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The Geohistorical Time Arrow: From Steno's Stratigraphic Principles to Boltzmann's Past Hypothesis

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ABSTRACT

Geologists have always embraced the time arrow in order to reconstruct the past geology of Earth, thus turning geology into a historical science. The covert assumption regarding the direction of time from past to present appears in Nicolas Steno's principles of stratigraphy. The intuitive–metaphysical nature of Steno's assumption was based on a biblical narrative; therefore, he never attempted to justify it in any way. In this article, I intend to show that contrary to Steno's principles, the theoretical status of modern geohistory is much better from a scientific point of view. The uniformity principle enables modern geohistory to establish the time arrow on the basis of the second law of thermodynamics, i.e., on a physical law, on the one hand, and on a historical law, on the other. In other words, we can say that modern actualism is based on the uniformity principle. This principle is essentially based on the principle of causality, which in turn obtains its justification from the second law of thermodynamics. I will argue that despite this advantage, the shadow that metaphysics has cast on geohistory has not disappeared completely, since the thermodynamic time arrow is based on a metaphysical assumption—Boltzmann's past hypothesis. All professors engaged in geological education should know these philosophical–theoretical arguments and include them in the curriculum of studies dealing with the basic assumptions of geoscience in general and the uniformity principle and deep time in particular. © *2014 National Association of Geoscience Teachers*. [DOI: 10.5408/13-107.1]

Key words: philosophy of geology, uniformity principle, geohistorical time arrow, Nicolas Steno, thermodynamics time arrow, past hypothesis

INTRODUCTION

This article is essentially a philosophical–historical article dealing with the basic assumptions of geological thinking related to the uniformity principle and to the geohistorical concept of time (two hallmark concepts in the geosciences). As such, it is meant especially for philosophers of science and educators (professors) in the field of geological sciences who are interested in deepening their own and their students' knowledge (especially in the advanced degrees) concerning the basic assumptions of the field in which they specialize or intend to specialize.

Nowadays it is hard to find books in geology in which concepts such as the uniformity principle or deep time are not mentioned. In addition, the discussion of these concepts usually starts at the beginning but is dogmatic and superficial and contains many errors and confusions. We may, therefore, conclude that, on the one hand, the geology educators understand the theoretical importance of these concepts but that, on the other, they are not inclined to invest effort or devote enough time to study them and analyze them from a philosophical–historical perspective.

Philosophy of science has almost completely neglected the philosophical treatment of the basic assumptions of geology mainly due to the mistaken extreme reductionist conception, according to which geology as a science derives completely from physics and chemistry.[2] This explains the difficulty of finding philosophical literature devoted to the philosophical–conceptual analysis of the basic assumptions of geological research.[3] In other words, there is a lack of philosophical–educational discussion of the basic theoretical assumptions of geology on which this science is based,[4] and in this respect, geological education is significantly deficient in comparison to other natural sciences, such as physics, chemistry, and biology.

In this article, I attempt to convince geological educators and philosophers of science that the philosophical–scientific involvement with the basic concepts of the field is of utmost importance, it is bound to exert great influence on the overall conception of geologists concerning their research methods, and in this respect, it can even have a certain effect on practical work in the field. Research conducted recently (Dodick and Dolphin, 2013) strongly supports this argument, and the following quotations, from the abstract of their article, show this well.

> *"We show that, in fact, the geological sciences have their own philosophical structure, being both historical and hermeneutic, and it is this specific structure that aids students in addressing these global issues…. We find that geoscience instruction could well be improved by incorporating history and philosophy of science and employing historical case studies."*

Geology as a historical science accepts the time arrow, explicitly or implicitly; i.e., it assumes that the direction of the time arrow is from past to future. In this sense, it adopts

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[2]For more details, see Kravitz (2013, 33–38).

[3]One of the few attempts to deal in depth with the basic assumptions of geology from a philosophical perspective published recently can be seen in a collection of articles in Baker (2013).

[4]I am referring mainly to the uniformity principle and the concept of time in geology.

the principle of asymmetry, i.e., one direction and irreversibility of the time arrow.[5] My aim in this paper is to examine the question whether this assumption can be justified from a theoretical point of view[6] and, if so, in what respect.

In order to answer this question, the article focuses on the philosophical–conceptual analysis of the principles of Nicolas Steno's stratigraphy and the principle of uniformity, with an emphasis on its strong relationship with the second law of thermodynamics. In order to establish the philosophical analysis, I first examine the principles of Steno's stratigraphy and find time arrows on which they are based. I continue with a short review of the historical development of the various components of the uniformity principle. This review enables us to find the fundamental assumptions concerning the arrow of time that Charles Lyell and other geologists adopted in their geohistorical explanations of the geological past of Earth.

Finally, I argue that the modern causal explanations concerning the geohistory of Earth can actually be derived from the uniformity principle that contains the second law of thermodynamics. In this sense, and contrary to Steno's intuitive–metaphysical assumption concerning the arrow of time, modern geohistory is based on a physical law, on the one hand, and on a historical law, on the other. Despite this advantage, in the last section, I argue that the metaphysical shadow has not been completely removed from geohistory because the thermodynamic time arrow is based on a metaphysical assumption—Boltzmann's past hypothesis. Therefore, in this sense, the geohistorical explanations have not attained the desired degree of completeness.

