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Ane Bang-Kittilsen

Improving Geoscience Maps for Non-Experts

Applying Cartographic Research Methods to Governmental Map Development

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Thesis for the Degree of Philosophiae Doctor

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Norwegian University of Science and Technology
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Preface and acknowledgements

The research presented in this thesis was conducted as an employee at the Geological Survey of Norway (NGU) while I was a PhD candidate at the Department of Civil and Environmental Engineering of the Norwegian University of Science and Technology (NTNU). This work was carried out under the supervision of Professor Terje Midtbø (NTNU) and co-supervisor Dr. Malin Andersson (NGU).

I owe gratitude to my leaders including the board of directors at NGU for the unique opportunity to do a PhD within cartography, not previously done within the survey, to my knowledge, which I could not refuse: Gisle Bakkeli, Frank Haugan and Morten Smelror.

The field of cartography is and has been an endless wellspring of inspiration for me, starting during my time as a Master's student with the lectures and discussions with my supervisor Axel Baudouin at the Institute of Geography, NTNU, extending into professional collaborative endeavors involving maps at the Norwegian Institute of Bioeconomy Research (NIBIO) and NGU. Cartography provides an opportunity to employ creativity while pursuing utility, blending the practicality of a tool with the expressive nature of visual art, all encapsulated within the map.

I want to thank my supervisors Terje and Malin for their invaluable guidance and unwavering support, and my subsequent leaders for sustaining this opportunity. Furthermore, I would like to express my gratitude to colleagues at NGU, among them Louise Hansen, Guri Venvik and Anne Liinamaa-Dehls. I also want to thank all those who assisted in distributing and participated in the experiments.

For my beloved kids Tale and Gard. I hope you continue to discover and pursue paths that are inspiring and fulfilling, and that bring you joy.

Abstract

Traditionally, geological maps have been tailored for a specialized audience, demanding domain knowledge for meaningful use. However, in response to contemporary societal challenges and the growing call for increased openness and transparency in public governance, there is a pressing need for geoscience maps that are accessible and comprehensible to a wider and more diverse range of users. As digitalization offers new possibilities and faces increasing demands, a vast amount of geological data and knowledge is accessible and machine-readable through standardized services. Despite these advancements, practical experience indicates that these maps are not utilized to their full potential, and there is a concern that they may not be comprehended accurately. It is imperative to enhance the comprehensibility of these maps for a broader user base and ensure their usability by both people and machines. This highlights a gap between geoscience map production efforts and insights from cartographic research.

Within geoscience, a rich tradition of map creation exists. Nevertheless, there remains a disconnect between geoscience and cartographic research. This study addresses this gap by integrating cartographic research methods into the geological map production process. The study started by identifying and studying specific challenges within geoscience visualization. This was done by exploring a broad range of materials, along with workshops and discussions with peers within this and other geological organizations. Then, three consecutive experiments were performed in the period of October 2016 and December 2021 to study these challenges in-depth. The primary objective of the first experiment was to examine participants' cognitive representations of the city's subsurface through the analysis of sketches they drew. The findings indicated a general lack of detailed knowledge and shared graphical and linguistic framework. However, it is also possible to see the contours of a common cognitive image of the subsurface, which can facilitate the communication of geological information in the urban environment. This approach involves employing cross-sections, recognizable landmarks, and associative patterns.

The subsequent experiments were conducted on the web, primarily to access a broad and diverse pool of participants. For the second experiment, groups of participants were shown different cross-section alternatives to enable a comparative analysis of how various visualizations affected uncertainty assessment. The results indicated that a more detailed reference map or the use of smaller symbols tends to decrease the sense of uncertainty. Additionally, the dashed line proved to be a reliable convention for representing uncertainty. Furthermore, it was concluded that

uncertainty should be visualized to create awareness of its existence, and more techniques need to be developed, preferably across fields, to visualize various kinds of uncertainty and absence.

In the third experiment, three official geoscience hazard maps were tested. Symbol intuitiveness was compared based on the answers of 450 participants presented with different map alternatives. The results highlighted the importance of dedicating time for testing and evaluating map design. As with the former experiment, findings indicated all elements in the map must work together to ensure proper comprehension. Incorporating map experiments into map development provides a valuable framework for interdisciplinary cartography discussions, enriched by both expert insights and empirical evidence, to inform design decisions.

This research aimed to translate its findings into practical applications. A holistic model for map development is proposed, emphasizing learning and evaluation phases to promote knowledge-driven map creation. By bridging the gap between geological expertise and cartographic insights, this aim is to enhance the impact of geoscience maps, facilitating informed decision-making in society.

Purpose

In this introductory section, the objective is to provide an overview of both the articles included in this thesis and the supplementary work that extends beyond their scope. Furthermore, this section aims to explain how these efforts are connected within a larger cartography framework. Special attention is devoted to ensuring the practical applicability of the outcomes for future endeavors in map development, particularly at the Geological Survey and potentially analogous data-providing institutions.

This is a cumulative thesis comprising three published and peer-reviewed journal papers. Each article corresponds to a separate experiment.

- Chapter 1 presents the rationale and research questions.
- Chapter 2 covers the theoretical foundations.
- Chapter 3 details the methods used.
- Chapter 4 includes a summary of the main contributions, including the relevant publications from the author.
- Chapter 5 discusses the findings and provides an outlook for future research.

Contents

Figures and tables

1 Introduction

This chapter covers the significance and importance of the research within this project, including a short introduction to the increased demand for geoscience maps for non-experts. Subsequently, the limits to earlier research and the aim and research questions for this study are presented.

1.1 Significance and importance of the research

Since our physical and cultural surroundings are complex, often a simplified representation of the world is used as the basis for decisions in society. Thus, it is the representations that are the reality we act upon (Boulding, 1972). From this perspective, it is easy to acknowledge the responsibility of the cartographers.

Gersmehl (1985, p.334) suggests the following three responsibilities for the cartographer:

> "A person who puts information on a map has a duty to be fair to the data, to be clear to the map reader, and to try to anticipate the ways in which a third person may be affected by a foreseeable misinterpretation of the map. At the very least that third duty should include a resolute refusal to display or even imply any more accuracy and precision than we can justify."

To maintain a knowledge-driven management of society, trust is crucial. An open and transparent government is a prerequisite for this trust. International and governmental initiatives are drivers for making geospatial data open and freely available. However, these initiatives mostly guide the technical aspects (for example, INSPIRE, 2023) and do not ensure that the maps are understandable and that users know how to use them. Delivering data in the correct technical way does not alone ensure usability or utility. This study aims to improve maps delivered to the non-experts by applying cartographic research methods in map development within a geological survey. More specifically, the objective is to study how users imagine the subsurface and interpret geoscience map symbolization to find action points and guidelines for better practices.

1.1.1 Societal challenges in need of geoscience maps

Geoscience knowledge is increasingly needed to meet societal challenges connected to climate change and urbanization. Climate change leads to more extreme weather. More heavy rainfall increases the risk of landslides (Gariano & Guzzetti, 2016). Sea level rise leads to increased coastal erosion (Zhang, 2004). Urbanization influences the natural water cycle, with its impermeable covers of asphalt and buildings, and human-made handling of water in pipes. Lowered ground water levels can lead to subsidence and unstable ground (Venvik et al., 2020; Pacheco-Martíneza, 2013) and heavy rain can lead to flooding. Society also needs a supply of resources for urbanization, for example water, minerals, aggregates and building materials such as dimension stone. In the new mineral strategy for Norway, it is stated that "large quantities of minerals and metals are required [..], and global demand for the metals required for the green transition will continue to increase [to succeed with the green transition and achieving a zero-emission society]" (Ministry of Trade, 2023 p.9). Thus, the need for knowledge about the geology of the subsurface is increasing. The main communication channel for knowledge about geological resources and risks to society is geo-referenced information through standardized Spatial Data Infrastructures (SDIs). Along with other thematic and base maps, geological knowledge is delivered as data and maps showing drill holes, observations, point and linear features like faults and area features like surficial deposits and bedrock.

Demand for simple and easy-to-use maps

Geological maps have traditionally been made by experts, for experts, and implies "an initial knowledge threshold for use" (Häggquist & Söderholm, 2015. p.99). There is an increasing demand for and delivery of simplified, derived products that are intended to meet specific challenges and reach the broader user group of planners, decision makers and experts in other domains. However, the challenge to communicate the complex geology of the subsurface, often dominated by interpretations and uncertainties, through a map, to a non-expert, for quick and easy decisions-making, must not be underestimated. There are significant concerns that the knowledge is not used adequately, for example using the map without understanding its limitations (van der Meulen et al., 2016).

Geology is, according to Jain (2014, p.1), "the study of earth, its materials, processes that affect them, the products formed and the Earth's history since its birth, 4.54 billion years ago". Bedrock is made and remade through earth crust processes, with unthinkable strength, forcing movements and distortions. At the same time, water, wind and ice mark the material closest to the surface. The landscape is formed by weather processes, but also floods, avalanches, rockfalls and human activity (Ramberg, 2008).

Multiple sources of uncertainties exist within the representation of the mostly intangible and invisible subsurface. Errors can occur in observations and measurements, in geological interpretations and while processing data before making them available for others (Bond, 2015; Longley et al., 2005).

The prevailed high value of 2D representations

A map makes it possible to perceive spatial information and patterns at a glance. Within geology, a main trend during the last decades has been 3D-modelling and -visualization. It is commonly assumed that a 3D illustration will make it easier to understand the geology for the novice user. This is because the ability to look at a 2D map, and from that being able to envision it as 3D-elements requires years of training. For some geological surveys, like the Geological Survey of the Netherlands (TNO), the transition from 2D to 3D-mapping is done and 2D map sheets are replaced by 3D subsurface modelling (Stafleau et al., 2019; van der Meulen et al., 2013). There are also many geological web-based 3D-viewers in use (Bang-Kittilsen, 2019). In Norway, 3D is commonly used in the oil industry and large infrastructure projects. At the Geological Survey of Norway, it is also mostly project-based (Jarna et al., 2015). From the informal discourse from a series of workshops on geological modelling (European 3D Geological Modelling Community), the impression is that while most agree data should be modelled and stored in 3D, 2D is still seen as by many as most effective for communicating geology to the broad user group. 3D is still immature as a knowledge source, at least through the standardized pipelines of the open government. 2D maps are the standardized way of delivering data into the official Norwegian knowledge base, and the geological products from that are adapted to societal tasks like area management and decision-making today. For the topic of this study, cartographic communication in 2D-products will benefit both worlds.

1.1.2 Limits with earlier research

Montello (2002, p.298) states that academic cartography in general, although carried out with great quality, "has not connected well with production cartography". There is extensive cartographic research on map design and use (Roth et al., 2017). However, for professionals making thematic maps in other fields of science, cartography is commonly, at best, a secondary competence. They are not likely to have the time to be updated on cartographic research.

Roth et al. (2017) call for a shift from convenience participant sampling where fellow students and employees of a university are recruited. They emphasize purposeful sampling, both to obtain a sufficient number to make statistically sound analyses and to reach representative and actual users. For the example of user studies for interactive maps, the median participant number is 31 participants, while focus and interviews have less than 15. These numbers and the diversity they represent are aspects that Roth et al. suggest should be expanded. For web-based studies, the median is 84 participants (Roth et al., 2017).

Roth et al. (2017) emphasize the importance of case-studies in cartographic research to highlight challenges in existing practice. It is hard to find relevant examples of cartographic research conducted within map production organizations. Harding (2013) carried out tasked-focused user interviews to identifiy factors that implicate the usability of geographical information delivered by the Ordinance Survey. In-house governmental research pushes towards a holistic approach, to ensure relevance and quality over time both on a product and organizational level.

1.1.3 Objective and focus

This study separates itself from previous studies in combining the following:

- Cognitive map-design research.
- Performed in-house a map producing organization (Geological Survey of Norway).
- Identifying and targeting the specific challenges faced with geoscience maps.
- Including a high number and representative group of participants in the experiments, both experts and non-experts.

The objective is to narrow the gap between what experts and non-experts can draw from our maps. That is, to improve communication of our geoscience knowledge for non-experts. Geoscience data collection is mostly set in geologist-driven long-lasting mapping projects. The maps are shared as standardized services to the public knowledge base, and the users mostly use their own geographical information systems or web portals. Both areas would require a larger trans-disciplinary project to make an impact. The focus was therefore set in the middle, on optimizing map symbolization (see Figure 1). This figure will be elaborated on and explained in detail in the discussions chapter.

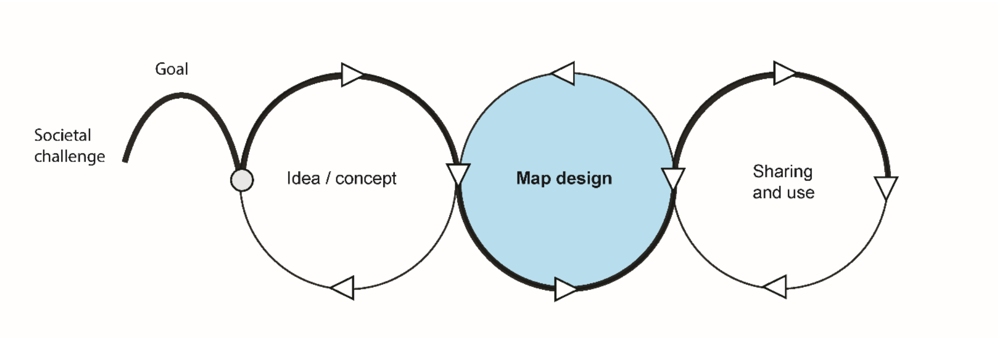

Figure 1 Map design is the focus of this study.

The study first started with an open-ended exploration of geoscience visualization, with a focus on identifying and discussing challenges for further studies. Secondly, the cognitive maps of the users, central to cartographic communication, were studied. Thirdly, the focus is on addressing the primary challenge identified: Communicating uncertainty effectively and understanding how various visualizations influence the perception of uncertainty. Last, improving ongoing map design and map development by applying cartographic research methods.

1.2 Research questions

The main objective and overarching research question for this study was:

1. *How can geoscience map products for the broader user group be systematically improved?*

Geoscience visualization challenges: To define the scope and focus for the research, the second research question, was:

2. *What are important challenges with geoscience visualizations that need to be met (within governmental geoscience core activities)?*

The cognitive image of the subsurface: Keeping the work open-ended, the lens was then directed towards the user. Elementary for cartographic communication are our cognitive maps, and the common image beheld by the inhabitants. A lot of research is done on cognitive maps of the city and environment, but not the subsurface. There are important differences between topographic and geological features. The next research questions were therefore:

3. *What can be learned from the cognitive images of the geological subsurface?*
4. *Do people share a cognitive image of the subsurface and if so, what are the key elements of such a perception?*

Visualizing uncertainty: One of the main challenges identified with geoscience maps is communicating uncertainties. Uncertainty arises because precise measurements and observations of subsurface geology are difficult. The research question for the second experiment was:

5. *How do different visualizations affect the map reader's sense of uncertainty?*
6. *How can uncertainty be visualized in geoscience standard products?*

Make better maps: Aiming to improve the standard geoscience maps offered by the governmental unit The Geological Survey of Norway, the last research questions complete the full circle in the main objective:

7. *How do differences in map symbolization affect map intuitiveness?*
8. *What can be learned and how can map research be applied within governmental map development?*

1.3 Relevant publications

In the appendix the following relevant publications as part of the thesis are included:

Article 1: The image of subsurface geology.
Bang-Kittilsen, A., 2020. The image of subsurface geology. *International Journal of Cartography*, 6 (2), 222–240. https://doi.org/10.1080/23729333.2019.1637489

Article 2: Imaging the subsurface: How different visualizations of cross-sections affect the sense of uncertainty.
Bang-Kittilsen, A. & Midtbø, T., 2021 Imaging the Subsurface: How Different Visualizations of Cross-Sections Affect the Sense of Uncertainty. *Journal of Geovisualization and Spatial Analysis* 5 (1). https://doi.org/10.1007/s41651-020-00071-6.

Article 3: Improving intuitiveness in geoscience hazard maps: A web-based experiment supporting governmental map development.
Bang-Kittilsen, A. and Midtbø, T., 2024. Improving intuitiveness in geoscience hazard maps: A web-based experiment supporting governmental map development. *Cartography and Geographic Information Science*. https://doi.org/10.1080/15230406.2024.2314541

1.4 Comments on authors contribution

The research is based on the authors idea and the author performed all experiments, analyses, and writing. The author is the first author of all articles. Supervisor Terje Midtbø has contributed with input on the method and the conducted research. Guidance and feedback throughout all experiments, analyses, and writing processes were given by supervisor Terje Midtbø and co-supervisor Malin Andersson.

2 Theoretical foundations

This study builds on the tradition of cognitive map-design research; however, an additional objective of finding actions to improve organizational practices was added. In this chapter, the specific theories used in the research are presented. First, the basics of cartographic communication and graphical semiology are presented. That is, some fundamentals for understanding the key role of symbols in map communication. A special focus is given to uncertainty visualization, as this is especially important in geoscience. Second, a short overview is given to user-centered design, as the second dimension to this map design research is to improve map design practice within the survey.

2.1 Communicating through maps

Maps and visualizations can be tools for documenting, analyzing to discover new knowledge, and communicating knowledge (Bertin, 2010). The latter is the most relevant aspect in relation to this research. See Figure 2 for a common model of map communication. Knowledge is stored as content of the mind. This knowledge is important for both navigation, reasoning, inference, memory (Peer et al., 2021) and therefore for map reading.

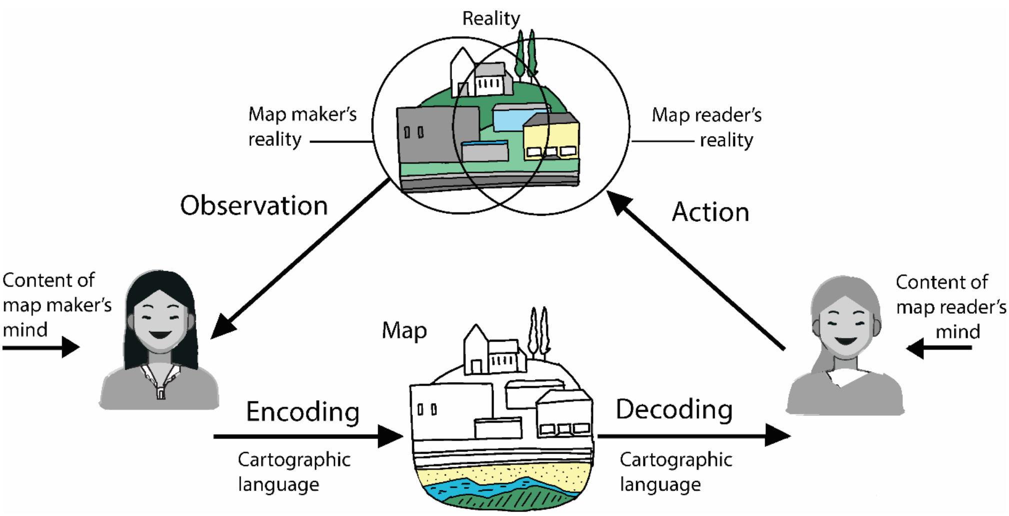

Figure 2 A model of cartographical communication (after Koláčný, 1969)

2.1.1 Cognitive maps

A cognitive map can be defined as "a representation of allocentric spatial relations of objects with one another in a specific environment" (Farzanfar et al., 2023, p.64). According to Boulding (1972), an individual's subjective knowledge framework is referred to as their "image." This image is a mental representation of the world that is shaped by their experiences, beliefs, and values. It plays a crucial role in influencing their actions and decisions, he argued, as it provides a lens through which they perceive and interpret the world around them. Neuroscientists today are trying to establish how spatial information is stored in the brain. Peer et al. (2020) suggest spatial information have both a map-like and a graph-like form in partially overlapping neural systems. Although not treated further in this thesis, it should be noted that Peer et al. argue that graph-based is the preferred system in "dense forests, complex buildings and cities without organized axes" (p.47). This could possibly have relevance in how we store information about spatial geology.

Parts of our cognitive image are shared with others: "The development of images is part of the culture or the subculture in which they are developed, and it depends upon all elements of that culture or subculture" (Boulding 1956, p.16). Montello (2002, p.283) suggests that "in a sense map design can be seen as mind design: The way a map is designed will influence the views of the world it simulates or inhibits". The representation of the world creates the reality which society makes decisions from. As opposed to a survey, interpreting words and images may reveal things not previously known for the participant (Aase & Fossaskåret, 2014).

Cognitive maps have been given many different meanings (Langfield-Smith & Wirth 1992) and are used widely in applied research, from studying conceptual space (Nathalie et al., 2007), network representations of causal beliefs (Langfield-Smith & Wirth, 1992) as well as our relations to our environment and physical space (Lynch, 1960; Stea & Downs, 1973). The concept of mental map is more commonly used and is well established in geography, behavioral science, and psychology (Götz & Holmén, 2018). The concept is best known from research into our understanding of space, primarily to understand how we navigate based on lab experiments with rats and how it is physically constructed and used by our brain (Tolman, 1949; McNaughton et al., 2006).

Within geology, research on cognitive images has been performed within education, and typically focuses on the development of spatial abilities and the ability to envision geology in 3D (for example Kali & Orion, 1996). Cognitive mapping has also been used to compare novices and experts in their spatial reasoning, for example structural geology (Shipley, 2013). Comparing fresh students with experts can give an idea of how non-experts envision the subsurface structures and processes.

2.1.2 Semiology and semiotics

The concept of semiology was introduced by linguist Ferdinand de Saussure (Cobley, 2014). He described how we communicate through conventional codes, a signifier (for example a word) and signified (what the word represents). The bound between the signifier and signified, he said, is arbitrary. If we were to agree, the name could be replaced by something else (Cobley, 2014). Yakin and Totu (2014) presents Saussure as the proponent to the thought that "language does not reflect reality but rather constructs it" (p.6). American philosopher Charles Sander Peirce added to the theory presenting a triadic model for a sign: an object, and representamen and an interpretant. He argued that a sign never can have a definite meaning, but that it needs to be continuously qualified. Peirce called the study of signs for semiotic, categorizing signs into icons (resembles its referent), indexes (associated with its referent) and symbols (related to its referent only by convention) (Yakin & Totu, 2014). Semiotics "is the study of how meaning is generated and interpreted through signs and symbols" (Mingers & Willcocks, 2017, p.2). Shilina & Zarifian (2023) states the differences between Saussure's theory of *semiology* and Peirce's *semiotics* are that the former investigates the role of signs as part of social life, while the latter aims to construct a "formal doctrine of signs". According to Ware (2009), semiotics has been dominated mostly by arguments based on example rather than formal experiments.

2.1.3 Cartographic language

According to Li et al. (2021) there exist two significant theoretical frameworks pertaining to map language or cartographic language: the theories of cartographic communication and the semiotics of graphics. Cartography as a science of communication is well established (Morrison, 2011; Board, 1978). An early linear communicational model shows how the cartographer encodes information to make a map, and then the user decodes the map. Drawing on aspects of information theory to rationalize the process of transferring knowledge from the mapmaker to the map-user, its aim is to optimize 'map effectiveness' by treating the map as a vehicle for communication (Kent, 2018). The best-known model of cartographic communication, is by Koláčný (1969), see Figure 2 for a simplified version. The contents of the cartographer's and map user's mind occupies a central place in the model.

The second body of knowledge related to cartographic language is the Semiology of Graphics from 1967 (Bertin, 2010), which will be described here in more detail. Bertin places graphics as a sign system alongside language and mathematics. With the aim of helping the statisticians make better graphics, he explained how to make effective graphics by choosing the right visual variables for the information by matching organizational level (nominal, ordinal and quantitative) and variable length (number of classes or categories). He also emphasized that new knowledge could be found through graphical data processing, by reorganizing and reordering data until patterns are identified (Bertin, 1981). There were critics, mostly towards the cookbook-structure of the book, with a lack of references to previous research (Rød, 2000; Muller, 2006). Despite this, his theoretical framework has become a natural part of any textbook in cartography and is also significant outside cartography (Harvey, 2019).

Bertin (2010) described eight visual variables: *shape/form*, *value*, *texture*, *color, orientation/direction,* and *size* in addition to *location*, the spatial variables x and y (see Figure 3). Since Bertin's seminal work in 1967, there have been numerous efforts to expand upon his theory of the seven visual variables. The transition to digital cartography has facilitated these endeavors, offering expanded possibilities and capabilities. The inclusion of three new variables—*crispiness*, *resolution*, and *transparency*—has been suggested for representing uncertainty (MacEachren et al., 2012; Roth, 2017). Also *color value* and *color saturation* are added (Roth, 2017), replacing Bertin's *value* variable, defined as a variation in lightness (2010). One of Bertin's (2010) variables, *texture*, is changed to what Bertin called "density" in an overview by Roth (2017) while *texture*, as it was explained by Bertin, is missing. This variable is characterized by a constant relationship between the area covered by foreground (black) or background (white), for example, increasing the diagonal line size together with the same increase in the distance between the lines. It can represent ordered data. See Figure 3 for an overview of visual variables, where *texture* is reinstated in its original form, *color value* and *saturation* replace *value*, and the word *sharpness/blur* is selected over *crispiness*.

The properties Bertin used to describe the visual variables by, are associative and selective in addition to nominal, ordinal and/or quantitative. A a selective variable makes it possible to see patterns though the immediate recognition of a group of signs based on a change in the variable. With an associative variable, symbols can be perceived as a group despite differences in this variable (Bertin, 2010). According to Bertin, the data should be represented by visual variables with the same characteristics as the data. Using visual variables at a higher level can result in adding detail that is not present in the data. Using visual variables at a lower level, results in reducing levels of detail and preciseness. If this is not correctly done, the map would be less effective, or even fail, in communicating the content. The number of categories or classes (variable length) is subject to perceptual limits, which means there is a limit to how many distinct variations of a visual variable can be effectively perceived. To ensure good contrast with numerous classes, one approach is to combine two variables (redundance), such as *color value* and *size*. For ordered data, a scale with values in one direction is called a sequential scale. When a value scale stretches in two ways, for example temperatures below and above freezing point, or a breakpoint for risk map action, a bipolar scale with diverging symbols can be selected. This is called a diverging scale or bivariate mapping.

