The Great Infra-Cambrian Ice Age

There is considerable geological evidence for an extensive glaciation some 600 million years ago. Its end caused an alteration of climate that made possible the proliferation of animal life in Cambrian times

by W. Brian Harland and Martin J. S. Rudwick

The best-known of the ice ages, since it is the most recent and has been the most intensively studied, is the one that began early in the Pleistocene epoch of the past one or two million years. At least two series of glaciations of comparable or even greater extent preceded the Pleistocene ice age by many millions of years. One series occurred between 300 million and 250 million years ago during the Permian and Upper Carboniferous periods. The other goes back to Infra-Cambrian times: just before the beginning of the Cambrian period some 600 million years ago. There is evidence for still earlier glaciations, but little is known about them.

Recent investigations indicate that the Infra-Cambrian ice age was an event of the first magnitude that preceded a critical time in the evolution of life. It is highly probable that there was a cause-and-effect relation between the ending of this prolonged period of cold climate and the rapid emergence of advanced forms of animal life. We shall concern ourselves with two main themes: the evidence for a major glaciation in Infra-Cambrian times, and the evidence that the climatic change at the end of the glacial period resulted in a substantial new fauna. First, however, it will be helpful to review some aspects of the other ice ages.

The Pleistocene ice age produced the massive ice sheets that are still represented by remnants in the polar regions of the earth. Indeed, the Pleistocene ice age may not have ended; the pattern of climate that has prevailed over the past few thousand years may be characteristic of a relatively short interglacial period. The extent to which the Pleistocene ice had spread at one time was first recognized in the 1840’s, when Louis Agassiz showed that the distinctive landscape produced by glacial action could be found at some distance from the glaciers of the Alps and was even evident in the hilly regions of Wales and Scotland, which now support no glaciers at all.

Agassiz is perhaps best known for his demonstration that the Pleistocene ice had also spread widely over low-lying areas both in northern Europe and in North America. He argued that the till, or boulder clay, that is the characteristic deposit in these areas was not, as was commonly supposed, left behind by running water (and sometimes deemed a result of the biblical Flood). Agassiz proposed that this material was the debris left behind by vast sheets of glacial ice. Tills consist of boulders and pebbles, many of them angular rather than rounded, embedded in a matrix usually made up of sand and clay. The boulders are often scratched, and the rock on which the till rests may be polished and incised with scratches and grooves.

A century’s work on glacial geology has confirmed the validity of Agassiz’ views. It has also revealed that the Pleistocene ice age was a highly complex event. The margins of the ice sheets advanced and retreated several times, and the glacial advances alternated with warmer interglacial periods, some of which lasted for tens of thousands of years.

Going backward in time from the Pleistocene, the next unambiguous evidence of extensive glacial action dates from the Permian and Upper Carboniferous periods. This evidence is found largely in the Southern Hemisphere; it consists of rocks called tills—mixtures of pebbles, boulders and clay consolidated into rock. The tills are interpreted as the products of glacial transport; in places they rest on striated pavements of older rock, and the tillite boulders themselves may be striated. Other tills are interbedded with marine sediments. In these formations some of the boulders and pebbles are found distorting the parallel layers of finer sediment in which they lie, and it appears that the boulders fell into the sediment from above. This can be explained if floating ice sheets extended outward from the land in Permian-Carboniferous times, as they do today in the Ross Sea of Antarctica. As the icebergs drifting away from the ice sheet melted, the debris embedded in the ice would have dropped into the sediment on the ocean bottom over a wide area. Marine tillites that appear to have been formed in just this way extend over thousands of square miles as uniform and distinctive strata. Similar marine tills, not yet consolidated into rock, have now been recognized on the floor of modern oceans.

The glacial origin of most Permian-Carboniferous tillites is clearly established, but their distribution—throughout the continents of the Southern Hemisphere and even north of the Equator into India—is puzzling. This distribution has long been one of the strongest arguments in favor of the hypothesis that the continents have drifted across the surface of the earth [see "Continental Drift," by J. Tuzo Wilson; Scientific American, April, 1963]. If, as the hypothesis postulates, South America, Africa, Australia and India were once joined in a single compact continent that has been named Gondwanaland, the glaciation would obviously have extended over a much smaller area than if these continents had been in their present position. Similarly, if the continents
were joined in Gondwanaland, it is possible to attribute the direction of striations on some pavement rocks in Africa and India to the action of a single large ice sheet; otherwise it is necessary to assume that there were many widely separated centers of glaciation. It seems likely, moreover, that there was a succession of Permo-Carboniferous glaciations, because some formations dating from those periods contain many distinct tillite strata.

