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Social Studies of Science 2011 41: 539 originally published online 13 May 2011
DOI: 10.1177/0306312711403825

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Social Studies of Science
41(4) 539–561

DOI: 10.1177/0306312711403825
sss.sagepub.com
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Between and beyond data: How analogue field experience informs the interpretation of remote data sources in petroleum reservoir geology

Petter G. Almklov
NTNU Social Research, Trondheim, Norway

Vidar Hepsø
Norwegian University of Science and Technology (NTNU), Trondheim, Norway

Abstract

This paper explores how experience from field trips to geological *analogues* informs the interpretation of remote data sources in petroleum reservoir geology. It is based on observations of a group of petroleum geologists on a field trip to an analogue field and descriptions of the typical office work of such professionals in the same company. Special attention is given to representational artefacts and data types employed in the different settings. Field trips are experiences in which the geologists develop skills in handling the relationship between geological and physical structures experienced in the field and conventional representations of them. When trying to make sense of the offshore reservoirs deep beneath the seabed, they have to make do with fragmentary data from remote sensor arrangements. When creating integrated ideas of a reservoir based on sparse remote data sources, petroleum geologists draw analogies to the patterns observed in the field and draw from the skills developed when performing similar extrapolations in the field.

Keywords

analogies, artefacts, data, fieldwork, geology, materiality, petroleum

Corresponding author:
Petter G. Almklov, NTNU Social Research, Dragvoll Gaard, 7491 Trondheim, Norway.
Email: pettera@svt.ntnu.no

> Everything is grey in geology and there is very little that is black and white. (Geologist in interview)

Geology is a science that occupies itself with many phenomena inaccessible to direct human perception. This is especially evident in the context of offshore petroleum exploration and extraction. It also has an explicit tradition of using analogies for interpretation and creative extrapolation of data (see, for example, Rudwick, 1976). In this paper we discuss a concrete manifestation of this tradition. When working with offshore oil reservoirs, geologists and their colleagues in the oil company draw on field experience from *analogues*. An analogue is a geological site that displays some similarities to the field they are working with and that may aid them in interpreting data from it. We discuss how knowledge of such similar fields influences work with oil fields that are buried deep beneath the sea and hidden from direct human perception. Field trips to analogues inform office work, both as a source of knowledge about the geological structures as well as of bodily and reflexive experience with the mechanisms by which geological data represents such structures. Analogy is thus drawn both from the properties of the field itself and from the field experience.

The notion of similarity implies a continuum in terms of truthfulness. A thing is truly identical only to itself. On the other hand, it is hard to find two things that are completely without similarity. Reasoning by analogical inference, using knowledge from one geological structure to understand another, also resides within this continuum. It is neither completely true nor completely false. Nonetheless, it helps solve complex tasks by comparison with similar ventures in personal or collective experience (Gentner and Holyoak, 1997). Reasoning by analogy helps geologists make guesses based on perceived similarities when their data are inconclusive.[1] Geology is a discipline where educated guesswork about unknown underground formations is part of the professional ethos. Such reasoning may be common, but often underestimated, in other science and technology communities as well.[2]

First we will provide an example of how a geological analogue, and the practice of representation, becomes instilled into the bodies and minds[3] of a group of subsurface professionals through immersive experiences in the field. Then, we give some examples of how such experience informed interpretations of data from the reservoir. The paper is based on observations from two empirical settings. First, we followed a group of geoscientists performing fieldwork in Greenland, and then we examined how another group of subsurface specialists worked with their oil field data from an onshore office. Using these examples, we argue that the experience gained on field trips to analogical fields is an important part of the repertoire on which the subsurface professionals intuitively and sometimes explicitly draw when interpreting data. Our discussion of the role of field experiences in data interpretation illustrates how contextual knowledge of *something similar* may aid the 'educated guesswork' that office workers perform, constructing notions of the reservoir beyond and between what their data tell them.

Tools, representation and embodiment

Geologists have, through centuries of practice and epistemic development, domesticated a number of conventional representations and artefacts as cornerstones of their professional practice. Several simple tools employed in the field serve to shape the geologists' perceptions of phenomena. Visual representations and codifications do not just aid the preservation and mobilization of observations: they also shape the profession, in terms of what it sees and brings into its discourse (Goodwin, 1994).

In the field geologists employ tools and artefacts, some of which have been part of geological practice for centuries, such as the compass, hammer, magnifying glass and hydrochloric acid. Equally important are the representational artefacts: maps, drawings and logs used for recording observations and guiding attention. All these tools can be regarded as 'perceptual aids' in the sense that they build on *amplification and reduction mechanisms* (Ihde, 1999). They amplify some elements or aspects of the phenomenon while reducing others. Thus, seeing with tools gives the geologist the ability to inspect more aspects and perspectives of the rock. In the field trip setting, the amplification–reduction structures are those of a 'weak program' (Ihde, 1999: 158–177). Though the tools influence the perception of the rock, they do not replace the immersive experience of bodily presence and perception; rather, they supplement it.

Seeing or envisioning the geological site is not a passive reception of visual data but a bodily activity where tools, representational forms and training shape one's vision (Frodeman, 1996).

> [V]isual intelligence involves more than the use of our eyes. Spatial understanding is kinetic: to understand three-dimensional space one must *move through it*. ... One looks at the outcrop, of course; but one also moves back and forth in order to see it at different angles, strikes or digs the rock out, and feels its density and resistance. (Frodeman, 1996: 424; emphasis in original)

Frodeman (1995, 1996) traces the growth of his own geologic understanding using a hermeneutic perspective. What goes on at the outcrop involves something more than mechanized matching of features between contemporary environments and strata representing the geologic past:

> My thesis is that geology depends upon a type of visual intelligence whereby the geologist applies a set of templates that organize sets of marks into a body of significant signs. What was once mute stone becomes significant as the rock reveals its latent language to the trained eye. (Frodeman, 1996: 418)

This practice and way of perceiving the environment relies not only on conscious reflection, but also on non-verbal awareness. It is an expert's way of seeing, formed by experience and practice, and a type of knowledge that may not be available to verbal discourse (Ingold, 2000; Roth et al., 2002). When we speak of knowledge in this article, our conception of it also includes non-verbal perceptual skills gained through experience.[4] One skill practiced through fieldwork is that of mapping. Mapping involves symbolic and material tools that serve to amplify some aspects of the rock, reduce others, and transform the rock into mobilized codifications in a universal spatial language.