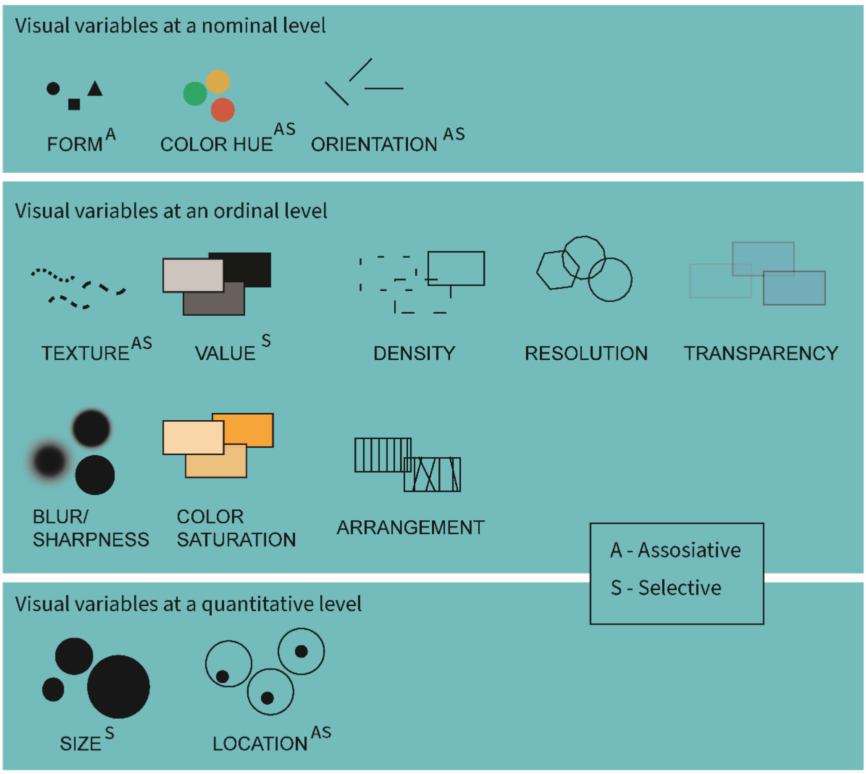

Figure 3 Visual variables according to their typical use (after Bertin, 2010; Roth, 2017).

Symbols with varying visibility create the perception that the most prominent and easily discernible symbol holds greater significance (foreground). Consequently, the most important categories should possess greater prominence within the image, while less relevant ones should fade into the background. Similarly significant categories ought to exhibit uniform visibility.

2.2 Visualizing uncertainty

Representations of the world are always incomplete and contain uncertainty (Longley et al., 2005). Data can be "subject to measurement error, out of date, excessively generalized, or just plain wrong" (Longley et al., 2005, p.127). A short introduction to uncertainty visualization is presented in Article 2. Uncertainty in maps has an increased focus across fields, especially connected to the discourse on climate change (Padilla et al., 2021; Bond, 2015).
An important premise for representation, not treated here, is how uncertainty is captured. This will set limits to its representation. In the same way, the most effective representation to aid effective and adequate use should be a premise for how uncertainty is registered. The focus here will be uncertainty visualizations for two-dimensional maps and profiles.

2.2.1 Typography of uncertainty and absence

As explained in the introductory chapter, uncertainty visualization is especially relevant for geology. Bond (2015, p.191) states that "at each stage of the value chain of producing a map, assumptions and simplifications are made. Documentation of these assumptions is generally not passed along the data collection-processing workflow to the interpreter who creates the geological framework model." Jones et al. (2004) discuss the challenge with *tacit* knowledge, which they state also can be in the mind of the experts who map the geology and interpret the maps. This knowledge, for example to envision structures in 3D from a 2D map, or envision the possible interpretation uncertainties in the map, is earned through education, experience and trial and error. It is in a form that is not easily communicated, either "because the owners are not aware that they possess the knowledge, or because they are unable to express it in a useful, understandable format" (p.45). Tacit knowledge can be the mapper's expertise, preconceived bias, insight, gut feeling, and intuition. Some knowledge exists in an *explicit* format that can be communicated and understood by other colleagues, but there is usually also a large amount of *implicit* knowledge that is not (yet) in a format that is easily accessible to others (Jones et al., 2004). Explicit knowledge refers to information that is documented, such as maps or publications. Implicit knowledge, on the other hand, encompasses unrecorded observations, such as field observations not included in published maps, or geological theories that have influenced interpretations.

The following types of uncertainty can be listed (derived from Bond, 2015; Lark et al., 2015; MacEachren et al., 2005; Polson & Curtis, 2010; Zuk, 2008):

- Conceptual and attribute accuracy (potential errors when defining types, dependent of the geoscientist's training and experience).
- Interpretation uncertainty (errors potential errors following imperfect and partial information from observations and measurements).
- Cartographic uncertainty or lineage (potential errors from data processing).
- Positional uncertainty (potential errors when deciding the position, dependent on the type of observation and measurement).
- Completeness (comprehensive data and systematic ways of dealing with missing values).
- Cognitive uncertainty of the user.

A white area in a map is commonly interpreted as an area not mapped. However, the absence of a phenomenon in a map can have multiple causes:

- The phenomenon is not present.
- The area is not mapped.
- There are no observations, but the possibility of occurrence cannot be ruled out (e.g., a potential mineral occurrence).
- The occurrence is too small to be represented at the mapping scale.
- Although the area is mapped, the specific characteristic was not described.

In conclusion, there can be multiple dimensions of uncertainty and absence, some of which are crucial to communicate. The map can serve as a vehicle for communicating some of these.

2.2.2 Methods for visualizing uncertainty and absence

According to Boukhelfia and Duke (2009), there is no socially agreed system for depiction of uncertainty. MacEachren et al. (2005) present the following distinctions for visualizing uncertainty:

- Changing the appearance of the *object* (intrinsic) or adding a symbol (extrinsic). See Figure 4i) where a point symbol representing uncertainty is added to an area object. The additional objects can also for example be a mesh of uncertainty measurements across the surface (MacEachren et al., 2005).
- Employing the same *representation* (intrinsic) or introducing a new representation (extrinsic) to show the uncertainty.
- Choosing between *static* visualization and *dynamic* options like animation or interaction.

In geology, there are multiple research tracks focused on visualizing uncertainty, often distinct from cartographic research. Geoscience research typically does not frequently reference cartographical research, and vice versa. Common techniques are:

- Multiple models showing different interpretations or results of different algorithms (Bond, 2015).
- Two models, one showing the geological theme, the other distribution of uncertainty.
- One model showing both geological interpretation and the uncertainty assessment integrated (Bond, 2015; Zehner, 2021).

There is a great amount of research on methods for assessing and visualizing uncertainty in geological 3D models (Zehner, 2019). A brief review reveals methods made by and for experts, and therefore not described further here. Extrinsic representations can use all the visual variables as the name of the map and legend will guide. Therefore, the focus here will be at intrinsic approaches, where uncertainty is shown in the same image as the data. MacEachren (1992) argued for adding visual variables to represent uncertainty, which should build on metaphors that could be associated with uncertainty: "Out of focus" (see Figure 4c, *blur*), "foggy" (crispiness) and "transparent atmosphere (Figure 4f and g, *transparency*). When data is certain, the visual variables will be presented in their purest, clearest, and solid form. When data is uncertain, they will be presented for example out of focus, highly transparent, or with low color saturation.

Boukhelifa and Duke (2009) have tested *blur* and *traffic lights* to represent uncertainty. In their experience, using *blur* as a visual variable may not be useful in print, as it can be associated with low-quality print. It also has a short variable length and can appear more blurred when overlapping with other data. They also underline difficulties with adopting methods from the literature in real-life applications. The traffic light colors associates to stop, wait, go and thus, rules of action whether the information can be used with or without caution.

There are geological standards for visualizing uncertainty (FGDC, 2020; Soller et al., 2020). For example, A dashed or dotted instead of a solid line. These are well established symbol conventions for uncertainty. The variants can vary in thickness and colors to represent other types of borders and lineaments.

Visualizing absence

Robinson (2019) proposes the following list of statis methods for visualizing absence relevant for the standardized map services: *blank*, *hue*, *saturation*, *value*, *texture*, *transparency*, *blur*, *shadow*. According to MacEachren (1992) color saturation is the best method for visualizing uncertainty. *Blank* is according to Robinson (2019) best to use when it represents maximum of the visual variable *transparency*. However, this approach can pose challenges in distinguishing between areas that are not mapped and areas with no observations. *Color value* is not ideal because it may categories look sequential distinct more than qualitative different. *Transparency* can be hard to use in some mapping contexts, for example over a terrain or other map layers. Depth of field (DOF) blur can be used, associated to *unclear,* or *fog*, and therefore possibly missing or absent information.

Setting the goal

Sophisticated and advanced uncertainty visualization can be important for the expert user. For non-experts with limited need for detailed attention to the specific map, the objective is to make the reader aware of the caution that should be exercised during use. Complex uncertainty information increases complexity and may reduce legibility of the map and the use of the information.

Different communication goals for visualizing uncertainty can be set (Reinke and Hunter 2002):

- Notification ("to give notice of or report the occurrence of [quality]").
- Identification ("to establish the identity of or determine the taxonomic position [of the quality parameter]").
- Quantification ("to determine, express, or measure the quantity of [the quality parameter]").
- Evaluation ("to determine or appraise the significance of [a data quality parameter]").

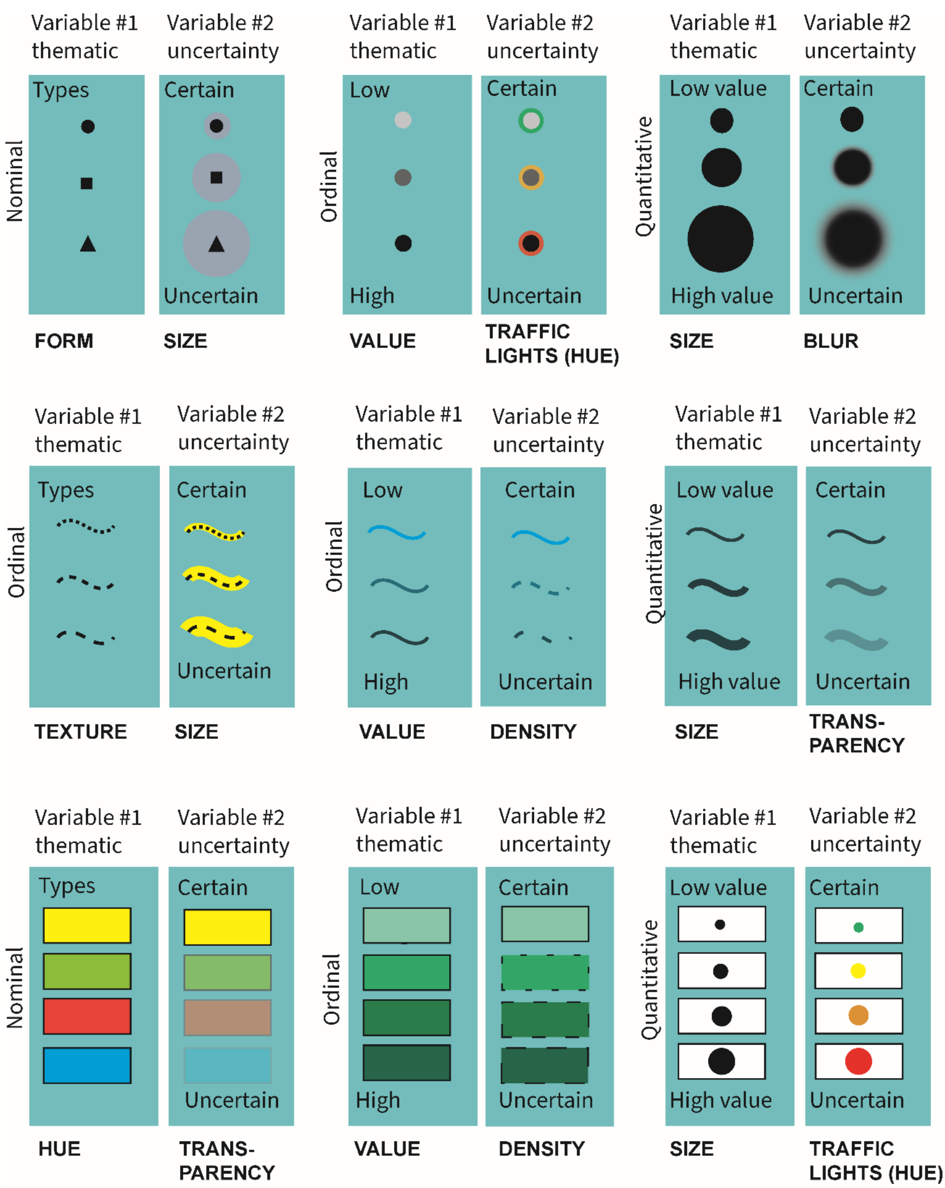

Figure 4 Examples of uncertainty visualization with different combinations of visual variables for different types of objects. The traffic light is a variant that separates itself from the typical nominal variable hue where the order between them is known.

2.3 User-centered design

Research on the use, users, and usability within geographical information (GI) sciences is a rapidly growing field. This growth is driven by the increasing numbers of maps, users, and devices, which in turn create a myriad of challenges (Griffin & Fabrikant, 2012). The current research focuses on creating graphics that communicate adequately and effectively, e.g., creating better maps, inspired by Bertin (2010). To obtain this, methods inspired by cognitive map research are used, within a framework and setting inspired by user experience (UX) and user-centered development.

Two of the important origins for this research are cognitive science and computer science. Methods from neuroscience, or more specifically, cognitive science, were used from the sixties in cartography (Board, 1978). Research following this tradition are typically laboratory experiments set up to study perception and cognition in association with performing map tasks (Keskin et al., 2016, Çöltekin et al., 2010, Dong et al., 2010). Neuroscience and cartography are still linked together and overlapping. Neuroscience focuses on the brain, for example how we develop spatial knowledge and navigate (Peer et al., 2021). Cartographic research is concerned about how we, through understanding the visual system, can improve the tools, e.g., maps, to aid our brain when handling spatial issues. Ware (2021, p.39) states:

> "All humans do have more or less the same visual system. This visual system has evolved over tens of millions of years to enable creatures to perceive and act within the natural environment. Although very flexible, the visual system is tuned to receiving data presented in certain ways, but not in others. If we can understand how the mechanism works, we can produce better displays and better thinking tools."

Within cognitive cartography there are three fields: cognitive map-design research, map-psychology research and map-education research (Montello, 2002). According to Montello (2002), the focus of cognitive map design research is "the understanding of maps, mapping and map use in order to improve them (make them more efficient, effective, rewarding)".

The field of human-computer interaction (HCI) is rapidly evolving. Concepts and trends consequently shift. Central concepts are usability, user-centered design, and UX. The goal of HCI-research is to improve user experience. For research on cartographic UX design, the focus is to improve map interaction through improving map interfaces of various sorts, like geovisualization, animations, web maps or web applications. There are methods both for research and development. Research methods overlap with the above-mentioned for cognitive science.

Usability can be defined as "The extent to which a product can be used by specific users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" (ISO, 2018). An overview of the related concepts from Nielsen (1994) is shown in Figure 5. There are multiple approaches to improving products. Haklay (2010) describes user-centered design as "a development philosophy that puts usefulness and usability at the centre of the process and evaluates them empirically. Usability engineering (UE) can be defined as:

> "An approach aimed at integrating central concepts and lessons that were learned through HCI research into software design processes. The integration of UCD principles in the software development process is done through the creation of frameworks, techniques, and matrices that can be deployed systematically and rigorously. By developing such methods and tools, UE aims to ensure that the concept of usability is translated into measurable criteria" (Haklay, 2010, p.107).

User-centered design principles can be practiced through usability evaluation. Usability evaluation is a part of usability engineering. In cartography, there is a wide range of research for interactive maps inspired by UX and usability engineering (Roth et al., 2015, 2017; Shobesberger, 2012) and for geovisualization tools (Çöltekin et al., 2017, Slocum et al., 2003). Usability can within cartography be defined as: "a range of issues which connect the human user of spatial data with its representation, its processing, its modelling and its analysis" (Virrantaus, Fairbairn & Kraak, 2009, p.2).

To implement a user-centered design process, there should be prototyping and iterations (Robinson et al., 2005, Roth et al., 2015). For example, the following steps can be made for interactive maps: (1) work domain analysis (i.e., a needs assessment); (2) conceptual development; (3) prototyping; (4) interaction and usability studies; (5) implementation; and (6) debugging (Roth, 2015).

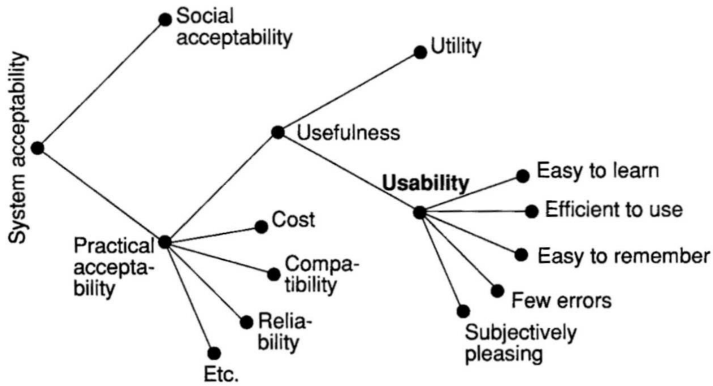

Figure 5 Nielsen's model of system acceptability attributes (Nielsen 1994, p. 23)

Solely focusing on cognitive map design or UX design has its critics, because it does not take either user context or the power of map makers into consideration. Perkins (2008) and Griffin et al. (2017) advertise for a higher focus on map user context, the former inspired by social sciences and the humanities. They suggest looking more critically at the map maker and map development process, making the map makers more attentive to the implications the map has on users and society. This was first and foremost done by Harley (1989). He said the map makers should deconstruct the maps to consider "the effects of abstraction, uniformity, repeatability, and visuality in shaping mental structures, and in imparting a sense of the places of the world."

Action research has, according to Coghlan and Brydon-Miller (2014. p.xxv), multiple definitions, but that these agree that action research "is a term that is used to describe a global family of related approaches that integrate theory and action with the goal of addressing important organizational, community and social issues together with those who experience them." Herr and Anderson (2014) say that the challenge is to make the results transferrable to other settings. However, they argue that new theory, products, and instruments potentially can be useful in other contexts.

3 Method

The study started open-ended, studying, and discussing geological visualization in a broad manner, from diagrams to 2D and 3D maps and visualizations. The aim was to understand more about the specific challenges for geological maps and graphics. A literature review of methods of use, user and usability studies resulted in a selection of methods, including sketch maps, informal interviews, web experiments, think-aloud in test experiments, questionnaires, and comparative map analyses. Three experiments, all including both experts and non-expert participants, were conducted. See Figure 6 for an overview of experiments, tasks, methods and methodology. The study was completed with hands-on work on improving specific map-products in development. Incorporating elements from action research, the objective was to enhance both products and processes, specifically increasing focus on map users within real map-production processes.

3.1 Use, user and usability study methods

Within cartography, significant scientific research has been done in studying maps and their users. Methods are commonly inspired by adjacent fields. For example, studies of interactive maps use methods from research in user experience (UX), studies on map perception and cognition methods from neuroscience research and context-aware research from social sciences. The focus varies between, for example, map applications and interfaces, map design and map use.

Some common methods in use, user and usability research are borrowed from cognitive science. The overlapping research methods within cartography and neuroscience include measurements of eye movements, observations, time taking or think-aloud while performing tasks. Here, the focus is on perception and cognition. These are commonly controlled lab-experiments, where user behavior is carefully tracked. There are many examples of eye-tracking studies in cartography, for example, exploring the efficiency of user's visual analytics strategies (Çöltekin, Fabrikant & Lacayo-Emery, 2010).

Koletsis, Cartwright and Chrisman (2014) list nine methods that are applied in evaluation of maps: use of representative end users, think-aloud protocols, questionnaires, focus groups, participant feedback/formal and informal interviews, reading tasks, real and simulated environments, and statistical analysis for interpreting the results.

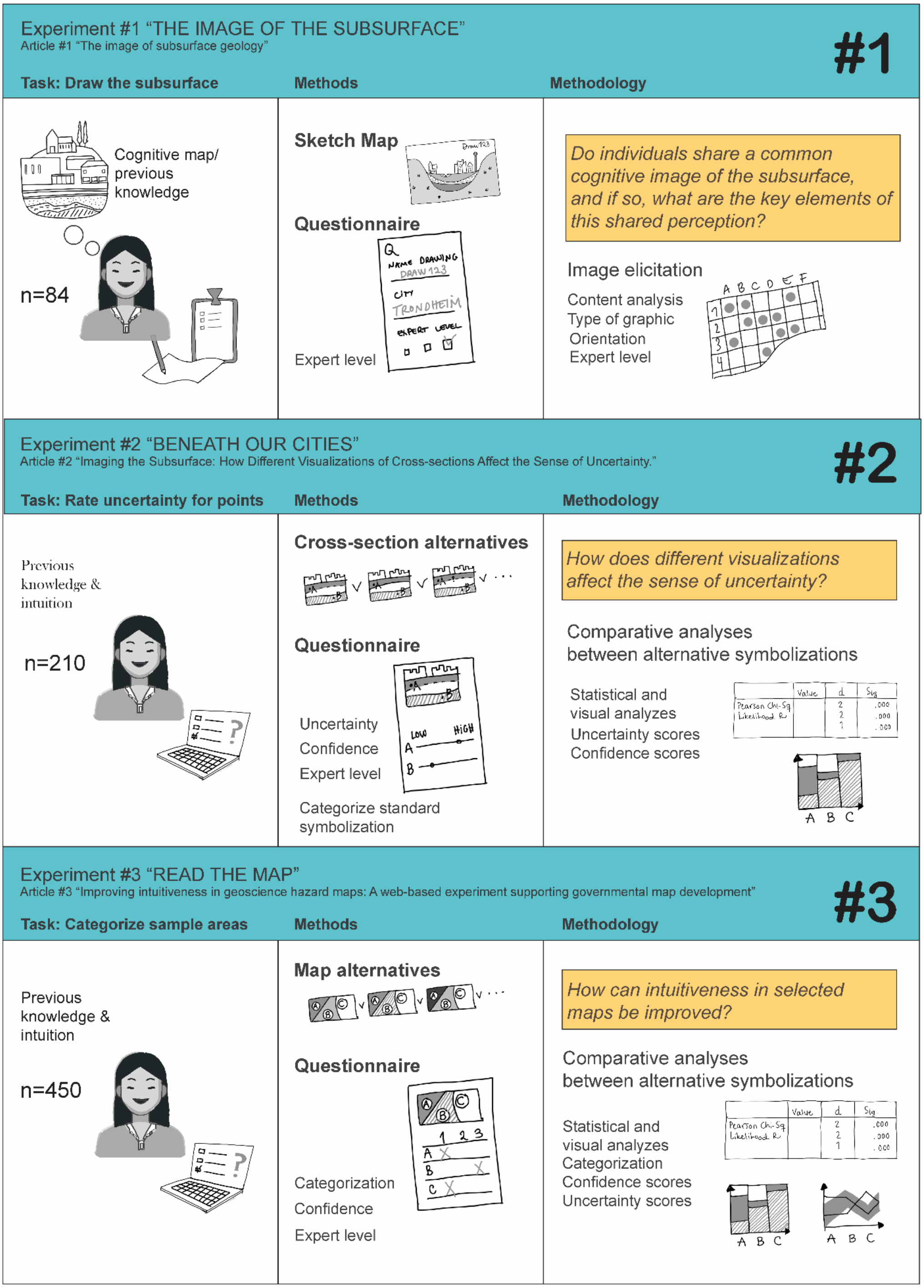

Figure 6 Experiments included in this study.

For an overview of methods applicable for user-centered design, see Figure 7. To select methods, the following factors can be considered (Schobesbergers, 2012):

- Development stage: Determine the stage of the project (idea/demand, prototype, post-release).
- Study environment: Choose between field, laboratory or remote.
- Subjectivity: Choose between subjective methods (interviews, think aloud, focus groups) or objective research methods (measuring tasks, structured questionnaires, observation, user logging, eye movement analysis).
- Research type: Opt for qualitative approaches (observation, interviews, or think-aloud method) and/or quantitative approaches (surveys, logging, or eye-tracking).
- Information collected: Gather data on users, system usability, requirements, goals, tasks, scenarios, or application usability.
- Response times: Consider time required for execution of studies and evaluation.
- Intrusiveness: Remote methods and non-participating observation may be less intrusive.
- Financial and personal resources.

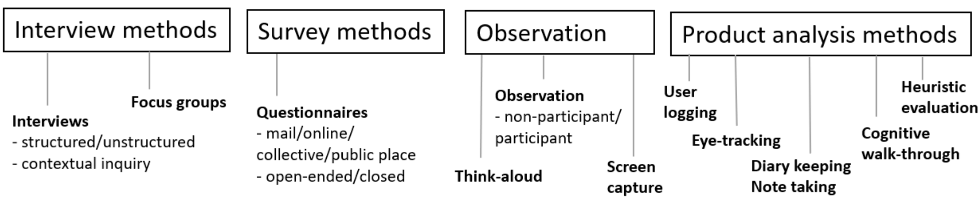

Figure 7 Classification of selected methods for data collection methods for user-centered design (after Schobesberger, 2012).

The following sections will describe the choices made for the current research.

3.2 Exploring geoscience visualizations and its challenges

During the first part of the study, geoscience visualization and literature were explored. The focus was to study both visualization excellence and identifying and selecting challenges for the non-expert user groups for further in-depth study. The literature included published maps and models, 3D web-viewers, field diaries, textbooks, articles, and presentations. During and following this review, challenges were discussed, encompassing both internal issues and those identified through participation in in-house and European workshops concerning the subsurface (COST Action

TU1206 – Sub-Urban – A European Network to Improve Understanding and Use of the Ground Beneath Our Cities and the European Geological 3D Modelling Meetings). Subsequently, specific challenges were selected for further in-depth exploration.

3.3 Sketch maps and content analyses

With the aim of studying the cognitive image of the subsurface, the sketch map method was selected. Additionally, the think-aloud method was used for the test experiment. This is a pilot study not found in previous research. The experiment can be categorized as open-ended and inducive research, exploring and observing the drawings, trying to find general conclusions.

Article 1 includes a more comprehensive description of the method. The drawings were delivered on paper or from a simple web drawing application. The participants were asked to draw the subsurface of their city of work or where they live. In addition to the drawing, the participants filled were asked about their age, education, and expert levels in a questionnaire on paper or online.

The methods for analyzing the maps were inspired by general visual research methods from Rose (2001). Variables for analysis were content, words used, type of graphic and orientation.
For the content analysis, categories were set from similar surface experiments from previous research in sketch maps for the surface. Then, categories were added and deleted from iteratively going through the drawing to make them fit. For parts of the analyses, only the sketches of the same city (Trondheim) were used, to ensure compatibility.

3.4 Web-based map experiments

Bertin (2010) used high efficacy as a goal for graphics, meaning the map reader effectively would perceive the communicated information. *Effective* is the commonly used measurement from map experiments measuring success from eye-tracking and time-taking, reflecting a positivistic tradition. Results from these types of experiments are central for UX and cognitive map research in cartography. For the current research, however, these methods were considered to potentially create a distance to the geoscientists and not give easily applicable results for the current challenges at the geological survey. The survey does not have a goal to create the best web map viewer. It is also possible to have full control over for example legends and background maps where the map is mostly used, in the end-user's environment. Instead, to meet identified challenges, the goal was set to select intuitive map symbols for the map services, to make the maps more truly available and symbolization more often interpreted correctly. *Intuitiveness* is introduced in this research as an important measurement, see Article 3. Adinolfi and Loia (2022, p.9) define intuition as follows: "Intuition is knowing that emerges out of self-organizing holistic associations`. An intuitive map sign or symbol can be defined as: "Easy and intuitive to interpret and that allows users to understand the referential meaning accurately. The referential meaning of [the map] symbol refers to the meaning (information, content and/or functions) as assigned by [the map owner]." (Islam & Bouwman, 2016, p. 122).