Over the past decade the Gondwanaland hypothesis has been strongly supported by studies of paleomagnetism. Such studies are based on the fact that during the formation of certain rocks magnetic constituents of the rock are "frozen" in the earth’s magnetic field and so point in consistent directions. It is found that the magnetic constituents in continental rocks are consistently out of line with the earth’s present field; this may be taken as evidence that the poles have wandered with respect to the continents or that the continent has drifted with respect to other continents. Generally the evidence indicates both that the continents have slowly changed their position with respect to the poles and the Equator (which is to say that there has been polar wandering) and that the continents have changed their positions with respect to each other (which is to say that there has been continental drift).

Support for the Gondwanaland hypothesis has come from many other lines of evidence, but the paleomagnetic evidence is decisive. It indicates that the rocks associated with tillites were formed at high latitudes, that is, at latitudes near poles. Thus a reconstruction of the continental positions in Permo-Carboniferous times would place the South Pole somewhere in Gondwanaland and the North Pole in an enlarged Pacific Ocean. Paleomagnetic evidence also shows that both Europe and North America were then situated in lower latitudes. The extensive coal beds and salt deposits formed in those times in both regions confirm that the climate there was warmer.

We turn now to the tillites of Infra-Cambrian times, the most notable of the many rocks older than the Permo-Carboniferous formations that have been identified as tillites. In 1891 the Norwegian geologist Hans Henrik Reisch found an ancient deposit he interpreted as being a glacial moraine. The deposit, now believed to be a tillite, lay atop a striated rock surface be-

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GEOLOGIC TIME CHART indicates the chronological relation of the great Infra-Cambrian ice age to two other major glaciations; in Permo-Carboniferous and Pleistocene times.
side Varanger Fjord in northern Norway. Both the tillite and the rock surface are demonstrably Pre-Cambrian. Since then tillites of about the same age have been reported from many other parts of the world. Indeed, the term "Varangian" from Varanger Fjord, is used increasingly to refer to rocks of this age. Until fairly recently the glacial origin of these tillites was not disputed.

and they were generally taken as evidence for widespread ice sheets in late Pre-Cambrian times.

During the past generation, however, doubt has been thrown on the glacial origin of these deposits, chiefly because it is now recognized that there are ways other than ice action in which tillite-like rocks might be formed. These alternatives are as follows. First, where steep submarine slopes or cliffs exist, earth tremors may detach large angular blocks of rock, which may slide down the slope, possibly becoming striated, and then be embedded in finer sediment. Second, sediments newly deposited on a gentle submarine slope may become unstable and move downward in various ways. They may shear into large slices, glide downward with smaller lumps of mud and become embedded in other sediments in deeper water. It would be unusual for such "slump deposits" to resemble boulder-filled strata. If boulders should happen to be present on the slope, however, they could be intimately mixed with finer sediments in a mudflow that would look much like a till; this is the third alternative. Such mudflows have been found in nonglacial environments. Since a relatively steep slope is needed, boulder beds of this kind would be restricted to belts a few kilometers, or at most a few tens of kilometers, wide.

The fourth alternative involves the disintegration of sediments on a submarine slope, which then flow downward as a "turbidity current." Such dense mixtures of sediment and water have been shown to be capable of flowing for scores or even hundreds of kilometers into the ocean basins down inclines with a slope of less than one degree. Depots formed in this way could extend over very wide areas. "Turbidites" have in fact been recognized in many successions of rock strata, particularly by their "graded bedding." This results from the faster settling of the coarser material after the disturbance has ceased, so that each stratum is graded upward into sediments of decreasing grain size. Turbidity currents are known to be capable of transporting pebbles, but the largest pebbles yet found in unquestioned turbidites are not more than a few centimeters across.

Some of the supposedly glacial Infra-Cambrian tillites have been re-examined in the light of these alternative explanations. For instance, one of us (Harland) has investigated some of the tillites in Scandinavia, Spitsbergen and Greenland. These are distinct and conspicuous strata, generally between 10 and 100 meters thick and with little variation in thickness or composition over areas exceeding 1,000 square kilometers. The boulders in the strata are commonly a few tens of centimeters across, although a few exceed a meter in diameter. Their shape varies from sharply angular to rounded, and

EFFECTS OF GLACIATION from Infra-Cambrian times appear at a site in Norway discovered in 1891 by the Norwegian geologist Hans Henrik Reusch. Shown here is a section of bedrock striated either by movement of a glacier or by later sliding of the glacial deposit; the larger holes were made by boulders in the till, or boulder clay, of the deposit.

