



# Ice Ages

## An Alien Idea



James Croll

When most people think about ice ages, the first thoughts that come to mind might be from a movie: big glaciers, cold temperatures, woolly mammoths, and sabre-tooth tigers. Perhaps imagining exactly what an ice age was like is difficult because these trademark animals are long extinct, and the glaciers have receded far away from most civilization. No wonder almost a hundred years of accumulated evidence and lengthy arguments were needed to convince scientists that the Earth had undergone a number of these climactic cycles. When the last ice age ended about 12,000 years ago, human civilization began to flourish as it developed new techniques of agriculture and city-building. Modern science has developed a great interest in the ice ages, not only for its effect on humans, but in light of the questions surrounding the recent issue of human-provoked global warming. While modern students find it natural to accept that an ice age once existed, the first presentations of ice age theories were mercilessly attacked by the most knowledgeable minds of the time. This is the story of how scientists battled over the idea of ice ages.

When scientists talk about ice ages, they really are talking about snow, in the form of glaciers. Glaciers are formed by the packing of snow over time. The key to making a glacier isn't super-cold temperatures, but actually a very snowy region that keeps cool over a long time. As new snow falls, it compresses older snow and pushes out the air until the snow turns into ice and acts as a giant solid. This new surface is impermeable to water and oxygen, which explains why so many well-preserved fossils can be found in glaciers. In very snowy areas, glaciers can be formed in as little as five years; in very arid areas, it might take over 3,000 years. The hallmark of an ice age, as compared to normal glacier formation, is when glaciers approach sea-level and persist throughout the year over great stretches of land. As the glaciers drift and recede, they can move an enormous amount of soil, rocks, and even life forms thousands of miles. Since the last ice age was over 10,000 years ago, determining the effects of glacial action on rock from normal erosion was difficult. Because of this difficulty, proposing and defending a model of ice ages was immensely difficult for its first advocates.

The most effective way to understand how a scientific idea eventually comes to be accepted or rejected is to examine the debate surrounding it. In the case of ice ages, we will

go back to the mid-nineteenth century in Europe, where the Swiss naturalist Louis Agassiz had been convinced by a number of people that the best way to account for geological oddities was that glaciers had once covered the European continent. At first, many people detested his ideas and were only convinced after extensive argumentation. The story doesn't end there, though, because Agassiz couldn't explain why the Earth had formerly seen extensive glaciation but no longer had such features.

At that point, the Scottish scientist James Croll proposed that variations in the Earth's orientation toward the Sun were responsible for colder time periods. But he was never quite able to convince his contemporaries of this argument. His ideas would lie dormant for almost a hundred years before being picked up by the Serbian mathematician Milutin Milankovitch. Milankovitch improved upon Croll's equations and came to a significant conclusion: slight changes in the Earth's orbit could cause significant changes in its climate. Further scientific evidence showed that these climate changes amplified each other, leading toward what we now consider an ice age.

**1. Note the significant international work on this scientific puzzle (Switzerland, Scotland, Serbia, and later the United States), competition between theories, and time required for scientific ideas to be settled. How does this accurate reflection of science compare to the view that is often portrayed in science classes and science textbooks?**

In Europe in the 1800s, three perspectives dominated how the Earth developed over time: (1) the cooling globe model of Comte de Buffon; (2) the Neptunist theories of Abraham Werner (named after Neptune, the Roman god of the sea); and (3) the deluge story of the Bible. The following is a short summary of these ideas that you may have already encountered in your geology course. With Buffon's cooling globe, the Earth began as a molten ball of rocks and iron and cooled uniformly over time to the present configuration. In Werner's Neptunist view, the Earth began as a giant ocean carrying sedimentary rocks that

eventually collected and formed bedrock and the upper layers into which the great waters receded. Finally, in the Biblical model, the Earth was created and the catastrophic Noachian flood formed the current topography. All of these models had their supporters and detractors and featured scientific and philosophical arguments. At times they even crossed boundaries and shared ideas.

