I

ICE AGES

How much can global climate change? While we frequently hear this question debated nowadays in terms of a warmer future, it was originally at the heart of one of the biggest geologic controversies of the mid-nineteenth to twentieth centuries—the existence and causes of great Ice Ages in the past. An Ice Age in the largest sense is a period of Earth history when there is permanent ice cover on the planet. The Northern Hemisphere has been in such a generally cold state for about the past 2.5 million years, known as the Quaternary era. The term *Ice Ages* is also used, however, to refer to a series of global climate oscillations that occurred within the Quaternary when large ice sheets periodically advanced into and retreated from the mid-latitudes. So from the big perspective of Earth history, humans are still living in an Ice Age with large glaciers near the poles on Greenland and Antarctica. But on the finer scale, Earth is between Quaternary Ice Ages with no big ice sheets currently extending beyond the high latitudes.

Researchers now take it for granted that only twenty thousand years ago glaciers flowed south out of Canada all the way to the present location of New York City; but two centuries ago it was difficult to conceive of something so extreme. The Ice Age debate ignited, modestly enough, over misplaced rocks. Large granite boulders were found sitting on the limestone bedrock of the Jura Mountains in Switzerland. They resembled rocks outcropping in the Alps, but these were 100 kilometers (62 miles) away. What could have transported the boulders such a distance? The conventional view was that Noah's Flood had done it, but in 1837, Swiss American geologist Louis Agassiz (1807–1873) shocked the geological world, claiming that the Alps had once been covered by gigantic glaciers that flowed out from the mountains and carried along anything in the way. Worse yet, Agassiz went on to suggest that northern Europe and North America had been covered by even larger, continental-sized blocks of ice. Such a fantastic theory needed more than a few misplaced boulders to be taken seriously.

THE EVIDENCE UNDERFOOT

As geologists combed through more dirt, mud, and rock though, they found traces of an ancient Ice Age almost everywhere. Parallel bedrock scratches carved by flowing glaciers flowing were seen from Scotland to Nova Scotia. Hummocky piles of sediment were found meandering along the plains of America and Europe outlining the margins of now-vanished ice sheets; Cape Cod and Long Island are two such hummocks. Shoreline features showed that global sea level had risen by over a hundred meters as ice sheets melted away. Thick sequences of wind-blown silt born from the grinding action of ice on rock blanketed areas south of the ice sheets and became the fertile soil on which much of the American ''breadbasket'' relies today. Taken together, it became clear by the 1860s that Agassiz's glacial theory was correct, and that ice sheets up to several kilometers thick had covered North America from the Arctic Ocean to Chicago, and Europe from the northern tip of Scandinavia to central Germany. Farther away from these ice sheet-covered regions, the Ice Age chill left its imprint in other ways all over the world. Alpine glaciers expanded in most major mountain ranges, large lakes grew in some areas that today are arid, and vegetation patterns shifted radically. Over recent decades, scientists have developed new techniques to ever more precisely map out conditions around the Ice Age world based on climate indicators such as the chemistry of ocean plankton shells, old layers of snowfall in glaciers, and cave stalagmites. This vast body of evidence paints a rich patchwork of environmental change and makes it clear that no corner of the world was unaffected. But what could cause something as massive as an Ice Age to come and go?

THE CAUSES OVERHEAD

A wide and imaginative variety of ideas was proposed to explain the Ice Ages, including variations in the strength of the Sun, the frequency of sunlight-blocking volcanic eruptions, Earth's passing in and out of cosmic dust clouds, and random internal fluctuations within the climate system akin to daily weather, although on a much larger and longer scale. Most attention, however, focused on astronomical factors.

Earth's orbit around the Sun varies through time in three ways due to the gravitational tug of the other planets on it. The orbit stretches to become more or less elliptical over a 100,000-year cycle, the tilt of Earth's spin axis bobs up and down a few degrees every 40,000 years, and the axis wobbles, or precesses, like a spinning top, making a complete revolution every 20,000 years. In 1842 French mathematician Joseph Adhémar (1797–1862) proposed that these astronomical factors might explain the Ice Ages, although there was a curious aspect as to how they affect Earth. The orbital variations have negligible impact on the total amount of sunlight striking Earth over the course of a year, but they can have large effects on how solar energy is distributed between different seasons and latitudes on the planet. So, what would the critical season and location be for driving the growth and decay of ice sheets? Adhémar suggested that colder winters in the northern high latitudes would allow more snow to build up and eventually become an ice sheet. Serbian polymath Milutin Milankovitch (1879–1958), the twentieth-century