RELATED VIEW shows the same quartzite bed overlain by a tillite, which is a till that has consolidated into rock. The till was made up of boulders and pebbles in a clay matrix.
DISTRIBUTION OF TILLITES provides an indication of glacial action. The upper map shows the present distribution of Intra-Cambrian tillites, represented by circles, and of Permo-Carboniferous tillites, represented by hexagons. On the lower map the tillites are shown as they may have been distributed in the Intra-Cambrian age. The continents are arranged according to a hypothesis for Permo-Carboniferous times; presumably that is closer to the Intra-Cambrian arrangement than is the map for present time.

A few are striated. In the main the boulders are composed of sedimentary rocks, many of which can be matched o the lower strata of the Intra-Cambrian period, but there are in addition many nonsedimentary boulders. These are probably "erratics," derived from still older formations that were exposed in more distant areas.

The fairly constant thickness and boulder content of these northern Intra-Cambrian formations over a wide area seem to eliminate the mudflow hypothesis. The evidence favoring a slump-deposit origin for the formations is not much more persuasive, and the presence of large boulders seems to rule out an origin based on turbidity currents. These considerations, however, do not eliminate the possibility that mudflows and turbidity currents played a secondary role. Indeed, today mudflows and slides are an inseparable part of the formation of tills at the margins of glaciers and of the erosion of Pleistocene tills [see "Quick Clay," by Paul F. Keil; SCIENTIFIC AMERICAN, November, 1963]. The same material could move even farther underwater; it would be likely to undergo sliding and slumping and even to initiate turbidity currents. Thus if the Intra-Cambrian boulder beds are true tillites, it is hardly surpris-
FORMATION OF TILLS may in some cases have occurred by means other than glacial action, or those means may have supplemented the action of glaciers. All involve events occurring in water.

At top are (a) a rockfall; (b) slumping and sliding; (c) a mass flow; (d) obliteration of previous structure by mass flow, producing a structureless till. At bottom are (e) turbidity current; (f) the

ing to find local evidence of slumping or even graded bedding. Reusch’s moraine with its striated pavement, for example, appears instead to be a lens-shaped deposit of slumped tillite resting on contemporary sandstone grooved only by the submarine slumping of the till itself.

Both the extent of the Infra-Cambrian tillites and the size of the boulders included in them seem to be powerful arguments in favor of their glacial origin. Even more decisive evidence can be found. In some of the tillites that show a fine stratification individual pebbles and boulders can be seen to have distorted the layers of finer material below and around them. The only adequate explanation for this is that the pebbles and boulders dropped from floating ice. At least some of the Infra-Cambrian boulder beds must therefore be accepted as true tillites.

In addition to these boulder beds now situated in Arctic regions, many tillites have been reported from Infra-Cambrian strata in other parts of the world. For most of them the possibility of a glacial origin is also worthy of serious consideration. It is necessary to confine the argument to tillites laid down in water; this eliminates mountain glacial tillites, which might have been deposited in any latitude and at any time. Also ruled out of consideration are the many alleged tillites known to belong to strata much older than the Infra-Cambrian. We shall thus focus attention on those water-deposited tillites that lie within a few hundred meters below Cambrian rocks, which are identifiable as the oldest strata that are

DISTRIBUTION OF ICE at various periods is shown in these polar projections. Land ice is represented by the lighter color; sea ice, by the darker. Maps a and b show respectively the Northern and Southern hemispheres as they appear at present. Map c depicts the situation in the Northern Hemisphere during the Pleistocene ice age, the most recent major glaciation. Map d shows the Southern Hemisphere during the next preceding major ice age,
considered according to the present position of the continents or according to a possible Pre-Cambrian arrangement [see illustration on page 31], it is difficult to confine them, as is possible with the Permo-Carboniferous tillites, to a restricted portion of the globe.

There are two alternative hypotheses to account for this fact. One states that the ice was widespread at all latitudes. The other prefers to accept a period of rapid polar wandering, which brought many different areas successively into high latitudes. The latter hypothesis is not supported by any evidence; indeed, it seems to have been suggested only in order to avoid postulating the presence of ice in the tropics. Yet paleomagnetic evidence indicates that some tillites were formed at quite low latitudes. It is therefore simplest to postulate a single complex ice age during which, on at least two occasions, ice drifted into the Infra-Cambrian tropics.

