Review Article

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Analogical arguments in geology

Abstract

Analogical inference is widely used in geology research as a crucial technique for deriving conclusions and constructing hypotheses about the geology of Earth and other planetary bodies. Deriving conclusions by analogical reasoning in geology is no trivial matter and can even be quite complex, especially when applied to processes which occurred in the distant past (deep time) or to geological processes that are taking place (or have taken place) on other planetary bodies. In such cases, analogical reasoning might lead the geologist astray, to the extent of his reaching mistaken conclusions. Many geologists, like most people, use analogy intuitively, without always being aware of how the process works or of its pitfalls. Lack of such knowledge often leads to hasty, incorrect analogical argument, and consequently to incorrect conclusions. Since it is my view that some of these mistakes can be prevented through a better understanding of analogical inferencing and the problems involved, I develop in this paper key issues relating to analogical argument, and suggest means for preventing bad analogies. It is to be hoped that the following presentation will increase awareness among geologists and perhaps thereby succeed in preventing incorrect analogical inferences.

Keywords: philosophy of geology, analogical inference, geological explanation

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Introduction

As David Hume and many others have observed, problems of induction are in fact problems of projection, since conclusions reached by inductive inference do not follow from the premises by logical necessity. In general, but not always, analogical arguments, as other inductive reasoning, includes all inferential processes (including abductive inference) that expand knowledge in face of uncertainty, also belong to the category of inductive reasoning, since their conclusions do not follow with certainty but are only supported with varying degrees of strength.[1] Given that analogical arguments generally belong to the category of inductive reasoning, Hume's same problems of induction naturally obtain for it as well. When we call a thing by a certain name and then learn to apply that same name to other things similar to the first in some respect or other, we are in fact projecting from the particular to the general. Projecting from one instance to another forms an integral part of our learning process; without such projection we would be at a loss to describe and relate to our world. In other words, pragmatically speaking, since we cannot avoid inductive reasoning and analogical inference, we must accept them as a natural (existential) part of our lives. This claim gains support in particular from the philosophical school of American Pragmatism associated with Charles Sanders Peirce, John Dewey, Nelson Goodman and others. While the pragmatists cautioned against bad inductive and analogical inference (for example, a man falling from a skyscraper screaming "so far so good"), they nevertheless affirmed that in practice we could never do without them.[2]

Geology research makes copious use of analogical inference as crucial element for reaching conclusions and constructing hypotheses about geological phenomena and processes on Earth and other planetary bodies. Yet the literature on the science and philosophy of geology rarely addresses the formal structure of such inferences or the problems involved therein. That said, over the years there have been several attempts to provide precise description of the form and function of analogical arguments used in geological explanations.[3–5] From these attempts one can learn how geologists use analogy in practice. The use of analogy in practice combines the inductive premises illustrated with an abductive inference that forms a causal hypothesis.[6,7]

The present article constitutes a further attempt to explain the basic structure of analogical inference in geology and the problems involved. As mentioned, deriving a conclusion by analogy is no simple task, so that a geologist is at times led astray and ends up with incorrect.[8] In order to avoid mistakes or at least minimize their extent, geologists firstly must grasp what is involved in the process of analogical reasoning and what logical elements and cognitive aspects it comprises. In what follows, then, I first lay out the principles of the process as understood in philosophy, along with its problems. I begin with the logical structure of analogical argument, followed by a description of the types of analogy and the cognitive processes involved; finally, I briefly propose means for minimizing - perhaps even preventing- incorrect analogies in geology.

The logical structure of analogical inference

Analogical inferences are not applicable to conclusions that arise from assumptions made on the basis of logical necessity; rather, they are regarded as most probable or least probable. In geo-historical explanations, high probability is achieved thanks to the uniformity principle assumed by geologists, which conceals the fundamental generalization about causality – the claim that the causal relation between geological causes and outcomes does not change significantly over time, therefore we may assume that the same causes lead to the same outcomes.[6,9,10] Specifically, to produce an analogy between two entities is to start by pointing out one or more similar attributes. An analogical inference is based on a similarity of two or more things, and projecting this similarity on some other aspect of these same things. In other words, an analogy is produced through the observance of common features or relations between certain things and the conclusion that another similar feature or relation can also be found in them. Such simple inductive inferences are a regular part of our daily thinking; without them we could not survive.

Somewhat simplified, the pattern of argument (inference) by analogy can be described as follows:

Premise A - thing A contains features/ relations 1, 2, 3, ….

Premise B - thing B contains features/ relations 1, 2, 3, ….

Premise C - it is found that thing A also contains feature/ relation 7.

Conclusion - therefore thing B also contains feature/ relation 7.

In a more formal way, an analogical argument has the following inductive form, in which the conclusion is not guaranteed to follow from the premises.[11]

1. S is similar to T in certain known respects.
2. S has some further feature/ relation Q.
3. Therefore, T also has the feature/ relation Q, or some feature/ relation Q* similar to Q.

In this argument, S and T refer to source domain and target domain, respectively. A domain is a set of objects, properties, relations and functions, together with a set of accepted statements about those objects, properties, relations and functions. More formally, a domain consists of a set of objects and an interpreted set of statements about them.[12]

Since in geology we deal, among other things, with processes and geological phenomena that occurred a long time ago, analogical inferences play a major role in our profession, and their level of methodological and epistemic complexity exceeds even that of most natural (experimental) sciences[6,13,14] that are not concerned with "deep time". In geo-historical explanations, in addition to the similarity between features of geological phenomena and events, geologists are also looking for similarities between causal laws that generally comprise an explanation of the mechanism operating in the geological process.[5]

Types of analogy and analogical argument

Patterns of analogical arguments as described above are quite intuitive, and we all make regular use of them in daily life. However, for purposes of geological research they are insufficient, not always effective, and sometimes even cause no small amount of damage. Consequently, in geology, as in the other natural sciences, analogical reasoning absolutely requires exploiting complex analogical inference of different types, as can be seen in Table 1. In this table, methodology introduced by Hesse[15] and terminology by Keynes[16] have been given tabular representation.

