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Association and Indeterminacy in Geomorphology

You find a rock. It looks like an ordinary piece of flint, broken and rough. On a part of it is a patina whose soft grey color contrasts with the shiny brownish surfaces of conchoidal fracture. You could have found this rock in nearly any kind of an environment almost anyplace in the world. There is nothing distinctive about it.

You hand this same piece of rock to a colleague and ask what he can make of it. He considers it soberly before he says, "You know, that could be an artifact." There springs to mind then a picture of a primitive man, squatting barefoot before a fire warming his hands. The firelight casts his shadow against the cliff below which he crouches.

The difference between the reaction before and after the passing thought that this might indeed be the tool of ancient man is the difference between mild disinterest and a kaleidoscope of mental pictures. This difference reflects differences in the associations of thoughts.

The present essay is concerned with how associations are used in geologic reasoning, and then with certain philosophic considerations which seem to be influencing the methodology and direction of geomorphology.

When you picked up the piece of flint the associations which flashed through your mind were specific to the limits of your knowledge regarding the object itself. This stone was unusual only in that it appeared to have been worked by human hands. The mental pictures which were projected by the thought process stemmed only from an intellectual interest. The specimen itself is valueless. If, however, the rock had been a sample of ore, the chain of thought might have led to interest of quite a different kind. Our everyday experience in geology emphasizes that the purposes of this branch of natural science are twofold—intellectual and utilitarian—being constituted of the two principal elements which generally tend to stimulate the mind of man.

In geomorphology, as in other branches of science, mental pictures depicting associations in the natural world have an intrinsic value which stems from the wonderment that a knowledge of nature seems to produce nearly uniformly among thoughtful human beings. But associations in the natural world are not only objects of interest in themselves; they are also tools of the art.

The association of different observations is a form of logic. What is here called "association" might be viewed by some merely as another word for reasoning. But this type of reasoning which is used in geology is so extensively elaborated that it bears but little resemblance to mathematical logic, even if the logician may be able to discern in geologic reasoning the same precepts and, indubitably, the same methods which constitute the bases for any kind of logical reasoning. If the reader, then, wishes to equate the word "association" as used here with logic or with reasoning, we pose no objection, but it is the basis for this reasoning that is here being examined.

The simplest and most fundamental type of association deals with the process acting. When one observes in an outcrop a uniformly bedded sandstone he associates this with his general knowledge of the way in which sand may be deposited. A sand deposit usually implies that there was a source of quartz materials, a process by which these materials were reduced to relatively uniform size and sorted, and a physical situation leading to progressive accumulation of the materials in a depositional environment. The outcrop is interpreted, then, by means of a general knowledge of the processes of weathering and subsequent transportation by water or wind.

In contrast to the observations of materials in a vertical section, another line of associations relates a feature of the landscape to particular processes. The occurrence of an alluvial fan at the mouth of a canyon is interpretable in terms of the form and location of the materials, in this case both indicating that the sediment making up the fan had its source in the canyon and that it was transported from there to its present position, presumably by water or by gravitational flow lubricated by water.

Implicit in the utilization of associations is the principle of uniformitarianism: geologic processes presently observed are presumed to be the same as those operating throughout geologic time. The association of a cropping of uniformly bedded sandstone with presently observed conditions under which sand may be so deposited stems from the assumption that processes presently observed are the same ones that operated in the distant past.

The concept of association goes far beyond a principle even so general as that of uniformity. That principle in itself does not necessarily suggest sequential operations, nor does it treat of the relationship between individual observations and the generality to which these observations may be applicable. For example, in the sample case cited, let it be supposed that the sandstone is transected by a dike of igneous material. The knowledge of process leads to the conclusion that the sand must have been deposited at a time previous to that in which the igneous material was intruded.

The idea of uniformitarianism does not in itself deal with time relationships. The geologist studies the bones of a dinosaur. In the same formation where the bones were discovered the footprints of a beast are found preserved as casts. The bones of the feet can be compared with the footprint and, let us say, the print seems to have been made by the animal whose bones are now fossilized. There is nothing at the present time quite like this creature, and it is by the use of association rather than by reasoning stemming from uniformitarianism that the bodily form of the dinosaur can be shown to be compatible with the casts of his footprints. It would seem, then, that the use of associations provides an indispensable extension to uniformitarianism in geologic reasoning.

Whole fields of geology, particularly paleontology, are based more on association than on any principle which relates presently observable processes to those which occurred in previous epochs. Interpretations must be made of phenomena unlike any known to occur under present conditions. This implies that the concept of association is of no lower an order of generality than is the principle of uniformitarianism.

