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Earth sciences, an “out of system” science: epistemology, models and skills

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Abstract
With regard to a long experience in teaching and spreading Earth sciences in the Italian context, both to students and to the general public, the work proposes a brief analysis of the relationship between Earth Sciences and the lack of interest towards this discipline in all the public. From this analysis emerged that Earth sciences appear as an "out of system" discipline, particular definition used and illustrated in the text. As a result, it seemed to be necessary to deepen some aspects of its epistemology and of the methodological and experimental procedures that the different branches of the discipline require. More precisely, it has emerged the peculiarity of a science that questions the application of the experimental scientific method, highlighting the need to identify different models and tools in experimental and investigative practice. The relationships between facts, phenomena and events require, and in the same time they can promote e, among students but also researchers, specific and transversal and skills and abilities, including the capacities of analysis, synthesis and abstraction that are fundamental both as soft skills and in the world of research.

Key Word: Earth sciences, epistemology, models, skills

Introduction

My professional career has been mainly centered on teaching, for which I did not initially have a particular vocation but which, in the times, has proved to be stimulating and passionate and has pushed me, in the last 20 years, to devote myself mainly to the promotion of the teaching learning of Earth sciences. In different roles, teacher, educator, researcher, I have tried to find the most reliable solutions to involve, interest and excite students and public. I have tried, in the time, to understand the causes of this widespread lack of interest in this science. It is truly remarkable that this occurs in particular in a context, such as Italy, where, precisely because of its nature, fragile and still young from a geological point of view, just the lack of knowledge in the Earth sciences is causing more and more damage and death. And it is truly remarkable that Erath Sciences are becoming, in the last years, richer in suggestions, information and discoveries and they are also showing their reliance to reach Sustainable Development Goals of AGENDA 2030: the close links between human well-being, the health of natural systems and the presence of common challenges that all countries are called upon to face are increasingly evident.

A brief analysis of the context

Some causes of this lack of interest are well known: they have been widely analyzed, for example in the Italian school context, and unfortunately they still do not see a significant change: science teachers are too often not adequately trained on the topics of geosciences, they are not passionate on these topics and then not able to passionate their students. Science teachers are not even confident on geosciences and then not able to use investigative and discovery approaches: teaching methods remain too often transmissive and poorly involving. Going up the level of this analysis, the causes could be attributed to the nature itself of Earth sciences, a very young discipline that seems to remain a fragmented body, made up of numerous disciplinary branches, which study different materials, rocks, minerals, water, soil, air, ice and different phenomena, metamorphism and fossilization, volcanoes and earthquakes, catastrophes of the past and climatic variations.

If we take a look to the history of Earth sciences, without the presumption of being exhaustive, but in an effort to grasp a guideline, we could identify their birth, as many schoolbooks do, with the Wegener's theory in 1911, or even with the plate tectonics theory in the 1980s. Actually, the founders of modern geology, Steno, Hutton, Lyell, Argan, shone for significant discoveries in the field of Earth sciences as early as the 18th and 19th centuries: each of them proposed a fragment of the puzzle that constitutes the history of Earth geology, developed a principle, formulated a theory, sometimes original, others derived in contrast with those of others, often based on the observations of its geological context, paving the way for the theory of continental drift and the plates tectonic. A short quote is due to Mary Anning, the fossil hunter, because in Earth sciences, even more than in other scientific disciplines, the pink quota is poorly represented.

The philosophy that inspired the work of these scientists was characterized by principles of unity and coherence: the idea of considering the Earth as a complex system, distinguished by the interaction of its components, in fact, was progressively achieved in the early twentieth century, but it had not yet been possible to conceive a theory that would unify the different branches in a single stream. The following years, throughout the twentieth century, were characterized by the research of many scientists, each one attentive to his own field, each one concentrated on building his own little model, in a reductionist approach, far from the idea of the complexity of the knowledge system and certainly not interested in unifying the theories of the discipline. It will be necessary to wait 70 years for the most modern theory of geology to become established: plate tectonics, capable of giving a unified explanation to all the great phenomena involved.

