“How the world gains understanding of a planet”

An Analysis of Scientific Understanding in Earth Sciences and of the Communication of Earth-Scientific Explanation

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Let’s start diggin’ Mother Earth

Why is it important for the general public to gain some understanding of Earth Science?

Figures 1a and 1b. *Figure 1a (left): The “Blue Marble” image, taken by astronauts, 07-12-1972. Source: http://nix.larc.nasa.gov/info;jsessionid=13gh1dewxfdi2?id=GPN-2000-001138&orgid=12 (site visited 10-01-2011). Figure 1b (right): Presenting the world. Source: http://members.greenpeace.org/blog/greenpeaceusa_blog/2010/04/ (site visited 02-08-2010).*

Recall the famous “Blue Marble” Earth image of South Africa and Antarctica, taken by the Apollo 17 astronauts, on the 7th of December 1972 (*Figure 1*). The world got its first full view of our planet from space. It is a symbol that anyone in the world can relate to, regardless of nationality, ethnic origin, or religious beliefs. It is therefore a unifying image of the world and a symbol of the possibilities of science. However, the image of the world and of science has changed a lot through the centuries.

Until the seventeenth century, science was mainly an activity for philosophers and artists. The philosopher Aristotle (384 – 322 BC) was one of the first to aim to systematically classify the animal system. The artist Da Vinci (1452 – 1519) was an architect, inventor, philosopher, scientist, writer, and painter in one. Finally, the scientist Newton (1643 – 1727), a classic example of a scientist, was also a philosopher, artist, astrologer, and alchemist. They all combined several disciplines in their work.

In the seventeenth century scientists from the upper class and technicians from the middle class started working together. The first instruments appeared and experiments were introduced to test the theories.

During the first half of the twentieth century, around 1930, philosophers of science and scientists started to define science. The logical positivists of the Wiener Kreis argued that all scientific disciplines must have the same theoretical structure. According to them, science had to be able to be empirically verified. The philospher Popper (1902 – 1994) added that science had to be falsified. Famous scientists, such as Einstein (1879 – 1955) and Planck (1858 – 1947) did their big discoveries around the same time. Scientists started to specialize and focus on one discipline. Until 1970, the classical science operated as the example of what science should be: an attempt to truthful representation of facts.

Towards the end of the twentieth century, science found a place in modern society and became a part of the culture. More people went to universities and communication channels developed rapidly. Different scientific disciplines improved their communication with each other. Earth Science is just one example of a scientific area that consists of different disciplines and use theories from mathematics, physics, and chemistry. Interdisciplinary science found its way back into society.

Earth Science is an example of an interdisciplinary science. It combines physics, mathematics, chemistry, and biology. To understand the processes of the Earth, geoscientists look for evidence of what happened in the past. Even though only a few scientists understand these earth-scientific processes, an enhanced understanding of the environment by the broader public is important in our day-to-day lives.

We are all connected to the Earth and dependent on her resources. Growing populations increase our demand on natural resources. We currently have a severe impact on the Earth, her ecosystem, and thereby ourselves, by extracting and using these resources in unsustainable ways. We are also vulnerable to natural disasters such as floods, earthquakes, volcanic eruptions, and hurricanes, which can kill large numbers of people. Other disasters are not immediately obvious, such as climate change, or the acidification of the oceans. If we want to set a sustainable life standard for the world, we need to know more about our planet, find out how she works, appreciate her fragility, and understand the interactions of the many processes in the Earth.

Earth-scientific knowledge enables us to make informed decisions about important issues, such as the use and management of natural resources, recycling (e.g. understanding what non-recyclable rubbish waste does to the environment), sustainability (e.g. appreciating the risks of extracting oil has on the environment), and housing (e.g. awareness of zones at risks, like living near an active fault and not building on a 100 year floodplain).

In this thesis I will argue that earth-scientific understanding is an integration of embodied and theoretical understanding and therefore requires more than just the communication of factual knowledge. It involves insight in the processes and procedures as well as a practical approach. I will argue that there is no difference in the process of acquiring scientific understanding by laypeople, students, and scientists. The public can gain understanding of earth-scientific issues through the same tools as scientists.

I will argue that teaching procedural understanding stimulates the students to seek out evidence, deal with uncertainty and risk, access, apply, and use the relevant conceptual knowledge to critically evaluate related evidence. In order to avoid an overload of information, the focus should be on learning how to access the relevant and reliable factual knowledge, for example though the internet, when they are motivated to do so. Therefore, I will argue that these tools should be used in the communication and education to laypeople, and not just to students, while presented at age-and grade-appropriate levels.

With this thesis I hope to contribute to the improvement of earth-scientific communication, in order to enhance earth-scientific understanding of the public.

Project Description

There seems to be little geological understanding by the public, such as the (lack of) knowledge that geological events often happen on longer repeat times than society remembers. There is a decline of interest of young people in pursuing scientific careers (*Department of Education, 1994*). The Dutch public only has a vague notion of what science entails: 36% is not capable to describe science, 43% never reads about science, 47% never watches a scientific program, and 28% believes they are badly informed (*Becker & Van Rooijen, 2001*).

From surprised reactions of laypeople to natural disasters it appears that just showing scientific results is not enough to convey scientific understanding to the public. Earth-scientific explanation consists of more than just stating the facts. Science has her own language, with precisely defined concepts; so that scientists can easily and precisely communicate with each other (*Van Woerkum and Van der Auweraert, 2004*). Unfortunately, this language is not shared between scientists and the public (*Van Woerkum and Van der Auweraert, 2004*). The public does not understand the scientists, but scientists do not understand the public either (*Knoop, 2004*). However, this dialogue is important, in order to mobilize the community support for unpopular measures to resolve misunderstandings.

It is therefore essential to investigate how science communication might be improved. When a scientist is able to explain a research to a broad public, the content may lose in precision, but gains in societal relevance (*Van Woerkum and Van der Auweraert, 2004*). It may be impossible to align scientific language to common language (*Van Woerkum and Van der Auweraert, 2004*), in order to enhance the scientific understanding of the public, but we might be able to improve science communication.

My aim with this thesis is to investigate how earth-scientific communication may be improved, in order to enhance earth-scientific understanding of the public. By analyzing earth-scientific understanding and the communication of earth-scientific explanation, I aim to gain a better insight in the process of understanding, for both scientists and laypeople, and to further develop the notion of understanding within the Earth Sciences.

Finding an answer to this research question requires elaborating on a number of sub-questions first:

- What is earth-scientific explanation? (*Chapter 1*)
- What is earth-scientific understanding? (*Chapter 2*)
- How does an earth-scientist gain earth-scientific understanding? (*Chapter 3*)
- How do people reach understanding? (*Chapter 4*)
- How can earth-scientists communicate their understanding? (*Chapter 5*)

This research is based on the newest insights in the philosophy of science, psychology, and science communication, and builds on an extensive literature study. All three disciplines have something to say about how people learn and understand science. Philosophy of science aims to define scientific explanation and understanding and how scientists use and gain it. Psychology investigates the individual learning processes. Science communication involves in the communication of science to a specific target group. I do not intend to provide a complete overview of the existing literature on the philosophy of (earth-) science, psychology, or science communication, nor alter practices to a single approach or guarantee some sort of truth-value. However, I did test my recommendations during my internship at the Museon, while working on an earth-scientific exhibition and giving related classes to 10-12 year olds.

Summary

Earth-scientific knowledge enables us to make informed decisions on the use and management of important natural resources such as, recycling (e.g. understanding what non-recyclable rubbish waste does to the environment), sustainability (e.g. appreciating the risks extracting oil has on the environment), and housing (e.g. awareness of zones at risks, like living near an active fault or not building on a 100 year old floodplain). If we want to set a sustainable life standard for the world, we need to know more about our planet, find out how she works, appreciate her fragility, and understand the interactions between the many processes of the Earth.

Unfortunately, there seems to be little geological understanding by the public, exemplified by the lack of knowledge concerning geological events that happen on longer repeat times than society remembers. In addition there is a decline in the interest of young people pursuing scientific careers. From the surprised reactions of laypeople to natural disasters it appears that just showing scientific results is not enough to convey scientific understanding to the public. Earth-scientific reasoning is crucial for society to learn, since many issues, such as global warming and various risk and resource assessments, are based on Earth Science.

The public does not understand the scientists, but scientists do not understand the public either. Science has her own language, with precisely defined concepts designed for scientists to easily and precisely communicate with each other. Unfortunately, this language is not shared between scientists and the public. This dialogue is important in order to mobilize the community support for unpopular measures and to resolve misunderstandings. It is therefore essential to investigate how science communication can be improved. When a scientist is able to explain research to a broad public, what the content may lose in precision, it gains in societal relevance. However, it may be impossible to align scientific language to common language, in order to enhance the scientific understanding of the public.

The aim of this thesis is to investigate how earth-scientific communication might be improved in order to enhance the public's earth-scientific understanding. By analyzing earth-scientific understanding and the communication of earth-scientific explanation, I aim to gain a better insight in the process of understanding, for both scientists and laypeople, and to further develop the notion of understanding within the Earth Sciences. The analysis is based on the newest insights in the philosophy of science, psychology, and science communication. It builds on an extensive literature study and an analysis of the current state-of-the-art of science museums. Finding an answer to this research question requires elaborating on a number of sub-questions first:

1. What is earth-scientific explanation?
2. What is earth-scientific understanding?
3. How does an earth-scientist gain earth-scientific understanding?
4. How do people achieve understanding?
5. How can earth-scientists communicate their understanding?

(1) A scientific explanation is a logically valid argument in which the explanandum is deduced from an explanans, containing at least one universal law and relevant initial and background conditions. Earth Science combines various logical techniques and her logic results from at least three complementary logical paths (deduction, induction, and abduction). The method of Earth Science involves at least two types of scientific explanation: through the reconstruction of the past and by causal reasoning from the present. In Earth Science there is often more than one explanation possible of some phenomena (multiple working hypotheses). Even though each earth-scientific event is unique, earth-scientific phenomena often cannot be

directly observed, and earth-scientific datasets are often underdetermined, a well-grounded scientific consensus can be reached.

(2) The important difference between understanding and scientific explanation is that for scientific explanation phenomenon P is explained by theory T, whereas understanding involves a subject, one who understands phenomenon P by theory T, such as a scientist. Deriving understanding from an explanation is a matter of ability. Earth-scientific understanding has a dual nature, containing both theoretical and embodied components. Combining theoretical and embodied understanding leads to the best earth-scientific understanding. Earth-scientific explanation is not the same as, and does not automatically lead to, earth-scientific understanding. However, earth-scientists do gain theoretical earth-scientific understanding based on earth-scientific explanation.

(3) In order to gain earth-scientific understanding, earth-scientists use a broad suite of tools such as images, descriptive and interpretive maps, symbols, diagrams, analogies, simulations, sketches, cross-sections, fieldwork, experiments, and modelling and apply them to activities. These tools are “developed” through constant intervention in the material world. Therefore, they are not merely cultural trends or social settings, but say something about reality. The geo-tools combine theoretical and embodied components. A combination of skill and relevant tools is essential for achieving understanding. The earth-scientific toolbox contains at least three categories of geo-tools: objective descriptive geo-tools (such as images, maps, symbols, and diagrams), subjective descriptive geo-tools (such as sketches and cross-sections), and geo-tools involving integrated understanding (such as analogies, simulations, experiments, modelling, and fieldwork). Different levels and forms of understanding can be acquired from using the same tools, but also different tools might be used to gain the same understanding. Results may be interpreted in a variety of ways depending of background knowledge and skills in handling the tools of their users. Objective descriptive geo-tools are used in the beginning phase of earth-scientific research and require little theoretical background. Understanding is enhanced by, or even partly consists of, visualization. Subjective descriptive geo-tools are generally included in the preparation of geological fieldwork and used during the fieldwork itself. They are based on objective observations, but personally drawn. Theory stops being merely a premis and developing new theory becomes a goal with the geo-tools that require integrated understanding. These geo-tools provide earth-scientists and students with a feeling for the protocols, research techniques, and procedures during simulations. They also permit a greater understanding of a theoretical structure. Each discipline may prefer their own tools for achieving understanding.

(4) The process of learning differs per individual. Not only does it differ between certain disciplines which geo-tools are used in the process of learning and achieving understanding, it also depends on the person who uses the geo-tool. In order to learn, all the domains should be encountered on. Most laypeople and students learn Earth Science by doing, combining both content and method, where some are more visual ; others are more logically orientated. Earth Science includes opportunities for discovery and exploration, data collection and analyses, verification or falsification and conclusions that must be well grounded and argued, i.e. the methodology of Earth Science. When connecting the geo-tools and the steps as examples of geological research to the (dominant) learning processes, it becomes clear that geological research passes several stages in the learning circle and cognitive processes, and encounters several intelligences. Understanding of earth-scientific issues by the public can be gained through the same tools that scientists are using. Scientists and students are just people with a specific interest. The difference is that earth-scientists have practiced their skills to handle the tools in more depth and can refer to other investigations and background information. They simply know more in their domain of expertise, and can work faster and

more efficiently, with this knowledge. The choice of method for achieving earth-scientific understanding is based on personal learning style and preferred intelligence. Scientists do not differ from other people. The public can reach earth-scientific understanding in the same way earth-scientists do. The same level of understanding can be reached when they have the same frame of reference, skills, and theoretical background.

(5) It is required in the scientific community to communicate acquired scientific understanding in order for other scientists to acquire the same insight. When communicating and teaching earth-scientific explanation, the focus should be on the process of doing earth-scientific research, using the geo-tools. Earth-scientists should transfer their understanding, rather than merely their factual knowledge. Note that scientific communication and education is based on the pragmatic use of explanation. It differs from scientific explanation in that the pragmatic use of explanation entails that it has an explanans (i.e. theory), an explanandum (i.e. phenomenon), and an explainer. Explanation in the pragmatic sense is a relative notion. It is personal and subjective. Earth-scientific communication and education should focus on research and presenting the knowledge in an inspiring way and presenting it at age and grade-appropriate levels, so that laypeople acquire the tools. Since understanding involves collecting and connecting new knowledge to the existing frame of reference, this is likely to be more efficient for science communication than just "communicating" the factual knowledge. Earth Science is best taught through fieldwork, in combination with theoretical knowledge.