The argument can be put another way. Various attempts to reconstruct Cambrian climates suggest that generally warm conditions, with extensive deposition of limestones and the formation of salt deposits, prevailed in a belt extending from, say, the Indian Ocean to Scandinavia and Greenland. Such reconstructions are only approximate at best, but in this case (as in most others) they are consistent with the paleomagnetic evidence. The location of the North Pole, obtained from paleomagnetic readings of Cambrian and late Pre-Cambrian rocks in northern Europe, Greenland and North America, was in an area near the Equator in the present Pacific. Therefore the ancient latitude of rocks in the strata above and below many Infra-Cambrian tillite formations was nearly equatorial, and the tillites themselves would seem to have been formed in the tropics.

To check this point magnetic determinations have been made for sedimentary rocks closely associated with the tillites in Greenland and Scandinavia. These too yielded readings that pointed toward an equatorial position. The only difficulty, then, is the indication that ice existed near the Infra-Cambrian Equator. Failing any other explanation, however, we are prepared to accept that it did exist there.

Although the Infra-Cambrian glacial deposits, and other deposits derived from them, are extremely widespread, this does not mean that the entire earth was covered with ice; indeed, that would be most unlikely. During an intense glacial period increasing cold would extend the total area of sea ice, although large areas of ocean at low latitudes probably would remain open. On land the ice sheets might develop mostly at middle latitudes. Whatever the exact distribution of ice, the water-deposited tillites clearly indicate that icebergs or sea ice transported material from the land or shallow seas into warmer waters.

It is difficult enough to know the positions of continents in, say, Permian times; there is even less certainty about these positions in Pre-Cambrian times. We are obliged to use the best possible Permian reconstruction, rather than a map of the earth today, as a basis for reconstructing a still earlier map. We infer that the Infra-Cambrian Equator ran somewhere near the Arctic rocks that have been mentioned. In addition it seems that one pole may have been

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found to contain fairly abundant fossils.

Even if the argument is restricted in this way, one is left with many substantial formations. This in itself is a remarkable fact. The distribution of Infra-Cambrian water-deposited tillites is almost worldwide. Whether they are

which occurred in Permo-Carboniferous times. The continents are arranged as in the lower map on page 31, according to the hypothesis that several of them were close together in a single area now called Gondwanaland. The circles represent tillite occurrences; since the South Pole presumably was shifting, the tillites formed at any one time would have occupied a relatively small area. Map e shows Infra-Cambrian ice; with a dominant continental area represented symbolically by the large circle since the actual configuration is unknown and with much sea ice tillites could have formed along the Equator in spite of the warmer climate in that region.
located for a long time near Central Africa and South America; this would account for the evidence of repeated ice action in late Pre-Cambrian rocks in those areas.

What of the ice ages before the Infra-Cambrian? Although many tillites in much older Pre-Cambrian rocks have been described, their exact ages and original latitudes are not yet known. They are fairly clearly separated from the Infra-Cambrian glaciation; the Infra-Cambrian tillites are in many places underlain by a succession of more than 10 kilometers of strata without a trace of glacial action. It seems that glacial periods have been infrequent, exceptional and only occasionally widespread events in the history of the earth. If tillites can be correlated or distinguished from one another, such as by dating them through the decay of radioactive elements in associated rocks, they may come to be an important means of dividing up the long Pre-Cambrian record by showing that it was punctuated by distinctive climatic episodes. And if ice ages are to be explained by changes in the amount of radiation from the sun (there is as yet no obviously better explanation), then the chronological pattern of ice ages will provide a valuable clue to the timing and magnitude of solar events.

The usual conception of an ice age is too much molded by what is known of the Pleistocene glaciation. The preceding Permo-Carboniferous ice age seems to have been spread over some tens of millions of years. The Infra-Cambrian ice age may well have lasted as long, but it far surpassed the Permo-Carboniferous in geographical extent.

An ice age of such severity would explain much that is otherwise puzzling about Infra-Cambrian history. The withdrawal of water into huge ice sheets on the land would have led to a general drop in the sea level. This would have exposed newly deposited shallow-water sediments, which would then have been subject to erosion, slumping and flow. Older, consolidated rocks would also have been eroded by the ice sheets; from that action would have come most of the boulders in the tills on the sea floor. The location of the land ice probably varied from high latitudes at the beginning and end of the glacial cycle to middle latitudes at the coldest part of the cycle. It may not be necessary to postulate land ice at low latitudes: floating sea ice and drifting icebergs could have carried material far beyond the boundaries of the continental ice sheets, depositing sediments of similar composition over wide areas of the sea floor. Such deposition would account both for the existence of tillites in the Infra-Cambrian tropics and for the observed similarities and extent of the tillite formations.

