20. J. F. A. P. Miller, *Science*, in press.
21. J. Sterzl, J. Kostka, I. Riha, L. Mandel, *Folia Microbiol.* **5**, 29 (1960); A. M. Silverstein and R. A. Prendergast, *Blood* **22**, 770 (1963); A. M. Silverstein, G. J. Thorbecke, K. L. Kraner, R. J. Lukes, *J. Immunol.* **91**, 384 (1963).
22. E. Traub, *J. Exptl. Med.* **69**, 801 (1939).
23. J. Hotchin, in *Cold Spring Harbor Symp. Quant. Biol.* **27**, 479 (1962).
24. D. Stowens, *Pediatric Pathology* (Williams and Wilkins, Baltimore, 1959), p. 187.
25. F. W. R. Brambell, *Biol. Rev.* **33**, 488 (1958).
26. J. L. Fahey, *Advan. Immunol.* **2**, 41 (1962).
27. E. C. Franklin, H. Fudenberg, M. Meltzer, D. R. Stanworth, *Proc. Natl. Acad. Sci. U.S.* **48**, 914 (1962); M. Harboe, C. K. Osterland, M. Mannik, H. G. Kunkel, *J. Exptl. Med.* **116**, 719 (1962).
28. Supported in part by the U.S. Army Research and Development Command, Project 6X61-01-001-03.

Earth Science Today

Preston E. Cloud, Jr.

Earth, air, fire, and water, the "elements" of the Aristotelian philosophers, remain the foci of interest for the modern devotees of Ge or Gaia, Greek goddess of the earth, who gave her name to the science of geology, or, more broadly, earth science. It is ironical that the Latin or "scientific" term should have had to be translated to its English or "vulgar" equivalent to give the subject its present healthy breadth. This happened because geology as practiced up to the forties had come pretty generally to imply specifically the study of those parts of the solid earth accessible to direct methods of observation. The use of indirect methods of observation to study the solid earth became known as geophysics, and the realms of air and water were temporarily abdicated. Fire, in the form of volcanology, remained in the bosom of geology, but the problem of the sources and gradients of terrestrial heat was shared with the geophysicists. Geochemistry and paleontology remained linked with the mother science in the basic methodology of direct observation, and usually in name, although they have outside affiliations and have had their separationist movements.

Why is it that we now see, all over the world, not only a continued proliferation of subdisciplines and specialties, but also an ever-increasing overlap of interest between fields once thought remote from one another, and growing cohesive forces of the type manifested by the increasing use of *earth science* to include air and water as well as earth and fire? This reflects what I consider to be the most distinctive and stimulating feature of modern science as a whole—the renewed realization, after a long period of isolationism, that all forms of truth and comprehension are interrelated, and that all of science, whether pure or applied, has a basic coherence under the universal laws of physics and mathematics, with chemistry and biology as first-order derivatives. What unites the earth sciences as an independent affiliated grouping of derived and integrating disciplines is their common interest in the structure, composition, dynamics, and history of the solar system, and, in particular, the earth. What is most characteristic philosophically, and most gratifying to me personally, about the earth sciences today is their blending of the useful parts of classical science with the most exciting aspects of advancing science.

Obsolescence, if recognized, is the surest sign of progress. It is manifested in classical science by diminishing productivity in ideas or useful applications of some area once at the forefront of advancing science. It is manifested in advancing science by the discovery that what once looked like the mainstream or an important short cut has proved on travel to be a bayou or a blind alley, or by the simple exhaustion of the new things that can be discovered by a given technique. Another characteristic and healthy feature of earth science in the modern world is the rapid rate of obsolescence in both classical and peripheral efforts. All of the systematic sciences, and I use *systematic* in the broad sense of classifying *and* explaining, are in a state of ferment as new equipment, new measurements, and improved computer facilities provide different and in some instances more fundamental bases for classification and rapid quantitative methods of evaluation—this is true, not only of mineralogy but also of paleontology and petrology. In geochemistry and geophysics, once promising methods of investigation of geologic age, geothermometry, and remote sensing of physical properties are abandoned almost as regularly as new ones are invented. We must expect both fewer striking advances and fewer flat failures in the remaining useful areas of classical science, because so much has been tried already, and both more striking successes and a larger number of flat failures in advancing science, because so much is new. It is merely important to bear in mind that a good balance of the two is necessary—the new because the largest individual gains are likely to be made here, the classical not only because it provides the annealing matrix, the tempering perspective, and the ultimate base line against which advances in the forefront fields are measured, but because it is here that most of the questions arise and here that many of them will continue to be answered.

