1 To diagnose the Earth

It is not an easy thing to say what the scientists are doing or what science is.
Feibleman, 1972, p. 1

Diagnosis is considered to be a medical term, meaning to distinguish or identify a disease, but as used here the word has broader implications. Diagnosis is 'an analysis of the nature of something' (W. Morris, 1981). In medical practice a diagnosis involves taking the history of a complaint, examination of the patient, identification of the problem, statement of the diagnosis and finally the statement of a prognosis. Therefore, the physician describes the condition, predicts the course of the disease, and prescribes a cure. In each case, the physician is dealing with a single individual, and he is trying to apply generalizations to one person. This is very similar to the practice of the earth scientist, who in most instances is dealing with a singular situation, perhaps a single but complex feature at or near the earth's surface such as a mountain range, an outcrop, a river or a hillslope.

The procedure followed by the physician during diagnosis is a scientific method, and, in fact, the objectives of this short work are to discuss briefly the scientific method in earth science and then to stress the problems encountered in its application. However, the first thing that a reviewer of the literature on the scientific method discovers is that there is little agreement about it, and the opinions are extreme. Sarton is emphatic that 'The great intellectual division of mankind is not along geographical or racial lines, but between those who understand and practice the experimental method and those who do not understand and do not practice it' (Mackay and Ebison, 1977, p. 134). Bertrand Russell (1961, p. 243) concludes that 'whatever knowledge is attainable, must be obtained by scientific methods, and what science cannot discover, mankind cannot know'. Conversely, Medawar (1976b) a Nobel Laureate, says, in effect, that there is no scientific method. He concludes that if an effective scientific method existed then scientists would be more successful in their endeavors than they are, and if a method existed that leads a scientist with certainty to the truth then there is no excuse for not solving scientific problems. This perhaps facetious conclusion can be coupled with his statement that 'the scientific method is an enormous potentiation of common sense' (Medawar, 1979a, p. 27). Potentiation is defined as a powerful accumulation. So, according to Medawar, the scientific method is simply the way of common sense, but according to Boorstin (1983, p. 294; see also Nagel, 1961, pp. 1–14) 'Nothing could be more obvious than that the earth is stable and unmoving and that we are the center of the universe. Modern Western science takes its beginning from the denial of this common sense axiom . . . Common sense, the foundation of every day life, could no longer serve for the governance of the world'. Perhaps by common sense Medawar means trained and critical thought.

In 1986, Sigma Xi (1986), the Scientific Research Society, sent a questionnaire to its membership. One statement related to science and the scientific method, as follows: 'The word science is often invoked as if it meant a particular "thing" comprised of scientists, public and private laboratories, publications, and government agencies. For me, however, "science" connotes a process or procedure for making inquiries about our world and for evaluating the hypotheses these inquiries generate'. Of the scientists who responded to this questionnaire, 95% agreed with the statement that science connotes a method for making inquiries about the world. This suggests that in the minds of most scientists it is the method employed in carrying out their research that distinguishes science from other human endeavors.

Scientists in many fields give a great deal of attention not only to the method by which their activities are carried out, but also to the success of these activities (Susser, 1973; Harvey, 1969; Sayer, 1984). Medicine provides a good example, where, of course, there is great public concern with success, and there are a number of books available on differential diagnosis, which describes the manner by which a physician proceeds to diagnose an illness and to prescribe for it.

NATURE OF EARTH SCIENCES

Most earth scientists do not find philosophical discussions of their field very interesting. In fact, many scientists treat the philosophy of science with 'exasperated contempt' (Medawar, 1984, p. 132). This is understandable because the terminology of the philosopher is as difficult to comprehend to the uninitiated as is the language of scientific specialists. Indeed, geologists seem to exhaust their philosophical proclivities in speculating about the nature of geology as a science (Simpson, 1963; Watson, 1966, 1969; Van Bemmelen, 1961; Bucher, 1936, 1941; Kitts, 1963b; Spieker, 1965), and they are less interested in discussing their role as scientists (Kitts, 1977, p. XI). With the exception of T. C. Chamberlin (1890, 1897), G. K. Gilbert (1886, 1896), Douglas Johnson (1933, 1940), and Hoover Mackin (1963) geologists tend to go about their scientific endeavors without giving much thought to the manner in which they proceed.