STENO'S STRATIGRAPHIC TIME ARROW

Nicolas Steno (1638–1686) is credited with some of the basic principles of stratigraphy. These principles form the exclusive basis for the interpretation of a large part of the history of Earth. As a matter of fact, these principles have turned geology into a historical science.[7] After conducting geological research in Europe for many years,[8] Steno summarized these principles in his famous geological work "De Solido Intra Solidum Naturaliter Contento Dissertationis Prodromus."[9] Here is a quotation from this work, expressing the principles in summary:

"The following can be considered certain about the position of strata:

1. At the time when a given stratum was being formed, there was beneath it another substance that prevented the pulverized materials from sinking further; consequently, when the lowest stratum was being formed, either there was another solid substance underneath it or some fluid existed there which was not only different in nature from the fluid above it but was also heavier than the solid sediment from the fluid above it.

2. When an upper stratum was being formed, the lower stratum had already gained the consistency of solid.

3. When any given stratum was being formed, it was either encompassed at its edges by another solid substance or it covered the whole globe of Earth. Hence, it follows that wherever bared edges of strata are seen, either a continuation of the same strata must be looked for or another solid substance must be found that kept the material of the strata from being dispersed.

4. When any given stratum was being formed, all the matter resting on it was fluid and, therefore, when the lowest stratum was being formed, none of the upper strata existed.

As far as form is concerned, it is certain that when any given stratum was being produced, its lower surface and its edges corresponded with the surfaces of lower and lateral bodies but that its upper surface was as far as possible parallel to the horizon; all strata, therefore, except the lowest, were bounded by two horizontal planes. Hence, it follows that strata which are either perpendicular to the horizon or inclined to it were at one time parallel to the horizon." (Scherz, 1969, 165)

These principles have been adopted by geologists as logical–methodological principles that gave rise to the geological concept of "deep time" (Cutler, 2009, 143–148). In order to foster understanding of the assumptions on which these principles are based, I describe them as generally and abstractly as possible by means of accepted concepts in modern stratigraphy[10]:

1. *The principle of superposition*. In any continuum of strata, any stratum will be *younger* than the stratum on which it rests and *older* than the stratum that rests on it. In other words, in an undisturbed continuum of sedimentary rocks, any stratum will be younger than that on which it rests and older than that resting on it; i.e., in a stratigraphic column, the strata of rocks are arranged according to *the order of their formation*—from the *older* (at the bottom of the column) to the *younger* (at the top of the column). The principle of superposition requires adoption of other principles described below.
2. *The principle of original horizontality*. The sedimentary layers are stratified more or less horizontally;

[5]Consideration about the development of some conceptions of time in geology can be found in Overton (1994) and Gould (1987).

[6]I am referring here to a philosophical, not a practical, justification. In the world of practical phenomena to which we are exposed in the course of our lives, every one of us can testify concerning phenomena that are subject to change over time. The most obvious and painful of them is the phenomenon of aging. All of us are exposed to this phenomenon, which provides empirical proof of the existence of the one-directional and irreversible time arrow.

[7]We must take into account that these principles are methodological principles that do not necessarily describe the geological state of affair, accurately. In order to avoid errors in practical life, the geologist must use them reasonably, taking their limitations and the environmental factors that might have a significant effect on them into consideration. With regard to errors in the process of geological interpretation, see Schumm (1998).

[8]For more in-depth discussion regarding Steno's studies, see Scherz (1969:11–47).

[9]The name of this work in English is "The Prodromus to a Dissertation on Solids Naturally Contained Within Solids." See a translation of this work in Scherz (1969:133–234).

[10]For more in-depth discussion regarding these principles, see Hansen (2009, 19–20). For more about the practical role of these principles in modern stratigraphy, see, for instance, Doyle et al. (1994, 13–34, 63–91), Fritz and Moore (1988, 1–42), and Schoch (1989, 1–26).

therefore, we should assume that layers slanted or furrowed have undergone deformation *after* stratification.

3. *The principle of lateral continuity*. The stratified layers are continuous sideways. This continuity proceeds until it encounters another unit *equal in time*. Therefore, *relative time*—established for a geological unit in a certain location—is the same as that of any other location in the continuum of the same unit. On the basis of this principle, we may assume that any activity such as a fault or a planar fracture or discontinuity, severing the horizontal continuity, occurs after the stratification of the original sedimentary layers. In other words, we can extend the principle of original horizontality and argue that any geological structure intersecting another structure is *younger* than the rocks that it intersects. These cross-cutting relationships enable us to figure out the *order of geological events* that occurred in a certain area. This refers to the inclusion relationships as well. If a certain phenomenon is included in another, it is the *earlier* one of the two. For example, pebbles comprising a conglomerate derive from rocks that had *existed before* and had been subjected to erosion.

Steno assumed these principles intuitively on the basis of common sense, primarily for the purpose of determining the *relative age* of sedimentary rocks, and they have constituted the basis for the reconstruction of the history of a certain area.[11] They enable us to assume, quite easily, that strata of sedimentary rocks were formed prior to the occurrence of any process that changed or distorted them, such as faulting, folding, intrusive penetration, or gully erosion. In other words, with the help of these principles, stratigraphy determines the relative age of rocks and geological phenomena. On this basis, geologists determine the *relative order,* or continuum of geological events in time, without taking the overall geological time or the constraints deriving from the application of the uniformity principle into account. They do indicate not the exact and absolute time in which any geological unit was created or any geological event occurred but only whether the event occurred before, after, or in the course of the occurrence of another event. These are practical principles that express the chronology of the stratification of sedimentary rocks. Some geologists explain this chronology by using a chronology criterion. The following quotation explains this clearly:

> *"The chronology criterion claims, that the structural relation of two solid bodies in firm and generative contact will always reveal, which body has been formed first, and which body has been formed last. This criterion is in practice identical with Steno's geological principles of superposition by means of which it is possible to establish the chronological order of a series of geological and any other structural event. In "De Solido" the chronology criterion leads to two principles. The principle of shaping (molding) and—although not explicitly formulated—the principle of intersection. The two principles can be formulated in one sentence: When a solid structure is in generative contact with another solid structure, is that structure youngest, which takes form from the other, or which intersects the other."* (Hansen, 2009, 16)

What were the basic but concealed assumptions that Steno employed in order to establish his principles? A direct look at these principles teaches us that Steno employed two metaphysical assumptions that have no logical or empirical justification: the uniformity principle of natural laws and the one-directional and irreversible time arrow.[12] Steno implemented the uniformity principle in the natural sciences, particularly through Galileo's laws,[13] which were known at that time, thus turning stratigraphy into a physical science. For example, Steno based the principle of superposition on the law of gravity. He noticed that particles sink in fluid in quantities relative to their size and weight. The first to sink are the largest, followed gradually by the smaller ones. Changes in the size of particles cause the creation of horizontal strata or stratification. In other words, if we assume that uniformity is preserved in the laws of nature (in this case, in the law of gravity), the strata are stratified one after the other so that in any kind of geological continuum, any given layer must be earlier than the layers above it and younger than the layers below it. The following quotation from the work of Steno proves to what extent he relied on uniformity in the laws of gravity:

> *"The larger bodies contained in these same strata obey for the most part the laws of gravity, not only with respect to the position of any individual body but also to the relative positions of different bodies to each other."* (Scherz, 1969, 161)

What else did Steno assume in this statement? He assumed that the process of stratification, as described above, occurs in the course of a long time in one direction—from past to future. A direct look at the concepts used by Steno in the formulation of his principles[14] enables us to identify this assumption easily and to understand that his reliance on it turned geology into a historical science. This assumption indicates that Steno entertaining a realistic approach, consciously or unconsciously assuming that the time arrow is one directional and irreversible.

Realistic geologists, like Steno, claim that events that happened in the past belong to the past, that they cannot return, and that geologists have no causal influence on them. However, since geologists observe present events directly, they are able to understand and to explain the past on the

[11]When Steno wrote these principles, he assumed that they applied partly to all types of rock (layers) and not only to sedimentary rocks. In fact, part of these principles (such as the cross-cutting relationship) can be used to determine the age of nonsedimentary rocks. A simple example is an intrusive igneous dike. In spite of that, today Steno's principles apply mostly to sedimentary rocks.

[12]The uniformity principle in nature, as David Hume (1711–1776) has shown, is a specific principle that cannot be logically and empirically justified. There is no logical obligation to assume the uniformity of nature, and this argument cannot be empirically confirmed, because any such attempt would have to assume this argument as a basic assumption. The same thing can be said about the time arrow.

[13]In the years in which Steno published his geological work (1668–1669), he was familiar with Galileo's work, but Newton's laws of motion and gravitation were not yet known. They were published officially in 1687, 1 y after Steno's death.

[14]See, for instance, the concepts emphasized in italics in my explanation and interpretation of Steno's principles.