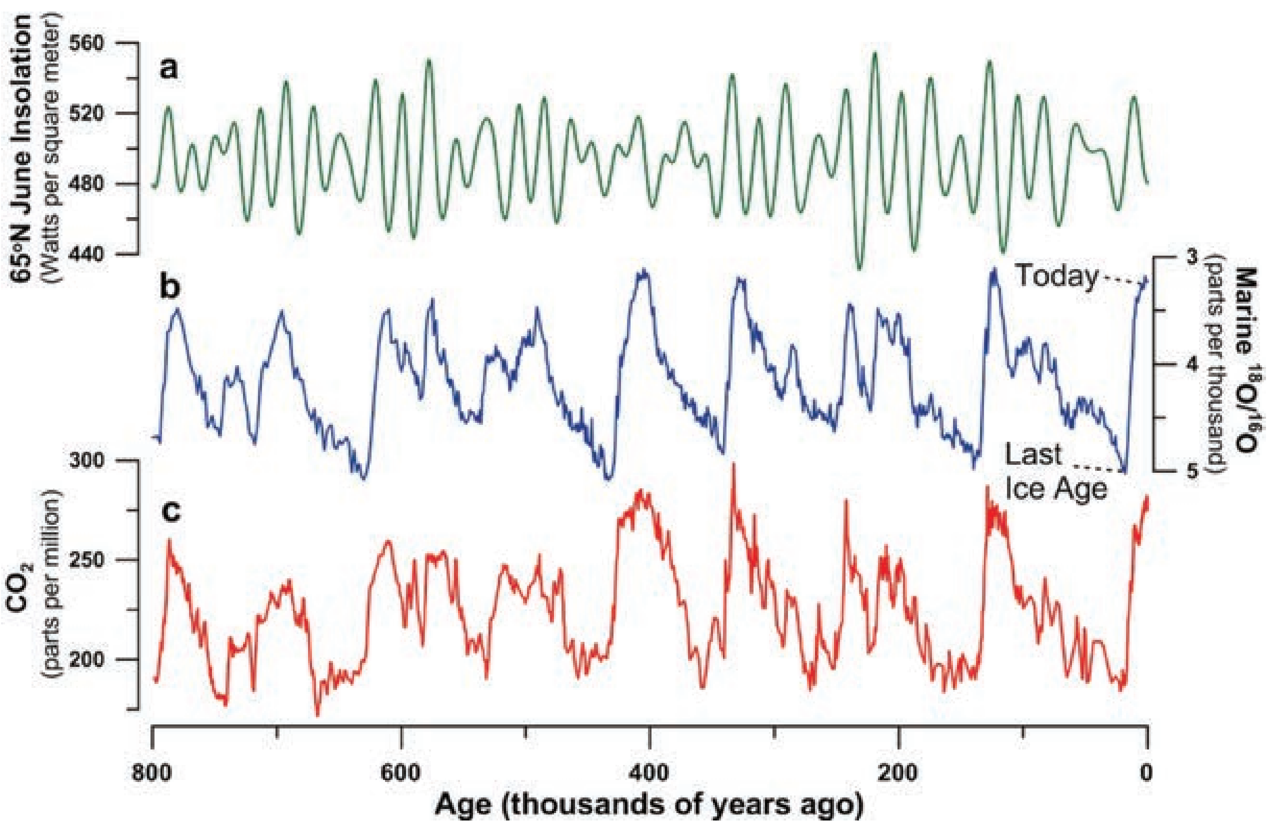

Figure 1. *Ice Ages and drivers of climate change over the past 800,000 years: (a) Arctic summer insolation variations due to Earth's orbital cycles (Laskar, 2004), (b) the marine oxygen isotope record (Lisiecki and Raymo, 2005), which reflects the amount of ice on the planet, with the present and peak of the last Ice Age denoted, and (c) atmospheric CO_2 concentrations recorded in Antarctic ice cores (Lüthi et al., 2008). Insolation variations are thought to be the initial trigger of Ice Age cycles, though feedbacks within the climate system, such as the reflectivity of ice and atmospheric greenhouse gas levels, are important for amplifying the climate changes and making them global in extent.*