Table 1 A characterization for an individual analogical argument (tabular representation)

Stages of argument	Source (S) causal inference	A kind of analogy	Target (T) causal inference
Premises/Facts	P	Positive analogy	P*
	A	Negative analogy 1	~A*
	~B	Negative analogy 2	B*
	N	Neutral analogy	?
Conclusion	Q	Hypothetical analogy (Plausibly inference)	Q*

Details and definitions

Positive analogy - Represent accepted (or known) similarities:

P- Accepted propositions about (S).

P*- Corresponding propositions are all accepted as holding for (T).

Negative analogy - Represent accepted (or known) differences:

A- Propositions accepted as holding in (S).

~A*- The analogous propositions that fail to hold in (T).

~B- The analogous propositions that fail to hold in (S).

B*- Propositions accepted as holding in (S).

Neutral analogy:

N- The accepted propositions about (S) for which it is not known whether an analogue holds in T.

Q- The proposition in the neutral analogy that is the focus of our attention.

In order to illustrate the concepts describe above, I will refer to Thomas Reid's[17] argument for the existence of life on other planets.[18] Reid notes a number of similarities (positive analogies) between Earth (source domain) and other planets in our solar system (target domain): all orbit the sun and are illuminated by it; several have moons; all revolve on an axis; all are affected by gravity. From these similarities, he concludes, it is "not unreasonable to think that those planets may, like our earth, be the habitation of various orders of living creatures".[17]

In Reid's time, these similarities were already known in some manner or other, so he could have used them as positive analogy to confirm his argument. However, since in his time there was as yet no certainty about the conditions for the emergence of life, he was not ware of those differences among the planets that influence emergence of life and its sustainability. In this sense, then, he did not actually use any form of negative analogy 1, 2. For instance, it was not known at the time what the necessary conditions are for the emergence of life, such as the water compound and heavy elements, mainly carbon, nitrogen, oxygen, silicon, and iron. Neither was it known at that time that a planet's atmospheric composition and distance from the sun have an effect on the emergence of life .In the course of time, scientists, through experiments conducted on earth, came to know what conditions are necessary for the emergence of life.

At the same time, in those days there had not yet developed sophisticated technological means for observing the planets, it was not possible to say anything precise about the chemical composition or geographical structure of other planets in our solar system. In this respect they could not yet compare earth to other planets, in other words, they could not draw positive analogy or negative analogy 1, 2 between Earth and other planets concerning emergence of life .The only option was to remain in the status of neutral analogy. Today scientists have far more data about chemical composition and geological structure of the planets, so they have the option of performing more positive analogy and negative analogy 1, 2. For instance today it is obvious that the giant planets Jupiter and Saturn cannot sustain life, because their outer layer consists largely of hydrogen and helium; their surface is not solid; and they lack the necessary compound of water. Thus, scientists today can perform negative analogy of type 1and determine that life exists on earth due to presence of water while there is no water on other planets, concluding that life is not possible on them. Likewise, it is hard to assume that life could flourish on the ice giants Uranus and Neptune, since they have no water in liquid form. Here the possibility that there is water on these planets is already assumed (positive analogy) but the water is not in liquid form (negative analogy 1). Much more suitable for sustaining life, with respect to size and composition, are Venus, Mars, and Earth (positive analogy). The main differences among them which enable life on Earth but not on Mars or Venus are environmental conditions and presence of liquid water (negative analogy 1). The difference is due to the distance from the sun and the atmospheric composition of the planets (negative analogy 1, 2). Yet it should be noted that science is still intensively studying the chemical composition and geological structure of the planets; it is quite possible that in future some of the positive analogies considered valid today will become negative analogies or at the very least remain as neutral analogy. In any case, as geologists continue to amass knowledge about the chemical composition, geological structure and climate of other planets, so too will the probability increase for performing positive and negative analogies involving Earth. These analogies will allow scientists to draw more plausible conclusions about the possibility of life outside Earth.

What cognitive processes are involved in analogical thinking

Beyond understanding the logical structure of analogical inference in geology as described above, to which we shall return presently, it is also important to address empirical studies in Cognitive Science on the subject of analogical thinking. As we shall see, the area of research addressed in these studies is mainly higher order thinking and four forms of human thinking known as relational reasoning:[14,19–21] analogy (reasoning involves recognizing similarities between seemingly dissimilar objects, ideas, or situations), anomaly (reasoning represents a deviation from an expected rule), antinomy (reasoning represents instantiations of incompatibility), antithesis (reasoning demands the recognition of relational opposites or two ends of a continuum).

These forms of relational reasoning, while individually of significance, often operate in Concert,[22] and individuals who can effectively use relational reasoning stand a much better chance of achieving depth and breadth of thinking.[19] Due to considerations of space this paper focuses on studies dealing mainly with analogical reasoning, since this is a central axis in studies on higher order thinking and relational reasoning,[23,24] and is particularly pertinent to geological and geo-historical explanations. Familiarity with these studies can give geologists deeper understanding of the cognitive processes taking place in their mind when engaged in analogical thinking; this in turn will perhaps increase awareness among geologists and thereby hopefully prevent incorrect analogical inferences.