What they all had in common, however, was that the Earth either had a static or uniformly directional climate. For example, in the Neptunist and Biblical models, the temperature of the Earth was the same in the past as it was now; in the Buffon model, the Earth was much hotter in the past and cooled over time. There were no cycles of hot-cold climate changes in any of these models. Despite their varying origins and proclamations, they worked well within known laws of physics until around 1850. At that time, the second law of thermodynamics, or entropy, became well established. With entropy, nearby systems of different temperatures would balance, with hot objects always losing heat to cold objects (i.e. the Earth to outer space). This described Buffon's system perfectly, and challenged Neptunist and Noachian models to explain how the climate didn't cool over time. However, the inclusion of entropy in the climate models did not lend any support to the possibility that climates could undergo long periods of hot-cold cycles.

**2. That the concept of ice ages seemed so alien to naturalists of the time should now make sense. To think of such a variation in climate was entirely against everything they knew. Given this previous information, it's important to state this bluntly: Even when theories dominate a field, more powerful theories may later be developed that better explain phenomena and make new and more exact predictions. How does this illustrate that scientific knowledge, even when well established, has a tentative character?**

But evidence existed that didn't fit well with any of the prevailing ideas. Mountain-dwelling people and explorers had always known something was very strange about rocks in the mountains. Massive granite boulders, formed from the bedrock of the Earth, could be found sticking out like a sore thumb on flat grasslands, isolated limestone hills, or far up in the mountains. Most of these boulders featured strange scratch marks that looked nothing like volcanic or erosion marks. In English these objects were called "erratic boulders," and naturalists of the day struggled to explain their origins.

Jean-André de Luc proposed that pressurized air in caves launched these rocks far into the air and landed them far

away. Horace-Bénédict de Saussure found de Luc's ideas ridiculous, instead arguing that catastrophic floods elevated the boulders. James Hutton pointed out that water could carry small sediments but not very large boulders. He instead argued that only glaciers could carry such massive rocks far from their original source, but he also argued that this occurred long ago before erosion had carved the peaks and valleys of the mountains. In other words, the boulders settled on flat land long ago and through erosion and uplift found themselves in unnatural situations. Note that none of these models required a dramatic change in climate.

Before the model of ice ages, the most popular method of explaining erratic boulders was called the "drift theory," which was sort of like placing Hutton's theory into a Neptunist worldview. Drift theory claimed that at some distant point in the past when the landmasses were covered in water, icebergs drifted from the arctic regions southward toward Europe and America. As they entered this warmer climate, they melted and released rocks, silt, and debris. The drift theory was supported by a number of notable scientists. But anyone who did not support the idea that the world was entirely covered by water opposed the drift theory.

Explanations involving a great change in climate began to appear around 1815. That year, the hunter Jean-Pierre Perraudin arrived in the Swiss Alps and noticed topographical similarities between the ice-laden mountains and the ice-lacking lowlands. Perraudin began telling associates that he thought glaciers had once penetrated these lowlands, and very probably other parts of Switzerland as well. These ideas had an effect on the engineer Ignatz Venetz, who first began publishing these ideas in 1821 and finally had devised a comprehensive system in 1829. According to Venetz, these formerly extensive glaciers carried erratic boulders to their current positions.

Venez had a rough time convincing people of his ideas, but managed to persuade Jean de Charpentier, the director of a salt mine in the Swiss town of Bex. Charpentier also received resistance to this idea, but was encouraged when he found support in an unlikely location: the Swiss peasantry. The one thing in common between Perraudin, Venetz, and Charpentier is that they had all traveled and lived among the glaciers. In chats with locals along the way, Charpentier realized that the peasants had long known that the granite boulders were entirely unlike the limestone mountains. The local people also maintained glaciers had long ago carried these boulders to their current locations. Still, Charpentier needed to convince the educated masses outside of Switzerland. His biggest problem, however, was that he just wasn't very good at defending his ideas in front of others.

