

9. Philosophy of Earth Science

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Abstract: This essay presents a philosophical analysis of earth science, a discipline which has received relatively little attention from philosophers of science. We focus on the question of whether earth science can be reduced to allegedly more fundamental sciences, such as chemistry or physics. In order to answer this question, we investigate the aims and methods of earth science, the laws and theories used by earth scientists, and the nature of earth-scientific explanation. Our analysis leads to the tentative conclusion that there are emergent phenomena in earth science but that these may be reducible to physics. However, earth science does not have irreducible laws, and the theories of earth science are typically hypotheses about unobservable (past) events or generalized--but not universally valid--descriptions of contingent processes. Unlike more fundamental sciences, earth science is characterized by explanatory pluralism: earth scientists employ various forms of narrative explanations in combination with causal explanations. The main reason is that earth-scientific explanations are typically hampered by local underdetermination by the data to such an extent that complete causal explanations are impossible in practice, if not in principle.

1. Introduction

Earth science has received relatively little attention from philosophers of science. To be sure, plate tectonics and the dinosaur extinction event are frequently cited in the literature, but most of earth science is *Terra Incognita* to philosophers. One reason for this lack of interest may be found in the widespread idea that earth science is not an autonomous science, but is easily reducible to allegedly more fundamental sciences such as physics and chemistry. While in the past decades serious doubts have been raised about the reductionist program, and disciplines such as biology and psychology have thereby achieved the status of autonomous “special sciences”¹ (Fodor 1974; Dupré 1993), earth science has barely been mentioned in these debates, probably because the phenomena and processes in its domain are assumed to be purely physical and chemical and therefore easily reducible to lower levels.

This essay will make it clear that earth science deserves the attention of philosophers of science. The geosciences have typical features that distinguish it from other natural sciences. These features will be highlighted in the course of an investigation of the nature of earth-scientific explanations. §2 briefly reviews the disciplinary *aims* of earth science. §3 aims to answer the question of whether *reductionism* applies to earth science. First, the nature of earth-scientific *theories* and *laws* is discussed. Subsequently, we investigate whether emergent earth-scientific phenomena exist that are irreducible to phenomena at the chemical and physical level. §4 investigates what kind(s) of *explanation* can be found in the earth science. We discuss whether narrative explanation is employed, and whether narrative explanation is reducible to causal explanation.² The notion of *underdetermination* plays a central role in our

¹ The term “special sciences” reminds us of the Monty Python movie *Life of Brian*. Imagine a dusty square in Jerusalem, with a mob of scientists from every discipline, chasing philosopher Brian whose statements they accept unconditionally. Then Brian appears at a window and shouts to the crowd: “You are all individuals!” All scientists reply in unison: “We are all individuals!”, except the physicist, who replies: “I’m not.”

² We use the term ‘causal explanation’ generically, for the type of explanation employed in the physical sciences (in contrast to, for example, narrative, functional and teleological explanation). Of course, we are

argument: earth-scientific theories and hypotheses usually are underdetermined by the available evidence, and therefore complete causal explanations are out of reach. Earth science typically employs combinations of causal and narrative explanations. Finally, we will highlight a methodological strategy that is typical of the geosciences: *abduction* or *inference to the best explanation*.

2. Object and Aims of Earth Science

Earth scientists study the earth, that is to say, its structure, phenomena, processes, and history. What exactly is it that earth scientists hope to achieve with their study of the earth? In his *System of the Earth*, James Hutton, one of the founding fathers of earth science, proposed

to examine the appearances of the earth, in order to be informed of operations which have been transacted in time past. It is thus that, from principles of natural philosophy, we may arrive at some knowledge of order and system in the economy of this globe, and may form a rational opinion with regard to the course of nature, or to events which are in time to happen (Hutton 1785: 2).

Apparently, Hutton saw the main aim of earth science as historical description (acquiring knowledge of the “course of nature”), but the statement contains a suggestion that causal explanation and prediction are aims as well. More recently, Rachel Laudan distinguished two aims:

One is historical: geology should describe the development of the earth from its earliest beginnings to its present form. The other is causal: geology should lay out the causes operating to shape the earth and to produce its distinctive objects. (Laudan 1987: 2).