In the office, the amplification-reduction structure is that of a 'strong program'[5] (Ihde, 1999: 158–177). The artefacts are the dominant vehicles of perception, and only those aspects of geology that are amplified are accessible. All the immersive and embodied characteristics of the geological context are missing and, to compensate for this loss of context, they employ complex representational artefacts or a 'cascade of inscriptions' (Kastens et al, 2009; Latour, 1990: 42). The oil reservoirs off the coast of Norway are thousands of meters below the ocean floor and almost all information available at the office comes from indirect sources, through complex socio-technical arrangements. The measured data and models must suffice because of the lack of direct physical access to the structures. The oil reservoir is reconstructed, or conjured into existence, at the office onshore. This is done with visual forms, quite similar to those used on the field trip, in this case built up from the combinations of the different data types, each transporting fragments of information about the reservoir to the office.

Rudwick (1976) explores the historic origins of the visual language of geology and demonstrates how the trajectory towards more abstract and simple visualizations signalled the development of the geology.[6] More generally, standardized, abstract and mobile visualizations connect different fields to a professional discourse. A good example of this is Goodwin's (1994) description of archaeologists in the field and their practice of coding the colour of soil samples by comparing them with the standardized colour codes on a Munsell chart (this is also used by geologists). Such a coding of a phenomenon is a step towards generating a 'professional vision' of it, of bringing it into a professional discourse. The brownish soil thus enters the discourse of archaeologists, and information about this very local piece of dirt gains mobility within the archaeological community.

Geology, like archaeology, is built around a number of such codifications of rock and soil and of larger structures and formations. The codified observations are usually positioned in space by coordinates and presented on maps or graphs. Mastering this disciplined domestication of nature, creating and using these systematic representations of the geology in the wild, is an important part of the geologists' training. Simply put: to bring the field to the office, the geologist must use such codifications and mobilize aspects of the structures.

Systems for representing knowledge are a crucial part of geology's professional culture. Knowledge is always partly personal, embodied and implicit, but these aspects of it are always involved in a dynamic relationship with certain kinds of externalized entities (for example, Hutchins, 1995). In modern geology, these systems are largely based on a high degree of standardization that enables the mobilization of knowledge (Bowker and Star, 1999). Viewing the symbolic entities as tools for, as much as representations of, human knowledge, we inspect the processes through which such entities are created and used. Rather than focusing on representation, we focus on 'the activity of *representing*' (Giere, 2004: 743, emphasis in original). Codifications of the oil reservoir not only are displays of representational content but also are tools for trained professionals to explore the reality 'behind them' (Almklov, 2008). One may have, in Polanyi's (1962: 55) words, a 'subsidiary awareness' of the tool one uses to explore the world towards which one's 'primary awareness' is directed, much like a blind person's use of a cane to probe the world beyond it.

Methodology and fieldwork

Both authors have field experience within a major Norwegian oil company. Almklov performed ethnographic fieldwork for his PhD in a subsurface department the company

(Almklov, 2006, 2008), as well as some subsequent study in other parts of the oil industry. A geologist by training, he also has previous experience with field trips and geological logging. Hepsø is currently an employee in the oil company and for years has studied the work practices of subsurface professionals and their mediation with artefacts (Hepsø, 2009; Rolland et al., 2006). In this article, we draw on all this experience but will mainly describe two key settings. The first is a geological field trip, where Hepsø accompanied a group of 15 professionals to an *analogue* on East Greenland in August 2005. All citations from Greenland are from this period. The other setting is based on our observations in onshore subsurface departments of other teams, where professionals of the same (and related) backgrounds as those on the field trip interpret indirect data sources from an oil reservoir. The major method employed is participant observation and unstructured interviews. We followed the professionals' everyday activities and received substantial input through participation in meetings. In Almklov's case, the fieldwork included contributing as a novice geologist to the normal work of the subsurface departments. Drafts of the paper have been discussed with company subsurface specialists.

When discussing geoscientists' work in both settings, we will treat mainstream geological theories, fantastic as they may seem, as uncontroversial, rather than safeguarding ourselves with phrases such as 'regarded by geologists as … ' and so on. This is for economical reasons in terms of space and because analysing such discourse would be an entirely different project.

First setting: Fieldwork in East Greenland

The analogue

East Greenland is regarded by geologists as a key area for understanding the development of the North Atlantic from the Carbon-Cretaceous age and onwards. The Atlantic area was originally a shallow water area where sediments accumulated. Such sediments are usually stacked in horizontal layers, as variations over the years led to the deposition of sand, silt and clay. Later on, the layers were lithified and subjected to tectonic movements. Both the Norwegian Continental Shelf[7] (NCS) and the East Greenland structures are sedimentary deposits originating from this basin in the same era. They are continuations of the same geological structure, but whereas the NCS has been buried under layer upon layer of new sediments, its Greenlandic counterpart migrated westwards through eons and was lifted onto dry land. The dry rock in the mountains of Greenland is regarded as *analogous* to the reservoir formations from which the company is currently producing hydrocarbons on the NCS. One major difference is that there are no known petroleum resources in Greenland.

The expedition to East Greenland aimed to use the open and complete series of Jurassic sedimentary formations to improve the understanding of time-equivalent layers on the NCS, and to link the Jurassic geology of the NCS with observations in the field. The group of 15 who took part in the fieldwork was made up of about half geologists and half geophysicists. All the participants, in their 30s and 40s, were experienced professionals. We will proceed first by giving a detailed account of the logging at a specific site before recounting and discussing more general observations.

The Raukelv logging trip: Codification and artefact use

The purpose of the logging was to record the sedimentary layers in a vertical section of the Raukelv formation. Logging is an essential way to understand geological structures in the field. Sedimentary logging especially is focused on the layering of the rock. The night before the logging trip the participants reviewed documents from previous work in the area. They also were instructed to use the company's standard sheet for sedimentological logging (Fig. 1), with which they were all somewhat familiar.