The reasons for using intuitiveness instead of effectiveness are:

- The concept is commonly used when discussing map symbolization across fields.
- When people are faced with too much information, heuristics and intuition are expected to play a higher role than analytical map reading (Adinolfi & Loia, 2022).
- "Intuitiveness" puts focus on subjective factors and the user.

3.4.1 Experiment steps

The following steps were made for Experiment 2 and 3:

1. Selecting maps/ challenges: Map owners were informally interviewed throughout together with document analyses to learn about why the map was made, for whom, limitations in the data, why the existing symbology was selected and known challenges with the map.
2. The selected maps were deconstructed and analyzed according to cartographic theory. For example, the number and length of information variables and whether they were correctly matched with visual variables.
3. A test study was performed with 20 participants to ensure data were fit for analyses and gave useful input to improvements on the formulation of question and alternatives.
4. The final test scheme was designed, and the web experiment was published. Participants were invited, both novices to experts.
5. The results were analyzed statistically together with visual data exploration.
6. The results were presented to the development team and action points for further development of the maps were discussed (Experiment 3).
7. The method and results were evaluated for relevance outside this study.

3.4.2 Deconstructing maps for cartographic evaluation

Being base maps, the traditional geological maps showing bedrock and surficial deposits typically have many more categories shown than the recommended maximum for effective cartographic communication. The color use can reveal the hierarchy of categories where the same color hue represents the same category of rocks, and color value and saturation show variation within this category. For example, the strength of the color can reflect the age of the bedrock; stronger means the bedrock has a younger age. These conventions are learned through practice and are not easily found in any official publication.

The base geological maps delivered by the Norwegian Geological Survey of Norway are in part digitized from printed maps and partly a product of digital mapping. Large amounts of work have been done to transfer the printed maps to a seamless digital database. The main content of the original database for these maps is the legend information: It is a single information variable for non-overlapping areas (polygons). As the categories have mostly been stored flat as nominal categories in the database, the deduction of attributes and maps demands partly manual reclassification. Deducted maps can inherit uncertainty and complexity following this flat structure, where some categories are described with some extra attributes in the definition and others not. For example, *thickness of deposits* or *continuous masses* may or may not be included in the type.

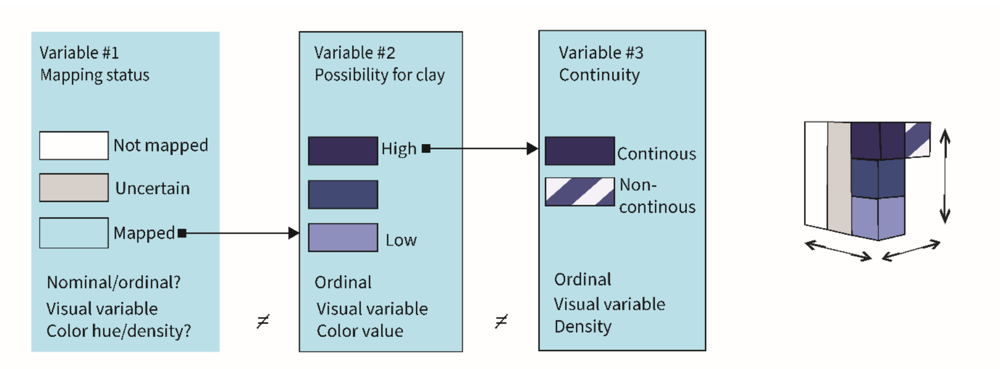

Figure 8 Deconstruction of the Maine Clay map information. All the categories are originally from a continuous area map with a flat structure of categories. The result highlights a complex structure of information and symbols.

To be able to evaluate the existing use of symbols and test alternatives in a map, there is a need to deconstruct it. Using Bertin's theory of the semiology of graphics (2010), the number of information variables, their categories and organization level are identified. A visual method was developed as part of the work with Experiment 3, to make sense of a complex structure of information, see Figure *8*. A visual technique makes it easier to evaluate whether the visual variables are completely logically matched, or how it can be done.

3.4.3 Map experiment setup

Considerable effort was invested in controlling differences between the map experiments to ensure conclusive outcomes. The aim was to draw conclusions for each individual test variable while maximizing participant inclusion in statistical analyses. This effort culminated in a matrix for the third experiment, yielding eight test maps from two variants of three test variables (2x2x2), as shown in Table 1. This approach enabled the utilization of all participants in each statistical test, enhancing their robustness. Furthermore, the uniform differentiation of the remaining two test variables contributed to more reliable results.

Table 1 Map alternative setup for three test variables with two different alternatives (variants).

	Map alternatives							
	1	2	3	4	5	6	7	8
Test variable 1	1	1	1	1	2	2	2	2
Test variable 2	1	1	2	2	1	1	2	2
Test variable 3	1	2	1	2	1	2	1	2

3.4.4 Web-based experiment

To reach a high number of participants, web-based experiments were used. An off-the-shelf web survey application was chosen. This application could automatically place participants in random and even sized groups and show the questions in random order with different texts and images. Also, it was already adaptive to both computer and mobile devices.

There have been some concerns about using web experiments in non-controlled environments (Midtbø and Nordvik, 2007). However, Reips (2002) lists 18 advantages compared to seven disadvantages. The access to a high number and diverse group of participants, voluntariness, reduction of experimenter effects, cost-effectiveness, and openness are some of the advantages. Among the disadvantages are possible multiple submissions, dropouts, and a lack of experimental control. Participants may be distracted by their surroundings, use different devices, and with an open link, it can be difficult to ensure seriousness and representativeness. However, this can be argued to reflect the natural settings where maps are used and be an advantage. As recommended, a question about efforts was added to enable the removal of unserious answers (Reips, 2002). Regarding representativeness, there were concerns; some did not take part because they thought the experiment was for experts only. For Experiment 3, a lot of effort was put into making the experiment inviting and easy, ensuring potential participants that each answer is valuable. A combined invitation and user guide were produced (Figure 11) to promote the survey and recruit participants. The survey was set up in both Norwegian and English languages.

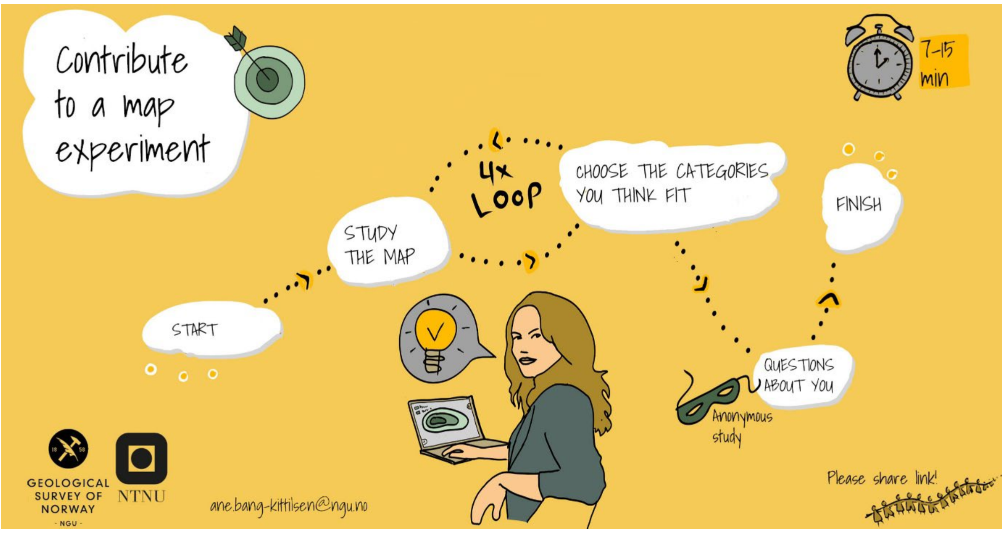

Figure 9 Invitation and user guide.

3.4.5 Statistical analyses and visualizations of results

The setup of the questions determines the potential statistical methods and visualizations to be used. The most basic method used was the frequency diagram, counting answers in each category and comparing them with another variable, like expert or novice. To check for statistical significance, ANOVA (for multiple alternatives and ordered levelled categories) and t-test (for two alternatives and ordered levelled categories) were used. The Chi-square test was used for nominal ordered categories. Using a box plot, the mean and standard deviation can be compared across alternatives, proving useful to understand the numbers behind a significant statistical test. The bar graph was used to show the proportions of answers for the different answer categories. To compare a set of answers between map alternatives, a line graph was used with a line thickness reflecting the amount of the same set of answers (Figure 10). Making one box plot, bar graph or line graph for each alternative or question, the graphs could then be compared when evaluating each alternative.

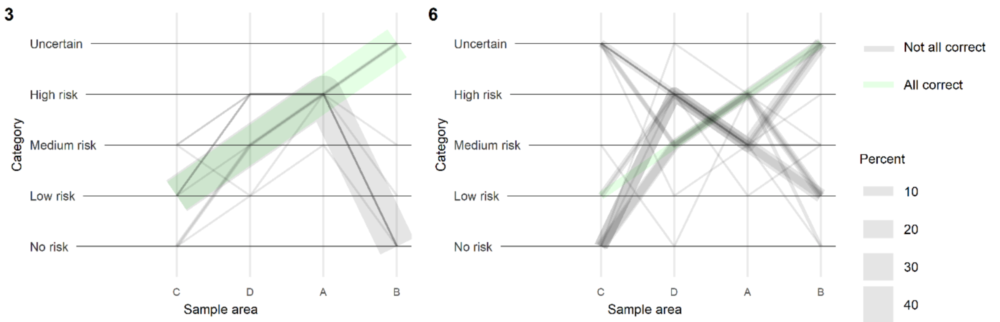

Figure 10 Line graphs showing all participants answers makes it easy to see which map alternative is the more intuitive to understand the order of categories (lines gradually going upwards). This one shows the results for two alternative Radon maps.

The method evolved through the three experiments was an iterative process of statistical before visual analysis and eventually discussions with the map development team, before regrouping and running new tests based on the new knowledge, see Figure 11.

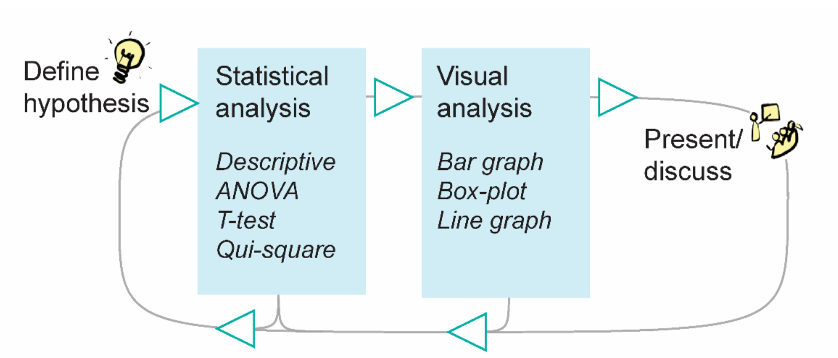

Figure 11 The four parts of analysis for experiment 2 and 3.

The research took place within the Geological Survey of Norway. Throughout the study period, document analysis, discussions, and informal interviews were conducted on several topics, including geological data, visualization methods, and uncertainty visualization, across different specialties including bedrock, quaternary geology, urban geology, geophysics, and mineral resources. Document analysis involved reviewing field notes, publications, and online resources, while informal interviews consisted of discussions addressing specific issues or open questions about challenges. Additionally, Experiment 3 involved formal project meetings to discuss improvements of maps in development.

3.5 This study

This pilot study draws from various theories and research methods in cartography but is conducted within the context of governmental map development. Previous research often includes quantitative studies, performed under controlled conditions, with eye-tracking equipment and recording the time used to perform tasks. The objective was to find methods more easily incorporated into practice in future projects and more readily applicable results. Therefore, mixed methods with web experiments to produce data for quantitative analyses and qualitative methods to ensure relevance were selected.

4 Summary of the work

The primary objective of this chapter is to provide an overview of significant findings before, during, and after the experiment phases. Also, the three experiments, along with their corresponding publications, will be presented.

4.1 Geoscience visualization and its challenges

After conducting an exploratory review of extensive material, the notion that geoscience is fundamentally a visual science is reinforced. Graphics play a pivotal role in the field, ranging from simple sketches in field notes to intricate diagrams, illustrations, maps, and models. The use of visual representations in geoscience has been a tradition since the beginning of the discipline. Many geoscience maps are not only colorful and visually appealing but also serve to captivate the viewer's interest and evoke wonder. Some of these maps have even been groundbreaking in their contributions to scientific understanding. One such exemplary map is the work of Mallet & Mallet (1858), depicted in Figure 12. This map effectively communicates seismic activity, providing compelling evidence that supported the subsequent theory of tectonic plates.

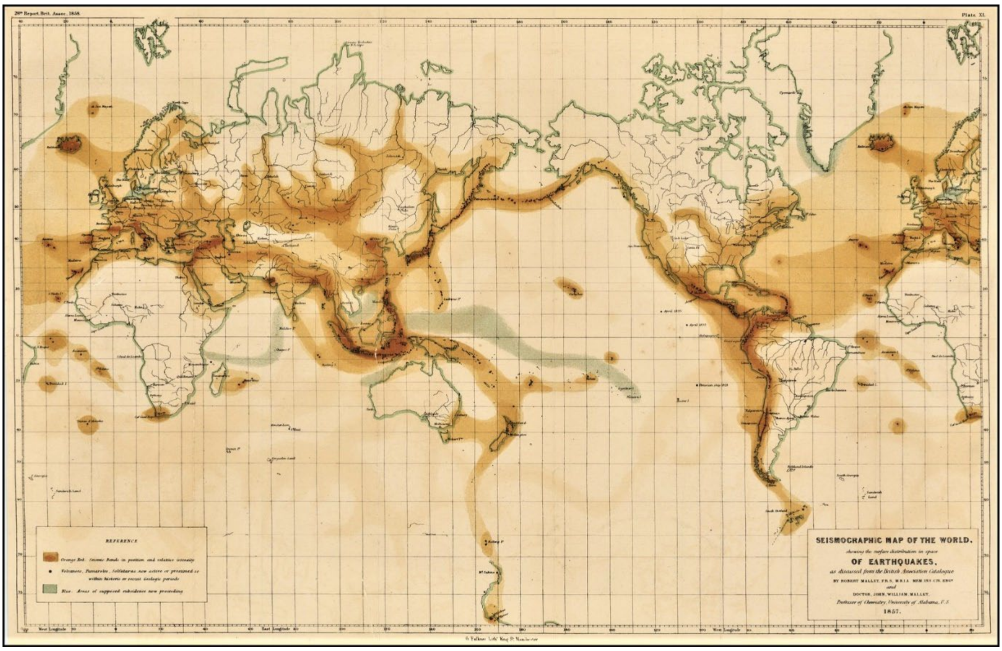

Figure 12 Seismographic map of the world by Robert Mallet and John William Mallet (1858).

The use of graphics can sometimes serve to captivate the reader's attention. It can also document and underline a statement. More importantly, however, it often serves as the main vehicle for communicating information.

The rich toolbox of visualization methods includes, but are not limited to:

- 2D maps: Both reference maps and thematic maps serve as fundamental tools for visualizing geographical data.
- Cross-sections (or profiles): These vertical 2D presentations depict interpretations of surficial deposits, bedrock, or data such as seismic or gravimetric information.
- Structural diagrams: Used to illustrate geological structures, these diagrams provide insights into the arrangement and orientation of rock layers.
- Ternary diagrams/triangular graphs: These diagrams represent three variables that sum up to 100%, often utilized for categorizing grain size and other compositional analyses.
- Stereonets: Employed to display the strike, dip, and plane orientation of planar geological features in three-dimensional space
- 2½D and 3D models, including VR-maps: These advanced visualization tools offer immersive experiences and enhanced spatial understanding, enabling researchers to explore geological phenomena in greater depth.

While geoscience visualization possesses significant illustrative capabilities, geological information remains underutilized in society, particularly in small municipalities due to a shortage of experts and in early phase infrastructure planning. Through discussions and document reviews conducted during the research period, several key obstacles to effectively communicating geoscience maps to non-experts have emerged:

- A significant initial threshold for use.
- Maps primarily created for experts.
- Use of domain language.
- Challenges in depicting three-dimensional phenomena on two-dimensional maps.
- Difficulty in conveying absence and uncertainty.
- Complexities in communicating the implications of interpreted information compared to measured data.
- The significance of the information and its practical applications are not widely known.
- Insufficient prior knowledge and familiarity with map usage practices among non-experts.

- Limited coverage of detailed maps.
- Lack of customized maps tailored to specific user needs.
- The existing infrastructure for geographical information is geared towards standardized two-dimensional map displays.

Experiment 1 was set up to understand more about the differences between experts and non-experts, in how they imagine geology.

4.2 The cognitive image of the geological subsurface

Experiment 1, concerning the cognitive image, is thoroughly presented in Article 1. The experiment was open-ended, aiming to elicit experts' and novices' cognitive images of the subsurface. Inspired by the 1960 book by Kevin Lynch called *The Image of the City* where the knowledge gained from how people perceive the city is later used to design cities that are better to live in. For the current experiment, however, the idea behind was to make people draw the subsurface for the purpose of improving the representations of subsurface geology: A shift of goal from designing the city better to improving graphical representations of geology. The idea is that if graphics are made by building on common anchors of knowledge and ways to view the world, the user threshold will automatically be lowered and user confidence higher.

This was a pilot study, as no previous research on the cognitive image of the subsurface was found, apart from studies of the development of spatial abilities (Ormand et al., 2014; Ishikawa & Kastens, 2018) and understanding of structural geology (Kali & Orion, 1996).

The sketch maps from Experiment 1 reveal limited knowledge of the subsurface, and lack of a common graphical and linguistic language. Cross-sections with landmarks, clear language and patterns were typically drawn. This suggests there are knowledge pegs and common ground that could be used as base line for visualizations for the non-experts. Cross-sections have a long tradition in geology (for example Darwin, 1876), and patterns have been especially common for representing grain size in maps and borehole logs.

As can be seen in Figure 13, many participants treat geological features differently than visible surface-features, with a lack of precise delineation. This could be an expression of both uncertainty and of an image of geological phenomena lacking distinct borders between types. In either case, this should encourage research into enhanced visualization methods for the future. The question whether this reflects a sense of uncertainty lay ground for the next experiment.

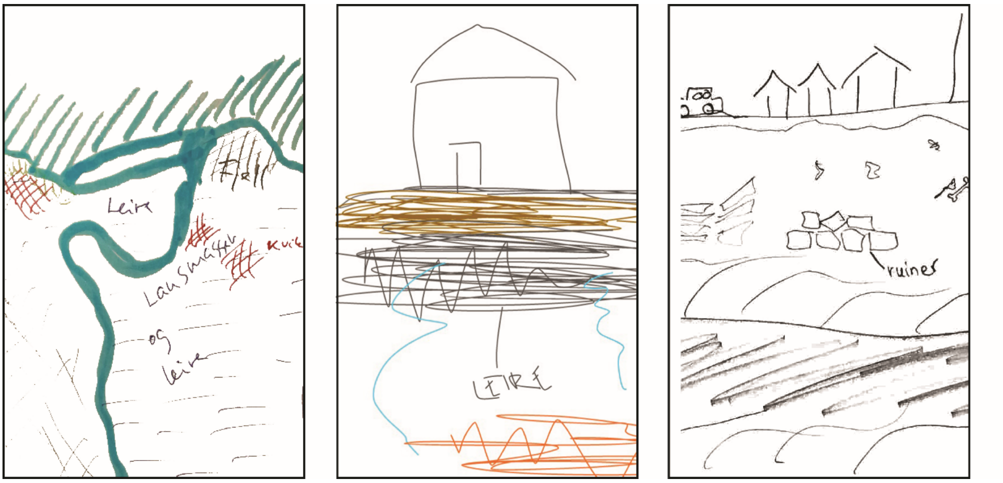

Figure 13 Examples from participant sketches. These images clearly show participants delineating measurable objects like houses and rivers, while geological features are treated differently (Bang-Kittilsen, 2020).

The dominance of cross-sections made by the participants in Experiment 1 made the choice of using these in Experiment 2, where the focus was set on what effects experts and non-experts assess uncertainty in points dependent on visualization choices. The digitalization and open data policies of maps have led to a simplification of the map products, and progress in visualization is needed.

4.3 How different visualizations affect uncertainty

Experiment 2 is documented in Article 2. The aim was to learn more about how non-experts interpret uncertainty from some alternative visualizations. A main challenge in making simplified products is that geological information can be permeated with interpretation and uncertainties. Although standards and suggestions for uncertainty visualization exist, also in geology, these are not that commonly not present in the digital version of the map. A line or border in a map has mostly a significantly different quality between a geological interpretated line and a measured line of a building or a property. Still, it is often represented by the same symbols in the same map: a solid line of the same thickness. How is the map reader to know the difference between these lines without domain knowledge in geology and carefully studying the metadata? The background map is another challenge. There is no control over what the user selects as reference information. How does the detail of the background map affect the sense of uncertainty of the geological information?

Experiment 2 was set up as a web experiment where the participants were randomly assigned to different alternative cross sections with slightly different symbolizations. In addition, they were asked to fill out a questionnaire about themselves. The groups were compared with statistical methods.

The results from the experiment show that participants perceive greater uncertainty when conventional symbols for uncertainty are used. Also, the experiment results show the degree of detail in the reference map affects the sense of uncertainty of the geological data. The results of the experiment show awareness of uncertainty is increased when symbols are larger, and that the background map matters. When using a detailed background map, the participants perceive the geological information as more certain.

The strength of the conventions for line symbols for geological uncertainty visualization (FGDC, 2020) is also measured through a simple test included in the questionnaire. Results show that the symbols used for the areas on each side of the line affect the interpretation of the line symbol.

This experiment lays out the ground for future products tailored for the non-expert. For Experiment 3, the focus was set on testing and improving existing products.

4.4 Incorporating cartographic research in map development

There is a demand for understandable, easy-to-use deducted maps. However, to the map owner's concern, there are frequent examples of misinterpretations of some of the published maps. The non-expert map user may not have enough knowledge of how to use and, also important, not to use the map available. Mapping and predicting risk are done by experts, who do not necessarily know enough about how the map users understand and use the maps.
Three different thematic maps with alternative symbolizations were tested in an experiment set up as a web experiment for Experiment 3 *Read the map*: the Radon risk map, Possibility of clay with marine limit and the InSAR map. 450 participants completed the experiment.

This research was conducted within an organization responsible for developing the maps that the research aims to improve. The author is part of the map development teams. Challenges with the map were discussed with the map owners before setting up the experiment to test the maps with a broad user-group. The idea behind the third experiment was to test the impact of the design choices on whether a map is understood intuitively correctly.

The results demonstrate how minor alterations can significantly impact the intuitiveness of a map, highlighting the importance of both adhering to cartographic principles and rigorously testing the maps. The visualized results from the experiment were analyzed and discussed with the map owners. Finally, action points for further development of the maps were suggested and discussed. The research incorporates elements of action research, aiming at stimulating learning and development within cartographic work at the survey. The method and results are documented in Article 3.

4.5 Discussion and further work

In this chapter, special emphasis is placed on advancing future work and translating the research experiences into practical guidelines.

4.5.1 Bias and other geoscience map challenges

Understanding the subsurface composition and the ongoing processes that shape it, which continue to impact us, requires advanced methods and years of education. Interpretations do always contain subjectivity (Poulsen and Curtis, 2010; Wilson et al. 2019), a challenge often referred to as geologists bias. According to Ramberg (2008, p.18), the geological structures we observe both in nature and in the laboratory are "not infrequently the subject of a variety of theories and interpretations". Communicating geoscience knowledge, along with its inherent uncertainties, poses a significant challenge.

Geoscience spatial visualizations mostly represent *invisible* and not easily measurable objects, compared to *visible* objects like farmland, roads, and buildings. It separates itself from other *invisible* information, like electoral results, by being *physical* opposed to *non-physical*. Geologists refer to their 3D maps as *models*, acknowledging their uncertainties, subjectivity, and bias. In a map, they are typically still represented alike, with uniform areas or volumes and solid border lines. However, the geological features within a map are often not spatially uniform. A useful comparison can be drawn between geological features and visible features like roads and properties, using the distinction made by Aase and Fossåskaret (2014) between prototypes and categories. While categories exhibit uniformity, resembling familiar features such as roads or properties, prototypes define a typical composition of an area, to which the elements within the area bear more resemblance than to other prototypes, such as typical geological phenomena. Consequently, the areas represented by polygons differ ontologically between for example property owner and bedrock type. Additionally, geological borders, or boundaries, often present unique challenges. They can represent gradual transitions, have a direction in the deep and a movement compared to the feature on the other side of the boundary. An expert uses this information to deduct the layering of bedrock types and to envision the geology in 3D. A non-expert would typically struggle to understand all these aspects.

In the realm of GIS, the true value lies in the ability to combine vast amounts of information based on their location, thereby uncovering new insights. Geologists utilize a variety of visualization methods to effectively communicate their knowledge. The standard infrastructure for geographical information, as outlined in the regulations for the official Norwegian geodata (Government, 2023), is well-established for two-dimensional digital map services. In its current form, expertise in cartography and geology is essential for critical evaluation. Therefore, there is a pressing need for further development of these standard services and end-user applications to effectively convey the specificities and uncertainties of subsurface geology.

4.5.2 Increasing the awareness of the subsurface

As anticipated, the sketch map exercise in Experiment 1 revealed that participants have limited knowledge of the urban subsurface. Compared to their drawings of the city above the subsurface, the cognitive image is more diverse but lacks detail. This is unsurprising, as the subsurface is largely invisible, and our navigation of the city does not heavily rely on knowledge of it.

In contrast to maps of the city, maps of the subsurface are less common and utilized, unlike navigation maps readily available on popular smartphone apps and websites. To improve the knowledge levels, it is imperative to ensure easy access to various visualizations, such as cross-sections and 3D models, through standard geographical information channels.