More knowledge does not automatically improve scientific understanding. Earth-scientific understanding is more than just knowledge of facts and theories; it involves skills and embodied knowledge as well. In scientific communication, we should not present science as a ready-made package. In order to avoid an overload of information, the focus should be on learning how to access the relevant and reliable factual knowledge, for example though the internet, when the public is motivated to do so. These channels are highly improved. By reducing conceptual knowledge in the curriculum, there can be more focus on the process of doing research (deep and procedural understanding) and the validity and reliability of evidence. By using a deeper approach with students, (pragmatic) explanations become more advanced and the questions become more focused on explanations and causes. Teaching procedural understanding stimulates the students to seek out evidence, deal with uncertainty and risk, access, apply, and use the relevant conceptual knowledge to critically evaluate the evidence.

Explaining the process of doing earth-scientific research and accompanying laypeople to help them use and acquire the geo-tools are the best ways to communicate Earth Science and enhance earth-scientific understanding of the public.

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Figure 2. *"The Thinker", by Auguste Roden in 1880, sitting on the Earth. The statue is often used as a symbol to represent philosophy. Source: http://www.abelramirez.com/Gallery.html (site visited 10-01-2011).*

Chapter 1 Earth-Scientific Explanation

1.1 Introduction

In this chapter I will provide the definition of Earth Science and aim to answer the first sub-question: What is earth-scientific explanation? I will search the answer in the philosophy of science. I will discus two types of earth-scientific explanation: through the reconstruction of the past and by causal reasoning from the present.

1.2 Scientific Explanation

Hempel constructed an objective, non-pragmatic, concept of scientific explanation. According to Hempel, a very good scientific explanation is a logically valid argument in which the explanandum is deduced from an explanans, containing at least one universal law and relevant initial and background conditions (*Hempel, 1965*). Phenomenon P is scientifically explained by means of explanation E (*Hempel, 1965*).

Scientific explanation may result from at least three complementary logical paths (*Figure 1.1*):

(1) Deduction
(2) Induction
(3) Abduction

An earth-scientific explanation depends for a part in deduction (*Frodeman, 1995*). Deduction reasons from the general (i.e. laws of nature) to the particular (i.e. explanation or prediction) and is based on syllogisms. It is a solid form of logic, but the premises must be truthful.

Major premise (general)	: All basalts (A) are magmatic rock (B).
Minor premise (subject)	: Gabbro (C) is a basalt (A).
Conclusion (particular)	: Gabbro (C) is a magmatic rock (B).

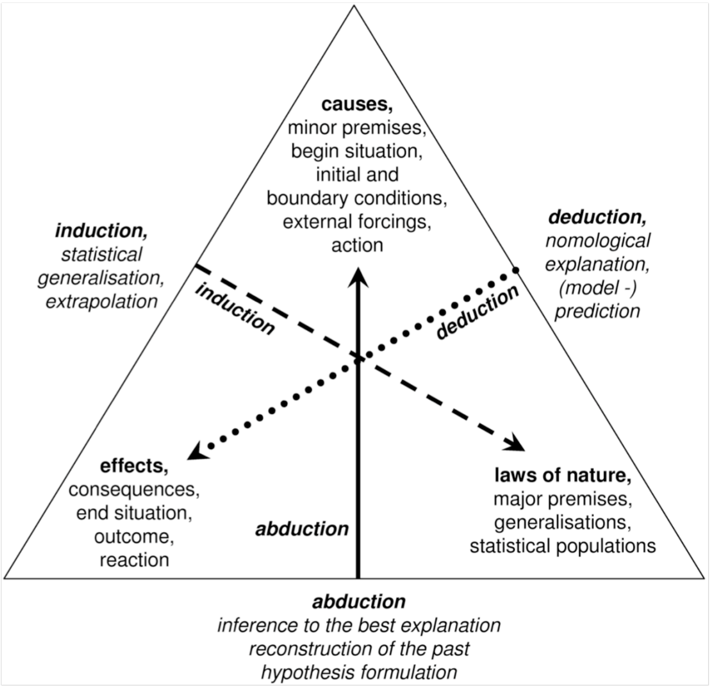

Figure 1.1. *The diagram shows the relation between abduction, deduction and induction. Several alternative terms encountered in literature are given. Each form of logic has its own weaknesses and strengths (Kleinhans et al, 2010).*

Induction reasons from particular instances to general theories and is the method used to confirm scientific theories. Facts are determined by repeated observations. It develops statistical generalizations. For example, new layers of sand form on top of older layers of sand (particular). If the ground is not turned around, the top layer is always younger than the bottom layer (generalisation).

Finally, abduction is a method to select hypotheses from observations, rather than conclusive explanations (*Lipton, 1991*). It combines final conditions and facts with laws or generalizations of nature into new theories. For example, Wegener (1912) observed the possible connection of Africa and South-America. He found the same glassier imprints on different continents. Locations and directions of old glaciers fitted perfectly. He observed the same for fossils of animals that could never have crossed the oceans and found the same sequences of rock types. Wegener came up with the hypotheses of plate tectonics. This explanation is a reconstruction of the past and involves causal reasoning.

A good scientific explanation is required when you are attempting to specify a (objective) kind of understanding, fitting a phenomenon into a broader theoretical framework *(De Regt, 2009*). Scientific explanations go beyond the original explanadum (phenomenon) by providing an explanans (theory) for the explanandum, showing how the original explanadum follows from the explanans, and integrate it with other explanada (*Brewer et al, 1998*). Scientific explanations must be testable (*Brewer et al, 1998*) and concern both universal and statistical laws (*De Regt and Dieks, 2005*). Universal laws are general principles, derived from observation of regularities in reality. Given an initial set of premises, universal laws are applied to these to deduce an outcome logically. Statistical laws do not guarantee a certain outcome, because we do not understand the mechanisms involved.

In this thesis, I distinguish scientific explanation from pragmatic explanation. Pragmatic explanation involves the communication of a scientific explanation tot non-specialists. The pragmatic use of explanation entails that it has an explanans (theory), an explanandum (phenomenon), and an explainer. The pragmatic explanation depends on the explanatory skills of the explainer and is preferably adapted to the learning style of the other person. The same explanation may not be intelligible, illuminating, or relevant, to another person. Therefore, explanation in the pragmatic sense is subjective. I will elaborate on this type of explanation in upcoming chapters.

1.2.1 The Definition of Earth Science

According to James Hutton, one of the founding fathers of Earth Sciences, earth-scientists aim to form a rational opinion of the course of nature and events that have happened in the past or going to happen by examining the appearances of the Earth (*Hutton, 1785, in Kleinhans et al, 2005*). From the principles of natural philosophy, we may arrive at some knowledge of the order and system of this globe. Charles Lyell formulated that the present is the key to the past (*Lyell, 1833, in Kleinhans et al, 2005*), which is perhaps the biggest assumption of earth-scientific research. Rachel Laudan described two main goals of Earth Science: historical and causal (*Laudan, 1987, in Kleinhans et al, 2005*). Earth science should describe the development of the Earth from its earliest beginnings to its present form and lay out the causes operating to shape the Earth. In other words, earth scientists study the structure, the phenomena and processes, and the history of the Earth (*Kleinhans et al, 2005*).

The activities and the practice of Earth Sciences involve philosophical decisions, whether implicit or seen as part of the tradition and/or training associated with a particular scientific field or discipline methodology (*Inkpen, 2005*). Earth-scientists do not take the world for granted; they question what they are looking at. This is a philosophical method and understanding the philosophy of science is relevant for understanding the development of science and scientific methodology (*Inkpen, 2005*). While studying the Earth, earth-scientists aim to describe and explain the (history of) mostly, but not exclusively, inanimate processes on Earth, and earth-like planets, and, when possible, predict future phenomena (*Kleinhans et al, 2005*).

The method of Earth Science involves two types of scientific explanation (*Kleinhans et al, 2005*):

(1) Reconstruction
(2) Causal reasoning

1.2.2 Reconstruction

A reconstruction consists of narrative of the actual sequence, drawn from the abduction from an earlier situation. The narration of the actual sequences is the historical aim of Earth Science. However, since reconstruction draws from the abduction from an earlier situation, earth-scientists often use the term “theory” in cases of hypothetical historical events (*Kleinhans et al, 2005*).

Earth-scientists have two methodological strategies in order to work with these abductions *(Chamberlin, 1890*):

(1) Inference to the best explanation
(2) Multiple working hypotheses

Unlike more fundamental science, Earth Science is characterized by explanatory pluralism, which entails that there are more explanations possible (multiple working hypotheses). These so-called theories are often empirically, but not logically, equivalent: they cannot be true at the same time *(Kleinhans et al, 2005).* It may never be known whether the best scientific explanation is also the one and only true scientific explanation, besides the fact that explanations accumulate over time. Perhaps the true one is not discovered yet (*Lipton, 1991*).

In Earth Science, the concept of parsimony is used, which is the power of the simplest explanation to explain a phenomenon (*Kleinhans et al, 2005*). For example, when the oldest layer is on top, instead of the youngest layer, the earth-scientist chooses the simplest explanation, which is that the ground has turned over once instead of trice (inference to the best explanation). The best theories are selected according to their consilience, simplicity, and analogy, i.e. simplicity x consilience = value (*Thagard, 1988*). A theory is more consilient when it explains more facts and simplicity requires the least assumptions and hypotheses necessary in order to explain the theory.

1.2.3 Causal Reasoning

Causal reasoning draws from the deduction from the present situation, based on the assumption that the present is the key to the past. The deduction from present situation, instead of abduction from the past, involves causal reasoning (*Hempel, 1965*). There is more to the narratives than merely description. It involves a causal space-time description of events and processes (*Salmon, 1984*). In general, theories or narratives in Earth Science explain the geological phenomena by the integration of robust-process explanations, actual-sequence explanations, observations, and background theories *(Kleinhans et al, 2005).*

1.3. Difficulties for Earth-Scientific Explanation

Kleinhans summarizes some of the major difficulties in Earth Science *(Kleinhans et al, 2005)*:

1. The timescale involved in shaping the earth is several orders of magnitude larger than the life of human observers of even written history. It is therefore problematic to detect and observe the long-term effects of slow processes that might be extrapolated to the past.
2. Many earth-scientific processes cannot (yet) be observed directly of even indirectly (deep-mantle convection, landforms, sediment deposits, erosion, mountain building, flooding)
3. Many processes are intrinsically random or chaotic, and may be very sensitive to initial conditions. Complex systems involve an infinite number of possible laws and initial conditions. Noise and chaos lead to a certain uniqueness of earth-scientific phenomena: exact duplications of events are seldom, and the probability that a phenomenon would occur or happen precisely the same the next time, is near zero.

The difficulty with earth-scientific explanations is that all events are unique to some extent, contrary to physical processes such as C14 decay. This process is exactly the same for all 14C atoms. Unique events are not recurrent: their significant properties are not shared by any other event or they are too chaotic and complex for effective comparison with other events (*Tucker, 1998*). Therefore, explanations of unique events are radically underdetermined, because any theoretical background that is relevant for their explanation is underdetermined (*Tucker, 1998*).

Earth-scientists seldom possess all the data necessary to give a complete reconstruction (*Frodeman, 1995*). A complete causal explanation is impossible in practise, if not in principle (*Kleinhans et al, 2005*). Earth-scientists are forced to fill in the unknown parts of the causal explanation (*Frodeman, 1995*). The uniqueness of events may require outrageous explanations (*Davis, 1926*), such as Wegener's concept of plate tectonics. Due to underdetermination problems, earth scientists often cannot provide ideal, complete causal explanations. However, well-grounded consensus on a historical narrative endorses real knowledge of the past, providing that the group that shares a consensus on beliefs should be based on scientific grounds, uncoerced, i.e. without social pressure, heterogeneous, and sufficiently large *(Tucker, 2004*).

As well as for reconstruction as causal reasoning, it is necessary in Earth Science to simplify for grids, discrete time steps, maps, diagrams, and models. According to Friedman, scientific theories provide understanding by unifying other theories and/or phenomena, relating (or reducing) unfamiliar phenomena to familiar ones, without imposing demands on the form of theories (*Friedman, 1974*). Kitcher adds to this the importance of seeing connections, common patterns, in what initially appeared to be different situations (*Kitcher, 1981*).

Unfortunately, earth-scientific principles cannot be reduced globally, because there are too many exceptions. All earth-scientific "laws" differ from the laws of physics and chemistry in the sense that their validity is less universal and more tied to the specific constellation of the planet in question. Even though specific earth-scientific laws can be reduced to physics or chemistry, the theories are typically hypotheses about unobservable (past) events or generalized, but not universally valid, descriptions of interwoven processes (*Kleinhans et al, 2005*).

1.4 Conclusions

Earth Science combines various logical techniques and her logic results from at least three complementary logical paths (deduction, induction, and abduction). The method of Earth Science involves at least two types of scientific explanation: through the reconstruction of the past and by causal reasoning from the present. In Earth Science there are usually more explanations possible (multiple working hypotheses) and the simplest explanation is often chosen as the best explanation (parsimony). Even thought each earth-scientific event is unique, earth-scientific phenomena often cannot be directly observed, and earth-scientific datasets are often underdetermined, a well-grounded scientific consensus can be reached.

Chapter 2 Earth-Scientific Understanding

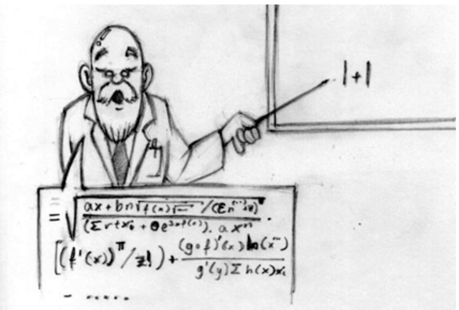

Figure 2.1. Graphic by Doruk Golcu. http://selections.rockefeller.edu/cms/science-and-society/bridging-the-gap-improving-science-communication.html (site visited 04-08-2010).