This may be the reason that Mackin (1963, p. 137) in a footnote to his excellent paper on rational and empirical methods in geology, complained that geology is scarcely mentioned in the large literature on the history and philosophy of science. Nevertheless, since then Kitts (1977) and Watson (1966, 1969) have written extensively on the subject, and Gilbert's work has attracted considerable attention (Yochelson, 1980; Pyne, 1978, 1980; Kitts, 1973) as has Chamberlin's (Laudan, 1980; Pyne, 1978) and the work of Hess (Franklin, 1980).

It is generally agreed that geology is a derivative science (Scriven, 1959; Pantin, 1968; Bucher, 1941) that utilizes information and concepts from astronomy, chemistry, physics, and biology (Fig. 1.1). If as David Kitts (1974) concludes, geologists are not much inclined to discuss their role as scientists, part of the problem is that they generally attempt to apply this diverse information to singular or particular events or things, and therefore, their explanations may often be weak in comparison to those of other sciences (Kitts, 1963b, p. 25; Nagel, 1961, pp. 547–606; Simpson, 1963). Also, it has been stated that because geology is historically oriented and because it deals with such great complexity, during long periods of time and over large areas, that it is different from other sciences. Usually this means that geology differs from chemistry and physics and that somehow the difference is demeaning to the geologist. This is a peculiar attitude that seems to have been

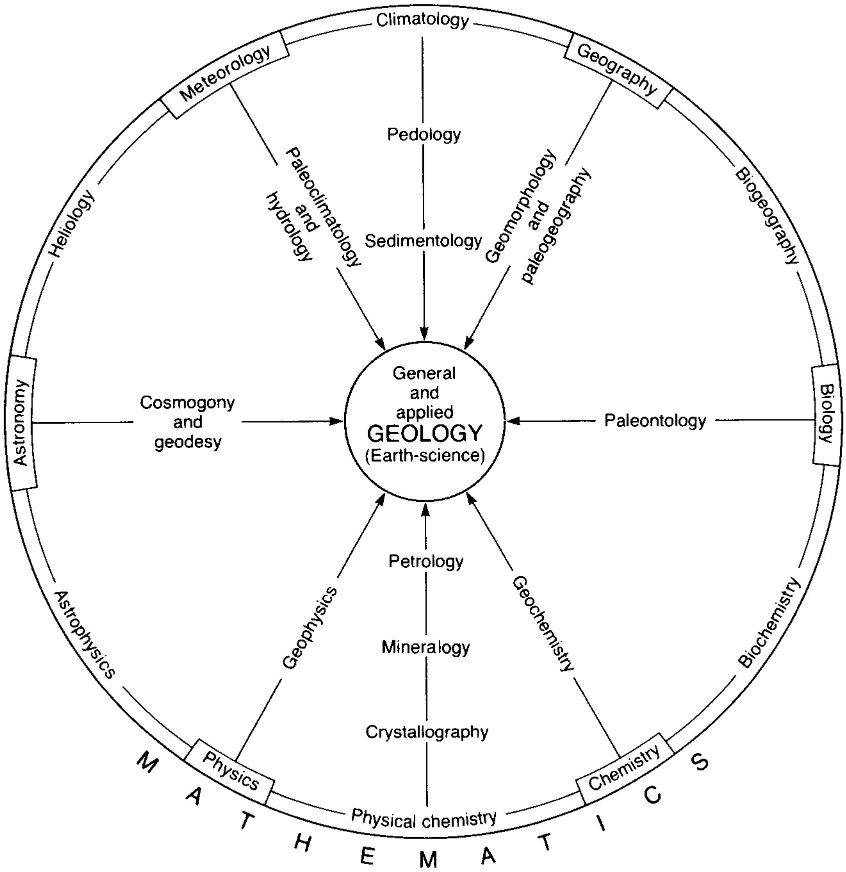


Figure 1.1. Geology as a derivative science (from Van Bemmelen, 1961).