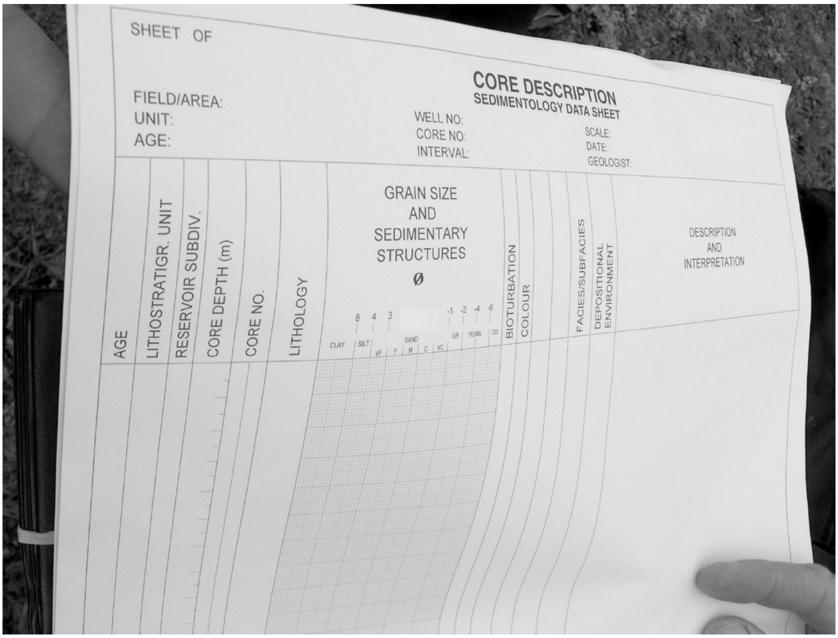

Figure 1. Data sheet for sedimentological logging

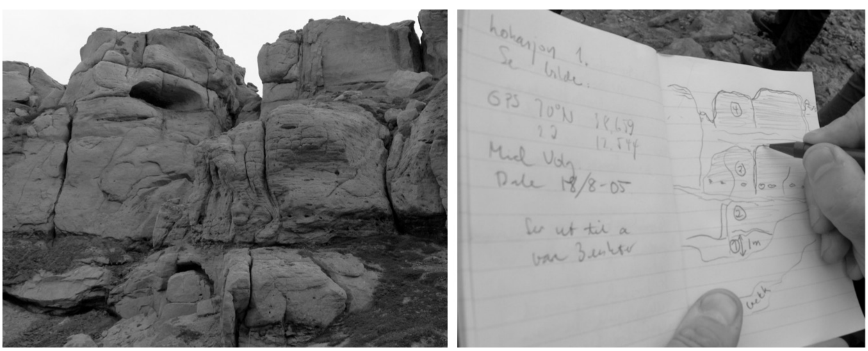

Figure 2. Left: snapshot of the Raukelv canyon vertical section. Right: Drawing the overall sketch of the same section

Observing, mapping and collecting

The group was split into teams of five to six people, each with a geologist as an instructor. The individuals in each group walked around observing and gaining an overview of the formations in the canyon-like landscape. The first issue was to find a good site for logging. Not any area could be chosen; a minimal overview of the horizontal sedimentary layers had to be established before a representative vertical section could be made. The vertical section also had to be accessible from top to bottom. It also was necessary to study each segment and layer in detail, by seeing, touching and feeling the rock by hand. Each team found a place to carry out the logging by walking around awhile, observing and evaluating both the horizontal and vertical features of the site, and, not least, evaluating its accessibility. Their choices were also based on considerations of what would be a representative section, in the sense that the logged sequence would represent the geology at some lateral distance from each sample point.

During the initial screening of the outcrop, the geologists looked for an overall picture of the structure. Frodeman (1996: 419) indicates three important aspects of the 'visual intelligence' of the geologists in the field. Their attention is often directed toward *contrasts*, *patterns* and *aberrancies* when they are trying to make sense of the outcrop. Contrasts are often signs of boundaries between layers and are visual clues that guide more detailed inspection, as noted by an informant:

> It can be variations of colour, texture, hardness and shape can make sedimentary layers visible. You also typically see the contrast by sight observing different colours, shapes and textures and you touch it too of course. (Geologist)

Second, in a search for patterns, they try to bring together a set of similarities and differences that imply *order*. When asked how they are able to see patterns, a geologist tells:

> I can see if a pattern is circular if the sedimentary layers we are looking at are repeated several times. This could indicate that it is the same processes that caused the development over a long time period.

The job of imposing order through contrast and finding patterns implies a repeated movement from micro to macro elements of the outcrop. The best distance and perspective therefore vary. Special features of the stone like grain size and lamination become visible in the micro view of the outcrop, inspecting it close up or even with a magnifying glass. Other features are best seen from a distance like faults, colours of layers, and the relations between layers. Throughout these movements between scales and perspectives, and the hermeneutic shifts they imply, the geologists also have a keen eye for anomalies in the outcrop. These are significant because they deviate from the normal patterns of the imposed order (Frodeman, 1996: 418–419). They may be clues that challenge or support the geologists' interpretation and are investigated with great effort and interest.

As the team started to get a sense of the general traits of the outcrop and before the detailed logging was initiated, they made an overall description of the site. One group made a simple drawing (see Fig. 2) of the main structure to articulate its structural features. In this phase, they expressed scepticism about the use of photography to document the composition of the section, since they believed that it can hide a more comprehensive understanding of the section. One geologist in the team said:

> Yes we also use photography here, but we disagree on early use before the description is developed. Photography makes things simpler but might lead to situations where you do not see the big picture and significant issues. One has to develop clear mental pictures of the structure up front.

The drawings are not mere low-resolution images, but have representational qualities of their own, emphasizing the 'big picture' and 'significant issues'. They are more *idealized* versions of the structure than photographs would be, helping geologists envision the outcrop (Frodeman, 1996; see also Lynch, 1990). The drawing emphasizes the contrasts and patterns, and it also imposes homogeneity in what is between the lines. Contrasts are turned into boundaries between units.

