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GUEST EDITORIAL

Three Theories in Time

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The launching of a new home for an interdepartmental center for research in aspects of Earth science affords us a welcome opportunity to rejoice in the present. At the same time it stimulates us to try to visualize today's search for better knowledge of our planet—or at least the outer part of it on which we live—within a larger framework of time and enquiry.

Looking backward through more than a century, we are aware of two great achievements in the synthesis of the activities that take place at and near the surface of Planet Earth. The earlier achievement is the 19th-Century synthesis of the way in which species evolve—or more broadly, the basic explanation of how the biosphere, throughout some three billion years of geologic time, has kept going. The later achievement is the recent synthesis of the dynamics of Earth's lithosphere—how the lithosphere keeps going—unquestionably the highest achievement of the 20th Century in Earth science.

Looking forward into a future of unknown length, we can see, in its infancy, a third achievement of comparable importance: a comprehensive theory of the variations in characteristics of the atmosphere—the variations we call, in plain language, changes of climate—the effects of which are of prime importance for man and most other living things. In this perspective of past and future combined, we see the science of three aspects of a dynamic Earth: the dynamics of the biosphere expressed in organic evolution, the dynamics of the lithosphere expressed in its giant-size moving plates, and the dynamics of the atmosphere expressed in its still mysterious changes through time. The first two aspects are represented by great theories, one of them so recent that it is still unfinished in detail. The third, thus far, is no more than a preliminary outline of problems, and so it lies almost wholly in the future.

Because many of those present today are not Earth scientists, let me comment on the 19th-Century theory and briefly recount the story of the 20th-Century theory before turning to the third theory the future will surely bring.

THEORY OF DYNAMICS OF THE BIOSPHERE

The 19th-Century synthesis was a unifying theory. It accounted for features and relationships that before its appearance had been mysterious and apparently unrelated. It explained the origin of species and thereby also made clear the ancestry of man. It elucidated the meaning of the fossils buried in sedimentary strata, along with most of the former puzzles connected with fossils. It made understandable a major foundation stone of the geologic column, the principle of faunal succession. But it took a long time to do these things.

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Although to many people, the theory of organic evolution and the name of Charles Darwin are almost synonymous, the theory was not wholly the work of any single scientist. Yet neither was it what we mean by a group effort, because the contributors were working as scattered individuals. In the mid-19th Century the idea of evolution was in the air, and had been there for a long time. The inheritance of acquired characteristics had been discussed, not at all favorably, by Leonardo da Vinci 350 yr earlier. In one aspect or another, evolution had been in the minds of Montaigne in the 16th Century, Descartes in the 17th, and Malthus in the 18th. Before the end of the 18th Century Erasmus Darwin, grandfather of Charles, and before him Buffon, had held that all organisms are descended, with gradual transformations from a common ancestor. The elder Darwin proposed that environment alters heredity and that competition forces changes. In some of these ideas he was followed by Lamarck. In 1818 a physician, W. C. Wells, published a paper that argued natural selection, and in 1831 a paper by Patrick Mathew set forth a succinct statement of the process. Charles Naudin in 1852 and, as everyone knows, A. R. Wallace in 1855, put forth theories of natural selection independently arrived at. Charles Darwin's *Origin of Species* in 1859, bolstered with a wealth of detailed observations, publicized worldwide both the fact of evolution and the concept of natural selection. The essential support for the concept, by genetic research, was supplied by Mendel in 1865. Ever since then, and in many ways, Earth scientists have been making use of this 19th-Century theory of dynamics of the biosphere. And there have been popular versions too. One of those current in New Haven runs like this:

Said an ape as he swung by his tail
To his little ones, male and female,
"From your offspring, my dears,
In a few million years
May evolve a professor—at Yale."

THEORY OF DYNAMICS OF THE LITHOSPHERE

Turning now to our second theory, the dynamics of the lithosphere, we begin with a statement by Charles Darwin that, in a curious way, links this second theory with the earlier one. In the first edition of *The Origin of Species* (Chap. xii, pp. 357–358, 389) he took issue with Edward Forbes and other naturalists, who wished to account for the global distribution of organisms by supposing that existing continents had formerly been united. "We are not authorized," he wrote, "in admitting such enormous geographical changes within the period of existing species . . . " With this statement Darwin took sides on a question out of which, later, developed the theory of the lithosphere.