2.1 Introduction

The important difference between understanding and scientific explanation is that in scientific explanation phenomenon P is explained by theory T, whereas understanding involves a subject, such as a scientist.

In this chapter I aim to answer the second sub-question of this thesis: What is earth-scientific understanding? I will search the answer in the philosophy of science. I will elaborate on the criteria for scientific understanding, study theoretical and embodied understanding, and pose a critical point of view on the feeling of (apparent) understanding.

2.2 Scientific Understanding

Not all philosophers of science agree on the definition of scientific understanding. According to Aristotle (384 – 322 BC), a scientist understands an explanation, and thereby the phenomenon to which the explanation applies to, when the arguments and data that support the explanation are known. He states that having a scientific explanation is the same as having acquired scientific understanding. Dilthey (1833 - 1911) was one of the first to make the distinction between scientific explanation and understanding. According to Hempel, understanding is a just by-product of scientific explanations, implying that possessing explanations automatically leads to understanding the phenomena to which those explanations apply (*Hempel, 1965*). However, Leonelli argues that gaining understanding through explanations does not happen automatically, but is a cognitive achievement in its own right (*Leonelli, 2009*). To know something does not only mean comprehending it, but involves skill (*De Regt et al, 2009*). According to Salmon, knowledge of causal relations is crucial to scientific understanding (*Salmon, 1984*). This is because causal processes, causal interactions, and causal laws provide the mechanisms by which the world works; to understand why certain things happen, we need to see how they are produced by these mechanisms in order for the theory to become intelligible (*Salmon, 1984*).

The variation in types of understanding calls for a different approach for defining scientific understanding. There are different methods to gain understanding (*De Regt et al, 2009*). Therefore, De Regt and Dieks formulated criteria for scientific understanding.

2.2.1 Criteria for Scientific Understanding

• Criterion for Understanding Phenomena (*De Regt and Dieks, 2005*):
"A Phenomenon P can be understood if a theory T of P exists that is intelligible and meets the usual logical, methodological and empirical requirements".

A scientific theory may be considered unintelligible by some (in one scientific communication, at one time), but can also be regarded intelligible by others (or another time). Intelligibility is defined by De Regt as "the value that scientists, or a group of scientists, ascribe to the collection of qualities of a theory, in one or more of its representations, that make the use of the theory possible for building models" (*De Regt, 2009*). Theories may become more intelligible when we become more skilled in working with them (*De Regt and Dieks, 2005*).

• Criterion for the Intelligibility of Theories (*De Regt and Dieks, 2005*):
"A Scientific Theory T is intelligible for scientists (in context C) if they can recognize qualitatively characteristic consequences of T without performing exact calculations".

However, these proposed criteria do not spell out why and how an explanation provides understanding. Using an explanation requires understanding of that explanation, such as the ability to reason with a theory and to use it (*Boon, 2009*). Therefore, Boon formulated a criterion for understanding scientific fields.

• Criterion for Understanding Scientific Fields (*Boon, 2009*):
"Scientists understand a scientific field if they acquire the ability to use scientific knowledge of the field in developing explanations and predictions of other phenomena that are relevant to the field (including the ability to meet the methodological criteria of the field)".

2.2.2 Distributed Understanding

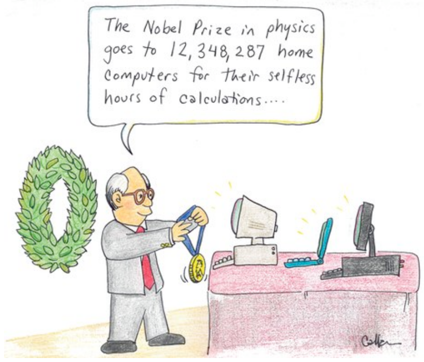

Figure 2.2*. Graphic by Callan Bentley.* *http://www.earthmagazine.org/earth/article/212-7d9-4-1e* *(site visited 04-08-2010)*

The process of acquiring understanding can focus on a single individual (*Hutchins, 1995*), thus making it a personal effort. Each person has the ability to gain some form or level of understanding (*De Regt et al, 2009*). The level of understanding, or the type of understanding, may differ, depending on skills and commitments (*Leonelli, 2009*), but can still contribute to scientific understanding as a whole.

The process of acquiring understanding can also focus on an individual working with a set of tools (*Hutchins, 1995*). No one human can physically do all the things that must be done, know everything that can be known, and/or understanding everything that can be understood. At some point, everyone reaches a level that is not understandable any more (*Dieks and De Regt, 1998*). The human mind cannot understand theories in all their complexity and therefore may use models (*Kleinhans et al, 2010*). It is impossible to know all the digital and online data and formulas (*Leonelli, conference 2010*).

Finally, the process of acquiring understanding can focus on a group of individuals, interacting with each other and with a set of tools (*Hutchins, 1995*). Hutchins introduced the concept of distributed cognition (*Hutchins, 1995*), claiming that scientific knowledge is distributed over many individuals, with instruments and other artefacts as part of the cognitive system. Each scientist contributes to a research with his or her strengths. One scientist may know more of a specific theory than another scientist in the same discipline. The form, level, and quality of earth-scientific understanding acquired by individuals depends on their skills (*Leonelli, 2009*). Each individual can gain some, and contribute to, earth-scientific understanding. Thus, scientific understanding involves distributed understanding. However, a level of trust in the data is necessary (*Leonelli, conference 2010*). Scientific knowledge cannot be disconnected from the people; it's acquired socially (*Van Woerkum, 1999*).

2.2.3 The Feeling of Understanding

The previous sections discuss criteria and ways to gain scientific understanding. However, does a scientists understand a theory when he gained the feeling of understanding?

The Greek scientist Archimedes (287 – 212 BC) tried to determine whether the king's crown was made of solid gold or not. It could have been mixed with silver. Archimedes knew the weight of gold and silver per unit volume, but did not know how to measure the volume of a complicated object such as a crown. One day, he noticed the water level rose when he lowered himself into the bath. "*Eureka!*" Archimedes found an answer to his problem. Unfortunately, the feeling of understanding is not necessarily accompanied by actually gaining scientific understanding.

Understanding is a form of knowledge, whereas the feeling of understanding is not (*Lipton, 2009*). The feeling of understanding ("Aha!") has no relation to whether that understanding is reliable or truth-conducive and therefore we should distinguish between the feeling of understanding and understanding itself (*Ylikoski, 2009*).

According to Lipton, the "aha" feeling plays important role in the way understanding is acquired (*Lipton, 2009*). The desire for understanding is the main motivation for doing science (*De Regt et al, 2009*). Gopnik argues that the "aha" feeling to explanation is as an orgasm to reproduction. We construct and use theories to achieve explanation and the pleasant "aha" feeling is an affect of activities that lead to understanding, motivating us in doing science (*Gopnik, 2000*). However, Lipton argues that the feeling of understanding may not only serve as a motivation, but also plays a role in selecting explanations in the context of inferences to the best explanation, since the strength of the feeling may be used as a symptom of explanatory quality of the theory (*Lipton, 2009*). A theory is more intelligible when it has a higher explanatory quality. Scientists prefer a more intelligible theory to a lesser one, because they are able to use the theory (*De Regt, 2009*).

It seems that the "aha" experience should not be understood as "I understand the explanation" but merely implies "I've discovered a new approach". Whether this approach will turn out to be productive can only be decided after the fact. Either way, it is useful in the process of achieving understanding.

2.3 Theoretical and Embodied Understanding in Earth Sciences

> *"To be is to do"* - *Socrates*
> *"To do is to be"* - *Sartre*
> *“To be or not to be”* - *Shakespeare*
> *“To-do leads to to-be and gives Aha!”* - *Sara Voûte*

One way to understand the processes of the Earth is to understand earth-scientific explanations (theoretical understanding). Theoretical understanding consists of knowledge of facts, theories, explanations, and concepts, visualized by diagrams, mathematical representations, computer programs, simulations, and/or modelling tools (*Leonelli, 2009*). The phenomena are available independently of specific procedures or ways of acting, and require theoretical skills, in order to master how it works and being able to manipulate it towards an understanding of a phenomenon (*Leonelli, 2009*). However, we do not understand the occurrence of a storm merely by referring to the barometer’s indication (*Friedman, 1974*). One can memorize a principle and have all background conditions available, but this knowledge does not have to lead to understanding the principle. One may still be unable to use this knowledge. Therefore, scientific knowledge involves more than knowing the theory. To-know implies not only to-possess theoretical knowledge, but also to-be-able-to-use it toward understanding actual phenomena.

The ability to use theoretical knowledge to that aim is made possible with embodied knowledge (*Leonelli, 2009*). Embodied understanding consists of the awareness on how to act and reason and requires the ability to intervene, instead of explaining or predicting, to acquire control, to explore and modify (*Leonelli, 2009*). Understanding is impossible without embodied knowledge from direct interaction with the environment, including laboratory (*Leonelli, 2009*). Embodied understanding is pragmatic and non-objective. Pragmatic understanding of theories is necessary in order to reach scientific understanding, because it enables to construct models (*De Regt, 2009*).

Earth-scientific knowledge has a dual nature, containing both theoretical and embodied components. A farmer need not be earth-scientifically schooled, but can still gain a level of earth-scientific understanding by working the land and experiencing the effects of heavy rainfall or drought. The farmer’s embodied understanding can be of great use for an earth-scientist, who often comes to the farmer’s advice. The earth-scientist might be earth-scientifically schooled, but lacks the practical knowledge and understanding, which is also part of earth-scientific understanding. It is possible to work with theories, manipulate formulas and symbols, memorizing tricks, or using computers, without possessing understanding, but it is also possible to understand a theory without being able to make precise calculations (*De Regt and Dieks, 2005*). According to Leonelli, it is important to combine theoretical understanding (“knowing what”) and embodied understanding (“knowing how), since theories and explanations are just as important as the ability to use this knowledge and apply it (*Leonelli, 2009*).

Understanding natural phenomena by means of theoretical knowledge requires some embodied knowledge to apply explanations to reality and embodied knowledge needs to be coupled with theory-informed interpretations to know how it works and to provide understanding (*Leonelli, 2009*). Achieving earth-scientific understanding entails not only to possess theoretical knowledge, but also to be able to use it. It requires skills. For example, skill allows biologists to materially intervene with and reason about the world (*Leonelli, 2009*). The same applies to geologists.

2.4 Conclusions

Earth-scientific explanation is not the same as, and does not automatically lead to, earth-scientific understanding. However, intelligibility is a requirement, in order to comprehend the theory and earth-scientists do gain theoretical earth-scientific understanding based on earth-scientific explanation. There are two different ways in which the term “understanding” is connected to “scientific explanation”:

(1) Theoretical understanding - to be able to use a theory and understand a phenomenon by having an adequate explanation of the phenomenon.
(2) Embodied understanding - to understand a theory based on skills (pragmatic and non-objective), by having the ability to reason with a theory, to use it, and to intervene in it.

Integrated understanding consists of a balance between exercise and coordination of theoretical and embodied knowledge. Therefore, I conclude that combining theoretical and embodied understanding, through reconstruction and causal reasoning, leads to the best earth-scientific understanding.

Chapter 3 Geo-Tools to gain Earth-Scientific Understanding

3.1 Introduction

In this chapter I aim to answer the third sub-question: How does an earth-scientist gains earth-scientific understanding? Earth-scientists use a broad suite of tools, in order to achieve earth-scientific understanding, while combining theoretical and embodied components. There is no universal way to reach understanding, but specific tools can be introduced for particular situations, which help scientists to enhance understanding (*De Regt and Dieks, 2005*), and methods may differ between individual scientists and disciplines.

In order to understand a phenomenon, one must also understand the tools that are used (*Ylikoski, 2009*). Tools, such as visualization, abstract reasoning, familiarity, simplicity, and causality, might lead to achieving an understanding of the world (*De Regt and Dieks, 2005*), but they do not guarantee that such an understanding will be truthful (*De Regt et al, 2009*). These tools are “developed” through constant intervention in the material world. Therefore, they are not merely cultural trends or social settings (*De Regt et al, 2009*) and can say something about reality.

The earth-scientific toolbox contains at least three categories of geo-tools. In this chapter I will elaborate on a case study of a geological investigation (*Figure 3.1*) and review the role played by visualization, used in symbols and diagrams, and the use of other senses, during experiments, simulations, and fieldwork. These are all activities through which an earth-scientist achieves understanding. In order to be able to achieve understanding, it is necessary to know how to use the tools, i.e. to have skills (*De Regt and Dieks, 2005*). The tools available for scientists depend on the (historical, social, and/or disciplinary) context in which these scientists live and work (*De Regt and Dieks, 2005*).

3.2 An example of an Earth-Scientific Research

A man goes into a restaurant, sits down and starts reading the menu. The menu says:

Broiled Accountant	*5.95 per plate*
Fried Engineer	*7.95 per plate*
Toasted Teacher	*7.95 per plate*
Grilled Geologist	*25.95 per plate*

The man calls a waiter over and asks: "Hey, why does the Grilled Geologist cost so much?"
The waiter says, " Are you kidding? Do you know how hard it is to clean one of them?!?!"

What is it that earth-scientists get their hands dirty on? Earth-scientists do more than just picking up rocks during a sunny day in beautiful natural surroundings. An earth-scientist clambers around, sketches the landscape, takes samples, does compass measurements, writes down notes in a fieldbook and/or draws them on a map, and changes his or her plan according to circumstances. All of this is related to, and relevant for, a specific research. Different earth-scientists may study some sites for decades, in order to solve an earth-scientific problem.

In this section I will elaborate on a case study of an (example of) earth-scientific research and link the specific steps to scientific explanation and understanding. My focus will be on geological fieldwork. Geology is a discipline within Earth Science that focuses on plate tectonics and mountain building. I made the upcoming diagrams and examples when I participated in geological fieldwork simulations in the Eifel volcanic park in Germany and the

Mars Desert Research Station (MDRS) in Utah (*Voûte, 2010*). I developed general protocols at Martian and Lunar analogue sites for doing geological fieldwork (*Figures 3.1 and 3.2*), which may be useful to follow by astronauts with minimum geological training.