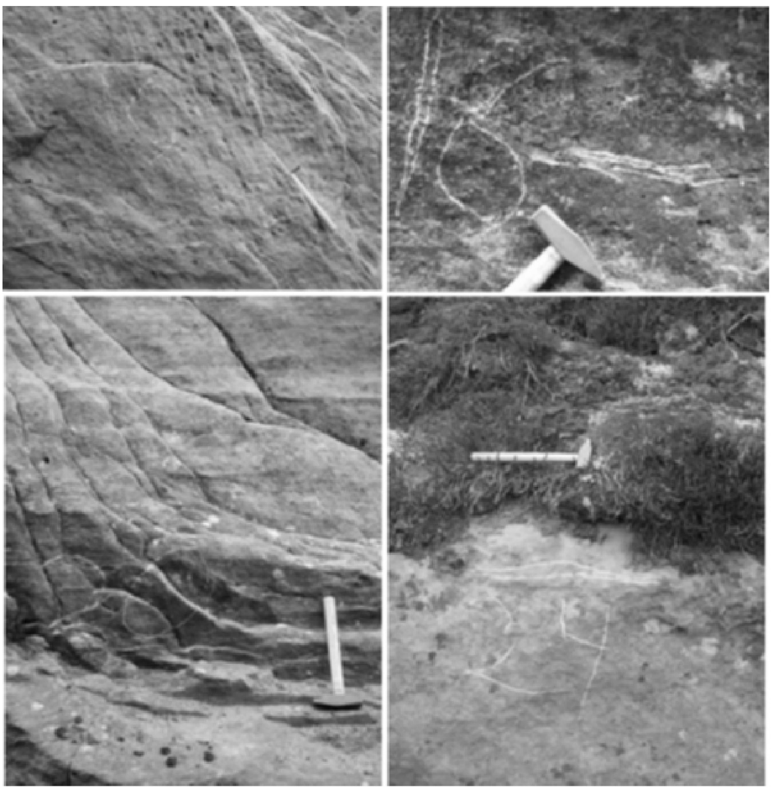

Figure 3. Identified layers with numbering in the section. Note the use of the hammer as a reference point of layer size

Figure 4. Collaboration in logging

Using the first sketch, they make an overview of the layers, start taking samples of them and numbering them. Figure 3 contains the pictures taken of four layers (10, 18, 20 and 24) in the sequence, with numbers written on the rock. In addition to sketches and photos, hand-samples are often hammered out.

Logging is a collaborative effort. Data are shared and discussed among the group members who carry out the logging, and there is a division of labour, with one member measuring and doing close-up studies of the rock and another writing down the data (see Fig. 4). One geologist says:

> You develop and nurture a shared understanding in this process. We usually do the logging in small groups of two to three people. While one is measuring the other is writing down the data, while the third might take pictures. Through this division of labour you actually develop a shared understanding through joint collaboration.

A shared terminology, colour codes and symbols are used. Though the logging sheet standardizes the information flow, quite imprecise descriptions can be included. For example, grain sizes are referred to as fine, coarse, or very coarse. Such loose references and categorizations are discussed and calibrated within the team. A number of rules of the game also exist, which the team agrees upon before logging is started.

> We discuss and agree how to use the symbols and categories in the proposed standard. We also try to be specific on the contexts when we are making objective observations and when we are interpreting the phenomena we have described. (Geologist)

The team typically tries to agree on the major elements of the description of the section. One geologist says:

> Once you agree on the description you can use the method of elimination and check places further ahead or nearby. However, in the end, it is the person that writes the log that has the final say.

Figure 5. Use of tools in the logging to describe the layering and properties of each layer

The logging sheet is a key artefact in logging. It is the information infrastructure that coordinates their efforts. For data collecting, several simple tools are employed. Geologists use a hammer to obtain rock samples, crush rock or get beneath oxidized material. The hammer is also used to examine the hardness of a rock. Like other well-known artefacts such as clocks and lighters, the hammer is used as reference to document the scale of the layers and indicate layer or feature details on pictures (see Fig. 3). A magnifying glass (8×) is used to evaluate the grain size and porosity of the sediments and measuring sticks are used to measure the height of the layers. A compass is used to measure the orientation of the cross-bedding. This will indicate if the sand grain has changed deposition orientation due to tidal or river influences. The compass is also used to find the strike and dip of an outcrop (Fig. 5). Strike and dip are estimates of the direction and tilt of planar surfaces and thus imply an element of extrapolation. As one geologist explains:

> Strike and dip is important to understand the geometry of the outcrop, both the vertical and horizontal lines. Without it, it is very difficult to get a 3D [three-dimensional] understanding of the area you are logging.

According to the team, interpretation is carried out continuously on the site in this type of logging work. The team members walk back and forth, discussing and returning to check out aspects of the horizontal and vertical sections, evaluating the interpretation of the structure against concrete details and vice versa. As suggested by the use of a pen as a measurement device to determine the height of a layer in Fig. 5, there is an element of approximation in the logging.

> I estimated the height of the formation to be 30 meters while John argued that it was only around 20 meters. The deviation is not that important: it is the total understanding that matters. (Geologist)

Documenting and reporting

When the group has gained an overall structural understanding of the outcrop, they start logging the properties of each identified section. Sedimentary logs depict a vertical cross-section of the layers in the formation. As such, it describes the succession of rock types and vertical variation in grain size and lithology. The process of logging is instrumental in developing a distinct geological understanding of rocks and reservoirs. The product of their efforts, the stratigraphic log, is a central geological information infrastructure, especially in sedimentology. It is a vertical section, a line from the bottom up, with detailed observations and measurements. Without jumping the gun here, the reader should note that the logging performed by instruments lowered into wells at the offshore field is one of the key sources of geological information from an oil field, and that the manual logs, as in Fig. 1, and the well logs have many structural traits in common.

The structure of the log is based on a series of descriptions and codifications placed in a vertical sequence. Some of the entries in the log are unmediated descriptions, whereas others require the use of simple tools. The tools do not just aid their vision, as some also help codify their observations, transforming them into data. For example, the measuring stick puts a number on the thickness of thin layers and the compass allows them to note down the direction of a dipping surface within a Cartesian geometry. In the log, they note 'objective' information, such as height, colour, the dip of a horizon, pebbling and rock type. These properties all presume knowledge of abstract conventions and tie the field to the geological discourse. Then, a separate column is reserved for the interpretation of the observations. The idea behind this standard is that, if these elements are specified well enough, other geologists can use them as starting points for their own interpretations. The log explicitly differentiates between what are believed to be objective descriptions of the formation and interpretations of those descriptions. One of the geologists commented, knowing well that it is not easy to split the description from the interpretation: 'The limit between the first and the second is blurred, but there is always some noise that you want to remove.'

Bodily presence and tool use: Logging is not for chickens

Geology in the field is a scientific practice where the body plays an important role as a vantage point and point of reference. Two geologists commented:

> Awareness of the structures and our conceptions of them are matured when we are present with our bodies. Scale is important in geological practice. The body is the reference when you study geological objects and layers. What we look at is always seen in relation to ourselves: is it larger or smaller than ourselves?