If our interpretation of the Infra-Cambrian ice age is correct, at least in broad outline, it can hardly be mere coincidence that a geological event of such intensity was followed, after a relatively short interval, by a biological event of equally striking character. Both the sudden appearance and the
FOSSIL RECORD of early Cambrian times, immediately after the end of the prolonged cold of the Infra-Cambrian ice age, shows many new animals. Some are drawn here nearly life-size. Among them are arthropods ("d" and "k" through "o") mollusks ("b", "e" and perhaps "f" and "g"), brachiopods (i, j); echinoderms (h); sponges (a); and other organisms (such as "c") that probably belong to phyla, or animal groups, that became extinct long ago. Rocks of Cambrian times are the earliest to show such a varied fauna.

Remarkable composition of the animal life characteristic of Cambrian times are sometimes explained away or overlooked by biologists. Yet recent paleontological research has made the puzzle of this sudden proliferation of living organisms increasingly difficult for anyone to evade.

In contrast to the burgeoning of animal life in the Cambrian period, the only kind of life for which Pre-Cambrian rock strata (including those of Infra-Cambrian age) provide clear evidence is plant life, chiefly lime-secreting algae. The strata of Cambrian age, however, contain the fossils of a remarkably varied array of multicellular animals. These animals were neither primitive nor generalized in anatomy: they were complex organisms that clearly belonged to the various distinct phyla, or major groups of animals, now classified as metazoan. [See illustration above]. In fact, they are now known to include representatives of nearly every major phylum that possessed skeletal structures capable of fossilization; the only important exception is the phylum of chordates, which includes the vertebrates.

Moreover, most of these phyla first appear in the fossil record during the early part of the Cambrian period, the 40-million-year Lower Cambrian. Their
record extends more or less unbroken from then up to the present day. Yet before the Lower Cambrian there is scarcely a trace of them. The appearance of the Lower Cambrian fauna is thus a uniquely important event in the history of animal life. Moreover, on the time scale of the fossil record as a whole the emergence of the fauna can reasonably be called a “sudden” event [see illustration on page 34].

One can no longer dismiss this event by assuming that all Pre-Cambrian rocks have been too greatly altered by time to allow the fossils ancestral to the Cambrian metazoans to be preserved. It is true that one peculiar soft-bodied fauna has been found in Australia in strata that appear to be Infra-Cambrian, although they are younger than the Infra-Cambrian tillites [see “Pre-Cambrian Animals,” by Martin F. Glaessner; SCIENTIFIC AMERICAN, March, 1961]. But even if all the Pre-Cambrian ancestors of the Cambrian metazoans were similarly soft-bodied and therefore rarely preserved, far more abundant traces of their activities should have been found in the Pre-Cambrian strata than has proved to be the case. Neither can the general failure to find Pre-Cambrian animal fossils be charged to any lack of trying.

If all the evidence is viewed without preconceptions about evolutionary processes, the suggestion is clear that at the end of the Infra-Cambrian period there was a phase of rapid and radical evolutionary change in animal life. In this period of a few millions of years, or at most a few tens of millions, the metazoan phyla evolved into the relatively large and complex organisms that are found as fossils in Cambrian rocks. Perhaps ancestral metazoa had existed previously. If so, however, it seems probable to us that only a few of them were of a size larger than microscopic until the very end of the Infra-Cambrian period.

Whatever other factors may have been involved in this evolutionary event, some trigger mechanism seems required to have set it in action. This impetus could have been the major climatic change that came at the end of the Infra-Cambrian ice age. The ice age itself would have created extremely adverse conditions for life. In particular, the lowering of the sea level would have sharply reduced the area of the shallow seas, which include many of the most favorable habitats for marine life. In contrast, at the end of the ice age the improvement in climate and the rise of the sea level would have re-created a variety of favorable but biologically empty environments, in which the opportunity would exist for radical evolutionary changes to take place.

A causal connection between the Infra-Cambrian ice age and the appearance of the Cambrian fauna thus appears at least possible, and perhaps probable. Certainly a climatic event of an intensity unparalleled in the later history of the earth seems to have been closely followed by a biological event of profound significance in the history of life.

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TILLITE TIME PATTERN indicates the periods in which tillite deposits were made. Each circle represents one or more such deposits. Question marks indicate some uncertainty about the age of the deposits; radiometric techniques have provided some limits to the uncertainty, as shown by arrows. Latitude indications show where in relation to the Equator of that time a deposit was formed.