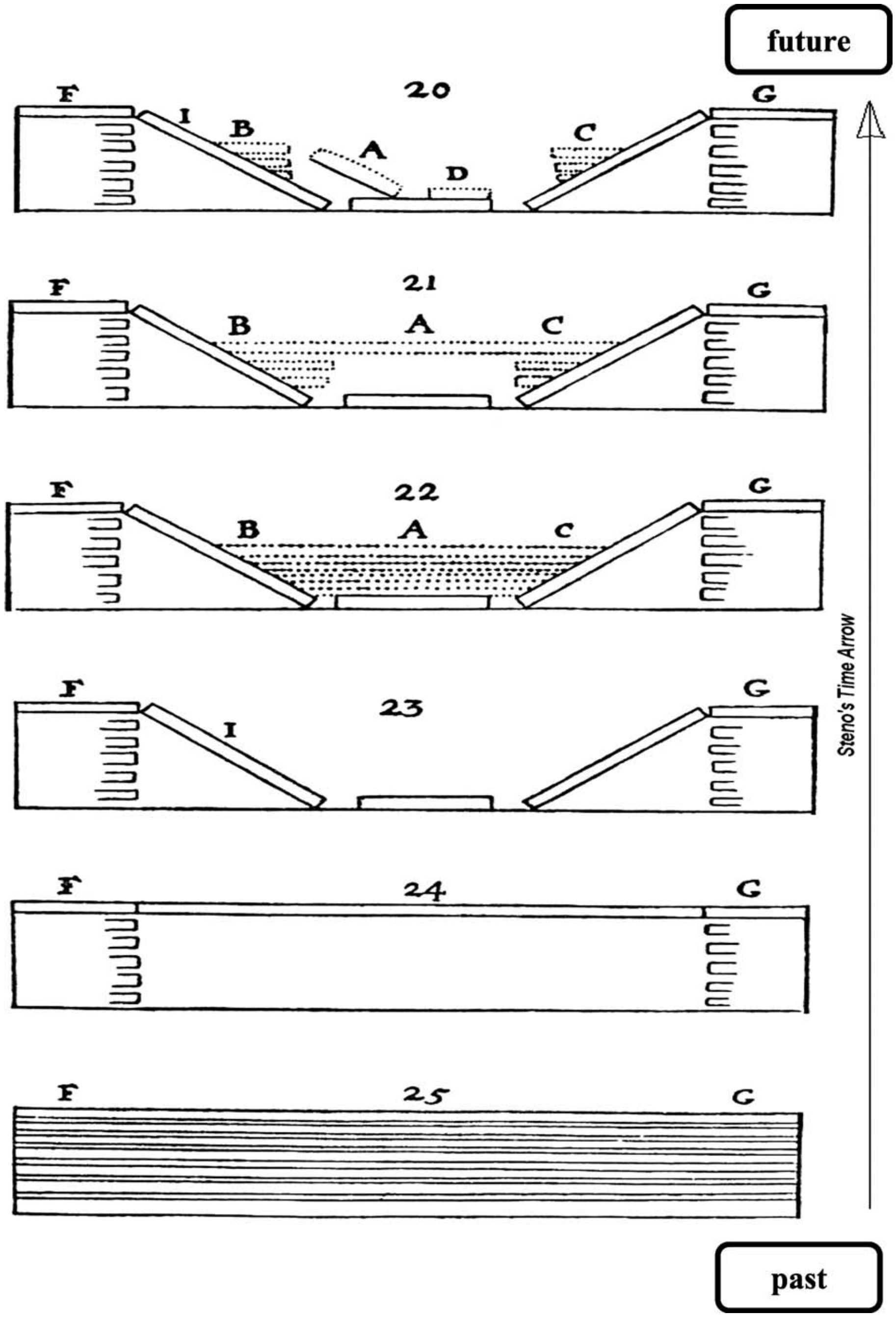

FIGURE 1: A scheme describing the stratigraphy and direction of the historical geology (direction of time arrow) of Tuscany, as described in Steno's work "De Solido" (from the translation by Shertz, 1969, 216).

basis of causal relations and the uniformity principle.[15] They claim that the past always precedes the future and that future events are causally influenced by past events—namely, that causality is one directional from past to future. The causes occurred in the past, and the results occur in the present or in the future; therefore, the cause must always precede the result. Hansen expressed this point of view by means of chronology criterion:

"The philosophical importance of the chronology criterion is first and foremost, that it allows the observer to distinguish between effects and possible causes. Since causes always precede effects, the chronology criterion—and in practice the principles of superposition—forms a purely logical basis or, more correctly, an axiom saying, that it is possible on a purely structural basis to distinguish possible from impossible causal explanations." (2009, 17)

One may argue that the assumption of asymmetry and irreversibility of the passage of time is a more basic assumption preceding the assumption of causality. In

[15]More philosophical consideration of realism in relation to the past in geology can be found in Kravitz (2012, 8–21; 2013, 20–22).

other words, a geological realist cannot present causal arguments concerning geological events that happened in the past without assuming the direction of the time arrow. What kinds of time arrows did Steno assume? One can say that Steno, as a realist in relation to the past, unconsciously or consciously assumes at least three kinds of time arrows:

1. The metaphysical time arrow, determining the order of events from past to future. In this arrow, we can include the psychological arrow that relies on the psychological feeling of the flow of events from the future to the past.
2. The epistemic time arrow, according to which the past is closed and there is no epistemic access to it except by means of assumptions referring to the present. In this respect, this arrow can be linked to the mutability arrow, according to which the future is subject to change but the past is not.
3. The causal time arrow, according to which every result in the present has causes rooted in the past and these causes precede the results.

As mentioned, Steno assumed the existence of these arrows on an intuitive metaphysical and common sense basis, following biblical chronology. Evidence concerning the basis of this chronology can be seen in the following quotation from his work[16]:

> "*1. If all particles in a stony stratum are observed to be of the same nature and of the fine size, it cannot reasonably be denied that this stratum was produced at the time of Creation from a fluid that then covered all things…*
>
> *2. If, in a certain stratum, fragments of another stratum or the parts of plants and animals are found, it is certain that the said stratum must not be counted among the strata that settled out of the first fluid at the time of Creation.*" (Scherz, 1969, 163)

Steno was a devout Catholic; therefore, his geological work and conception of time were strongly influenced by biblical chronology, starting with creation, moving through the deluge, and continuing up to the renewal of the world after Noah, etc. (Scherz, 1969).[17] This one-directional chronology can be seen clearly in the stratigraphic scheme that he designed in the course of his work in Tuscany[18] (Fig. 1). On looking at the scheme, we can identify the three phases of the geological history of Earth, according to the biblical chronology, that covertly assume the one-directional and irreversible time arrow. Thus, for instance, the process of sedimentation following the water coverage of Earth in the process of creation is described in phase 25. The second stage is described in phase 22—sedimentation after Noah's flood. The last stage covers the last period, which has continued to this day.[19]

To summarize, despite his reliance on biblical chronology, Steno also relies on the uniformity of law in physics, such as Galileo's laws of gravity. Correspondingly and independently of the uniformity of law, he assumed that the stratigraphic (biblical) time arrow is one directional and irreversible. However, we can conclude that Steno's explanation was incomplete from a scientific point of view, since it was not based on a physical law that could justify this assumption. Such a law was formulated 200 years after Steno's death, and on it, as I explain below, modern geohistory is based.