That theory explains, or strongly promises to explain, not only the creation and extinction of ocean basins and the movements of continents, but also the making of mountain chains and the differentiation of the material of Earth's crust into rock of very different kinds. Indeed, like the biosphere theory before it, the theory of the lithosphere has powered a tremendous thrust toward a more accurate reading of Earth's history. Each of the two theories was the result, in part, of the state of technology in its time. The later theory could not have developed sooner. It had to await the working-out of several crucial methods of remote sampling, sensing, measuring, and testing.

The construction of its various supports constitutes an interlacing network, which is always oversimplified in general descriptions.

In an earlier form it was a theory that continents drift across the surface of the globe, and it paid little attention to the dynamics of the drifting motions. So we mention first the sorts of evidence from which drifting was inferred, and then the discoveries that led to the theory of the moving forces. In its twofold nature, this theory is analogous to the theory of the biosphere. First came the synthesis of the fact of evolution, then the explanation of natural selection, the mechanism by which evolution proceeds.

The evidence that continents were formerly joined and have moved apart can be assembled into three groups: First, congruence of coasts that face each other across an ocean; second, matching of geologic features on pairs of opposite coasts; and third, former positions of continents inferred from remanent magnetism in their strata. The congruence of coasts was first noticed by Francis Bacon in 1620, almost as soon as the maps constructed during the 16th Century age of exploration had become available; subsequently it was detailed and appealed to by several others. But not until the 1960s, when ocean floors had been explored, was it realized that the true edges of continents lie, not at coastlines but at a depth of 1000 m on the submerged continental slopes, and that the computer-determined best fits of those edges, obtained by Blackett, Bullárd, and Runcorn, were very good indeed.

The matching of geologic features on pairs of continents was pursued by Eduard Suess before the end of the 19th Century, and soon afterward by Alfred Wegener, Alexander Du Toit, and several others. The matching embraced several kinds of things: like sequences of strata, like assemblages of plants and animals (including identical species of certain plants on lands now widely separated), like glacial features occurring with roughly comparable dates on five continents, and finally, like mountain structures and major faults. All these similarities were employed in "fitting the continents back together" (by some into a single former continent and by others into two former continents). The original land or lands must have begun to break up near the beginning of the Mesozoic Era, about 200 million y.a.

Former positions of continents were revealed by the remanent magnetism in strata. This indicated, for each group of strata, different relative positions of the Earth's magnetic pole. The drifting continents are somewhat like ships sailing across a wide ocean, each ship with its log book in which is recorded the compass bearing of its course at many times throughout its voyage. To reconstruct the path of a drifting plate, one need only learn to read the log. Times and rates of movement were determined from the radiometric dates of key strata in the continents. The sheer amount of intelligent labor involved in seeking out critical localities, collecting samples, determining their magnetic bearings, and plotting and interpreting the data, is something we cannot but admire.

The measured bearings differ from one continent to another, indicating that the plates have moved independently. Former positions at particular times during movement, as inferred from magnetic data, are generally compatible with the climatic indications of fossil plants and animals that lived then and there. An obvious example is the extensive, warmth-loving coal floras that occupied parts of North America and Europe 300 million y.a. Magnetic tracking seems to indicate that those floras were then positioned in comparatively low latitudes.

A quite different sort of measurement gives another possible indication of continental movement. It has long been known that the Great Pyramids of Cheops and Chephren at Gizeh in Egypt, built 4500 y.a., are 4′ out of alignment with the true-north direction. It was suggested early in 1973 that the cause, never explained, might be cumulative movement of the African Continent relative to the pole during the last 4500 yr.