generated by the inability of the geologist to produce quantitative 'laws of nature'. Indeed, the consideration of both vast spans of time and large areas is not common to other physical sciences (Simpson, 1963; Watson, 1969) with the obvious exceptions of astronomy and cosmology. The geologist, therefore, is involved in the study of 'complex natural experiments conducted on a large scale in both time and space' (McKelvey, 1963). The experiments with which geological history confronts us are neither reversible nor repeatable, and they are accomplished on a scale of time and space that precludes as a matter of course exact reproduction. Moreover, they cannot be directly observed; but they must be reconstructed historically (Bubnoff, 1963, p. 3). This is the fundamental distinction between geology and most other sciences. The earth scientist deals with complex systems that function over long periods of time, and each system, although not unique, may be singular (Nairn, 1965; Watson, 1969). That is, each system is different from similar systems, and each may reflect processes no longer active at a particular location (e.g. glaciation). Hence, the opportunity for reproducibility and falsification is minimal. Therefore, it is not surprising that geologic and geomorphic predictions may have 'low resolution' and may be weak in comparison with other sciences (Pitty, 1982).

The variability of geologic processes and rates, during long periods, and the limited number of situations that can be sampled, creates a problem not encountered when dealing with closed systems, isolated variables, experimental results, and the statistical analysis of very large numbers of measurements (Hagner, 1963, p. 235). Geology, as with biology, psychology, history, economics, geography and engineering is an 'irregular subject' in the sense of Scriven (1959) because there can be considerable error in the application of generalizations to specific cases (see also Kitts, 1963a; Leopold and Langbein, 1963; Grinnell, 1987, p. 27). But depending upon time and scale this is true of other sciences. For example, in meteorology it is possible to predict the general climate of a region based upon past records, but it is not easy in the short term to predict changes in the weather. In physics and chemistry, if the behaviour of the single atom is considered rather than the average behaviour of many, the ability to predict is also very low. The engineer uses factors of safety to compensate for the difficulty of specific predictions. Unfortunately, the need to predict in earth science is usually for specific cases (site stability, well locations).

Geology also contains within itself a great dichotomy between historically-oriented and process-oriented research. Bucher (1941) uses the terms 'timeless' and 'time-bound' to describe the differences. Timeless knowledge involves 'the search for general properties and patterns of behavior or "laws" that characterize the object and their reactions to each other. These properties and laws apply always, everywhere. They are independent of the stream of time'. Time-bound knowledge is concerned with a specific object (river system, hillslope, mountain range, sedimentary deposit) and its change with the passage of time.

Strahler (1954) prefers to distinguish between historical geology (time-bound knowledge) and physical or dynamic geology (timeless knowledge) on the basis of repeatability or the probability of recurrence of a particular state or form. He proposes that 'historical investigation be defined as referring to the analysis of complex states having very small probabilities of being repeated, that is, to states of low recoverability. Dynamic investigation in the same context refers to the analysis of states having a high degree of probability of being repeated, such analysis leading to the formulation of laws of general validity.' Most of us operate in both of these areas of earth science, some more than others, but this situation sometimes leads to problems of communication and interpretation (see Chapter 3).

The following statement by D. A. Pretorius (1973), although written for the economic geologist, is equally applicable to many aspects of geology and is an admirable statement of the problems facing the earth scientist attempting postdiction:

> It is the nature of the history of the earth that a geologist has available to him only partial information. Occasional lines from disconnected paragraphs in obscurantist chapters are what can be read. Violence in the handling of the book through time has caused many of these chapters to be ripped and reassembled out of context. That the gist of the early chapters can be deciphered at all is a credit to perseverance and imagination not always associated with other sciences. The geologist operates at all times in an environment characterized by a high degree of uncertainty and ornamented with end-products which are the outcomes of the interactions of many complex variables. He sees only the end, and has to induce the processes and the responses that filled the time since the beginning.