To summarize, then, geologic reasoning is based on a logic called here the use of associations. Associations are useful in four different ways. First, particular associations may indicate the sequence of events in time. Second, an association found locally may indicate a general relation having limits far beyond the immediate locality or scope of the observation. Third, a particular association may be indicative of the processes acting. Fourth, synthesis of a variety of observations is, in effect, a broadening of the scope of associations considered in a given context.

Generalization may be thought of as a synthesis of individual bits of knowledge into a broader framework, but synthesis is merely the broadening of a context of association. The number of associations which are involved in a particular thought process is possibly one measure of the degree to which synthesis is achieved. Thus the use of association, much in the manner indicated by the simple examples cited above, constitutes the methodology of synthesis, or integration. From this point of view the utilization of the concept of association represents one of the fundamental bases of geology.

In the inductive method, the purpose of describing a phenomenon may be, for example, to eliminate extraneous details to see what, on the average, is the pattern represented by the data. The generalized description may be either quantitative or qualitative. The question of what data should be included would be determined primarily by the question asked rather than by an *a priori* determination of whether the data apply to the generalized description required. As many cases as possible would be studied to see what patterns are displayed among the examples. Whether quantitative or qualitative, the search for patterns in information is essentially inductive.

The difference between inductive and deductive approaches does not lie in the presence or absence of a working hypothesis or multiple hypotheses, but these approaches may differ in the stage at which the hypothesis is derived. The difference does not dispense with the need, at some stage, for developing an hypothesis which must be tested against data and reason.

Those of us working in geomorphology have a particular interest in the philosophy of research, both because of the nature of our subject and the history of its development. The aim of this portion of the geologic science is to understand the forms of the earth's surface. It is not difficult to see, then, that it is a subject which might first have been approached by classifying the observed forms, i.e. devising categories for pigeonholing different types of hills, valleys, scarps, rivers, and drainage patterns. From such classification, certain generalizations were drawn—an inductive approach.

A continued interest in classification, during the first third of the present century, took the form of assigning names to features of the landscape. Streams were designated as subsequent, superimposed, etc., and each such designation carried with it appropriate inference about both operative processes and historical sequence. Little attention was paid to the study of process, which, looking back at the record, now appears to have led to a neglect of field studies as the foundation of geomorphic science. As a result, the subject became one of decreasing interest to other workers in geology. An important aspect of this growing disinterest was that geomorphology, as practiced, seemed to lose its inherent usefulness.

In science usefulness is measured in part by ability to forecast, i.e., to predict relations postulated by reasoning about associations and subsequently subject to verification by experiment or field study. With this in mind, it is apparent that preoccupation with description could lead to decreasing usefulness because classification and description are usually insufficient bases for extrapolation and thus for prediction.

At mid-century there began a revitalization of geomorphology, which has taken the form of a more detailed investigation of processes operative in landscape development. Study of process has been accompanied by increased use of quantitative data and mathematical expression. The trend toward quantitative study in geomorphology, in contrast with description, should not be viewed as a basic difference in method of investigation, as mentioned earlier, but rather as a difference in the type of problem being attacked. Both quantitative and qualitative geologic research are based on the use of associations and the concept of uniformity.

This trend parallels that in geologic research in general. Before 1930, less than one page in a hundred in the "Bulletin of the Geological Society of America" contained mathematical formulation. The percentage now approaches ten in a hundred. Civil engineering shows a similar trend, but the level has always been higher.

Coupled with the forward increase in the quantitative method in geomorphology there is, encouragingly enough, a greater concentration on geologic mapping in many investigations, and in others, at least a detailed study of stratigraphy in the field. The work of John T. Hack (1960) on geomorphology of the central Appalachians is a model which it is hoped a growing proportion of workers in the field will emulate. He made detailed geologic maps of local areas which he then used as the basis for study of form and process in which both qualitative and quantitative arguments were used. Similarly, John P. Miller mapped extensive areas in the Sangre de Cristo Range, New Mexico, and used these as the basis for geomorphic studies (see Miller, 1959).

Among the geologic sciences, geomorphology has, for some time in America, been approached in a manner sufficiently different from other aspects of geology that it may have come to be viewed as different in philosophy. We contend that in philosophy and in method it is one with other geologic sciences. Association, uniformity, working hypothesis, reasoning, quantitative and qualitative data are concepts and tools as much needed here as elsewhere in geology.