The matching of the various geologic features on opposing continental coasts had been described and discussed in good detail before and during the 1920s and 1930s. In hindsight, most of the matchings seem in themselves to require drifting as their explanation. This explanation indeed was urged, in those days, by the proponents of drifting, but with little success. Here were a handful of geologists, most of them living and working in the southern hemisphere (because that was the hemisphere in which the best matching then known was located), urging the idea of drift. Meanwhile the northern hemisphere, although the site of less obvious matching, was the home of the vast majority of the world's geologists, few of whom had probably ever visited the southern regions. These people were firmly dismissing the idea, although as we now realize, they should have been more impressed than they actually were by the variety of the evidence, drawn from various scientific fields, that supported the probability of continental movement.

I remember well that when I was an undergraduate geology student at the University of Chicago in the 1920s, one of the first broad assertions that came through to me from lectures of T. C. Chamberlin, R. T. Chamberlin, and R. D. Salisbury was the "doctrine of the permanence of continents and ocean basins." This doctrine expressed succinctly the powerful northern opposition to the idea that continents have moved. What supported the opposition so widely was the apparent lack of forces adequate to make continents move.

The theory of the driving force, still being elaborated today, is the result of specialized investigations by many people, mostly geophysicists, mainly in the 50s and 60s. It is a product, partly of the great programs of mapping and measurement of the world's ocean floors and their underpinnings that began with the end of World War II, and partly of specifically directed tests suggested by the great variety of accumulating data. Research that makes use of sonic sounding, seismic measurement, and measurements of gravity, heat flow, and paleomagnetism, as well as radiometric dating and extensive coring of sea floor sediment, has built up a picture that even now, after several years have passed, is still astonishing. Now widely publicized, that picture reveals Earth's lithosphere as a group of thick plates that are indeed moving, in various directions, at rates of a few centimeters a year, some of them carrying on their backs continents that float in the substance of the plates. As they move, the plates lose heat and become more dense. Generated all along their trailing edges by the continual addition of hot lava that wells up through deep rifts in the ocean floor and freezes, the plates are simultaneously destroyed along their cooler, leading edges, where they bend far downward into the reservoir of hot material down below, and melt. As two opposing plates bend downward to be engulfed, the continents they carry meet and sometimes collide. The collision squeezes their thick pockets of sedimentary strata and converts the pockets into high mountain ranges. Slow collisions of this kind seem to explain how mountain chains are made, thus solving a puzzle that had not been understood before. At other times, plates and slices of plates slide and shoulder past each other. At its present rate of northward sliding, forecasters say that in 10 million yr, more or less, Los Angeles will arrive alongside San Francisco, thus making the traffic problem even worse than it is already. Nothing like this seems to be predicted for Seattle. It seems to be indicated that Seattle will just move quietly through a short distance, bend gradually downward, and melt.

What is the driving force that brings these movements about? The answer is not yet known, but the idea that seems to have found most favor is one that goes back to the 19th Century and that was restated in 1928 by the Scottish geologist Arthur Holmes. He proposed that hot material beneath Earth's crust, heated by radioactivity, is slowly turning over by convection, and is dragging plates of lithosphere along with it as it cools.

Although still very incomplete, this theory of lithosphere dynamics explains so many relationships that its essentials have been widely accepted. Conversion of most of the skeptics to the basic concept occurred within less than a decade, the decade of the 1960s. The development of the theory as a whole has consisted of three phases: a phase (lasting through the 1920s) of early ideas, a phase (ending with the end of the 1950s) of description accompanied by much specialized groping for solutions, and then, in the 1960s, the phase of rapid synthesis of the unifying theory.

Comparing the theory of the lithosphere with that of the biosphere, we find similarities. Both theories began with very early, scattered observations. The main part of the work that led to both was spread over several decades. Also both were contributed to by many people, against very strong opposition. As we have seen, the theory of the biosphere was not the result of a group effort. Likewise the building of the theory of the lithosphere consisted for a long time only of scattered observations; only in its later phase did it become a group effort.

A more basic similarity between the two theories lies in their essential character. Each embraces a history and describes an ongoing process. The biosphere theory explains the peculiar distribution of organisms and the genetic relations among fossil organisms. These are history. It also sets forth the ongoing process of natural selection, which explains the history. Similarly, the lithosphere theory explains the peculiar distribution and the peculiar shapes of continents as the result of a history of breaking apart and movement. But it also establishes the ongoing process of building, movement, and destruction of lithospheric plates, the process that makes the history understandable.