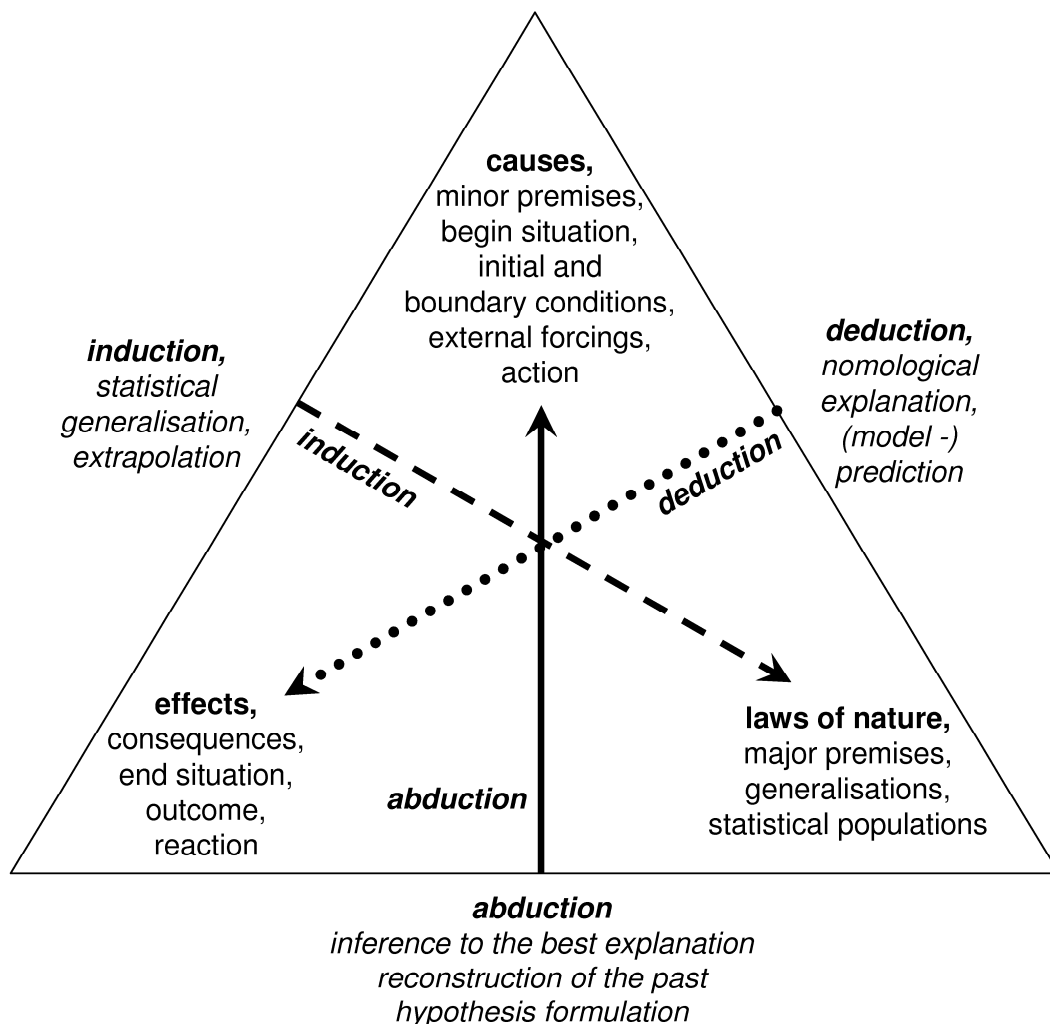
This twofold aim arises because some phenomena, like the comet impacts and their effects on the history of life, appear to be understandable only as results of cumulative coincidences, to be inferred and reconstructed from scant evidence, whereas other phenomena, like ocean circulation, appear to have a structure that can be understood on the basis of physical laws.

There are two related issues at stake here (see Kleinhans et al. 2005 for more discussion). First, the question of whether earth science is an historical or a nomological (law-formulating) science, or a combination. Second, the question of whether earth science aims for description, for explanation, or for both. The questions are related because historical sciences are typically associated with descriptive aims, while nomological sciences are associated with explanatory aims – the traditional distinction between historical description and nomological explanation. However, this is not a necessary connection: one might alternatively claim that historical sciences can explain as well, or that neither historical nor nomological sciences explain. Incidentally, ‘real’ sciences may feature both historical description and nomological explanation, which implies that the distinction is one between ‘ideal types’.

The second question relates to a long-standing debate on the question of whether there exists a separate category of explanations, so-called narrative explanations, that can be provided by historical descriptions. Those who reject this idea either defend that historical

aware that this type of explanation can further be specified in a variety of ways, but for present purposes this may be ignored (cf., §4).

sciences do not furnish explanations at all, or believe that their explanations are of the same kind as those in the physical sciences (choosing the latter option still leaves us with a choice between various rival theories of scientific explanation). In Section 4, we will argue that while earth science is partly a historical science, it does provide explanations because the historical



descriptions provided by earth scientists are narrative explanations that integrate causal explanations, sequential reconstructions of the geological past, observations, and background theories.

Figure 1. Three types of explanation based on causes, effects and laws, two of which are necessary to arrive at the third. Problems of induction are well known. Abduction is fallible in practice due to problems of underdetermination. Also deductive explanation, particularly in the form of computer modeling, may be hampered by underdetermination problems (see Section 4.3).

While earth science has, at least at first sight, a single object (the earth), a deeper look into any textbook shows a bewildering variety of subdisciplines and approaches. Concepts and techniques are both developed within earth science and borrowed from other disciplines, such as logic, mathematics, physics, chemistry, biology and computer modeling. A unified body of theory, topics or techniques seems to be lacking. Earth science is divided into many

subdisciplines with different aims³. Subdisciplines with historical aims ask different questions and use different explanatory strategies than subdisciplines that focus on causal questions. This can be clarified with the help of Figure 1, which visualizes the distinction between deductive, inductive and abductive explanation.

Scientists are interested in causes, effect, and laws (the three corners of the triangle). Typically, they possess knowledge about two of these and want to infer the third. The three resulting modes of inference are cases of deduction, induction, and adduction, respectively. Employing causes and laws to predict effects is a form of deduction. Combining causes and effects to identify a law or generalization is a form of induction. And inferring causes from knowledge of effects and laws is a case of abduction. For example, geomorphologists claim to be studying general physical processes by deduction and induction, while geologists reconstruct the geological past by abduction. Practitioners associate the former with causal explanation and the latter with historical description, which is believed to be of lesser value by many practitioners of the former. Accordingly, the question whether historical narratives can be reduced to general process-oriented explanations is a hot topic in institutes which home both subdisciplines (This will be discussed in more detail in §4.1, also see Kleinhans et al. 2005 for more discussion).

3. The Autonomy of Earth Science

Can earth science be reduced to lower-level sciences like chemistry and physics? According to the traditional model of reduction (Nagel 1961), this requires that the laws and theories of earth science can be deduced from the laws of chemistry and physics, and this in turn requires bridge principles that connect the terms used in the different laws. Nagel-type reduction is “global”, in the sense that if a theory is reduced in this fashion all phenomena in the domain of the theory are reduced as well. There are two major obstacles to Nagel’s model of reduction: (1) bridge principles often do not exist; (2) higher-level laws do not conform to the traditional criteria for lawfulness; in particular the requirement that laws are universal and exceptionless generalizations (necessary for global reduction). We first discuss the nature of earth-scientific theories and laws, by investigating whether they conform to Nagel’s traditional conception of laws or to a recent alternative conception. Subsequently, we consider whether the existence of allegedly emergent phenomena in earth science can be used as an argument against reductionism.