Geological research can basically be subdivided into seven steps (*Figure 3.1*). Once the goal of the research is defined (1), based on theoretical research, a geologist collects all the data that is needed. A general site survey will be done (2), in order to assess the different options for accessible, feasible, and interesting sample sites. The geologist decides where to go in the field during the specific site survey (3) and starts systematic sampling (4). The samples will be analysed (5), depending on the possibilities and necessities. The data will be analysed by the geologist (6) and a full interpretation will be made, based on observations and results (7). Finally, conclusions will be drawn from the interpretations. Each step needs some type of understanding, in order to make relevant and efficient decisions.

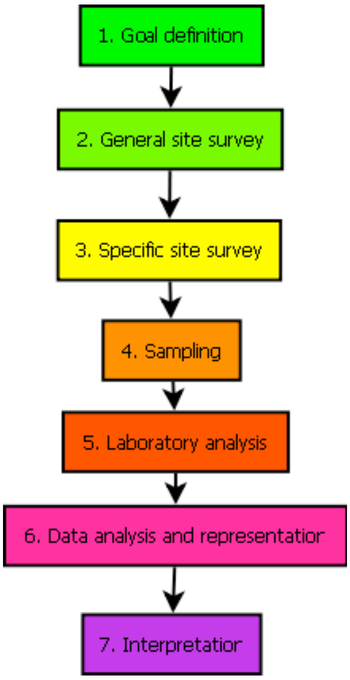

Figure 3.1. This flowchart is a summary of the overall and detailed flowchart (Figure 3.2), in which the basic steps of an example of a geological fieldwork are visualized (Voûte, 2010). Note that step 6 and 7 can loop back to step 4. Figure 3.2 elaborates on more loops.

3.2.1 Goal Definition

Before the start of each research the goal needs to be defined. The main goals of a geological field expedition or analysis can be roughly divided into three categories (*Figure 3.3*):

- Geological survey
- Scientific fieldwork
- Exploratory fieldwork

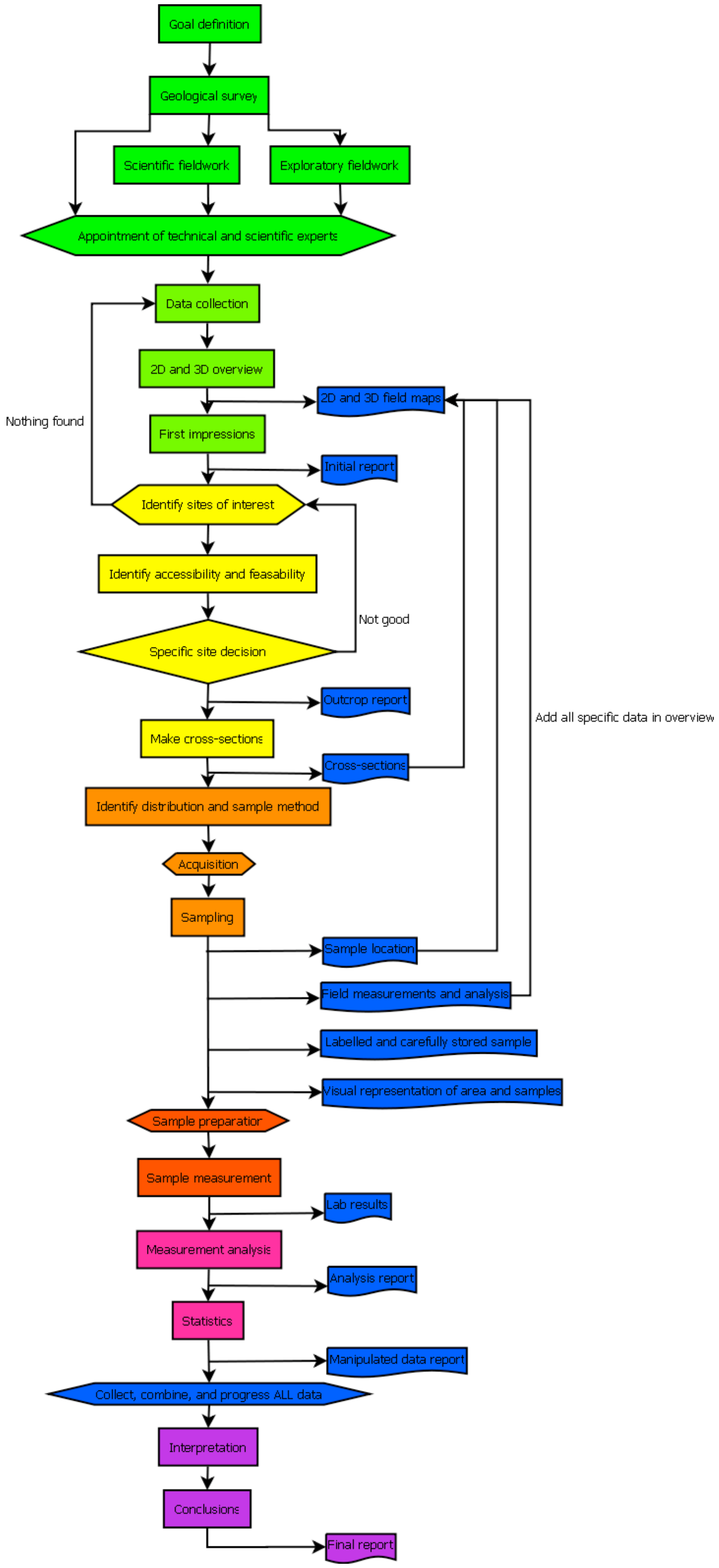

Figure 3.2. This flowchart shows a stepwise overview of a possible procedure of doing a geological research, and is the extended version of Figure 3.1. Squares represent processes, squares with side-points represent actions, diamonds represent decisions, and the blue figures are output files. Each colour represents a different general step in the procedure, which are explained in more detail in the sections of this chapter. Note that the flowchart works from large scale to small scale, with some loops back to large scale, in order to place details in the bigger picture.

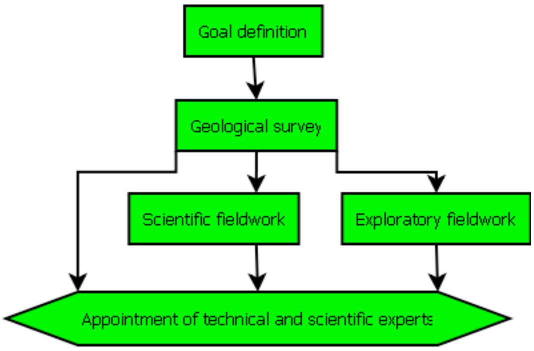

Figure 3.3. *This flowchart is part of the overall flowchart (Figure 3.2), and highlights the basic actions involved in the first step of geological research: goal definition (Voûte, 2010).*

When the main goal is scientific of exploratory fieldwork, a geological survey is always needed when this has not been done before, in order to visualize the concentration of information that might be found in the area, its accessibility, and feasibility for further (scientific or exploratory) fieldwork. Information about geological structures, topography, morphology, and lithology are essential. Scientific fieldwork entails specific investigation and hypotheses testing, through sampling, in the name of collecting knowledge, whereas exploratory fieldwork aims to find new resources for exploration. Theoretical understanding is used to form a research goal and develop a plan of approach for the upcoming research: adding scientific information to the reconstruction of the past by abduction, which could include an exploratory fieldwork.

3.2.2 General Site Survey

A general site survey (*Figure 3.4*) entails background research, necessary to set-up a geological background overview and the collection of several maps of areas of interest. Sites need to be assessed on where the goal is most likely to be fulfilled. The region should contain an (expected) abundance of the type of rocks you want to investigate, with the wanted samples scattered around in good concentration, well preserved, and as clean as possible (*Westall et al, 2000*). Other site requirements are good visibility and accessibility.

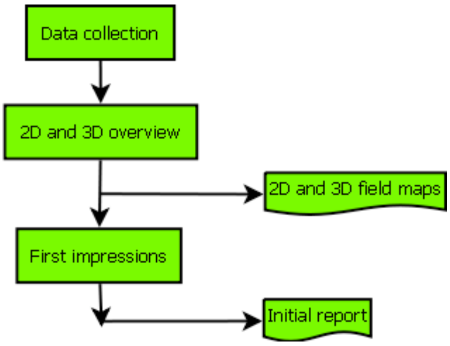

Figure 3.4. *This flowchart is part of the overall flowchart (Figure 3.2) and highlights the basic actions involved in the second step of geological research: general site survey (Voûte, 2010).*

3.2.3 Specific Site Survey

Based on the research goal and general site survey, sites of interest need to be found through which the goal can be achieved and problem areas might be identified (*Figure 3.5*).

For specific site planning, a map of 1:50.000 is preferred, in combination with a large-scale map, used to gain an overall understanding of the area and choose optional sites. The level of understanding increases stepwise.

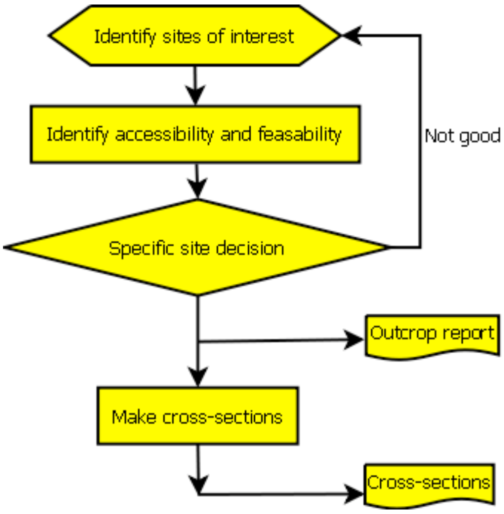

Figure 3.5. *This flowchart is part of the overall flowchart (Figure 3.2) and highlights the basic actions involved in the third step of geological research: specific site survey (Voûte, 2010).*

3.2.4 Sampling

After all the preparations, the earth-scientist can go into the field (*Figure 3.6*) and take samples, or measurements, depending on the research question. During sampling, it is essential to locate and document the visited and sampled sites (*Table 3.1*). Accurate maps and profiles can only be constructed when sampling locations are well documented. Figure 3.7 shows how easy it is to confuse structures without a scale-reference. Figure 3.8 shows the importance of adding a frame of reference when noting down the location of the sampling site. In order to take relevant samples and sample efficiently, three main subjects are important when sampling (*Westall et al, 2000*): (a) distribution, (b) acquisition, and (c) preparation.

The distribution (a) of specific sample locations is usually based on the interpretation of a topographic map and a geological map. It is essential to take enough samples, in order to be able to do several tests on the same rock and to prepare a back up for the results. A back up is necessary to show that the results are consistent. Sampling too much is only time-consuming.

Three main sampling procedures can be defined (*Vriend et al, 2005*): (1) Random sampling, (2) Grid sampling, and (3) Judgement sampling. Random sampling (1) involves sample locations that are located randomly over the area. This type of design is useful when no information about the area is a priori available and in order to get an unbiased impression. Grid sampling (2) involves sample locations that are located in a grid with spacing of equal distances. This type of sampling is very labour intensive but useful in order to make a continuous map of the area. Judgment sampling (3) is based on a priori knowledge about the area, when specific locations are chosen. This approach is logistically favourable and can be used to study a specific part or system within the area. However, it obviously results in biased estimates. A combination of random and judgment sampling is often applied.

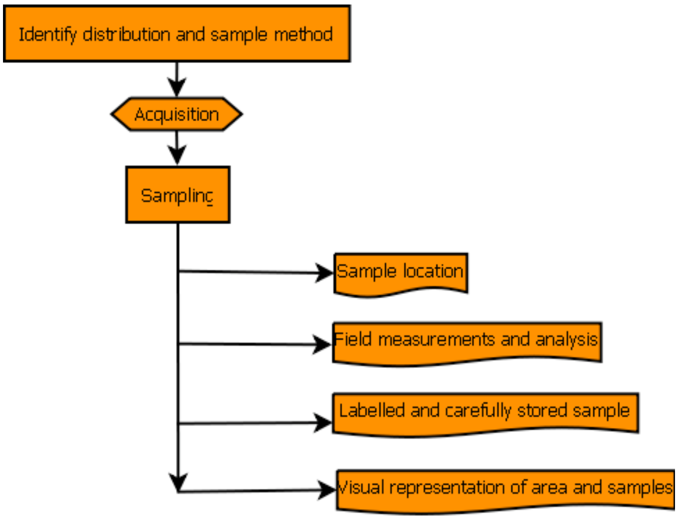

Figure 3.6. *This flowchart is part of the overall flowchart (Figure 3.2) and highlights the basic actions involved in the fourth step of geological research: sampling (Voûte, 2010).*

Best practise in geology touched earth-scientists that each sampling procedure involves taking extra samples at intervals. These so-called “field duplicates” are collected close to the original sample location, commonly within 100m and thus basically at the same map location. Usually every 10th sample location is sampled in duplicate, which should be meticulously recorded. This is done as a check for consistency. If the results of the duplicate often do not correspond to the results of the other sample near the same location, there probably is something wrong with the measuring protocol or instrument, but could also be due to an anomaly in nature.