Figure 6. Steep mountain rail on the way to analogues in Harris Mountain

> Geology is a bodily experience, where you make your conception of the formation and its layers based on the physical climbing you do. The development and description of structure and texture, it's about handling and touching things. You make your conceptions of the layers as you cross sedimentary layers on your way up the section.

Never was the bodily aspect of logging more evident than on a trip a few days after the Raukelv logging. The team was slowly ascending a steep trail following an already existing log, getting a sense of the scale of the formations. The Harris Mountain is a lower Jurassic formation, consisting of very dark mudstone, sandstone, and local conglomerates that are up to 450 meters thick. The trail climbed up at an angle of 35º to 45º (see Fig. 6). Erosion and loose stones made it difficult to walk up the formation. It was steep and it was scary. 'Logging is not for chickens' was a geologist's dry comment on the physical experience with climbing and challenging our own limits.

The geologists' understanding of sediments is historical, and thus bottom-up is the natural way of understanding it, as they envision the processes by which layer upon layer have been deposited through time.[8] A geologist comments:

> It did strike me some time ago that these fieldtrips are a kind of body time travel, where you walk upwards following the layers that have accumulated for millions of years.

The tools the geologists use in the field are extensions of the body, like a hammer, magnifying glass, compass and measurement sticks. The relationship between the geologist and reality is interfaced with these instruments. The relationship is what Ihde (1999: 158–177; 2004: 469–486) calls a 'weak program'. The amplification–reduction structure is minor (therefore weak) due to the properties of the tools used. All the observations of sedimentary details have the body as a reference point. The tools magnify certain aspects of the rock and guide geologists' attention, as they focus on and note down single properties on the sheet. Still, the perception of the qualities of the rock, whether by touching it with the fingers, feeling it with the teeth, or smashing it with a hammer, provides an immersive sensual experience. In addition, the mere experience of transporting one's body around the site to look at it from different perspectives and from different distances, grounds the knowledge of it in a bodily experience. Hence, though the tools aid the conversion of the rock into conventional representations, the unrepresented context is always present to the senses within this weak amplification–reduction structure.

What comes back?

One geophysicist reported after the logging was finished how the trip made some of the abstract qualities codified in logs and models seem more concrete:

> When you can physically walk in various parts of the section to get an overview, take out samples, study the rock with a magnifying glass, you definitely get a very concrete understanding of permeability and porosity in the rocks. (Geophysicist)

Porosity is calculated as the fraction of pore volume over the gross volume of the rock. Permeability is the rock's ability to allow a flow of fluids. This is a more elusive parameter that depends upon porosity, but it may also vary with fluid and rock chemistry. It is often directional, as it is typically higher horizontally than vertically in layered rock. Field trips typically illustrate how and why permeability is different in different directions (see Fig. 7), as noted by a geophysicist:

> Walking and climbing the log has definitely given me increased understanding of rock types that I have not seen up until now with my use of models from mathematics and physics. We simplify porosity and permeability a lot in our models. In general I think that it is actually us geophysicists that get the most out of this fieldwork. We are exposed to a new way of thinking and have to adjust our preconceptions.

Figure 7. Real-life porosity and permeability

We asked several of the participants in the Greenland field trip if the analogues were used in the development of reservoir modelling tools.[9] One of the leading geologists concluded:

> I am sorry to say that the domain of analogues and the domain of reservoir modelling are worlds apart. Our ability to match those data taken during a fieldwork like this and the tools we use for modelling can definitely be improved. Complexity in geological structures is difficult to model mathematically. However, this does not mean that we do not bring this analogue understanding with us when we create the models. They inform our work, reside in the *background* of our practice. (emphasis added)

The trip to the analogue is not about the data they bring back. It provides an understanding of the *background*, as suggested by the quote. The models of the oil reservoir, on the other hand, are data-driven. They are based on the foreground: the codifications of the rock mobilized and brought to the office from the reservoir beneath the sea. On the field trip, this foreground/background relationship is subject to reflection (though not necessarily explicitly), for example when choosing a representative though practically accessible section for logging and when noting down 'representative' properties from a layer. On field trips, the important knowledge is not about the actual porosity of the rock or the height of each layer. These data, though meticulously recorded on the logging sheet, are rarely used later. If the data themselves were the important part, these trips could be outsourced to a few specialists, rather than a large group like this one. In this case, the group has been transforming rock into conventional representations, experiencing the separation of signs from the signified through their own bodies and perception (see also Kastens et al., 2009). The geophysicist cited above says that the analogue resides in the background of their practice. The data are the objects of attention, both on field trips and in the office, but the answer to the question of what comes back from the logging trips is not primarily a set of immutable mobiles (Latour, 1987), but instead a group of professionals with an increased understanding of the context from which geological data are extracted.

Second setting: At the office

The office

In subsurface departments, onshore geologists and geophysicists work in interdisciplinary groups with other subsurface professionals, especially reservoir and production engineers. Though no such engineers were on this field trip, they occasionally are sent on trips to analogues.[10] The task of the subsurface department is to 'manage' the reservoir, which means to locate and produce as much oil as possible from it. In this work, it is crucial to understand the structures of the reservoir and the behaviour of its fluid contents. The specialists from different disciplines cooperate closely in this work. The main contributions from the geoscientists are related to their knowledge of the solid structures of the reservoir, whereas the reservoir and production engineers are more interested in the dynamics of the fluid flow in the pores and cracks. Together, they plan new wells, evaluate information from existing ones, and advise the production facility in how to 'squeeze' as much oil as possible from the reservoir. The subsurface department is also responsible for updating and adjusting the subsurface models after the fluid composition changes due to production, or when new information becomes available about properties and structures of the reservoir.

The offices are like those of most large corporations, except that there are more visualization tools and advanced collaboration rooms. UNIX workstations with large double-screens, and printouts of logs, seismic cross-sections and geological maps can be found in the workspaces. In this setting, they do not have the possibility of climbing the structures, touching or crushing the rock, inspecting the rock visually or taking pictures of it. Few of the subsurface professionals have any contact with the rock in the reservoir, except through maps, numbers in tables, codifications of rock types, measured properties displayed on logs, and so on. Some go offshore to the platform when wells are being drilled, and they occasionally may look with a microscope at a sample of the cuttings filtered out from the drilling mud. But the contrast to the first setting is striking. The touch and feel of the reservoir, its structures and tactile qualities, and its scale and complexity are not presented to their bodies and perception and must be conjured out of the data.