3.1 Theories and Laws

What is the nature of the theories and laws that earth scientists actually use? First of all, it should be noted that because of the historical aim of earth science, its practitioners often use the term ‘theory’ in cases of hypothetical historical events. The most famous example is the “impact theory” that is proposed to explain the mass extinction 65 million years ago; this “theory” states that about 65 million years ago a meteorite collided with the earth, causing a radical climate change and a mass extinction of species among which were the dinosaurs. This hypothesis is a theory in the sense that it postulates an event or chain of events in the past (and therefore not directly observable anymore) that explains observed phenomena, but it is not a theory in the sense that it specifies laws or a general model for the explanation of phenomena.

³ A non-exhaustive list of disciplines is: geology, geophysics, sedimentology, physical geography, geomorphology, biogeology, biogeography, civil engineering, geodesy, soil science, environmental science, planetology, geochemistry, meteorology, climatology, oceanography.

An obvious case of the latter kind is the theory of plate tectonics, often hailed as the grand unifying theory of earth science playing a role comparable to that of natural selection in biology. Plate tectonics provides a mechanistic underpinning of continental drift and was originally conceived by Alfred Wegener as an hypothesis explaining mountain building and the shape of the continents. It explains a host of other phenomena and processes, which cover almost all temporal and spatial scales relevant to earth scientists: continental drift and mountain building are long-term processes, whereas earthquakes and volcanic activity are short-term phenomena which may readily occur within a human lifetime.

But what is the precise nature and status of the generalizations that plate tectonics contains? Do they qualify as laws? The theory describes the formation and movement of plates, and postulates an underlying process in the earth's inner parts (mantle convection) that is responsible for the forces that cause the plates to form and move. There have been attempts to model the mantle dynamics of other planets, which lead to the completely different patterns of rigid-lid mantle convection on Venus and mantle superplume dominance on Mars, agreeing with interpretations of various surface observations. Thus, plate tectonics provides a general model of crust formation and movement and of mantle convection that is valid for very different situations and planets. A simple example of a generalization (a candidate law) within plate tectonics is: "Earthquakes are generated in the rigid plate as it is subducted into the mantle." Is this a law? Not according to the traditional criteria, because it is not universal: it refers to a specific spatio-temporal situation, namely the earth as we know it today. It contains specific earth-scientific terms such as 'earthquake', 'plate', 'subduction' and 'mantle'. If we specify bridge principles by translating these terms into the language of chemistry and physics, we see that they refer either to contingent distributions of matter in Earth:

- 'Mantle' refers to the stony but slightly fluid layer surrounding the core of the planet, made of minerals rich in the elements iron, magnesium, silicon, and oxygen (as opposed to the core, which is the central metallic part of the planet);
- 'Plate' refers to a broken piece of the rigid outermost layer of the Earth (at present, the Earth contains 12 plates).

Or else they refer to processes related to the specific structure of the Earth:

- 'Earthquake' refers to the failure of the plate when static friction is exceeded and a movement of one block with respect to the other block occurs, giving rise to oscillations or seismic waves;
- 'Subduction' refers to the sinking of heavy material of the crust into fluid material, caused by the collision between two plates (which is in turn driven by convection in the mantle).

Although plate tectonics is applicable to other earth-like planets as well (see e.g. Van Thienen et al. 2004), it is clear that its "laws" differ from the laws of physics and chemistry in the sense that their validity is less universal and more tied to the specific constellation of the planet in question. For example, plate-tectonic models would not apply to the gas giants of the outer solar system. In other words, the model does not contain laws in the traditional sense of universal, exceptionless regularities; it merely describes contingent phenomena, dependent on the particular configuration of the earth's structure.