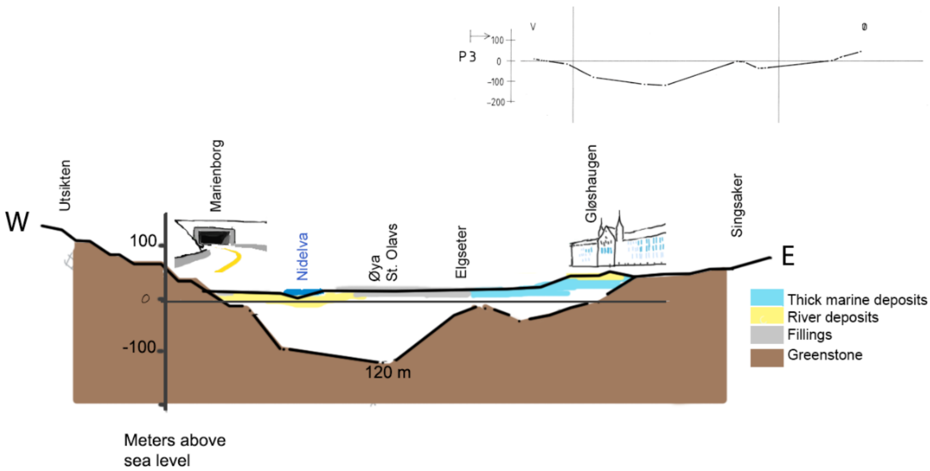

Figure 14 A sketch made to exemplify redesign of cross-sections, a suggestion for further work. Original gravimetric profile by Tønnesen, 1996, in the upper right corner. Colors, landmarks, and relevant available map information can be added (Map data from the Norwegian Mapping Authority and the Geological Survey of Norway). Offering these through standard map services to society may lead to increased awareness and knowledge of the subsurface.

The findings from the experiment, coupled with insights from discussions with peers, advocate for sharing more cross-sections with a broader user base. This initiative not only enhances the collective understanding of the subsurface but also fosters greater awareness of its significance. Moreover, redesigning the cross-sections to enhance clarity and integration into the familiar urban landscape can further amplify their effectiveness.

The result from the experiment together with the output from the 3D modelling workshop discussions together gives arguments for sharing especially more cross-sections with the broader user group. This would improve upon the collective image of the subsurface and help increase the awareness of the subsurface and its significance. The cross-sections could preferably be redesigned to make them easier to understand and place in the users' well-known city space.

In neuroscience, spatial knowledge research is frequently linked with navigation. Given the pivotal role navigation plays in shaping spatial understanding, this underscores the experiment's conclusion to incorporate surface elements commonly employed for navigation. These elements encompass landmarks, paths, nodes, and edges.

4.5.3 Emphasizing uncertainty visualizations

In geology, uncertainty exists across multiple dimensions, yet there is a lack of standardized practices for visualizing it, a challenge shared with cartography and other fields.

While not extensively employed in digital mapping, certain geological conventions for representing uncertainty do exist, including the use of dotted and dashed lines. Experiment 2 demonstrates that these conventions are both useful and understandable, even for non-experts. Additionally, advancements in technology within cartography have opened up new possibilities for representing uncertainty. These include using transparency, fuzziness, crispiness, blur, color saturation, resolution, and traffic lights as visual cues.

Experiment 2 revealed that the level of detail on the base map influences the perception of detail in the main map, as does the size of symbols. For instance, broader outlines, larger text, and pixels can give the impression of reduced detail. Gridded data is common, and it is advisable to maintain the grid without smoothing lines. If data is not initially gridded, it is possible to transform it to a grid where pixel size reflects detail level.

The importance of using some kind of visualization will increase the chance that the user will be aware of the existence of uncertainty in the map and be more cautious when drawing conclusions and making action. For the broader user group, uncertainty visualization adds to the information complexity which can create more alienation and make the maps time-consuming and difficult to understand. Therefore, it must be done with the intended user and use context in mind.

It is crucial not to underestimate the importance of including prototyping and testing in design processes. Cartography is inherently subjective, and the transition from theory to practice is often complex, particularly in the context of diverse media, services, and applications. Further research is needed to determine the effectiveness of uncertainty representations in official map products within real user environments

4.5.4 Integrating analysis and testing into map development

Experiment 3 involved selecting a series of published maps, deconstructing them, discussing challenges with the map development team, and familiarizing oneself with the data and background. Subsequently, the web experiment was set up to reach a diverse group of users, both non-experts and experts. The results were analyzed both statistically and visually, and the findings were subsequently discussed with the team.

Geologists often possess extensive experience in mapmaking, having refined their craftsmanship and integrity over time. In the absence of empirical evidence, map design heavily relies on expert opinions and adherence to symbol conventions, even though these may not always align with best practices in cartography. On the other hand, creating maps that are cartographically well-crafted but lack the necessary grasp of geological knowledge, experience, and conventions pose potential risks. The visualizations and results from a map experiment can serve as a platform for developing improvements across fields.

Both for the analyses of experiment results and heuristic evaluation of map design, it is necessary to deconstruct the map to identify information variables and their characteristics. Deconstruction in the current experiment led to detecting hierarchies in the data. From what at first sight appeared to be one information variable, multiple information variables were isolated according to their organization level (nominal, ordinal, quantitative). This was done to ensure a logical and cartographically correct choice of symbols, see Figure 8. When new map design prototypes are suggested, it is imperative to evaluate the design again to ensure it works as intended, especially when data complexity is high.

Given the potential for errors in implementing cartographic guidelines and the challenges of applying them to complex data, it becomes crucial to convey the underlying principles of the semiology of graphics. Becoming familiar with these principles allows for the treatment of semiology of graphics as an elastic theory, thereby increasing the potential for learning and development in the field:

> Since all models are wrong, the scientist cannot obtain a «correct» one by excessive elaboration. […] Just as the ability to devise simple but evocative models is the signature of the great scientist, so over-elaboration and overparameterization is often the mark of mediocracy. (Box, 1976, p.792)

There is a significant untapped potential for closer collaboration between research and practice within geographical information (GI). This collaboration could result in research findings that are more directly applicable and enhance the usability of maps, GI systems, and geographical information, benefiting society. Maps have evolved from static, unchangeable pieces to interactive, dynamic products that continuously adapt to changing societal needs. Therefore, there is a need for more dynamic and user-oriented map development practices. Conducting tests, demonstrating statistically significant results, and visualizing findings provide opportunities to collaboratively draw conclusions and identify action points for further development across fields, enabling knowledge-based map development.

4.5.5 A new holistic model for map development

For producers of geographical data and graphical representations and applications, the central concern is qualitative: Does the product contribute to qualitatively better decision-making? Is the knowledge being effectively and adequately utilized, or are there areas for improvement? This necessitates a holistic approach with an increased emphasis on testing, evaluation, and research.

In the final phase of this research, which includes Experiment 3 and the writing of Article 3, was conducted as an integral part of map development efforts. Drawing insights this work, the following concept model is proposed for enhancing map development. This model builds upon and extends existing frameworks for user-centered development (Robinson, 2005 & Roth, 2015), cartographic process (ITC, 2023), and action research models (Coghlan, 2019). The model emphasizes three key phases for incorporating evaluation, testing, analysis, and research.

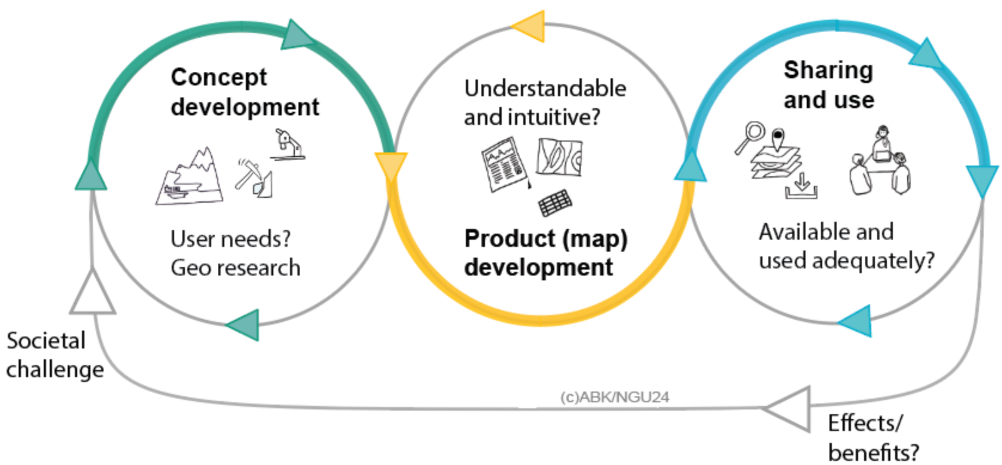

Figure 15 Map development with emphasis on learning and development. Cartographic research can be applied in all the back loops. The iterations can go all the way back to the societal challenges that are in constant change.

The three key development phases are: idea and concept, the product (map), and sharing and use (see Figure 15). The iterative process also extends back to evaluating the effects and benefits on societal challenges, remaining adaptable to changing challenges and evolving knowledge.

The left circle in the figure represents the domain where experts identify knowledge that can address a specific societal challenge, drawing upon both existing and new knowledge. This may involve domain-specific research, fieldwork, laboratory analysis, and graphical information processing as described by Bertin (2010), which entails visually reordering and reprocessing data to uncover new insights. For the initial iteration, some research questions may include:

- What is the nature of the challenge, and how can (geological) knowledge contribute to addressing it?
- Who are the users, what are their needs and how can these needs be met?

The middle circle encompasses product development, including map design. This stage involves an iterative process of prototyping and testing alternative designs with representative users to ensure that the map effectively addresses its intended purpose. Questions to consider during this phase include:

- Is the product understandable and intuitive (usable) for potential users?

The right circle symbolizes the process of ensuring that the map is made available and effectively utilized in relevant societal processes, supporting both machine and human actionability. Despite the valuable insights offered by the map, its use and success are not guaranteed. Various obstacles may hinder its adoption, such as technical challenges, a lack of understanding regarding its purpose and usage, or inadequate legislation. During this phase, it is crucial to ask:

- Is the product being adequately used?
- What obstacles, if any, exist for its use?

Completing the entire model, the arrow extends back to encompass a critical analysis of whether the product in use achieves its intended implications and effects. Despite a map's effectiveness according to graphical semiology, its ability to lead to correct decisions in real-world scenarios is not guaranteed, a phenomenon known as the accuracy-efficiency bias (Hullman et al., 2018).
The success of a map in generating interest and attention should be evaluated, particularly when maps are underutilized. Focusing solely on perception and deriving rules from it can be positivistic, potentially overlooking important aspects such as user context and aesthetics. Fish (2021) proposes a set of elements for map design aimed at creating compelling, persuasive maps that can be utilized

for evaluation or with such intent. She argues that these elements allow cartographers "to create emotional interest and bring distant topics to life" (p. 159) in an "age where drawing attention to maps is vital for communicating complex topics such as climate change" (p. 163). Concluding the model, the overarching question is:

- Is the introduction and utilization of the product yielding the intended or anticipated impact on the societal challenge? If not, what are the reasons for this?

In the proposed model, it is essential to recognize that the boundaries between the cartographer, user, map owners, and stakeholders are fluid. Stakeholders and users may participate in information collection, with users occasionally taking on the role of the cartographer. Furthermore, stakeholders may define the required map or even evaluate its usability.

4.5.6 Further work

Several challenges were identified as potentially valuable for research but were not within the scope of this study:

- Developing methods to intuitively visualize ontologically different objects simultaneously.
- Developing methods to visualize various types of uncertainty and absence simultaneously in an intuitive manner.
- Investigating the implication of map design on map use, including visual variables, aesthetics, and simplicity.
- Studying the effect of how the map and categories are named on confidence and understanding.
- Exploring legend design.
- Investigating the structure and naming of the map and its categories.
- Studying map use contexts for potential new themes and products.
- Examining how metadata and informational text are formed and delivered to influence reasoning.
- Ensure that cross-sections and other depth-related information are accessible and effectively utilized by non-experts within their respective contexts.

The new model for product or map development was introduced at the geological survey as part of a series of internal courses on agile work and mindset. The objective is to utilize the model, along with suggested methods from user, use, and usability research, to facilitate future work on ensuring utility and usability of products.

5 Conclusion and outlook

This chapter briefly presents the conclusion, suggested guidelines, and outlook.

5.1 Conclusion

The overall research question for this study was how a geological survey *can systematically improve geoscience map products for the broader user group*. The overall research question has been addressed with a new suggested holistic model for map development focusing on evaluation and learning (Figure 15). User and usability studies can be added to user-orientation of products throughout the value chain of data and maps. Including scientific, or scientific-inspired methods, offers a comprehensive and structured approach to systematically improving the map products delivered. Also, it appeals to geologists, being mostly scientific employees themselves.

Case studies play a crucial role in testing and challenging existing theories while also identifying new areas that warrant further research. In this context, they provide insights into:

- The untapped gain of extending geological maps beyond 2D in standard interfaces where users seek knowledge.
- A prevailing challenge associated with applying cartographic textbook principles to complex data and phenomena.
- The urgent need for additional research focused on visualizing diverse types of absence and uncertainties.

In addition to the overall research question, the subsequent research questions been addressed with the following findings:

What are important challenges with geoscience visualizations that need to be met (within governmental geoscience core activities)?

The research identifies geology as a visual science with extensive graphical tools in use. However, it highlights a gap in visualizing geological information, especially concerning uncertainty, which might impede its effective utilization.

What can be learned from the cognitive images of the geological subsurface and do people share a cognitive image of the subsurface and if so, what are the key elements of such a perception?

The study reveals significant limitations in the cognitive representation of subsurface features. There is a lack of standardized visual and verbal language. Common elements in sketches include cross-sections with landmarks and unclear borders for geological phenomena.

How do different visualizations affect the map reader's sense of uncertainty and how can uncertainty be visualized in geoscience standard products?
The findings suggest that there is a need for visualizing uncertainty to acknowledge its impact. Traditional methods, such as using dashed and dotted lines, have proven effective in presenting uncertainty. Presenting coarse data with detailed symbols and reference information increases confidence and reduces uncertainty assessment.

How do differences in map symbolization affect map intuitiveness? What can be learned and how can map research be applied within governmental map development?
The study acknowledges the importance of adhering to principles of graphical semiology when designing maps. However, it notes challenges in implementing these principles due to the complexity of data and uncertainties. The choice of symbology can lead to unintended effects, which can lead to misunderstandings.
The research emphasizes the value of user surveys in informing design decisions and facilitating discussions around map design. This platform has the potential to bridge the gap between various fields of expertise and achieve a shared understanding of the underlying phenomena (domain knowledge), cartographic best practices, and user processes and needs.

5.2 Guidelines

1. Map users typically possess a limited cognitive image of the subsurface. This lack in prior knowledge and cognitive anchors poses significant challenges in effectively communicating subsurface information, as cognitive images play a crucial role in map reading. Therefore, there is a need for more maps tailored to non-experts.
2. To align maps more closely with the cognitive maps revealed by the participants' sketches, thereby potentially enhancing their appeal and usability, consider the following suggestions
    a. Add surface landmarks.
    b. Use clear understandable language accessible to non-experts.
    c. Utilize patterns that easily associate to type of geology.

3. Geological map features often differ ontologically from other map objects, as they represent interpretations and models rather than precise measurements. It is essential to visually reflect these differences in representations.
4. When visualizing uncertainty, consider the following questions:
    a. What types of uncertainty need to be visually communicated? (e.g., scale, type, error, position)
    b. At what level do users require information about uncertainty? (notification, identification, quantification, evaluation) c. What is the most suitable visualization method for this type of uncertainty? (e.g., altering object appearance, adding supplementary objects or maps, considering context or media) Refer to Figure 4 for visualization ideas.
5. The following good practice can be derived from the current research:
    a. Ensure that the reference information matches the level of detail for the geological information.
    b. Use larger symbols and font for geoscience information to compensate to overly detailed reference information.
    c. Incorporate symbols that convey uncertainty, such as dashed and dotted lines (see Figure 4).
6. Map design should always be based on best-practice cartography. Investing time in testing map design can lead to maps that are more intuitively understandable for a broader audience.
    a. Utilize scales that intuitively and accurately reflect the data; avoid using the rainbow scale.
    b. Evaluate symbology in various reference maps and contexts, considering how other map elements influence the interpretation of symbol sets for specific information variables.
7. Conduct heuristic evaluations of maps based on established principles and cartographic guidelines, including a thorough deconstruction of map information to consider all elements comprehensively.
8. Conduct user studies to inform knowledge-based map design decisions. See Figure 15 for ideas on phases for research and learning in map development.
9. Test prototypes with representative users.

5.3 Outlook

A more comprehensive acknowledgment of geological knowledge is imperative to address pressing societal challenges. A way to create the necessary awareness in society is to share quantitatively more and qualitatively better visualizations for the non-experts. The user, the utility and usability should be put at the centre of map development. Adding cartographic research in the different steps in development can bridge the gap between the fields of science to make geoscience information more available for a broader audience than experts. More geoscience maps for the broader user groups would improve their cognitive image of the subsurface, which in turn should lead to awareness, more effective communication, and improved management, not leaving it as a domain for scientists and experts only.

In cartography, greater attention should be given to resolving the communication gap between expert knowledge and users in general, promoting trust and facilitating knowledge-based decisions for a sustainable future. One important priority involves reducing the gap between cartographic research and its counterpart in geoscience, addressing the unique challenges found here. A collaborative endeavor has the potential to foster interdisciplinary insights, promote knowledge exchange, and contribute to the holistic advancement of both fields.

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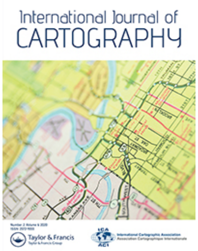
Appendix: Papers

Paper I



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The image of subsurface geology

A. Bang-Kittilsen

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Paper II

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Imaging the Subsurface: How Different Visualizations of Cross-sections Affect the Sense of Uncertainty

Ane Bang-Kittilsen [1,2] • Terje Midtbø [1]

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Abstract
Geologists struggle to communicate the uncertainty that arise when mapping and interpreting the geological subsurface. Today, open data sharing policies make new value of geological information possible for a broader user group of non-experts. It is crucial to develop standard methods for visualizing uncertainty to increase the usability of geological information. In this study, a web experiment was set up to analyze whether and how different design choices influence the sense of uncertainty. Also, questions about the intuitiveness of symbols were asked. Two-hundred ten participants from different countries completed the experiment, both experts and non-experts in geology. Traditional visualization techniques in geology, like dashed lines, dotted lines and question mark, were tested. In addition, other visualizations were tested, such as hatched area and variations of symbol size, zoom levels and reference information. The results show that design choices have an impact on the participants' assessment of uncertainty. The experts inquire about crucial information if it is not present. The results also suggest that when visualizing uncertainty, all the elements in the representation, and specifically the line and area symbols that delineate and colour the features, must work together to make the right impression.

Keywords Visualization · Uncertainty · Subsurface · Geology · Cross-section

Introduction

How do users evaluate the quality of representations of the physical world? Tversky and Kahneman (1974) discuss information visualization in general and claim that the assessment of probability "resembles the subjective assessment of physical quantities such as distance and size". They list a range of factors that must be present for good judgement of representativeness: Knowledge of prior outcomes, sample size, conception of chance, predictability, validity and conception of regression. Communicating uncertainty in maps can help users make better judgement of the confidence in the representation, and to "avoid ill-informed decisions" (Kinkeldey and Senaratne 2018).

✉ Ane Bang-Kittilsen
ane.bang-kittilsen@ngu.no

1 Department of Civil and Environmental Engineering Faculty of Engineering, Norwegian University of Science and Technology, Trondheim Norway

2 Geomatics and IT Geological Survey of Norway, Trondheim Norway

Uncertainty in Geology

Unlike many surficial features on the surface of Earth, the geological subsurface is hard to map. Representations of the intangible and invisible subsurface are therefore more likely to be unprecise and erroneous. When mapping geological features, especially in 3D, interpretations and interpolations are needed to transform raw data, from for example seismic investigations and bore hole logs into 2D and 3D models. These models present the interpreted reality, which can be effectively used by a wider user group. In some areas where bedrock outcrops and data density are high, the seismic may be easy to interpret and verify, while more difficult in areas of low data density. The resulting model is dependent on the geologists' a priori knowledge and experience and therefore subjective (Polson and Curtis 2010). When these models are made, geologists struggle to model and communicate the uncertainty involved (Randle et al. 2018; Pérez-Díaz et al. 2020; Schaaf and Bond 2019).

According to Lark et al. (2015) there are multiple types of uncertainty in geological borders: (1) *Conceptual uncertainty*, which exemplifies whether a border is gradual or not. (2) *Scale-dependent uncertainty* is shown, for example, when a line that may seem continuous at the observed scale is in reality noncontinuous. (3) *Cartographic uncertainty*, which is uncertainty about errors that were implemented during the map-making process. (4) *Interpretation uncertainty* represents the uncertainty when parts of the border cannot be observed. Uncertain borders lines have been communicated with many different words: "known", "probable", "certain", "uncertain", "accurately located", "approximately located", "inferred", "projected", "concealed" and "queried" (Soller et al. 2002). The different types of interpretation uncertainty are not commonly communicated or, when used, even understood by the user.

Geologists have traditionally used perspective illustrations and cross-sections to portray subsurface geology. 3D models are increasingly used, but a review of 3D web viewers from European geological surveys (Bang-Kittilsen 2019) shows 2D cross-sections are still commonly standard output for end-users (see for example Kessler et al. 2018; Baumberger and Oesterling 2018). Most cross-sections typically have coloured areas symbolizing different geological categories, but no communication of uncertainty.

Standards that have been established for communicating uncertainty within geology are connected 2D maps and cross-sections and are typically used for lines or borders: Uncertain location, invisible border, uncertain type and existence (FGDC 2006). The traditional visualization techniques include changing the appearance of the line or border symbols according to types or degree of uncertainty. Dashed and dotted lines together with question marks are standard techniques geologists apply to communicate uncertainty (Soller et al. 2002; FGDC 2006). Uncertainty about the location is indicated with a range from solid line via dashed line to dotted line. Only borders that were observed in the field can be drawn with confidence on the map as solid lines. Question marks along the line indicate uncertainty about the existence of a border (Soller et al. 2002). It is easy to find research about techniques for assessment and visualization of uncertainty in subsurface geology (see for example Tacher et al. 2006; Schweizer et al. 2017; Zehner 2019), but none of these methods is well established among geologists (Zehner 2019).

To optimize the benefits from geological data, there is a need to simplify and make geological representations that are understood and interpreted adequately by the user. As Häggquist and Söderholm (2015) claim, "the use of geological information implies an initial knowledge threshold, i.e. a basic understanding to appropriate the benefits of this good, and the opportunity cost of learning-by-using will have a significant impact on demand." To lower this threshold, it is important to use a graphical language that is easy to understand for the user. Presenting models, maps and cross-sections that are totally dissociated from the complex data and knowledge they are based on may create bias (McInerny et al. 2014). For the data to be usable for decision-making, it is important that it is correct. Since correctness may be hard to ensure throughout a dataset because, for example, a lack of outcrops or knowledge of the subsurface, the need for locating and quantifying uncertainty is important (Tacher et al. 2006). The practice should be to follow the basic rules of cartographic theory and graphical communication within the limits of standards for data and map exchange in the standardized geographical infrastructure. These standards limit the number of techniques to choose from. The challenge, therefore, remains to communicate complex information, both the interpreted geology and the different dimensions of uncertainties, without increasing the user threshold to an expert level.

Uncertainty Visualization

Bonneau et al. (2014) describe uncertainty to be "the lack of information", while Longley et al. (2005) define uncertainty as the difference between a real geographic phenomenon and the user's understanding of the geographic phenomenon. In Hunter and Goodchild (1993), uncertainty is described as the "degree to which the lack of knowledge about the amount of error is responsible for hesitancy in accepting results and observations without caution". All information contains multiple kinds of uncertainty; for geographical information uncertainty exists across space, time and attribute (MacEachren et al. 2012). Information or data uncertainty is often conceptualized by error, but this is, according to MacEachren et al. (2005), often a too narrow approach to uncertainty: Each category can be split into 9 types: Accuracy/error, precision, completeness, consistency, lineage, currency, credibility, subjectivity and interrelatedness. The INSPIRE directive aims to create a European Union spatial data infrastructure (INSPIRE 2020). INSPIRE (2013) defines 17 categories for data quality: Completeness (commission and omission), logical consistency (conceptual, domain, format and positional), positional accuracy ("absolute or external accuracy", "relative or internal" and "gridded data position"), thematic accuracy ("classification correctness", "non-quantitative attribute correctness", "quantitative attribute correctness", "temporal quality", "temporal consistency" and "temporal validity") and usability. Uncertainty can arise along the whole value chain from data collection, processing, analyses and modelling to final use (Pérez-Díaz et al. 2020).

Visualization of uncertainty, according to Pang et al. (1996) "strives to present data together with auxiliary uncertainty information". The ultimate objective of visualizing uncertainty "is to provide users with visualizations that incorporate and reflect information regarding uncertainty to aid in data analysis and decision making" (Pang et al. 1996).

There are multiple techniques for uncertainty visualization that by MacEachren et al. (2005) and Kinkeldey et al. (2014) are described as a combination of the following dichotomies: Intrinsic techniques change the appearance of existing objects while exintric techniques add new objects that represent uncertainty. Visually separable or integral techniques refer to whether the signification can be read independently or not. This is often the same as intrinsic or exintric techniques. Adjacent or coincident techniques represent respectively visualization of uncertainty in second representation or in the same. In addition, the representation can be either static or dynamic where the latter can be interactive or an animation. Explicit or implicit techniques refer to direct representation or indirect through a series of possible outcomes.

Bonneau et al. (2014) claim that "difficulties in applying pre-existing methods, escalating visual complexity, and the lack of obvious visualization techniques" are overlooked, and that this leaves uncertainty visualization an "unsolved problem". Kinkeldey et al. (2014) found that most studies within uncertainty visualization focus on developing new methods for visualization, and fewer on user studies. Kinkeldey et al. (2014) have done a review of geospatial uncertainty visualization user studies. In the selected studies, usability of different visual variables is often tested, contributing to a graphical semiology of uncertainty visualization. However, they conclude that comparison and generalization are hard because the usability is dependent on the task in hand and whether the method is static or dynamic, for example. A review of studies concerning the effect uncertainty visualization have on decision-making can be found in Kinkeldey et al. (2015). There is proof that uncertainty visualization affects decision-making (MacEachren et al. 2005; Deitrick and Edsall 2006; Kinkeldey et al. 2015), but not that it necessarily makes decisions better (MacEachren et al. 2005; Kinkeldey et al. 2015).

This study is in the crossing-point between these above-mentioned groups of studies, targeting specific needs within subsurface geology to make the user attentive to uncertainty in the representation.

In a study by Bang-Kittilsen et al. (2019), participants were asked to draw the subsurface geology. Results show most participant prefer to use cross-sections. The study aimed to elicit cognitive maps on subsurface geology using sketch maps (Bang-Kittilsen 2019). The study included results from 84 participants, both experts and non-expert. The conclusion was that participants predominantly draw the subsurface as cross-sections. Geographical context and plain language were commonly used in the drawings. The content elements, their categorization and visual depiction were diverse. The participants' uncertainty about the geological subsurface had a wide range of expressions in the drawings. This included white spaces, absent borders, sketchiness and dashed lines.

These ways of portraying uncertainty are tested in this study. Traditional symbology for uncertainty (see for example FGDC 2006) is tested along with geographical context, zoom level and symbol size. The study focuses on effective cartographic communication, and more specifically on the effect of different design choices have on the assessment on uncertainty. Real geological data is used in the examples in cross-section. The question of how geologists model uncertainty is beyond the scope of this study. The participants are divided in two main groups: Domain experts, who have extensive knowledge of subsurface data acquisition methods and are aware of the possible extent of bias and uncertainties. The other group is the non-experts, who typically lack this knowledge and who may be more inclined to perceive the information as facts.