At any time the need for a set of questions, implicit or explicit, is paramount. Over and above that, there is a time for new data and there is a time for new theory. Progress depends on both. For several decades governmental authorities had been collecting data on rivers. No one knew just how to apply this store of information to geomorphic inquiry. No one knew what questions to ask. Then, in 1945, Horton set forth a new hydrophysical theory of the landscape that was refreshingly exact in its principles in contrast with the anthropomorphic word pictures of William Morris Davis. The analysis of river data began soon after. There followed a decade and a half of analysis using the data available in conjunction with the ideas stimulated by Horton's theory. Not much more is likely to be gleaned from either. The time is set for new theory and new data.

The shift in interest from description toward process and from the qualitative toward the quantitative in geomorphology appears also to be leading toward an important shift in viewpoint which may have far-reaching effects on the field. New sets of associations are evolving because of the particular questions now being asked. We think we see operating in landscape development a principle long recognized in physics but new to geomorphic thinking—a principle of indeterminacy.

By indeterminacy in the present context we refer to those situations in which the applicable physical laws may be satisfied by a large number of combinations of values of interdependent variables. As a result, a number of individual cases will differ among themselves, although their average is reproducible in different samples. Any individual case, then, cannot be forecast or specified except in a statistical sense. The result of an individual case is indeterminate.

Where a large number of interacting factors are involved in a large number of individual cases or examples, the possibilities of combination are so great that physical laws governing forces and motions are not sufficient to determine the outcome of these interactions in an individual case. The physical laws may be completely fulfilled by a variety of combinations of the interrelated factors. The remaining statements are stochastic in nature rather than physical.

These stochastic statements differ from deterministic physical laws in that the former carry with them the idea of an irreducible uncertainty. As more is known about the processes operating and as more is learned about the factors involved, the range of uncertainty will decrease, but it never will be entirely removed.

An example may be drawn from river processes. Into a given reach of river between tributaries, a certain rate of flow of water and a certain amount of sediment are introduced from upstream. Both change during the passage of a given flood or through a season or a period of years. To accommodate these various rates of discharge of water and sediment, a number of interdependent hydraulic variables will change, including width, depth, velocity, slope, and hydraulic roughness. A particular change in discharge and sediment may be accommodated by several combinations of values of these dependent or adjustable factors.

Specifically, the physical equations which must always be satisfied are equations of conservation, such as the conservation of mass. In the river, this is expressed in the statement,

$$Q = wdv,$$

or discharge is the product of width, depth, and mean velocity. Another physical equation is the relation of velocity, depth, slope, and hydraulic roughness expressed by the Chezy or Manning equation. Another is the relation between shear stress and the sediment load. In a particular case these physical relations can be satisfied by a variety of combinations of values of the dependent variables.

In addition to the physical laws of conservation, another kind of principle is operating, a principle which deals with distribution of energy in time and space and is probabilistic in form. It operates as tendencies guiding the combination of the dependent factors. There is a tendency toward minimum work or minimum rate of energy expenditure and, separately, a tendency toward uniform distribution of energy expenditure. These are usually opposing tendencies. These tendencies operate through processes which tend to keep an equilibrium among the factors by restraining change.

In the river, such processes, or governors, include scour and fill, changes in bed configuration (ripples, dunes, and antidunes), and the Bagnold dispersive stress on the bed. Such processes act in the same manner as the mechanical governor on the old steam engine. Any tendency to change one factor at the expense of another induces a resistance to that change, and so the hydraulic factors hover around a mean or equilibrium. But at any moment in time, the specific relations cannot be forecast except in a statistical sense.

Such governing action is well known in the process of scour and fill. If local deposition occurs on the bed of an alluvial channel, depth tends to decrease slightly, velocity may increase, and slope may tend to increase, the net result of which tends to limit deposition or to induce compensatory scour. The average relation or the most stable relation in river mechanics appears to be one in which total energy expenditure is minimized and energy utilization is uniformly distributed through the channel reach, a consequence of the requirements for a stable open system (Leopold and Langbein, 1962).

In the development of land forms there are many different processes acting at innumerable localities. There are, in other words, a great many hills, rills, valleys, cliffs, and other forms, and on each, a large number of variable factors operate. Geomorphologists have considered that the variations observed among examples of the same features are due to two principal causes: (a) slight variations in local structure, lithology, vegetation, or other factors, and (b) irreducible errors in measurements. We postulate a third no less important one—statistical variation resulting from the indeterminacy discussed above. At first blush, this addition may seem trivial, obvious, or implied in the first two causes, but philosophically it seems important. The following example may illustrate the point.