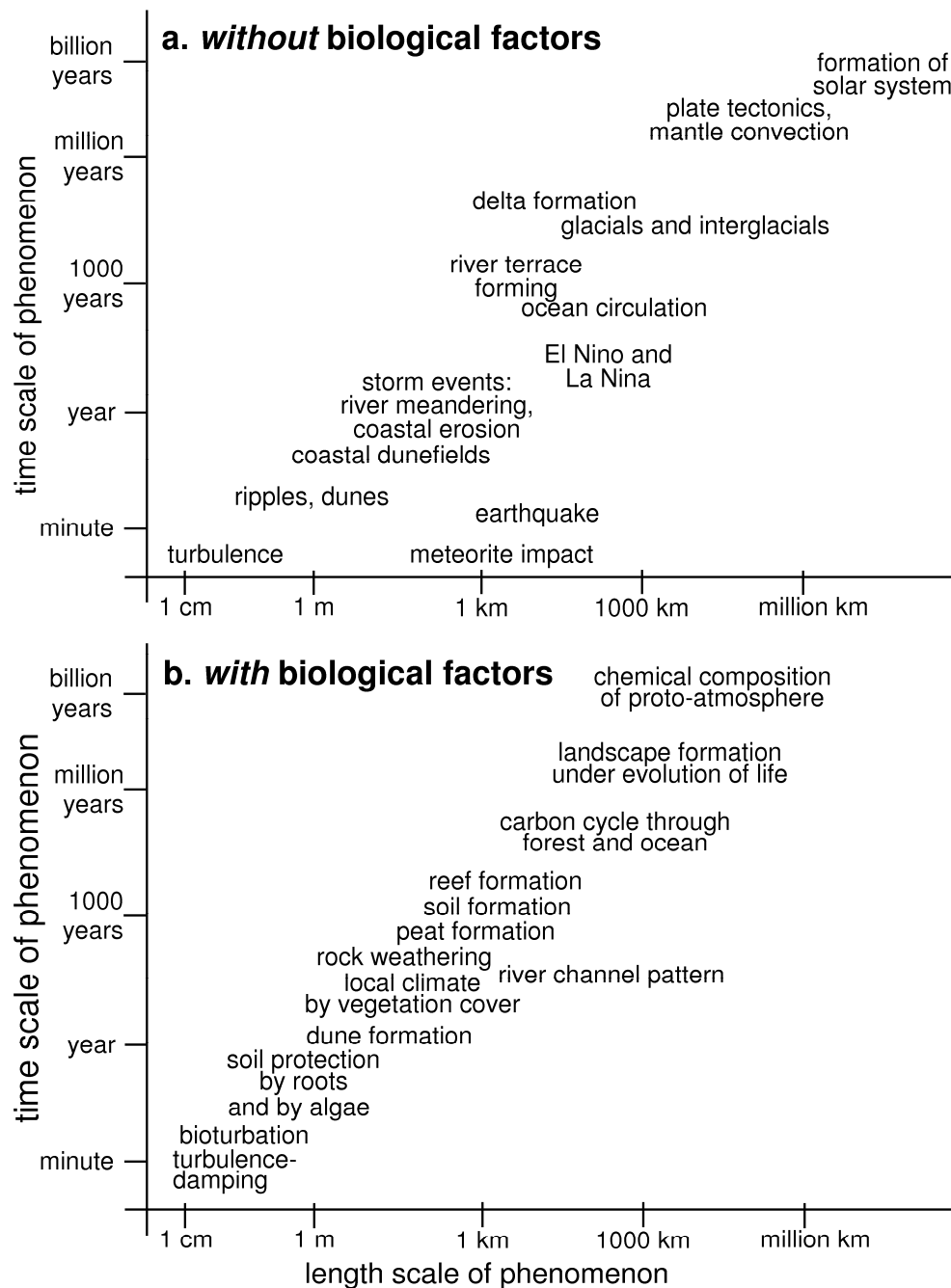


Figure 2. The correlation of time and length scale of earth scientific phenomena, split out between phenomena where biological factors are not important (a) and where these are important (b). The correlation is caused by the limited range of energy available to do work at the earth's surface. Two major exceptions are earthquakes and meteorite impacts; the former because it uses energy from within the planet and the second because it brings extraterrestrial kinetic energy.

But perhaps there are autonomous, irreducible earth-scientific laws to be found elsewhere? A candidate might be the set of principles used in the ordering of rock and sediment layers in historical explanations. The most important of these are the principles of superposition and of cross-cutting (Kitts 1966). Superposition means that a layer on top of

another layer must have been formed *after* the lower layer was formed. The lower layer is a necessary temporal antecedent but not a cause of the formation of the upper layer. For instance, it is very unlikely that a sediment layer is deposited *below* another layer, because it would involve breaking up, eroding and redepositing of the upper layer, which obviously destroys it. Likewise, a layer cross-cutting other layers means that the cross-cutting layer was formed *after* the other layers. However, examples can be given in which these principles lead us astray. A set of layers may have been overturned in severe folding during mountain building, volcanic activity or fluvial channels may form a cross-cutting layer at the same time of the deposition of the planar sediment, and so on. Earth scientists are aware of these pitfalls and deliberately seek for evidence for such exceptions when applying the general principles. But the examples show that these geological principles cannot be regarded as laws in the traditional Nagelian sense: they have many exceptions. Consequently, these principles cannot be reduced globally, that is, according to the Nagelian model of reduction. However, this is an argument against Nagel's model rather than an argument against the reducibility of earth-scientific principles. As in the case of plate tectonics, there is a more liberal sense of "local" reduction that applies to generalizations and principles that are less universally valid than physical laws.

We conclude that earth science does not have irreducible laws, and that the theories of earth science are typically hypotheses about unobservable (past) events or generalized—but not universally valid—descriptions of contingent processes. In contrast to physics and chemistry but analogously to biology, an important part of theories of earth science consists in descriptions of contingent states of nature (Beatty 1995). The traditional account of reduction (Nagel's model) fails to apply because earth-scientific generalizations do not conform to the traditional criteria for lawfulness. This implies that reductionism is still a viable option (though not in the strict Nagelian sense), because Beatty's account does not entail that higher-level laws are autonomous and is therefore compatible with reductionism.

Incidentally, not only do earth-scientific generalizations resemble biological ones, but there is a close interaction between earth science and biology. Indeed, many earthscientific phenomena would not exist without interaction with life. Figure 2a provides a random selection of examples of earth-scientific phenomena from very small to very large length and timescales. This typical reference to the length and timescales of such phenomena is discussed later. Figure 2b gives examples of earth-scientific phenomena which would not exist without biological elements. For example, the composition of the atmosphere of the Earth compared to that of Venus and Mars has much more oxygen and much less carbon dioxide. This so-called oxygen revolution was largely caused by photo-synthesizing organisms (mostly algae) about 2 billion years ago. The presence of oxygen, in turn, led to increased oxidation of minerals, weathering of rocks, and chemical changes in the oceans. A second example is the variety of effects of life on rivers. Plant roots may stabilise the banks of rivers, which may actually cause rivers to change from a wide, shallow "braided" planform with many mid-channel bars to a narrow, deep "meandering" planform with one or a few channels only. Animals burrowing in or treading on the banks may initiate diversions of the flow and completely new courses of the river. At a larger scale, vegetation in the upstream catchment of a river may strongly damp the surface runoff from rain storms, leading to a much more regular water discharge regime than in unvegetated catchments, with all sorts of consequences for the morphology and geology.