We will first discuss the data from which this is done before recounting some episodes in which interpretation and extrapolation of data appeared to be informed and inspired by analogue field experiences. When describing this process, we must warn the reader that such individual and 'collective imagining' (Murphy, 2005) and guesswork based on vague similarities was not as clearly observable, and as straightforward to describe, as was the logging in the field.

The data and tool use in the office

Though many types of data available at the office can carry information about the reservoir, the most important can be grouped into three main types.

Seismic data record reflections of acoustic waves sent down into the reservoir. By specific arrangements of sound sources and microphones and extensive computer processing, petroleum geologists are able to reconstruct layers and other structures in the rock from contrasts in acoustic properties. Most importantly, such contrasts are supposed to reveal density differences between porous and non-porous rock. The data sets from modern seismic surveys are normally three-dimensional and they cover the whole volume of a reservoir. Its main weakness, aside from errors inherent in the method, is the low resolution of detail. Good quality seismic data will provide an experienced geophysicist with a view of the overall structures of the reservoir, but they will not distinguish thin layers, small faults or other 'small' variations. Nor will they pick up variations that do not influence the acoustic properties of the rock. The theoretical limit of resolution below the reservoir floor is in the magnitude of 15 meters, but in practice it is more than double that limit. Though the principles of seismic data acquisition are not new, there have been great leaps forward with the development of computers, both for processing and three-dimensional visualization. For our purposes, we can regard the seismic

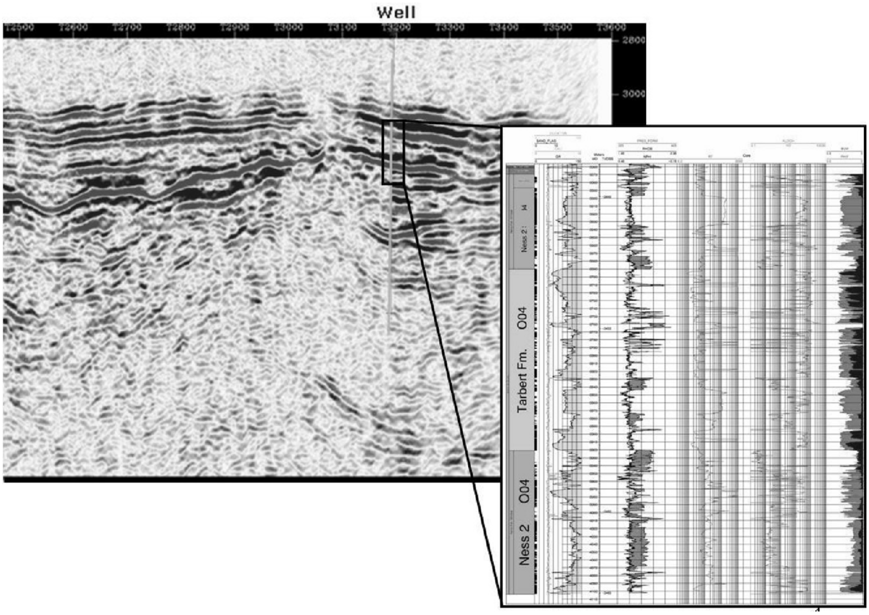

Figure 8. Seismic cross-section with a drawn well. A segment of the corresponding well log is shown to the right. To the left in the log are the names of the formations the well penetrates (like 'Ness 2'). The curves are the results of radioactive and electrical measurements in the well bore plotted in an axis along the well path

charts as blurry, three-dimensional, low-resolution images of the reservoir. Though it is quite easy for a geoscientist to create and use three-dimensional displays, the seismic data are usually displayed as two-dimensional horizontal map-like visualizations or vertical cross-sections (see Fig. 8) cut out of a three-dimensional 'cube'. Different colours in the cube or on the cross-sections represent variations in the acoustic response of the rock. Interpreting these shapes is itself a skill that requires training and experience: a skill that often is described by geophysicists in quite esoteric terms. Well observations are used to correct the depth of observed horizons in the seismics by 'tying them in'. The seismic data set is thus calibrated to fit with the depth of observed horizons in the wells.

Well logs are collections of different data types based on physical measurements performed by tools lowered into the wells, normally in connection with drilling or well operations.[11] The logging company may also document observations of cuttings–small rock fragments cut loose during drilling that are transported to the platform. Thus, the log is actually an information infrastructure onto which different measurements and observations along the well path can be plotted. Some observations require manual interpretation by the logging company, while most of the readings are automatically registered by different sensors (see Fig. 8). Though the data collected are diverse, they are all representations of the properties of the rock, including the fluids in its pores, in *immediate proximity* to the well. For the subsurface professionals, the logs are lines through the reservoir along which they have detailed and trustworthy information, quite similar to the vertical sections in the sedimentological log from the field.

Production data are real-time measurements of the oil and gas volumes transported out of (and in the case of injection for pressure support, pumped into) the reservoir. The pressure development in the reservoir is also monitored. These data give the subsurface group clues about how much oil there might be left in the reservoir, and aid them in optimizing existing wells and planning production. Production data can also give clues for interpreting the solid structures of the reservoir, although always indirectly. For example, the production data may indicate the presence of a flow barrier but not show where it is. Whereas the two other data types can be placed uniquely in space, the production data contain information about the fluids in the reservoir and are thus dynamic. Though it is possible to tell which well an amount of oil flows through, it is not so easy to tell from where in the reservoir it flows.

The reservoir is brought to the shore in a piecemeal way, mainly in the form of these data types. Intricate constellations of artefacts and people divide and mobilize individual properties of the reservoir. Each data type is based on a selective amplification of specific aspects of the reservoir. This is achieved in standardized ways, making the readings mobile, comparable and localizable. When such abstractions representing different qualities are created and brought to the office, they can be viewed together and used for constructing models of the reservoir (Almklov, 2008).[12]

We will now discuss how subsurface professionals try to understand the reservoir by interpreting such data. We argue that they invoke something more, something beyond the data at hand, and that their knowledge of an analogous field helps them 'fill in the blanks' in this reconstruction process.

Extrapolation: Searching beyond the data

Though most of the data are quantitative measurements, tying them together is not primarily a matter of adding up the numbers. Making sense of the reservoir through remote data types can instead be viewed as searching beyond the data, extrapolating one type by creatively interpreting it in light of the other in order to gain knowledge about the ground from which the data had been abstracted. Extrapolation from observations has always been an intrinsic element of geology. For example, speculation about the extension of veins of metal ore based on the observation of outcrops and mine shafts has a long history in geology. Such considerations are similar to those made when choosing a representative logging site: What volume of rock can a data point be said to represent?