Imagine a broad hill slope of uniform material and constant slope subjected to the same conditions of rainfall, an ideal case not realized in nature. Assume that the slope, material, and precipitation were such that a large number of rills existed on the surface in the form of a shallow drainage net. Would it be supposed that rills comparable in size and position were absolutely identical? The postulate of indeterminacy would suggest that they would be very similar but not identical. A statistical variation would exist, with a small standard deviation to be sure, but the lack of identity would reflect the chance variation among various examples, even under uniform conditions.

In addition to known physical relationships there are other relations of a stochastic nature that can be used to explain certain geomorphic forms (Langbein, 1963), and they imply that variance in form is an inherent property. It is here suggested that the same principle may have general applicability to many aspects of geologic science. The landscape, in other words, exhibits a variability which may be expected as a result of incomplete dynamic determinacy. General physical laws are necessary but not sufficient to determine the exact shape of each land form. Some scatter of points on graphs showing interrelations between factors is expected, although the mean or median condition is reproducible in different sets of samples.

The same set of conditions, for example the same climate, the same lithology, and the same structure, can lead to a spectrum of different dimensions and positions of the otherwise identical aspects, for example, the rills just mentioned. These variations exist even though there are (a) common climatic and geologic environment, and (b) a common set of hydraulic principles.

Hence we conclude that there remain certain unsatisfied conditions, certain degrees of freedom (excess of unknowns over number of equations that can be written to connect these unknowns). Implicit in this observation is the possibility of applying principles of probability to an interpretation of those aspects of the landscape subject to variance. The analysis is helped by the central-limit theorem that a mean condition exists. The variance about the mean is a function of the degrees of freedom.

Thus it appears that in geomorphologic systems the ability to measure may always exceed ability to forecast or explain. The better to account for variations in land forms, it may be possible to introduce new relationships, each deriving importance in proportion to the extent that they satisfy nature, i.e. agree with reality in the field. These new or alternative relationships may be stochastic rather than physically deterministic. Thus probabilistic relationships may provide better agreement with actual conditions than the direct physical relationships which have previously been used. The stochastic statements, which may at times enlarge upon physical relations based on Newtonian laws of mechanics, will differ from the latter in having an inherent variance implicitly or explicitly stated. But this probabilistic or stochastic statement may turn out to be the more important element and lead to more specific understanding of processes than the previous approximation which supposed exact physical laws.

What we believe will be an example of the substitution of a probabilistic statement for a physical one, and thus of an improvement in understanding is in the much-studied logarithmic distribution of velocity in turbulent flow. The approximation to field observation provided by momentum theory is deterministic in nature, but it is well known that it contains implicitly a variance. It now begins to appear that explanation of the logarithmic velocity distribution based on stochastic principles may be more basic in leading to understanding and will agree as well or better with actuality than the physical models previously used. Further, the stochastic relation will lead directly not only to mean values but also to a statement of the variance about the mean.

Equilibrium in geomorphology, from this point of view, can be achieved in a variety of ways and is fixed or definable for a large number of cases only by their means. Those cases which deviate from the mean are not necessarily in any less perfect equilibrium than other cases which coincide with the mean. In this sense geomorphology inherently involves variance, which is an intrinsic property of geomorphic forms.

In this light, statistical processes and statistical treatment are necessary objects of study and tools of the science. They can be studied only quantitatively. This is, if need be, justification enough for the growing emphasis on a quantitative rather than a descriptive treatment of land forms.

But justification of our tools, our methods, or our emphasis, should not occupy attention in geomorphology. If results are of intellectual interest, or lend themselves to practical prevision or forecasting, the science will prosper. To this end, geomorphologists might best look to the scope of the associations in our reasoning processes.

Any aspect of science may founder temporarily on the shoals of small questions, of details, as well as on the dead-end shallows of description. Resurgence of activity and interest can revitalize a subject when the questions posed for investigation are big ones, questions which, if answered, have wide applicability or lead to broad generalization. But generalization is the broadening of associations, the spreading of a foundation for reasoning. The big question is one the answer to which might open up new or enlarged areas of inference or association.

The measure of a research man is the kind of question he poses. So, also, the vitality of a branch of science is a reflection of the magnitude or importance of the questions on which its students are applying their effort. Geomorphology is an example of a field of inquiry rejuvenated not so much by new methods as by recognition of the great and interesting questions that confront the geologist.

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