THE UNIFORMITY PRINCIPLE AND THE THERMODYNAMICS TIME ARROW

As explained above, Steno used the laws of physics in order to explain the stratigraphic principles, but his conception of time was based on biblical chronology; therefore, it did not possess a scientific basis but rather was based on intuitive–metaphysical assumptions. The state of modern geohistory is substantially different. In order to show how modern geohistory grounds its time arrow on a scientific basis, I briefly review the historical development of the various components of the uniformity principle. This review enables us to learn about the basic assumption of the time arrow employed by contemporary geologists in the course of reconstructing the geological past of Earth.

Various Elements of the Uniformity Principle

As was emphasized by Gould, the confusion of actualism with uniformitarianism[20] began in the time of Charles Lyell (1797–1875), who, overtly or covertly, united four elements in a single uniformity principle (Gould, 1987)[21]:

1. *The Uniformity of Law*. The laws of nature do not change (static and uniform) in time and space.
2. *The Uniformity of Processes (actualism)*. Geological phenomena that occurred in the past may be explained by means of geological causes and factors operating in the present. Accordingly, the laws of geology act over time by means of the forces acting in the present.[22]
3. *The Uniformity of Rate (gradualism)*. The rate of change of geological processes is slow, stable, and gradual and continues over time.
4. *The Uniformity of State (nonprogressionism)*. The history of Earth does not have a definite direction. The geological state of Earth changes in cycles and

[16]As it is possible to see in this quotation, the fact that Steno mentions "Creation" in his work is a good indication of the influence of the Bible. In addition, at the time when Steno worked, natural philosophers often linked their explanations to the Bible.
[17]For further discussion about the concept of time in Steno's geology, see Frangsmyr (1971). For more in-depth discussion regarding the age of Earth in Steno's geology, see Ziggelaar (2009).
[18]Regarding to discovery geology of Tuscany by Steno and others, see Rodolico (1971).
[19]For more in-depth discussion regarding this issue, see Cutler (2009, 145–146).
[20]Regarding difficulties to define the uniformity principle, see, for example, Austin (1979) and Shea (1982).
[21]For further discussion of this point, see Rudwick (1972, 164–217), Gould (1984, 11–12), Virgili (2007, 575–577), Camardi (1999, 537), Austin (1979, 32), Anderson (2007, 451), Kravitz (2012, 23–52) and Kravitz (2013, 22–24).
[22]This component is based on—and in certain respects derived from—the first component of the uniformity of law. To state it differently, when Lyell mentioned the uniformity of causes and forces, he was referring not only to physical and chemical uniformity of the material but also to the uniformity of processes in the course of the interaction between material and energy that produces specific geological events.

does not really progress in any direction. Earth always looks and behaves in the same way over long geological time; in other words, Earth is in a dynamic steady state.

In spite of this, Gould's subdivisions of uniformitarianism are slightly different from those of Hooykaas (1963). The latter envisioned four subdivisions, as follows:

1. *Uniformity of Law (UL)* – the laws of nature are uniform across time and space.
2. *Uniformity of Methodology (UM)* – Also known as Uniformity of Process (UP) – Weak form: present-day processes are most appropriate for explaining the geological past. Strong form: the geological past must be explained by invoking processes that can be presently observed today. This form of uniformitarianism sometimes gets summarized in the maxim that was first stated by Sir Archibald Geikie (1835–1924): "The present is the key to the past." If a past phenomenon can be understood as the result of a process now acting in time and space, one should not invent an extinct or unknown cause as its explanation. This latter view is closely related to the parsimony principle (Occam's Razor), as was pointed out more than 40 years ago by philosopher of science Nelson Goodman.
3. *Uniformity of Kind (UK)* – past and present causes are of the same kind, are of the same energy, and produce the same effects.
4. *Uniformity of Degree (UD)* – geological circumstances have remained the same over time.

Many geologists continue to be confused by the terms "uniformity of nature" and "uniformitarianism." Whewell introduced the latter to encompass all that was being argued in Lyell's book, *Principles of Geology*. In that book Lyell had discussed three principles (Camardi, 1999):

1. *The Uniformity Principle* (a strong version of UM or UP) from which Lyell held that past geological events must be explained by the same causes now in operation.
2. *A Uniformity of Rate Principle (UR)*.
3. *A Steady-State Principle (US)*.

Lyell's version of the uniformity principle is not merely methodological. It is stipulative in that it says what must be done, not what may be done. Indeed, all of Lyell's principles are stipulative, with number 1 stipulating that explanations must be done in a certain way, and numbers 2 and 3 stipulating that nature/reality is a certain way (i.e., these are ontological claims). Using Gould's (1965) distinctions, UL and UP are methodological (so long as we do not say one must), and UR and US are both stipulative and substantive.

In the course of the history of geology, most of the elements of uniformity of rate and uniformity of state were refuted on theoretical and empirical grounds.[23] Lyell himself, at the end of his professional career, accepted Darwin's theory of evolution on the basis of empirical–paleontological findings and renounced the idea of uniformity of state (Gould, 1987). This renunciation introduced a historical element into his theory and emphasized the difference between himself and Hutton. On the basis of this renunciation, Lyell promoted the objective understanding of the history of Earth in terms of a series of chronological events over a long period. By renouncing uniformity of state, he rejected the notion of nonprogressionism and accepted evolutionism (Gould, 1984). Of no lesser importance is that Lyell's work was greatly influenced by the work of William Thomson (Lord Kelvin; 1824–1907) concerning the laws of thermodynamics in general and the second law of thermodynamics in particular. Kelvin is known to have rejected the theories of James Hutton (1726–1797) and Lyell concerning the uniformity of rate and the uniformity of state because they refuted the second law of thermodynamics (Dott, 1998). This rejection was in line with Darwin's evolutionism, and on this account, Lyell renounced the element of uniformity of state; therefore, this element was abandoned by geologists in the 19th century and replaced by evolutionary geology (Austin, 1979).[24]

The two central remaining elements of the uniformity principle are uniformity of law and uniformity of process. One can, therefore, say that in order to employ the geological–evolutionary worldview (evolutionism) current among modern geologists, modern geology uses the uniformity principle as a methodological principle encompassing two major elements: uniformity of law and uniformity of process.