It is sobering to bear in mind also that the current revolution in science is based largely on, and probably could not have happened without, the revolution in instrumentation born of mortal conflict between nations. As happened after the invention of the plain-light microscope, the Nicol prism, and other important tools, the more significant new things that can be learned with this new instrumentation will also tend to become mined out. This makes our findings no less exciting, but reminds us that the revolution can be sustained only in a framework of continually advancing in-

The author is professor of geology, department of geology and geophysics, School of Earth Sciences, University of Minnesota, Minneapolis 55455. This article is the main substance of a talk presented to a conference of Minnesota earth science teachers at Minneapolis, 13–14 February 1964.

strumentation *and* constructs, and that careers keyed to particular tools, even modern ones, can also become obsolescent. The resolving power of the human mind is not significantly better than it was in the days of Newton, Bacon, or Gilbert. Better or worse, there is no reason why it should be shackled to a particular instrumentation, particular subject matter, or a particular method of investigation.

It is our duty in the educational institutions of the country, therefore, to assure that a healthy balance is preserved in curricula, course content, and research experience, both because the bearing of our subject on the earth as an abode for man will always be important and because the earth sciences, along with all others, are evolving so rapidly that the student preparing for a career in science must be protected equally from the morass of pure traditionalism and the quicksands of frontiersmanship. His training must be such as to generate a high degree of interaction with other sciences and a high level of diversified research experience in the solving of problems that have never been solved before.

What are, then, some of the characteristics of earth science, as now practiced, and some of the challenges that will put our curricula to test in the future? Let us consider first some of the distinctive features of modern earth science as an amalgamation, then of some of its important parts, and, incidentally, a few of its achievements and goals.

Modern Trends

If we were to tabulate the things that most generally characterize the earth sciences in the modern world we might include:

1) A growing restiveness with traditional methods of investigation.

2) An increasing tendency to express observations and conclusions quantitatively wherever it is possible to do so.

3) An increasing degree of interaction with other sciences.

4) The assumption or requirement of an increasing degree of familiarity with mathematics as a form of communication, and with physics, chemistry, and biology in the presentation both of foundation courses and of advanced classes in college and university curricula.

5) A high degree of sophistication of instrumentation that is increasing our resolving power in all fields and permitting us to make new observations and discoveries, both in new fields and in fields that once appeared on the verge of foreclosure.

6) Along with the foregoing, and perhaps an unavoidable consequence of it, an increasing tendency to specialize earlier and more intensively and hence to limit the range of individual interaction and the flexibility of potential individual adaptation to future changes in the main currents. It would be defeatist, however, to accept this as unavoidable. I see no reason except that of personal choice or health why anyone should be "all washed up" at 40 or even at 70, even at the end of the 20th century.

It is a challenge to all of us to structure and constantly to modify our training programs and motivating mechanisms in such a way as to prepare men (including women) not only to reach and push forward the ever-expanding frontiers of knowledge in at least some small sector, but also to participate in the creation of new resources to sustain and improve human lives, and to prolong scientifically useful careers as far as possible.

Working against all of the unifying or centripetal forces and motivations we have been considering are the powerful centrifugal forces of differences in the basic substructure, specific subject materials, and methods of the various fields, and the value judgments and prejudices of their practitioners. What are some of these characteristics that make the earth sciences at once such an exciting, such a demanding, and at times such a frustrating master discipline?