One notable difference between the two theories lies in the methods by which the necessary data were obtained. The 19th-Century scientists relied mainly on field observation and later on laboratory study and on experiments in the controlled breeding of animals and plants. But in the mid-20th Century, scientists made use of many kinds of heavy equipment and sensitive instruments for extracting essential data from the sea floor. The needed information could not have been obtained by other means, and the equipment could not have been planned and constructed without massive funds, supplied in large part by governments. In contrast, Darwin was supported entirely by a rich wife, Emma Wedgwood. She served the cause of 19th-Century science well, as a sort of one-woman National Science Foundation.

THEORY OF CLIMATIC VARIATION

We come now to a theory of the atmosphere. Although hardly less important, potentially, than the other two syntheses, the theory of the atmosphere does not yet exist. Instead of a developed and tested concept, we have only a group of *ad hoc* hypotheses, most of them mere speculations. As long ago as 1890, the German climatologist Eduard Brückner wrote of the study of climatic change: ". . . there are few fields in which speculation is so far in advance of established facts . . ." More than 70 yr later, Martin Schwarzbach wrote that up to 1960, 53 "theories" of the causes of glacial-age climates had been put forth, and that most of them are speculations. What lies behind this very unsatisfactory situation?

We all know that climatic variations are basically variations of temperature, through time, within the atmosphere. Also we are well aware that in several respects the atmosphere is a more difficult body to research in thermal terms than is the lithosphere. It is less dense; it is more mobile—its motions are more complex and more rapid; it absorbs and loses heat more easily; and it leaves no direct trace of changes in its temperatures. The traces it leaves are indirect responses, recorded in fossil organisms and in the inorganic character of sedimentary strata themselves. Most atmospheric heat is of external origin, and it varies at any time with latitude, altitude, distribution of lands and oceans, and other factors. These characteristics imply a thermal pattern that is highly complex.

No doubt a good many people suppose that to arrive at a theory of climate one would send up balloons. Actually, however, it is the other way around: we don't go up; we go down. Using drills, we take long cores from swamps and lakes, from ice sheets and ice caps, and from the sea floor, to find, in the layers of deposited sediment and deposited snow, a record of responses to long series of changes of climate that date back through tens and even hundreds of thousands of years.

The reason why we go down is because research in climatic change, like the research that led to the theories of biosphere and lithosphere, deals with two very different aspects of climate. The first concerns what happened in the past—the history. The second concerns the way in which the causative process—the process that is happening today—works. In the studies that led to the theories of biosphere and lithosphere, a working understanding of the past record antedated full development of the causes. The theory of climatic variation will surely show a similar history of development. It will result from a two-pronged attack. The first prong concerns the erection of an accurate framework, within which we can see the sequence of well-analyzed climatic events, as far back through geologic history as possible. And the framework will be firmly fastened together with radiometric dates. This framework provides something real to be explained. The second prong involves the explanation, the description of the ongoing processes. It will consist of constructing models that can be tested against the framework, plus the making of measurements that as yet have not been devised.

The cornerstone of our climatic framework was laid before 1850, on the day when evidence of two superposed layers of glacial drift was discovered in Europe. Today, 125 yr later and despite much labor, our framework is still primitive, and shows much distortion caused particularly by uncertainties in its radiometric dating. But its improvement is accelerating today, because it is responding to an increasing input of manpower.

Everyone connected with this framework knows well that it must be made to show, as accurately as data permit, parameters such as these:

1. Separate identification, in the record of a former climate, of temperature and precipitation.

2. Amplitudes of fluctuation.

3. Relation of range of fluctuation to geographic position.

4. Periodicities (if any) in the spacing of peaks of fluctuation.

5. Separate identification of secondary effects and general, more widespread changes. The secondary effects were mentioned as early as 100 yr ago by James Croll, but they are still neither well defined nor well quantified.