EXPLORER'S VOICE: JEREMY SHAKUN

Jeremy Shakun

When I was a kid and there was nothing good on TV, I almost always flipped on The Weather Channel. I had my favorite weatherman. I followed hurricane season a bit like pro football. And I really got psyched when big snowstorms were coming (I even saved a container of snow from the Blizzard of '93 for years in my parents' freezer). I also loved the outdoors—climbing mountains, going skiing, playing in creeks, you name it. So when I stumbled onto paleoclimatology during college—the science of piecing together Earth's climate history from mud, rock, and ice (sort of like a crime-show forensics detective but with hiking boots)—I was hooked. Here was a career where I could do fun science outside.

During graduate school, I was blown away as I learned about all of the clever ways that scientists had figured out how to reconstruct past climate from rings on trees, mud on the sea floor, stalagmites in caves, and much more. Even more interesting was finding out how much the climate had changed in the past, from cold snaps when the entire planet was frozen over to warm spells when crocodiles swam in the Arctic. And sometimes the climate had jumped abruptly in just a few years. This education helped me to realize that the planet can change far more dramatically than I ever would have guessed based on my own experience. What really made me appreciate the significance of paleoclimate though and approach research with a new perspective—driven more by the science and less by a desire to get out in the mountains—was growing to understand the mountain of evidence showing that humans are changing the climate, and will continue to do so ever more profoundly if we keep burning fossil fuels. As certain as this basic point is, there is also lots of uncertainty in just how much, how fast, and in precisely what ways climate will change in the future—and these details may be very important to how well society is able to cope with global warming.

Paleoclimate is full of unanswered but relevant questions that can help us glimpse what the future might hold. A big one comes from Antarctic ice cores. These two-mile long cylinders of old snowfall layers compressed into ice and full of trapped air bubbles show that temperature in Antarctica rose and fell in lock-step with atmospheric CO_2 levels over the ice ages of the past million years. That makes sense—CO_2 causes warming, right? But there's a catch; Antarctic temperature appears to have often changed before CO_2 levels did. Does this mean that CO_2 was an effect and not a cause of climate change in the past... and so maybe our carbon emissions won t cause much warming in the future either? Unfortunately not. A key point is that while the CO_2 trapped in ice core air bubbles reflects its global concentration, since CO_2 is well-mixed by the winds, the temperature recorded in the ice only reflects local conditions. Temperature can of course do different things at different places, and when we combined temperature records from all over the world spanning the end of the last ice age, we found that global average temperature tracked closely behind CO_2—just like you would expect if rising CO_2 was critical to ending the ice age. We then looked at how global temperature varied since the ice age ended, and during which time human civilization arose, and found something even more striking. A long-term cooling of less than 1°C over the past several thousand years reversed during the twentieth century, and the globe has since warmed by roughly the same amount. It is thus clear that global climate has already or will soon warm outside the bounds that human society has ever experienced.

My future research plans are to collect more paleoclimate records from the Arctic to the Antarctic and the mountains to the ocean to better understand how potent of a greenhouse gas CO_2 is, what controls the melting of ice sheets, and where tipping points in the climate system might lie that could accelerate global warming. Given the significance of climate change to society in the twenty-first century, I also think that scientists must help communicate the knowns and unknowns of the science to the public, who will have some big decisions to make on how much global warming we allow to happen and how we adapt to the changes it brings.

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champion of the astronomical theory, however, realized that the Arctic is already sufficiently cold enough to be snow covered all winter, and so summers would have the larger effect on whether an ice sheet lives or dies by controlling how much snow survives from one winter to the next. These orbital cycles could be precisely calculated for millions of years into the past (see Figure 1), which meant that the astronomical theory could be tested if the timing of several past glaciations could be determined. The best place to look was the oceans because they record a continuous history of events on the continents through the constant rain of sediment to the seafloor, if it could be determined as to how to read this book.