The well log (Fig. 8) provides the geologists with data that have great detail and quality compared with what they know about the rest of the reservoir. These scattered lines of trustworthy information from the well paths through the reservoir supplement the vague shapes provided by the seismics. As mentioned earlier, well data are used to correct the depth of the seismics. Logs and seismic data also are used together, and complement each other, in interpretive extrapolation. The well log provides a starting point for speculation about rock structures that are too small to resolve with the seismics. The seismic data in turn are useful for interpreting the logs, by providing an overall image of the rock volumes around the well. Typically, the seismics aid speculations, for example, about how far a good oil-containing sandstone zone extends outwards from the well. Such exercises were common in one of the fields we studied, where the remaining oil-filled layers were well below seismic resolution in thickness and only possible to see on logs. To understand how these thin layers were extrapolated from the well data, imagine a geologist standing in a field in Greenland, drawing horizons outwards based only on data that the groups collected from their stratigraphic columns. The logged columns are, like the well log, thin lines along which rich and high resolution data are collected. To appreciate the contribution of the seismic, imagine them watching the outcrop from afar, being able to see only the general structures but not the individual zones. The simplest and most typical assumption would be made when the structures seen on the seismics above and beneath these thin layers were quite similar. Then the geologists would normally suppose that the layers in between those layers had the same shape, and they would draw horizons extending outwards from the well based on the shapes of the nearby horizons that they could actually *see* on the log. By means of such extrapolation they could construct knowledge about the parts of the reservoir on which there were no data. They could access the area beyond the reach of all the sensors of the well log, and way beneath the seismic resolution. Such extrapolation often focused on visual patterns of the seismic, but the speculations about the kinds of geological structures the data represented and the geological order or pattern behind the data also informed their interpretations. When the extrapolations were difficult or contested, such speculations were made explicit.

During drilling and well operations, the extrapolation from logs is important for evaluating and making decisions about the new well. Due to the pace and cost of operations, they must be made quickly. For example, it is important to evaluate the volume, porosity, permeability and extension of the oil zones that the drill bit penetrates when choosing the production strategy for the well (Almklov, 2008). Although the sensors in the well-logging assembly have short range, the observations of a single well can alter interpretations of large areas. One of us witnessed a situation where a new well showed surprising log data that 'made no sense', suggesting that the geologists' conception of this segment of the reservoir was wrong. Several possible explanations were put forward for why an expected oil-bearing zone was 'missing' on the log. The subsurface team needed to decide whether to sidetrack the well and go for the planned backup location, or to continue drilling more deeply into the chosen segment. To proceed, they had to make sense of what this observation could mean about the geological structures. The most experienced geologist was studying the seismic intensely, amid the hectic discussions in the collaboration room. After a while, he raised his voice and suggested an explanation for the strange log data. He suggested that there was probably a fault beneath the seismic resolution, and made a pencil drawing of a fault pattern where big landslides were accompanied by patterns of smaller ones. He assumed that such a landslide pattern was probable from the pattern of the visible faults, though he had no direct evidence of the smaller faults. Faults are potential flow barriers and they indicate that layers may have been shifted up or down. Thus, any speculation about the extension of zones observed in the well would have to take these possible faults into account. The pattern he proposed would explain the strange well data. As his theory was later strengthened by new data from the well, it changed their conception of that part of the reservoir. The seismic data had not been wrong, but the geologists' probably had made erroneous assumptions about the structures beneath seismic resolution. The aberrant logging data challenged, and eventually changed, their conceptions of the background. Later, in an interview, the geologist explained his interpretation by making reference to the field's analogue in England, where he had taken several field trips and in which similar landslide structures are visible. This was one of the more explicit examples of how analogue field experience directly informed the interpretation of data sets in the office. More often, extrapolations were drawn and estimates of the representativeness of well data were made in a more low-key way.

'Soft' extrapolations of hard data are actually the more common kind of information about oil reservoirs. Also in the office '[g]eologic seeing is ... a series of daring imaginative leaps disciplined by examination and measurement' (Frodeman, 1996: 426). Different subsurface specialists hold more or less idiosyncratic ideas about what is beyond the range of the myopic well log and beneath the resolution of the coarse, blurry seismic images. Such ideas sometimes manifest when data are discussed and extrapolations are drawn as cartoon-like figures on whiteboards, paper or computer screens, thus integrating the discussion of the fragmented data. The full-field reservoir models are largely based on similar principles but constructed in extensive collaborative projects lasting for months or years, when all available information is sought for integration into a single model. As one of our informants put it, it is necessary to stretch the data 'beyond one's comfort zone' when making models that cover the entire reservoir. The geologists need to extrapolate the data in order to fill in all the blanks, and they must make compromises when doing so. These cartoon-like models, with their solid lines covering the unknown, in many ways serve to obscure the fact that the data supporting the drawn objects vary from being reliable when near the wells to being flat-out guesses in other areas.

Conclusion

We set out to describe how field experience gained on an analogue on dry land informs the interpretation of remote data from an offshore oil field. We found that fieldwork experience from a similar site helps subsurface specialists to creatively connect and integrate fragmentary information from the oil field.

On East Greenland, geology is flesh and blood, and the body is an inescapable vantage point for both artefact use and developing analogical reference. Geology here is a practice immersed in nature, as instruments and artefacts are combined with presence and sensual perception. The field trip is an embodiment of knowledge of the analogue field and, by way of analogy, of the oil reservoir. In addition, we suggested that the artefact use and codification on the trip is a form of practiced reflection on the relationships between different codifications and what they codify. By crushing rock with a hammer, looking at it through magnifying glasses, recording its properties on data sheets, and drawing sketches of it from different perspectives and distances, practitioners familiarize themselves not only with the geological formation, but also with how different amplification–reduction structures transform it, and how conventional codifications relate to it.

When watching geologists in the field, we noted how they interact with both the terrain and their visual representations of it. The main exercises during such field trips are to translate the terrain, not into any naturalistic picture, but into an abstract *eidetic* image, representing the rock through the professional vision of geology (Lynch, 1990).