The goal of this study is ultimately to improve the geological representations aimed for a broader user group than domain experts, such as decision-makers and planners. The research questions for the study are:

(1) How do differences in design choices affect the sense of uncertainty for the participants, experts and non-experts?
(2) Which symbols do the participants think are intuitive for different kinds of uncertainty and does area background affect the choice of symbols?

Method

A two-step web experiment was set up in order to unravel the participants' reactions to the research questions. The purpose of the first part of the study was to analyze how different design choices affected the participants' assessment of some point locations in the physical world whether they are accurately portrayed in the cross-section. The intuitiveness of conventional symbols for uncertainty was tested in addition to zoom level/symbol size and variation in reference information. At this point of the experiment, participants were divided into four groups that were presented with the same cross-sections with indicated point locations, but with different graphical design choices. In the second part, the participants were again divided into four new groups. Now they were asked to select their preferred symbols in different scenarios. This part was also set up to analyze the implications of adding area fill behind the symbol. Participants were, within both parts, divided into groups, in order to make it possible to analyze and discuss the relevance of multiple variables and combination of symbols.

Pilot Study

A pilot experiment was set up and completed by 20 participants. The first three participants were observed and asked to think aloud while doing their choices. In addition, an anonymous link was sent to selected experts in 3D modelling, cartography/GIS/planning and finally to some employees at the Geological Survey of Norway. Five participants were 18–34 years of age, 12 participants 34–54 years of age and three were older than 55. There were 10 women and 10 men, 14 of these hold higher education. There was an even distribution of non-experts, participants of medium knowledge and experts in geology (6-6-7) and slightly fewer non-experts than experts in cartography/GIS (4-7-9).

The results and feedback from the test group were used to adjust symbols and language in the questions to make it easier to understand, and to verify that the results could be used within the planned statistical analyses. The changes included changing distances and sizes of the dotted and dashed lines to a larger degree resemble standard symbology. The language in the questions in part one was adjusted to make it evident that the question was about the "specific point location".

Part 1

In part 1, the participants were presented with four cross-sections with annotated layers of geology. The cross-sections were presented in a random order (after the first), and the participant got 1 of 4 alternative visualizations, randomly assigned for each image group. In each image group, despite different visualizations, the same cross-section data with the same point locations marked was used (see Fig. 1).

The experiment used illustrations based on real geological data from Hansen et al. (2013). The original cross-sections were put in their geographical context in a 3D viewer. After that, 2D images were exported and simplified, both graphically and linguistically. The simplifications were carefully made with guidance from the first author (Hansen).

Within the cross-sections for all groups, the points were placed beneath the ground and inside a geological layer. The participants had to use a slider (visual analogue scale), which represented the participants' certainty of placement in one geological layer to another (Fig. 2). They were asked to position the slider towards the most likely geological layer at the different point locations A, B and in one cross-section also a point C.

The point locations were added at the same depth and distance from a border within each group. The end points represented the values 0 and 100. If the point was close to a border between two geological layers, the expected result was closer to the mid-point. Placing the slider at the middle returned the value 50, which represents the highest level of insecurity in the participants. The research question was to measure the effect of portraying uncertainty in different ways. Participants were therefore presented with different graphical presentations of the same cross-section with the same point locations. The symbols for uncertainty were not explained to the participant or described in a legend.

The first group of images wished to compare the dashed line compared to no line and solid line. In addition, one image used a hatched area to cover an area, which was marked as uncertain in the original cross-section.

The second group of images in the study showed images with differences in how the border was drawn (Fig. 1, 2nd row). Both points A and B were close to the border, but in two of the images, the line close to point B had a dotted line or dotted line with a question mark (intrinsic visualization). The other two images used a solid line or no lines as borders.

In these first two groups of images, we wanted to examine the difference in how experts and non-experts experienced the use of conventional geological symbols.

The third group of images was made to analyze the effect of scale and symbol size on the assessment of uncertainty. Two of the images were "zoomed in" to the two-point locations, while the other two showed a larger area. One of each pair of images had larger symbols than the other (Fig. 1, 3rd row).

In the fourth group, the difference between the images was only the reference information or geographical context (Fig. 1, 4th row). The research question was to see whether reference information above ground influenced the assumption of uncertainty. Here, uncertainty is shown by making the reference information more or less detailed and correct. This was put first in first part of the experiment, so the participants had no prior knowledge of the scale.

The questions resulted in bipolar scale data from 0 to 100 for each question. For visual analogue scale (VAS) data, used for example in medicine, parametric tests like analysis of variance (ANOVA) and t tests are suitable (Philip 1990). ANOVA is a powerful tool that tolerates violations to the normality assumption if the group sizes are not too small (Philip 1990; Laerd Statistics 2020b). In this study, ANOVA was used to compare the results between the groups and across expert levels. The ANOVA tests whether the variance between groups is larger than the variation within groups. In this case, this was used to analyze whether the differences in graphical representation made statistically significant differences in the answers. If the ANOVA test resulted in statistically significant results, post hoc tests (Bonferroni, least significant difference (LSD)) were used for multiple comparison. Means were compared to see whether the difference indicated a higher degree of uncertainty. To compare groups pairwise, the independent t test was used. Box plots were also used to explore the results.

Part 2

In the second part of the study, the participants were asked to select suitable symbols for different categories. They were asked which symbol they thought were the most intuitive of four different categories: Certain and well-defined transition between two layers, uncertainty of location, gradual transition and uncertainty whether there was a border at all (Fig. 3). The study tested whether the conventional symbols were selected equally by experts and non-experts. The experiment included a limited set of

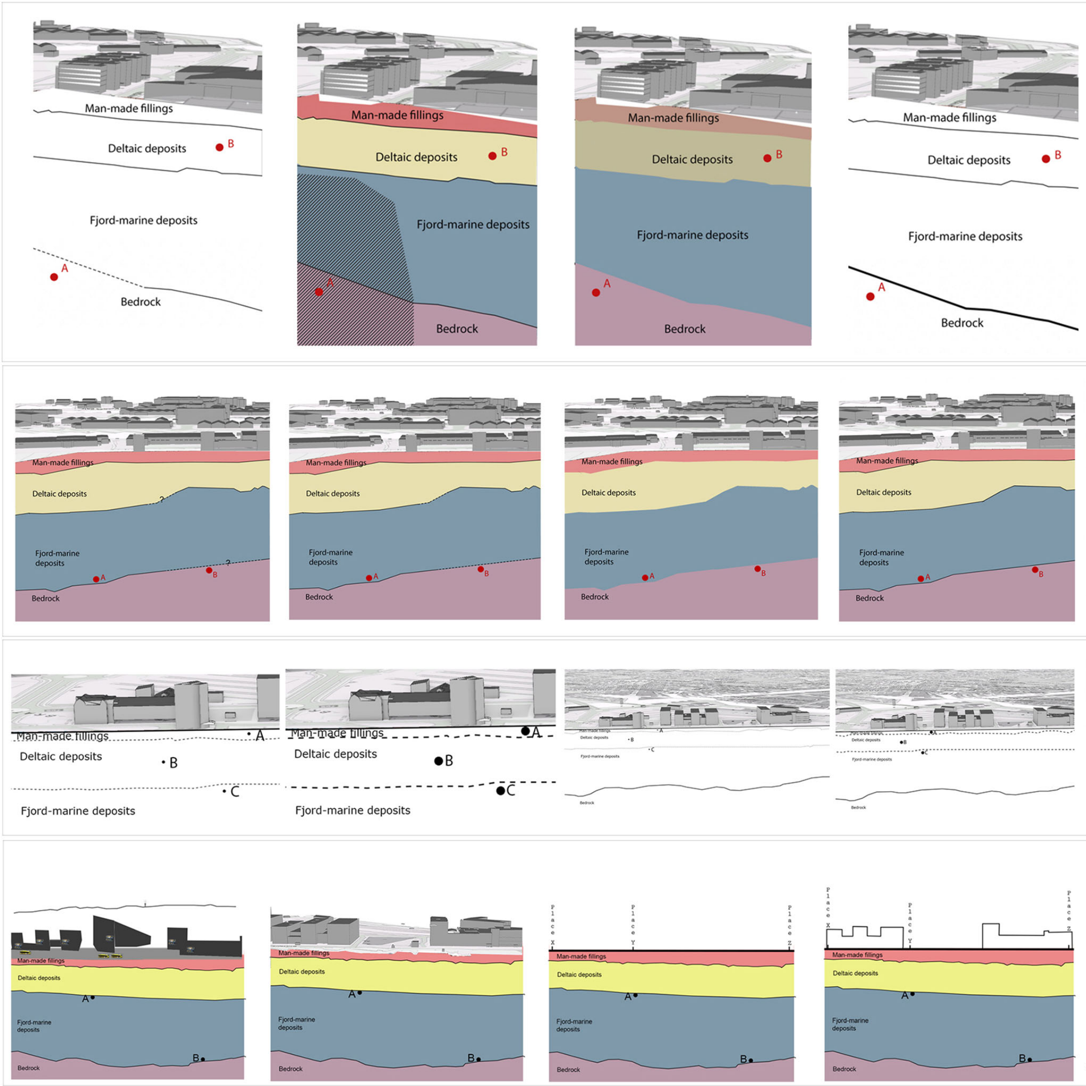

Fig. 1 A collection of all cross-sections used in the survey. Each row shows the four cross-sections with points and their various visualizations that were presented to the four groups. The participants were randomly assigned to one image inn each row, with questions about the point locations. 1st row: Uncertainty visualized with dashed line and hatched area compared to no line and solid line. 2nd row: Uncertainty visualized with dotted line and question mark compared to no line and solid line. 3rd row: Cross-sections with different symbol size and zoom levels. 4th row: Cross-sections with different reference information

types of uncertainty in addition to gradual transitions. This was done to present the complexity of geological visualization, where lines in a representation are used to illustrate different forms of transition, from faults to mixed materials.

The nine different symbols to choose from were conventional line symbols for uncertainty (i.e. FDGC 2006) as well as alternative ones. Variables differed in resolution and crispiness (MacEachren 1995). In addition, random symbols of parallel lines were used. The symbols were presented in small images inspired by legend graphics (Fig. 3).

For each question, the participants were asked to select one or more symbols from the image map that for them the best represented the category (Figure). The questions came in random order, but at the same page. The image map had identical alternatives for line symbols, but these were presented in a random order for each question.

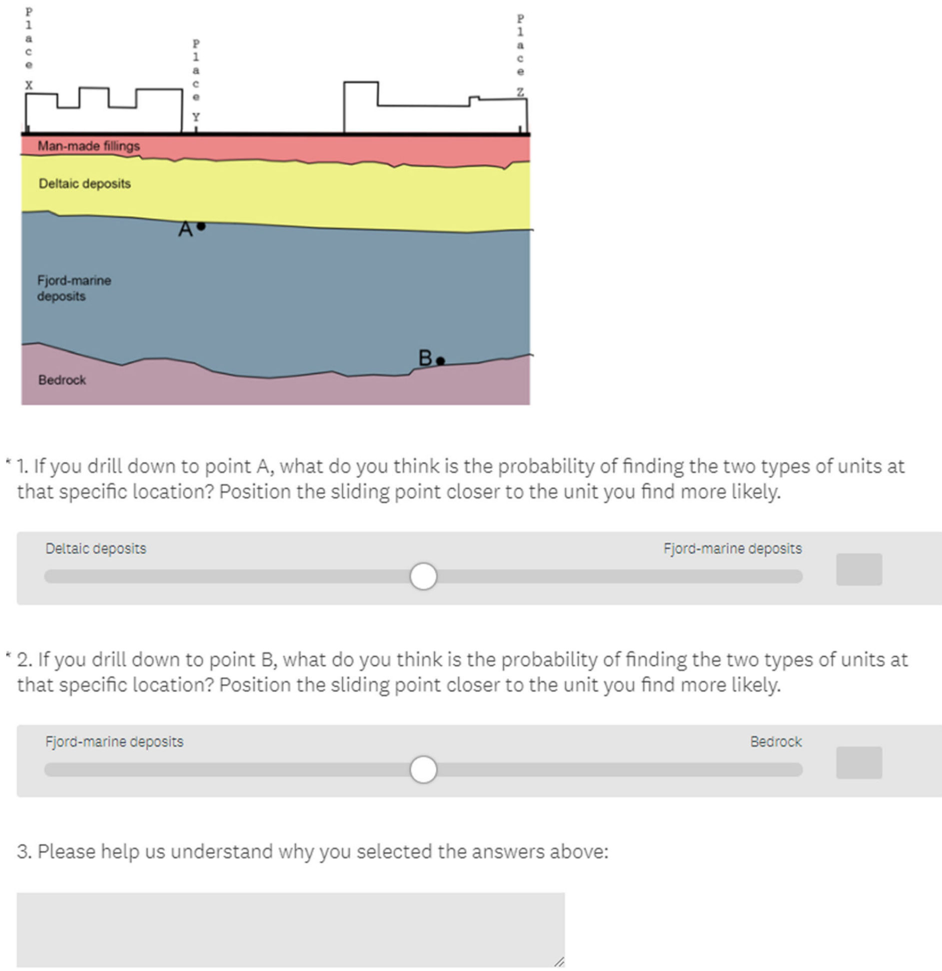

Fig. 2 Screenshot from the survey. Moving the slider to the left close to 0 reflects the participant is confident that this category is found in the physical world. Moving the slider to the right gives a value closer to 100 and confidence about the second category. A value close to 50 and the mid-point reflects high uncertainty

In addition, another dimension was added to provide for an open-ended analysis. The participants were divided into four groups and shown different area backgrounds (Fig. 4); no background or different variations of visual variables: form (pattern), value (grey tones) and colour (hue). Bertin (2010) provided a comprehensive theory of graphical semiology, which was used as a source of inspiration. The system represented a method to fit information variables to visually variables of the same organization levels to make effective graphics. By selecting the right type of graphic and visual variables, loss of information is prevented, and inherent spatial patterns can be identified if they exist. The shape and colour variable are nominally ordered visual variables and are to be used with nominally ordered information, like marine or river deposits. The value variable is ordered and used to portray ordered information, like thick and thin marine deposits. In typical geological maps, there is often a mix or hierarchy of nominal and ordered categories in the same legend, with nominal variables represented by different colour hue, and subgroups that are ordered for example because of age (bedrock) or thickness (surficial deposits) with difference in value (lightness).

This was an open-ended analysis, to measure and discuss potential effects of the area background on the choices of symbols. Presenting lines on the top of area fill is closer to its practical use. Adding 4 variants to 4 groups made it possible to analyze whether symbols present a uniform understanding regardless of area fill background. Also, the different

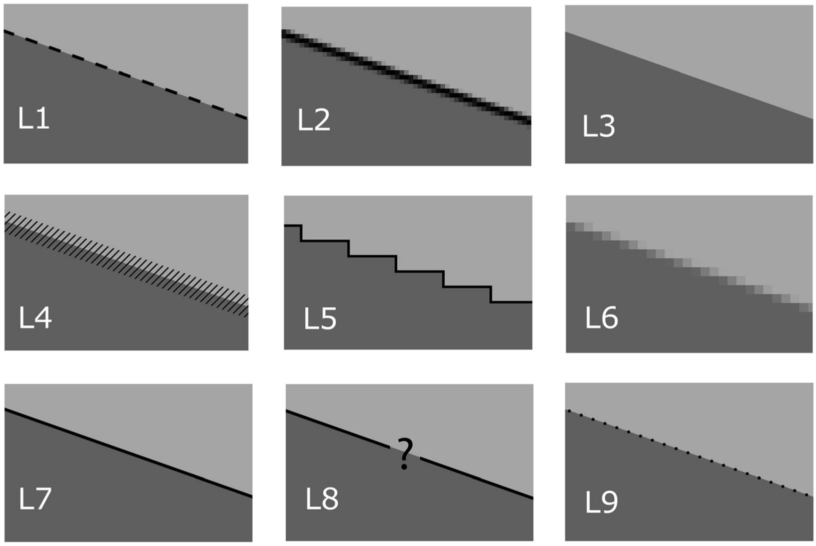

Fig. 3 The questions about preferred symbol type used an image map where the participant could select multiple images by clicking on them

backgrounds would make the results more valuable when it comes to practical use (see Fig. 4).

Part 2 returned a dataset with nominal values of 0 or 1 (chosen or not chosen).

Participants

A wide group of participants was needed to make a statistically viable analysis possible; therefore, a web experiment was selected to collect data. The goal was to reach participants with both limited, medium and expert knowledge of geology. In order to preclude single-country conventions, the experiment was set up for both Norwegian and English-speaking participants. Conducting a web experiment could mean a risk of weakened control over the test, but gave possibilities of more participants, and more experts specializing in 3D geology. The link was sent to employees of the Geological Survey of Norway and collaborating units and contacts, a group for 3D geological modelling experts in Europe as well as Facebook and LinkedIn groups for professionals within planning and maps. To ensure non-expert participants and a high number of participants completing the test, the test was made simple and short, but still using real geological data.

The participants were asked about their age, country, level of education and knowledge levels in geology and cartography/GIS. The questions about knowledge levels were included as this is expected to be a factor (Kinkeldey et al. 2014:384).

Two hundred ten participants completed the experiment. From these, 150 were included in part 1 (elimination explained in detail below) and 206 included in part 2. Four participants were excluded from part 2 as they marked the effort they put into the survey as < 5 (on a scale from 0 to 100). For an overview of the 150 participants in part 1 (see Table 1).

Thirty-eight percent of the participants said they worked within the field of geology, 24.7% in GIS/cartography. There was a dominance of men (62%) and the participants were with few exceptions highly educated.

Participants who marked their participation effort to lower than 15 (on a scale from 0 to 100) were excluded. For part 1, two misunderstandings were revealed through comments and feedback. First, some participants answered about the whole stratigraphy (or drill-log) from the surface down to the position, and not just at the specific position. Second, looking at the answers and comments for one participant, it seemed like

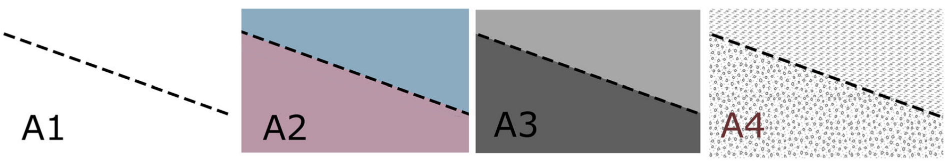

Fig. 4 Each group of participants was presented with different area background for the symbols, representing the visual variables colour, value and pattern

Table 1 Overview of participants, number of participants and percentage of total

Participants (included in part 1)	150				
Gender			Knowledge level geology		
Women	57	38%	Low	58	38.7%
Men	93	62%	Medium	37	24.7%
Education			High	55	36.7%
No higher education	2	1.3%	Knowledge level cartography and GIS		
Some higher education	16	10.7%	Low	31	20.7%
Bachelor or higher	132	88%	Medium	62	41.3%
Country (of work)			High	57	38%
Norway	101	67.3%	Age		
Germany	12	8%	< 18		0.7%
Slovenia	6	4%	18–24	17	11.3%
Switzerland	5	3.3%	25–34	27	18%
USA	4	2.7%	35–44	46	30.7%
Poland	3	2%	45–54	36	24%
China	3	2%	55–64	19	12.7%
Other (Finland, Austria, Belgium, Czech Republic, UK, Denmark, Ireland, Sweden)	13	8.7%	> 65	4	2.7%

the scale bar was misunderstood to represent probability/certainty from 0 to 100%, and not as a bimodal scale from one category to the other. Mapping the probable answers of each type of misunderstanding, a general rule was set for exclusion. Participants who put the slider towards the wrong category on both questions in image group two, where the point locations were furthest from the borders, were excluded. This left 150 participants for analysis. For part two, only participants with an effort lower than 5 were excluded from the analysis.

Results and Discussion

Part 1

Table 2 provides an overview of the results. There were four different cross-sections, each with questions about 2–3 point locations (A, B, C). Each of the cross-sections had four different visualizations, where each participant was randomly assigned to one of these (Fig. 1). One-way ANOVA tests were performed to compare the results between these four groups for each question. In addition, ANOVA tests were performed with expert levels as factor. The tests that returned statistically significant results were tested with post hoc tests. For knowledge levels in geology, there were no significant results from the ANOVA tests. This might be because the different visualization techniques make it difficult to detect differences between participants of different knowledge levels, compared to a more focused study with less variables. It is likely that different knowledge levels have different effect dependent on the visualization used. When discussing the results below, expert levels are therefor also explored in more detail.

Comparison Between Uncertainty Visualized with Dashed Line and Hatched Area

In the first assignment, it was investigated whether two types of uncertainty visualization gave a significant difference in the answers (Fig. 5). Both intrinsic and extrinsic visualization techniques were used. One cross-section had uncertainty marked as a dashed line on a white background, the other as a hatched area. These were compared to no lines and thick line on a white background. The one-way ANOVA test returns a significant difference between all groups for point A (0.001), which was the point in the uncertain area. For point B, the difference is not significant (0.201). When comparing the individual groups with the Bonferroni post hoc test, the results show that the dashed line (L1) returns significant values when compared to all the other groups, while the other groups have no significant difference (Fig. 5). The solid line (L2) gave a statistically significant difference between groups for point A (0.003). The hatched area did not give any significant difference in answers, only compared to

Table 2 The results from the ANOVA test from groups with different visualization technique and with different knowledge levels. There are statistically significant differences ($p < 0.05$) (marked with "*"), for three of the four cross-sections based on visualization technique but not on expert levels

Cross-section	Visualization techniques used	Vis. technique				Knowledge levels		
		Point	df	F-ratio	p value	df	F-ratio	p value
1	Dashed line/solid lines and no colour background, hatched area/no lines with colour background	A	3	6.064	0.001*	2	0.368	0.693
		B	3	2.185	0.092	2	0.816	0.444
2	Dotted line/question mark/no line/solid line	A	3	0.201	0.896	2	0.726	0.486
		B	3	0.916	0.435	2	2.365	0.098
3	Different zoom levels/ symbol size	A	3	2.602	0.054	2	0.673	0.512
		B	3	5.650	0.001*	2	0.488	0.615
		C	3	2.959	0.034*	2	0.681	0.508
4	Different reference information	A	3	0.827	0.481	2	0.386	0.681
		B	3	3.144	0.027*	2	0.154	0.858

the dashed line. It did not give a higher mean on uncertainty assessment compared to the examples with no uncertainty visualization. A hatched area has the advantage that it can better show the area extent of high uncertainty, while the line only describes the uncertainty connected to the line.

The results from this study suggest that this technique requires a legend and explanation, and therefore more time for the user to read and perceive the information. Results from this study therefore supports the conclusion from Slocum et al. (2003) that extrinsic visualization is better for in-depth studies of uncertainty, while intrinsic visualization gives a better overview. According to Harrower (2002), there is "growing evidence that integrated uncertainty symbolization (e.g., bivariate symbols) is superior to separate displays, at least in static maps." The answers show that the level of uncertainty was much higher for the participants who were shown the dashed line compared to the thick, solid line (see Table 3). The difference was also significant between dashed line and hatched area (0.008) and close to significant for dashed line and no line (0.059). The uncertainty for point B was also a bit higher for the alternative with the dashed line. This may suggest an "out of sight, out of mind" effect for uncertainty.

When comparing experts and non-experts, there is a higher significance for experts than non-experts for the comparison between the dashed line and no line. This suggests the experts know the dashed line usually means uncertainty. The results give no answers to how effective these symbols would be when the non-experts become familiar with them. As Harrower (2002) concludes: "Knowing how users react in a test setting to maps they have likely not seen before ("cold" test subjects) makes it difficult to know how these maps could become integrated into their everyday intellectual activities."

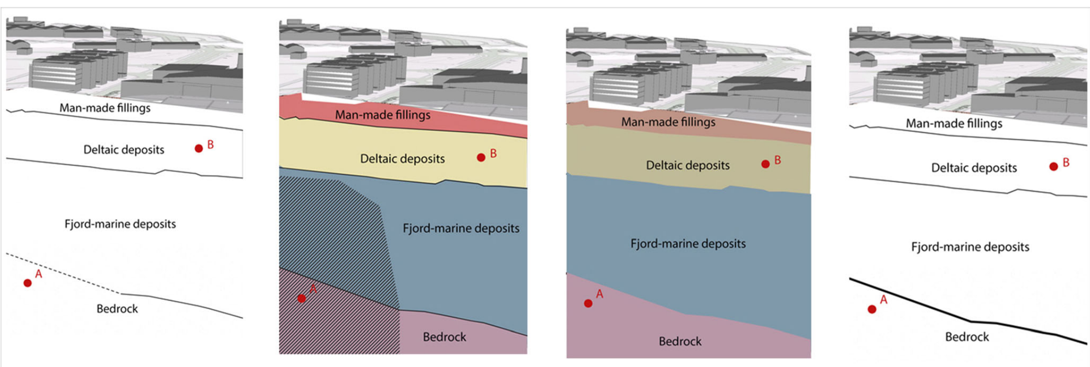

Fig. 5 Results show that participants were more uncertain that point A was situated within bedrock when below the hatched line, than in the other groups. The hatched area gave no increased uncertainty in this study

Table 3 The mean value for the participants for different designs. The dashed line is an effective way for communicating uncertainty (closer to the mid-point of 50). The results also show that the presence of the dashed line increases the uncertainty for the other point

	Dashed line, no colour	Hatched area, colour	No lines, no colour	Solid lines, colour
Mean point A (reversed)	26.98*	15.06	17.93	14.11
Mean point B	12.31	8.38	7.24	9.28

Comparison Between Uncertainty Visualized with Dotted Line and Question Mark

Figure 6 presents the cross-sections evaluated for uncertainty visualized with dotted line and question mark. The ANOVA and *t* tests comparing the groups gave no significant results. When comparing pair of groups (uncertainty visualized or not), the independent *t* test returns a *p* value of 0.136. There is a difference in the mean values (uncertainty visualized in point B is on average higher when uncertainty is visualized), but still not a significant difference. This may be explained by the graphical differences between the images being too small. The colours used are probably too dominant compared to the symbols that varies between images. With more graphically distinctive symbolizing, results may have been different, and therefore, no conclusions can be drawn from these results about the symbols used for uncertainty in this part.

Comparison Between Cross-sections with Different Symbol Size and Zoom Level

The research question for this assignment was whether decreased symbol size would give an impression of detail and correctness that would make the participants' uncertainty decrease (Fig. 7). The different zoom levels were also expected to give a similar effect. It was expected that when the image was easier to read, uncertainty would decrease. The results show when "zoomed in" and symbol size decreases, participants are more certain about the category. Nine outliers were detected in an outlier analysis and were removed as is recommended before running an ANOVA analysis (Laerd statistics 2020a). One-way ANOVA test returned significant differences in mean for point B (0.001) and C (0.034), while the value for point A is close to significant (0.054). This means the 0 hypothesis must be rejected: The results show size of symbols and/or zoom levels do matter when it comes to sense of uncertainty.