In cognitive sciences an analogy is sometimes defined as a kind of similarity in which the same system of relations holds across different sets of elements.[25] Analogies thus capture parallels across different situations. The elements that belong to the two situations need not be similar, but the relations that hold the systems together must be alike. According to this concept, analogical ability – defined as ability to recognize and reason about common relational structure across different contexts – is a core mechanism in human cognition and a key contributor to higher order cognition. In other words, the analogical reasoning is the process of representing information and objects in the world as systems of relationships, such that these systems of relationships can be compared, contrasted, and combined in novel ways depending on contextual goals.[25–29]

While all human beings possess, as fundamental aspect of cognition, the ability to perform inference on one level or another, drawing conclusions by analogy,[30] still most people could significantly improve this ability by better understanding the process , by practice and by studying examples.[19] As will be shown, given that geology deals with large-scale processes over deep time, this kind of learning process can be quite complex, demanding intensive and systematic work.[14,20,21]

Many cognitive scientists have tried to reach a consensus about the process of creating analogies. The most influential view in this field is Gentner's structure-mapping theory, so the present article focuses mainly on this approach (for more current views of analogical reasoning and general comparisons between them.[31] According to this theory, analogies are about relations, rather than simple features. Therefore, it is structural properties that determine the content of an analogy.[32] In this context, the process of analogical reasoning can be divided into three core sub-cognitive processes in a useful way: retrieval, mapping and knowledge transfer, and abstraction.[30,31,33–35,54] These processes can be described in the following simple way:

1. **Retrieval**: Searching for potential analogues from long-term memory according to the known situation, which involves the known term and reconstructions as well as an analogy relation, in short-term memory. Put simply, given a situation, find an analog that is similar to it.
2. **Mapping and knowledge transfer**: Aligning the reconstructions of source domain (S) and target domain (T), and transferring knowledge by projecting inferences from the source to the target domain. In other words, given two situations, align them structurally to produce a set of correspondences that indicate 'what goes with what,' project candidate inferences that follow from the analogy, and arrive at a structural evaluation score which provides a numerical measure of how well the base and target align.
3. **Evaluation**: Once analogical mapping is done, the analogy and its inferences are judged.

For geological analogies the most prominent and crucial process is analogical mapping and knowledge transfer. According to studies in cognitive sciences, mapping is the core process of analogy, and has therefore been the main focus of analogy research.[30] In this process the geologists establish correspondences between source and target on the basis of common relational structure, making inferences based on an established structure-mapping.[8] More precisely, the mapping process aims to establish the analogical relation between source and target domains, i.e. the alignment of structures from both domains. In other words, structure mapping is the process of aligning key objects and relations within one system of relationships to another to draw higher order relationships that enable the reasoner to make inferences about the systems' commonalities and differences or to understand one relational system.[29]

In the present article, this mapping process applies not only to "simple" analogy (based on relational/structural similarity) but also to overall similarity (literal similarity) that shares both relation structure and object properties.[30,36–38] As we will see, this process (as the knowledge transfer process) requires imagination, creativity, extensive experience and exhaustive knowledge of two geological phenomena, processes, and systems being compared. During the transfer phase the analogical relation is used to translate information between the two domains. Normally knowledge is transferred from source to target domain and used there to introduce new concepts or structures, give new explanations, or solve given problems. In this case, knowledge connected to the common system in the source– but not yet in the target– is projected to the target as a candidate inference.[32] This new knowledge is in no way logically justified and should be regarded merely as a hypothesis, but when used carefully it can be the source of valuable inspiration.[34]

In order to make an affective comparison: mapping, structural alignment and knowledge transfer between the source and target on the basis of common relational structure, we need appropriate criteria; these will be discussed in the next section.

What criteria should we use to evaluate good analogical arguments

As mentioned, analogical inference can never have certainty, since it is not deductive, hence lacks logical necessity. At the same time, we can formulate several simple criteria for improving its plausibility and probability. These basic criteria are broadly based upon Mill's probabilistic conception[39] by which each element of positive analogy boosts the probability and the epistemic degree of support of the conclusion. As we will see below, this conception is also partially supported by contemporary computational structure-mapping theories by which each structural similarity between two domains contributes to the overall measure of similarity and to the strength of the analogical argument.[39–42,81]

Over the years some logicians and philosophers of science have identified more general criteria for evaluating analogical arguments and for improving the probability and epistemic degree of support of the conclusion.[16,39,43–46] Here are some of the most important ones, particularly relevant to geological analogies:

1. The more similarities (positive analogies) between two geological phenomena/ processes/systems, the stronger the analogy.
2. The more differences (negative analogies) between two geological phenomena/ processes/systems, the weaker the analogy.
3. The greater the extent of our ignorance about the two geological phenomena/ processes/systems, the weaker the analogy.
4. Multiple analogies (positive and negative analogies) supporting the same conclusion make the argument stronger.
5. Analogies involving causal relations are more plausible than those not involving causal relations.
6. Structural analogies between two geological phenomena/ processes/systems are stronger than those based on superficial similarities.
7. The relevance of the similarities and differences to the conclusion must be taken into account.

Which criteria of analogy are more important to geological thinking

Since geology is a historical and analytic science derived from the laws of physics,[6] in my opinion for geological analogies the most prominent and crucial criteria are the last three. I would like now to focus on these; obviously, the rest of the properties (criteria) are also extremely important for analogical argument in geology, but they are trivial and self-evident in any analogical inference, so will not be dealt with at any length in the present article.