As a learning experience, a trip is not merely about feeling the terrain, nor drawing geological maps or generating logs. It is also about the link between the two, about the coding of the rock formation into the language of the geological community. It is an epistemological experience as it fosters reflection on what knowledge is really contained within the data at the office and, more importantly, *what is not*.

The practical task of logging fosters the development and embodiment of a hermeneutic understanding of the field through a repeated movement between small-scale perspectives of different rock properties and large-scale perspectives of formations and cross-sections. Since the trips provide opportunities to develop personal experience and to reflect upon the conventional representations of it, they also serve as a natural grounding for the institutions of the geological episteme (Douglas, 1986), and, more specifically, the geological units they use in their daily work.

We described the challenges facing the subsurface professionals at the office when they try to envision and understand the oil reservoir. Their artefacts no longer supplement the sensual experiences of the field trips, but instead provide interfaces with the phenomena. The tools fill a *mediating* role. A subsurface professional experiences the phenomena he or she studies *through* representational artefacts. We argued that experience from analogue trips has an important place in the repertoire of interpretation, as it allows practitioners to discuss the characteristics of the data and to address generic problems presented by the fragmentary information they have on the reservoir. The analogy provides a background that gives meaning to their data.

We discussed how knowledge from analogue trips informs the extrapolation of the detailed data collected along existing well paths. Where the geologists only have shadowy coarse images from seismic surveys, such extrapolation enables them to extend outwards from the data into the volumes of rock. Analogical reference also can help them see more from combinations of data than is visible in their surface features. Earlier, we asked, what comes back from the field trips? One thing that is brought back is experience that aids them in situating immutable mobiles in a context. Their embodied and reflexive knowledge enables them to see how the data as text rests on a context or background that is *similar* to the analogue they had visited.

Onshore, an educated guess based on experience is better than a random one. Guessing and extrapolation have weak argumentative power. The result is often indistinguishable from the person who guessed, and it fits poorly within the discourse of engineering. Though reference to analogues as inspiration for extrapolation and interpretation is made occasionally in discussions, it seems that this knowledge 'resides in the background' of the work, as one informant stated. It is the data that are explicitly discussed, and reside in the foreground. On the field trips, our informants collected data out of a context in which their body was immersed. When 'recontextualizing' (Almklov, 2008: 876) the data at the office and envisioning the reservoir they may represent, this knowledge of a field that has some similarity to the reservoir below the bottom of the ocean is a creative resource that may be invoked by a drawing or when looking at a well log and trying to make sense of the rock around it.

We focused here on field trips to analogue sites and they inform reservoir geology. We believe that this process has general importance. First, although analogue trips are important, subsurface professionals base their guesswork not only on experiences from trips, but also on all sorts of personal and collective experiences that draw upon other operations, other oil fields, and theories, among other sources. The sources of analogy thus are *not* limited to analogue fields. Second, geology is a field with an explicit tradition of creative extrapolation and imagination, but we suspect that in other contexts and other sciences, a holistic grasp of fragmentary data also rests on analogies (Hesse, 1966). Such analogies enable practitioners to master their fields by filling gaps beyond and between their fragmentary immutable mobiles.

This article covered two essential elements of geology as a discipline: its fieldwork practices and its methods of interpretative extrapolation, of generating an integrated understanding of the reservoir out of fragmentary observations. Though most methods of data collection in the field could be viewed as applications of chemistry or physics, extrapolation based on field experience makes geology a distinct discipline. In this article we have shown that these extrapolations rest on a wide knowledge base, from which the ability to draw inferences based on analogy is a key component.

Notes

We are indebted to the three anonymous reviewers and Michael Lynch for valuable input in a highly constructive review process. Thanks also to the subsurface professionals that gave valuable feedback on earlier drafts of the paper. The work with this paper has been supported by the Center for Integrated Operations in the Petroleum Industry at NTNU.

1. See Bateson's (1972: 129–133) discussion of 'meaning' as patterns or restraint of possibilities, which gives the perceiving guess with better than random success, in our case about the oil reservoir. Much work has been done on analogue reasoning within psychology: see Gentner and Holyoak (1997), and Vosniadou and Ortony (1989).
2. See Peirce's (1958) discussion of abduction, of perceiving some similarities of pattern and guessing that more may be present, and its importance in science alongside induction and deduction. This was elaborated later by Bateson (1979), who regarded this process as pivotal both in human perception and in scientific reasoning.
3. Like Ingold (2000: 166), we understand perceptual activities to consist 'not in the operation of the mind upon the bodily data of sense, but in the intentional movement of the whole being (indissolubly body and mind) in its environment'.
4. For a discussion of different approaches to embodied cognition in relation to science and mathematics, see Núñez et al. (1999: 47–53).
5. Not be confused with the strong programme in the sociology of scientific knowledge.
6. Rudwick (1996) has also carried out interesting research on geological travels as a source of theoretical innovation.
7. A continental shelf is the relatively shallow underwater area proximal to a continent. It consists of sedimentary rocks eroded from the continent through time, and under certain conditions will contain hydrocarbons.
8. Interestingly, the geophysicists in the author's logging team raised questions about why they logged upwards from the bottom of the structure and not the other way around. The procedure felt 'unnatural' to some of them, who were not as trained in the same field as the geologists and were more used to remote data coming in from the top.
9. A reservoir model is a mathematical model in which the reservoir is represented as grid cells. Each cell contains information on a handful of properties, such as rock type, porosity, and permeability, which emulate the perceived characteristics of oil, water, and gas in the reservoir, faults, and stratigraphic layers.

10. In one of the departments, the policy was that all new subsurface professionals were to go on a field trip to one of the analogues within 2 years.
11. See also Bowker's (1994) study of the early days of well logging.
12. The office is arguably a 'centre of calculation' (Latour, 1987: 232ff.) due to the fact that its power consists of its control of an array of immutable mobiles. Calculation is, however, only one way that data are combined in this case.

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Biographical notes

Petter Grytten Almklov has an MSc in Geological Engineering, and received his PhD in Social Anthropology from NTNU in 2006. He is currently Senior Researcher at NTNU Social Research, working with epistemology and knowledge representation in the oil industry, as well as occupational and societal safety.

Vidar Hepsø received his PhD in Social Anthropology in 2002. He is Adjunct Professor at NTNU, Department of Petroleum Engineering and Applied Geophysics, and Principal Researcher in a Norwegian oil company, mainly focusing on knowledge work, technology and organization, especially with regards to ICT.