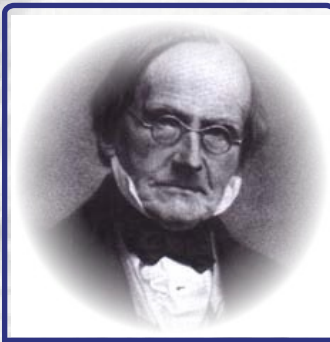


**So far, we've seen just how many people and how much evidence is often required to develop and support a scientific claim. Also, we can see how prior experience and thinking impacts the progress of ideas. For example, as of 1830, most people who observed and experienced the Alpine glaciers came to think that glaciers had once extended far beyond the region. Comparatively, many people who argued against extensive glaciation had never seen a glacier.**

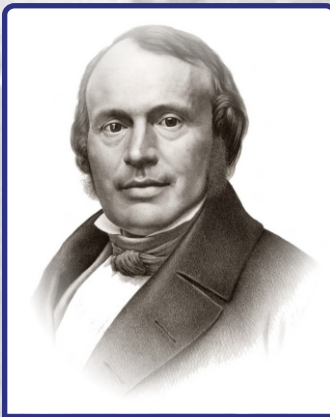
At a scientific meeting in 1836, Charpentier met the Swiss naturalist Louis Agassiz. Agassiz had recently made a name for himself by studying fossilized fish with the luminary French naturalist Georges Cuvier. The thirty year-old Agassiz handled himself in an approachable manner and won readers over with a lively writing style. Hailing from the Swiss town of Neuchatel, Agassiz agreed to travel the 100 kilometers to meet Charpentier in Bex. Really, Agassiz wanted to convince Charpentier that his whole idea of extensive glaciation was wrong, but after a few days of living near the glaciers, Agassiz couldn't help but admit Charpentier was correct. Whereas Charpentier was a poor communicator, Agassiz was a master and he championed the idea. In 1837, the Swiss Society of Natural Sciences met in Neuchatel, and Agassiz surprised the crowd by presenting a paper not on his trademark fossil fishes, but on glaciers. Agassiz knew he was going to stir trouble, as he remarked in his paper,

I am afraid that this approach will not be accepted by a great number of our geologists, who have well-established opinions on the subject, and the fate of this question will be that of all those that contradict traditional ideas. Whatever the opposition to this approach, it is unquestionable that the numerous and new facts mentioned above concerning the transportation of boulders, which may easily be studied in the Rhone valley and in the vicinity of Neuchatel, have completely changed the context in which the question has been discussed up to the present time.

He was right: his paper enraged many audience members. Agassiz walked out in a huff, a number of other scientists shouting that he was an amateur. He continued to present and publish his ideas, and in 1837 he started using a term he read in a friend's poem: Eiszeit, or German for "ice age." By 1840 Agassiz had written a book, *Studies on Glaciers*, in which he remarked:



Jean de Charpentier



Lious Agassaz

In my opinion, the only way to account for all these facts and relate them to known geological phenomena is to assume that...the Earth was covered by a huge ice sheet that buried the Siberian mammoths and reached just as far south as did the phenomenon of erratic boulders...It extended beyond the shorelines of the Mediterranean and of the Atlantic Ocean, and even completely covered North America and Asiatic Russia.

To help defend his ice age theory, he established a glacier observatory through which people could visit and observe first-hand the effects of ice on terrain. He showed that glaciers did indeed move, and could do so at fast rates. This transport moved rocks both small and large to new locations. At the melting end of the glacier, or "snout," rocks, sand, and other debris were left in a mixed pile known as a "moraine."

These first-hand observations became critical to bolstering the theory. In Britain, a scientific culture developed around visiting the Alps and their glaciers. Such expeditions were made possible at the time by improved rail lines and invitations from Swiss scientists like Agassiz. The Brits, in turn, considered Alpine expeditions a part of gentlemanly adventure. They insisted that a well-rounded man should be physically fit to make such an expedition, and that the women could come along if they liked, but only if they limited their participation to taking in a calming view of the mountains from the inside of a lodge.



**Note the sexism that permeated society. Science is done by human beings, thus it reflected the sexism of the wider culture.**

Scientists did come and study glacial flows and erosional effects alongside Agassiz, but when they got home they bragged almost as much about spending five days on a glacier as they did their scientific work. Overall, people were starting to accept that periods of extensive glaciation could be responsible for forming regions geologically similar to the Alps, such as the Scottish Highlands. The problem, however, was that no scientists, including Agassiz, could provide a physical mechanism for how the Earth had seemingly gone through such a massive change in climate. Furthermore, when current glaciers receded in the summer, naturalists found tropical fossils in their temperate climate. It seemed that there had been many hot-cold variations in climate, but nobody could pinpoint exactly why.