Why are structural and causal analogies especially crucial for geological analogical inference and arguments? How do we determine which similarities and differences are relevant to the geological conclusion? In order to answer these questions, I will refer to the common logical structure of geo-historical explanation.

Given that geology is a historical and analytic science derived from the laws of physics, in geo-historical explanations, in addition to similarity between features, objects and relations of geological phenomena and events, geologists are also looking for similarities between causal laws that generally explain the mechanism operating in the geological process. In this sense, they assume that the causal mechanism that produces the geological phenomena does not change significantly (the uniformity principle); hence, the relationship between cause and outcome in two similar geological phenomena does not change over time. This kind of causal law is based on the laws of physics, so it permits the geologist to argue legitimately that it is possible to reconstruct the past based on observations of outcomes and process in the present. In order to reconstruct the past and to provide a reasonable geo- historical explanation, geologists have four possible structures (patterns) of logical-causal arguments, in which C indicates cause and E indicates effect.[7] In these arguments, sentences (1) and (2) are introductions (or premises) and sentence (3) represents the conclusion of the argument. The arguments are as follows:

I.

(1) If C occurred then E occurred

(2) C occurred

(3) Therefore, E occurred

II.

(1) If C occurred then E occurred

(2) C has not occurred

(3) Therefore, E did not occur

III.

(1) If C occurred then E occurred

(2) E occurred

(3) Therefore, C occurred

IV.

(1) If C occurred then E occurred

(2) E has not occurred

(3) Therefore, C has not occurred

As we see, in all the above inferences, the first premise is identical and constitutes a causal conditional sentence, the first section of which refers to the cause, and the final section - to the outcome. From a formal logical point of view, this sentence claims that if the first section is real then the final section is real as well, and describes a relation between the first and final section without going into the reason (content) and meaning of the relationship between the two parts of the sentence. However, although this is a conditional sentence (material implication) integral to the entire logical argument, and to the content and meaning of the concepts it contains, it is also concerned with causal relations between the cause and the outcome, so that the final section of it isn't necessarily implicated logically, or by definition, from its first section, but is due rather to the causal relation between them. This premise, in fact, allows a causal argument to be presented as a logical argument. Presenting a logical argument does not involve any intention to determine something about the state of the world. The only intention is to indicate a logical implication between the assumptions of the argument and its conclusion. In this case, the first premise serves as a liaison between logical and causal implications, and, therefore, has great importance in a geo-historical explanation.

As can be easily seen, in all inferences mentioned above, the first premise is identical and constitutes a causal conditional sentence and is used as a causal covering law, as defined in Hempel's covering law model.[6,47,48,82] Since all three criteria mentioned above (5,6,7) are interrelated and are related in some sense to causality, they can also fit this model. This claim is also supported by Gentner's structure-mapping theory.[81] According to this theory, along with structural consistency,[30] analogical mapping is guided by the systematicity principle. In analogical mapping, people prefer to map large, deeply connected systems, rather than sets of unrelated matters. To put it more precisely, systematicity reflects a preference for common systems that include higher-order constraining relations, such as causal relations.[49,50] In geological explanations, these relations must be derived from the laws of physics, chemistry and sometimes biology (in the case of paleontological explanations). In other words, in geology the analogy should not be based only on ordinary structural alignment between two domains (source and target), but must explain the structural[30] relations between them through a common causal structure and causal explanations based on laws of physics, chemistry, etc. For example, Ernest Rutherford, in 1911, presented his planetary model of the atom. In this model, at the center of the atom is a nucleus in which most of the atomic mass is concentrated. Electrons circulate around this nucleus like orbiting planets in our solar system. In other words, Rutherford performed a structural analogy between the atom (target domain) to our solar system (source domain). This analogy gained support from the structural similarity between Coulomb's law.

$(F = \frac{K*q_1*q_2}{R^2})$ to the law of gravity $(F = \frac{G*m_1*m_2}{R^2})$.

Despite this, his analogy was patently false, since he based it mainly on structural analogy and was not aware of essential (causal) differences between Coulomb's law and the law of gravity. Unlike in the planetary system, the force holding the electrons in the atom is not gravity but mainly electromagnetic force. This is why the electrons cannot revolve around the nucleus in the same way the planets revolve around the sun. Were the atom to revolve according to the same laws of the planets revolving around the sun, it would collapse and never be stabilized. This is because an accelerating electric charge emits electromagnetic radiation and loses energy. Given that the electron is an electric charge in rotational movement, it would eventually lose its energy and soon crash into the atom's nucleus. With the development of quantum theory, levels of energy were posited which prevent such a crash; they allow the electrons only discrete levels of energy, while the Pauli exclusion principle was enlisted to prevent the electrons from all falling into the lowest level.