Table 3.1. *Example checklists for field observation and documentation. From kn-scale (overview description), tot tens of m-scale (location description), to dm and mm-scale (sample description).*

1. Overview description	2. Location description	3. Sample description
GPS	GPS	GPS
Regional (*formation, lithology, colours…*)	Local (*formation, lithology, colours*...)	Specific description:
Layers (*number, colour, size*...)	Layer measurements (*strike, dip*...)	Type (*rock, soil, geo, bio*...)
Size and scale	Size and scale	Size and scale
Structure	Structure	Structure (*layers, laminations, orientation…*)
Estimated distance…		Rock (*sedimentary, igneous, metamorphic*)
Direction of view		Texture (*grain size, grain form, porosity…*)
		Mineralogy
		Other properties (*hardness, density…*)
		Label
		Method (*hammer, drill, scraping…)*

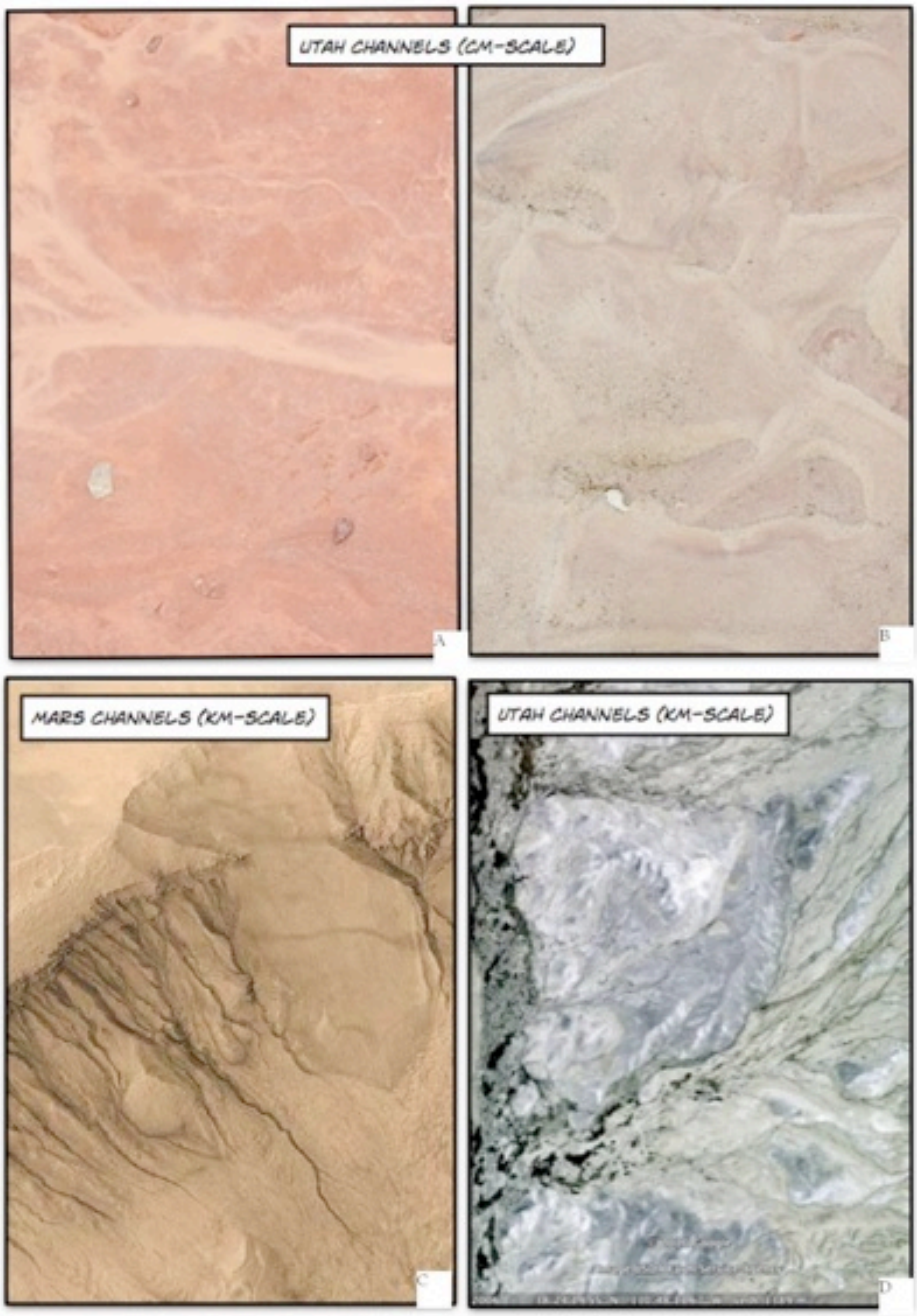

Figure 3.7. *From left to right and from top to bottom: Pictures 3.7a, 3.7b, 3.7c, and 3.7d. Pictures 3.7a and 3.7b were taken during Extra-Vehicle Activities (EVA's) around the MDRS Habitat, taken by me. Cm-scale channels can be seen. Picture 3.7c shows Martian channels on km-scale, taken by the Mars Global Surveyor Orbiter (http://www.nasa.gov/multimedia/imagegallery/image_feature_016_prt.htm). Picture 3.7d shows Utah channels on km-scale, taken from Google Earth, just west of the Habitat, of the Skyline Rim. Note that without a scale references, differences between cm and km-scale are difficult to see. It's hard to distinguish Mars from Utah.*

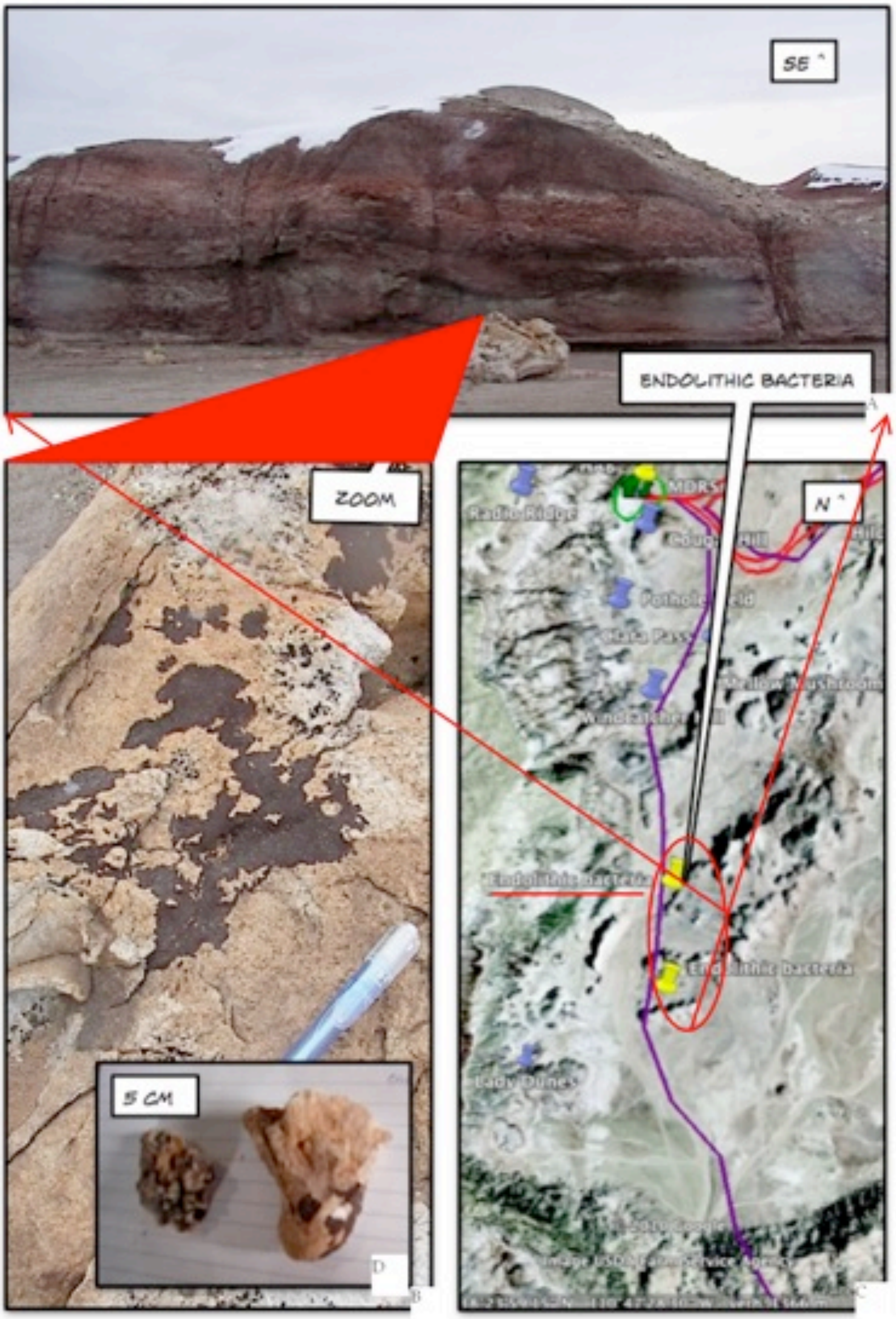

Figure 3.8. From top to bottom and from left to right: pictures 3.8a, 3.8b, 3.8d, and 3.8c. Picture 3.8c shows the planned traverse done beforehand with Google Earth towards the southern river (purple path). In the top north the MDRS Habitat is visible and in the bottom south the Kissing Camel Range, covering an area of approximately 1km. Picture 3.8a shows the loose block where scattered endolithic bacteria can be found. I took the picture. Point of direction is towards the southeast. The block was around 2m broad. Picture 3.8c is a close-up picture of the endolithic bacteria, with a pen as scale reference. Picture 3.8d shows the samples taken from the rock with the endolithic bacteria. I took both pictures. The samples have a length of 2-5cm.

The acquisition (b) of the samples should be done in teams of two, for safety reasons. Whatever sampling technique used, or whichever geological goal is defined, without knowing exactly where a sample is coming from, results are useless. A loose rock could come from anywhere and doesn't have to be connected to the direct area. The notation of the location of the samples is of the utmost importance. By taking photos of the whole outcrop (large-scale) and of the sample (small-scale), the location of the sample can be illustrated.

For the preparation (c) of samples, the samples need to be fresh. This means the samples should be free of weathering or dust. Fresh samples can be attained by hammering or by core drilling. For some measurements it is necessary to measure the orientation of the sample, in order to preserve information about its original position in the outcrop.

3.2.5 Laboratory Analysis

In the field a geologist can gain insight in the relative timing of events and the relative age of the different lithologies that might be found (causal understanding). In the laboratory the geologist can gain insight in the absolute timing of events and the absolute age of the different lithologies that might have been found (reconstruction). Several laboratory tests can be done, depending on your research question (*Figure 3.9*).

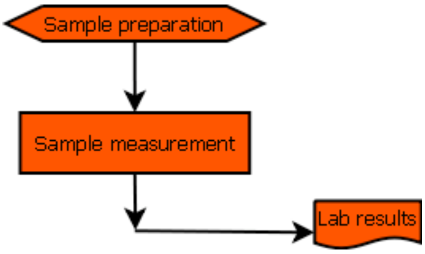

Figure 3.9. *This flowchart is part of the overall flowchart (Figure 3.2) and highlights the basic actions involved in the fifth step of geological research: laboratory analysis (Voûte, 2010).*

3.2.6 Data Analysis and Representation

Data obtained from the laboratory analysis should be analysed (*Figure 3.10*) and the results should be combined with the field observations. Data analysis leads to the induction of observations to generalisations, which happens during the interpretation.

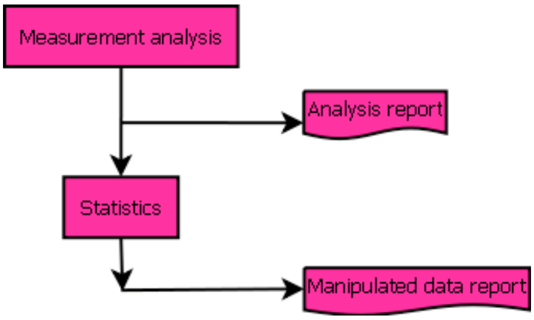

Figure 3.10. *This flowchart is part of the overall flowchart (Figure 3.2) and highlights the basic actions involved in the sixth step of geological research: data analysis and representation (Voûte, 2010).*

3.2.7 Interpretation

Interpretation occurs on every stage of the research. However, at the end of the research, an earth-scientist is ready to make a synthesis the data and attempt to prove or disregard the hypothesis. Interpretations should take into account data quality, variations, results, discussions, conclusions, and mapping (*Vriend et al, 2005*).

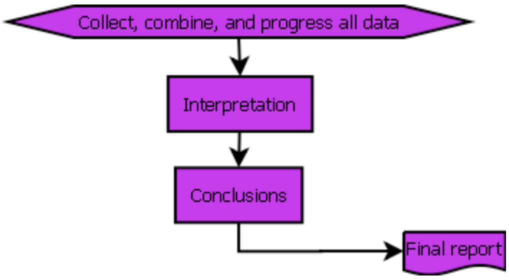

Figure 3.11. This flowchart is part of the overall flowchart (Figure 3.2) and highlights the basic actions involved in the seventh, and final, step of geological research: interpretation (Voûte, 2010).

3.3 The Geo-Toolbox

In the case study at least three categories of geo-tools are encountered on: objective descriptive geo-tools, subjective descriptive geo-tools, and geo-tools that require integrated understanding. Knowing where and how to use these tools are the required cognitive abilities to gain understanding (*Boon, 2009*). Each geo-tool may lead to (different levels of) understanding, such as the embodiment of the earth-scientific explanation and different tools might be used to gain the same understanding. Some geo-tools can be used in several different steps of an earth-scientific research.

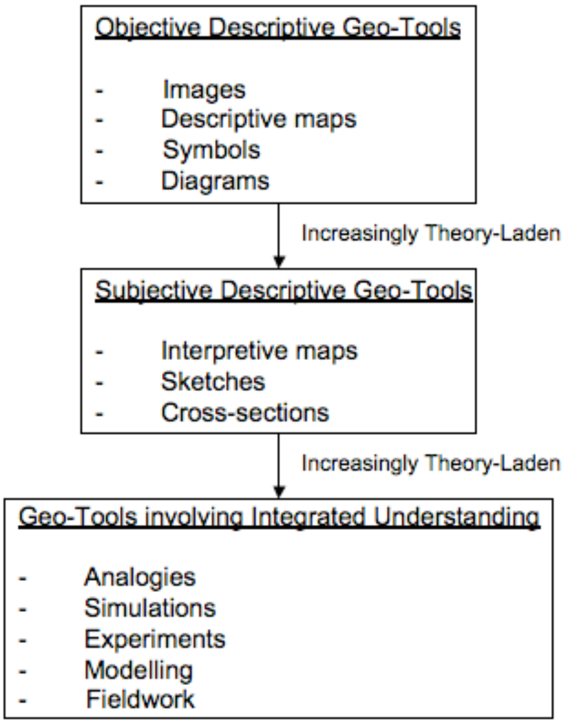

Figure 3.12. The three categories of geo-tools.