“Ceased to communicate structural geologists with volcanologists and geophysicists, geographers with geomorphologists, the sedimentologists diverged from stratigraphists, the micropaleontologists by paleontologists, minerologists by petrographers; geologists applied distanced by researchers of naturalist mold” [1]. In scientific research, it is not rare, however, that the researcher, attentive to his objectives, can legitimately lose the idea of complexity within the discipline as a whole; the resulting image is therefore not that of an organic science with its own defined state, but that of many sciences, fragmented, divided, less solid and less recognized.

It is not easy to keep in mind this complexity, understood in the sense of its Latin etymology of *cum plexus*, which does not mean difficult but strictly intertwined, or its being complicated, always with the Latin meaning of *cum plicatus*, then bent together, interconnected. But till the different researches and individual theories are not connected, it is certainly not possible to identify a single formal structure of the discipline. Perhaps, however, this complexity, due to the presence of many fields of study which, although in different forms, have to do with the Earth system, is responsible for its weakness, but is also its wealth.

The need of a stronger epistemology

If we consider the meaning and significance of epistemology of a scientific discipline, we find the need of having clear knowledge of his nature, its purposes, its foundations and the research methods, what is qualifies as science and defines the limits of the humans knowledge in the field. Generally, all scientific disciplines are based on an epistemology, necessary to deal with the fundamentals of the discipline itself, with the conditions that allow building the scientific knowledge and with the methods to achieve this knowledge. Sometimes, particularly in UK and USA, epistemology meaning opens to theory of knowledge, the discussion of the validity, the meaning of observation and experiment and the means by which to interpret them. These concepts are related to the Philosophy of Science, which I do not have the presumption of being able to elaborate, but the perception that the nonexistence of uniqueness, of organicity of the discipline can be interpreted as one of the reasons of the lack of interest arises spontaneously. It is not a coincidence that the epistemological reflections have involved mainly biologists and physicists, mathematicians and astronomers and none of geologists.

The latest generations of geologists were engaged in other directions: raw materials, geological hazards, ocean exploration, geophysical surveys, but of course also inquiries about the history of the Earth in all its aspects, from biological to structural ones. On the nature of Earth science and on the need of an epistemology many geoscientists, as Hubral, 2001; Tarantola, 2006; Kali and Orion, 1996; Kastens and Ishikawa, 2006; Corbett et al., 2011; Chellingsworth et al., 2011, have expressed themselves in the past, in the epistemological fundamentals of Earth sciences, perhaps too few philosophers of science, even because of the atypical characteristics of this discipline, which makes it “out of system”.

The specificity of Earth Sciences.

Appears evident that the specificity of Earth Sciences derives precisely from a strong fragmentation and it is from this specificity that perhaps we need to start: from the presence of many scientific branches, of many research fields. Each branch studies phenomena and events that have occurred at different times, billions and millions of years, what we call deep time, but also in actual times, they can happen today or may happen tomorrow, and whose study allows us to update, to actualize past phenomena. Each branch studies different environments, earth, air, water, space, soil, subsoil; continuously interconnected and closely intertwined, of infinitesimal dimensions and enormous spaces. Each branch mainly studies inanimate objects, not living or no longer living, but any living thing is strictly independent from the soil on which it lives, from the water that it drinks, from the air it breathes and of course from the planet on which it lives.

It means a contest rich of relationships, of flows, of streams, of connections, interacting in all their different components that, together, constitute a system: a spiral that coils on itself, a mesh that intertwines, a network of information, of events, in which every knot, every mesh is fundamental, but even more important are the relationships that bind them. A mesh that unravels, a knot that unravels and the structure loses consistency...Consequently, it is necessary that every node is studied, understood, analyzed, in its structure, in its history, in its transformations, be it a geological event, a so-called catastrophe, a natural phenomenon, but also a simple fragment of rock, a mineral as well as a meteorological or climatic phenomenon.