ORBITAL RHYTHMS IN OCEAN MUD

In the mid-twentieth century, following the discovery of the neutron, paleoceanographers found a way of solving this problem. Most oxygen atoms have an atomic weight of 16, but a smaller portion of oxygen atoms have two extra neutrons giving them a weight of 18. Since water containing oxygen-16 atoms evaporates more readily than water with oxygen-18 atoms, oxygen-16 is preferentially removed from the ocean as ice sheets build up on land, and the residual ocean water grows increasingly rich in oxygen-18. This changing concentration of oxygen isotopes in ocean water, which tracks the amount of glacial ice on the planet, gets recorded in the oxygen-bearing calcite shells of marine plankton that accumulate on the seafloor over time. This isotope record was analyzed in 1976 and provided a stunning confirmation of the astronomical theory; it displayed variations with precisely the same periodicities as Earth's orbital cycles—20,000, 40,000, and 100,000 years. Not only that, but the record also showed that there had been dozens of Ice Ages over the past couple million years (see Figure 1). Clearly the planet's climate had been anything but stable during recent Earth history and orbital variations were the ultimate cause behind it. But since orbital cycles merely redistribute sunlight around the world rather than changing the total amount of energy striking it, how did they trigger global-scale Ice Ages?

One factor is straightforward. Ice sheets are very reflective, and so as a region cools and an ice sheet grows, it reduces the amount of sunlight absorbed, causing further cooling and ice growth in a self-reinforcing feedback loop. This factor might account for much of the cooling around the ice sheets, but it probably cannot explain why the tropics and Southern Hemisphere also cooled down. A plausible solution to this riddle was discovered over the past few decades from long ice cores drilled through the Antarctic Ice Sheet. Air bubbles trapped in the ice provide an 800,000-year-long record of atmospheric carbon dioxide (CO_2) concentrations and show that the level of this greenhouse gas marched in lockstep with the Ice Ages (see Figure 1). Since CO_2 is uniformly distributed throughout the atmosphere, it provides an obvious way to link climate changes around the world. Paleoclimate data and computer models suggest that several other factors likely also contributed to Ice Age climate change, including varying atmospheric dust levels, vegetation changes, and ocean circulation fluctuations.

Scientists are now fairly confident that they have pinned down the main ingredients responsible for producing an Ice Age, but a detailed theory of the chain of events linking the subtle orbital shifts overhead to the large Ice Age climate changes recorded underfoot remains to be fully established. And as CO_2 levels today are almost 50 percent higher than at any time in the past 800,000 years due to human fossil-fuel burning, and as they are expected to double or triple this century, better understanding Ice Age history may shed light on our greenhouse future.

SNOWBALL EARTH

Much larger and more ancient Ice Ages than those in the Quaternary era have come to light since the 1990s, and they have once again stretched the imagination of scientists to reconsider what is possible for Earth's climate. Bedrock formations in many places around the world display cobbles lying in ocean muds, and the only way they could have gotten there is by melting out of icebergs. Plate tectonics causes continents to move around the world over millions of years, so it could just be that these so-called dropstones were deposited near the cold poles as continents drifted over them. However, the orientation of magnetic minerals in some rocks can be used as a sort of paleo-compass to determine where they were deposited, and this evidence shows that many of these deposits formed near the equator. Glaciers dumped icebergs into the ocean in the tropics? If there were glaciers here, it seems like they must have been everywhere—a Snowball Earth. Other evidence also seems to support this idea of an ice-covered planet. Carbon isotope ratios in the ocean plummeted during such Snowball events, which could reflect the die-off of most marine life as might be expected during such a deep freeze. Banded iron formations are sometimes associated with Snowball deposits, and as they are deposited only in anoxic waters, they may signify an ice-sealed, oxygen-starved ocean (see Figure 2). These various pieces of evidence suggest that there was an extended Snowball phase from 2.4 billion to 2.1 billion years ago as well as several other briefer Snowball events around 750 million to 650 million years ago.

Early climate modeling in the 1960s showed how a Snowball Earth could form. If an ice sheet advances beyond a critical latitude of roughly 30°, the feedback