The post hoc test revealed there are statistically significant differences between the groups having the zoomed-in image with the small symbols and both zoomed-out images for point B and C. This was also the case for the zoomed-in image with larger symbols compared to the zoomed-in with small symbols for points B and C. This means the 0 hypothesis may be rejected on the counts of zoom level. For symbol size, the LSD post hoc returns close to significant values for point B (0.88 and 0.72) when comparing different symbol size, but the same zoom levels. For points B and C, the group having the zoomed-out images were less certain about the categorization, with the highest difference for point B. For point A, the groups seem to agree that this most certainly are fillings, with a mean close to the endpoint.

These results suggest that it is possible to use zoom and symbol size to give an impression of higher or lower uncertainty with the overall representation.

There was no significant difference found between experts and non-experts in this category.

Comparison Between Cross-sections with Different Reference Information

The inquiry when comparing cross-sections with different reference information above ground was whether this information (base data) has an effect on the overall uncertainty levels (Fig. 8). The groups were shown the exact same representation of the geology, while the reference information above the surface varied from tics with place names to sketches of 2D to 3D building outlines.

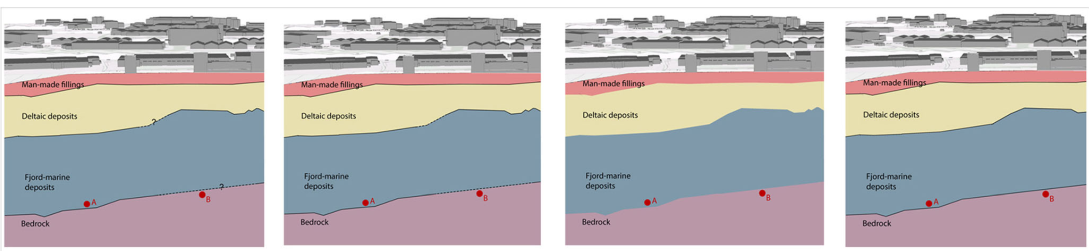

Fig. 6 Uncertainty visualized with dotted line and question mark gave some differences between groups, but they were not statistically significant. This could probably be explained by the colours being too dominant in the images, leaving the differences represented by the uncertainty visualization too small

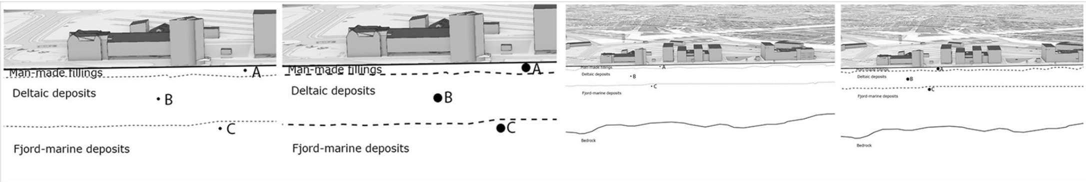

Fig. 7 Zoom levels and symbol sizes make a difference. Smaller symbols in a zoomed-in image decrease the uncertainty

Two outliers were removed. The one-way ANOVA test found a statistically significant result for point B (0.027) while A was not (0.481). Point B is located near the border of bedrock, and some experts comment that the bedrock surface is easy to detect from possible seismic data, which have influenced the different results. The *t* test comparing the two images with less detailed reference information compared with the two with 2D building outline and 3D buildings returned a significant value of 0.021 for B (0.160 for A). This may be explained by the hypothesis that when the reference information looks precise, it can be expected that the user has increased confidence to that the geological borders and categories are correct. A similar hypothesis was discussed by MacEachren (1995:437). He suggested three visual variables "crispiness", "resolution" and "transparency" for uncertainty visualization. Crispiness refers to different degrees of detail and how precise sign vehicles are defined. Resolution, according to MacEachren (1995), refers to "the spatial precision of the map's geographical base, with a coarse base (possibly) suggesting lack of certainty about data depicted on that base.

The results from this experiment confirm the hypothesis that more precise reference information gives a higher confidence in the categorization. When the cross-section has only tags and place names as reference information, the mean value is closer to the mid-point, which reflects higher uncertainty (49.5). When the reference information contains 2D building outlines, the mean value is closer to the endpoint (24.66), which means a clearer certainty about the category. The Bonferroni test returns a value of 0.017 for B. Thus, increasing the group size gives clearer results, all confirming the hypothesis. In the questions regarding this alternative, which was the first in the experiment for all participants, some participants commented that they struggle to understand what they are supposed to do or see and wonder about the intention of the experiment. Some participants commented they answered the first questions wrong. Some of the participants likely did not understand the connection between the subsurface and the reference information above ground or understand its relevance. The amount of misunderstandings may have influenced the results. With a better explained assignment, the patterns may have been more evident.

There were no significant differences when comparing experts with non-experts.

Geographical information systems and databases limit the cartographic language to its objects like lines, areas, voxels and volumes. Out-of-the-box visualization offers simple variation of visual variables. There are unlimited possibilities, though, only limited by development of new methods. Sketchy visualizations are offered today in Geographical Information Systems (GIS), available with some programming (Wood et al. 2012; GISSE 2020).

In geology, in order to make more understandable maps, the whole presentation could be made sketchy. Alternatively, the geographical base or the geological features could be made sketchy. Areas where dense, detailed and certain measurements are available or areas where digging and blasting have revealed "the truth" can have solid, standard cartography, while uncertain areas are made sketchy.

Experts Versus Non-experts

Results from this study suggest that experts understand uncertainty visualized the conventional ways, even when there is no legend. The one-way ANOVA returns statistical significance of 0.019 between expert level groups for point A in the image with dashed line, and 0.136 for point B. This analysis includes

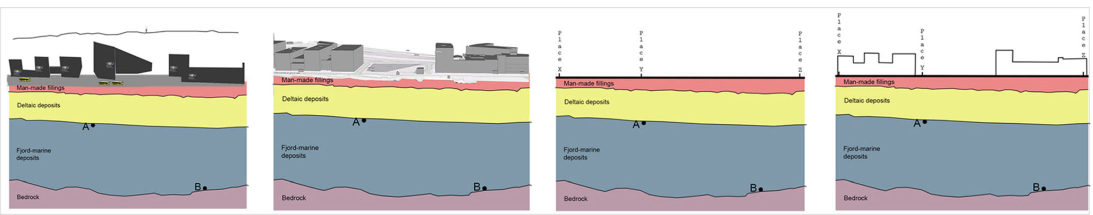

Fig. 8 Results from this comparison confirm the hypothesis that increased detail in the reference information decreases uncertainty, and therefore confidence in the information presented

42 participants. Also, for the question mark and dotted lines, there is a difference in mean values following the same trend. This result suggests uncertainty information is of great guidance for the geologist to evaluate uncertainty. For the non-experts, the uncertainty visualization must be made more obvious, so that also non-experts make the same assessment. Another difference between experts and non-experts is also identified through the comments, where experts think it is difficult to answer the questions because they lack information about drillings and other data the interpretation is based on. Another example from the comments is that the bedrock surface can be easy to map compared to other geological layers. They know it is hard to separate the softer layers from a seismic image. The different answers from experts and non-experts show a potential of communicating more of the elements that requires domain knowledge in the representation more distinctively. This could be shown visually for example by making the bedrock line more distinct than the other lines.

Part 2

For this part of the experiment, the participants were asked to select suitable line symbols for different kind of uncertainty, which is typically found in geological representations. The research question aimed to assess what participants prefer, whether the conventional symbols in geology also are the preferred symbols by the non-experts. In addition, part of the question was to evaluate the impact area background has.

The participants were divided in four groups, where each group had a different background area fill together with the line symbol. The questions and alternatives were randomized, but at the same page. Table 4 presents the distribution of participants across groups and knowledge levels.

The most preferred symbols (independent of area fill) (Fig. 3) for the respective questions are shown in Table 5. As expected, almost all the participants selected the solid line (L7) for certain and well-defined transitions between two geological layers. For gradual transitions, the randomly selected symbol with oblique lines (L4) was the most selected, followed by

Table 4 The distribution of the 206 participants across groups and knowledge levels in part 2

		Level of knowledge in geology		
	Percent	Low	Medium	Experts
A1	17.5%	12	10	14
A2	32.5%	24	19	24
A3	32.0%	30	14	22
A4	18.0%	11	11	15

the stepwise transition with no line present (L6). The dashed line (L1), oblique lines (L4) and solid line with a question mark (L8) were the main alternatives chosen to best represent uncertain location. The alternative when two, separable layers are divided by a solid line with a question mark (L8) was preferred by half of the participants for representing uncertainty if there actually are two separate layers (Figs. 3 and 4 and Tables 5 and 6).

Comparing Groups Across Knowledge Levels

For uncertain location, the question was: "Select the line symbols that you think are suitable for representing an uncertain location between two layers". When comparing across knowledge levels (Table 5), the Pearson chi-square test returned a statistically significant value for the dashed line (L1) and the thick, blurry line (L2). As Table 5 shows, more experts preferred the dashed line, while 25% of the non-experts suggested the thick blurry line.

Symbols selected when the issue was uncertainty if there actually are two separate layers gave statistically significant results from the Pearson chi-square for the dashed line (L1). Half as many non-experts as experts selected this. It should also be noted that the question mark seems effective for all knowledge levels for uncertainty if there is a transition.

Comparing Groups Across Area Fill Behind the Symbols

The results show that area fill makes a difference when choosing line symbols (Table 6 ; Figs. 3 and 4 for images of line symbols (L1–L9) and area background (A1–A4)). The Pearson chi test resulted in multiple significant results, marked with "*" in Table 6. No line (L3) for certain borders should be disregarded for group A1 as a blank symbol marked "no line" probably was too abstract for the participants. It is common to show cross-sections with no border line between the features. The dashed line for gradual transition was chosen by more participants when the background area was different grey tones, but almost by none when there was patterned fill. Together with the patterned background, the dashed line was less distinct.

The dotted line was chosen by almost half for uncertain location when there was no area background, and only by 17% when the background was grey tones.

To show uncertainty if there actually are two separate layers, the dotted line was more often chosen than when there was no area background. When the background was filled with a pattern, more participants chose the solid line for this category. Also, some participants chose a solid line when the background was grey tones. This can possibly be explained by either, that some of the participants did not read the question right ("line symbol") and/or that the area and line symbols are being intertwined and perceived as a whole. Regardless of the

Table 5 Participants choosing the symbols L1–L9 for the different categories compared to knowledge levels in geology in percent (%). The Pearson chi-square test shows statistically significant difference ($p < 0.05$) between groups marked with "*"

	Certain			Gradual transition			Uncertain location			Uncertain existence		
	Low	Medium	Expert	Low	Medium	Expert	Low	Medium	Expert	Low	Medium	Expert
L1	13	6	4	8	15	9	35*	52*	53*	21*	33*	44*
L2	14	11	11	19	19	12	25*	17*	9*	18	11	7
L3	22	28	27	4	2	4	4	2	1	9	7	5
L4	3	0	3	69	48	59	47	43	36	35	26	25
L5	31	20	25	18	15	9	6	7	5	6	2	5
L6	6	2	4	42	52	44	23	22	11	26	15	12
L7	90	96	93	0	0	1	3	0	1	4	2	5
L8	1	0	4	3	7	3	35	35	47	45	57	47
L9	8	2	3	9	9	11	23	30	29	22	30	27

reason, it illustrates typical challenges with graphical communication. The challenge increases as the data presented gets more advanced and domain specific.

Other results

Degree of Difficulty, Relevance and Effort

As mentioned earlier, 25% of the participants were excluded for part 1, as they very likely had misunderstood this part of the assignment. All 210 participants that completed the experiment are included in this evaluation part of the analysis.

When asked about the relevance of this type of information privately or professionally, the results show that 44% of the participants convey it as very or extremely relevant (Table 7). This is no surprise when 37.6% of the participants were working in the field of geology, and 54% in cartography and GIS. More surprisingly, 26.6% answer it as not so or not at all relevant with subsurface information. This may be because of the use of domain-specific language and no explanation on what the subsurface information means in practice. Table 8 presents the effort that the participants felt they put into the survey. An average of 9 min and 29 s was used to complete the experiment.

Evaluation of the Method

It proved difficult to get a large number of participants to do the experiment. One-in-three participants did not complete. Some stated that the reason they did not complete the survey was because they wanted to change their answer in the first part when they looked at the possible symbolization of uncertainty in the second part. It was, however, not possible to go back and correct answers. One person stated the language was too difficult ("geological unit"). A participant said the slider

Table 6 Percent of the participants who selected the different line symbols L1–l9 across different area background (A1–9). The areas marked with "*" came out as statistically significant difference ($p < 0.05$) between expert levels in the Pearson chi-square statistics

	Certain line				Gradual transition				Uncertain location				Uncertain existence			
	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
L1	3	7	9	11	11*	6*	18*	3*	50	40	44	57	39	33	29	32
L2	19	10	6	19	19	13	15	22	17	15	20	16	0*	9*	15*	24*
L3	0*	31*	38*	16*	3	1	3	8	0*	0*	2*	11*	19*	3*	3*	11*
L4	0	3	2	3	69	60	52	65	36	45	39	46	19	21	38	38
L5	36	19	21	38	11	19	12	11	6	7	6	5	3	6	3	8
L6	8	4	2	5	50	43	52	32	17	16	27	8	14	21	18	16
L7	94	93	94	89	0	1	0	0	3	3	0	0	0	4	3	8
L8	0	0	5	3	0	3	6	5	36	39	42	38	53	52	52	35
L9	3	1	9	3	8	9	9	14	44*	24*	17*	35*	42*	30*	12*	27*

Table 7 The relevance of subsurface information privately or professionally, according to the participants

	Relevance Frequency	Percent
Extremely	51	24.3%
Very	42	20%
Somewhat	55	26.2%
Not so relevant	32	15.2%
Not at all relevant	24	11.4%
I do not know	6	2.9%

with numbers was confusing, and there were examples of misunderstandings, as described above.

The slider as a measure of confidence and certainty gave statistically significant results in this study. The challenge, however, is to decrease the number of misunderstandings dealing with real data, unfamiliar for many and domain-specific expert language.

Conclusions

Unused potential of improved graphical communication and ultimately more optimal use of geological information exist when communicating geological representations. Unfortunately, a gap in the degree of understanding exists between experts and non-experts when it comes to the interpretations of maps.

There is a crucial need for communicating uncertainty in geological subsurface representations. Uncertainty visualization gives the geologists and others the means to express different degrees of certainty about locations that are intangible or invisible, but also where the model is influenced by the geologist's subjective interpretations. Without uncertainty visualization, crucial information will always be lacking.

Results from all parts of this study provide evidence that different design choices have a significant effect on the assessment of uncertainty, even though these are not explained in a legend. Design choices that, in this study, proved to be effective are as follows: Changing the appearance of borders between geological layers, making the reference information less detailed and changing scale and symbol size. The dashed line was proven to be a solid choice for experts, and an effective symbol for uncertainty overall. Adding uncertainty into cross-sections could be an excellent tool, which would add understanding both for experts and non-experts. The different answers from experts and non-experts show a potential of communicating more of the elements that requires domain knowledge in the representation more distinctively. A more focused experiment, using a similar method as in part one, but with more guidance in the beginning, could potentially give more knowledge into how users perceive uncertainty visualizations.

The results from this study show that uncertainty visualization, which changes the appearance of the objects, seems effective if the design choices are conventional and/or intuitive. The awareness of possible effects of difference design choices is important and alternative designs should be user-tested before developing new representations. The knowledge of which symbols increase or decrease the sense of uncertainty could be developed and effectively used to improve the usability of geological representations. For expert users, there may be a demand for a comprehensive 3D model of uncertainty for in-depth studies. These cases require more advanced solutions for visualization that the methods tested here.

Subsurface information is different from visible surface information, as it communicates something invisible, intangible and not directly observable, which in many cases is full of uncertainty. The graphical border between geological layers is now used for a lot of information: Type of transition (for example fault or gradual transition), uncertainty and in some cases also as direction of movement. New visualization techniques should be developed for visualizing geology in the same model as the observable and more easily measurable objects above the ground. There is an important difference between measured and interpreted information, and it would be beneficial to the user if this difference became evident with the help of graphical techniques.

In a representation, all elements together influence what the user perceives. The users should be in focus and the time and effort they need to interpret the information and understand the potential uncertainties should be reduced. Testing different designs with the intended user group should be done to ensure information is perceived in the right manner.

Table 8 The effort that was put into the survey and degree of difficulty, according to the participants themselves

Effort	Frequency	Percent	Easy or hard	Frequency	Percent
0–20	34	16.2	Very easy	16	7.6
21–40	46	21.9	Easy	47	22.4
41–60	50	23.8	Neither easy nor hard	110	52.4
61–80	62	29.5	Hard	29	13.8
81–100	18	8.6	Very hard	8	3.8

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Ethical Approval Not applicable.

Informed Consent Yes, voluntary decision to participate in the study.

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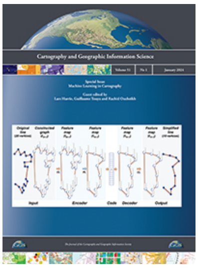
Paper III



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Improving intuitiveness in geoscience hazard maps: a web-based experiment supporting governmental map development

Ane Bang-Kittilsen [a,b] and Terje Midtbø [a]

[a]Faculty of Engineering, Norwegian University of Science and Technology, Trondheim, Norway; [b]Geomatics and ICT, Geological Survey of Norway, Trondheim, Norway

ABSTRACT
Changing societal needs means that new or existing maps need to be continuously developed. It is important that these maps are interpreted in the right way, to avoid misinterpretations and bad decision-making. The map design choices are based upon experience and cartographic theory, and in the end, are a product of expert opinions. This in-house research project aims to test and communicate the impact of these design choices to support the development processes for two Norwegian geoscience maps: Possibility of marine clay and the national Radon susceptibility map. Interviews were conducted with the map owners and based on known challenges with the maps, a web-based experiment was set up to measure intuitiveness for a series of map alternatives. A total of 450 participants, from novices to experts, took part in the experiment. By analyzing and visualizing amounts of correct answers, confidence in the map reading tasks and uncertainties, it was possible to conclude about map intuitiveness and how accessible the map is expected to be. The results show that including an experiment like this can improve cartographic work processes, support map design choices with empirical evidence, and that seemingly small improvements in design significantly improve the participant scores.

KEY POLICY HIGHLIGHTS

- Map experiments performed as part of thematic map development processes give room for focus, learning, and advancement in cartographic work.
- Minor differences in symbolization can have a significant impact on how easily the map is intuitively understood. Thus, the value of optimizing symbology to strictly follow cartographic rules should not be underestimated.

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Introduction

"Major disasters cause massive disruption to societies and overburden national economic systems," Altan et al. (2013) states in a joint report on value of geoinformation for disaster and risk management. Report authors conclude that these major disasters *"could be minimized and considerable losses of life and property could be avoided through improved risk assessment, early warning, and disaster detection and monitoring."* Geological surveys are among the governmental organizations that offer thematic maps to meet the demand for geoscience knowledge. Geoscience maps made to improve risk assessment include, but are not limited to, maps for seismic hazards, risk of rock-, clay-, landslides, subsidence, and radon gas. The maps are delivered through standardized map services as part of the national geospatial data infrastructure and The Norwegian Public Base of Geospatial Data. They are most often used in the end-user's web maps and applications. Also, they are republished as screen captures by users in reports, such as planning documents, and newspaper articles. The map owner has limited control of these publications; for example, where the legend is found and how it is displayed. It is common to see news articles featuring a screen capture of a web map without the legend (for example Amundsen, 2017; NRK, 2020; Setså, 2020). There are examples in the media where susceptibility maps are misinterpreted, and conclusions are drawn from insufficient information. For example, a national media source (NRK, 2020) concluded an area has no quick clay, based on a map that only shows the potentially large, continuous masses of clay. In web maps, obtaining a legend is often not as straight forward as it is in traditional paper maps. Map owners express concerns about the potential for incorrect conclusions and actions, emphasizing the importance of optimizing symbolization to help the users. Nevertheless, it is common for the maps to be created without undergoing systematic user testing.

CONTACT Ane Bang-Kittilsen ane.bang-kittilsen@ngu.no

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Xie et al. (2021) concludes that *"the difficulty of interpreting maps has been underestimated. This fact is especially problematic for thematic maps, the type of map that is finding increasing currency in discourse and the media."* Maps of the subsurface often use expert language and are riddled with uncertainties associated to mapping scale, expert interpretation, and measurements of the intangible and invisible subsurface (Bang-Kittilsen & Midtbø, 2021; Häggquist & Söderholm, 2015; Pérez-Díaz et al., 2020). Traditionally, geological maps have been made by experts for experts. A large gap exists between what a geologist can derive from, for instance, a bedrock map, compared to what a non-expert can discern (Häggquist & Söderholm, 2015). In response to the high demand for simplified map products, addressing specific societal challenges, maps are derived from data originally collected for different purposes, with no knowledge of the secondary application or potential users. However, it may be the best information available for addressing a particular question. The drawback with the derivation process, however, is that it may lead to increased uncertainties and generalizations. The simplified geoscience maps are, as a result, challenging to interpret and use effectively.

When faced with rapidly growing access to knowledge that could shed light on a societal challenge, particularly when dealing with complex knowledge, it is expected that heuristics and intuition assume a more significant role (Adinolfi & Loia, 2022). To support public administrators, the total number of maps in the public knowledge base in Norway was 148 in 2023 (Government, 2023). It cannot be expected that the average user will learn enough about geology or have the time to carefully read the map with all supporting information to ensure adequate understanding and use. It is expected that heuristics and intuition trump analytical reading: A typical user behavior can be quickly glance at the map, recognizing ordered colors from light to dark and immediately drawing conclusions about whether their location of interest being at risk or not. Therefore, it is important to understand how users perceive elements such as white or blank areas and how they recognize when data is uncertain.

Bertin (2010) used the word "efficacy" to describe the success of a map, a synonym for effectiveness: *"If, in order to obtain a correct and complete answer to a given question, all other things being equal, one construction requires a shorter observation time than another construction, we can say that it is more efficient for this question."* In this study, the focus is on the immediate understanding, the concept of intuitiveness is used. The definition used in this study, is slightly modified from Islam and Bouwman (2016) to fit map symbols instead of web interface signs: An intuitive map sign or symbol is *"easy and intuitive to interpret and that allows users to understand the referential meaning accurately. The referential meaning of [the map] symbol refers to the meaning (information, content and/or functions) as assigned by [the map owner]."* Experience demonstrates that the concept of "intuitiveness" is readily understood by non-cartographers, and the concept embraces the fact that map reading is an individual process colored by the map user and their previous knowledge and experience. The concept of efficiency is perhaps more alienating, often associated with objectiveness and automation.

Within cartography, there has been significant scientific research on users, map use and map symbolization (Roth et al., 2017). Many are inspired by cognitive research, performed in laboratories where participants are observed while performing specific tasks (Bunch & Lloyd, 2006; Nelson, 2000). Time use and success rates are commonly measured, sometimes in conjunction with other methods such as eye-tracking and/or thinking aloud (Candela et al., 2022; Çöltekin et al., 2009, 2010; Dong et al., 2014; Koletsis et al., 2017; Ooms et al., 2012). This research is typically characterized by a high degree of experimental control, targeting generalizable cartographic issues, like map reading or usability of symbols, map types or map interfaces. Context-aware research, targeting specific users or contexts, is commonly done with qualitative methods (Opach & Rød, 2022; Perkins, 2008; Suchan & Brewer, 2000). This can involve interviews, observation of a few users and document analysis, to gain deep understanding that ensures relevance of the research questions, methods, and results. A recommended approach for user and usability studies is mixing methods (Ooms, 2016), for example combining quantitative methods with qualitative context-aware methods, so that researchers can leverage from the advantages of both approaches.

While there is extensive cartographic research on map use and users, their impact on map production can be questioned (Montello, 2002). A key factor may be the distance to actual map production communities, especially for thematic maps made by experts from other disciplines. Roth et al. (2017) emphasizes the importance of case-studies to highlight the challenges within current practices. When specific users and contexts are targeted in cartographic research, this is typically performed using an external viewpoint with an outsider's perspective. For controlled experiments, there can be an additional gap from real-life scenarios as they are challenging to reproduce in a lab environment (Lloyd, 2005). Controlled lab experiments increase the required time for each participant, which, in turn may limit the number of participants and reduce representativeness. In addition, participants are often employees and fellow students at the university. Roth et al. (2017) calls for a shift from convenience participant sampling to purposeful sampling.

In the development of thematic maps, the map owners are experts in geology or other related fields. They maintain cartographic integrity by following the traditional practices of mapmaking within their respective fields of expertise. There can be limited opportunities to stay up to date with the latest developments in cartography. This may also be the case for the involved GIS and cartography experts. The rising demand for digitalization and standardization of data and maps for the national data infrastructure places a significant strain on available resources. The integration of cartographic research into map development is anticipated to provide opportunities for mutual learning and advancement.

This study distinguishes itself from most previous studies in that it includes elements of participatory action research. That is, the main researcher is an employee working within the map development teams with the aim of improving both the maps and the work processes. Meetings, informal interviews, and document analyses are integral components in addition to map experiments. This study is characterized by a high number of participants, purposeful participant sampling, and the use of officially published maps that are regularly updated. The study thus complements existing research in enlightening specific challenges and possibly identifying new, general challenges.

The goals for the study are both to make design decisions for the selected maps and to create opportunities for learning and development in the cartographic work at a geological survey. An empirical experiment was initiated in response to the map owners' concern that the users might hastily form overly simplified conclusions, without appreciating the information complexity. To address the anticipated user behavior, which is dominated by heuristics and intuitiveness, the focus of the experiment is on assessing the immediate interpretation of the map symbols for two currently used map products.

Research questions:

- What can be learned from applying map experiments into map development?
- How intuitive are the map symbols without a legend present?
- What increases and decreases intuitiveness?
- How can map intuitiveness be measured, analyzed, visualized, and communicated to support design decisions?

This study presents a method for testing, visualizing, and analyzing how intuitive, and therefore how successfully a map is expected to communicate the information content without a legend. Including map experiments can aid the development of maps that are easier to understand and thus more accessible to broader user groups, and at the same time with a reducing risk of misinterpretation and poor decision-making. This case study will provide valuable insights into the significance of emphasizing map design and how this can be achieved. Such emphasis, in turn, has the potential to enhance land use management and facilitate informed decision-making.

Study design and method

The following steps were taken to set up the study, which will be described in more detail in this chapter.