But above all, it is essential that the links that connect each of these “objects” with the historical, geological, geographical, paleogeographic, paleoclimatic picture are clear and with its physical and chemical variables, obviously in relation to a timeline. Every geological event cannot be separated from the climatic, atmospheric, chemical and physical conditions that occurred at the time, as well as it is crucial to bear in mind the consequences it may have had, on the geological, abiological, but also biological environment, on the living, whatever the period in which it occurred. But, as its streams are closely intertwined, like all phenomena, recent and past, as taught Hutton, are connected and comparable: we must not lose sight of the unity of the Earth System; this unity, and this complexity, should always be placed in the foreground, because complexity of a system does not depend only from the fact that we do not know details of its structure and the relationships between its parts, it is an intrinsic property, independent from knowledge of details we can have.

Is this complexity that characterizes the Earth Sciences.
The complexity sci¬ences represent a set of disciplines which study systems with many parts that interact to produce a global behavior not explicable through the analysis of the individual constituent elements. The risk that each branch of research remains isolated from the others, grows as knowledge deepens, but moving away from the main trunk is current and perhaps inevitable. But the more it diverges, the more the system loses unity and therefore strength. "Therefore, teaching the Earth systems approach requires that teachers and students understand the concept of a system. In fact, the majority of the Earth disciplines are based on a circular, interpretative approach of experimental observations, rather than on a rigorous, direct appli¬cation of theories to a set of accurate measurements. Earth disciplines offer many examples of processes driven by circular feedback."

[2] It seems particularly useful to build a unique epistemology, coherent and therefore able to give uniqueness, coherence and therefore strength to this discipline and to develop an epistemology of complexity. In particular, in this picture of interweaving and interrelationships, of links and flows, it allows to support the idea of non-linearity, useful when the linear model seems too simple and not adequate. In a non-linear model every component, every phenomenon, must be related to other systems and it is not possible to find a separate law for each fact. A complex system cannot be static or linear: it is a combination of random processes and non-linear interactions; it is the result of an evolution of the process in which sometimes it is not possible to recognize relationships of cause or effect between the different components, because both are the result of their common history. Certainly, complexity means not uniqueness, which is rich in suggestions, but also difficulty in having an overall view; as indicated in the Great Ideas of the United States , the Earth is a system of systems and for our mind it is often difficult to understand how different facts can be connected on different levels of hierarchy, in a sort of nebula still evolving; moreover, for the quality of natural phenomena of Earth science, with few exceptions such as Steno's law of superimposition and Hutton-Lyell's theory of *uniformitarianism* (actualism), many topics are difficult to study due to the lack of regularity and repetition, also maintaining consistent boundary conditions.

A complex system is defined by "characteristics of self-reference and self-organization aimed at ensuring the stability of its structure and the reproduction of its components through the maintenance of the processes necessary for its survival" [3]. But complexity of a system does not depend only from the fact that we do not know details of its structure and the relationships between its parts, but it is an intrinsic property, independent from knowledge of details we can have, something that "does not disappear even when the operation of the system can be completely rebuilt from its simple elements" [4].

Each scientific discipline has its own dimension to study, it differs from each other in terms of scope of study and variety of techniques used but the traditional sciences (Orion,2007) "are reductionist, therefore inadequate to study their complexity". Instead, learning the Earth sciences provides a unique opportunity to conceptualize the phenomenon through time and space, in a complex and interactive historical approach. Understanding how the Earth works requires a retrospection that makes inferences about the past. By interpreting the present as the result of large-scale natural experiments, the Earth sciences lay the foundation for understanding the complex relationships between the sciences and formulating hypotheses about the possible future.