From this it can be understood that the main flaw in Rutherford's analogy was its failure to meet criteria 5, 7. It did in fact partially meet criterion 6, but without taking into account causal differences between the laws of physics governing the two systems for which Rutherford was performing the analogy (the solar system and the atom). Rutherford's analogy, then, failed to meet criterion 5, because he did not perform negative analogy between the two systems with respect to the laws of physics; this resulted in failure to meet criterion 7, mainly due to his not being familiar enough with the two systems involved in the analogy. As the examples in the next section show, such errors are not uncommon, in geological research and are well known in the cognitive sciences. Thus, for instance, we find in these studies that people sometimes find it difficult to determine the relevant structural commonalities between source and target domains. The task is especially difficult when the relation structure of the target is highly unfamiliar.[51–53]

This claim connects us directly to criterion 7 and its importance in analogical explanations in geology. The relevance of the similarities and differences between two geological phenomena/ processes/ systems (criterion 7) to the conclusion is highly dependent on causal relations and structural analogies (criteria 5, 6). It is not possible to explain similarities and differences between two geological phenomena/ processes/systems without any causal explanation. In other words, the relevance factor must be explained it terms of causality because not every similarity increases the probability of the conclusion and not every difference decreases it. Some similarities and differences are known to be utterly irrelevant and should have no influence whatsoever on our probability judgments; or, in some cases, they might lead the geologist astray to the extent of reaching mistaken conclusions (see some examples in the next section). So we need to be more careful with relevance, which depends upon the subject matter, historical context and logical details (logical, mathematical, causal, functional and structural relations),[54] particular to each analogical argument.

These claims are also supported by Hesse's model.[15] In this model, the vertical relations in table 1 must be causal relations "in some acceptable scientific sense" and the essential properties and causal relations of the source geological phenomenon/process/ system must not have been shown to be part of the negative analogy. In other words, the hypothetical analogy, the feature and relations transferred to the target phenomenon/ process/system, must be causally related to the positive analogy. The causal condition rules out analogical arguments where there is no causal knowledge of the source phenomenon/ process/system. It derives support from the observation that many analogies do appear to involve a transfer of causal knowledge.

However, it is crucial to note here that in geological analogies the negative analogy is no less important than the positive analogy. The more differences between two geological phenomena/ processes/ systems, the weaker the analogy (criterion 2). In mapping analogies between two geological phenomena/processes/systems as described above, we tend intuitively first of all to compare them through positive analogies which highlight their similar properties while neglecting their differences. This tendency is especially noticeable when the similarity between the source domain and the target domain is very low.[55–57] In this sense, this fact contradicts criterion 7, which in itself can lead to critical errors in complex analogical arguments in geology. Therefore, an experienced geologist must curb this tendency and balance it with negative analogies. Certainly, it is important in analogy to compare similar properties of phenomena/processes/ systems – yet recognizing their dissimilarities is no less important. This claim is supported also by Gentner's structure-mapping theory. In this theory, the structural alignment process, in addition to facilitating the abstraction of relational commonalities, also highlights alignable differences between analogs.[55,58] Understanding the differences and not just the commonalities between the two systems sometimes actually highlights false similarity of the kind that could lead us to incorrect or irrelevant (in the causal sense) conclusions. To make this clearer, a simple visual example of this can be seen in Figure 1 (for further illustrations see Rutherford's and Reid's analogies described above, and some examples from the field of geology in the next section).

Figure 1 describes an analogy between two sets of numbers, with positive analogy indicated by a bidirectional arrow and negative analogy by unidirectional arrow. In this case, if we perform only positive analogy between the set of numbers in source domain to a set of numbers in target domain, and compare only their first numbers- 1,2,3, we would conclude mistakenly that with respect to causal/ structural relations, we have here two arithmetic series in which the difference between each to successive members is a constant ,in this case, 1. However, if we also take into account differences between the two sets by negative analogy 1 with respect to the numbers 4,5,6 in source domain, and by negative analogy 2 with respect to numbers 33 ,22 ,11 in target domain,we immediately realize that there is no structural/causal relation whatsoever between the two series. In source domain we have here a normal arithmetic series, while in target domain we have simply a set of numbers comprising 1,2,3. It follows that there is no basis for comparison between source set and target set, since this kind of analogy fails to meet relevance criterion 7. It is thus important for geologists in their arguments, as noted above, in addition to a first causal/structural premise, to make also correct, relevant assumptions in positive and negative analogies of all kinds (1,2) Otherwise, the conclusion of their argument will not necessarily be correct.

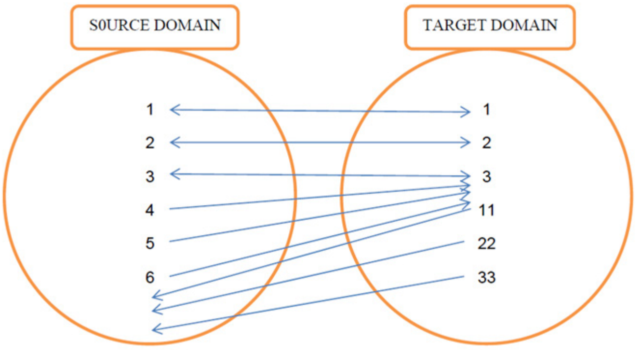

Figure 1 An example of a negative and positive analogy.

A geologist working only in accordance with the recommendations cited above will actually minimize the probability of error in his analogy, yet there remain nonetheless many pitfalls awaiting him that can lead to mistakes in performing analogies on two complete geological systems (the term "complete geological system" is used here arbitrarily to denote an assemblage of features/ relations belonging to the same geological whole to be studied or explained. For instance, in the course of field work a geologist would use his judgment to determine what constitutes a complete geological system, and to determine which geological processes, phenomena, and sub-systems it comprises). Therefore, as one sets out to perform an informed analogy, one must initially jettison the search for analogies on the level of complete geological systems and concentrate rather on modularity on the level of building blocks of those same systems. In other words, it is advisable in the first instance not to perform analogies on the level of complete geological systems but to content oneself instead with analogies on the level of their building blocks - discrete geological phenomena, local geological processes, and sub-systems of the complete systems being compared. Two complete geological systems being compared by analogy contain a great many features/ relations, rendering comparison between all of them extremely difficult. Because of this, chances of faulty analogy between two complete geological systems are high and not always given to the geologist's control. By contrast, an analogy on the level of building blocks is simpler, more reliable, and lowers probability of error with respect to the complete geological system. Only in the second instance, after completing the stages of analogy on the level of building blocks, should one proceed cautiously to analogy on the level of two complete systems, all the while taking precise account of the outcomes of the analogies carried out on the level of building blocks.