Paleontology

In paleontology, at least as closely allied in subject matter and philosophy with biology as with geology, we are on the verge of exciting advances not only in paleoecology and paleobiochemistry, but in systematics itself. The use of the phase microscope and the electron microscope is permitting us to see things we have never seen before, or better than we have ever seen them before. It would be a rash or an ignorant paleontologist nowadays who would apply the term unfossiliferous, without qualification, to any sedimentary rock. The electron probe will permit the associations between biogenically concentrated elements and possible biologic structures to be measured essentially at the molecular level. The use of a host of new laboratory tools of high resolving power for the detection of amino acids and other organic substances, and of optical activity and other organic functions, is providing new data on the origin of life, the evolution of the atmosphere, pre-metazoan evolution, and the sources of organic fuels.

One day we may be able to subdivide and correlate the Precambrian paleontologically. The use of computer techniques in the analysis of variance may eventually allow systematics in part to loosen the bonds of Linnean nomenclature in favor of the greater flexibility of a coordinate system. The methods of crystallography and geochemistry, in the hands of paleontologists, are giving us clues to or confirming paleoecological deductions about paleotemperature, paleosalinity, tropisms, and migrations of fossil organisms in ways that were inconceivable 20 years ago. With all of these advances it is also an essential part of the job to keep alive and advance the basic knowledge and skills of systematic paleontology, for the proper designation of the organism is the key that unlocks the basic information available about it. It is axiomatic that we must know the names (or coordinates) of our subject materials in order to discuss them sensibly with others.

Geochemistry

Geochemistry, with its bewildering array of apparatus and instrumentation, has pushed back the age of the solar system and presumably the earth to near 5×10^9 years, is rapidly filling in the blanks in the radiometric timescale of the earth back to 3.6×10^9 years, and is putting the nonradiogenic isotopes to work on all kinds of interesting problems related to the environment and evolution of everything from fossils to ore deposits. Isotope geochemistry is perhaps the most rapidly moving subdiscipline, but solution geochemistry is coming increasingly to the fore with the availability of new equilibrium data and methods for their approximation, and with the growing concern of geologists of all persuasions with thermodynamic and kinetic factors in geologic processes. Taking merely the first three of over a score of achievements listed in the annual report of a single laboratory, we see that geochemists at the Carnegie Institution's Geophysical Laboratory have in one recent year (1 July 1962–30 June 1963) (i) found that the addition of a few percent of sulfur to common rocks can produce typical sulfide ore assemblages over a range of temperature and pressure, (ii) given more rigorous application to the promising geothermometer and oxygen barometer inherent in the equilibrium compositions of ilmenite and titaniferous magnetite, and (iii) demonstrated seemingly beyond further reasonable doubt the sometimes disputed correlation between geography and the petrography of oceanic and nonoceanic basalts. The study of the isotopic compositions of meteorites is casting light not only on the origin and evolution of the solar system but also on the differentiation of the earth's mantle and ocean basins.

Economic Geology, Petrology, Mineralogy, and Metallurgy

How and where usable concentrations of ores and fuels are formed is and will remain, of necessity, a central problem for geology, and assures its continued importance in the modern world and any foreseeable world to come. Economic geology, therefore, needs and uses not only the best of the traditional methods and equipment but also any new techniques that will assist in identifying the processes and settings that bring about the unusual concentrations of ordinary substances that constitute its basic subject matter. In this search geochemistry and geophysics are increasingly important partners. In the future we may look for an increasing linkage also with hydrometallurgy in joint effort to evolve methods whereby useful substances may be concentrated in place from dispersed conditions, complexed at depth for removal to the surface in fluid form, or utilized in place at depth.

Economic geology might be thought of as a special case of petrology, which likewise draws increasingly from and contributes increasingly to geochemistry, so much so that modern economic geology, petrology, isotope geochemistry, and solution geochemistry together comprise essentially a single broad grouping of the earth sciences. It is a grouping in which there are sharp differences of opinion about the relative significance of different approaches and some danger that even the more useful aspects of classical science may locally be relegated to the background. This may be one of the reasons it is such an exciting field to live with.