I made no set distinction in the hierarchy and sequence of the geo-tools within the three categories. However, these categories are sequential to one another and are increasingly theory-laden (*Figure 3.12*). Theory stops being merely a premises and developing new theory becomes a goal with the geo-tools that require integrated understanding.

At the end of an earth-scientific research, a collection can be made of all the maps with symbols, images including diagrams and remote sensing data, and results acquired from simulations, fieldwork, experiments, and modelling. With the help of analogies, sketches, and cross-sections, all the data can be categorized and classified. During the process of earth-scientific research, the scientist has achieved (different levels of) theoretical and embodied scientific understanding through different methods of explanation.

3.3.1 Objective Descriptive Geo-Tools

In the case study four objective descriptive geo-tools are encountered on: images, maps, symbols, and diagrams. These geo-tools are used since the beginning phase of an earth-scientific research and require little theoretical background. Understanding is enhanced by, or even partly consists of, visualization (*Dieks, conference 2010*). Even though visualization is but one of the many possible tools for achieving understanding, it is one that has proven to be very effective in science (*De Regt, conference 2010*). Visual reasoning and imagination are often used as routes towards understanding and the pictorial language is at the heart of earth-scientific communication, such as symbols and diagrams. Visualizations play a fundamental role in scientists' causal reasoning about mechanisms and in determining the phenomenon to be explained, through which we can gain experimental evidence about the functioning of the mechanism and understand how the mechanism is produced (*Bechtel, conference 2010*). Visualizations are sources of understanding without explanation (*Lipton, 2009*).

Images

Images can be true to nature, such as pictures and films. Others can be focussed on structure and show a simplified image of reality by leaving details out or exaggerating rock layers, visualizing concepts and relationships. Both types of images can enhance the understanding of a situation, whereas structural images may enhance understanding of spatial information (*Verduin-Miller, 1964*). For example, remote sensing is the observation, or the collection of information, of object with an instrument that has no direct contact with the observed object. In Earth Science this technique is used to collect data of the surface of the Earth, by means such as satellites, air balloons, or ships. Aerial photographs are photographs taken of a ground area from an elevated position, such as from a plane, helicopter, or balloon. Two pictures are taken of the same area from different angles and with the help of a stereoscope or anaglyph a 3D image of the area can be viewed. Stereography is a very useful tool in structural geology and used to see depth and represent 3D orientation data in a 2D graphical form (*McClay, 2008*). It is commonly used to solve problems involving the angular relationships of lines and planes in 3D space. The same can be done with satellite images. This technique is very useful for tracing beds, faults, folds, and other geological features (*McClay, 2008*), i.e. for making interpretive maps. Remote sensing provides a relatively new step in visualizing the world, with instruments such as TomTom, Google Earth, and Virtual Earth.

Descriptive maps

Geologists use several maps during geological fieldwork. At base camp, the geologists keeps a fact map, on which all the facts will be noted, and neat map, which is the clean version of the field map. At the end of each day, newly gained information should be evaluated by noting down the new facts. During a geological survey, the goal may be to develop topographic maps. Topographic maps give information about scale, elevation, contour intervals, and magnetic deviation. There are other types of maps, such as road maps, overview maps with a big scale and generalised information, and theme maps with a specific subject, i.e. geology, water, or destinations. Each map has its own scale. Maps can give instant information about the location of physical phenomena, patterns, and processes. A map can show the orientations, concentrations, correlations, and spreading. The Geographical Information System (GIS) offers a computer system that links and structures spatial and non-spatial data, and allows it to save, maintain, manipulate, analyse, and reproduce the useful information. This technique is now widely used for the production of digital maps. Even though maps are objective descriptive, they are theory-laden.

Symbols

Mathematical representations, or symbols, provide a level of understanding and explanation that is sometimes impossible by other forms of description and investigation *(Morrison, 2009).* Symbolic representations mean that the phenomena can be modelled, conceptually and mathematically, and therefore general relationships can be established and tested between systems *(Inkpen, 2005).* Symbols can be used in equations, but also increasingly theory-laden in maps.

Diagrams

A diagram is an analogue image, showing one phenomenon in a simplified way. This could be done with circles, arrows, and bright colours. Diagrams exist in many forms, such as qualitative diagrams, which visualize concepts and (3D) processes, and quantitative diagrams, which visualize data. There are different types of diagrams, such as bar charts, block diagrams, size charts, line charts, curve diagrams, scatter diagrams, flowcharts, and image graphs. Understanding the development of a process can be enhanced with a diagram (*Verduin-Miller, 1964*), by transferring geographical reality into a schematic drawing or model, such as a climate diagram. A list of numbers may only have a meaning when processed in a diagram. Diagrams enable scientists to keep track of specific details within a mechanism and how they are organized. With diagrams, the behaviour of a proposed mechanism can be simulated, either mentally or mathematically, or a combination of these two (*Bechtel, conference 2010*).

3.3.2 Subjective Descriptive Geo-Tools

During a geological survey, the goal may also be to develop geological maps, which cannot be stated as purely objective and thereby are increasingly theory-laden. In the case study two subjective descriptive geo-tools are encountered on: sketches and cross-sections. These geo-tools are generally included in the preparation of geological fieldwork and used during the fieldwork itself. They are based on objective observations, but personally drawn. Sketches and cross-sections of observations simplify the phenomena and help earth-scientists understand the phenomena. Observations generate causal information (*Lipton, 2009*).

Interpretive maps

Geologists use an interpretation map on which the exact location of the samples is indicated, preferably supplemented with photographs and sketches in the fieldbook (a notebook used in the field). An interpretation map may result in a geological map. Geological maps give information about geological structures and lithology.

Sketches

Sketching structures in a fieldbook helps the geologist to take a closer look at the structures, visualizing and connecting the observation, and making the first step towards interpretation and understanding. Making sketches of an outcrop forces the geologist to look more closely and more information might be gained from the outcrop, which might be overlooked when just taking a picture. On sketches and pictures, the point of view (north, east, south, west) should be indicated, and a scale reference should be used, such as a hammer, a coin, or a person *(McClay, 2008).* They differ from diagrams in their subjectivity.

Cross-sections

Cross-sections are images (increasingly theory-laden) that are focussed on structure. By making cross-sections, a vertical slice of the terrain will be drawn and interpreted. Cross-sections are an essential part of a structural synthesis of structural geology (*McClay, 2008*).

3.3.3 Geo-Tools involving Integrated Understanding

In the case study five geo-tools, which involve integrated understanding, are encountered on: analogies, simulations, experiments, modelling, and fieldwork. These geo-tools enhance the embodied understanding of the earth-scientist. The level of understanding depends on the relevant skills and theoretical background an earth-scientist already possesses. These geo-tools are sources of understanding without explanation (*Lipton, 2009*), providing earth-scientists and students with a feeling for the protocols, research techniques, and procedures during simulations. They also permit a greater understanding of a theoretical structure. By applying theoretical structures to specific situations or contexts, such as a field location, an earth-scientist can identify the parameters and limits of the theory and compared them to the practise (*Inkpen, 2005*).

Analogies

Analogies have often played an important role in the history of science. Understanding a complex system or abstract mechanism can be done by relating it to a simpler system (*Held, 2005*) or compare it with familiar mechanisms (*Russ et al, 2008*). For example, scientists expanded their knowledge of gases by comparing the molecules to billiard balls or enlarged their understanding of the heart by comparing it to a pump.

Simulations

Simulations provide understanding and a feeling for consequences (*Lenhard, 2009*). There are different types of simulations. Usually they entail representing the reality in a simplified form, by using images and symbols. Simulations are not per definition visualization, but can be computational too, in experiments, models, or enhance embodied understanding, in virtual reality, or fieldwork.

Experiments

Experiments are an important scientific activity and experimentation is complementary to fieldwork and modelling (*Leonelli, 2009*). The classical role of experiments is testing hypotheses in controlled laboratory settings (*Cleland, 2002*). They involve to some extent the same materials as nature *(Morgan and Morrison, 1999*), but with much better accessibility (*Kleinhans et al, 2010*). Experiments allow us to obtain a feeling of what happens (*Kleinhans et al, 2010*), and they offer countless possibilities for exploration and surprising results (*Leonelli, 2009*). Therefore, they enhance embodied understanding, by applying theoretical understanding. Feeling and manipulating the material in experiments adds insight to observation and modelling (*Kleinhans et al, 2010*). Experimentation is a very effective way to combine embodied and theoretical knowledge into a deeper integrated understanding (*Leonelli, 2009*). Experiments may lead to new ideas and hypotheses (*Hopp et al, 2009*). Hypotheses formed during an experiment are mostly gained through abduction (*Kleinhans et al, 2010*).

Modelling

Models make the connection between theory and phenomena, in scientific practice (*Morgan and Morrison, 1999; Knuuttila and Merz, 2009; De Regt, 2009*). Models are other tools by which theories can be made visible in an abstract, idealized, and simplified way (*Held, 2005*) and through which predictions can be made (*Inkpen, 2005; Morgan and Morrison, 1999*), while representing a phenomenon or physical system (real, fictional, or ideal) that is aimed to be understood scientifically (*De Regt, 2009*). A model is used to test whether a hypothesis does not conflict with the laws of physics (*Oreskes et al, 1994*) and the model results can be compared to the observations (*Kleinhans et al, 2005*). Models are extremely useful to study the sensitivity of results to certain parameters and to explore the viability of hypotheses (testing multiple working hypotheses) given certain laws of nature (*Oreskes et al, 1994; Kleinhans et al, 2005*). They are “instruments of investigation” (*Morgan and Morrison, 1999*). Models come in different types: theoretical (in mathematical language), simulations, experiments, or computational (such as weather forecasting and earth simulating models) (*Lenhard, 2009*). Simulations enhance understanding of modelled phenomena, mechanisms, and/or processes, by gaining (virtual) experience of the unreachable. During simulations, scientists try different theoretical assumptions and gain a familiarity with how a certain model behaves (*Lenhard, 2009*). Experiments validate existing models in order to form a basis for further testing hypotheses, and quantify relationships and mechanisms (*Hopp et al, 2009*). Computer simulations of reality are another way to probe the operation of reality (*Inkpen, 2005*). The model with the least parameters is the most accurate and least uncertain (*Van der Perk, 1997*). The process of modelling requires imagination, inspiration, creativity, ingenuity, experience and skill (*Savenije, 2005*). Model-based reasoning involves the manipulation and modification of models (*Leonelli, 2009*). However, no matter how useful a model could be, if a researcher cannot use it because he or she lacks the relevant skills, it is useless (*Leonelli, 2009*). Therefore, modelling enhances embodied understanding, but requires a high level of theoretical understanding. Modelling develops mechanism-based explanation (causal reasoning) and a reconstruction of phenomena.

Fieldwork

Fieldwork in the earth-scientific sense means going into the field to collect samples and obtain information that cannot be obtained by other means. It provides a unique experience within earth-scientific research. Fieldwork helps to bring theoretical knowledge and previously mentioned geo-tools into practise, and therefore enhances both theoretical and embodied understanding. During fieldwork all the senses are used: seeing, feeling, tasting, hearing, and smelling. The abstract becomes concrete and it provides an understanding that does not entirely needs explanation. It is a very important and powerful tool in earth-scientific research.

During sampling, measurements of the lithology and geological structures might be done. Examples of geological features are faults and folds. Categorization is a tool to structure and interpret the world, usually based on a standard protocol. Detailed tables and systems exist for determining rock samples. Structuring the world is a basic cognitive need, because without this activity the world would appear disordered and random to us (*Boon, 2009*). The sample needs to be described in detail. Rock type and mineralogy are needed for defining the stratigraphy. Classification is a research tool, and therefore an aid to interpretation. It is a useful tool for a researcher, or a group of researchers, rather than a determination of the absolute structure of the world (*Inkpen, 2005*). Deformation of minerals (*Fry, 1997*), i.e. rotation, shearing, flattening, folding, and faulting, can give insight in the relative timing of events and the relative age of the different lithologies that might be found (*McClay, 2008*). Change in mineralogy can indicate change in grade of metamorphism (*Fry, 1997*). Field measurements of geological structures can be plotted in stereographic projections, such as Wulff net or Smidt net (abstract visualization). Stereographic projections visualize geological structures (*McClay, 2008*).

3.4 Disciplinary Differences within Earth Science

Earth Science can be subdivided into several different disciplines, such as: geology, geophysics, hydrology, physical geography, meteorology, and planetary geology. These different disciplines interact, and even though there are many similarities between the disciplines, each discipline uses their own tools for achieving understanding. Every field shows variation; within departments, between departments, and even between under to post graduates (*Kolb, 1981*).

Geophysicists need to concentrate all their skill and resources on acquiring theoretical interpretations of phenomena (*Leonelli, 2009*). Their most significant tool is modelling. Theoretical understanding is the most useful kind of understanding in geophysics. This leads to gaining insights that might not have been obtained if geologists insisted on making empirical sense of their finding through research, such as in hydrology and physical geography, which is more about doing rather than theorizing (*Inkpen, 2005*). For their research purposes, the best understanding is embodied rather than theoretical (*Hopp et al, 2009*; *Kleinhans et al, 2010*).

Meteorology has a long tradition of observation, and has probably the largest and most diverse data collection systems on Earth, based on a high-density network of sensors as well as remote sensing (*Kleinhans et al, 2010*). Global Circulation Models are run continuously on supercomputers for ensemble forecasting of the weather and the uncertainty of the prediction, as well as for climate modelling. The obvious societal relevance is one reason why this discipline has much more resources than other geosciences. Experiments are less common, because it is hard to scale back in laboratory.

Finally, planetary science uses a lot of remote sensing, such as ground-penetrating radar and satellite images, and modelling, in order to gain insight in tectonics, climate, and landscape evolution (*Kleinhans et al, 2010*), since the possibilities for fieldwork and experiments are rare. Terrestrial analogues and concepts are used from the other earth-scientific disciplines.