As an undergraduate, the definition of geology that I learned was that it is 'the science of the earth as revealed in rocks'. This definition of geology has been replaced by a somewhat more inclusive definition in the glossary of the American Geologic Institute (Gary *et al.*, 1972), as 'the study of the planet earth'. The definition continues as follows: 'It is concerned with the origin of the planet, the material and morphology of the earth, and its history and the processes that acted (and act) upon it to affect its historic and present forms.' This definition also implies that the main concern is the explanation of present conditions and the interpretation of history. However, later in this rather lengthy description, prediction is acknowledged, and it is stated that 'All of the knowledge obtained through the study of the planet is placed at the service of man, to discover useful materials within the Earth; to identify stable environments for the support of his constructed arts and utilities; and to provide him with a foreknowledge of dangers associated with the mobile forces of dynamic Earth, that may threaten his welfare or being.' The newer definition involves the geologist in extrapolation not only into the past but also into the future.

EXTRAPOLATION

In the area of applications some earth scientists are very concerned with ongoing processes of fluvial, aeolian, coastal and glacial erosion and deposition, groundwater movement, seismic activity, active tectonics, etc., and therefore, these geologists predict. Indeed, with the increasing importance of environmental geology, engineering geology and geomorphology, prediction has been emphasized in the past few decades. Therefore, earth scientists must extrapolate from the present not only to the past, but also to the far future, especially when the stability of hazardous-material disposal sites is being evaluated.

Extrapolation, of course, involves the projection of known information or relationships to the unknown. This involves both extrapolation to the future, which is prediction, and extrapolation back in time, which is retrodiction or postdiction. Figure 1.2 is an attempt to show schematically how studies of modern processes and their effects provide a description and explanation of the present, which can be used by analogy to develop models of the past and future. Past changes and conditions in turn, influence the present, and, therefore, the future.

It is possible to learn a great deal about the present. Measurements of erosion and deposition can be made and the dynamics of aeolian, fluvial, glacial, coastal and marine systems can be investigated. Information on the morphology and dynamics of these systems permits the development of a model of contemporary situations. Extrapolation from the present to both the past and future is then possible (Fig. 1.2). However, it is obvious that if both the present and the past are known, then prediction is enhanced because the record is extended by historical information. Therefore, when present conditions are known and understood and when the history of the situation has been established, predictions can be made with some degree of confidence. This is especially true when the time spans that are involved are relatively short. For example, a history of river behavior during the last 100 years, when coupled with data on the present morphologic, hydro-

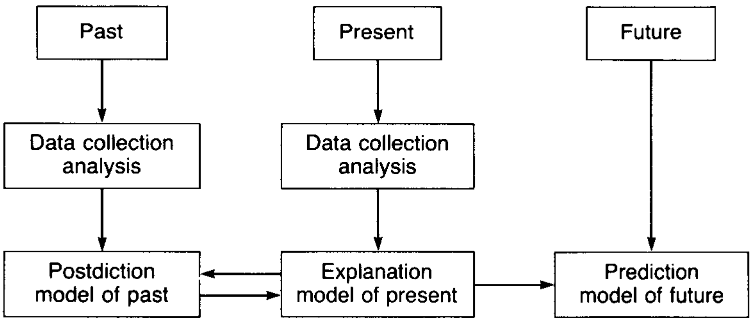
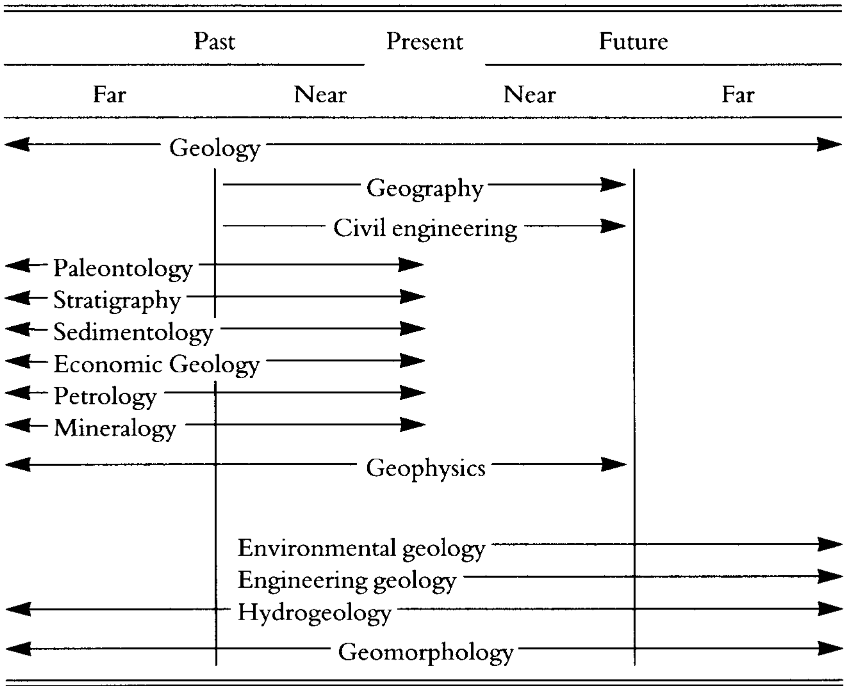