(1) Selecting maps and their challenges: Map owners were informally interviewed, and document analyzes were done throughout the study. The goal was to learn about why and for whom the maps were made, data limitations, why the existing symbology was selected and known challenges with the maps.
(2) The selected maps were deconstructed and analyzed according to cartographic theory. For example, the number and length of information variables and whether they were correctly matched with visual variables. To get to know the data, experiments with alternative symbolization were done, and alternatives for the map experiment were selected.
(3) A pilot study with 20 participants was conducted to ensure the test was understandable and that the resulting data was fit for analysis.
(4) The final test scheme was designed, and a web experiment was published. Participants, from novices to experts, were invited.
(5) Results were analyzed statistically together with visual data exploration.
(6) The development team were shown the results for discussion, and action points for further development of the maps were set.
(7) The method and results were evaluated for relevance outside this study.

The maps in the experiment

Marine clay is a type of surficial deposit that exists in previously ice-covered land areas. These are marine deposits, but because of land rise, the areas are now also above sea limit. Due to their typically flat terrain and the presence of a thick layer of topsoil, these areas are often converted into farmland or human settlement. When the salt is gradually washed out, certain marine clays can liquefy (turn quick) making the ground unstable. Under certain conditions, this poses a risk of landslides or slope failures (With et al., 2022). Examples of quick clay landslides with catastrophic consequences are the Rissa landslide in 1978 (Gregersen, 1981; L'Heureux & Solberg, 2013), Tuve and Småröd landslides in Sweden (Larsson & Jansson, 1982; Rosvall & Kjellberg, 2009), Mint Creek in Canada (Geertsema & Torrance, 2005) and Gjerdrum landslide in 2021 (OED, 2021). These all caused a loss of lives and property. Mapping and securing these deposits therefore have high national priority in the affected countries. Two of the maps that are used to help identify possible areas at risk are known as the "Possibility of marine clay" and the "Marine limit." The former map must be used together with the latter to be complete. Marine clay occurs beneath the marine limit, the maximum level of the sea after the last ice age. The combination will from here on be called "Marine clay map." The maps are delivered by the Geological Survey of Norway (NGU), see Figure 1.

Radon is a natural gas generated from uranium and thorium in the underlaying bedrock. Long term exposure to radon in indoor air can cause lung cancer. Several national organizations have started mapping radon to prevent inhabitants being exposed to high levels of radon (Ielsch et al., 2010). The map selected for this study (Figure 2) was made on

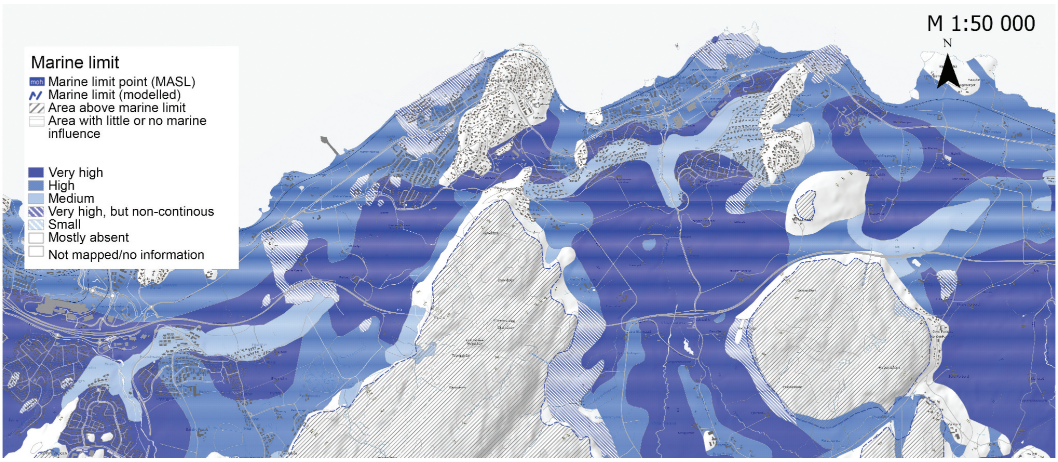

Figure 1. The marine clay map (possibility of marine clay map including marine limit), NGU (2022).

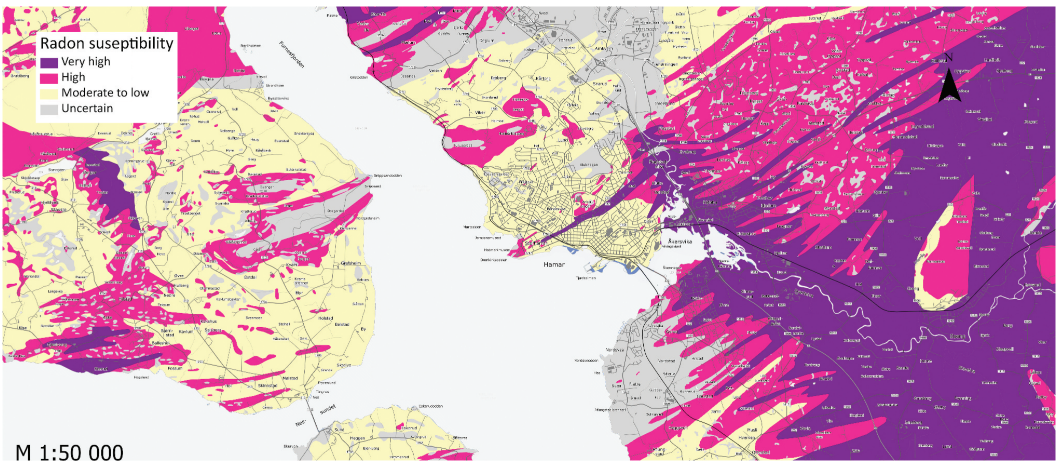

Figure 2. The current radon susceptibility map (NGU, 2022).

assignment from and in collaboration with the Norwegian Radiation and Nuclear Safety Authority by combining data for indoor measurements, radiometric data, as well as surficial deposits and bedrock maps (Smethurst et al., 2017; Watson et al., 2017). A new, improved map is under development by Wang et al. (2023). It is of utmost importance that these maps communicate the information as accurately as possible, so they can effectively contribute to risk management.

A web-based experiment was set up to reach a high number of participants that represent a broad user-group, while also complying to COVID-19 restrictions. Also, there was a need for a method that later potentially could be used for low-threshold follow-up studies on the same or other maps.

Emphasis was placed on the success of a categorization-task, as there was a lack of control over time use and potential disturbances during the web experiment. The legend was removed as it can be challenging to find on web maps (Hagemeier-Klose & Wagner, 2009) and often missing in screen captures of web maps found in news articles. Also, the focus was on symbol intuitiveness, rather than the user's ability to learn and complete a task with a legend provided.

The experiment was set up using a standard web tool for surveys to ensure randomization. In the beginning a brief guide was provided and the various map types were presented in random order. These measures were implemented to reduce the possible influence caused by initial participant uncertainty about the tasks in the experiment on the results. Each participant was randomly presented with only one map alternative for each of the map types. The participants were asked to provide information about their gender, age, education, knowledge levels in "geology" and "maps, GIS and cartography" and any previous knowledge of the maps. A translated copy of the survey is available at https://www.surveymonkey.com/r/readthemap and in the supplementary material on Dataverse (Bang-Kittilsen, 2024).

Pilot study

A pilot study with 20 participants was conducted within the map owner's organization. Formulations and question alternatives were modified according to feedback and test analyzes of the results were conducted to ensure fit-for-use. The questions regarding uncertainty were revised to minimize potential misunderstandings and additional employment categories were included.

Inviting users

Users were invited through social media and e-mail, through both formal and informal channels. There were no restrictions to whom could participate. The informal channels included Facebook groups for students, planners, and teachers. The semi-formal invitation was sent through the social media accounts of the Geological Survey of Norway and NTNU's intranet for engineering student groups. Also, colleagues and friends reposted both on Facebook and Twitter, in addition to forwarding the invitation through an e-mail.

Analyzes

To measure intuitiveness, the factors selected were task performance (categorization task) and detected information uncertainty (yes/no), together with participant uncertainty (yes/no) and confidence (0–100). Standard statistical analyzes were used to test whether there were statistically significant differences between the map alternatives (Table 1). When statistically significant differences were identified, a thorough examination of these results was conducted using descriptive statistics and graphical representations. Graphs were presented to discuss the results with the map owner and development team.

A simple intuitiveness score from 0 to 5 was calculated for each sample area. A correct answer that did not indicate participant uncertainty received the highest score of 5. A correct, but uncertain response gave a score of 4, close to correct (score of 3), further from correct (score of 2), incorrect and uncertain (score of 1). Finally, an incorrect answer not marked with uncertainty received a score of 0. The underlying idea was that even if many participants correctly guessed the category for "high risk," the score would be lowered if a significant number of them also perceived this a safe area. If most participants had a correct and close to correct, this would give a better score. A calculated mean gave an overall score for the map alternative.

Table 1. Statistical tests and graphs used.

Variables	Graphs	Tests	Rationale
Categorization	Bar, line	The Chi-square test (Normal distribution) or Fisher's Exact Test	Nominal data, < 5 in each cell
Uncertainty, Confidence	Box, line	ANOVA, T-test	Interval and ratio data

Results and discussion

Map analysis and test scheme

Marine clay map

Interviews with the map owner reveal challenges with the marine clay map. One issue brought forward was the cartography used for the marine limit. The geologists wanted a dashed line to communicate uncertainty, therefore thickness and interval length has been a topic of discussion. The area above marine limit is filled with diagonal lines to signalize it is not relevant as there in general is no overlying marine sediments.

The possibility of marine clay map is derived from the established Norwegian surficial deposits map, produced by the Geological Survey of Norway (Hansen et al., 2014). Breaking down the apparently single data variable "Possibility of marine clay" reveals that some categories are ordered in relation to one another, while others have a nominal relation. The ordered categories are "low," "medium," "high" and "very high possibility of clay occurrence." The "very high" category has a variant: "thin or not continuous." In addition, there are categories that indicate "not reported" and "not mapped." As a result, a basic sequential color scale is not suitable. The original cartography uses an integral bivariate technique with shades of blue to show the probability of clay where the simple area fill is replaced by a diagonal line pattern fill to show the second variant "thin or not continuous." The separation between the categories "not reported" and "little or no chance of marine clay" proved challenging. In the map, they are represented with respectively no or white fill and look similar in the legend. This obvious misinterpretation was not tested in the experiment but was communicated to the map development team. This complex categorization is caused by the heterogenous art of the data. Surficial deposits are mapped and categorized according to their origin for a general purpose. Therefore, according to the map owner, reclassification for the deducted clay map had to be done by manual interpretation of each of the over 70 types of surficial deposits in discussion with the other experts of the team. For example, the "deposits from flooding" gives a "high possibility of clay" and "marine mud deposit" gives a "very high possibility of clay" (NGU, 2022).

A copy of the dataset is published as a map service by The Norwegian Water Resources and Energy Directorate with a slightly different cartography, reusing the map layer together with the quick clay hazard map. For the marine limit, they use a solid, but thinner line with a lighter color.

Marine clay map test scheme

The interviews and map analysis resulted in a test scheme (Table 2) and eight alternative images for the experiment (Figure 3). The map alternatives were set up from different combinations of the symbolization from the two published map variants. Images from the map section were laterally reversed to make the location less recognizable. Map alternative 1 has the authoritative symbolization and map alternative 8 has the alternative symbolization as it is presented by the cooperating institution. *The other map alternatives are different combinations of the two sets of visual variables*. The map alternatives were set up to make it possible to use all participants in analysis of every variable tested.

Participants were asked to categorize four sample areas (A-D) in the following map categories: 1: Not mapped/no information, 2: Area above marine limit. 3: Mostly absent. 4: Low possibility of clay, 5: Medium possibility of clay, 6: High possibility of clay, 7: Very high possibility of clay.

Radon susceptibility map

The radon susceptibility map is based on a 1:250 000 bedrock map and 35 000 in-house measurements of radon and surficial deposits map in 1:50 000–1:250 000. Bedrock objects where buildings have high indoor concentrations of radon were categorized as "high" or "very high," the remainder were "moderate or low." The areas classified as uncertain/unknown in the radon susceptibility map lack sufficient indoor measurements, or the measurements are too uncertain to conclude. The current version of the map is shown in Figure 2.

The visual variables used do not strictly follow the semiology of graphics, as they use hues for the "high" (pink) and "very high" (purple) categories that do not have a clear order. Also, a possible effect of the yellow area is that it may be perceived as "background," while the pink and purple are perceived as "foreground." In the yellow area, there can also be high concentrations of radon, although less common than in the other. A known challenge is that although the map is made for overview use only, some users conclude on a single residential property. This is not within the scope of this study, therefore it is not tested or discussed further.

Deconstructing the seemingly single information variable "radon susceptibility" reveals information in two dimensions: Three ordinal categories of susceptibility and one category for uncertain or unknown risk. The latter has a nominal relation to the other categories. Grey may be claimed to have a nominal relation to the other three colors used, being a color between black and white.

Radon susceptibility map test scheme

In this experiment, 8 map alternatives (Figure 4) were set up from different combinations from the existing

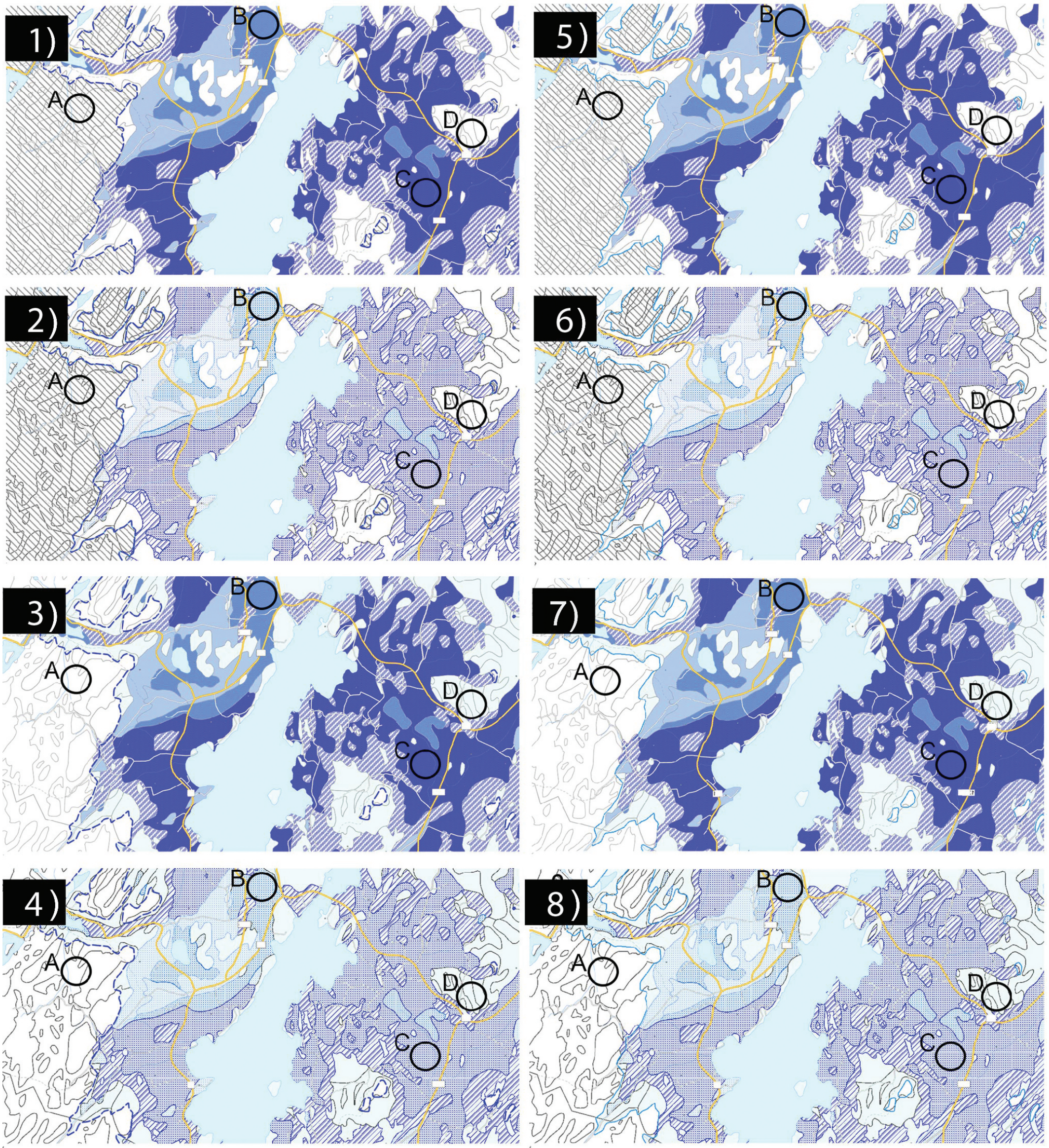

Figure 3. Map alternatives for the marine clay theme.

Table 2. Test scheme for the marine clay map.

Test variable	Alternative	Maps	Alternative	Maps
Can participants order symbols for possibility of clay from low to high possibility?	Solid blue colors with high contrast	1,3,5,7	Hatched blue area fill with lower contrast	2,4,6,8
Do participants intuitively link the diagonal fill to the area above the marine limit?	Diagonal line fill	1,2,5,6	No fill	3,4,7,8
Does the different symbol for marine limit have any affect?	Hatched, thick, blue line	1,2,3,4	Thin, blue, solid line	5,6,7,8

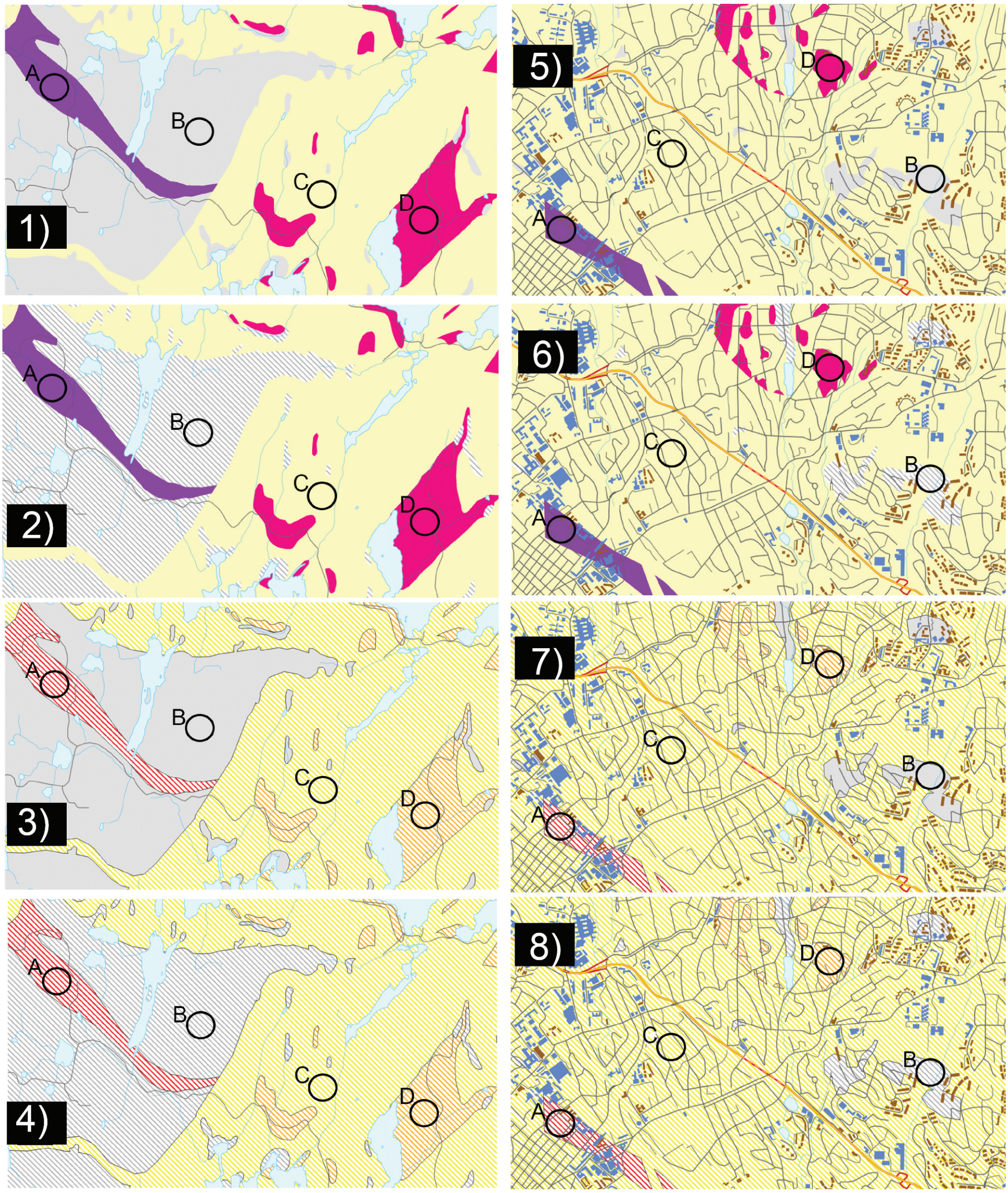

Figure 4. Map alternatives maps for the radon susceptibility map.

Table 3. Test scheme for the radon susceptibility map.

	Alternative 1	Maps	Alternative 2	Maps
Are participants able to order area fills for degree of susceptibility from low to high?	Yellow, pink, and purple solid fill	1,2,5,6	Yellow, orange, red diagonal line fill	3,4,7,8
Which alternative make participants connect the fills for uncertain area better?	Grey solid area fill	1,3,5,7	Grey diagonal line area fill	2,4,6,8
How does different map section/location affect the results?	Rural	1,2,3,4	Urban	5,6,7,8

map (Figure 4, map alternative 1) with a map using typical susceptibility map colors (Figure 4, map alternative 8) according to the test scheme (Table 3). The alternative map has a scale from yellow via orange to red, leaving out the green color, as it is not possible to conclude the area is free from radon. In addition, instead of a solid fill, diagonal line fill was used, which is used in the more known "Quick clay hazard map" (Havnen et al., 2017). The variables for testing were: Area fill for susceptibility categories (original map colors vs risk colors in diagonal line fill), area class for uncertainty (original solid gray, diagonal gray line fill) and map section (urban, rural). The categories the participants were asked to choose from were "no susceptibility," "low susceptibility," "medium susceptibility," "high susceptibility" and "no information/not mapped."

Experiment results

Participants in the experiment

A total of 598 participants started the survey and opened at least the start page, while 450 participants (76%) completed the whole experiment. The average time used was 12 minutes and 32 seconds. Only the completed surveys were included in the analysis. Figure 5 presents an overview of the participant demographics. There was a predominance of highly educated participants, slightly more men than women and a normal distribution across age categories, with a peak on 35–44 years. The participants predominantly reported low and intermediate knowledge levels in geology and maps/GIS and cartography. As Figure 5d) shows, increasing knowledge in geology is followed by increased self-reported knowledge in maps, GIS, and cartography.

A few participants said they recognized the areas in some of the maps, a single participant even gave the right place name for one of the maps (Radon).

Marine clay map

The participants were asked to categorize four sample areas. The null hypothesis is that the differences in cartography do not create statistically significant difference in answers. The alternative hypothesis is that it does. The Fisher's Exact test shows significant values for all sample areas (p-values <0.001). From this, the null hypothesis can be rejected.

From the bar graphs in Figure 6 it can be observed that:

- Participants generally think that the susceptibility is higher when stronger colors are used (map alternative 1,3,5,7), than with the hatched area fill.
- More participants recognize the area above marine limit when this area is white (map alternative 3,4,7 and 8) and not when filled with diagonal lines.

The expected result was that most participants would be able to order the categories from low to high guided by

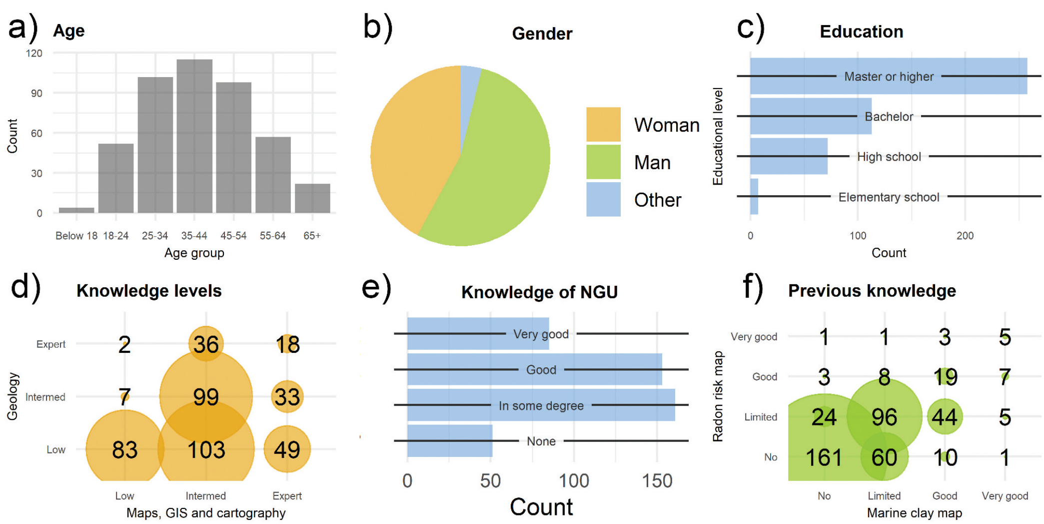

Figure 5. Graphs showing distribution of participants across a) age, b) gender, c) education level (completed), d) knowledge levels in geology and maps, GIS and cartography (self-reported), e) knowledge of NGU (activities) and f) previous knowledge of the maps in the experiment.