Such a methodology could assist geologists especially in performing analogies on large-scale geological phenomena which cannot be grasped intuitively, at scales outside human perception, unlike anything in the familiar world. In Geoscience such phenomena are related in one way or another to deep time and to astronomical distances. In dealing with such dimensions, geologists are sometimes hard put to perform analogies to familiar concepts of everyday time and space.[14,21] They have difficultly comparing the magnitude between phenomena at extreme scales. Cognitive Sciences studies noted this difficulty (for example).[59–61] These studies recommend, in addition to the methodology of mapping by structural alignment discussed above, two additional useful techniques to perform analogy –progressive alignment and hierarchical alignment.[14,62–64] These two techniques largely resemble the technique presented above, since here too it is advised not to perform high-order analogy but rather progressive and hierarchical mapping, from lower level to higher level. For example, hierarchical alignment advocates the hierarchical organization of all analogical steps within each new analogy to highlight common relation structures between the base, intermediate, and target concepts.[14] In other words, hierarchical alignment refers to identifying the relation between all previous concepts when progressively aligning concepts.[20] Regarding geological scales, it can be said that starting with small differences and then moving to larger ones is likely to lead to better learning than jumping immediately from human scale to very large magnitude scales.[21]

Progressive mapping of this kind can be valid for several types of analogy described in the literature –projective analogy, mutual alignment analogy, proportional analogies, predictive analogies, analogical problem, etc. Hence, for the purpose of the present paper, we will not distinguish between them (for further details see).[33,34,65]

Examples of incorrect analogous explanations in geology

To demonstrate the importance of the above criteria, let us outline famous cases in the history of geology of failure to take into account all the criteria for good analogical inference; as a result, the geologists were led to incorrect conclusions. For lack of space the cases will not be discussed here in exhaustive detail, nor is that our present purpose; rather, we wish to demonstrate the difference between a faulty analogical inference and a good one that provides the best possible explanation.

Example 1

In the mid-nineteenth century Kelvin began estimations to calculate the age of Earth by applying the laws of thermodynamics, working on the assumption that Earth began in a completely molten state. He was the first to apply the second law of thermodynamics to geology; in so doing he essentially rejected the Uniformitarianism of Hutton and Lyell concerning the cooling of Earth and its loss of energy.[66] In this sense he was also the first to describe Earth in geo-historical terms on the basis of the second law of thermodynamics. More specifically, Kelvin was claiming against Hutton and Lyell, that the Earth is a geo-historical system that is losing energy over the long term and, consequently, Earth is cooling. He thus rejected the theories of Hutton and Lyell on Uniformity of Rate and Uniformity of State, on the grounds that their theories contravened the second law of thermodynamics.[67] Kelvin's geological explanation in fact set out the thermodynamic one-directional and irreversible time arrow, thereby laying the scientific foundation for the geo-historical approach accepted by most geologists today. Kelvin, in his estimations of the age of Earth, sought to reevaluate Darwin's theory of evolution while promoting the hegemony of physics over geology.[68] He calculated Earth's age on the basis of the second law of thermodynamics; in so doing he essentially rejected Darwin's simple and inaccurate calculation carried out at the Weald valley in southern England. Moreover, Kelvin basically refuted the entire doctrine of Uniformitarianism. According to the second law of thermodynamics, Earth's entropy is constantly increasing, so Earth's energy is diminishing and it is cooling. As a result of the loss of energy, the forces and causes generating geological processes are weakening over time. In contrast to Uniformitarianism, Kelvin claimed that geological causes and forces observed in the present are not the same as those which took place in the past. Hence, it is not possible to calculate Earth's age with any precision on the basis of observations of the rate of geologic change occurring in the present. That is to say, Kelvin, on the basis of the second law of thermodynamics, refuted the two principles of classic Uniformitarianism: Uniformity of Rate and Uniformity of State.

Despite relying on the laws of thermodynamics, Kelvin famously made a significant mistake in his estimation of the immense age of Earth. His mistake resulted from basing his calculations mainly on the laws of thermodynamics while totally ignoring the geological/paleontological evidence already known at the time.[68]

More specifically, although Kelvin did indeed base his analogical inference on the thermodynamic model, in compliance with criterion 5, above, his compliance with criteria 2, 4, 6, and 7 was inadequate. For instance, he did not take into account essential structural (criterion 6) differences between Earth and an ordinary molten steel globe (criteria 2, 7); did not adduce multiple analogies (criterion 4); and ignored other relevant analogies (criterion 7) relating to paleontology and geologic structure of Earth (criterion 6). As a result, his estimation of the age of Earth was wrong. The primary mistake is attributable mainly to the overly abstract analogy between Earth and a steel globe which began as a molten object then gradually cooled, in accordance with the laws of thermodynamics. In other words, he drew too broad an analogy between two complete systems –system of a molten steel globe and Earth geosystem–failing to take into account modularity at the level of building blocks of those systems (individual geological phenomena, local geological processes, sub-systems). By contrast, his geologist contemporaries made better estimations of the age of Earth, based on geologic data (paleontological observation and stratigraphy). That is, their compliance with criteria ,4 ,6 and 7 was better than that of Kelvin. However, it should be noted that both sides wrongly estimated the actual age of earth. The prevailing opinion today is that this is because radioactivity was as yet unknown. Had Kelvin known about radioactivity, it stands to reason that, as a physicist, he would have accounted for it. The same holds true for geologists of his time; had they known about radioactivity they surely would have included it in their analysis and estimations, thereby complying more strictly with criterion 5. Ultimately, today the best calculation of Earth age takes into account the laws of thermodynamics, paleontological observations, stratigraphy, radioactivity, tectonic structure of earth's crust, various empirical measurements, etc. Thus present-day explanation can be seen to comply with all the above criteria for strong analogical inference; to date this is the best explanation of the immense age of Earth.