For this reason, [5] thinks that geology in often thrown into the "mold of physics", pushing towards the distinction between historical sciences like geology and ahistorical sciences like physics, even if geology also contains non-historical aspects that deal with configurations and processes, and a balanced understanding of our science requires considering all these aspects. Orion (2002) claimed that because the natural environment is a system of interacting natural subsystems, we should understand that any manipulation in one part of this complex system might cause a chain reaction. The understanding of physical systems such as the Earth is also based on the ability to enlarge the systems' borders and expose hidden dimensions of the system. The Theory of Complexity (ToC) (in McComas, W. F. and Olson -1998, The Nature of Science in International Science Education Standards Documents in The Nature of Science in Science Education: Rationales and Strategies) can be defined as the study of inter and multidisciplinary complex systems and their behavior in relation to problems in the environment. According to the Theory of Complexity, scientific representations of reality are due to phenomena and problems, both immersed in a system that understands them and that we call "environment".

A Non-Galileian Model
It is universally known that the typical modality with which science proceeds to reach an objective, reliable, verifiable and shareable knowledge of reality is the scientific method, or experimental method, introduced by Galileo in the 17th century. It consists in the collection of empirical data that is based on the formulation of hypotheses, ad on the rigorous, rational, when possible, mathematical analysis of these data. Basically, there is only one scientific method and if it is not applicable to a context, this is not science. Every phenomenon must be verifiable, verifiable, repeatable; every variable introduces variations, which in turn can be formulated through mathematical functions; every error, deviance or shift from the standard curve can and must be analyzed and corrected when possible. The process of hypothesis, experimental verification, analysis and synthesis, applicable appropriately and necessarily in many scientific disciplines, does not find its application in most phenomena of the earth sciences.

Even in biology, the science of life, we cannot always repeat phenomena, but Mendel arrives at formulating his laws by repeating the same experience with peas for years and generations, until he obtains a regularity and then formulates it through a law. The circular and non-linear connections between the components imply that they cannot be separated, physically and conceptually, without destroying the whole system. As a consequence, the method of analysis typical of classical science, based on decomposition into independ¬ent modules, can be inappropriate for understanding a complex system. A system is an entity that maintains its existence and functions as a whole through the interaction of its parts. However, this group of interacting, and interdependent parts that form a system must have a specific purpose, and in order to optimally bring out its purpose all parts must be present. Gudovitch (1997), studied systems with of high school students in which a system-thinking model consists of four stages: The first stage includes an acquaintance with the different Earth systems, and an awareness of the material transformation. The second stage includes an understanding of specific processes causing this material transformation. The third stage includes an understanding of the reciprocal relationships between the systems. The fourth stage includes a perception of the system as a whole.

If simplify is inevitable in the process of knowledge, not just as inevitable is trivialize or oversimplify model systems or problems. However, in the Earth Sciences it is not always possible to reconstruct, with all the variables, geological phenomena, such as landslides, avalanches, earthquakes and to obtain the same result. It is not easy, and in some cases quite impossible, to reproduce in laboratory some geological events, as the plate tectonics and related phenomena, orogeny, volcanoes; mathematical models or virtual simulations are necessaries, but the obtained results are often different from each other or do not fit with the experimental data. Although it is possible to reconstruct the rock cycle or a sequence of erosion-transport-sedimentation, because of the interaction of chemical-physical factors, the results can be inconsistent and the process rarely reproduces the same manner. A hard work is necessary to reproduce the natural phenomena: avalanches, earthquakes or landslides are not easily reproduced in a scientific laboratory in the natural conditions and contexts in which they occur. Different environmental factors, the chemical and physical parameters, the time, the interaction with the biosphere, the human action, may change significantly the results, even in the presence of small variations. Even the uniformitarianism (actualism), a fundamental principle of geology, when there are data interruptions in deep time and therefore the incompleteness of stratigraphic and fossil records, being impossible to observe them directly, remains fragile from a theoretical point of view.

For this reason, also the realization of activities in the classroom or in the laboratory is not easy and repeatable, as happens in physics, chemistry and, in part, in biology and, in most cases, necessary to integrate the observation and formulation of hypotheses, using models and simulations, using large computers to describe their behavior. Since it is not possible to reproduce in the laboratory the movement of the plates, the eruption of a volcano, or the movements of the air, it is necessary to use models, virtual or hands-on. The models, as in all the fields of science, allow us to insert the different variables, changing or keeping some constants. Considering in particular aspects of the most effective educational approaches in the discipline, the models to be developed should have primarily the function of stimulating observations, hypothesis, reasoning and, therefore, the formulation of more general rules and, when possible, of laws. Finally, the model may be able to stimulate the abstraction and the ability to identify connections between different elements and principles, intra- and inter-disciplinary.