3.4 Conclusions

Earth-scientists use a broad suite of tools, in order to achieve earth-scientific understanding, while combining theoretical and embodied components. A combination of skill and relevant tools is essential for achieving understanding. The earth-scientific toolbox contains at least three categories of geo-tools: objective descriptive geo-tools, subjective descriptive geo-tools, and geo-tools involving integrated understanding. Different levels and forms of understanding can be acquired from using the same tools, but also different tools might be used to gain the same understanding. Results may be interpreted in a variety of ways depending of background knowledge and skills in handling the tools of their users.

Objective descriptive geo-tools are used in the beginning phase of an earth-scientific research and require little theoretical background. Understanding is enhanced by, or even partly consists of, visualization. Subjective descriptive geo-tools are generally included in the preparation of geological fieldwork and used during the fieldwork itself. They are based on objective observations, but personally drawn. Theory stops being merely a premises and developing new theory becomes a goal with the geo-tools that require integrated understanding. These geo-tools provide earth-scientists and students with a feeling for the protocols, research techniques, and procedures during simulations. They also permit a greater understanding of a theoretical structure. Each discipline may prefer their own tools for achieving understanding.

Chapter 4 Learning Styles of Scientists and Laypeople

4.1 Introduction

Earth-scientists reach earth-scientific understanding by using specific tools in specific situations (*Dieks and De Regt, 1998*). Is there a difference in the learning process of scientists and laypeople? In this chapter I aim to answer the fourth sub-question of this thesis: How do people reach understanding? I will search the answer with the help of psychology. I will analyse different learning styles, of scientists and laypeople alike. I will investigate the differences and/or similarities between achieving understanding by scientists and laypeople. If there is no difference, we may focus on the process of doing earth-scientific research, using the geo-tools, during science education and communication.

4.2 The Learning Process

The process of learning differs per individual. Not only does it differ between certain disciplines which geo-tools are used in the process of learning and achieving understanding, it also depends on the person who uses the geo-tool (*Kolb, 1981*). It is even the case that the personal choice for a specific learning process influences the choice of discipline, because it makes the workload lighter and easier when the personal learning style fits with the academic program (*Kolb, 1981*). Even though one might have an initial preference, these forms of intelligence are not static, but can be developed (*Gardner, 1993*).

4.2.1 The Learning Cycle

Kolb identified four general learning styles (*Kolb, 1981*):

(a) Concrete Experience (to feel)
(b) Reflective Observation (to watch)
(c) Abstract Conceptualization (to think)
(d) Active Experimentation (to do)

The process of learning can be visualized in a four-stage learning cycle. Depending on the individual learning style, a different starting point may be preferred. Geological research involves passing the four stages in Kolb's learning circle (*Figure 4.1*).

Kolb distinguished four individual learning styles (*Kolb, 1981*):

(1) Divergers (feel and watch)
(2) Assimilators (think and watch)
(3) Convergers (think and do)
(4) Accommodators (feel and do)

Divergers (1) have a preference for concrete experience (a) and reflective observation (b). They view concrete situations from different perspectives and are imaginative and interested in people. Assimilators (2) have a preference for reflective observation (b) and abstract conceptualisation (c). They are less interested in people, less concerned with the practical use of theories, find it important that a theory is logically correct, and apply inductive reasoning. Covergers (3) have a preference for abstract conceptualization (c) and active experimentation (d). They are relatively unemotional, prefer to deal with things rather than people, and apply deductive reasoning. Accommodators (4) have a preference for concrete experience (a) and active experiments (d). They are risk-takers and adapt quickly to specific immediate circumstances.

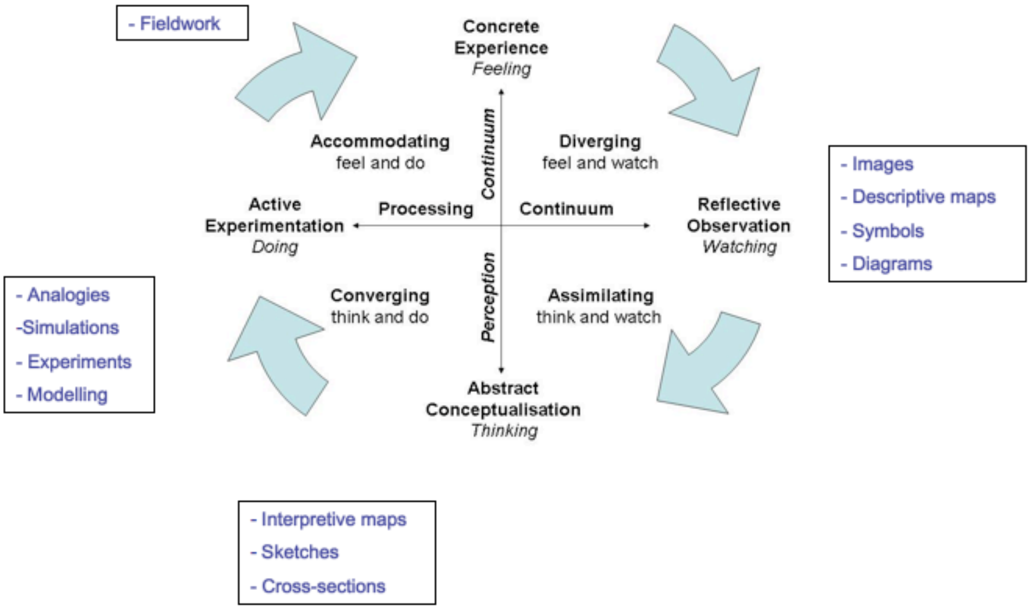

Figure 4.1. *Kolb's learning cycle (Kolb, 1981, in which I included the dominant geo-tools. Certain geo-tools may be a part of more learning styles, but this is a generalized version.*

Individual scientists, or a specific discipline within Earth Science, may favour one type of explanation (*Kleinhans et al, 2005*). According to Kolb, geologists generally are assimilators (2), whereas geographers usually are accommodators (4) (*Kolb, 1981*). Geologists prepare their fieldwork with images and maps (reflective observation), while making sketches and cross-sections (abstract conceptualization). During fieldwork, they categorize and classify the data (abstract conceptualization). Whereas geographers set up analogies and simulations, and focus on experiments and modelling (concrete experience and active experimentation).

4.2.2 Cognitive Processes

Achieving scientific understanding is a cognitive achievement and gaining though specific scientific training (*De Regt et al, 2009*). Bloom distinguished three domains that influence the learning process: cognitive, affective, and psychomotor (*Bloom, 1956*). The cognitive domain focuses on knowledge, comprehension, application, analysis, synthesis, and evaluation. The affective domain focuses on emotion and the psychomotor domain focuses on the physical. Bloom developed taxonomy for the cognitive domain (*Bloom, 1956*).

Krathwohl (*Krathwohl, 2002*) revised the structure of the knowledge category (*Table 4.1*). Instead of subdividing knowledge in "knowledge of specifics", "knowledge of ways and means of dealing with specifics", and "knowledge of universal and abstractions in the field" (*Bloom, 1956*), he distinguishes factual, conceptual, procedural, and metacognitive knowledge (*Krathwohl, 2002*). Factual knowledge involves the basic elements that students must know to be acquainted. Conceptual knowledge involves the interrelationships among the basic elements within a larger structure that enable them to function together. Procedural knowledge involves methods of inquiry and criteria for using skills, algorithms, techniques, and methods. Metacognitive knowledge involves knowledge of cognition in general as well as awareness and knowledge of one's own cognition.

When the taxonomy is applied to the geo-tools, the distinction between the three categories becomes clear, as well as the subdivision in the geo-tools involving integrated understanding.

Table 4.1. Krathwohl's revision of the knowledge category (Krathwohl, 2002), of Bloom's taxomy of the cognitive domain (Bloom, 1956), in which I integrated the dominant geo-tools, based on the case study. Hence, there are more possibilities possible, depending on the type of research.

	Images	Maps	Symbols	Diagrams	Sketches	Cross-sections	Analogies	Simulations	Experiments	Modelling	Fieldwork
a. Factual knowledge a1 knowledge of terminology a2 knowledge of specific details and elements					X	X	X	X	X	X	X
b. Conceptual knowledge b1 knowledge of classifications and categories b2 knowledge of principles and generalizations b3 knowledge of theories, models, and structures	X	X	X	X	X	X	X	X	X	X	X
c. Procedural knowledge c1 knowledge of subject-specific skills and algorithms c2 knowledge of subject-specific techniques and methods c3 knowledge of criteria for determining when to use appropriate procedures							X	X	X	X	X
d. Metacognitive knowledge d1 strategic knowledge d2 knowledge about cognitive tasks, including appropriate contextual and conditional knowledge d3 self-knowledge									X	X	X

Krathwohl (*Krathwohl, 2002*) also developed a new structure of the cognitive process domain (*Table 4.2*). To remember is to retrieve relevant knowledge from long-term memory. To understand is to determine the meaning of instructional messages, including oral, written, and graphic communication. Note that this is not yet scientific understanding. To apply is to carry out or use a procedure in a given situation. To analyze is to break material into its constituent parts and detecting how the parts relate to one another and to an overall structure or purpose, i.e. causation. To evaluate is to make judgments based on criteria and standards. To create is to put elements together to form a novel, coherent whole or make an original product. Note that here scientific understanding is achieved.

When the taxonomy is applied to the case study of a geological research, the cognitive process is visualized.

Table 4.2. Krathwohl's revision of Bloom's taxonomy of the cognitive domain (Krathwohl, 2002), in which I integrated the the step of an example of a geological investigation.

	Goal Definition	General Site Survey	Specific Site Survey	Sampling	Laboratory Analysis	Data Analysis and Representation	Interpretation	Conclusion
1. Remember 1.1 recognizing 1.2 recalling		X	X	X	X	X	X	X
2. Understand 2.1 interpreting 2.2 exemplifying 2.3 classifying 2.4 summarizing 2.5 inferring 2.6 comparing 2.7 explaining		X	X	X	X	X	X	X
3. Apply 3.1 executing 3.2 implementing				X	X			
4. Analyze 4.1 differentiating 4.2 organizing 4.3 attributing						X		
5. Evaluate 5.1 checking 5.2 critiquing							X	
6. Create 6.1 generating 6.2 planning 6.3 producing	X							X

4.2.3 Multiple Intelligences

Bloom distinguished three domains that influence the learning process: cognitive, affective, and psychomotor (*Bloom, 1956*). He argues that in order to learn, all three domains should be encountered on. Gardner evolves this theory into the theory of multiple intelligences (*Gardner, 1993*).

According to Gardner, this difference in choice of tools, and thereby preference for an initial domain, is due to eight forms of intelligence:

(1) Verbal (linguistic)
(2) Logical (mathematical)
(3) Visual (spatial)
(4) Musical (rhythmic)
(5) Physical (kinaesthetic)
(6) Naturalistic
(7) Interpersonal
(8) Intrapersonal

Each individual has to some degree, some forms more developed than others (*Gardner, 1993*). Some people excel in mathematics, and therefore prefer the factual and conceptual tools, but are unable to perform during fieldwork, and therefore avoid the procedural tools (*Kolb, 1981*). Scientists may prefer certain theories and tools to others, because they possess the skills to work with them (*De Regt et al, 2009*), either by training or initial preference. Unfortunately, developing mathematical skills lessens the creative skills, and vice versa (*Kolb, 1981*).

4.3 Scientists versus Laypeople

Scientists use the same cognitive mechanism as everybody else (*Ylikoski, 2009*). The difference in learning styles and the learning process applies to everyone. Scientists and students are just people with a specific interest (*De Regt et al, 2009*). Even though a scientists understand is of a difference degree than the understanding of laypeople (*Ylikoski, 2009*), the methods of acquiring scientific is no different.

The difference is that earth-scientists have practised their skills to handle the tools in more depth and can refer to other researches and background information. They simply know more in their domain of expertise, and can work faster, more efficient, with this knowledge. Researchers have acquired different combinations of skills, depending on their goals, training, and professional experience (*Leonelli, 2009*). It takes time and effort to learn a set of skills (*Leonelli, 2009*). The more control and the more precise the predictions, the deeper the understanding (*Ylikoski, 2009*). Understanding comes in degrees (*Ylikoski, 2009*). Whereas novices categorize by surface structures, objects, and have a greater variability in classification, experts categorize on the deep structure, the theories (*Chi et al, 1981*). Both are able to gain some understanding of the problem, to construct a somewhat enriched representation of it.

Non-scientists value empirical accuracy, scope, consistency, simplicity, and plausibility in their explanations (*Brewer et al, 1998*). They want their theory to explain a wide range of data, with fewer assumptions and hypotheses. Their explanation involves causal and mechanical reasoning and should be functional. Scientists add precision, formalism, and fruitfulness to the requirements of an explanation (*Brewer et al, 1998*). They want the explanations to be based on fundamental arguments and usable for future research.

Every individual choice between competing explanations depends on a mixture of objective and subjective factors (*De Regt, 1996*). The choice of method for achieving earth-scientific understanding is based on personal learning style and preferred intelligence.

4.4 Conclusions

The process of learning differs per individual. Not only does it differ between certain disciplines which geo-tools are used in the process of learning and achieving understanding, it also depends on the person who uses the geo-tool. In order to learn, all the domains should be encountered on. When connecting the geo-tools and the steps an example of a geological research to the (dominant) learning processes, it becomes clear that geological research passes the four stages in Kolb's learning circle, Krathwohl's cognitive process, and encounters upon several of Gardner's multiple intelligences. Thus, I conclude that earth-scientific understanding may be best reached by combining theory with practise, i.e. follow all the steps of an earth-scientific research and gain procedural insight.

Chapter 5 Earth-Scientific Communication and Education

5.1 Introduction

Scientific communication and education are both based on the pragmatic use of explanation, i.e. the communication of an earth-scientific explanation. Scientists use the tools they used to achieve scientific understanding to communicate their understanding to others (*Leonelli, 2009*) and they use it in their educational programs. Since the public acquires scientific understanding in the same way as scientists, using the different geo-tools and providing insight in the scientific processes and procedures seems to be the best way to communicate as well as educate Earth Science.

In this chapter I aim to answer the final sub-question of this thesis: How can earth-scientists communicate their understanding? Two problems arise in this situation: scientists use jargon that the public does not know, or the words are shared, but the meaning of these words is not (*Van Woerkum and Van der Auweraert, 2004*). I will discuss some communication models, before elaborating on both science communication and education, to the public, in the classroom, and in earth-scientific museums.