Example 2

Catastrophism in the 19th century based its explanations mainly on geological causes and processes inside Earth, not outside it, such as: violent volcanic activity, extreme climate change, rapid mountain formation, widescale flooding, etc .Hence, the approach sought too explanations of other phenomena/events which are taking place or have taken place on Earth by analogy to activity inside Earth. This is also why this approach could not provide a good explanation for K-Pg Boundary extinction of animal and plant life. While proponents of the approach did indeed provide a causal explanation based on many analogous intra-terrestrial phenomena –that is, it complied with criteria 4 ,5 – still the analogy was limited, failing to take into account extra-terrestrial phenomena ultimately more relevant (criterion 7) and provided better causal and structural explanations (criteria 5, 6). Only in the 20th century did Catastrophism reawaken, with catastrophy theories proposing causal factors from various cosmic activity. Thus, for instance, paleontologist Otto Schindewolf and many others suggested that mass extinction of plant and animal life resulted from the explosion of a supernova relatively near our solar system (Supernova Hypothesis). Schindewolf claimed that radiation from the supernova explosion caused simultaneous mass extinction of many species of animal and plant life in the K-Pg Boundary .This fatal radiation, he conjectured, severely damaged the ozone layer and was also responsible for animal macromutations. This conjecture was refuted for lack of empirical evidence to confirm it or similar analogies to support it (criterion 4). Consequently, over time it was supplanted by competing theories. One well-known hypothesis is the one put forth by Grove Karl Gilbert as early as the end of the 19th century, known as Impact Hypothesis. Gilbert claimed that the crater in the Colorado Plateau in northeast Arizona was created by the impact of a meteor striking Earth. This claim was confirmed in the early 20th century by Daniel Moreau Barringer (1860-1929), based mainly on analogy to impact events that occurred on other planetary bodies. In this respect, this hypothesis complied with criteria 7 ,6 ,4 ,1. Later, based on mineralogical testing and topographical investigation of the interior and exterior parts of the crater (criterion 6), geologists reached the conclusion that the crater was created by a catastrophic meteor impact event some 50000 years ago. This meant that the crater was not the result of intra-terrestrial volcanic activity, but of an extra-terrestrial body – the meteorite. This hypothesis was supported by experimental modelling of extra-terrestrial bodies impacting Earth at high velocity and by faults and deformities observed in the crater's stratification pattern.[69] The crater is surrounded by a ridge of fractured rubble (breccia) formed by an explosion triggered by meteorite shock waves. In the vicinity were found metamorphic effects in shocked quartz, formed by extremely high pressure and temperature at the time of meteorite impact. Moreover, the crater is in an area of sedimentary rocks (unrelated to volcanic rock); it is found on the plain, with no relation to the typical conical volcano shape. These findings further strengthened the geological explanation in criteria 7 ,6 ,5 ,4 ,1. Additional support for the impact hypothesis was subsequently proposed, nicely meeting these criteria. For instance, in 1956 Max Walker de Laubenfels proposed another supporting hypothesis which would explain the extinction of the dinosaurs in the K-Pg boundary based on a violent collision between a giant meteor and Earth.[69,70] Yet additional support for this hypothesis came in the mid-1970s, in research by eminent scientists Digby Mclaren and Harold Urey, who conjectured that multiple extinctions of plant and animal life on Earth during the last 50 million years were caused by comets impacting Earth.

In 1980 research by Walter Alvarez, Luis Alvarez and colleagues was published, positing (like de Laubenfels), that the animal and plant life extinction in the K-Pg Boundary resulted from impact of an asteroid in the Yucatán Peninsula in Mexico at Chicxulub Crater.

According to Alvarez, the force of impact of the comet (or asteroid) was so great that it caused changes in the entire planet Earth. The strongest evidence for this was high concentrations of iridium found in the crater's vicinity and in many other sites in the world from the K-Pg Boundary.[71] Iridium is a metallic element of the platinum group found for the most part in Earth's core, not on its crust. By contrast, iron meteorites are rich in iridium, containing 10000 times the amount found in rocks on Earth's crust. From this geologists surmised that iridium in the crater and its vicinity came from an asteroid. Microspherules of molten impact debris were also found around the crater, formed by friction of the asteroid in the atmosphere, then cooling rapidly. Shocked quartz, also found in the crater's vicinity, is generally found in asteroid impact or nuclear explosion sites; no volcanic mechanism can create them.[13,69,71] Based on the causal/structural evidence and explanations, most geologists became convinced that a large asteroid impacted Earth some 66 million years ago.