The Uniformity Principle and the Second Law of Thermodynamics

The only law of physics that capable of explaining developmental geological phenomena on a macroscopic level is the second law of thermodynamics. Naturally, in geology, various physical laws are assumed and applied, but there is only one historical law that defines geology as a historical science. If geology, as a historical science, assumes the uniformity of law, it must rely, among others, on the second law of thermodynamics, the only one that enables a historical explanation. That is, since geology deals mostly with the past (Kitts, 1978), reliance on the second law of thermodynamics is an essential condition for any geo-historical thinking.

The first scientist to explicitly use the second law of thermodynamics to explain geological phenomena and to renounce the uniformitarianism of Lyell and Hutton was Kelvin, who applied it in his theory of the reduction of the temperature of Earth and its loss of energy (Hubbert, 1967). In contrast to Lyell and Hutton, Kelvin maintained that Earth is a developing system that loses energy and, therefore, cools over time. He rejected the theories of Lyell and Hutton concerning the uniformity of rate and the uniformity of state, because they conflict with the second law of thermodynamics (Dott, 1998).[25] In this sense, Kelvin assumed the thermody-

[23]For empirical evidence on refuting uniformity of state and uniformity of rate, see, for instance, Austin (1979, 39–40) and Gould (1965, 226).

[24]About geological evolution of the Earth, see, for example, Dott and Batten (1976) and Ozima (1987).

[25]Although Kelvin erred in his calculations concerning the age of Earth, he was the first to assume the evolution of Earth on the basis of the second law of thermodynamics. However, Kelvin's mistaken calculation in some sense was an anathema to Darwin, because it denied the extended time needed for evolution (in the guise of natural selection) to occur. Thus, ironically, although Kelvin's calculation argued for a progressive geological evolution, it argued against Darwin's biological evolution. With regard to Kelvin's calculation of the age of Earth, see Burchfield (1975, 1998).

namic, one-directional, and irreversible time arrow and laid the foundation for the geological developmental orientation that is accepted by most geologists today.

Most modern geologists assume, like Kelvin, that the uniformity principle applies according to the second law of thermodynamics, which, by its nature, promises the rejection of the uniformity of rate and the uniformity of state. For historical sciences, such as geology, that deal with natural phenomena, the relevant scientists have to rely on the thermodynamics time arrow, in order to provide a scientific foundation to the historical explanation. In this sense, in contrast to Steno's metaphysical time arrow, modern geohistory is based on a physical time arrow, namely, the thermodynamic time arrow.[26]

What distinguishes the second law of thermodynamics and why is it so important for the modern geohistorical explanation? Unlike most laws of physics, the second law of thermodynamics is a law of historical succession that describes the macroscopic world of nature as a world governed by an asymmetric and irreversible time arrow—in other words, it describes a series of unique events, joined to each other and developing in one direction. Therefore, most physical phenomena, irreversible in the time dimension, are explained by this law. In statistical mechanics, the second law of thermodynamics is a law of probability based on a basic concept in physics, that of entropy. Entropy is a measure of disorder in physical systems. The second law of thermodynamics states that in closed, isolated physical systems, entropy can be maintained or can even grow in the course of time up to a point of thermodynamic equilibrium, which is the most probable final state from a statistical point of view (as an aspect of microscopic dispersion of states) in which the system can exist (a state of maximal entropy and disorder). The law enables the inference that every closed and isolated physical system has a time arrow with a clear direction, from a state of low entropy (in the past) to a state of thermodynamic equilibrium (in the future), in which the system receives the highest value of entropy that it can sustain. In statistical mechanics, this law describes an evolutionary process progressing from a state of low entropy to a state of growing entropy. In this process, the geological phenomena and events are singular events in a certain sense, and each is influenced by the one that preceded it in time (Von Engelhardt and Zimmermann, 1988)[27]; therefore, it is possible, on principle, to infer from every state, what its predecessor was. In other words, the second law of thermodynamics assures the one-to-one causal relation between cause and effect, thus enabling the geohistorical explanation in geology in its most basic sense. To be more specific, when geologists assume the uniformity principle based on the thermodynamic time arrow, they secure causality by means of the following three deterministic assumptions:

1. Every effect necessarily has a cause (classical principle).
2. Every cause necessarily has the same effect (derives from the second law of thermodynamics, stating that causes are sufficient conditions for effects to happen).
3. The cause always precedes the effect (the causal time arrow, probably arising from the thermodynamic time arrow).