Figure 2. *A banded iron formation from western Australia, similar to the ones deposited on the sea floor during Snowball Earth episodes. Since these rocks only form in low-oxygen conditions, their association with Snowball Earth deposits suggests that the ocean became ice-covered and oxygen-starved at these times.* © CARY WOLINSKY/NATIONAL GEOGRAPHIC CREATIVE

loop between ice sheet growth and cooling associated with greater reflection of sunlight back to space becomes unstoppable, and ice will advance all the way to the equator. More difficult to explain perhaps is how Earth would ever escape from a Snowball state. The likely answer is that volcanoes continued erupting and belching CO_2 into the atmosphere. While CO_2 is normally taken up by the ocean, biosphere, and lithosphere, these carbon sinks would have been shut down during a Snowball event, allowing CO_2 levels to build ever higher. This process would have come to an end eventually when greenhouse warming would have started melting back the ice, triggering a rapid global meltdown as retreating ice now amplified warming by increasing solar absorption. A super-greenhouse state would ensue until the excess CO_2 could be scrubbed from the atmosphere. Is there any evidence of this mind-blowing snowball-to-greenhouse climate whiplash? Yes, in fact there is. Snowball Earth dropstone layers are often topped off by thick limestone sequences that may reflect the products of intense rock weathering on land as carbonic-acid rain, the result of elevated CO_2 levels, fell over glacially chewed-up continents.

Snowball Earth raises a plethora of difficult questions that remain unanswered. Was such an event really possible, and, if so, how did life survive? Some scientists think that Earth was more like a Slushball with open waters in the tropics, perhaps providing a refuge for organisms. Others think that life clung to deep-sea hydrothermal vents beneath a fully frozen Snowball Earth. Did this global event change the course of evolution? Life remained incredibly simple for the first 4 billion years of Earth history, but multicellular organisms rapidly emerged and diversified shortly after the last Snowball event, suggesting it may have spurred natural selection. On the other hand, the evolution of photosynthesis led to the rise of oxygen, shifting carbon in the atmosphere from the potent greenhouse gas methane (CH_4) to weaker CO_2, suggesting a way that life may have instead triggered a Snowball cooling.

THE LITTLE ICE AGE

The world has recently warmed out of a general cold spell from roughly 1350 to 1850 C.E. called the Little Ice Age. This period was only a tiny fraction of the big chill of a Snowball Earth or even the last Ice Age, but it still had significant impacts on people. Soon-to-be American President George Washington (1732–1799) led troops across an anomalously icy Delaware River in 1776, River Thames frost fairs were held in London from 1607 to 1814 on water that today does not freeze, and the collapse of Viking settlements in Greenland around 1450 may have been related to the encroaching chill. Even drinking habits may have been affected—northern European grape harvests suffered during the Little Ice Age, driving a switch from wine to beer, a preference that later migrated to the Americas. Glaciers in many mountain ranges around the world also advanced (see Figure 3). The Little Ice Age mostly pre dates instrumental weather observations, but tree rings, ice cores, and glacier advances indicate that the Northern Hemisphere, and perhaps the globe as a whole, may have reached nearly 1°Celsius (33.8°F) colder than present.

What brought on this little chill? Several factors may have acted in concert. Long-term climate records suggest that the Little Ice Age may have been the culmination of a multi-thousand-year cooling trend, likely related to orbital variations, although astronomical forcing is too gradual to explain the colder centuries and decades within the Little Ice Age interval. An intriguing candidate to explain these fluctuations may be the Sun. There were several weaker-than-average intervals of solar output during the Little Ice Age, including the seventy-year-long Maunder Minimum of the seventeenth century when almost no sunspots—an indicator of solar activity—were observed. Volcanoes have the power to cool the planet for a few years after a major eruption by blocking out sunlight, and a string of several large eruptions could also have made the climate colder. Yet another possibility is that the global overturning circulation of the ocean, which brings a substantial amount of heat northward across the equator in the Atlantic, may have weakened and contributed to Northern Hemisphere cooling. Lastly, the climate exhibits internal fluctuations unrelated to any particular driving force, and this variability likely also played a role in shaping Little Ice Age cooling.

Figure 3. *An 1870 postcard of the Rhône Glacier in Switzerland held up against the same scene today shows that it, like many glaciers around the world, was considerably larger during the Little Ice Age of the fourteenth to nineteenth centuries.* **DOMINIC BUETTNER/THE NEW YORK TIMES/REDUX**

SEE ALSO *Atmosphere, General Circulation Models of the; Climate Change; Geologic Time; Ocean Circulation; Plate Tectonics; Volcanoes; Weather Forecasting by Numerical Processes.*

BIBLIOGRAPHY

Crowley, T. J. "Causes of Climate Change over the Past 1000 Years." *Science* 289, no. 5477 (2000): 270–277.