3.2 The Emergent Nature of the Earth-Scientific Phenomena

In the previous section, it was argued that reductionism fails in the strong Nagelian sense, but a weaker (local) sense of reduction may still be applicable to earth science. Anti-

reductionists might reply by invoking the alleged “emergence” of earth-scientific phenomena as an argument against their reducibility. What precisely is emergence? Humphreys (1997: 341-342) lists the following possible criteria for emergence: emergent properties are novel; are qualitatively different from the properties from which they emerge; could not be possessed at a lower level; have different laws apply to them; result from an essential interaction between constituent properties; and are holistic in sense of being properties of the entire system (see Kleinhans et al. 2005 for more discussion). There is no agreement among philosophers on the question of whether or not emergence is compatible with reduction. Below we investigate whether emergence in earth science provides an argument against reducibility.

A first glance at earth science suggests that it is replete with emergence in one of the senses mentioned above: current ripples, rivers, deltas, volcanoes, mantle plumes and continents consist of matter that is organized in such a way that novel, qualitatively different properties arise that do not directly follow from physico-chemical laws but seem to comply with higher-level laws. The literature on emergent phenomena with scale-independent characteristics is extensive and focuses mainly on self-organization, self-similarity and chaos (see Smith 1998 and Ball 1999 for examples and details). For earth science we identify two classes of phenomena.

The first class consists of self-similar, chaotic phenomena. These are characterized by a repeated basic pattern lacking a dominant length scale; the basic pattern occurs at a large range of length or time scales in the phenomenon, which is then called self-similar. The self-similarity at many scales is novel and qualitatively different from the microscopic properties of the constituent properties. Commonly the largest scales occur much less frequently than the smaller scales, which is referred to as $1/f$ (f =frequency) scaling (Bak et al. 1987). There are many examples of this class in earth science. Clouds and river drainage networks are well known for self-similarity (Ball 1999), as well as river discharge records (Mandelbrot and Wallis 1969), sizes of avalanches on sand piles and of forest fires (Bak et al. 1987), elevation of landscapes and coastlines (Burrough 1981), iron ore deposits, fault lengths and fault surfaces (Lam and De Cola, 1993). In some cases self-similarity has been explained on the basis of lower level physical laws (e.g., sand avalanches, crystal growth and rock fault lengths), but in many other cases this has not (yet?) been accomplished.

The second class consists of emergent phenomena with a dominant length or time scale. Such a macroscopic regularity emerges from microscopic physical or chemical processes. The microscopic processes may initiate at random or fractal length or time scales, but only one or two frequencies become dominant in the macroscopic pattern. The dominant frequency, or period or length, is in many cases enforced by a boundary condition that is independent of the microscopic processes. Such phenomena are common in earth science. For example, a turbulent water flow in a river provides a chaotic forcing to the sand bed below the current. Out of this chaotic forcing emerges a pattern: a train of large underwater dunes. Despite the enormous variety in current velocity and sand characteristics these dunes (when in equilibrium with the flow) have roughly constant length/height ratios and have a height that is about 20% of the water depth. This is an empirical fact for water depths ranging from 0.1 to 100 m and grain sizes from 0.4 to 100 mm. So in practice, dune height and length are predicted from empirical relations (derived from data by induction) with the water depth as the most important independent variable. Yet, there have been a few promising attempts to predict sizes and behaviour of real-world dunes from physics-based models for flow turbulence and sediment transport, so this phenomenon is not emergent in the sense that it cannot be predicted from a lower level.

It should be clear by now that many earth-scientific phenomena possess emergent properties. The question is now whether these properties are also irreducible. At present, this question is hotly debated within earth science. Some earth scientists try to reproduce emergent patterns (e.g., a train of dunes or a braided river pattern) with simple models based on macroscopic rules only. By contrast, others attempt to reproduce these patterns with highly sophisticated mathematico-physical models. The former claim that the phenomena are irreducible, while the latter claim that given enough computing power and detailing of initial conditions the phenomena can be explained (in a mathematical model) on the basis of physical laws only. Accepting emergence as a given fact, debates about reductionism continue among philosophers as well as among earth scientists themselves. Meanwhile, philosophers have generally rejected the traditional Nagelian model of reduction, and rightly so, since in most higher-level sciences, the model is of little use. But this does not imply that in these sciences reduction is completely absent. Accordingly, we need an alternative account of reduction. Wimsatt (1997: S373) suggests that “a reductive explanation of a behaviour or a property of a system is one showing it to be mechanistically explicable in terms of the properties of and interactions among the parts of the system.” If one adopts this view of reduction, it appears that many emergent phenomena of earth science may be explained reductively in the future.

4. Explanation in Earth Science

In §2 we saw that earth scientists have at least two aims, namely to *describe* and to *explain* the (history of) inanimate processes on the earth. Indeed, it seems plausible that all sciences aim at explanation and understanding, over and above mere description, of the phenomena in their domain (see De Regt and Dieks 2005). But we have not yet answered the question of what the nature of earth-scientific explanations is: do they have a special status that distinguishes them from explanations in physics and chemistry? As argued in §3.1, earth-scientific theories are hypotheses about unobservable (past) events or contingent generalizations. How can such theories—which are largely of a descriptive or historical character—provide explanations? In the present section, we address this question. Moreover, we discuss the problem of underdetermination, which is a serious obstacle in the practice of constructing earth-scientific explanations. It will become clear that earth science employs explanatory pluralism: there are several types of explanation, each with its own merits and its appropriate model.⁴

4.1 Do Historical Narratives Explain?

The issue of whether historical narratives can explain, and if so, how they do, is one on which opinions greatly diverge. Some authors claim that narratives explain by integrating an event into a bigger picture (Hull 1989). A narrative thus conveys some greater holistic insight, particularly in history and the social sciences. But others sneeringly call historical sciences varieties of “stamp collecting”. Still others see a logical pattern in historical explanation that is fundamentally different from deductive-nomological and inductive-statistical explanation

⁴ We simplify the discussion of scientific explanation in a way that has no serious consequences for the case of explanation in earth science. We contrast “historical” (or narrative) explanation with “causal explanation”, where we take the latter to be exemplified by the physical sciences. Causal explanation can take the form of a deductive-nomological explanation (Hempel 1965) employing causal laws, or of a causal space-time description of events and processes (Salmon 1984). For our purposes differences between these two modes, as well as alternatives such as the unificationist view of explanation (Kitcher 1989), can be ignored.

schemes. For human historical narratives it has been argued that the plot, or argumentation structure of the story (e.g., perspective, ordering in time) conveys an explanation of the events in terms of their necessary (but not sufficient) conditions and their relations (see Von Wright 1971).

