterranean. The fact that no drift deposits were ever found in these southern areas made it all the easier for skeptical scientists to reject the rest of the arguments Agassiz presented.

As the years passed, Agassiz' assertions about the extent of the ice-age glaciers grew ever more extravagant. In 1865, while on an expedition to South America, he discovered evidence that the glaciers of the Andes had once extended far beyond their present positions. From this evidence Agassiz drew the conclusion that the ice sheets that had covered Europe and North America had extended into the continent of South America as well. No hard evidence of such an extension existed, so Agassiz succeeded only in raising the hackles of geologists. Lyell wrote: "Agassiz . . . has gone wild about glaciers . . . . The whole of the great [Amazon] valley, down to its mouth was filled by ice . . . .

[Yet] he does not pretend to have met with a single glaciated pebble or polished rock." Fortunately, however, enough evidence had already been found in Britain and on the mainland of Europe to ensure the acceptance of the glacial theory by all but the most dedicated diluvialists.

While the scientific battle raged in Europe, Agassiz himself departed for America. The trip was planned at the urging of Charles Lyell, who had recently visited the United States and wanted the Swiss naturalist to see the New World for himself. Lyell waved farewell to Agassiz from the dock at Liverpool in September 1846, confidently expecting to see him again before another year passed.

After a rough crossing, Agassiz' ship docked briefly at Halifax before sailing on to Boston. Agassiz hurried ashore, eager to find evidence to support his theory: "I sprang on shore and started at a brisk pace for the heights above the landing . . . . I was met by the familiar signs, the polished surfaces, the furrows and scratches, the line engravings of the glacier . . . and I became convinced . . . that here also this great agent had been at work."

Agassiz was welcomed to Boston by John Amory Lowell, who invited him to live in his comfortable home on Pemberton Square. Like others before him, Lowell soon fell under Agassiz' spell. As a successful owner of a textile mill and member of the Corporation of Harvard University, Lowell was in a good position to make sure that the great European naturalist made Massachusetts his permanent home. Early in the following year, a professorship was created for Agassiz at Harvard. Agassiz, who by this time was in some financial difficulty, accepted the offer gratefully. America was his home until his death in 1873.

Agassiz traveled widely in his adopted country, and he was delighted to find that news of his glacial theory had preceded him. In fact, the theory had already been accepted by many American scientists. As early as 1839, just two years after Agassiz' lecture at Neuchâtel, the American paleontologist Timothy Conrad published a brief paper noting that "M. Agassiz attributes the polished surfaces of the rocks in Switzerland to the agency of ice, and the diluvial scratches, as they have been termed, to sand and pebbles which moving bodies of ice carried in their restless course. In the same manner I would account for the polished surfaces of rocks in Western New York." Two years later, the

State Geologist of Massachusetts, Edward Hitchcock, delivered an address on the subject of Agassiz' theory before the newly formed Association of American Geologists.

By the mid-1860s, some 30 years after it was proposed, the glacial theory was firmly established on both sides of the Atlantic. Scattered opposition was voiced for many years, the last attack being a 1000-page treatise published by the English eccentric, Sir Henry Howorth, in 1905. But none of the opposition could stand against the evidence in favor of Agassiz' theory. The existence of an ice-age world was now taken for granted. Serious research on that world was about to begin.