Genthon, Christian, et al. "Vostok Ice Core: Climatic Response to CO_2 and Orbital Forcing Changes over the Last Climatic Cycle." *Nature* 329, no. 6138 (1987): 414–418.

Hays, J. D., J. Imbrie, and N. J. Shackleton. "Variations in the Earth's Orbit: Pacemaker of the Ice Ages." *Science* 194, no. 4270 (1976): 1121–1132.

Hoffman, P. F., and D. P. Schrag. "The Snowball Earth Hypothesis: Testing the Limits of Global Change." *Terra Nova* 14, no. 3 (2002): 129–155.

Imbrie, John, and Katherine Palmer Imbrie. *Ice Ages: Solving the Mystery*. Cambridge, MA: Harvard University Press, 1979.

Jansen, E., et al. "Paleoclimate." In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Susan Solomon et al., pp. 434–497. New York: Cambridge University Press, 2007.

Laskar, Jacques, et al. "A Long-Term Numerical Solution for the Insolation Quantities of the Earth." *Astronomy and Astrophysics* 428 (2004): 261–285.

Lisiecki, L. E., and M. E. Raymo. "A Pliocene-Pleistocene Stack of 57 Globally Distributed Benthic $\delta^{18}O$ records." *Paleoceanography* 20 (2005). doi:10.1029/2004PA001071.

Lüthi, D., et al. 2008. "High-Resolution Carbon Dioxide Concentration Record 650,000–800,000 Years before Present." *Nature* 453 (2008): 379–382.

Mann, Michael E. "Little Ice Age." In *Encyclopedia of Global Environmental Change*, edited by Michael C. MacCracken and John S. Perry, pp. 504–509. Chichester, UK: Wiley, 2002.

Ruddiman, William F. *Earth's Climate: Past and Future*. New York: W. H. Freeman, 2008.

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IDEAL GAS LAW

SEE *Avogadro's Law.*

IGNEOUS ROCKS, EVOLUTION OF

The phrase "evolution of igneous rocks" refers not only to a concept concerning the process by which silicate magmas change the composition of their liquids during progressive crystallization, but also to the title of one of the most important published geologic works of the twentieth century, Norman L. Bowen's 1928 book, *The Evolution of the Igneous Rocks,* published by Princeton University Press. In order to best appreciate the basic concepts that underlie these principles of chemical and mineralogical evolution of magmatic systems that Bowen pioneered, and which later geologists have further developed, it is useful first to review both a very brief history of igneous petrology (the study of igneous rocks) and the nature of the physical materials (melts and their crystalline products) that constitute magmatic systems, and then to look at implications for diversity of magmas and igneous rocks. Igneous rocks are those rocks—plutonic rocks when formed at deeper levels within the crust and volcanic rocks when formed at the surface—that consist of high-temperature minerals that have textural relationships to each other (for example, interlocking grain boundaries) indicating an origin as products of melt crystallization.

The existence of magmas must have been obvious even to the earliest human populations and their hominid ancestors, especially those in the highly volcanic East African Rift in which our ancestors originated, and around the Mediterranean, where volcanoes are common and to some extent shaped the development of classical culture. Volcanoes erupt magma that is observable at Earth's surface, and based on the chemistry of the erupted material, either lava flows or explosively erupted ash deposits form. But aside from this obvious connection of volcanic activity with hot and liquid magma, the inference that magmas had been present, and had crystallized to form rocks under Earth's surface, eluded observers until the late eighteenth and early nineteenth centuries. Igneous rocks in outcrop could easily be seen, but their origin as crystalline products of a crystallized, cooled original liquid was the source of active debate.

In terms of the history of geology, this debate particularly regarded fine-grained basaltic rocks and was between the Neptunists, led by German geologist Abraham Gottlob Werner (1749–1817), and the Plutonists, one of whose primary early adherents was Scottish geologist James Hutton (1726–1797). The Neptunists regarded basalts as having been formed through the deposition of sediment on the seafloor, much like dark limestone, and the Plutonists argued that the minerals of igneous rocks indicated a high-temperature origin. It took the invention of experimental petrology in the early nineteenth century to demonstrate the molten origin of igneous rocks. As an example, Scottish geologist Sir James Hall (1761–1832) crushed basalt, melted it to a glowing liquid state, and then allowed it to cool and form crystals that reproduced the original basalt. Other researchers observed cross-cutting veins and dikes of