Both petrology and mineralogy are making good use of recent advances in solid state physics and materials science. The x-ray diffractometer is joining or supplanting the petrographic microscope in the undergraduate laboratory, and spectrometer and electron-beam instrumentation are standard research and graduate-instruction equipment. Spurred by the demands of semiconductor metallurgy and nuclear technology, our understanding of the atomic structure of minerals is advancing dramatically, and with unprecedented practical implications and support.

Geophysics

Structural geology and solid-earth geophysics share an interest in the broad architecture of the earth, in which the geophysical data and methods play an increasingly important part. Reduction of the seismic data from the Chilean earthquake, for instance, led to the discovery that the earth continues to vibrate after shock like a ringing bell and set off a chain of investigations that are giving us an improved model of the deep internal structure of the earth. Data on heat flow from the ocean bottom have rejuvenated the hypothesis of subcrustal convection currents as means for differentiation of major crustal segments, provided a more plausible mechanism for drift of continents (if drift they did), and complicated the picture of oceanic history. Shipborne and airborne magnetometers and gravity meters are revealing anomalies that apparently require major east-west offsets of the ocean floor and a new model of the west Atlantic margin. The steady march of design improvement and data-reduction techniques assures continued refinement of resolving power and ever wider and faster applications. Plans are afoot to fly geophysical instruments around the moon and other planets.

Of course much of our advancing knowledge of the atmosphere and oceans also derives from geophysical techniques. Instruments in rockets, satellites, and balloons, or mounted on anchored buoys, or drifting, or carried aboard ship are measuring differences in the rate and nature of drift, transmission, reflection, refraction, or absorption of shock, sound, light, heat, electricity, magnetism, and radiation, both natural and induced, and these measurements are the basis for models of the structure of the atmosphere, the oceans, and crustal and subcrustal structure beneath the oceans. The resulting models in turn suggest other investigations, including ones leading to matters of such broad interest as the identification of ancient jet streams and equatorial positions from the data of ash-falls and other sedimentary fallout.

Oceanography, Limnology, and Meterology

I have already alluded to some of the advances in marine geology that have been achieved by geophysical methods. Actually, the whole of oceanography and limnology, as well as meteorology, is properly regarded as appertaining to the earth sciences. Perhaps the most spectacular advances in these fields, aside from our greatly refined knowledge of the atmosphere itself, and the oceanic substructure, are coming from studies of air-water linkage and the deep movement of the water in ocean and large lake basins. Theoretical, model, and field investigations have revealed the presence of deep undercurrents running counter to the major surface currents in the equatorial and western boundary waters of the great oceans. Large-scale seiches have been detected in the Great Lakes. And individual water masses have been observed over long distances by means of radioactive tracers, transmitting floats, and distinctive microbiological characteristics. Spurred by the recommendations of NASCO and a sense of economic and military urgency, the examination of the fine structure of the oceans, their atmospheric superstructure, their sedimentary floors and substructure, their differentiation from continental areas, and the resources in and beneath them is now being carried out with all of the tools of modern technology. We badly need a base line for the interpretation of our surficial sea-floor records and geophysical readings, however, and this can be provided only by deep drilling. Recent differences of opinion about how this is to be done have temporarily delayed the investigation, but it must be carried out if we are ever to know the history and understand the origin of the ocean basins.

Geology of Outer Crust

Areal geology, geomorphology, and soil science may be treated together because they are highly interrelated in that all to a large degree deal with the surface features of the earth and present their findings and interpretations in the form of rather sophisticated models unfortunately designated "maps," with the accompanying connotation of routine surveying. The construction of the most useful such models requires not only a high degree of information and intuitive judgment about things like vegetation, weathering characteristics, and subtle responses of land form to structure, climate, and lithology; it also demands a high level of mastery of the techniques of investigation in several allied fields such as petrology, hydraulics, geochemistry, stratigraphy and sedimentology, structural geology, and paleontology, including palynology. The essential "mapping," therefore, is increasingly supplemented not only by microscopical investigations, but by new methods of laboratory probing, by experimentation, and by quantitative theorization.