Figure 1.2. Diagram illustrating how information from the present and past is used to construct models of the past, present and future (from Schumm, 1985).

Table 1.1. *Time spans of concern to various earth science disciplines*

The near past represents historic time and the far past all of prehistoric time. The near future represents the next 50 years. The far future from 50 to 10000 years.



logic and sedimentologic situation, can produce predictions for at least 50 years if conditions remain unchanged during that time.

It should be noted that the term prediction is used in two ways in science. The first is the standard definition, which is to foretell the future. The second is to develop a hypothesis that explains a phenomenon. For example, a petroleum geologist predicts the occurrence of gas and oil, but the prediction relates to the occurrence of something that was formed in the remote past. We can predict that a geologic structure (fold, fault) exists based upon outcrop patterns, but the structure may have formed millions of years ago. Therefore, in some instances the term prediction is used synonymously for postdiction or extrapolation. This common second use of the term prediction may be why the terms postdiction and retrodiction are infrequently seen in geologic literature. They are included in the geologist's use of the term prediction.

Table 1.1 is an attempt to illustrate the predictive time spans of concern for some of the major earth-sciences disciplines, and for some geologic specialties. Many are clearly historical, whereas others deal primarily with the present and the near future. The near future can be defined as the next 50 years, which is the civil engineer's requirement for the lifetime of many projects. Nevertheless, the geomorphologist and environmental geologist are not only concerned with the present and the past but also with the near and far future. They are called upon to estimate landform stability for the disposal of toxic and radioactive materials, and in some instances there have been requests to estimate stability of sites for 10000 years. This is clearly impossible, and in any such attempt the worst-case scenario must be developed, but it is clear that prediction is now an important part of some aspects of geology. This is an important development because many of the definitions of science implicitly include the assumption of prediction. However, explanation of phenomena is as valid as prediction in science (Kitcher, 1982), and explanation itself may lead to prediction.

Sayer (1984) recognizes that prediction and explanation are valid goals of science, but he also identifies two other types, which fall between the two extremes of prediction and explanation. These he terms non-explanatory predictions and non-predictive explanations. For example, the search for oil is an exercise in non-predictive explanation. The petroleum geologist can explain all of the necessary conditions for the existence of oil but he cannot predict that it will be present. Drilling provides the proof. Furthermore, many techniques of prediction do not provide an explanation of the phenomena predicted. For example, we might be able to predict the afternoon weather by determining the number of people carrying raincoats or umbrellas to work, but no explanation of weather patterns would necessarily result. We may not understand river behavior, although the sand that is moving through the channel can be predicted as a function of the cube of flow velocity. Therefore description can be predictive or non-predictive.

The earth scientist's goal is to dispel ignorance about our planet. This has become increasingly important because, as Lewis Thomas (1979, p. 16) recognizes, human beings are swarming over the surface of the earth changing everything and meddling with it, 'making believe we are in charge, risking the survival of the entire magnificent creature'. He believes that we could be excused for this behavior on the grounds of ignorance, and indeed, 'in no other century of our brief existence have human beings learned so deeply, and so painfully the extent and depth of their ignorance about nature'. In fact, 'It is this sudden confrontation with the depth and scope of ignorance that represents the most significant contribution of twentieth-century science to the human intellect' (L. Thomas, 1979, p. 73). One can either be encouraged or discouraged by this remark. Why, with all our effort in the last century, have we not been successful in developing a thorough understanding of our planet?