Skill and Competences

The traditional definition of competence, which comes from literature, is the implementation of a performance in a given context that involves the use of attitudes and motivations, knowledge, competences and skills and is aimed at achieving a purpose. More precisely, competence is, "What, in a given context, one can do (ability) on the basis of a knowledge to achieve the expected goal and produce knowledge. It means to choose, use and master knowledge, skills and abilities appropriate in a given context, to set and / or solve a given problem". The acquired experience has shown that Earth Sciences are the discipline that more promote citizenship and transversal skills and, furthermore, develops the ideas of system and complexity. It is surprising how these skills can be easily applicable, malleable and adaptable to different contexts and contents of Earth sciences, where they become tools to think, observe, connect, relate, research, solve and communicate.

The goal is to be able to understand that every single phenomenon, a landslide, a flood, a volcanic eruption or an earthquake are part of a global system: all are connected to each other. It is possible to pass from a single case to a general law of nature. In the case of the approaches traditionally used in the sciences, inductive and deductive reasoning, in which the rule is given from the beginning, the definition of a law occurs regularly, and with relative ease. In the case of the abductive process, such as in the Problem-based Learning, ability to synthesize becomes an essential element: understanding why landslides can fall or earthquakes occur requires a general ability to synthesize.

More precisely, the analysis of the phenomena studied by the Earth sciences, phenomena not always predictable but interconnected, allows to promote

- the ability to synthesize and generalize, which implies being able to collect many cases in a more general case that involves them all;
- the capacity for abstraction, which implies being able to formulate a rule that describes the events of the case: the characteristics of a rock, the morphology of the slope, the geographical position.
  In the case of natural phenomena, of course, the variables are many and not always easy to connect: this represents a challenge for the scientist and for the student. It is not always possible to define a law, but we can always find a cause-effect relationship. Each landslide, any meteorological phenomenon can be triggered by a person kicking a stone or by the beat of a butterfly's wings. In reality, these are materials, phenomena and processes that are closely interconnected and interdependent with each other and with the different scientific disciplines. These phenomena, which have therefore affected not only the geological world but also the biological world, due to their nature of variability, unpredictability, complexity, cannot be naturally trapped in a universal law, typical instead of other scientific disciplines. Proposes a list of abilities as a part of the process that leads to the comprehension of the concept of system and complexity [2]. I fully share some skills, which are fundamental to the acquisition of the concept, but which, in turn, are promoted and acquired, when the system and its complex relationships must be recognized. More precisely, the ability
- to identify the components of a system and processes within the system; which means analysis;
- to identify flows and link among the system's components; which means to recognize relationships;
- to organize the systems' components and processes within a framework of relationships and to identify dynamic relationships within the system, which means *synthesis;*
- to make generalizations, which means *abstraction.*

First conclusions

It is not superfluous to recall the strong cultural importance of Earth Sciences, which is not obvious: in the past, too many have considered that the science of the Earth has no cultural depth. Instead, Earth Sciences offer a unique possibility of a conceptualized phenomenon across time and space, in a complex and interactive historical approach, because, as presented, it the discipline that most develops ideas of system and complexity. Earth sciences offer the tools to "break through" back in time, inherits the idea of deep time and applies it to the many other disciplines, particularly life sciences, support the idea that Earth as an evolving system and develop the epistemological model, of a rigorous science, not simply descriptive, capable of developing regularity valid throughout the Earth's system. Understanding how the Earth works requires the retrospection that makes inferences about the past; it requires to interpret the present as the result of large-scale natural experiments; it prepares the ground for understanding the complex relationships between the sciences and for making hypotheses about the possible future [6-8].

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