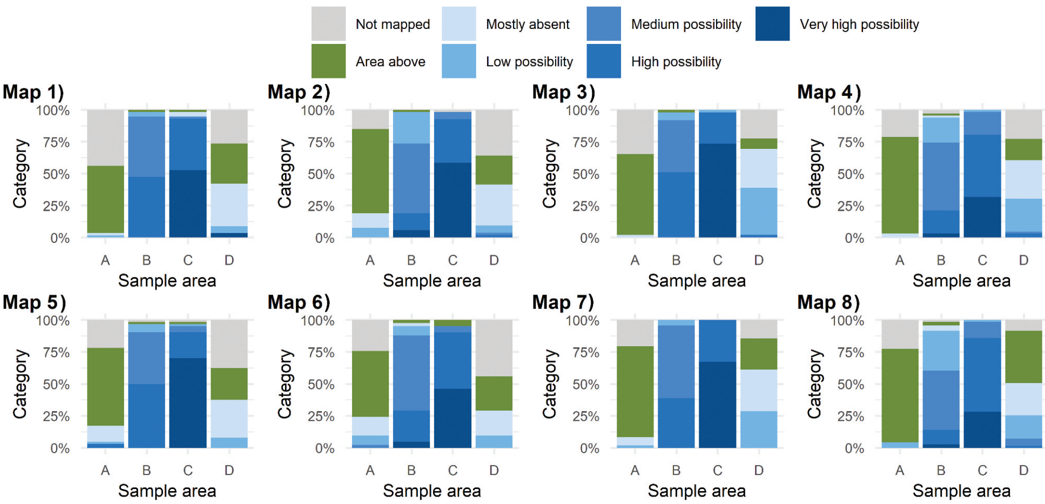

Figure 6. Bar graphs showing the percentage of answers for each category across map alternatives. The correct answers are A: Area above marine limit, B: High possibility for clay, C: Very high possibility, D: Mostly absent.

the color value from light to dark. For the map alternatives with the solid fill colors with higher contrast between colors (map alternative 1,3,5 and 7), the results show more than 90% of the participants could do this. As Figure 7 shows, map alternatives 2,4,6,8 have fewer participants that answer correctly, the "butterfly" pattern reflects participants, who were struggling to order the sample areas. Many participants commented that they understood darker color represented higher possibility. For the alternative map, where the hatched area displays lower contrast between the colors, the number of correct answers was lower. For example, a participant commented that the colors are challenging to separate from each other, that they are too similar. For the two variants of area fill for low to high possibility of clay (map alternative 2,4,6,8 versus 1,3,5,7), the Fisher Exact

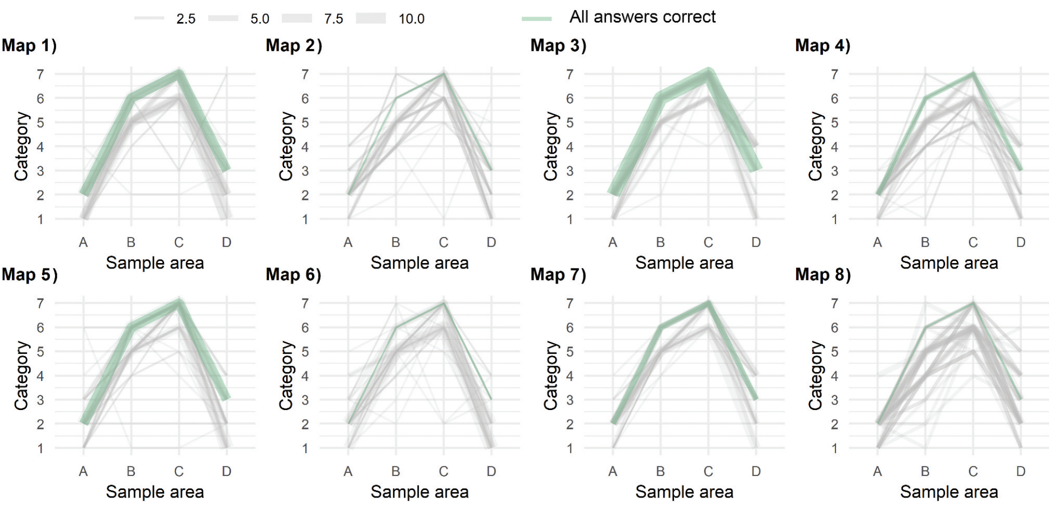

Figure 7. Line graphs showing the set of answers for all participants. The green line represents the percent of participants with the correct set of answers. Categories for possibility of clay (y-axis) are 1: No data, 1: Area above marine limit, 3: Mostly absent, 4: Low, 5: Medium, 6: High, 7: Very high possibility of clay.

test finds significant differences for B, C, and D (all p-values <0.001). There is higher participant uncertainty for sample area B (high possibility area sample) for map alternative with the hatched, lower contrast fill (map alternative 2,4,6,8).

The area above marine limit is filled with diagonal lines in the authoritative map. This was selected with the purpose of communicating that this area mostly can be disregarded for the theme of the map, but the symbol has higher participant uncertainty score (Figure 8, sample area A, map alternative 1,2,5,6, blue line) and information uncertainty score (orange line). The latter is incorrect; the uncertainty is higher for the areas *below* marine limit.

The same relative proportion of participants (64.9% and 65.3%) correctly think A is above the marine limit when the thick, dashed line is used as the thin, solid, light blue line. Marine clay map alternative 2 has a lot higher confidence score than map number 6 (see Figure 8) even though the only difference is that map alternative 2 uses the dashed, thicker blue line alternative. There is also high participant uncertainty for area A in map alternative 6. This map has a combination of diagonal line fill for both "above marine limit" and the categories for possibility of clay.

The result when quantifying the intuitiveness, shows map alternative 3 and 7 has the overall best scores for categorization, and a relatively high confidence score (Table 4).

A higher confidence is found with the odd numbered maps where the strong, blue colors are used. There is an exception for map alternative 2, which is also high. A thick, strong-colored dashed line for marine limit seems to compensate for the lower scores of the alternative cartography (see Table 4, map alternative 2).

Experiment results - radon susceptibility map

See Figure 9 for a comparison of the answers to the categorization task for the map alternatives. The Fisher's Exact test finds clear significant differences for all sample areas (all p-values <0.001).

From the bar graphs (Figure 9) the following can be observed:

- Participants struggle to order high (A) and medium susceptibility (D) for maps 1,2,5 and 6, with the currently used cartography.
- Most participants think the gray area in area sample B ("not mapped"/"uncertain") represents "no susceptibility."
- Participants often interpret "low susceptibility" as "no susceptibility" in urban areas (map alternative 5–8).
- Using two more distinct visual variables for "uncertain" and susceptibility categories for map alternatives increases the number of correct answers (map alternative 2,3,6,7).

We can conclude from the bar graphs, supported by the p-values, that there is a relationship between map alternatives and participants choice of category. And the null hypothesis that the differences do not matter, can therefore be rejected.

The line graphs in Figure 10 show the percentage of participants who mark the area samples with either

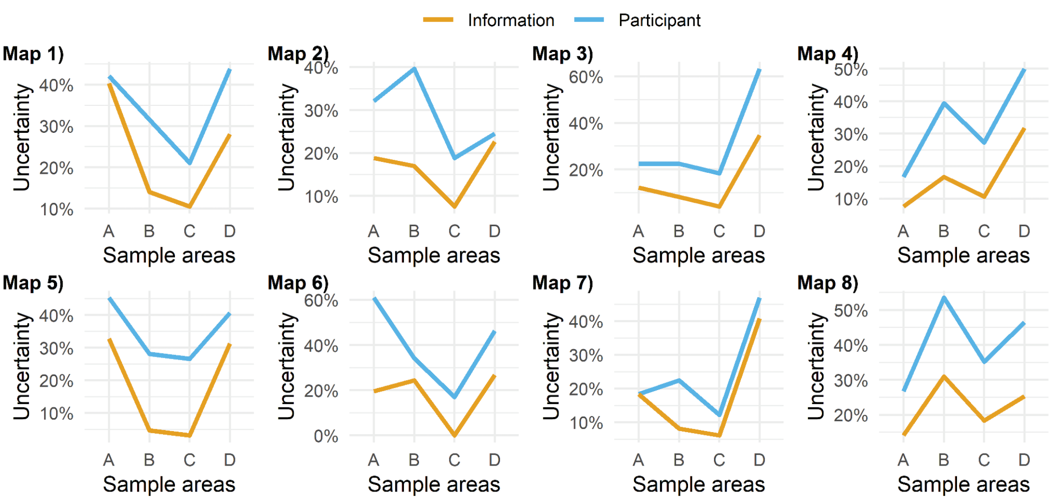

Figure 8. The line graphs show participant uncertainty (blue line) and information uncertainty (orange line) for the eight marine clay map alternatives.

Table 4. Intuitiveness and confidence scores for the marine clay map alternatives.

Map	A	B	C	D	Score	Confidence
1	3.8	3.8	4.1	3.0	3.7	55.6
2	4.1	3.2	4.3	3.5	3.8	58.3
3	4.2	3.9	4.5	3.5	4.0	56.1
4	4.4	3.2	3.9	3.3	3.7	46.9
5	4.0	3.8	4.3	3.4	3.9	54.0
6	3.7	3.3	4.1	3.2	3.6	45.1
7	4.3	3.7	4.6	3.0	3.9	57.7
8	4.3	2.9	3.9	2.4	3.4	44.0
Mean	4.1	3.5	4.2	3.1		

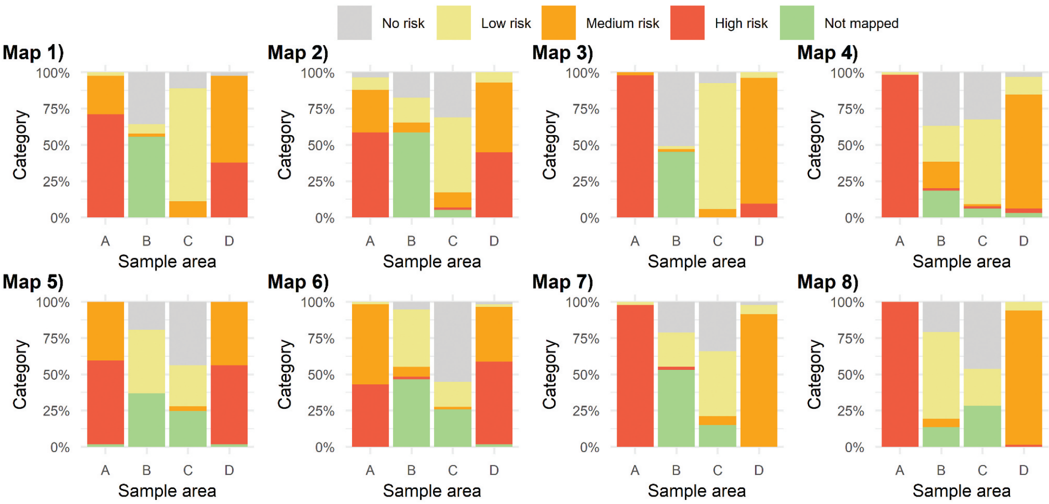

Figure 9. Bar graphs showing the percentage of answers for each category and sample area across maps. Map alternative 3 has the most correct answers; "low" for sample area A, "not mapped/uncertain" for B, "high" for C and "medium" for D.

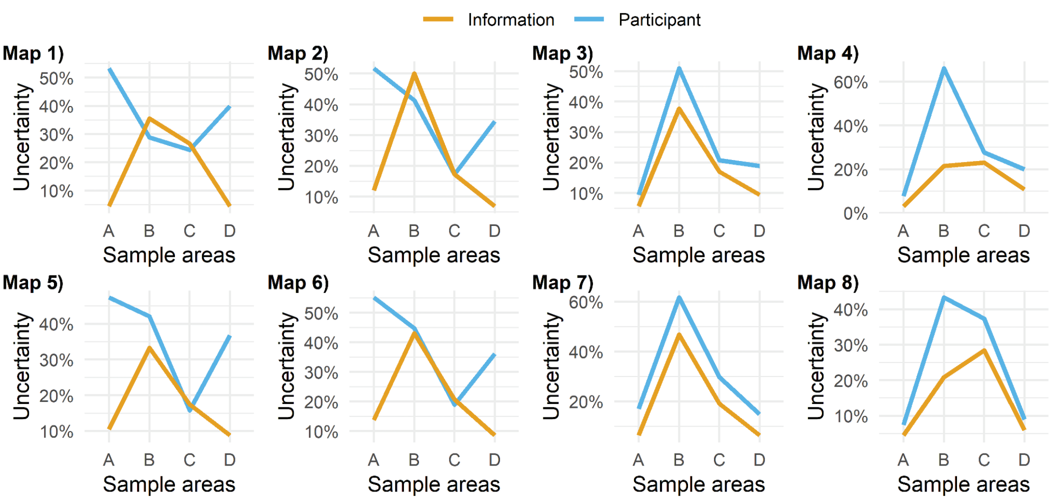

Figure 10. Line graphs showing the percent of participants marking the sample areas with participant (blue line) and information uncertainty (orange line).

uncertainty in categorization or that the information category seem to contain more uncertain information than others (if any). Here, the following observations can be made:

- There are significant differences between map alternatives for which sample areas the participants were uncertain about.
- Participant uncertainty is high for the medium and high categories when the strong pink and purple colors are used (map alternative 1,2,5,6).
- For map alternative 3 and 8 both participant and information uncertainty are high for the uncertain/not mapped category.

Map alternative 3 has the overall best intuitiveness score (Table 5). This map alternative also has a high confidence score and an adequate line graph curve on uncertainty. Also, the line graph for map alternative 3 in Figure 11 shows a cleaner image with few outliers.

On average, participants reported 52 in confidence (certainty about their answers on the categorization task) when solving the map task on a scale from 0 (low confidence) to 100 (high confidence). The maps with the lowest confidence scores are map 2 and 6. These maps have solid fill in yellow, pink, and purple for the susceptibility categories and hatched gray for "uncertain." The maps with the opposite use of hatched fill and solid color fill, create the highest confidence levels.

Discussion

Marine clay map

Comparing two marine clay maps (Figure 12), the line graph for map alternative 3 is cleaner, has more correct answers (green line) and is thereby more intuitive than map 8. None of the participants presented with map alternative 8 had all the answers exactly right, and the parallel lines below the green in the line graph, shows that the participants more often think the possibility of clay is lower when lighter colors and less contrast are used. This result can be explained by heuristics: When using value as a visual variable, the use of the full scale from light to dark colors, is recommended to improve visual contrast (Itten, 1974). These results also suggest that participants expect to find dark colors for high-possibility categories.

Using hatched fill (map alternative 2,4,6 and 8) gives lower scores on the categorization task (Table 2). However, the use of the thick blue dashed line for marine limit in map alternative 2 gives notably higher confidence score (58.3) and a lower score for participant uncertainty, than map alternative 6 (45.1), all other symbols being equal. This can possibly be explained by higher contrasts in the map image overall. In conclusion, the dashed line is still preferred to make a distinct separation between clay-areas and not clay-areas as intended.

For the area above marine limit, leaving the area blank is the most favored alternative among the tested alternatives. However, to separate it from not mapped and uncertain categories is a necessity. Therefore, a new, but less prominent symbol is being considered for the next version of the map.

Radon susceptibility map

The Radon susceptibility map is a continuous map showing four non-overlapping area categories. Three of these have an internal order from "low" to "high susceptibility." The fourth category is an area where it is not possible to categorize due to lack of data. This category has a nominal relation to the other three. This area has a gray color on the map, while the other categories are yellow, pink, purple displaying increasing susceptibility. Less than half of the participants intuitively identifies the "uncertain" sample area correctly in the Radon susceptibility map.

As expected, there is confusion about the order between the middle (D) and high susceptibility (A) categories when they are represented with pink and purple color, as in the existing map (map alternative 1,2,5 and 6). The used colors are too similar in value or darkness, and as a result none of them stands out as stronger than the other. As a result, about half of the participants put them in the wrong order.

Table 5. Intuitiveness and confidence scores for the radon map alternatives.

Map	B	A	D	C	Score	Confidence
1	2.6	4.0	3.8	3.9	3.6	56.1
2	2.8	3.7	3.7	2.8	3.3	47.8
3	2.2	4.9	4.7	4.5	4.0	62.2
4	1.3	4.9	4.3	3.0	3.4	59.0
5	2.0	3.9	3.6	1.8	2.8	55.6
6	2.4	3.6	3.5	1.4	2.7	47.7
7	2.7	4.8	4.7	2.4	3.6	61.5
8	1.0	4.9	4.8	1.3	3.0	62.9
Mean	2.1	4.3	4.1	2.6		

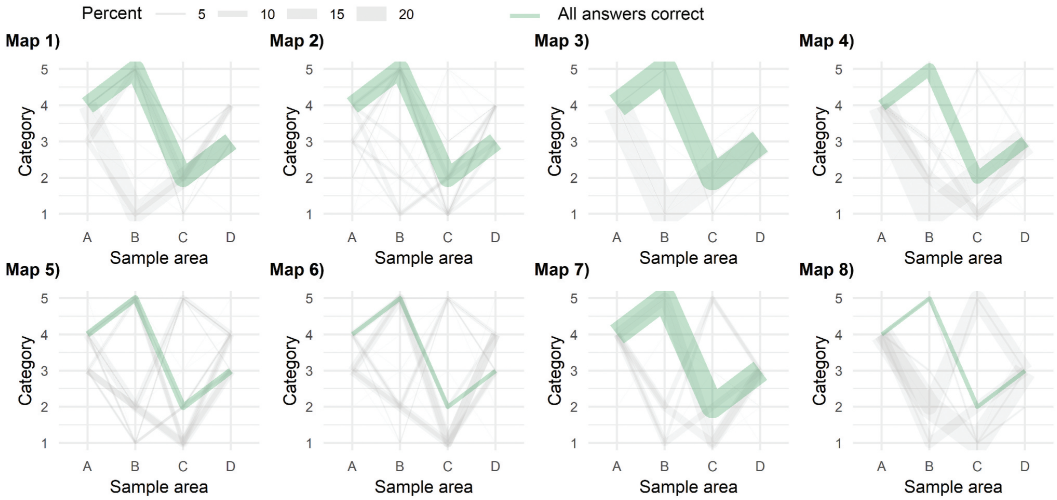

Figure 11. Line graphs showing all answers for the eight alternative radon map alternatives. The green line represents the percent of participants with the correct set of answers. The green line represents the group with all answers correct.

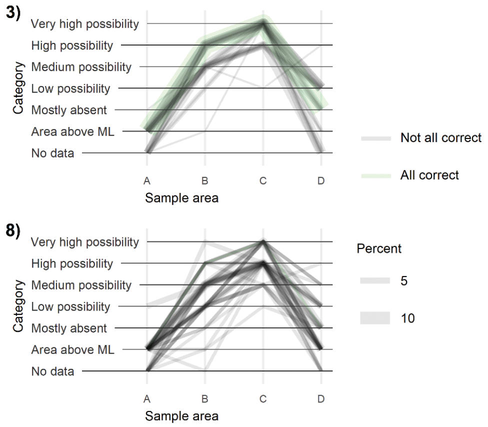

Figure 12. Comparison of results for map alternative 3) and map 8) for marine clay.

In addition, the distance in color between pink, purple in one end of the scale and yellow on the other is too large for it to be perceived as an ordered scale: Especially when faced with the urban map sections, the yellow area is most often interpreted as "no susceptibility," followed by "low susceptibility" and "uncertain" (see Figure 9, map alternatives 5–8). This may be explained by a figure/ground-effect, where participants may perceive the yellow area as background, and this as "no susceptibility." One difference between the urban and rural map sections is that the low susceptibility category covers a larger area in the urban map. This may increase the figure/ground-effect. The urban map also has more information like more roads and buildings. Cartographers have discussed the importance of their responsibility to help map readers quickly and accurately distinguish figure from ground (e.g. MacEachren & Mistrick, 1992). According to Vecera et al. (2004), *"These visual processes are important, because figures form the basis of much visual processing – humans are more likely to recognize and act upon figures than backgrounds."*

Finally, the results are better when a separate and distinct visual variable is used for the *uncertain*-category. For alternatives 4 and 8, 42.4% think the gray hatched area is "low susceptibility" compared to 15.9% that correctly think this is "uncertain." Changing the "uncertain"-category to having a solid fill (maps 3 and 7) more than doubles the correct answers. Alternatively, changing the fill for the susceptibility categories to the original solid fill colors, and keeping the gray diagonal line fill for *uncertain*, makes an even better result for area sample B. Using solid fill for susceptibility, and diagonal line fill for "uncertain," or the other way around, increases the correct answers from 29% to 51%.

Overall, map alternative 3 has the best results. See Figure 13 for a comparison between map alternative 3 and 6.

Presenting and discussing results

The results were presented to the map owners and map development team. The visualizations gave an

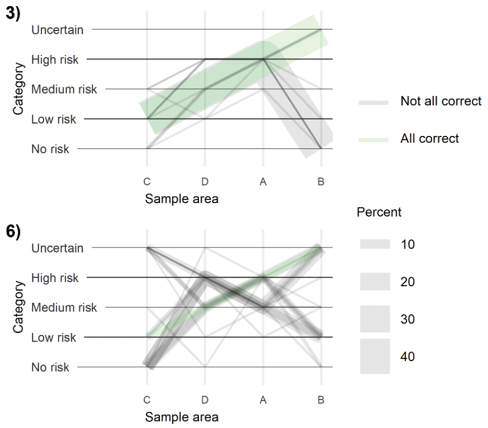

Figure 13. Comparing the answers from map alternative 3) and 6), where map alternative 3) has the overall best test results. For map alternative 6), participants struggle to order sample area for medium (D) and high susceptibility (A), and some also categorize the low susceptibility symbol as uncertain.

opportunity for the geologists to also draw conclusions themselves and ask questions.

The line graph where the thickness of the lines was varying with the relative proportion of participants with the exact same set of answers was effective in engaging the team. The graph was easy to grasp, and it was easy to see that some graphs were less messy, and thus representing a better map alternative. The statistics, frequency diagrams and bar graphs were necessary for the analyses and to explain the results in-depth. For the visual analyses, the more iterations of graphs and groupings, the better to reveal possible relationships and explanations. These results were in turn discussed with the visualizations of the results.

Taking the time to carefully deconstruct the maps, gaining in-depth knowledge of the choices behind the existing product, and visualizing and discussing the test results, gave ground for appreciation of each other's expert competence. The tests and following possible cartographic explanations gave room for common learning and development for the next versions of the maps. What was evident was that the geologists, being scientific employees, clearly appreciated the methodological input and scientific approach to the user-orientation of products.

Action points were jointly made. For both maps, there was now a request that prototypes based on the defined goals, were made by the cartographer for discussion, instead of the geologist. In addition, there is a demand for user studies for existing and new maps in other parts of the organization. There is an increasing demand in society and acknowledgment in the organization that the map products need to have high usability. Meetings, plans and resources must be set up to ensure user-oriented map development, where actual challenges with the maps can be identified and discussed, and new versions tested to reduce the risk of misinterpretation and misuse. To make better thematic maps, it is important to involve cartographic expertise early and foster the cross-disciplinary collaboration.

Generalizable results

The map experiment returned the following generalizable results:

- Minor differences in symbolization have a significant impact on how easily the symbols are understood correctly.
- Symbology should be tested as dependent of all other objects in a map, as the interplay of all objects in the map affects the result.
- If map categories have a mix of ordered and nominal relations between them, the hierarchy and structure of the information should be communicated with a corresponding set of distinct visual variables with the same hierarchy and structure to ease understanding.
- Contrast in the map image increases confidence.
- The use of darker color scale (full contrast) in solid area fill makes map readers perceive a higher susceptibility than with the use of a color scale with light colors and less contrast.

In a society where map literacy is variable and individuals are overloaded with information, paying more attention to map design has the potential to give a large positive impact. A general challenge to the cartographic community is how to display uncertainty. Further research is needed on how different kinds of uncertainty, for example interpreted as opposed to measured, overview data as opposed to detailed, not mapped as opposed to no occurrence and "inadequate data" could be symbolized in an intuitive way simultaneously in the same map, alongside with the thematical classes. New symbol conventions need to be developed, preferably across fields.

Evaluation of the map experiment

The map experiment returned a rich data material that enlightened the understanding of how easily the maps are understood. It was especially fruitful to analyze the results visually, regrouping and reanalyzing with increasing knowledge. The line graphs made it easy to identify the differences between map alternatives. Therefore, these graphs were valuable to create engagement when presenting and discussing results with the map development team and others. Bar graphs depicting the relative proportion of all answers were used to identify and find explanations for the differences. Communicating map intuitiveness through visualization of confidence and uncertainty in addition to answers on categorization, gave a more solid base for conclusions. A confident, but wrong answer could reveal serious problems with the selected cartography.

Using a web-based survey and lowering the threshold for the experiment with ready-made categories and keeping the time to finish down to 10–15 minutes can have contributed to the high number of participants.

Conclusions

In this study, the first research question was what can be learned from applying map experiments into map development. Performing research within the mapping and map producing organization proved fruitful for appreciating each other's expertise for common learning and development. The work resulted in a demand for more focus on map prototyping and testing.

The next research questions were how intuitive the map symbols are without a legend present, and what increases and decreases intuitiveness. This experiment gives evidence that even minor differences in symbolization can have significant impact on map intuitiveness. Two susceptibility maps were tested in the experiment, focusing on three variables for each map. Map intuitiveness was evaluated based on correct answers, confidence, and uncertainty evaluations. The most intuitive map alternatives are number 3 for both the marine clay and the radon susceptibility map (Figure 14).

Marine clay map alternative 3 has more correct answers, less diversification of answers and higher confidence scores. For the marine clay map, the conclusion is to keep colors with good contrast and find a new symbol for the area above marine limit. The diagonal fill area above marine limit created visual noise and is also confusing for the participants. Another action point is to simplify the categories, if possible, without losing essential information and to find symbols that more intuitively separates between a possibility of clay (uncertain) and not (unlikely).

For the radon map, the map with a diagonal line fill with a typical susceptibility color scale and a solid gray fill for "uncertain" (map alternative 3) proves most intuitive. This map uses standard risk-colors in diagonal line fill, with the uncertain category as a solid gray area. More participants perceive it alike and there are fewer outliers. The action points include selecting a better color scale for the susceptibility categories. Also, it is recommended to use a different, more distinct visual variable for the uncertain area. Finally, actions should be taken to reduce the risk for the "low"-category to be perceived as background, and therefore interpreted as *uncertain* or *no susceptibility*.

For the last research question, how map intuitiveness can be measured, analyzed, visualized, and communicated to support design decisions, this study exemplifies a way of doing this. A line graph where one line represented the amount of this set of answers, and where the line representing the correct was marked, proved especially effective to engage others in meetings and discussions, and to demonstrate that symbol choices can really make a significant difference.

Map experiments can improve the comprehensibility of the maps and potentially reduce the likelihood of premature conclusions, thereby mitigating misinterpretations. The visualized results supplied empirical evidence for knowledge-based discussions on further development of the maps. If the demands for an open and accessible public knowledge base are to be met, cartography should have a higher focus. Testing maps and their intuitiveness is one contribution to the democratization of maps to ensure adequate understanding and use of existing knowledge to solve societal challenges.

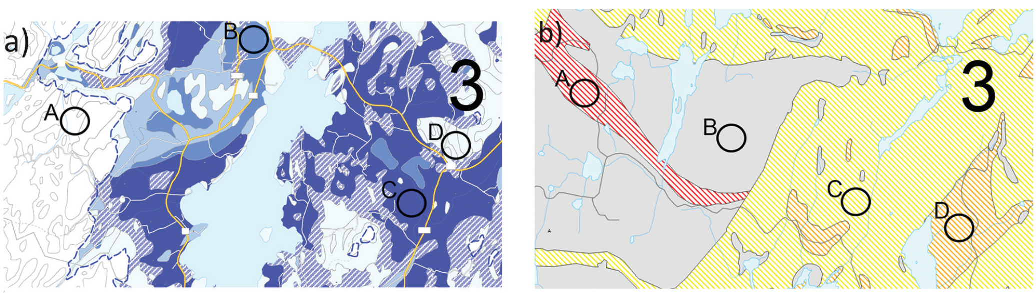

Figure 14. The two maps with the highest map intuitiveness scores.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Ane Bang-Kittilsen http://orcid.org/0000-0003-1427-0063
Terje Midtbø http://orcid.org/0000-0002-2262-7061

Ethics Declarations

The experiment was performed without collecting any personal identifying information.

Data availability statement

The data that support the findings of this study are openly available in Dataverse at https://doi.org/10.18710/FS2QXK.

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