**3. Scientists were beginning to seriously consider that periods of extensive glaciations may have occurred. But they were bothered because they could not provide a mechanism for these massive changes in climate. This same situation held for continental drift. Until a plausible mechanism was put forward for continental drift, the idea languished. Why do you think having a mechanism that accounts for natural phenomena is so important in science?**

By 1846 Agassiz's extensive research efforts had impacted his personal life. His wife left him and took their children to Germany. He was nearly bankrupt from a bad publishing deal, and despite a plethora of evidence he couldn't come up with a mechanism for climate change. He moved to the United States to take up residence at Harvard. Over the next thirty years, Agassiz extended his argument and claimed that ice sheets extended from both poles almost to the equator. This was an extreme stance that no other scientist would take.

Over the next twenty years or so, many European geologists felt that the Earth had undergone an ice age, and they proposed a number of possible explanations. In his 9<sup>th</sup> edition of *Principles of Geology* published in 1850, Charles Lyell hinted that perhaps the cooling period had something to do with the Earth's positioning with respect to the Sun. The fact that the Earth had eccentricities in its orbit – in other words, it didn't trace the same route on every revolution around the Sun – had been known since the great French scientist Pierre-Simon Laplace calculated it in the early 1770s. Lyell, however, was generally unfamiliar with the technicalities of astronomy and laid the problem out for some other inquisitive mind to solve. That mind would be the Scottish independent scholar James Croll.

In brief, Croll self-taught himself physics and astronomy while working a number of odd jobs. He owned tea houses and read philosophy to the customers, and for a time he was an insurance salesman. He published a theological work in 1857 before settling down to work in astronomy, deciding on his own accord to tackle the cause of ice ages. Croll began his research by pointing out the biggest problem: the lack of a causal agent for the ice age. Here's how he phrased it in his 1875 book, *Climate and Time*:

We may describe, arrange, and classify the effects as we may, but without a knowledge of the laws of the agent we can have no rational unity. We have not got a higher conception by which they can be comprehended. It is this relationship between the effects and the laws of the agent, a knowledge of which really constitutes a science. We might examine, arrange, and describe for a thousand years the effects produced by heat, and still we should have no science of heat unless we had a knowledge of the laws of that agent.

In other words, Croll argued that by understanding these first causes, the rest of the story would unfold. So, the question became this: where does the Earth get most of its surface heat energy? The answer, of course, is the Sun. Because the Earth orbits the sun in an ellipse, then it could only follow that there might be something about that orbital pattern that affected climate.

Croll's astronomical attack on ice ages came on many fronts. First, he began the painstaking task of calculating by hand the slight variations in the Earth's orbit over a long period of time. Then he worked on the tilt of the Earth. The Earth is tilted about its axis by about 23.5 degrees. Because of this rotation, the Northern and Southern Hemispheres receive different amounts of direct sunlight throughout the year, which we experience as the four seasons. Croll took the known factor of the tilt of the Earth and worked in some gravitational effects from the Sun and Moon and found that the Earth "wobbled" about its axis like a top over the course of 23,000 years. Consider that from year to year the North Pole always points toward the north star, no matter what time of the year. This means that our tilt stays in the same direction all the time. Croll is asserting that this direction actually changes, but it takes 23,000 years to wobble away from the north star and back again. That's a pretty slow wobble in human terms!

Now, Croll understood that these slight variations in eccentricities and wobbles didn't add up to a lot of change in the amount of heat received by the Earth, but he thought that each little change might amplify one another. For example, the Earth's orbit might be at its maximum eccentricity during winter, causing a slight weakening of solar radiation that might cool the oceans enough such that currents weaken and change climate patterns. Longer winters would lead to longer periods of snow being on the ground, and as the white snow reflects solar energy instead of absorbing it, it could amplify the cooling process. Changes in the jet stream would lead to further precipitation in northern climates, adding to the snow cover and helping in glacier formation. Croll plotted his data points and found peaks and valleys of a hot-cold cycle repeating about every 100,000 years.