We will argue that there is more to earth-scientific narratives than merely description. Like evolutionary biology, earth science is partly historiography: it reconstructs and tries to explain past events. The purpose of historical sciences is to provide a correct narrative of the sequence of past events and an account of the causal forces and antecedent conditions that led to that sequence.

The historical narrative-approach provides two kinds of explanations relevant for earth science: *robust-process* explanations and *actual-sequence* explanations (Sterelny 1996: 195). While the latter specifies the (causal) chain of events, the former focuses on underlying (robust) causes of the phenomenon. Both kinds of explanation are important in earth science, even for the same event, because they convey distinct breeds of information. Consider two explanations of a catastrophic landslide or mudflow. We may model an observed flow in high detail with physical models. In retrospect, the initiation of the flow happened at that precise moment in time and at that location can be explained by, for example, heavy rainstorms. This actual-sequence explanation leaves out that the flow was waiting to happen because a certain amount of mud or rubble was on the verge of slope failure. If this specific heavy rainstorm had not initiated the flow, it would very likely have been initiated by another rainstorm, or the spring melting of accumulated snow, or an earthquake. So earth scientists do not only model such flows with empirical or physical models but also map areas prone to mud flows as a part of the robust-process explanation for these flows.

In order to be genuinely explanatory, narratives in earth science need not be reduced to physical causal-law explanations. The practice of earth science demonstrates that a domain can be ontologically dependent on another deeper (i.e., physical) domain while at the same time being explanatorily autonomous. In historical narratives an event is not explained by subsuming it under a generalization. Instead, it is explained by integrating it into an organized whole (Hull 1989). In earth science, the ideas of continental drift and of glacials (ice ages) have played such a role. Mountain formation, earthquakes, volcanism, paleomagnetism, distribution of fossil remains, the form of the continents and the varying ages of rocks are integrated in an organised whole and all point to one and the same common cause: plate tectonics. Glacial landforms, erratic boulders, lack of vegetation in certain time periods and evidence for a much lower sea level than today all point to the common cause of glacials. The specific physical processes of plate tectonics and glaciation are captured as contingent regularities with only local reductions to physics and chemistry (see §3.1).

4.2 Underdetermination Problems in Earth Science

While the historical narratives provided by earth scientists can thus be genuinely explanatory, they face a major problem that we will discuss now, namely the fact that they are usually underdetermined by the available evidence. Philosophers distinguish between weak (practical) underdetermination and strong (logical) underdetermination. In the former case, there is insufficient available evidence to choose one theory over its rivals, while in the latter case theory choice remains impossible no matter how much evidence is gathered. Contrary to physicists, practicing earth scientists very often face situations in which theories are underdetermined by the available evidence. In fact, it is hard to find papers that do not contain at least a paragraph on the way underdetermination was dealt with in practice (although it is

usually not explicitly referred to as ‘underdetermination’). Typical examples of underdetermination problems are the following (see also Turner 2005).

First, the time scale involved in shaping the earth is orders of magnitude larger than the life of human observers or even written history. It is therefore problematic to detect and observe the long-term effects of slow processes that might be extrapolated to the past. Sometimes controlled scale experiments are conducted in the laboratory, but this generates scaling problems that make a direct comparison with the real world more difficult.

Second, many earth-scientific processes and phenomena cannot (yet) directly or even indirectly be observed. Sometimes a phenomenon eludes direct detection by instruments, for instance deep-mantle convection within the earth and other planets. Also, landforms and sediment deposits (with all the clues to processes and events in the past) often have been obliterated by erosion, mountain-building or flooding. An additional practical problem is that current techniques often disturb the observed processes.

Third, many processes are intrinsically random or chaotic and may be very sensitive to initial conditions. A veritable reconstruction of past events from the geologic record becomes extremely arduous because many events and phenomena are so complex that, in theory, an infinite number of possible laws and initial conditions could be involved. This problem has especially received attention in hydrology where it was named “equifinality”. Noise and chaos lead to a certain uniqueness of geomorphological phenomena: duplications of events are seldom found and the probability that the long-term river channel development in a particular river delta would take the same course when repeated, is near zero.

While complete causal (deductive nomological) explanations would be highly underdetermined, a narrative explanation does not require an exhaustively detailed set of observations and initial conditions. In many earth-scientific studies, initial and boundary conditions are implicitly (and without the details) given in the reference to the length and time scale of the phenomenon under study or the time period or study area, and in many other studies it is apparent from the context, such as the name of the scientific journal. For example, the Rhine-Meuse delta in the Netherlands has been studied by Henk Berendsen and Esther Stouthamer (2001) for the Holocene time period, which is the past 10,500 years. The point of this reference to time is to isolate the phenomenon and its causes from other phenomena by placing the latter in the description of the initial conditions, or, positioning it in the “bigger picture”. In this way it becomes unnecessary to specify the whole chain of causes and events from the largest scales (long times past and large areas around the study area) down to the scales of the phenomenon itself.