What part will the dramatic data of extensive glaciation by great sheets of ice play in the future theory? Before the mid-19th Century, glaciation occupied the center of the stage. Certain scientists in Britain called "glacialists," were concerned with showing that Europe had been overrun by glaciers in an *ice age* rather than having been submerged by a vast flood of water. Even before glaciers had fully triumphed over a flood, the Pleistocene had been redefined as the "Glacial epoch." But soon, the demonstration that Pleistocene glaciation had occurred not once but repeatedly, added to the importance of that epoch. By the middle of the 20th Century, research on fossil pollen and on sediment from the sea floor had demonstrated that, both climatically and stratigraphically, the change from Pleistocene to recent was gradual, and was punctuated by local recurrences of colder climates.

But the loss, by the Pleistocene, of its distinctive character did not end there. In the late 1960s, one of the many results of a decade of research in Antarctic lands and seas was the demonstration that, in that region, episodes of glacial climate were not limited to the Quaternary but had occurred also in earlier Cenozoic time. Analogous findings were made in high northern latitudes as well. In consequence we now speak, not merely of Quaternary glacial ages, but of late-Cenozoic glacial ages.

It is not easy to perceive an end to this gradual escape of cold periods from their former confinement to the Pleistocene. In time the existing gaps between the Cenozoic glaciations, the long-known Permian and other Paleozoic glaciations, and the various Precambrian glaciations will probably have been filled sufficiently to allow us, as we lean confidently on the Principle of Uniformity of Process, to talk without surprise about cold episodes at favorable times and places, as frequent occurrences throughout the entire 600 million yr of Phanerozoic time plus an unknown length of still-earlier time.

Nevertheless, although the Quaternary may have lost its claim to an exclusively glacial character, I believe the bulk of new data for the historical framework for the theory of climate will be drawn from it. For the Quaternary, with its widespread and comparatively accessible strata, still little damaged by erosion, offers a quantity of material and a degree of resolution that can hardly be matched by stratigraphically older sources of information.

Having said all this about the historical framework, we must not forget the second prong of research on the theory of climatic change: identification of the causes. The search for causes overlaps on the theory of the lithosphere, because from that theory we know that during the last 200 million yr plates of lithosphere have passed through different latitudes, and so have experienced gradual changes of climate. But there is more to the cause of climatic variations than merely running a plate through a warming oven (or through a refrigerator or a shower bath). There exists clear evidence of temperature values both lower and higher than those of today, persisting through time intervals that are too short for the leisurely speeds of moving plates. Also, at least some of the changes of climate were too widespread to have been confined to a single plate. In other words, not all variations of climate can be attributed to movement of plates, nor probably to any single cause.

Regardless of the number of causes, a comprehensive theory of climatic change is sure to embrace as large a group of related problems as does the theory of the lithosphere. For that reason it presents as great a challenge. But despite the complexities whose existence we must acknowledge, it would be foolish to assert that a viable theory cannot be constructed. In an age when science has reached the degree of philosophic and technologic capability represented by the theory of the lithosphere, it seems very unlikely that it cannot also achieve a theory of climate. Our present state of considerable ignorance is, I think, mainly a result of insufficient manpower and insufficient thought having been applied to theoretical aspects. Now that the computer is available routinely, these aspects are capable of being researched in great depth. But the inputs are so many and so complex that hundreds of computer hours are needed for one single, comparatively simple model.

The model makers, being people trained in meteorology, tend to see the possible causes of climatic fluctuation less in geologic changes and in solar variations, than in instabilities inherent in the system of air movements and heat transfers right in our own atmosphere. Because of this, they are broadening the spectrum of the possibilities before us.

Will the new theory, comparable in importance with its two predecessors in the 19th and 20th Centuries, come in the 21st Century? The building of the historic framework for the theory has started off on the right track. The formulation of models is poised for a start and will soon be under way. Our strong curiosity, our increasing manpower, and the rapid development of our technical skills lead me to expect that the theory of climatic variation will be with us before the end of the 20th Century.

There is one man's prediction. Quaternary scientists will play significant parts in assembling the data, and in elaborating the theory of climatic variation, that will add a new theory to its brilliant predecessors, and with it a whole chapter to the development of Earth science.

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