The answer lies in the complexity of the system, which makes complete descriptions and accurate predictions difficult. As a result, other scientists and engineers who want a definitive statement about future landform changes or geologic stability are often disappointed by the vagueness of the earth scientist's predictions. The civil engineer, however, forgets that the factors of safety that are used to insure some degree of permanency of a structure reflect the difficulty of determining exactly the material properties and conditions for which the structure has been designed.

If geological predictions are perceived as being too general, is there a problem with the methods employed? The approach employed by earth scientists is no different from that employed by other scientists. However, one should remember that even Nobel Laureates have great difficulty in describing the scientific method, and in fact, some philosophers of science deny its existence (Feyerabend, 1975, 1978). Indeed, if there is not a strict method of science, part of the reason is because of the great variety of problems encountered in science and the different modes of attacking a specific problem.

DISCUSSION

In this chapter I have attempted to describe the difficulty faced by the earth scientist who is investigating complex open systems and attempting to explain them and to postdict and predict their behavior. Theirs is a noble effort made difficult by the multiple variables acting and the time spans involved. Others who are dependent upon these investigations for answers to practical problems may feel that the answers are not sufficient, but they must be made aware of the problems faced by the earth scientist, which are the problems that will be discussed in Chapter 3.

It seems to me that a discussion of these problems is of value to an understanding of the methods of our complex science. Therefore, a major objective of this work is to consider the problems inherent in extrapolation of modern conditions and relations to the past and to the future (postdiction and prediction). This is done with the expectation that such a discussion may help to explain why pronouncements about natural systems are sometimes vague, why extrapolation can carry a high probability of error, and why there is disagreement about the scientific method.

In fact, if one accepts the statement by Grinnell (1987, p. 27), a cell biologist, that 'Investigators know that reproducibility of experiments is a requirement of scientific research. While one can raise questions about unique events, only recurring events can be subjected to scientific investigation', then there is no earth science. Of course, the great understanding of Earth and time produced by geological investigation refutes any such suggestion, but Grinnell's comment emphasizes that there is great difficulty in applying a simple method to a system that has such variety and great complexity as does the planet Earth, and therefore, in Chapter 2 we will consider geologic methods in the light of this complexity.

2 Scientific method

It is true that much time and effort is devoted to training and equipping the scientist's mind, but little attention is paid to the techniques of making the best use of it.

Beveridge, 1957, p. iv

In order to attempt to resolve the obvious disagreement among scientists concerning the scientific method, some understanding of what is implied by the words is needed, and therefore, definitions of the words *science* and *method* are required. The word science is derived from the Latin words scientia, knowledge, and scientificus, making knowledge (Little *et al.*, 1964, p. 1806). Hence, science involves the business of discovery and the production of new knowledge. It is an activity that supposedly creates objective knowledge. That is, science is the attempt to learn the truth about those parts of nature that are explorable (Chargaff, 1978, p. 156).

The word method is defined in *The Oxford dictionary* (Little *et al.*, 1964, p. 1243) as 'a special form of procedure adopted in any branch of mental activity, whether for exposition or for investigation'. Hence, method is a way of doing anything according to a regular plan. So, if there is a method there is a procedure or a systematic way of pursuing a goal. Interestingly enough, the scientific method is not defined in this very comprehensive dictionary, but in *The American heritage dictionary* (Morris, 1981, p. 1163) it is defined as 'the totality of principles and processes regarded as characteristic of or necessary for scientific investigation, generally taken to include rules for concept formation, conduct of observations and experiments and validation of hypothesis by observation and experiments'. The three major components of this definition are, 1. concept formation, which involves generation of hypotheses, 2. observation and experiments, which involve the procedures of data collection, and 3. testing of hypotheses by observation and experimentation. This short statement adequately describes a scientific method. Data collection and testing are critical components of this definition, but because of the diverse nature of 'science', it is not possible to state a single method that applies to all sciences.

METHODS

Beveridge (1957) says that research is a complex and subtle task. It is difficult to teach and, therefore, one should just go do it. In effect, one should learn by one's mistakes in carrying out research, but nevertheless, he wrote his book *The art of scientific investigation* to assist the young scientist. The title of his book implies that there is a great deal of subjectivity in the activities of science, and indeed, if we take