Stratigraphy and Sedimentology

Stratigraphy and sedimentology may also be discussed in the same breath, for sedimentology originated out of a desire to do better stratigraphy and the two are now highly intertwined. Although once confused with correlation and based primarily on paleontology, stratigraphy is now understood to deal with much more than the sequential arrangement of strata and their classification as marine, fresh-water, or continental. Like areal and structural geology, which also have at times been treated as pretty much applied geometry, stratigraphy, under the influence of sedimentology and geochemistry, has broken into the more bracing atmosphere of search for causes. We want to know as completely and accurately as possible what forces acting with what intensity under what circumstances and over what interval of time conditioned the erosion, transport, deposition, and diagenesis of the sediment we now see as rock. Inasmuch as it deals, therefore, with quantitatively expressible and experimentally verifiable hydraulic and geochemical processes and the arrangement of the results in specific geometrical patterns, the "new look" in stratigraphy and sedimentology is also quantitative and likely to be highly instrumented. One is about as apt to find flumes, wave tanks, constant-temperature baths, amino acid analyzers, or infrared spectrometers in the laboratory of the modern stratigrapher-sedimentologist as he is to find sieve-shakers or mineral separation equipment.

Volcanology and Miscellaneous

I mentioned volcanology earlier as a separate earth science, and probably 60 or 80 more subdivisions that are important to someone could be named. I will say no more about modern volcanology than that it has outgrown its once largely morphologic nature to merge almost completely with geochemistry, geophysics, and petrology as a powerful integrative approach to problems of magma and lava origin and differentation. Most of the other subdisciplines that I have not identified are also variants or boundary mergers of those that have been mentioned.

Applications to Moon and Planets

I do want to take notice, however, of the applications of geology to selenology, planetary physics, and astrophysics, which have at least a 65-year history and are currently enjoying rejuvenation. Moving out from the base line of G. K. Gilbert's early study of the surface features of the moon, U.S. Geological Survey geologists in collaboration with NASA are now engaged in a program of quadrangle mapping of the visible surface of the moon based on stereophotogrammetric interpretation and having for its aim the deduction and delineation of the characteristics and arrangement of rocks at and near the surface of the moon. Two quadrangles have now been completed and published; one was reproduced in part on the cover of the November 1963 issue of *Fortune* magazine, which gives details of the program. Pieces and possible pieces of the solar system from beyond the earth's orbit that are captured by its gravitational field are, of course, intensively studied; indeed more people are working at meteoritics today than were in the whole of geochemistry when I was in college. And of course geologists are profoundly concerned with the characteristics and history of other planets as possible abodes for life.

I have reserved hydrogeology and engineering geology for last mention because both are undernourished fields whose importance I want to stress. Hydrogeology refers to all phases of water—movement, storage, variation of properties, and availability for use above or in the ground. The problem is essentially one of fluid movement over or within porous media, and the properties engendered or altered in the process. Its study involves hydraulics, geology, the chemistry and microbiology of solutions, and all the complexities of interaction between ground and surface waters, the atmosphere, and the biosphere. Central problems include residence time and diffusion in the ground, the mixing of salt and fresh waters in coastal regions, water storage and recovery, and prevention of contamination. They are important to all of us and become increasingly critical with growing urbanization and population increase. Legislation now anticipated should assure increased attention to these problems, with consequent demands for improved instrumentation and trained personnel.

The importance of engineering geology is not yet as widely appreciated as it should be, but it becomes more crucial with every major construction project, every great military venture, and growing urbanization. Site selection for the launching and landing of missiles, satellites, and space ships should have the best possible engineering geology. Our expanding modern civilization needs geological help with the prediction and control of landslides, land subsidence, floods, and damage resulting from earthquakes, tsunamis, volcanism, and climatic and sea-level changes. Large commercial installations, building developments, and highway or bridge construction should require geological approval of the site and alterations to it. And large municipalities and groups of smaller municipalities need city geologists as much as they need city engineers. We can confidently expect that, in the future, this will be a major area of employment for geologists and of benefaction to mankind.

Finally, as new potentialities arise, it is worth bearing in mind that the road to continuing vitality in our science, as in our lives, is a readiness always to reexamine our aims, our methods, and our courses of action. "To have doubted one's own first principles is the mark of a civilized man" (O. W. Holmes).