The above account demonstrates the great importance of using as many analogies as possible (criterion 4), with more structural (criterion 6), causal (criterion 5) and relevant) criterion 7), to explain the extinction of plant and animal life during the K-Pg Boundary. At the same time, despite the abundance of evidence of collision with asteroids and other planetary bodies, causal relation between extinction in K-Pg Boundary and the collision of the meteorite on Earth occasionally remains debated. Despite some ongoing partial debate among geologists, most of them do hold that mass extinctions are somehow cyclical, and are sometimes caused by extra-terrestrial factors.[13,69–72]

Conclusion and recommendations

In order to avoid or minimize bad analogical inferences in geology, geologists must focus on four main topics:

1. Since geology is a historical and analytic science derived from the laws of physics, for geological analogies the most prominent and crucial criteria are three – 5, 6, 7. These criteria are interrelated and are derived in some sense from the structure of standard scientific explanation such as Hempel's famous covering-law model. Additionally, the relevance of the similarities and differences between two geological phenomena/processes/systems to the conclusion is highly dependent on causal relations and structural analogies. Therefore, we should be more considerate of relevance, which depends upon the subject matter, historical context and logical details (logical, mathematical, causal, functional and structural relations) particular to each analogical argument.

2. In mapping analogies between two geological phenomena/processes/systems, we tend intuitively to compare them through positive analogies which highlight their similar properties while neglecting their differences. This in itself can lead to critical errors, especially in complex analogical arguments in geology. An experienced geologist must curb this tendency and balance it with negative analogies. Certainly, in argument by analogy it is important to compare similar properties of phenomena/processes/systems – yet recognizing their dissimilarities is no less important. Understanding the differences between the two systems sometimes actually highlights false similarity of the kind that could lead us to incorrect or irrelevant conclusions.

3. In order to meet the criteria set out above, it is recommended, in performing analogy from source domain to target domain in geology, to conduct progressive mapping in accordance with the below stages.

   a. A good analogy will involve an appropriate level of concrete similarity, such that geologists will be able both to align the source and target and to appreciate their abstract relational commonalities. This claim is well supported by research on analogical problem solving that has shown that when corresponding objects in a familiar and novel problem are similar, people are more accurate in applying the solution from the familiar source to the novel target.[36,73,74] For this reason, when performing analogy, it is first necessary to perform mapping and local matching between the objects /elements and concrete features of the two domains, with respect to similarities (positive analogy) and difference (negative analogy). It is especially important in this process not to merely compare surface features which can generally lead the geologist to a false conclusion[50] but to attempt too to understand the deep structure of each object /element specifically, and to understand its goal relevance to the overall context of the analogy.[49] This requirement is especially valid for students and early-career geologists, who have not yet gained sufficient professional knowledge and experience, so that limited or erroneous source domain knowledge occasionally makes its way to the target domain through bad analogies.[76,77] Additional studies in cognitive sciences support this claim.[51] These studies show that when adults learn a new area of knowledge, they have a tendency to perform mainly object matches and focus less on relational matches; this in itself can cause them to fail in performing analogy.

   b. In order to examine the structural consistency between two geological systems, it is not enough to address only surface similarities;[30] rather, one must base the analogy on deep similarities[78] through structure-mapping (relational/structural alignment) between the domains, while taking into account similarity (positive analogy) and difference (negative analogy) between them. This mapping must include important spatial, temporal, and causal relations in addition to attributes of objects. At the same time it must be remembered that for geological analogy, as for other scientific analogies, the matching relational structure will generally be governed by causal relations rather than spatial relations.

   c. It is not enough to explain similarity and difference between objects/elements/concrete features and structural relations noted under A and B with simple causal relations; instead, causal relations alignment must be used, which are grounded in the laws of physics, chemistry, biology, etc. At this stage it is recommended to verify whether causal relations in the two domains are indeed grounded on the same laws of physics, chemistry, etc. (as seen in the example of Rutherford's analogy). A good analogical explanation in geology must absolutely be based on causal relations derived from the laws of physics; in analogical explanations in geology it is therefore recommended to use an the scientific explanatory model: Hempel's covering law model. In so doing it is recommended to prefer a logically valid, deductive argument of modus ponens (MP((such as logical-causal arguments I, above), or modus tollens (MT((such as logical-causal arguments IV, above). This is because unlike inductive/analogical reasoning, in deductive reasoning we infer from the general to the particular, ensuring that the premises provide conclusive proof of the truth of the conclusion. In other words, in this argument the conclusion follows from the premises by logical necessity, since it is contained in them.

   d. The candidate inferences describe above are only hypotheses; their factual truth is not guaranteed by their structural consistency and must be checked separately (Gentner & Clement, 1988). Since geology is an empirical science, deductive inferences such as those outlined above must be used to derive an testable conclusion, in accordance with Poppers falsifiability principle.[79] The conclusion must be empirically examined; it if fails this test, it follows that it logically contradicts at least one of the premises of the deductive inference, and hence must be rejected. However, if the conclusion passes the empirical test, we are permitted to hold on to it as inference to the best explanation, until such time as new evidence refuting it may present itself. This kind of deductive screening will lessen the risk of obtaining a false analogical inference and increase the chances of obtaining a better analogical inference.

4. In seeking a good analogy between two complete geological systems, it is advisable in the first instance not to perform analogies on the level of complete geological systems but rather to content oneself with analogies on the level of their building blocks - discrete geological phenomena, local geological

processes, and sub-systems of the complete systems being compared. The process of analogy on the level of building blocks is simpler, more reliable, and lowers probability of error with respect to the complete geological system. Only in the second instance, after completing the stages of analogy on the level of building blocks, should one proceed cautiously to analogy on the level of two complete systems, all the while taking precise account of the outcomes of the analogies carried out on the level of building blocks.

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Conflicts of interest

Authors declare that there is no conflict of interest.

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