This approach is not only practical but often also defensible (Schumm and Lichty 1965). First of all, there is a correlation between the relevant length scale and the relevant time scale of most phenomena (see Figure 2), so it is not necessary to study the evolution of a large object on a very short time scale or a small object on a very large time scale. For instance, current ripples, which have lengths of about 0.2 m, are formed and destroyed in minutes to hours, so to study ripples over decades is probably useless. Mountain ranges of thousands of kilometers long, on the other hand, are formed in millions of years. In other words, it takes a much longer time to build or break down large things than to build or break down small things. The reason is that the range of energy available is between two close limits (compared to the extreme energy levels familiar to astronomers): a lower limit necessary to exceed thresholds such as friction or entraining boulders by stream flow, and an upper limit given by the maximum energy available on earth. Consequently, no significant change occurs to the whole mountain range in a period of hours, even though one plot on one slope may have changed significantly by a flood or by mass wasting. Therefore it is commonly not useful to study large phenomena over very short periods or very small phenomena over large time

periods. Notable exceptions are relatively unique events such as the impacts of large meteorites or earthquakes.

4.3 Underdetermination and Explanation

How precisely do underdetermination problems lead to the impossibility of finding complete causal explanations and to the use of narrative explanations in earth science? Consider a typical earth-scientific research project that aims to construct a spatio-temporal description *and* an explanation of the course of the river Rhine in the past ten thousand years (see Berendsen and Stouthamer 2001). The hypothesis that the Rhine has been present in the Netherlands is practically unassailable. But for earth scientists this result is only the beginning. What they really want is a description and an explanation of the course of events that is generalizable to other, comparable phenomena in comparable circumstances. For such an explanation much more detailed evidence is needed to distinguish between competing theories. Earth scientists have to infer from present situations to past ones, or from a limited set of observations to a hypothesis or theory. The empirical data gathered by earth scientists often leave room for a wide range of different, incompatible hypotheses. These hypotheses commonly are empirically but not logically equivalent; they cannot be true at the same time. In sum, their inferences are hampered by problems of underdetermination.

The predominant methodology of historical sciences is that of formulating various competing explanations (causes) of present phenomena (effects) and discriminating between them by searching for “smoking guns”. Consider a candidate causal explanation for the presently available evidence, for example regarding the courses of the river Rhine through time. This would take the form of a description of the initial conditions, say, ten thousand years ago, plus a set of causal laws that govern the dynamics of the system. The laws are, as we argued above, derived from physics and chemistry (let us suppose they are given and deterministic). What really matters is the choice of the initial conditions; these are actually referred to as “the cause”. But these conditions are, and indeed can, never be specified *completely*—they merely give an incomplete description of a part of the universe (and this part is never a closed system). In practice, therefore, explanations in earth science are a combination of abductive narratives and causal explanations. The narratives carry most of the explanatory power, for example of how the shifting of the Rhine branches over the delta plane depended on the sea level rise and other factors.

The causal explanation parts are often applications of computer models to certain aspects of the delta development. Computer modelling based on laws of physics or chemistry is becoming an activity as central in earth science as experimenting and observing. However, the laws in the causal explanations are not simply given and deterministic as assumed above. For instance, of many phenomena it is not *prima facie* clear which physical laws apply. Moreover, the relatively simple laws of physics can seldom be applied directly to the initial conditions to check whether they (deductively) explain the observations under scrutiny. For instance, conservation of momentum and mass are simple physical laws that apply to fluid flow. These simple laws are the basic components of the Navier-Stokes equations that govern fluid flow, which cannot be solved analytically. Therefore these equations are implemented in so-called “mathematical” or “physical computer models”. The equations have to be simplified and discrete time steps and grid cells must be used to model the flow in space and time. These simplifications brings a host of necessary numerical techniques to ensure conservation laws and to minimize numerical (computer-intrinsic) error propagation. When initial or boundary conditions are specified for this model, certain laboratory or field conditions can be simulated and compared to the observations. But one can never be certain that a mismatch between

model results and observations is not due to the simplifications and numerical techniques. So this does not solve the problems of underdetermination, for as Oreskes *et al.* explain:

Verification and validation of numerical models of natural systems is impossible. This is because natural systems are never closed and because model results are always non-unique. ... The primary value of models is heuristic. (Oreskes et al. 1994: 641)

Systems that are “never closed” exhibit the underdetermination of initial and boundary conditions and the “non-uniqueness” refers to the equifinality problem. So models cannot be used to hindcast or forecast the systems studied in earth science, unless they are calibrated on data from the past. But in the latter case, one can hardly speak of a true “physical” model because the data carry a part of the explanatory weight.

But there are still great benefits to be gained by modeling. First, the human mind cannot comprehend the results of complex sets of equations in space and time under certain initial conditions, but a model provides comprehensive results. Second, a scientist can manipulate a model in ways that are impossible in nature or even in the laboratory. Various scenarios can be studied and ‘what-if questions’ be surveyed under the assumptions of the model, even if the modeled scenario is not what really happened according to the observations. Thus, these scenarios play an important role in robust-process explanations, both to extend the explanation and as counterfactuals in view of the observations. Third, a set of model runs may indicate (though not always prove) whether certain hypotheses are possible at all and whether they conflict with physical laws and mathematical constraints. Modeling in this sense is used as a test for the narrative robust-process explanations. Fourth, the comparison of various different models for the same phenomenon may indicate the robustness of the models: if the modeled phenomenon is similar in the different models, then it is to some extent independent of the model schematizations.

The above considerations make it clear that in earth science both historical narratives and causal explanations are needed in earth science. The two kinds of explanation are in fact complementary: causal explanations can be employed on a small spatio-temporal scale and may give further hints for narrative explanations on a much larger scale, such as the scenario modelling approach outlined above, whereas such broadly construed narrative explanations may in turn provide more insight into specific causal processes. The border line between these two types of explanation is often unclear because they gradually merge into one another.