To sum up, we can say that modern actualism[28] is based on the uniformity principle, which is essentially based on the principle of causality that in turn obtains its justification from the second law of thermodynamics (Kravitz, 2013). In this sense, we can say that in contrast to the state of Steno's principles, the theoretical state of modern geohistory is better from a scientific point of view. By means of the uniformity principle, in modern geohistory, the time arrow is based on the second law of thermodynamics and thus on a physical law, on the one hand, and on a historical law, on the other. Both Steno and modern geology assume the uniformity principle and the one-directional and irreversible time arrow. However, in contrast to Steno's uniformity principle, the modern uniformity principle contains the thermodynamic time arrow as well. Steno's assumption of the time arrow is independent of the uniformity principle, whereas in modern geology, the thermodynamic time arrow is "derived" from the uniformity of law that contains the second law of thermodynamics, among other laws of physics, and therefore the thermodynamic time arrow.

The Thermodynamics Time Arrow and Boltzmann's Past Hypothesis[29]

Nevertheless, the second law of thermodynamics is has difficulties and disagreements. On the macroscopic level, the law explains the irreversible phenomena and the asymmetry of the time arrow, as perceived intuitively by us, but this is not the picture obtained if we want to explain macroscopic events based at physical laws on the microscopic level.

Most of the theories in physics do not distinguish between past and present or, rather, are symmetrical with regard to the reversal of the direction of time. Equations representing these laws are symmetrical with regard to the description of the physical process; the reversal of the sign of the time variable in these equations makes no difference, and therefore, if you assume that the world is composed of microscopic particles (atoms), the reduction of the second law of thermodynamics to Newton's mechanic laws is

[26]In addition to the time arrows assumed by Steno and all others historical sciences.

[27]Von Engelhardt and Zimmermann invoke a "principle of evolutionism" that they contrast with the principles of "actualism" and "catastrophism." Thus, they seem to place "development" or "evolution" (more broadly construed than Darwinian) as a principle as fundamental to geology as that of the principle of uniformity. While discussion of this might be beyond the scope of the present paper, it should be mentioned as another component important to the understanding of geology as a historical science.

[28]The term "modern actualism" is introduced here in general form. Actualism is closely related to uniformitarianism but is not exactly the same. The term in philosophy applies to a view that restricts reality to that which is in motion, in process, or animate. In geology, actualism either posits a strong normative position that geological phenomena should be explained in terms of processes that exist or, in a weaker form, suggests methodologically that processes known to be actual be given priority in regards to the search for causal explanations. The methodological variety of actualism has been compared to the principle of simplicity (Occam's razor); i.e., the simplest explanation, the most natural one, is to be favored in the investigation. Given this character, it is seen that actualism coincides with uniformity of law and has some affinity with uniformity of methodology. It might be even be extended to uniformity of kind, though the substantive presumptions of the latter would be suspect.

[29]This section is based on my article in, and is mostly was copied as is from, Baker (2013, 28–29).

impossible. For example, if we follow the reaction of gas on the microscopic level, we will find that the motion of the gas molecules is governed by Newton's laws and equations of motion, which are symmetrical with regard to the direction of time. If we place $t+$ and $t-$ in these equations, we will obtain identical descriptions of the process from the physical point of view in both cases. However, if we examine the same gas on the macroscopic level, we will notice that the gas reacts according to the second law of thermodynamics—the gas spontaneously aspires to achieve a state of thermodynamic equilibrium. In other words, when we examine the gas on the macroscopic level, we identify an asymmetrical and irreversible direction of time, and when we do so on the microscopic level, the process is neutral (symmetrical) with regard to the direction of time. Therefore, the main difficulty lies in the fact that the second law of thermodynamics is irreversible and asymmetrical with regard to the direction of time and cannot be derived fully from the laws of motion of Newton's mechanics (or from the laws of motion of the quantum mechanics), which are symmetric and reversible in time.[30]

If the world of atoms described by Newton's laws of motion is symmetrical and reversible in the aspect of the time arrow, then it is difficult to explain why, in our daily observations, we encounter processes occurring in one direction (i.e., governed by the second law of thermodynamics). Physicists and philosophers attempted to solve this difficulty in the 19th century, and the subject is still open to discussion and disputes. The outstanding physicists who have tackled these problems are Ludwig Boltzmann (1844–1906) and James Clerk Maxwell (1831–1879). Both of them reached the conclusion that the second law of thermodynamics is a statistical law that is plausible but not mandatory; i.e., under certain exceptional conditions, it can be renounced without its universality suffering severe harm. In order to explain the irreversibility of the time arrow in reality, Boltzmann argued that natural phenomena are explained not solely by laws but also by initial conditions. Such states can occur not only in initial conditions of phenomena occurring in the direction of time, as observed today, but also in initial conditions in the opposite direction of time, which is possible but has never been observed in reality. Thus, Boltzmann attempted to solve the problem of reduction between Newton's laws of mechanics and the second law of thermodynamics using assumptions about the initial conditions of the system and not necessarily about the laws themselves. In his opinion, initial conditions are usually asymmetrical and irreversible from the time perspective. Boltzmann explained the rare state that appears to refute the second law of thermodynamics by means of his definition of entropy. He claimed to have succeeded in proving that any macroscopic state can be described by means of a large number of microscopic states equaling it. Boltzmann defined entropy as a physical size measuring several existing possible microscopic states for the purpose of describing a certain macroscopic state. He showed that the macroscopic state with the highest degree of entropy (thermodynamic equilibrium) is identical to the state describing the greatest number of possible arranged microscopic states. Moreover, a state of thermodynamic equilibrium is the most probable state in which a system will exist; therefore, it spontaneously aspires to achieve it. This is why we observe the asymmetrical and irreversible processes that occur according to the second law of thermodynamics.