5.2 Communication models

Lasswell introduced a communication model (*Lasswell, 1948*), which states the basic steps of communicating a message: “Who says What to Whom, How, and with what Effect?” (*Figure 5.1*). He distinguished five main factors in de communication process:

(1) The source (Who)
(2) The message (What)
(3) The receiver (Whom)
(4) The channel (How)
(5) The result (Effect)

The source is the person who sends the message. The message consists of the (verbal) information of the source. The receiver is the person for whom the message is attended for, and/or the public that receives the message. The channel is the way the source uses to transmit the message. The effect entails possible results of the message, such as attitude change, increase knowledge, or nothing.

Figure 5.1. *Lasswell’s communication model (Lasswell, 1948).*

Schulz von Thun added four aspects (*Schulz von Thun, 1982*) to the communication model (*Figure 5.2*):

(1) Business
(2) Expressive
(3) Relational
(4) Appealing

The business aspect entails the content of the message, such as the facts and the arguments. The expressive aspect consists of the non-verbal message of the source about the message. This is influenced by the personality of the source. The relational aspect consists of the non-verbal message of the messenger about the receiver. The appealing aspect entails the goal of the message by the source.

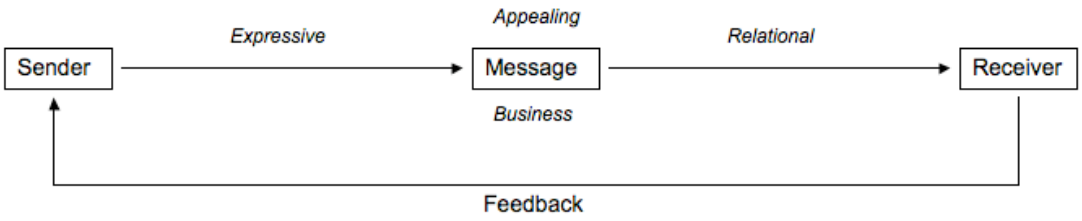

Figure 5.2. Schulz von Thun's communication model (Schulz von Thun, 1982).

Finally, the receiver will react to the source and the message (*Figure 5.2*). The sender needs to try to look through the eyes of the receiver before transmitting the message (*Van Woerkum, 1999*).

5.3 Science communication

Lasswell identified two effects of communication (*Lasswell, 1948*):

1. Increase of knowledge
2. Attitude change

These two effects can serve as the main goals of earth-scientific communication. Earth-scientists aim to increase earth-scientific knowledge (1), in order to help laypeople make informed decisions (2) about important issues, such as the use and management of natural resources, recycling, sustainability, and housing. It is often believed that the more laypeople know about science, the more they will embrace science (*Laugksch, 2000*). Unfortunately, increasing knowledge does not automatically changes the attitude (*Knoop, 2004*). In science communication, we should not present science as ready-made packages (*Van Woerkum and Van der Auweraert, 2004*). The public must be persuaded in order to change their attitude.

McGuire distinguished five sequential phases in the persuasive communication process (*McGuire, 1969*):

1. Attention
2. Comprehension
3. Agreement
4. Memorization
5. Action

The receiver must pay attention to the message and comprehend its content and arguments. The attitude will change when the receiver agrees with the message. If the receiver memorizes the message, it might lead to a change in behaviour as well. The communication is dynamic, based on interaction between sender and receiver (*McGuire, 1969*). Scientific understanding is shaped by intersubjective communication between scientists (*Leonelli, 2009*). If the scientist is not able to communicate his or her research than the results of the research will not be accepted by the scientific community as a contribution to science (*Leonelli, 2009*).

5.3.1 Development

Wiedenhof identified four periods in the development of science (*Wiedenhof, 1980*), in which the style of science communication changes:

(1) Laissez-faire
(2) Laissez-innover
(3) Laissez-organiser
(4) Laissez-consolider

The “laissez-faire” phase lasted until the beginning of the twentieth century (*Figure 5.3a*). The public had a high trust in science. Scientific knowledge was presented through the transmission of facts, i.e. the deficit model (*Figure 5.3b*). The “laissez-innover” phase lasted until the first half of the twentieth century. Science started influencing the technology. During the “laissez-organiser” phase, the public started questioning the objectivity of science. More people went to college and university and the public became more critical towards science. The realization came that it was not enough to just present the facts. The “laissez-consolider” phase involves public marketing of science. Science now has to be presented as an open product and communication is based on interaction, but also by presenting the process of science and engaging the public with science (*Van der Auweraert, 2007*), i.e. contextual model.

Recently, a fifth phase has been added to the list of periods (*Van der Auweraert, 2007*), in which panels and debates arise and the public gets a vote in the development of science and her decisions:

(5) Laissez-contextualiser

The type of natural history museum can be roughly aligned with the periods of development of science and science communication (*Figure 5.3*). The classical and traditional museums were generally opened in the first half of the twentieth century, whereas the modern museums opened towards the end of the twentieth century, and science centres in the beginning of the twenty-first century.

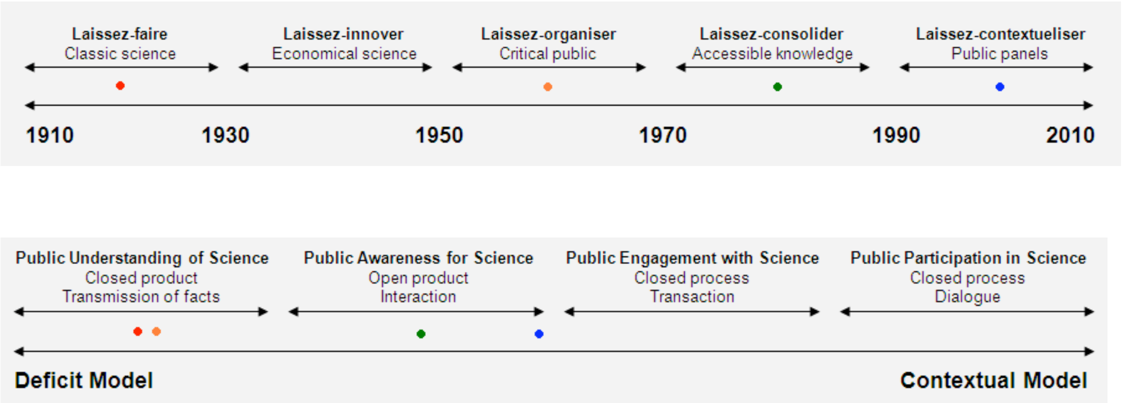

Figure 5.3. *Figure 5.3a (top) shows the development of science communication, based its five periods (Wiedenhof, 1980; Van der Auweraert, 2007). Figure 5.4b (bottom) shows the interaction continuum, based on the different forms of science communication (Van der Auweraert, 2007). The red dot indicates some Dutch classical science museums, such as Teylers Museum Haarlem (1784) and the Natural-Historical Museum Rotterdam (1927). The orange dot indicates some Dutch traditional science museums, such as Geological Museum Hofland (1969) and Museum for precious stones “De Oude Aarde” (1969). The green dot indicates some Dutch modern museums, such as Museon (1984) and Naturalis (1986). The blue dot indicates the Dutch Science Centre in Delft (2010).*

5.3.2 Teaching Earth Science

> *"Then said a teacher: Speak to us of teaching.*
> *And he said: No man can reveal to you nothing but that which already lies half asleep in the dawning of your knowledge." (Quoting Gibran, The Prophet, 1923)*

Most people learn science by doing science, combining both content and method (*De Regt et al, 2009; Centrum voor Educatieve Geografie, 2009; Jansen, 2010*). Since Earth Science consists of both theoretical and embodied understanding, teaching the process of an earth-scientific research can give the best earth-scientific understanding.

In many countries, this inquiry-based learning is stimulated (*National Research Council, 2000*) and the best way to learn Earth Science is through excursions and fieldwork (*Centrum voor Educatieve Geografie, 2009*). Recent research indicates that inquiry-based instruction increases the level of achievement of students (14-16 years old) and that this effect is long-term and visible in the level of knowledge, reasoning, and argumentation (*Wilson et al, 2010*).

By using a deeper approach with students, (pragmatic) explanations become more advanced and the questions more focused on explanations and causes (*Chin and Brown, 2000*). Teaching procedural understanding stimulates the students to seek out evidence, deal with uncertainty and risk, access, apply, and use the relevant conceptual knowledge to critically evaluate the evidence (*Duggan and Gott, 2002*). The focus should not be on how little the public knows, but how to best communicate Earth Science, without it being an overload of information (*Keil, 2003*). Most conceptual knowledge is too specific, and therefore it is best to focus on learning how to access the relevant and reliable knowledge (*Duggan and Gott, 2002*). Conceptual knowledge can be accessed and acquired by the public, for example though internet, when they are motivated to do so (*Duggan and Gott, 2002*). By reducing conceptual knowledge in the curriculum, there can be more focus on the process of doing research and the validity and reliability of evidence (*Duggan and Gott, 2002*).

It is not possible to teach all science this way, or each aspect of a subject, due to lack of time and the need for a diversity of methods (*Centrum voor Educatieve Geografie, 2009*). As discussed in chapter 1 and 3, different methods are used in Earth Science; so teaching a diversity of methods is essential. In the classroom, students can learn the required theoretical background and still develop the abilities required to do research. Teaching inquiry is most effective and efficient through a guided instructional approach (*Kirschner et al, 2006*) and with the attention to a specific subject, so that the students know what they are doing and why (*Centrum voor Educatieve Geografie, 2009*). Only when the students have sufficient background knowledge, they can perform a research more dependent (*Kirschner et al, 2006*), since understanding involves integrating new knowledge with already existing knowledge (*Carey, 1986*).

As discussed in chapter 4, not every student learns the same way. Therefore, earth-scientific education requires assignments for every learning style (*Centrum voor Educatieve Geografie, 2009*), which can be shaped during undergraduate education (*Kolb, 1981*). The process of doing geological research involves all four general learning style, and therefore is not only used by earth-scientists to achieve earth-scientific understanding, but also provide a good method for teaching Earth Science. In general, the logical principles to reconstructing geological structures can be taught somewhere between grade 7 and 8 (*Dodick and Orion, 2003*).

5.3.3 Earth-Scientific Museums

Recent research indicates that 97% of the (252 interviewed) museums in the Netherlands is focussing on education, in comparison to 91% in 1995 (*Cultuurnetwerk Nederland, 2008*). Learning in a museum allows the students to control their learning, and gain deeper understanding in the learning process (*Bamberger and Tal, 2006*). The advantage of museums, compared to a classroom, is not the knowledge students acquire, but the stimulants they get to all their senses (*Initiatiefgroep Musea & Onderwijs, 1999*), which appeals to the different forms of intelligence (*Gardner, 1993*) and learning styles (*Kolb, 1981*).

Based on a survey done by the Museon, a museum in The Hague, in January – April 2009, schools like the social interactivity and the practical application of scientific knowledge in museums (*Jansen, 2010*). Schools can connect teaching in the classroom with learning in the museum. Schools describe the ideal museum lesson as practical (doing, feeling, smelling, seeing, tasting), independent working groups, a lot of activity and interactions with the objects and the exhibition (*Van Hoogen and Mielen, 2006*). This is in agreement with the theories of science communication; focus on emotions, personalize, actualize, stir curiosity, surprise, interact, respond to existing knowledge and interests, vary stimuli (words, images, sounds, fragrances, to feel), and invite participation and involvement (*Hamelink et al, 2004*).

5.4 Conclusions

As concluded from previous chapters, understanding of earth-scientific issues by the public can be gained through the same tools that scientists are using. Therefore, when communication and teaching earth-scientific explanation, more focus should be on the process of doing earth-scientific research, by using the geo-tools, rather than transferring merely factual knowledge. Earth-scientists should transfer their understanding. Earth-scientific communication and education should focus on research and presenting the knowledge in an inspiring way and presented at age-and grade-appropriate levels, so that laypeople acquire the tools. Since understanding involves collecting and connecting new knowledge to the existing frame of reference, this is likely to be more efficient for science communication than just “communicating” the factual knowledge.

Chapter 6 Synthesis

Earth-scientific reasoning is crucial for society to learn, since many issues, such as global warming and various risk and resource assessment, are based on Earth Science. In this thesis I aimed to answer the research question “How can earth-scientific communication be improved?” by searching an answer through an extensive literature study in philosophy of science, psychology, and science communication and education. Each discipline has its own perspective on the process of understanding. I connected and integrated these insights, while arguing that combining useful elements of these disciplines may be useful to come to new conclusions, promoting an interdisciplinary approach.

In this thesis, I made a distinction between scientific and pragmatic explanation (*Chapter 1*). Earth-scientific explanation is a way towards earth-scientific understanding. Earth-scientific understanding consists of embodied and theoretical understanding and both are integrated in Earth Science. Combining these two types of understanding leads to the best earth-scientific understanding (*Chapter 2*). Earth-scientific understanding is acquired by earth-scientists though at least three categories of geo-tools (*Chapter 3*). There is no cognitive difference between scientists and laymen in gaining earth-scientific understanding, except for their difference in level of knowing, insight, and understanding (*Chapter 4*). Finally, Earth Science can be best taught through fieldwork, in combination with theoretical knowledge (*Chapter 5*).

I have argued that earth-scientific understanding is an integration of embodied and theoretical understanding and that there is no difference in acquiring scientific understanding by laypeople and scientists. The process of acquiring earth-scientific understanding (by scientists, with the use of the geo-tools) should be used in the communication and education to laypeople, and not just students. Scientists do not differ from other people. Therefore, the public can reach earth-scientific understanding in the same way earth-scientists do.

Earth-scientific understanding is more than just knowledge facts of facts and theories; it involves skills and embodied knowledge as well. Using geo-tools and explaining the process of doing earth-scientific research, instead of overloading the public with factual knowledge, is the best way to communicate Earth Science and enhance earth-scientific understanding.

In the attempt to solve the language problem, scientists should be given a basic training, starting in the beginning of their own scientific education, to learn to talk about their discipline in common language, i.e. language that is understandable for the general public.

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