4.4 Inference to the Best Explanation

Until now we have outlined the problems that earth scientists face. We do not want to suggest that these problems cannot be solved at all, however. In practice earth scientists *do* come up with explanations, which they regard as more or less corroborated. But how do the scientists arrive at these explanations? An important occupation of earth scientists is formulating hypotheses about possible causes for the phenomena observed. It appears that most earth-scientific explanations are the result of abductive inference, and that earth scientists typically rely on “inference to the best explanation” (Lipton 2004), supported by deductive causal explanation (for instance based on computer modeling). Furthermore, abduction in earth science is extended by a method already described by Thomas Chamberlin (1890) as “the method of multiple working hypotheses”. A number of hypotheses is developed which potentially explain the observations. By contrasting and testing a number of (incompatible) hypotheses, a biased attempt at confirmation is prevented. The hypotheses can

be processes that are known from observations, or “outrageous hypotheses” of processes that supposedly occurred in past times but are no longer active or that seem to be in conflict with the laws of physics or chemistry. Wegener’s hypothesis of “continental drift” is the most famous example of such an outrageous hypothesis: initially rejected as absurd, it is now accepted and supported by plate tectonics. The hypotheses are used to predict testable consequences (deduction), preferably for a wide range of different locations, with the use of different kinds of instruments and often with computer models. When these various data and model scenarios all point to the same (underlying) explanation or common cause, earth scientists accept this explanation as (tentatively) true.

For instance, the occurrence of about twenty-three glacial-interglacial couplets in the past 2.4 million years (“ice ages”) is best explained by a combination of a unique setting of continents and astronomical influences on the global climate. There are cyclic variations in the inclination and direction of the earth’s axis and the obliquity of the orbit, of which the periods correspond with those of the glacial-interglacial cycles. These variations cause solar irradiation variations at higher latitudes which leads to cooling. This, in turn, causes an increase of snow cover which leads to a larger reflection of sunlight and hence causes more cooling. But this orbital forcing has been the case for much of earth’s late history while glaciation was not observed, so something more is needed. About 2.4 million years ago, Antarctica was detached from the South American continent. Circumpolar currents developed instead of currents circulating between the equator and the pole, which lead to thermal isolation and, given the polar position, cooling of Antarctica. The result was increasing ice coverage and hence larger albedo, and consequently the whole planet cooled a few degrees. This cooling, added to the astronomically induced fluctuations, was enough to trigger the glaciation of higher latitudes. While this set of hypotheses is not without problems, an alternative set of hypotheses that explains these phenomena equally well is not easily conceived. For example, the fluctuation of solar activity due to its stellar dynamics (“solar forcing” on earth’s climate) is a competitive explanation for global temperature oscillations, of which effects have been demonstrated in the geological record. But there is no stellar theory that predicts the twenty-three rhythmic cycles, whereas the orbital forcing (systematic variations in the earth’s orbit) does. Most earth scientists believe that the former set of (triangulated) hypotheses is the best explanation for the observations, while the latter set of hypotheses is also true but only modify the effects of orbital forcing. This is an example of inference to the best explanation: the observed ice ages are surprising, but there are hypotheses explaining part of the evidence that would make the observations not surprising. So the set of hypotheses is tentatively accepted as the explanation, and further confronted with new evidence.

Inference to the best explanation is a form of abduction, and, like induction, it has its limitations (Lipton 2004). Foremost, abduction is a method to select *hypotheses* rather than conclusive explanations. We probably will never know whether the best explanation is also the one and only true explanation. In fact, the uniqueness of events and phenomena in the geologic past often requires hypotheses that are at first sight outrageous in view of our present experiences (Davis 1926, Baker 1996). For example, the hypotheses that certain landforms are caused by ice-age glaciers, and that whole continents are drifting and colliding, were once considered outrageous. Over time, however, they were supported with further evidence and robust-process explanations were formulated by extending the outrageous hypotheses and by adding causal explanation sketches. The latter are typically developed by using mathematico-physical models, but, as was argued in Section 4.3, these models are also troubled by underdetermination problems. If the narratives survive tests against an increasing body of evidence, the hypotheses are more generally accepted by consensus as the best explanations.

5. Conclusion

The aim of earth science is to provide descriptions and explanations and, if possible, predictions of phenomena on the earth and earth-like planets. Earth science can be viewed as a *reductionist* enterprise. However, earth-scientific theories do not contain laws in the traditional sense of universal, exceptionless regularities. In contrast to physics and chemistry but analogously to biology, an important part of theories of earth science consists in descriptions of contingent states of nature. Yet, earth-scientific theories can be reduced locally because they can be exhaustively translated in physical and/or chemical terms. Earth science provides many cases of *emergence*, but recent attempts at reductionistic modeling suggest that many emergent phenomena may be explainable by the laws of physics in the near future.

Earth-scientific explanations are strongly hampered by weak *underdetermination*. Underdetermination entails the impossibility to construct complete causal explanations, but narrative explanations remain possible because they do not require an exhaustively detailed set of observations and initial conditions. Rather, references to time- and length-scales of interest provide implicit limits for the amount of details needed and refer to relevant background theories.

In general, theories or narratives in earth science provide *explanations* by integrating robust-process explanations and actual-sequence explanations, observations, and background theories. The narratives carry most of the explanatory power in both actual-sequence and robust-process explanations. The causal-explanation parts are, for example, tests whether the hypotheses do not conflict with physical laws or scenarios and counterfactuals derived from computer modeling. A conclusive test of the causal parts is, however, impossible due to the weak underdetermination problems. Two strategies are therefore followed: the method of *multiple working hypotheses* and *inference to the best explanation*. If the narratives survive tests against an increasing body of evidence, the hypotheses are more generally accepted by consensus as the best explanations. When earth scientists reach a well-grounded consensus on a historical narrative, the best explanation is that they possess knowledge of the past.

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