The problem is that the statistical mechanics of Boltzmann, as presented here, are based on Newton's laws of mechanics, which are symmetrical with regard to time direction. Therefore, one may argue that as Boltzmann considered that entropy could grow in the direction of the future, it could also grow the other way round—in the direction of the past. Everybody can agree that entropy is bound to grow, but why should we assume that it grows only toward the future and not toward the past? If the increase in entropy does not have a clearly defined direction from the past toward the future, it might just as well flow from the future to the past. In this way, one could argue that just as energy flows from a warm body to a cold body, it could flow from a cold body to a warm body.

This embarrassing problem was raised by the physicist Joseph Loschmidt (1821–1895). Boltzmann suggested a solution to Loschmidt's problem by posing his famous "past hypothesis," thereby providing an answer to the question of why entropy grows in the direction of the future, or rather, why we witness asymmetrical and one-directional physical processes of the time arrow. By means of this hypothesis, Boltzmann placed the responsibility for asymmetry of the time, as observed nowadays, on the initial condition of the universe. At the starting point, the universe was in a state of low entropy, which grew continuously in the direction identified by us at present. This hypothesis enables us to maintain the symmetry of Newton's laws of motion on the microscopic level while explaining why, despite this symmetry, we observe asymmetrical and irreversible thermodynamic processes from the point of view of the direction of time. Nevertheless, Boltzmann's past hypothesis is no more than a hypothesis. Boltzmann never managed to prove it, and it remains a metaphysical assumption to this day. The controversy concerning this hypothesis has not ceased, and many physical and philosophical questions remain unsolved. Most of them are concerned with the initial state of the universe. Why was it in a state of disequilibrium? If the state of low entropy is so unreasonable, why should the universe be in such a state? These questions and many others are still discussed by physicists and philosophers, and I do not intend to deal with them or to resolve the subject of the time arrow in this paper; I only intend to emphasize that the problem of reduction between the second law of thermodynamics and Newton's laws of motion is still not solved.[31]

CONCLUSION

This state of affairs has implications for geology as a science dealing with the past. Modern geohistory is based on

[30] In other words, there is a fundamental difficulty in reducing the second law of thermodynamics, which is irreversible and asymmetrical in the aspect of the direction of time, to the laws of motion in Newton's mechanics, which are symmetrical and reversible in time. For a detailed discussion, see Sklar (1993), Price (1996), Callender (2001), and Albert (2000).

[31] For more in-depth discussion regarding the time arrow and Boltzmann's past hypothesis, see Albert (2000, 1–21, 71–96).

the assumption of the one-directional and irreversible thermodynamic time arrow. This is based on Boltzmann's past hypothesis, which cannot be derived from the motion equations of mechanics, as these are invariant with regard to the reversal of the direction of time. In a certain sense, this important fact exposes the metaphysical nature of geology as a historical science and its methodological principle—the uniformity principle. As I showed previously herein, this principle is based on the second law of thermodynamics, which determines the direction of the time arrow on the basis of Boltzmann's metaphysical hypothesis concerning the initial state of the universe. In other words, although in modern geohistory the second law of thermodynamics constitutes the basis for the uniformity principle, and can thus be considered as resting on firm scientific ground, the shadow of metaphysics has not been removed completely from it, because the thermodynamic time arrow is based on a disputable metaphysical hypothesis—Boltzmann's past hypothesis. In this philosophical sense, despite the sound scientific foundation of modern geohistory, it is still not far moved from Steno's metaphysical assumption concerning the time arrow. Until the problem of Boltzmann's past hypothesis is solved, the geohistorical explanations will not be conclusive[32]; however, it should be mentioned that this reservation does not destroy the legitimacy of geology as a science. In the practical way, physics serves as a scientific support for geology; therefore, the fate of geology will be the same as that of physics.

Thus, even if at present they have no direct effect on the everyday practice of the geologist, it is important that all professors engaged in geological education know these philosophical–theoretical arguments and include them in the curriculum of studies dealing with the basic assumptions of geoscience in general and the uniformity principle and deep time in particular. In other words, we should not make basic assumptions without being familiar with the philosophical–theoretical limitations, which might someday have a direct effect on the everyday practice of the geologist.

However, geoscience professors should know that it is impossible to avoid making use of the second law of thermodynamics in a geohistorical explanation, since it is the only historical law in physics. Therefore, if geologists are anxious to rely on physical laws and provide geohistorical explanations, they cannot refrain from accepting the second law of thermodynamics as a basic assumption. This enables them to distinguish between geological events that occurred in the past and those occurring in the present and to join them in a framework of cause and effect, with the cause always being situated in the past and the effect always being situated in the present, not the other way round. This is the most basic assumption on which the geologist bases a belief in realism in relation to the past. This means that the second law of thermodynamics and Boltzmann's past hypothesis (from which the thermodynamic time arrow derives) play a central role in geohistorical explanation, without which the modern explanation would break down (Kravitz, 2013). However, as I mentioned previously, instructors engaged in geohistorical explanations (in a framework of modern physics) should know the philosophical–theoretical limitations of this basic assumption and should underline them during the studies.

[32]As it seems today, the explanations of Boltzmann's past hypothesis will come from the cosmological research, since only cosmological research can arrive at conclusions concerning the initial state of the universe and answer questions such as ''Why was it in a state of disequilibrium?'' and ''If the state of low entropy is so unreasonable, why should the universe be in such a state?'' In other words, only on the basis of cosmological research will we be able to decide on the validity of Boltzmann's past hypothesis.

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