These data points were very important, because they gave scientists a way to test Croll's ideas. Croll argued that there should be variations of about 11,500 years in glacial drift between the Northern and Southern Hemispheres, and that the last glacial deposits should be about 80,000 years old. Croll was thwarted, however, by American crews working at Niagara Falls. The waterfall flows onto a glacial deposit and erodes it at a rate of one meter a year, and after much refinement scientists estimated the drift to be about 30,000 years old – a far cry from Croll's minimum limit of 80,000 years. Faced with this information and a lack of truly accurate methods of dating, Croll's theories went by the wayside for almost fifty years.



**Note the importance of Croll's astronomy background to move this geology idea forward! Important advances in science have occurred when a person from a different science discipline tackles a problem from that alternate perspective. However, they often have difficulty gaining credibility from established scientists in the field who may see him or her as an "outsider."**

By 1920, the Serbian mathematician Milutin Milankovitch had compiled enough evidence based on Croll's method to give it a new life. Having read Croll's work, Milankovitch wanted to understand the first principles not just of the ice age, but of the Earth's entire climate. Astronomical techniques had advanced immensely since Croll's publication, and Milankovitch had access to a number of improved data sets. However, the outbreak of World War I in 1914 found Milankovitch living in a Hungarian POW camp. Eventually he would be released under the condition that he would not leave the capital of Budapest.

During the War, Milankovitch developed a method to determine the temperature anywhere on the surface of the Earth. This involved knowing the amount of radiation reaching the Earth's atmosphere, the transfer and reflection of heat through the atmosphere, and the location of the Earth relative to the Sun. His first theoretical solutions were pretty close to observed averages over the globe, which enabled him to extend his calculations over 100,000 years back.

Milankovitch proposed that it was the tilt, and not a wobble, in the Earth's axis that was the significant factor in the formation of an ice age. Milutin calculated that the Earth varied from a 21 to 24 degree tilt, with the current tilt being 23.5 degrees. The cycle of changing tilt ran over 41,000 years. With this cycle, according to Milankovitch, it wasn't so much the coldness of winter as the coldness of summer. During cold cycles, the summer was cooler than normal. This prolonged the snow cover that would reflect heat radiation into space. Comparatively, the winters were warmer than normal, causing more snow precipitation to fall. As more snow fell and it lasted longer into the year, glaciers formed and remained over the years.

At this point, Milankovitch expanded his tables back to 650,000 years and produced "equivalent latitudes." These

equivalent latitudes pointed out that because of the Earth's tilting about its axis, locations geographically located at 65 N latitude could experience the equivalent climate of 55 N or 75 N, depending on the wobble. Finally, he realized just how significant snow could be in reflecting solar energy. During cold periods, the "snow line," or the elevation at which snow is permanently present, lowered almost to sea level. When the snow line reached sea level, it turned into an ice cap and reflected an enormous amount of sunlight, ushering in what could be considered an ice age. In 1941, Milankovitch published his extensive life's work, the *Canon of Insolation and the Ice Age Problem*. A few days after it started publication, the Belgrade bookshop in which it was housed was hit by bombs as a part of World War II. Fortunately, most of the manuscript survived and printing was able to continue at another location.

Over the next twenty years, scientists became increasingly skeptical over Milankovitch's data. Most couldn't accept that such a small variation in the Earth's axis could cause such a dramatic change in climate. Furthermore, modern radioactive data continued to date glacial deposits at inconsistent times with his predictions – the most recent major deposits occurring 25,000 and 72,000 years ago, and not 41,000 years ago. However, in 1970 Wally Broecker and J. van Donk used magnetic information to determine that the Earth's temperature had a smooth variation over 400,000 years with peaks and valleys at the 100,000 year marks, coinciding with Croll's data over Milankovitch's. Six years later, a team of scientists had picked apart that data to show that each of the cycles – Croll's 100,000-year eccentricity cycle and 20,000 year wobble cycle and Milankovitch's 40,000 year tilt cycle – all were responsible in their own way for an ice age. The climate responded differently in all situations, and while a single cause couldn't be pinpointed, it was undeniable that orbital factors caused ice ages.

**4. Many people wrongly think that results of single experiments quickly convince the scientific community to accept an idea. Use information from this story to explain how: a) controlled experiments with multiple trials are not the only road to well-established scientific knowledge, and b) acceptance of scientific ideas is often a very lengthy and complicated process.**

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